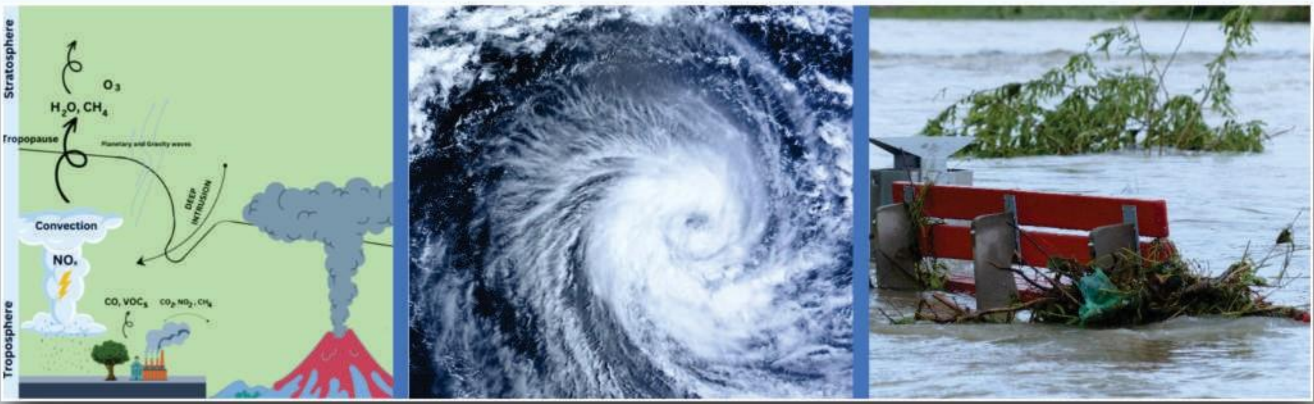
ABSTRACT BOOK



अंतरराष्ट्रीय कार्यशाला

समतापमंडल-क्षोभमंडल अंतःक्रिया एवं मानसून मौसम चरमावस्था के पूर्वानुमान

(एस.टी.आई.पी.एम.ई.एक्स)

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International Workshop on Stratosphere-Troposphere Interactions and Prediction of Monsoon weather EXtremes (STIPMEX)

02 - 07 June 2024

सत्यमेव जयते
Ministry Of Earth Sciences
Government of India

WORLD METEOROLOGICAL ORGANIZATION

STIPMEX

Preface

It is our pleasure to introduce the abstract volume of the International Workshop on Stratosphere-Troposphere Interactions and Prediction of Monsoon weather EXtremes (STIPMEX) being held during 2 to 7 June 2024 at IITM Pune. The theme of the workshop is based on linkages between processes related to stratosphere-troposphere interactions and challenges in prediction of Monsoon weather Extremes. There is a need to understand the above said linkages since the people are concerned about the Asian summer monsoon (ASM) and the rising extreme precipitation events over the Asian region including India during the past decade. The STIPMEX has brought together international and national experts in the field of stratosphere troposphere process and extreme weather prediction to discuss and brainstorm role of stratospheric processes and the scientific challenges required for improving the skills of weather forecasts, along with a component of capacity building through dedicated training given to students and early career scientists and academicians. The papers presented at the workshop would give insights on dynamical and chemical changes occurring via stratosphere-troposphere interactions and on the current status, challenges and future pathways of improving predictions of monsoon weather extreme events. The level of interest in the themes of the workshop is manifested with over 225 suitable papers submitted for presentation at the workshop. The submitted papers are organised into specific sessions, to provide each paper with sufficient time for presentation and to accommodate all of them within the allocated session time. The workshop theme emphasizes on the links between stratosphere troposphere process and the prediction of extreme weather events. The workshop begins with training sessions to the students on 2 June 2024. The training is organized in two parallel batches on stratosphere-troposphere exchange processes and prediction of monsoon weather extremes respectively. The training session features (1) hands-on high altitude balloon flight, (2) model/reanalysis data for understanding the stratosphere-troposphere interactions, (3) highly specialised talks from international experts on scientific challenges required for improving the skills of weather forecasts and(4) hands on experience with ECMWF forecast outputs. The scientific sessions featuring oral and posterpresentations are organized during 3 to 7 June 2024. 300 delegates from 20 different countries of Asian,European, American and African continents are participating in the workshop. We would like to thankall the participants for their contributions to the program and to this Abstract volume.

We thank the Secretary, Ministry of Earth Sciences, Govt. of India and Director, Indian Institute of Tropical Meteorology for their continued guidance, and encouragement to make this workshop feasible on this large scale. The financial support from Ministry of Earth Sciences (MoES), World Weather Research Programme (WWRP), Atmospheric Processes And their Role in Climate (APARC), Forschungszentrum Jülich, Germany is gratefully acknowledged. We are also indebted to all involved in the organization of STIPMEX. We hope that STIPMEX will be an interesting and informative workshop.

STIPMEX Organizing Committee

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Composition, Origin, and Fate of the Asian Tropopause Aerosol Layer – a View from Aircraft and Satellite by Infrared Remote Sounding

Michael Höpfner[1], Jörn Ungermann[2], and the GLORIA team[1,2]

[1]Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research (IMK-ASF), Karlsruhe, Germany
[2]Forschungszentrum Jülich, Institute of Energy and Climate Research (IEK-7), Jülich, Germany

Remote sensing in the infrared spectral region is a powerful tool to analyse the composition of the atmosphere in regions and heights which are not easily accessible. This contribution provides an overview of the application of this method to the analysis of the Asian Tropopause Aerosol Layer (ATAL). We span the arc from unveiling the composition and formation of ATAL particles during the StratoClim aircraft campaign in 2017 to the detection of these particles during the PHILEAS campaign in 2023. During these campaigns, the airborne GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) instrument sounded the altitude region of the upper troposphere and lower stratosphere within central region of the Asian Monsoon Anticyclone (AMA) in 2017 as well as its westerly and easterly outflow in 2023.
The measurements in 2017 provided the first evidence of solid ammonium nitrate (NH4NO3, AN) particles being a major component of the ATAL (Höpfner et al., 2019). Furthermore, the concurrent detection of large amounts of ammonia gas (NH3) in the upper troposphere indicated this gas as the main precursor for secondary aerosol AN-particle formation. Trajectories combined with temporally and locally connected satellite data of nadir-pointing instruments, showed the origin of NH3 on ground, transported to the upper troposphere by convection in spite of the great potential for wet deposition. The importance of NH3 for aerosol formation and AN for nucleation of cirrus cloud particles as inferred from laboratory observations will be reviewed.
In addition to the airborne dataset, satellite infrared limb observations by the CRISTA instrument on SPAS in 1997 as well as MIPAS on Envisat, from 2002-2011 provided a global picture of the evolution of AN as well as NH3. As possible continuation of satellite measurements of the ATAL and the upper atmosphere in general we will introduce the CAIRT satellite project as candidate for ESA's Earth Explorer 11.

MIPAS on Envisat, 2002-2012; GLORIA on Geophysica, 2017; GLORIA on HALO, 2023; CAIRT (2030ies).

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Advancing Atmospheric Composition Predictions and Related Services to Meet the Growing Societal Needs

Gregory Carmichael[1]

[1]University of Iowa, Iowa City, 52246, USA

Changes in atmospheric composition impact air quality and human health and play key roles in the Earth's weather and climate systems. For example, aerosol amounts, and physical and chemical properties determine their toxicity, radiative and microphysical impacts. Recent advances in observations and models are significantly enhancing our ability to quantify the distribution and properties of aerosols, understand their impacts on atmospheric radiation and cloud distributions and properties, and their impacts on human health. Furthermore, tropospheric ozone levels remain high in many parts of the world, impacting human and ecosystem health. Smoke and wind-blown dust also impact transportation and renewable energy production. To meet societal needs atmospheric composition information is needed at higher resolution and with longer lead times (including seasonal to sub-seasonal). Improving air quality predictions requires further improvements in key processes, emission estimates, and the observing system. Advancements in Earth System models and coupled data assimilation are also needed. This talk draws on illustrative results from on-going activities to highlight areas where further advances in models and observations are needed to enhance seamless prediction of environmental, weather and climate services across relevant spatial and temporal scales. The talk emphasizes that the high-quality atmospheric composition infrastructure, consisting of observations, model predictions, data management, and people, and which delivers high quality open access, atmospheric composition information as described at this conference is of critical importance to society.

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Relationship Between Water Vapor and Cold Point Tropopause During Boreal Summer

Mijeong Park[1]

[1]NSF NCAR, Boulder, CO, USA

The seasonal variation in water vapor follows the cold point tropopause (CPT) temperature, setting the “base” for the tropical tape recorder during the dry phase. During the wet phase, enhanced water vapor over the Northern Hemisphere summer monsoon regions makes its way into the lower stratosphere. The enhanced water vapor over the Asian monsoon region is collocated with relatively colder tropopause temperature. Compared to the Asian monsoon, tropopause over the North American (NA) monsoon is lower and warmer. It is unclear how the variability in the tropical CPT temperature can explain the near global water vapor variability in the lower stratosphere in Boreal summer. In this study, the unique relationship between water vapor and CPT temperature over the Asian versus NA monsoon regions using measurements from NASA’s Aura Microwave Limb Sounder (MLS) and the Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS). Diurnal to seasonal time scale variabilities in the CPT will be analyzed using the high-resolution measurements obtained from the Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC- 2). The results show that higher water vapor is entering the stratosphere through the NA monsoon regions during Boreal summer and show weak dependency on local CPT temperature

The Influence of Monsoon Sub-seasonal Variability on the Occurrence of Sub-visible Cirrus Clouds over the Asian Monsoon Region

Ajil Kottayil[1], Bernard Legras[2], Prajwal K[1], Aurelien Podglajen[2] and Erik Johansson[3]

[1]Satellite Remote Sensing and Applications, Advanced Centre for Atmospheric Radar Research, Cochin University of Science and Technology, Cochin 682022, Kerala, India.
[2]Laboratoire de Météorologie Dynamique, IPSL, CNRS UMR8539, ENS-PSL/Ecole Polytechnique/Sorbonne Université
[3]Swedish Meteorological and Hydrological Institute, SMHI, Sweden

Sub-visible clouds, composed primarily of ice crystals, typically occur in the upper troposphere and lower stratosphere of tropical regions. These clouds exhibit low optical depth, allowing greater permeability to solar radiation and thus inducing less cooling through the albedo effect. Additionally, due to their lower temperatures, they emit less longwave radiation. Consequently, such upper-level clouds generally contribute to warming. Despite being a significant source of annual rainfall, the summer monsoon experiences sub-seasonal fluctuations characterized by active and break phases, which can lead to devastating floods or severe droughts across the Indian subcontinent. This study aims to explore the formation mechanisms of sub-visible cirrus clouds associated with these monsoon sub-seasonal variations. We will employ Lagrangian back trajectories initiated from sub-visible cirrus cloud altitudes identified by the CALIPSO satellite and the back trajectories would be linked to clouds detected by GRIDSAT satellite. This analysis will focus on the June to September months for the period from 2007 to 2010. By tracing the origins of sub-visible cirrus clouds and determining whether they form in-situ or as a result of deep convection, we aim to elucidate the influence of monsoon sub-seasonal variability on their formation mechanisms.

Study the Influence of the Asian Summer Monsoon on the Upper Troposphere and Lower Stratosphere using Methane Distributions

Dmitry A. Belikov[1], Prabir K. Patra[2,1], and Naoko Saitoh[1]

[1]Center for Environmental Remote Sensing, Chiba University, Chiba 263-8522, Japan
[2]Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama 236-0001

The Asian Summer Monsoon (ASM) is the dominant type of atmospheric circulation that affects the upper troposphere and lower stratosphere (UT/LS) during the Northern Hemisphere summer. This large system extends from Southeast Asia to the Middle East. Its dynamics control persistent and intense convection over the Indian Peninsula and adjacent oceanic regions, intense surface heating over the Tibetan Plateau, and orographic uplift along the southern/southwestern slopes of the Himalayas. The deep convection associated with this monsoon system creates the conditions for the vertical transport of polluted boundary layer air into the UT/LS. This transport continues through horizontal advection, allowing these compounds to be dispersed to other regions or to rise further into the stratosphere. Therefore, the atmospheric pollutants and tracers, including methane (CH4) quickly transporting to large distances. In general, CH4 has a chemical lifetime of about one year in the tropical troposphere, which rapidly changes to about 100 years at altitudes of the tropopause and higher. This unique property makes CH4 a valuable species for investigating atmospheric transport in the UT/LS. To elucidate the complex transport pathways within and around the monsoon anticyclone, this study adopts a comprehensive approach. It involves the analysis of global three-dimensional distributions of CH4 observed by the Thermal Infrared (TIR) sensor on board the Greenhouse gases Observation SATellite (GOSAT). In addition, simulations with an Atmospheric Chemistry-Transport Model (ACTM) contribute to a holistic understanding of the complex interplay between the ASM and the distribution of methane in the Earth's atmosphere.

We found that the most active interhemispheric transport (IHT) occurs in the upper troposphere, in a layer of 200 hPa below the tropopause. The IHT over tropical South America and Africa is active almost all year round, while in the Asian region there is a significant seasonality caused by ASM. We confirm and clarify the influence of zonally asymmetric heating on the IHT in the ASM and highlight an important role of the monsoon-induced eddy circulation in the cross-equatorial transport of long-lived trace gases in the extended zone between tropical Africa and Southeast Asia. Zones of the most active IHT are clearly marked and quantified over the Asian, African, and American continents.

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Implication of Precursors of Secondary Organic Aerosols on UTLS and its Impact on the Indian Summer Monsoon

Pawan Vats, Shiwansha Mishra, Amit Kumar Sharma, and Dilip Ganguly*

Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India

The present study discusses the sensitivity of secondary organic aerosols (SOA) and its precursors on the Indian summer monsoon. It is evident from previous studies that the SOA formation is highly sensitive to changes in Volatile organic compounds (VOC) precursor emissions, stoichiometric coefficients, and specifically emissions of nitrogen oxides (NOx). There are evidences suggesting the underestimation of VOCs and SOA within chemistry-climate model is due to the underestimated VOCs in emission inventories. We perform several simulations using Community Atmosphere model including extensive interactive atmospheric chemistry (CAM4-Chem) from 2008 to 2013 with "specified dynamics". The model study involves the experiments particularly with CMIP6 emissions, improved anthropogenic VOCs, NOx emissions and stoichiometric coefficients (SC) to understand the effects of these factors towards SOA, and hence summer monsoon. The results from our analysis suggests that increasing SC, emission of VOCs leads to higher SOA formation over Indian region, which further enhances Hadely circulations in the mid to upper troposphere, resulting in enhanced precipitation in central India. Further, enhancement in the accumulation of SOA from Benzene (SOAB) in the Upper Troposphere and Lower Stratosphere (UTLS), which appears to result in the greater horizontal transport within the UTLS due to the large concentration of SOAB, with 95% level statistical significance. Previous studies suggested that longer atmospheric stay time of aerosols attributes to higher UTLS transport due to deep convection (Vernier et al., 2015; Srivastava et al., 2016). For all the simulations the presence of SOAB remains constant in UTLS throughout the year. The reason for the presence of SOAB in UTLS could be due to the decrease in the temperature with increase in height leading to the formation of more SOAB from semi-volatile oxidation which agrees with the results of Hoyle et al., (2011). The results from our sensitivity simulations suggest that the change in SOAB concentration with latitude-pressure is most pronounced in the UTLS during the monsoon season, likely attributable to active convection. More results with greater details will be presented.

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Relative Roles of Convection and Advection in the Sustenance of the Asian Summer Monsoon Anticyclone

P. P. Musaid[1], Sanjay Kumar Mehta[1], Susann Tegtmeier[2], Masatomo Fujiwara[3], Siddarth Shankar Das[4], and Someshwar Das[5]

[1]Atmospheric Observations and Modelling Laboratory (AOML), Dept. of Physics, SRM Institute of Science and Technology, Kattankulathur, 603203, India
[2]Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, SK, Canada
[3]Faculty of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan
[4]Space Physics Laboratory, VSSC, Thiruvananthapuram, India
[5]South Asian Meteorological Association (SAMA), New Delhi, India
*Corresponding Author: Dr. Sanjay Kumar Mehta (Email: ksanjaym@gmail.com; sanjaykr@srmist.edu.in)

The Asian Summer Monsoon Anticyclone (ASMA) is a gateway for atmospheric pollutants transported to the upper troposphere and lower stratosphere (UTLS). Thus, it is necessary to understand the relative roles of vertical transport due to convection and horizontal transport due to advection in the formation and sustenance of the ASMA. Outgoing longwave radiation reveals that the ASMA region shows characteristic features associated with strong convective activity in its eastern (70ºE to 120ºE) part while the dominance of subsidence in the western (20ºE to 70ºE) part. Over the convective region, the convergence of latent heat flux extends from the Indian mainland (65ºE to 110ºE) to the west Pacific Warm Pool (WP) (110ºE to 160ºE). On average the ASMA region is characterized by a main convective outflow level at ~9 km, however, it varies considerably over the longitude. We observed the outflow level is higher (~10.5 km) over the convective region while lower (~7 km) over the subsidence region. Further, the convective outflow level is higher in the WP (11.5 km) region when compared to the Indian mainland (10 km) region. We have further calculated the convective and advective terms using the thermodynamic energy equation that characterized the anomalously cold advection over the subsidence region and warm advection over the convective region. The convective region is further characterized by two anomalous warm advections with a stronger one located over the Indian region compared to the WP region. The anomalously cold advection occurs over the subsidence region mainly centered near 30°E longitude of the subsidence region. We observed the dominance of the convection over the Indian mainland (convective term ~ 4 K/day) compared to the WP region (~ 1 K/day). We further investigated the association between the convection over the Indian region and the cold advection over the subsidence region as well as warm advection and convection over the WP region.

Impact of Large-scale Atmospheric Circulation on the Ozone Variability in the Upper Troposphere-Lower Stratosphere (UTLS) of the Asian Summer Monsoon Anticyclone (ASMA)

Gopikrishnan G S and Jayanarayanan Kuttippurath

CORAL, Indian Institute of Technology Kharagpur, 721302 India.

Weather and climate are significantly influenced by events occurring in the upper troposphere and lower stratosphere (UTLS). Changes of ozone in the UTLS modify the thermodynamics and composition of the atmosphere, either directly or indirectly, and has a significant effect on global climate change. In this study, we use the ozonesonde measurements from 7 different stations in the Asian Summer Monsoon Anticyclone (ASMA) region and from a station outside this region to analyse the impact of large-scale atmospheric circulations including the El Niño-Southern Oscillation (ENSO) and the quasi-biennial oscillation on the UTLS ozone. The ASMA region is further categorised into three, namely the Indian Summer Monsoon Region(ISMR), Southeast Asian Region (SEAR), and East Asian Region (EAR), providing a diverse set of data for the summer (JJA) season for the period 1980–2020. A Multiple Linear Regression (MLR) model is used for trend computation, which assesses the variability of regressed ozone from explanatory factors and thus quantifies their individual contribution. The explanatory variables or proxies utilised are QBO, ENSO, the 11-year solar cycle and the stratospheric aerosol optical depth (sAOD). The MLR model shows a high correlationbetween observations in the lower troposphere (350–200 hPa) and those above 100 hPa across all regions. TheENSO have the highest positive contribution (0.5 ppbv-1 JJA-1) at the Java station, which is outside the ASMAregion, in the lower altitudes (350–200 hPa), and the contribution gradually decreases to 0.1 ppbv-1 JJA-1 at 200–100 hPa, but negative (0.2 ppbv-1 JJA-1) above 100 hPa. ENSO's impact on the ISMR has a mean contribution of about 0.1±0.3 ppbv-1 JJA- 1 in the altitude region of 350–100 hPa. The QBO shows greatest impact on the stations averaged over ISMR and for the measurements from Java, with an average contributionof about 0.2±1 ppbv-1 JJA-1. This effect is prominent in both lower levels (350–100 hPa) and higher levels (above 60 hPa), but negligible within 100–60 hPa. Nevertheless, the MLR contribution of QBO at Java showsa similar pattern to the ISMR, with a mean contribution of about 0.1±0.5 ppbv-1 JJA-1. However, the effect of QBO is almost negligible in the SEAR and EAR.

How would Stratospheric Aerosol Geoengineering Affect Tropical Monsoon Rainfall?

Prof. Govindasamy Bala

Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru -560 012

According to the latest IPCC report (2021), the planet is now warmer by 1.1°C relative the pre-industrial era and the current concentration of the major anthropogenic greenhouse gas, CO2, is nearly 50% above the pre-industrial levels. Several monthly temperature records have been broken in 2023. The trends in global temperatures and other manifestations of climate change such as the increase in frequency and intensity of extreme events, retreat of mountain glaciers, acceleration in sea level rise and the rapid decline of sea ice in the Arctic are continuously monitored and reported in the climate science literature. Catastrophic scenarios such as crop failure and forest dieback due to severe droughts, rapid melting of Greenland and Antarctic ice sheets and release of CO2 and CH4 from permafrost soils in high latitudes are projected to occur in the future, though with low probability. There are several issues that relate to the manageability of these severe impacts of climate change. These include:

- Can we cool the climate system rapidly within a span of few years in case of a climate emergency?
- Are there solutions to stabilize warming at 1.5 or 2°C in case these limits are breached?

During the last 2 decades or so, there have been serious discussions on how global warming could be arrested or reversed in case of a climate emergency or an overshoot. In this context, several climate scientists around world are now debating extensively about a planetary scale engineering solution popularly known as “solar geoengineering (SG)” or “solar radiation modification (SRM)”. Some argue that the ambitious target of limiting global warming to 1.5°C above the pre-industrial temperature level is not feasible without the implementation of SRM.

SG (or SRM) approaches would attempt to increase the amount of solar radiation reflected by our planet. Placement of mirrors in space or reflective aerosols in the stratosphere, and enhancement of the reflectivity of marine clouds are some options. The most studied option is the stratospheric aerosol geoengineering (SAG) which involves injecting sulfates aerosols into the stratosphere to deflect more sunlight to space. Over the last decade, my research group at IISc uses climate model simulations to investigate the impact of SAG on global and regional monsoon precipitation. Specifically, we have studied the sensitivity of monsoon precipitation to the latitudinal and altitudinal distribution of sulfate aerosols in the stratosphere. In my presentation, I will provide a brief background on SG followed by an extensive discussion of key mechanisms by which reflective sulfate aerosols in the stratosphere could affect the tropical monsoon rainfall.

Stratospheric Smoke Injections from the 2019–20 Australian Bushfires: Impacts on Radiation, Global Circulation, and Adjustments

Bernd Heinold[1], Fabian Senf[1], Anne Kubin[1], Jason Müller[1], Roland Schrödner[1], and Ina Tegen[1]

[1]Leibniz Institute for Tropospheric Research (TROPOS), 04318 Leipzig, Germany

The Black Summer bushfires that raged across Australia around the turn of 2019/2020 were unprecedented, characterized by extreme pyrocumulonimbus (pyroCb) events that transported extraordinary amounts of smoke into the lower stratosphere. During a key period between December 29, 2019, and January 4, 2020, multiple pyroCb events carried between 0.3 and 2 million tonnes of smoke particles to altitudes ranging from 12 to 14 kilometers. The resulting smoke layer dispersed widely over the southern hemisphere, persisting in the stratosphere even two years later as confirmed by lidar measurements. The intensity of the Australian fires was comparable to that of last major volcanic eruptions and had a notable climate impact. Smoke particles heat the atmosphere significantly more due to the black carbon they contain, in contrast to volcanic aerosol, which mainly reflects sunlight. Using the global aerosol-climate model ECHAM-HAM, we examined the dispersal and radiative effects of the Australian bushfire aerosol, as well as its impact on global circulation and atmospheric adjustments. The fire emissions, derived from daily satellite-based estimates, were prescribed from the Global Fire Assimilation System (GFAS). Since the model grid spacing did not allow an explicit resolution of pyroCbs, the injection height of the Australian fire smoke was varied between 5 and 15 km in sensitivity studies. These revealed how smoke injection and radiatively induced self-lifting influenced the plume evolution. Our simulations suggested a substantial disturbance in the radiation budget of the Southern Hemisphere, with a decrease in surface solar irradiance of more than 1 W m^{-2} from January to March 2020, corresponding to the dimming after a major volcanic eruption. Direct warming rates reached +0.5 W m^{-2} on average for the entire southern hemisphere and the months January to March 2020. The radiative impacts went beyond direct forcing, triggering complex adjustment processes. Stratospheric adjustments redistributed heating perturbations globally, leading to positive temperature perturbations in both hemispheres and additional longwave radiation emitted into space. These adjustments influenced the upper troposphere, decreasing relative humidity, cirrus amount, ice water path, and surface precipitation, along with weakening tropospheric circulation. Considering the recent surge in extreme wildfires globally, exacerbated by a changing climate, our findings underscore the necessity of incorporating pyroCb effects into global climate modeling.

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Influence of Merapi Volcanic Eruption on the Stratospheric Water vapor

Sandhya, M[1,2], and S. Sridharan[1]

[1]NARL, Gadanki, India
[2] NCMRWF, New Delhi, India

The long-term (2005-2014) observations of stratospheric water vapour mixing ratio (SWVMR) from Microwave Limb Sounder (MLS) instrument onboard Earth Orbiting Satellite (EOS) show annual variation with minimum during February-March and maximum during August-September at 100-56 hPa. There is a progressive shift in the maximum to later months as height increases. Besides, there is a large interannual variability of SWVMR with negative anomalies observed during 2006 and 2012 and positive anomalies during 2007 and 2014 and in particular during the winter 2010-11, when the stratospheric temperature also shows a large positive anomaly. The possible causative mechanisms for this large positive SWVMR anomaly are investigated. The positive monthly mean Southern Oscillation Index (SOI) anomalies and out of phase relationship between SOI and QBO at 50 hPa during the large positive anomaly of SWVMR in 2010-11 indicating that there is little role of ENSO and QBO for the SWVMR enhancement during this period. The daily variation of tropical averaged (10ºS-10ºN) residual vertical velocity, which is used to quantify the tropical upwelling, not shows evidence for the increase in SWVMR. The daily variation of meridional heat flux anomaly averaged for both the hemispheres (45ºN-75ºN and 45ºS-75ºS) (proxy for Brewer-Dobson circulation, BDC) shows high values during the winter 2010-11 revealing large planetary wave activity duringthat period. As the BDC transports minor constituents from tropics to higher latitudes and there is normally ananti-correlation between tropical SWVMR and BDC, there appears to be a minor role of high BDC for the observed large SWVMR anomaly. It is concluded in the present study that the large positive SWVMR anomalyis due probably to the tropopause temperature increase observed after the large Merapi volcanic eruption. On the largest eruption day, the total attenuated backscatter obtained by CALIOP shows the presence of a layer at17-18 km and aerosol cluster around 15 km over Indonesia indicating that probably the volcanic particles couldreach upper troposphere and lower stratospheric (UTLS) heights. The aerosol layer at UTLS height leads to increase of tropopause temperature which in turn causes increase of SWVMR a few weeks after the Merapi volcanic eruption. The observed pattern of stratospheric warming and tropospheric cooling also supports the role of volcanic eruption to the increase of SWVMR in the present study. The positive water vapour anomaliesduring the years 2006-07 and 2013-14 are also found to be preceded by volcanic eruptions.

Stratospheric Aerosol Characteristics during the Volcanic Eruptions using the SAGE III/ISS Observations

Bomidi Lakshmi Madhavan and Madineni Venkat Ratnam

National Atmospheric Research Laboratory (NARL), Gadanki – 517 112, INDIA

In recent years, several moderate volcanic eruptions and wildfires have perturbed the stratospheric composition and concentration with distinct implications on radiative forcing and climate. The Stratospheric Aerosol and Gas Experiment III instruments onboard the International Space Station (SAGE III/ISS) have been providing aerosol extinction coefficient (EC) profiles at multiple wavelengths since June 2017. In this study, we present a method to invert the wavelength-dependent stratospheric aerosol optical depth (sAOD) obtained by integrating the EC profiles of SAGE III/ISS from the tropopause altitude to 30 km to retrieve the number/volume size distributions and other microphysical properties, along with the evaluation of the sensitivity of these retrievals. It was found that the retrievals are strongly dependent on the choice of wavelengths, which in turn determines the shape of the calculated curves. Our method was able to retrieve the mono- and bi-modal shapes of the size distribution in the retrieval assessment. While the shapes of the size distribution are reliable, our inversion method overestimated the fine mode, which might affect the results of the size distributions. However, the influence of the overestimated fine mode effective radius is minimal. Further, we examined the changes in stratospheric aerosol spectral behaviour, size distribution properties, and time evolution (growth/decay) characteristics associated with subsequent moderate volcanic eruptions, namely, Ambae (15 0 S, 167 0 E; April and July 2018), Raikoke (48 0 N, 153 0 E; June 2019), and Ulawun (5 0 S, 151 0 E; June and August 2019), in different spatial regions. The observational period was classified with reference to Ambae eruptions into four phases (pre-Ambae, Ambae1, Ambae2, and post- Ambae). The pre-Ambae and post-Ambe periods comprise the 2017 Canadian fires and 2019 Raikoke/Ulawun eruptions, respectively. The spectral dependence of sAOD was comparable and lowest during the pre-Ambae and Ambae1 periods in all regions. The number concentration at the principal mode radius (between 0.07 and 0.2 μm) was observed to be higher during the Ambae2 period over the Northern Hemisphere (NH). The rate of change (growth/decay) in the sAOD on a global scale resembled the changes in the Southern Hemisphere (SH), unlike the time-lag-associated changes in the NH. These differences could be attributed to the prevailing horizontal and vertical dispersion mechanisms in the respective regions. Lastly, the radiative forcing estimates of Ambae and Raikoke/Ulawun eruptions, as reported in other studies, were discussed by taking clues from other major and moderate eruptions to gain insight into their role in climate.

Disturbing the Middle Stratospheric Balance: The Enduring Impact of Hunga Tonga-Hunga Ha'apai Volcanic Eruption

Ghouse Basha and M.Venkat Ratnam

National Atmospheric Research Laboratory, Department of Space, Gadanki 517112, India

Email:mdbasha@gmail.com; mdbasha@narl.gov.in

Despite being rare, large volcanic eruptions can have a long-lasting impact on the chemistry, radiation, and dynamics of the stratosphere and/or complete middle atmosphere. This study quantified the changes in the stratospheric water vapour and its relationship to temperature and ozone observed from space-based Microwave Limb Sounder (MLS) observations during the submarine volcano eruption Hunga Tonga-Hunga Ha'apai that occurred on 15 January 2022. The most notable aspect of this eruption is the plumes, which are water vapour columns that reached higher altitudes (1 hPa (47.6 km)) than earlier eruptions. We discovered that the eruption injected a record amount of water vapour (6–8 ppmv) directly into the stratosphere from 38–10 hPa vertically, which is present even after one year. The majority of water vapour is confined to the Southern Hemisphere (SH) tropics, i.e., 30◦S to 5◦N, and gradually descends to the SH polar latitudes over time. The WV from the lower stratosphere reaches mesospheric altitudes during January 2023. We quantify the impact of increased water vapour on temperature and ozone as well. Temperatures begin to fall during the month of March in the regions where there is an increase in water vapour. A ~5 K cooling occurs in July and August as a result of the thermal adjustment to the extra water vapour IR cooling. Our analysis shows a decrease in ozone caused by an increase in water vapour. Significant variability is observed in all three parameters at 26 km compared to other levels. Further, we noticed that after one year of eruption, the water vapour, Temperature and Ozone did not reach the background values. It is possible that this unusual eruption produced a different atmospheric reaction than other significant volcanic eruptions in the stratospheric region. More results will be present at the conference.

Unravelling the Dynamics of the Indian Summer Monsoon Circulation: Insights into ASMA Variability, Aerosol Distribution, and Pollution Transport

M. Venkat Ratnam

National Atmospheric Research Laboratory (NARL), Gadanki-517112, India vratnam@narl.gov.in

The Indian Summer Monsoon (ISM) circulation is one of the most dynamic systems among different monsoon circulations across the world. ISM is characterized by the low-level jet in the lower troposphere, the tropical easterly jet (TEJ), and the Asian Summer Monsoon Anticyclone (ASMA) in the upper troposphere and lower stratosphere (UTLS) region. High cloud cover with deep convective systems is commonly observed during ISM. Any changes in these elements will finally be reflected in the monsoon precipitation. ASMA is one of the important systems that persist for more than three months during the ISM season, extending from the Middle East to the Pacific. This anticyclone is characterized by a large, high-pressure system that forms over the northern Indian subcontinent and the Tibetan Plateau. Any pollutant entering into this ASMA will be trapped and persist for a long time, affecting the background through radiative forcing. The way ASMA varies, similar changes will be reflected in the chemical composition that includes aerosols and trace gases. Thus, the foremost objective is to understand ASMA variability itself. We used several reanalysis datasets to understand the variability of ASMA and to investigate how monsoon activity influences the ASMA. Huge differences among different reanalysis datasets are noticed in reproducing the dynamical changes of monsoon circulation including ASMA. Unusual behavior in ASMA is observed during El Niño conditions and during active and break monsoons. Next, aerosol and trace gas behavior within ASMA are investigated using long-term satellite measurements. Large asymmetry in the aerosol and trace gases distribution within ASMA is noticed. Long-term trends show increased pollutants in the ASMA, attributed to increased convection in global warming scenarios. Special experiments are conducted to obtain physical, optical, and chemical properties of aerosol within ASMA. Finally, the role of vertical and long-range transport of these pollutants into ASMA is also investigated. An overview of these investigations will be presented during the workshop.

Transport by Asian Monsoon Convection to the Upper Troposphere and Lower Stratosphere during the 2022 ACCLIP Campaign

Warren Smith[1], Laura Pan[1], Rei Ueyama[2], Shawn Honomichl[1], Teresa Campos[1], Silvia Viciani[3], Francesco D'Amato[3], Giovanni Bianchini[3], and Marco Barucci[3]

[1]NSF NCAR/ACOM, Boulder, CO USA
[2]NASA Ames, Moffett Field, CA USA
[3]National Research Council - National Institute of Optics (CNR-INO), Sesto Fiorentino, Italy

The Asian summer monsoon (ASM) has long been known as a weather system, but only recently has its role in atmospheric composition come to be explored in detail. During boreal summer, an anticyclone forms in the upper troposphere and lower stratosphere (UTLS) over Asia which is associated with a pronounced enhancement of chemical and aerosol species lofted from the boundary layer (BL) by ASM deep convection. Transport from the ASM UTLS anticyclone to the global atmosphere was the target of a recent airborne field campaign: The Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP 2022).

In this work, we overview the convective transport characteristics contributing to ACCLIP airborne sampling with the aid of Lagrangian trajectory modeling. Specifically, we use backward trajectories to connect airborne sampling to (satellite-derived) deep convection over Asia, and forward trajectories to connect airborne sampling to the stratosphere. Sensitivity of the results to the input meteorological analysis is explored. We consider aggregated campaign sampling as well as one or more specific sampling events of interest. Airborne in situ measurements of the tropospheric pollutant carbon monoxide (CO) from both research aircraft during ACCLIP are used to link the trajectory results with the observed UTLS environment.

The results reveal meaningful convective contributions from eastern and southern Asia to the air mass within the ASM UTLS anticyclone. Although ACCLIP sampling associated with southern Asia convection was preferentially less polluted, it often reached higher altitudes than convection over eastern Asia. Furthermore, we find that the majority of sampled air masses in the upper troposphere reached the stratosphere within the subsequent week. This work provides new insight into the role of ASM transport in impacting global atmospheric composition and provides valuable context toward community research on the ASM's chemical and climate impacts.

In situ and Satellite Observations of Tropopause Cirrus Clouds during the Asian Summer Monsoon: Results from the BATAL Campaign

Amit Kumar Pandit[1], Jean-Paul Vernier[1,2], T. Duncan Fairlie[2], Kristopher M. Bedka[2], Melody A. Avery[2], Harish Gadhavi[3], M. Venkat Ratnam[4], Sanjeev Dwivedi[5], K. Amar Jyothi[6], Frank G. Wienhold[7], Holger Vömel[8], Hongyu Liu[1], Bo Zhang[1], B. Suneel Kumar[9], Tra Dinh[10], Chris Roden[11] and A. Jayaraman[12]

[1]National Institute of Aerospace, Hampton, 23666, USA
[2]NASA Langley Research Center, Hampton, 23666, USA
[3]Physical Research Laboratory, Ahmedabad, 380009, India
[4]National Atmospheric Research Laboratory, Gadanki, 512112, India
[5]Meteorological Centre, India Meteorological Department, Bhubaneswar, 751020, India
[6]National Centre for Medium Range Weather Forecasting, Noida, 201309, India
[7]ETH Zurich, Zurich, 8092, Switzerland
[8]National Centre for Atmospheric Research, Boulder, 80307, USA
[9]Tata Institute of Fundamental Research Balloon Facility, Hyderabad, 500062, India
[10]Department of Physics, University of Auckland, Auckland, 1030, New Zealand. [11]University Corporation for Atmospheric Research, Boulder, 80307, USA [12]Bangalore University, Bengaluru, 560056, India

Cirrus clouds in the Tropical Tropopause Layer (TTL) have a net warming impact on the Earth's climate and they cause dehydration near the cold-point tropopause. Asian Summer Monsoon (ASM) is an important source of cirrus clouds in the TTL owing to frequent deep convection. However, better representation of convection and TTL cirrus clouds in global climate models is needed for accurate assessment of their response to changing climate which demands in situ measurements of ice crystals in these clouds. In this study, we present balloon-borne measurements of the micro-physical and optical properties of tropopause cirrus cloud layers obtained from the Balloon measurement campaigns of the Asian Tropopause Aerosol Layer (BATAL) over Hyderabad (17.47 °N, 78.58 °E), India during the monsoon season of 2017, 2018 and 2019. BATAL measurements reveal the presence of ice crystals smaller than 50 microns with spheroid shape. ERA5 temperature and water vapor observations from the SAGE III/ISS and Aura-MLS near the tropopause are used to see their connection with tropopause cirrus clouds observed from space-borne lidars- CALIOP and CATS. We also investigate the formation mechanism of a tropopause cirrus layer observed on 23rd August 2017 over Hyderabad in one of our balloon flights. We used a technique combining three- dimensional back-trajectories, satellite observations, and ERA5 reanalysis data. Satellite observations revealed that the overshooting convection associated with a category-3 typhoon *Hato*, which hit Macau and Hong Kong on 23 August 2017 injected ice into the lower stratosphere. This caused a hydration patch that followed the ASM anticyclone subsequently moving towards Hyderabad. The presence of tropopause cirrus cloud layers in the cold temperature anomalies and updrafts along the back-trajectories indicated towards the role of typhoon-induced gravity waves in their formation. This case study highlights the role of typhoons in influencing the formation of tropopause cirrus clouds through stratospheric hydration and gravity waves in the ASM anticyclone.

Network of ST/MST Radars and Balloon-borne Measurement Campaigns of the Asian Summer Monsoon Anticyclone (NetRAD-ASMA) - Initial Results

Siddarth Shankar Das[1,*], N. Poddar[1,2], M. V. Ratnam[3], A. K. Ghosh[4], A. Paul[5], M. Naja[6], S. Abhilash[7], S. Bhattacharjee[6], M. Durga, Rao[3], P. Nandakumar[5], V. Rakesh[7], S. K. Das[8], D. S. Raj[4], N. Das[4], G. Pandithurai[8], K. Raghunath[3], V. Venugopal[1,2], S. V. Sunilkumar[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram, [2]Department of Physics, University of Kerala, Thiruvananthapuram, [3]National Atmospheric Research Laboratory, DOS, Gadanki, [4]Satish Dhawan Space Centre, ISRO, Sriharikota, India, [5]Institute of Radio Physics and Electronics, University of Calcutta, Kolkata, [6]Aryabhatta Research Institute of Observational Sciences, [7]Nainital Advanced Centre for Atmospheric Radar Research, Cochin University of Science and Technology, Kochi, [8]Indian Institute of Tropical Meteorology, MoES, Pune, India

*e-mail : siddarth_das@vssc.gov.in & dassiddhu@yahoo.com

The Tibetan high is a climatological feature that occurs every summer in the Northern Hemisphere (NH) between 25-45°N and 70-105°E. Due to the strong thermal contrast, Tibetan Plateau (TP) is getting heated more than its surrounding areas and there is a high-pressure system developed at upper troposphere and lower stratosphere (UTLS). The anticyclonic circulation known as the 'Asian Summer Monsoon Anticyclone' (ASMA) develops as a response to the diabatic heating associated with convection over South Asia and lasts from around June to August with strong inter-annual variability. ASMA encompasses a westerly in mid-latitudes and easterly in the tropics. The occurrence of a tropical easterly jet (TEJ) in the NH summer and sub-tropical jet (STJ) in the NH winter are the prominent features associated with the ASMA region. It is known that the convection is the main mechanism which controls the seasonal variability in the strength of ASMA. The TP acts to enhance the coupling between the subtropical and tropical monsoon circulations, and have a significant impact on the intensity of precipitation over South Asia. Air mass transport within ASMA is one of the major sources of air pollution for the UTLS region. Remarkable horizontal and seasonal variabilities of minor constituents viz., water vapour, ozone, methane, nitrogen oxide, carbon monoxide, and aerosols are attributed to the strong winds and closed streamlines associated with this anticyclone, which act to isolate the air. In addition, TEJ and STJ play a key role in the horizontal distribution of tropical upper tropospheric humidity and mid-latitude ozone over the Indian region. The UTLS region is one of the key regions in and around ASMA, where the interaction of three processes, viz., dynamical, radiative, and chemical processes take place through a transition layer, known as "Tropopause". Thus, high-resolution measurements of winds, temperature, ozone and water vapour are essentially needed over ASMA region to understand the dynamics and chemistry of UTLS region. India has a network of Stratosphere-Troposphere (ST)/Mesosphere-Stratosphere-Troposphere) MST radars located at Gadanki (13.5°N, 79.2°E, 53 MHz), Cochin (10.04°N, 76.3°E, 205 MHz), Nainital (29.35°N; 79.45°E, 206.5 MHz), Guwahati (26.2°N, 91.75°E; 212 MHz) and Haringhata (22.94°N; 88.51°E, 53 MHz), which are located in and around the ASMA region and can provide a very high resolution measurement of winds, especially very air motion and turbulence intensity. In this context, an experimental campaign entitled 'NetRAD-ASMA (Network of ST/MST radars and balloon borne measurement Campaigns of the Asian Summer Monsoon Anticyclone)' Phase-I (winter campaign) was conducted during 12-16 February 2024 by operating the network of four ST/MST radars (Haringhata, Gadanki, Nainital and Kochi) along with regular radiosonde (6-12 hrs) measurements from Balasore (21.5ºN,86.9ºE), Nainital, Gadanki, Silkheda (23.56ºN,77.25ºE), Pune (18.53ºN,73.80ºE), Kochi and Trivandrum (8.5ºN, 76.9ºE). In addition, ozonesondes are also launched at an interval of 6 hrs during intense observation period from Balasore. To get background information, ozonesondes were also launched from Gadanki, Trivandrum and Nainital for 1-2 days. Micro-pulse, Rayleigh and Mie Lidars were also operated from Gadanki. Initial results show the enhancement of ozone concentration (Balasore) by about 60 nbar in the lower stratosphere, which persisted for more than 24 hrs. Balloon trajectory analysis shows drastic movement with the upper tropospheric westerlies and thus the stratospheric ozone was measured over the head Bay of Bengal which is about 150 km from the Balasore launching station. Vertical air motion observed from the Calcutta University ST-Radar (Haringhata) shows the presence of strong updrafts and downdrafts. Initial analysis shows that the enhancement of lower stratospheric ozone can be explained in terms of the balance between the photolysis of molecular oxygen and photo-dissociation of ozone as well adiabatic process in compression and expansion of air mass over the head Bay of Bengal. Such enhanced ozone is not observed over other location. The detailed results will be presented and discussed in the upcoming conference.

Insights from Tropical Tropopause Dynamics Experiments under GARNETS Program over the Indian Monsoon Region

Sunil Kumar S V[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Center, Thiruvanathapuram-695022

Correspondence to : sv_sunilkumar@vssc.gov.in

South Asia is one of the most important regions of the world which has global climate implications. This region is often considered as the main entry region of water vapour and other trace species to the global stratosphere. The distinct seasonal meteorology with prominent long-range transport pathways and stratospheric intrusion events during the winter and the Asian summer monsoon dynamics during the summer portrays the South Asian region as a perfect test bed to assess the diverse impacts of dynamic factors on the spatiotemporal variability of thermodynamics and tracer distribution in the upper troposphere and lower stratosphere (UTLS). However, despite of its significance, direct in situ measurements over this region are rather sparse. In this regard, systematically planned long-term and campaign mode in situ measurements of temperature, wind, water vapour and ozone in the UTLS region using balloon-borne radiosonde, ECC-ozonesonde and cryogenic frost-point hygrometer (CFH) at different stations (Trivandrum, Hyderabad, Kharagpur and Haringhata) over the Indian region is being carried out since April 2014 as part of Tropical Tropopause Dynamics (TTD) Experiment under GPS Aided Radiosonde Network Experiments for Troposphere-stratosphere Studies (GARNETS) program. The primary objectives of the GARNETS program are to examine the structure and dynamics of the tropopause layer, analyze the spatiotemporal variation of water vapor and ozone in the UTLS, and assess the role of monsoon dynamics, deep convection, atmospheric waves, and transport on the UTLS tracer distribution, cirrus formation, and thermodynamics.

The dataset acquired during the TTD campaigns served as a crucial tool in validating satellite- measured water vapor in the UTLS over the Indian Monsoon region. This unparalleled dataset has offered a novel insight into the Tropical Tropopause Layer (TTL), facilitating the delineation of its upper boundary through the utilization of static stability criteria. From these in situ observations, we have, for the first time, quantified the moisture budget in the UTLS over the Indian Monsoon region. In addition to that, this dataset also provides exciting insights on the UTLS stability, thermodynamic structure, ozone and water vapour variability, airmass characterisation of UTLS from chemical composition, moisture transport associated with monsoon dynamics and convection, and contrasting features of tropospheric turbulence and their generation mechanisms aiding a deeper understanding of the tropical UTLS structure and its intricate processes. Intriguing aspects of our study will be presented in the conference.

ATAL's Inter-annual Variability Derived from Satellite Observations and Airborne Measurements

Jean-Paul Vernier[1,2], Hongyu Liu[1], Amit Kumar Pandit[1], M. Venkat Ratnam[3], T. Duncan Fairlie[2†], Harish Gadhavi[4], Frank G. Wienhold[5], B. Suneel Kumar[6*], Gwenaël Berthet[7], Hazel Vernier[8], Jianchun Bian[9], Luke Ziemba[2], Christophe Mahnke[10] and Rubel Das[2]

[1]National Institute of Aerospace, Hampton, USA
[2]NASA Langley Research Center, Hampton, USA.
[3]National Atmospheric Research Laboratory, Gadanki, India.
[4]Physical Research Laboratory, Ahmedabad, India.
[5]ETH Zurich, Zurich, Switzerland.
[6]Tata Institute of Fundamental Research Balloon Facility, Hyderabad, India.
[7]Laboratoire de Physique Chimie de L'Environnement et de l'Espace, Orleans, France
[8]Groupe de Spectroscopie Moléculaire et Atmosphérique, Reims, France
[9]LAGEO, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[10] Institute of Energy and Climate Research, Julich, Germany

†Deceased on 27th April 2022
*Deceased on 12th February 2024
Correspondence to: jeanpaul.vernier@nasa.org

Asian surface emissions have drastically changed over the past decades with significant effects on air quality and precipitation over this region. During the Asian Summer Monsoon (ASM), air pollution is lifted up by convective systems into the Upper Troposphere and Lower Stratosphere (UTLS) as observed by in situ and satellite observations of enhanced Carbon Monoxide (CO) levels. An associated aerosol layer peaks in the UTLS coincidently with CO known as the Asian Tropopause Aerosol Layer (ATAL), a recurrent summertime aerosol feature extending between 13-18 km during the ASM. Significant progress has been made since its discovery to better characterize its optical, microphysical, and chemical properties but limited studies have looked at inter-annual variability and trends of the ATAL. In this presentation, we will describe how satellite observations from the Stratospheric Aerosol and Gas Experiment (SAGE) II and III/ISS missions as well as those obtained from the Cloud-Aerosol Lidar Pathfinder Satellite Observations are used to study the long-term variation of the ATAL and assess its evolution. In addition, aircraft, and balloon-borne measurements during the StratoClim, ACCLIP, BATAL and SWOP campaigns will also be combined with those from space-based observations. The overall goal is to further assess how the ATAL has varied over the past 2-3 decades and understand some of the current limitations. Through this work and interaction with participants at this workshop, we hope to gain understanding on the potential climate and hydrological impacts of those variations.

Strategy for More Ground-based Observations to Constrain the Lower Boundary Condition in Atmospheric Models

Marc von Hobe[1], Florian Voet[1], Felix Ploeger[1], Paul Konopka[1], Johannes Laube[1]

[1]Institute for Energy and Climate Research (IEK-7: Stratosphere), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

Processes in the planetary boundary layer (PBL), i.e. the part of the atmosphere directly above the Earth's surface, play an important role in driving weather and climate as well as atmospheric chemistry. The latter is impacted particularly by surface emissions, both natural and anthropogenic, and uptake of trace gases. In atmospheric models, trace gas concentrations in the PBL are typically prescribed as part of the 'lower boundary condition', constructed by the interpolation of available near surface observations. Consistent high-quality observations are provided by coordinated networks of ground-based observatories or sampling sites (e.g. GAW, NDACC, NOAA) around the globe. But while the station density and corresponding data coverage is generally good in North America, Europe and parts of Asia, large gaps of up to several 1000 kilometres between stations lead to significant uncertainties in interpolated or assimilated trace gas concentrations in some regions, particularly in the Global South. Reasons for the lack of observations are numerous and include limited accessibility, insufficient training of local scientists and technicians, and the lack of instrumentation and/or funding thereof.

In this presentation, we use the most recent version of the Chemical Lagrangian Model of the Stratosphere (CLaMS) to illustrate how additional measurements of selected trace gases in undersampled regions could make a difference by significantly reducing uncertainties related to the model's lower boundary. We then put forward a strategy to promote – and ultimately conduct – desired observations, particularly in India, South Asia, South America, and Africa. The strategy includes fostering of international collaboration and exchange of data and knowledge as well as supporting the use of accessible and affordable instrumentation and infrastructure.

Variability in the Tropospheric Ozone in Asian Summer Monsoon Region: Ozonesonde Observations (2011-2023) from ARIES, Nainital

Manish Naja[1], Mukesh Kumar[1], Prajjwal Rawat[2], Vikrant Tomar[1], Piyush Bhardwaj[3], Mahendar Rajwar[1], Rajesh Kumar[4]

[1] Aryabhatta Research Institute of Observational Sciences, Nainital, 263001, India
[2] NASA, city, postal code, USA
[3] CSTEP, Bangalore
[4] NCAR, USA.

South Asia is home to two pristine regions, the Himalayas in north and wide oceanic region in south. In-between a densely populated landmass with a large numbers of industries, coal based thermal power plants and agricultural activities, leading to greater levels of emissions of several trace species. Additionally, the dilution of these emissions are poorer in this region compared with southern part. The Himalayan range in north, with a complex topography, induces uplifting of the air-masses and redistributes them at greater distances. This is also region of Tibetan high, where high pressure system develop at the upper troposphere and lower stratosphere (UTLS) and develop an anticyclonic circulation known as the 'Asian Summer Monsoon Anticyclone' (ASMA). Therefore, considering the increasing levels of pollutants over this region, intensifying photo-chemistry due to the higher solar radiation and water vapour abundance, systematic surface observations of several trace spaces and balloon-borne ozone (EN-SCI 2ZV7 ECC) along with GPS radiosonde (iMet-1-RSB) observations were initiated from ARIES, Nainital (29.4N, 79.5E, 1958 m) in the Central Himalayas. Few test balloon flights were started in 2010 and regular weekly flights (Wednesday at ~1200 hours LT) startedin January 2011. Later, flight frequency reduced to fortnightly/monthly. On few occasions, extensive flights on additional days were also conducted during some specific field campaigns, including during spring biomass burning and ASMA periods. The flight duration (ascent and descent) has been ~2.5 hours with altitude coverage up to 28-35 km.

These extensive observations during 2011-2023 over the central Himalaya shows a very distinct seasonal variations in the lower and mid troposphere with a prominent maxima in spring, unlike those in western India and southern India. The biomass burning is shown to major cause of spring maximum. The long-range transport from the polluted and marine regions also play an essential role in controlling variabilities in vertical ozone distribution over the Himalayas. The dominance of downward ozone transport from the stratosphere is shown to be greater in late winter and early spring, which is confirmed by the variations in Ertl's potential vorticity. Detail study in this Asian Summer Monsoon region is in progress with additional data analysis from space-borne (MLS/OMI) data, model data and MERRA-2.

Quantifying the Radiative Impact of Asian Tropopause Aerosol Layer using the Balloon-borne Field Campaign Measurements

V.N. Santhosh[1], B.L. Madhavan[1], M. Venkat Ratnam[1], J.P. Vernier[2]

[1]National Atmospheric Research Laboratory (NARL), Gadanki, India – 517 112
[2]NASA Langley Research Center, USA

The Asian Summer Monsoon Anticyclone (ASMA) located in the Upper Troposphere- Lower Stratosphere (UTLS) region is known for trapping aerosols and trace gases. The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) have revealed a recurrent aerosol layer in August-September backscatter profiles near 13–18 km from the eastern Mediterranean Sea to western China and India, called the Asian tropopause aerosol layer (ATAL) echoed by several follow-up studies later. Despite the satellite-based observations providing valuable insights about spatio-temporal evolution and dynamical association, studies on their radiative impacts in terms of forcing and heating rates are sparse. One of the main hurdles in this aspect is the non-availability of in-situ measurements of the aerosol properties. Keeping a view on this, a series of NASA–ISRO *Balloon Measurement Campaigns of the Asian Tropopause Aerosol Layer* (BATAL) was conducted over different locations in India between 2014 and 2019 to study the nature, formation, and transport of polluted aerosols in the UTLS during the Asian summer monsoon period. Several miniature payloads to retrieve the aerosol and cloud-related properties together with meteorological parameters were launched from three different locations over India: Gadanki (13.46°N, 79.18°E), Hyderabad (17.47°N, 78.58°E), and Varanasi (25.27°N, 82.99°E). The main objective of the present study is to quantify the direct radiative impact of UTLS aerosols during the observed periods of ATAL. Also, quantify the relative contribution of ATAL to the total columnar aerosol forcing and heating rates. As part of this study, we have analyzed the in-situ measurements from ~ 100 balloon flights from which quality-controlled (cloud-screened) profiles were considered further. Preliminary observations indicate enhancement in aerosol backscattering ratios within the UTLS region at all three locations, but with variable magnitudes. Since Gadanki is at the outer edge of the ASMA region, backscatter ratios in the UTLS region are less in magnitude. Together with atmospheric parameters, we have derived the aerosol extinction profiles at multiple wavelengths at all three locations. Since the aerosol type information is not available from the in-situ measurements, we have considered the air mass trajectories to determine the possible sources of aerosols influencing the observation location within the boundary layer, and free troposphere while assuming the sulfate as the predominant source in the UTLS region. Radiative transfer calculations revealed negative forcing in the UTLS region with observed heating rates as low as -0.05 K day^{-1}. We further noted that the UTLS forcing alone could contribute up to 3% of the total columnar atmospheric forcing over Gadanki. These analyses are extended to other locations and we found similar inferences. These observations highlight the necessity to consider the contribution of UTLS aerosols towards the columnar aerosol radiative impact estimations, forming the basis for a detailed understanding of the impact of spatio-temporal variability with satellite and reanalysis datasets.

Understanding the Stratosphere-Troposphere Exchange Processes through the Direct Measurements of Vertical Air Motion over Central Himalayan Region using 206.5 MHz Stratosphere - Troposphere Radar

Nabarun Poddar[1,2,*], Siddarth Shankar Das[1], Manish Naja[3], Samaresh Bhattacharjee[3], and Veenus Venugopal[1,2]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram-695022, India
[2]Department of Physics, University of Kerala, Thiruvananthapuram-695581, India
[3]Aryabhatta Research Institute of Observational Sciences, DST, Nainital-263001, India
[*]*e-mail:* nabarunpoddar1998@gmail.com

The upper troposphere and the lower stratosphere is one of the key regions in the Earth's atmosphere, where the interaction of three processes, *viz*., dynamical, radiative and chemical processes takes place through a transition layer, known as "Tropopause". The tropopause is a stable layer formed due to natural temperature inversion, which separates the troposphere from the stratosphere. In general, the troposphere is highly humid and considered to be in radiative-convective equilibrium (well-mixed), whereas the stratosphere is dry and ozone rich, and considered to be in the radiative equilibrium (stably stratified). The vertical structure of the tropopause layer and its variability at various time scales plays an important role in the exchange of minor constituents, especially water vapour (H2O) and ozone (O3) between the stratosphere and the troposphere and also in the coupling processes between these two regions. These coupling processes are widely acknowledged by the atmospheric science community and are designated as "Stratosphere- Troposphere Exchange (STE)". These exchange processes play an important role in removing the water vapour from the air as it enters the stratosphere and in the reverse direction intrusion of stratospheric ozone into the troposphere. The stratospheric O3 which maximizes between 25 km and 30 km altitude, regulates the amount of ultraviolet radiation received on the Earth's surface. In addition to it, tropospheric O3 is an important greenhouse gas and acts as an oxidant, and thus plays a significant role in the climate system. The enhancement in the tropospheric O3 has major consequences on living beings, as it acts as a toxic agent among air pollutants. Tropospheric O3 will increase either due to the *in situ* photochemical formation associated with lightning, advection, and anthropogenic activities or due to the stratospheric intrusion. In general, the tropospheric O3 enhancement due to stratospheric intrusions is observed over the middle and high latitudes and is linked with synoptic scale disturbances. This is attributed to the dissipation of extra- tropical synoptic waves in the stratospheric region. The vertical air motion has huge implication in unravelling the structure and dynamics of the atmosphere which is controlled by the vertical motion of air parcels itself thus play a vital role in STE across the tropopause. The different weather phenomena experienced in the lower troposphere are indirectly controlled by this vertical motion of air. But similar to any region of interest, having accurate measure of vertical motion of air is very difficult owing to its relatively small magnitude compared to the horizontal components of wind. In this aspect, a state-of-the- art, indigenously developed stratosphere–troposphere (ST) radar operating at 206.5 MHz, which is a pulse- Doppler radar at Nainital (29.35°N; 79.45°E) at 1.8 km altitude gives the direct measurements of vertical air motion has been used to study the long-term characteristics of vertical air motion and its role in exchange of the minor constituents between the stratosphere and troposphere. This gives us an insight into the long- term characteristics of vertical wind (*w)* over the region with seasonal variations associated with the various local climatological features. Detailed results will be presented and discussed in the upcoming conference.

A Composite Study on the Effect of SSW and QBO on Stratospheric Meridional Circulation: Implications on Ozone and Water Vapor Distribution

Veenus Venugopal[1,2] and Siddarth Shankar Das[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, 695022, India
[2]Department of Physics, University of Kerala, Thiruvananthapuram, 695034, India

The tropical upper-troposphere lower stratosphere region's air is carried to higher altitudes by the Brewer-Dobson circulation (BDC), the stratospheric meridional circulation that extends towards the poles. The circulation is driven by the momentum deposited by breaking planetary waves. The propagation of these waves and, consequently, the intensity of the circulation, is modulated by the oscillations and extreme events in the stratosphere. The Quasi-Biennial Oscillation (QBO) is the prominent oscillation in stratospheric zonal winds. QBO is linked to the alternate descending zonal wind patterns that regulate the region where the planetary wave breaks, causing variations in the stratosphere's meridional transport. Whereas in Sudden stratospheric Warming (SSW), the enhanced wave activity as well as the changing zonal wind direction alter the intensity of the circulation. Using ERA5 reanalysis data and the Aura Microwave Limb Sounder observations, the current study investigates BDC changes caused by SSW and QBO and the resulting ozone and water vapour distributions. Eliassen-Palm Flux divergence and meridional residual velocities are used to evaluate the changes in the circulation. The wave dissipation in QBO's eastward and westward phases differs noticeably. An increase in wave activity is observed before the central date of SSW. The distribution of ozone and water vapour is altered as a result of the modifications in meridional transport. The detailed results will be presented and discussed in the upcoming workshop.

Does the Quasi-Biennial Oscillation Modulate Monsoon Hadley Circulation?

Karanam Kishore Kumar[1], U. Anjana[1], and Sneha Susan Mathew[2]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, Kerala, India
[2]Henry Baker College, Melukavu, Kottayam, Kerala, India

The equatorial stratospheric interannual variability is dominated by the presence of the Quasi Biennial Oscillation (QBO), which is a spectacular long-period oscillation with alternating eastward and westward winds every year in the 20-40 km height domain. The period of QBO varies between 22-36 months with mean period of ~28 months. It is now known that the QBO is driven by Kelvin, Rossby-gravity and gravity waves through wave-mean flow interactions and also modulates several tropospheric phenomena including monsoon circulation. On the other hand, Hadley Circulation (HC), which is one of the largest atmospheric circulations in the Earth's lower atmosphere that governs climate and weather of tropics and subtropics, also has predominant impact on the monsoon circulation. With a rising branch in the deep tropics, meridional flow at the tropopause level, descending limbs over the sub-tropics and return flow near the surface, the HC play a vital role in hydrological cycle over the tropics as well as sub-tropics. In the present study, using observations and reanalysis datasets, the impact of QBO on monsoon HC over the Indian region is investigated. The regional monsoon HC is characterised using a Index as well zonally resolved meridional mass stream function, estimated using Helmholtz decomposition of horizontal winds. The precipitation anomaly over the Indian monsoon region during summer monsoon months shows a very high degree of co-variability with the monsoon HC index with a correlation coefficient of ~0.71. The monsoon HC is composited during both eastward and westward phase of the QBO and an attempt is made to identify the potential pathways through which the stratospheric QBO modulate the HC. The significance of the present study lies in investigating the impact of QBO on the Indian monsoon HC and discussing the potential physical processes involved in the interaction of tropical stratosphere and troposphere in the contest of the Indian summer monsoon.

Tidal Variability and Aliasing Effects from Contemporaneous Satellite, Model, and Reanalysis Data in the Stratosphere

Uma Das[1], Subhajit Debnath[1], C. J. Pan[2], William E. Ward[3]

[1]Indian Institute of Information Technology Kalyani, Kalyani-751235, West Bengal, India
[2]Department of Space Science and Engineering, National Central University, Jhongli, Taoyuan, 32001, Taiwan
[3]Department of Physics, University of New Brunswick, Fredericton – E3B2Y1, Canada

Knowledge of tidal variability in the lower middle atmosphere has not received its due attention owing to the small amplitudes and aliasing issues. Extracting tidal variability from asynoptic satellite measurements is a challenge as time variations in mean temperatures and wave amplitudes can alias into other waves. It is believed that observed non-migrating diurnal tides, DS0 and DW2, in high-latitude winter stratosphere are the result of non-linear interactions between SPW1 and the migrating diurnal tide, DW1, but a few recent studies have shown that that varying amplitudes of stationary planetary wave of wavenumber one (SPW1) can alias into these non-migrating diurnal tides. Similarly, varying background temperature aliases into DW1 amplitudes. In the current study, we investigate tidal variability in the lower middle atmosphere by simultaneously addressing the issue of aliasing of different wave components by the analysis of temperature data from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite., Formosa Satellite-3 and Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC), European Centre for Medium-range Weather Forecasts (ECMWF) global reanalysis ERA–Interim, and Canadian Middle Atmosphere Model (CMAM30). The reanalysis and model data are resampled in Fourier space at times and locations of observations by SABER/TIMED as well as FORMOSAT-3/COSMIC. These satellite-sampled datasets are analysed to investigate the effect of satellite sampling on tidal variability deductions. It is found that DS0 and DW2 amplitudes observed in high-latitude winter stratosphere are the result of aliasing. It is also ascertained that these tides are not produced in the stratosphere by the process of non-linear interactions and hence this is not an important source of generation of non-migrating tides in the high- latitude stratosphere. It is also observed that there is no aliasing of the non-migrating tides into SPW1 amplitude and variability of the latter is extracted accurately over shorter time scales from COSMIC retrievals using a smaller window size of (±10 days). SPW1 variability obtained from SABER/TIMED is also accurate except for the fact that it is smoothed over the window size considered, which is ±30 days. This proves that variability in tidal amplitudes obtained from SABER/TIMED are not accurate but that of stationary planetary waves (SPWs), which have an important role to play in the high-latitude winter stratospheric phenomena including sudden stratospheric warmings, is correct. It is also concluded that tidal variability deduced from COSMIC is the most reliable at altitudes below 50 km. DS0 and DW2 in CMAM30 wind and temperature data show that DS0 is not produced by non-linear interactions and is a result of latent heat release in the troposphere region, while DW2 is generated by both non-linear interactions as well as latent heat release.

Impact of Volcanic Aerosols on the Tropical Stratosphere and Disruption of the QBO

Prashant Chavan[1,2], Suvarna Fadnavis[1], Anton Laakso[3], Jean-Paul Vernier [4,5], and Rolf Muller[6]

[1]Indian Institute of Tropical Meteorology, Center for climate change, MoES, India
[2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India
[3]Finnish Meteorological Institute, Kuopio, Finland
[4]National Institute of Aerospace, Hampton, VA, USA
[5]NASA Langley Research Center, Hampton, VA, USA
[6]Forschungszentrum Jülich GmbH, IEK7, Jülich, Germany

Volcanic eruptions significantly impact Earth's atmosphere by releasing sulfur emissions, thereby affecting atmospheric dynamics. Here we analyse the impact of volcanos during 2001 to 2013 on the tropicalstratosphere and Quasi-biennial oscillation (QBO) using the state-of- the-art ECHAM6-HAMMOZ model simulations. Our simulations show that volcanic sulfate aerosols enhance global stratospheric aerosol optical depth (SAOD) by 0.017±0.001 leading to the global reduction of radiative forcing at the top of the atmosphereby -0.46±0.03 W m^{-2} and at the surface by -0.43±0.02 W m^{-2}. These volcanic aerosols enter the tropical pipe (20ºS-20ºN) and propagate upward deep in the stratosphere. In the stratosphere, the sulfate aerosol anomaliesenhance by 117±9 ng m^{-3}. These aerosols increase the heating rates by 0.02±0.001 K mon^{-1} in the lower stratosphere tropical pipe. This stratospheric heating strengthens the amplitude of QBO and disrupts its phases.It causes prolongation of the easterly phase of QBO by 12 to 20 months and the westerly phase of QBO by 16to 24 months. The secondary meridional circulation induced by the QBO produces the triple-peak structure near the Equator. A triple-peak structure of the QBO amplitude is further strengthened by the heating caused by the volcanic sulfate. The centres of amplitude maxima of triple-peaks are near located 180 hPa, 40 hPa, and10 hPa. The model simulation shows the significant alterations in QBO phase and amplitude induced by a volcano have pronounced effects on Outgoing Longwave Radiation (OLR) in the tropical region, causing a 3-4 months delay in phase and a decrease in amplitude. Similarly, cloud cover and precipitation shows a 3-4 months phase delay along with a decrease in amplitude in the tropical region.

Impact of Rapid Reductions in Regional Aerosols on the Near-future Strengthening of the South Asian Monsoon

Chirag Dhara[1], Ayantika D.C.[2], R. Krishnan[2], P. Swapna[2], Manmeet Singh[2], N. Sandeep[2]

[1]Krea University, Sri City, 517646, India
[2]Indian Institute of Tropical Meteorology, Pune, 411008, India

The effect of anthropogenic aerosol pollution on the South Asian summer monsoon precipitation has attracted significant attention over the past decade. Yet, significant gaps remain in our understanding of how the monsoon may respond in the future to reduction in aerosols as with stricter controls on regional anthropogenic aerosol emissions. In this study, we perform sensitivity experiments with the IITM Earth System Model (IITM-ESMv2) to study the effect of rapid regional aerosol reductions on the near-future response of monsoon precipitation over South Asia. These simulations reveal a widespread intensification of organized deep convective activity and precipitation over and around South Asia with reduced aerosols. Our analysis shows that the simultaneous increase in GHGs and decrease in absorbing aerosols over the subcontinent are accompanied by a substantial increase in the land-sea temperature contrast that prompt a greater strength of cross-equatorial winds favoring moisture accumulation and a steady build-up of moist static energy over the South and South East Asian region. This results in strengthening and deepening of organized monsoon convection, which is accompanied by widespread increases in precipitation. We conclude that stronger regional air pollution control norms over South and East Asia in the future would play a crucial role in large- scale intensification of the monsoon over South and South East Asia in the span of the next few decades.

Design and Development of NOAA's State-of-the-Art Seasonal Forecast System (SFS) for Research and Operations

Vijay Tallapragada[1]

[1]NOAA NWS NCEP Environmental Modeling Center, USA

Starting in 2023, the United States Congress has allocated resources to NOAA for development of a new operational Seasonal Forecast System (SFS) at the National Weather Service (NWS), paving the way for the replacement of the Climate Forecast System Version 2 (CFSv2), the current operational seasonal forecast system at NWS's National Centers for Environmental Prediction (NCEP) implemented in 2011 and has been frozen ever since. The demand for a state-of-the-art seasonal forecast system, along with a contemporary reanalysis and reforecast database, has persistently ranked as one of the primary requirements among forecasters and stakeholders for many years, leading to the development of the new SFS using NOAA's NOAA's new community modeling framework known as the Unified Forecast System (UFS) for operations and research.

The SFS Project was formally launched in October 2023, with the SFS Application Team of UFS composed of model developers and forecasters from NCEP's operational centers, researchers from OAR laboratories and National Center for Atmospheric Research (NCAR) as well as collaborators from wider research and academic communities. The SFS aims to make significant progress in seasonal predictions for precipitation, drought, temperature, tropical cyclone frequency, and weather extremes, benefiting decision makers across the public and private sectors.

The SFS will build upon and extend the capabilities of NOAA's Global Ensemble Forecast System (GEFS) version 13, which is under transition to operation currently, with a focus on accurately representing slowly varying processes in land, oceans and sea-ice, as well as capturing key seasonal and subseasonal scale phenomena such as El Nino - Southern Oscillation (ENSO), Madden Julian Oscillation (MJO), Quasi Biennial Oscillation (QBO), global monsoons, severity and frequency of extreme events such as flash drought, flooding, atmospheric rivers, hurricanes, heat waves, among other hazard events. SFS will include coupled Data Assimilation (DA), improved physics characterization of processes in land, oceans, sea-ice, aerosols, development of land vegetation and groundwater, sea-ice growth and melt, ocean mixing, and atmospheric ozone, all of which are vital for subseasonal and seasonal scale predictions. A new reanalysis for the coupled atmosphere-ocean-sea ice system will be produced for climate monitoring and post-processing and calibration of longer range forecasts.

This talk will focus on developmental objectives for SFSv1 including some preliminary results from various prototypes that are currently being developed and tested.

Assessing Stratospheric Contributions to Subseasonal Prediction: the SNAPSI Project

Peter Hitchcock[1], Amy Butler[2], Chaim Garfinkel[3], Hera Kim[4], William Seviour[5], Blanca Ayarzagüena[6], Hamid Pahlavan[7], and Shunsuke Noguchi[8]

[1] Dept. Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA
[2] NOAA Chemical Sciences Laboratory, Boulder, CO, USA
[3] Fredy and Nadine Herrmann Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel
[4] School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea
[5] Global Systems Institute and Department of Mathematics and Statistics, University of Exeter, Exeter, UK
[6] Dpto. de Física de la Tierra y Astrofísica, Universidad Complutense de Madrid, Madrid, Spain
[7] NorthWest Research Associates, Boulder, CO, USA
[8] Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

SNAPSI ("Stratosphere Nudging And Predictable Surface Impacts") is a model intercomparison project aimed at isolating the contribution of the stratosphere to predictability on subseasonal timescales in the time periods around stratospheric sudden warming (SSW) events. Eleven operational centers have contributed ~50 member ensemble forecasts initialized near three recent SSWs: Northern Hemisphere events in 2018 and 2019, and a Southern Hemisphere event in 2019. In addition to standard, free running ensembles, additional forecasts are carried out in which the stratosphere is constrained in various ways, enabling a controlled assessment of the contribution of stratospheric anomalies to the subsequent evolution of the forecast. An extensive, publicly available and CMOR-compliant data request allows for detailed analysis of a range of processes in these subseasonal forecasts.

Four community working groups are focused on addressing core science questions for the project. These analyses will quantify the contribution of the stratosphere to subseasonal prediction skill, formally attribute surface extremes to the stratosphere, and assess both downwards and upwards mechanisms coupling the troposphere and the extratropical stratosphere. Two additional working groups are studying the tropical response, including the representation of the QBO and the impact of the stratosphere on tropical convection. Although the experiments were not designed with the intent of studying the influence of the stratosphere on the Asian Summer monsoon, one of the initializations is in late August allowing for a case study of possible stratospheric influence on the end of the monsoon in 2019.

In this talk I will present an overview of the project as well as highlights from the community working groups. Particular focus will be placed on tropical impacts including on the monsoon.

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The challenges and need for multi-model intercomparisons of chemistry climate models in the troposphere

David Plummer[1]
[1]Environmental and Climate Change Canada.

The chemistry climate modelling community has a particularly long track record of performing coordinated intercomparisons of models to assess their fidelity against observations and better understand their strengths and weaknesses. Particularly when the quantities being compared are designed to illuminate fundamental aspects of atmospheric processes, the comparison can provide more fundamental information on how well these processes are simulated in the models. In the case of a multi-model intercomparison, with a set of experiments and diagnostic fields implemented more or less identically across a large number of chemistry climate models, the level of agreement between models and with observations can be used to infer information on how robustly we are able to quantitatively simulate important atmospheric processes. Development of chemistry climate models initially focused on the stratosphere and process-based diagnostics also have a longer history of being applied to the stratosphere. Many (all?) of the current-generation CCMs now include a comprehensive representation of chemical processes in the troposphere yet, arguably, the assessment of tropospheric processes of chemistry climate models in the framework of a multi-model intercomparison has been slower to develop. The presentation will review some of the progress made through the coordinated Intercomparison of chemistry climate models in the stratosphere, present some of the challenges for making progress in the troposphere and argue for the development of new approaches to assess models within the framework of a multi-model intercomparison.

Changes in Water vapour in the Upper Troposphere and Lower Stratosphere (UTLS) of the Global Tropics: Role of Surface Warming in Recent Decades and Future Scenarios

V. K. Patel[1] and J. Kuttippurath[1]

[1]CORAL, Indian Institute of Technology Kharagpur, Kharagpur, India

Water vapour in the upper troposphere and lower stratosphere (UTLS) plays an important role in the surface energy budget and thus, affects the surface climate. The variability of water vapour in the stratosphere has a significant impact on both surface and stratospheric temperature. Therefore, we analyse the variability and changes in water vapour in the UTLS of the global tropics, where water vapour is generally more abundant compared to other regions. Here, we have considered the UTLS region between 300 hPa (upper troposphere) and 50 hPa (lower stratosphere), where we observe relatively higher water vapour at 300 hPa (0.3–0.8 g/kg) and lower water vapour at 50 hPa (< 0.003 g/kg). There are regional differences in the water vapour distribution in the upper troposphere, with relatively higher values in the West Pacific and Indian Ocean warm pool regions (0.6–0.8 g/kg). Similar water vapour distribution in the upper troposphere is also observed in Amazonia and Central Africa. On the contrary, relatively lower values of water vapour are observed in the warm pool regions at the tropopause (100 hPa) and lower stratosphere (70 hPa and 50 hPa, about <0.0024 g/kg) compared to other regions in the tropics. There is a gradual increase in water vapour in the lower troposphere, more pronounced in recent decade (2011–2020), which is consistent with the tropical surface warming. A similar increasing pattern is also observed at the tropopause in recent decade, but it is decreasing in the lower stratosphere (50 hPa) from 2011 onwards. It indicates that surface warming that drives evaporation affects the changes of water vapour in the upper troposphere, but stratospheric chemistry and transport mechanisms play an important role in the lower stratospheric water vapour variability. The positive correlation between tropical surface warming and water vapour is dominant in the lower troposphere, but their relationship is weaker in the lower stratosphere. In addition, the impact of El Niño- Southern Oscillation (ENSO) on water vapour variability is clearly visible in the tropical lower troposphere, but its impact on the lower stratospheric water vapour is suppressed. Water vapour in the tropical UTLS is estimated to increase in the future high emissions scenarios, although it is consistent with the rise in surface warming. This is a great concern for the UTLS warming, chemistry and dynamics.

Reconstructing High-resolution In-situ Vertical Profiles Measured in the Sparsely Monitored Asian Monsoon Region

R. Müller[1], B. Vogel[1], S. Hanumanthu[1], J. Clemens[1], M. Volk[2], S. Fadnavis[3]

[1]Forschungszentrum Jülich (IEK-7), Jülich, 52428, Germany.
[2]Institute for Atmospheric and Environmental Research, University of Wuppertal, Wuppertal, Germany.
[3]Indian Institute of Tropical Meteorology, Pune 411 008, Maharashtra, India.

Sources of green-house gases and other pollutants in South Asia, are poorly quantified. Here, we present aircraft (in 2017) and balloon measurements (in 2016) with high temporal and vertical resolution during the Asian summer monsoon where rapid upward transport of surface pollutants to greater altitudes occurs. Using Lagrangian model simulations, we successfully reconstruct observed (CO_2) profiles and investigate the surface origin of the observed airmasses. We argue that sources of pollutants and CO_2 on the Indian subcontinent driven by regional flux variations rapidly propagate to approximately 13 km with slower ascent above (to about 20 km). We suggest that the observed propagation of signals from the surface to the stratosphere via the Asian monsoon can be used to evaluate transport models, in particular with respect to the quality of reanalyses (e.g. ERA5 and ERA-Interim). Such comparisons are also useful for assessing CO_2 fluxes in South Asia.

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Horizontal Transport of Asian Summer Monsoon Air into the Northern Lower Stratosphere: the PHILEAS Campaign 2023

Bärbel Vogel on behalf of the PHILEAS team
Julich, Germany Juelich,Germany

The Asian summer monsoon provides a strong link between the near-surface pollution and the global atmosphere by connecting local sources at the surface with the large-scale circulation. It affects both the composition of the deep stratosphere and of the extratropical lowermost stratosphere (LMS). To evaluate the associated global effects on climate, a detailed understanding of the associated pathways is essential. The extratropical upper troposphere / lower stratosphere (UT/LS) is mainly influenced by quasi-horizontal export of polluted and moist air from the upper-level Asian Monsoon anticyclone (AMA), which is facilitated by frequent eddy shedding events. Currently, there is a lack of observations in the northern hemisphere transition area at middle and high latitudes where the Asian monsoon air is mixed into the northern lower stratosphere.

The recent HALO campaign PHILEAS (Probing high latitude export of air from the Asian summer monsoon) aimed to fill this important gap by aircraft observations from Anchorage/Alaska and Oberpfaffenhofen/Germany in summer and autumn 2023. Our presentation puts the PHILEAS campaign in a climatological context by comparing CLaMS model simulations of air mass origin tracer and transit time distributions in the monsoon season 2023 (e.g. South Asia) with the respective long-year average (2000 to 2022). Some first results from the aircraft measurements during the PHILEAS campaign will be presented

Physical and Dynamical Factors Affecting the Boundary Layer Tracer Pathway to the Asian Summer Monsoon Anticyclone

P. P. Musaid[1], Sanjay Kumar Mehta[1], Susann Tegtmeier[2], Masatomo Fujiwara[3]

[1]Atmospheric Observations and Modelling Laboratory (AOML), Dept. of Physics and Nanotechnology, SRM Institute of Science and Technology, Kattankulathur, 603203, India
[2]Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, SK, Canada
[3]Faculty of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan

In this study, we discuss the vertical transport pathways associated with the boundary layer tracer transport into the Asian Summer Monsoon Anticyclone using a Lagrangian transport model. Infrared Atmospheric Sounding Interferometer (IASI) observations from the European MetOp satellite series show significant differences in the boundary layer carbon monoxide (CO) concentration between the Indo-Gangetic plane and the Sichuan Basin to East China region. Strong and deep convection over the Bay of Bengal and the orography of the Tibetan Plateau help to maintain a consistent pathway in the eastern-central Indian region. While the east China region is not characterized by strong convection, IASI observations reveal that the anomalous concentration of CO centers near East China near the surface (950 hPa) and, at higher altitudes, the anomalous concentration moves to the Sichuan basin region. The Lagrangian trajectory analysis shows a dominant pathway over east-central India. However, we observe variability in the strength and tracer concentration of the pathway within the longitudinal extent of 80°-100°E, which is closely associated with transient monsoon conditions. The very deep convection in the west-pacific region (110°-150°E, 5°-20°N) acts as a short-timescale transport pathway. Interestingly, the tracer concentration within the longitudinal extent of 100°-120°E also varies in accordance with the variability of the pathway over eastern central India.

Estimation of Target Density and Age of Air Transported from the Asian Monsoon Anticyclone to the Arctic

C. Sivan[1], S. Fadnavis[1], Ajil Kottayil[2] and Bernard Legras[3]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India
[2] Advanced Centre for Atmospheric Radar Research, Cochin University of Science and Technology, Kerala, India
[3]Laboratoire de Météorologie Dynamique, IPSL, CNRS UMR8539, ENS-PSL/Ecole Polytechnique/Sorbonne Université, Paris, France

This study delves into the distribution of target density and the age of air parcels reaching the Artic region through long-range transport from the Asian summer monsoon anticyclone (ASMA). The investigation uses the TRACZILLA Lagrangian forward trajectory model for two distinct years (1) 2015 El Nino and (2) 2016 normal year. We launched parcels at the 370K potential temperature surfaces over the ASMA region (20^0 E - 120^0 E; 20^0 - 40^0 N).

We analyse target density, and transit times of parcel reaching over the Arctic. Our analysis reveals that in 2015 El Nino, the Baffin region (BB) (43.6%) exhibited the highest target density. The Greenland, Norwegian, and Barents Seas (GNB) region showed a lesser density (39%) compared to the BB. The Beaufort Gyre (BG) displays lowest target density and longer transit times.

In 2016 normal year, the target density at the GNB region (36.5%) is highest of all regions. In the Russian Coastline, it is higher than 2015 (15%). Conversely, target density is less in the BB (23.6%) compared to 2015. Above 95 % of the target density is located between 65^0-70^0 N latitude in the Arctic region. The lowertransit time is observed in RC during both years (2015: 53 days, 2016: 43 days) compared to other regions inthe Arctic.

Our analysis reveals that the maximum transport to Arctic is occurring at of 375- 380K in 2015 and 380K-385K in 2016. This study also reveals that the parcel from ASMA take more time to reach arctic region during El Nino year as compared to normal year.

Numerical Modeling of QBO and ENSO Phase Impact on the Evolvement of Sudden Stratospheric Warming and Waves processes

Didenko K.A.[1,2], Koval A.V.[2,3], Ermakova T.S.[2,3]

[1] Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences
[2] Saint-Petersburg State University
[3] Russian State Hydrometeorological University
email: didenko.xeniya@yandex.ru

Using the general circulation model of the middle and upper atmosphere (MUAM), a number of numerical scenarios were implemented to study the impact of the phase of the Quasi-Biennial Oscillation of the zonal wind in the equatorial stratosphere (QBO) and the El Nino–Southern Oscillation (ENSO) on planetary waves, as well as on the processes associated with waves. The formation and development of sudden stratospheric warming (SSW) with various combinations of tropical oscillations are also evaluated. The 4 ensemble calculations were performed (taking into account various combinations of the eastern/western phase of the QBO and the warm El Nino/cold La Nina phase of ENSO) for winter conditions of the Northern hemisphere (January– February) with 10 model runs in each. The simulation showed the occurrence of SSW including major ones in almost all runs for the conditions of El Nino, eastern and El Nino western QBO phase; and in half of the runs for La Nina, eastern QBO phase. The SSW was not simulated by the MUAM under the conditions of La Nina, the western QBO phase. Six runs of ensembles with the simulated SSW were averaged relative to the date of warming and the obtained data on temperature, zonal wind and geopotential were processed. The results showed the greatest wave amplitudes in geopotential height, the greatest positive anomalies of stratospheric temperature and negative anomalies of mesospheric temperature while El Nino, the eastern QBO phase. The lowest speeds of the westerly wind during the development of the SSW are simulated at El Nino, the western QBO phase. The obtained field distributions of the atmosphere hydrodynamic parameters during the simulated climatic mean SSW (taking into account various combinations of ENSO and QBO) made it possible to assess the conditions for the generation and propagation of planetary waves of various scales and processes caused by wave activity.

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Assessing Upper Tropospheric Humidity During Monsoon Depression Using NCMRWF Unified Model Forecasts

Shubha Singh[1], . Kondapalli Niranjan K[1], Anumeha Dube[1], John P. George[1],

Saji Mohandas[1] & V.S. Prasad[1]

[1]National Center for Medium Range Weather Forecast(NCMRWF), A-50, Sector 62, Noida -201309, India

Water Vapor being most Potent greenhouse gas in the atmosphere, significantly influences the atmospheric energy budget by contributing to both radiation and latent heating processes. Water vapor radiative effects in the tropics are important for the global climate. In the upper troposphere water vapor plays a particularly important role in determining cloud radiative feedback. The transport of moisture in the upper troposphere is associated with several key processes such as horizontal winds bringing moisture from lower levels or distant regions. Convective systems such as thunderstorms, contribute to increase in the upper tropospheric humidity (UTH) by injecting moisture through overshooting cloud tops and detrainment. The subsidence of air masses leads to adiabatic warming and decrease in relative humidity, impacting UTH. Tropical cyclones contribute to UTH through the evaporation of oceanic moisture and convective processes. Additionally the tropical tropopause layer (TTL), where deep convective injects water vapor into stratosphere, influences UTH. These sources interact in complex ways, influencing the distribution and variability of UTH in the upper troposphere. Understanding UTH biases can significantly enhance the accuracy of weather forecasts, particularly in regions prone to convective activity or frequent extreme weather. In this study, we evaluate UTH from NCMRWF unified model (NCUM) forecasts during a passage of monsoon depression. We have used diverse observational sources, Satellite Observations and the Radiosondes over the Oceans and land regions during the evaluation of depression (17th-23rd August 2023). Hence this study is valuable for weather and climate modeling, aiding in the understanding of complex climate processes such as cloud formation, precipitation and heat transfer.

Keywords: STI (Stratrosphere-Troposphere Interactions), UTH (upper troposhperic humidity), weather extremes, Radiosonde observations, NCUM model.

QBO-MJO Connection and its Implication to South Asian Precipitation

Seek-Woo Son[1]

[1]School of Earth and Environmental Sciences, Seoul National University, Republic of Korea

The Quasi-Biennial Oscillation (QBO) and the Madden–Julian Oscillation (MJO) are strongly linked during the boreal winter. The MJO is ~40% stronger and persists ~10 days longer during the easterly phase of the QBO (QBOE) than during its westerly phase. It significantly affects the interannual variability of MJO-related precipitation over South Asia. Despite its robustness in observations, the QBO–MJO connection is not well reproduced by numerical models. The mechanisms that drive the QBO–MJO connection also remain uncertain. In this study, we investigate the longwave cloud-radiative feedback mechanism for the QBO-MJO connection. By analyzing satellite data, we show that the cloud-top pressure and brightness temperature of deep convection are systematically lower during the QBOE. The deeper clouds are then more effective in reducing the longwave radiation escaping to space, and thereby enhancing the longwave cloud-radiative feedback within the MJO envelope during the QBOE. The issues in modelling the QBO-MJO connection are also briefly discussed.

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Causal Prediction and Attribution of Extreme Weather Events

Theodore G. Shepherd[1,2]

[1]**Department of Meteorology, University of Reading, UK**
[2]Jülich Supercomputing Centre, Forschungszentrum Jülich, Germany

Traditional approaches to prediction and attribution of extreme weather events focus on statistical definitions of the events (e.g. quantiles) and, for attribution, solely on the role of anthropogenic climate change. These approaches are limiting and do not leverage the vast amount of process-based knowledge that is available from theory, observations and models. For example, quantile-based definitions of extremes are usually univariate and do not reflect the spatio-temporal complexity of actual extreme weather events, which matters tremendously for impacts. Moreover, in a prediction setting where the reliability of the prediction must be assessed, the quantiles are generally not particularly extreme. And when it comes to attribution, an exclusive focus on anthropogenic climate change does not allow for a meaningful analysis of the uncertainty associated with physical mechanisms such as stratosphere-troposphere interactions. This situation creates a damaging disconnect between physical reasoning and statistical practice. I advocate for a complementary approach to prediction and attribution of extreme weather events using physical climate storylines and causal networks, which considers "extreme" in terms of impact rather than rareness, and which leverages the rich process understanding that exists within the meteorological research community. Some examples of this kind of approach are provided.

MJO Effect on the Tropopause, UTLS Water Vapour and Cirrus over the Indian Peninsula

Maria Emmanuel[1], Satheesan K[2]

[1]Ministry of Earth Sciences, Prithvi Bhavan, New Delhi, 110003, India
[2]Cochin University of Science and Technology, Kochi, 682022, India

The hydration and dehydration processes in the upper troposphere lower stratosphere (UTLS) region is mainly determined by convection, advection, vertical and horizontal temperature anomalies and presence of cirrus clouds. Whether the deep convection hydrates or dehydrates the upper troposphere, remains as a topic of debate (e.g., Randel et al., 2015; Ueyama et al., 2018). While the formation of cirrus causes local dehydration, the subsequent evaporation of ice crystals can cause hydration of the region (Wang et al., 2019). Hence, the lifetimes of the convection and temperature anomalies have significant roles in determining whether the hydration/ dehydration of the UTLS is effective. The intraseasonal oscillations such as Madden-Julian oscillation (MJO) cause continuous convective disturbances lasting for a few days that can provide time for effective dehydration/hydration in the UTLS. In this study, the role of MJO in the intraseasonal variation of tropopause, hydration/dehydration and cirrus clouds in the UTLS over Indian region is examined. The occurrence of deep convection peaks over Indian longitudes during the second and third phase of MJO. A clear cooling in the TTL and lowering of the tropopause are observed in these phases over the Indian peninsula and equatorial Indian Ocean with seasonality in its intensity. The WVMR in the upper troposphere confirms the occurrence of dehydration in the TTL during these phases. The occurrence frequency of cirrus clouds peaks in the convective phases of MJO over the southern Peninsular India and adjoining oceanic region in winter, pre-monsoon and post-monsoon seasons. The thickness of cirrus also shows significant variability. The dehydration in the TTL seems to be directly connected with the occurrence of multilayer cirrus. Direct connection between MJO and occurrence of dehydration and cirrus is masked by the monsoon dynamics in the summer monsoon season.

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Extreme UTLS Ozone Enhancement over the Southern Flank of Asian Summer Monsoon Anticyclone in August 2022

Saginela Ravindra Babu[1], Suvarna Fadnavis[2], Madineni Venkat Ratnam[3] and Neng-Huei Lin[1]

[1]Department of Atmospheric Sciences, National Central University, Taoyuan 32001, Taiwan
[2]Indian Institute of Tropical Meteorology, Pune 411 008, India
[3]National Atmospheric Research Laboratory, Gadanki 517112, India

In August 2022, the Asian Summer Monsoon Anticyclone (ASMA) displayed a unique behavior with increased meandering towards the northeast and abnormal easterly winds on its southern side. The Aura Microwave Limb Sounder (MLS) measurements detected a substantial increase in ozone within the upper troposphere lower stratosphere (UTLS) region around the southern flank of the ASMA in August 2022. Compared to the long-term monthly mean (2005-2021), a ~50% (>80 ppb) increase was observed in the UTLS ozone in August 2022. The balloon-borne ozonesonde measurements from Hong Kong (22.31°N, 114.17°E), located over the southern flank of the ASMA, also supported this significant enhancement in UTLS ozone. These measurements showed an ozone increase of over 86% at 16 km altitude compared to the period from 2001 to 2021. Additionally, on August 8, 2022, there was a record-breaking enhancement of UTLS ozone between 12 and 17 km, reaching a maximum of ~232 ppb (~200%) at around 16.5 km altitude. Concurrently, notable high values of potential vorticity (PV) at 100 hPa were observed in the south and eastern flank of the ASMA, spanning from the subtropical western Pacific area to southern China. Backward trajectory and satellite measurements from the Atmospheric Infrared Sounder (AIRS) indicated that stratospheric air from the northern high latitudes intruded into the southern flank of the ASMA, contributing to the enhanced ozone levels within the UTLS region. Overall, it is concluded that the anomalous anticyclone in August 2022 led to stronger easterly winds, sinking motions, and higher ozone concentrations in the southern flank of the ASMA.

The Impact of the Mesoscale Convective System on the Upper Troposphere Lower Stratosphere (UTLS) Composition over the Asian Monsoon Region.

Tesna Maria[1], Ajil Kottayil[1], Prince Xavier[2] and Silpamol D S[1]

[1]Satellite Remote Sensing and Applications, Advanced Centre for Atmospheric Radar Research (ACARR), Cochin University of Science and Technology (CUSAT), Cochin 682022, Kerala, India.
[2]Met Office UK, Exeter, United Kingdom

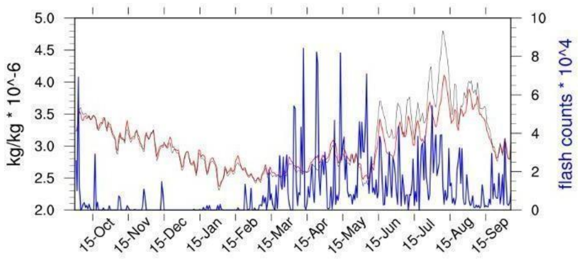
The Upper Troposphere and Lower Stratosphere (UTLS) is the atmospheric layer located between 14 - 20 kilometers altitude above sea level. It is within this region that the exchange of minor constituents, such as water vapour, ozone, and other trace gases, takes place between the troposphere and the stratosphere. Understanding these processes in the UTLS is important for comprehending the overall energy budget of Earth's atmosphere. This study assesses the influence of mesoscale convective systems (MCS) on UTLS water vapour and other trace gas distribution. Mesoscale convective systems (MCS) consist of organized clusters of convective storms that extend across several hundred kilometers. These systems produce widespread convective and stratiform precipitation and often cause intense rainfall events in the tropics. The MCS will be estimated from the Tropical Rainfall Measuring Mission (TRMM) daily precipitation data during the period 2000-2023 from June to September over the Indian monsoon region. This study will analyze the attributes of MCS, including their area, orientation, shape, and other parameters across different precipitation threshold levels. The MCS characteristics thus obtained will be linked to UTLS water vapor and other trace gases using AURA-MLS data by NASA for the period 2000-2023. A comprehensive analysis of the quantification of UTLS composition by MCS will be provided in this study.

Water Vapor Transport to the Upper Troposphere/Lower Stratosphere via Lightning-Intense Deep Convective Systems in the Third Pole Region

Prashant Singh[1], Bodo Ahrens[1]

[1]Institute for Atmospheric and Environmental Science, Goethe University Frankfurt, Frankfurt am Main, 60438, Germany

The Third Pole region is known for being a prominent location for intense deep convective systems that produce a high amount of lightning. Such a deep convective system can transport significant water vapor to the upper troposphere and lower stratosphere region (UTLS), especially over the high-altitude Third Pole region. Lightning data from the Tropical Rainfall Measuring Mission's on-board Lightning Imaging Sensor (TRMM-LIS) observation over ten years, along with data from ERA5 reanalysis and the Atmospheric Infrared Sounder (AIRS) satellite observation, points to a possible link between the lightning-deep convective system and water vapor in the UTLS region. We used the Icosahedral Nonhydrostatic Weather and Climate Model (ICON) in Climate Limited-area Mode (CLM) at the km-scale to investigate how lightning-associated deep convective systems affect the movement of water vapor and trace gases in the UTLS region. A one-year simulation shows increased water vapor concentration for lightning events at 100hPa with some time lag, which ERA5 and AIRS further support with some differences. Noticeably, ERA5 overestimates water vapor increase at 100hPa and 200hPa during the monsoon period, while AIRS underestimates it at 200hPa compared to the km-scale simulation. Possibly deep convection parametrization is one of the reasons for the additional water vapor transport to UTLS in ERA5. Several high lightning- intensity cases produced by the ICON-CLM simulation were analysed in detail over different seasons. Winter-isolated events show a much higher and distinct rise in water vapor concentration in the UTLS region over the Third Pole. Meanwhile, pre-monsoon and monsoon show variations in results. A Lagrangian analysis was used to understand the transport paths over the Third Pole during such events.



Daily total lightning activity over the Third Pole region (blue) and 100 hPa specific humidity from ICON- CLM (red) and ERA5 (black).

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Assessment of Surface Air Pollutants over the Indian Summer Monsoon Region: Linkage to Their Characteristics in the Upper Atmosphere

Atul Kumar Srivastava*

Indian Institute of Tropical Meteorology (Branch), Prof Ramnath Vij Marg, New Delhi, India
[*Correspondence E-mail: atul@tropmet.res.in]

When we talk about the causes of climate change, we typically think of greenhouse gases like carbon dioxide, methane etc. that form homogeneous mixtures spread evenly across the globe and lead to the well-known effects of the warming of the planet, which is commonly known as 'Global Warming'. However, in the recent past, it has now been realizing that not only greenhouse gases, atmospheric aerosols, the mixed bag of substances from liquid and solid, suspended in to the atmosphere also play crucial role in perturbing our climate system. Aerosols are the part of air pollution, which severely impact the air quality of the region. Long-term exposure to bad air quality has potential threat not only to the human health but also to the climate and thus our ecosystem.

The Indian Summer Monsoon (ISM) region, comprises with the Indo-Gangetic Plain (IGP) in the northern part of India, the home to about one-seventh of the world's total population has observed a strong enhancement in near-surface and columnar aerosol loading, which has significant seasonal heterogeneity in their characteristics. The widespread accumulation of aerosols, particularly in fine- mode across the IGP and the seasonal reversal of winds over the region may lead to the continental pollution outflow from the north-west IGP (one of the strong biomass-burning regions) through downwind of central and eastern IGP towards the marine region. Further, deep convection, which is mainly associated with the monsoon trough (an elongated low pressure zone) occurs frequently over the region during the summer/monsoon period, and is mostly responsible for rain activities over the region. It may also play an important role in uplifting the background pollutants, e.g. aerosols in the upper atmosphere. Polluted aerosols from the IGP are found to be lifted up during the high convection periods to the upper atmosphere, which may cause a significant effect on the energy budget of the atmosphere.

The Evolution of Monsoonal Hydro-Meteorological Extremes over India in the Backdrop of Changing Climate

Milind Mujumdar[1], Bhupendra Bahadur Singh[1], Mangesh Goswami[1,2], Madhusudan Ingale[1], Naresh Ganeshi[3,4], Toru Terao[5], Trenton Franz[6], S. N. Patil[2], and R. Krishnan[1]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune 411008, India
[2]Kavayitri Bahinabai Chaudhari North Maharashtra University, (KBC-NMU) Jalgaon – 425001, India
[3]Department of Atmosphere, Ocean and Earth System Modeling Research, Meteorological Research Institute, Ibaraki 305-0052, Japan
[4]Atmosphere and Ocean Research Institute, University of Tokyo, Chiba, 277-8564, Japan
[5]Faculty of Education, Kagawa University, Kagawa 760-8522, Japan.
[6]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE, United States of America

Frequent extreme events during the boreal summer monsoon pose various challenges to the scientific community, especially in the backdrop of global warming. In that, soil hydrodynamics plays a crucial role in altering climate (or hydro-meteorological) extremes through complex land-atmosphere feedback processes. This study, focuses on the linkage between monsoonal extremes and soil hydrology over India under changing climate. It is seen that during the wet monsoonal extremes, a coupling of surface and subsurface soil moisture (SM) is found to be stronger, favouring longer persistence of SM memory. On the other hand, during dry monsoonal extremes, the coupling gets weaker and SM memory decays faster. This may alter the surface and root-zone SM availability and regulate a corresponding hydrological extreme. We also note that that more than 70% of the area of the Indian landmass has experienced significant changes in characteristics of Extreme Temperature (ExT) events due to SM perturbations, through modulating surface energy partitioning, evapotranspiration and SM memory. Overall, the role of SM is crucial in governing the hydrological and temperature extremes over India and requires increased attention from the scientific community.

Response of the Asian Summer Monsoon to Aerosol Reductions due to COVID- 19 Lockdown Regulations

Ramesh Kripalani[1], Preethi Bhasker2, Kyung-Ja Ha[3]

[1]Retired Scientist, Indian Institute of Tropical Meteorology, Pune 411008, India
[2]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune 411008, India
[3]IBS Centre for Climate Physics, Pusan National University, Busan, South Korea

Highly unusual and unprecedented heavy rains were witnessed over South and East Asia during Summer Monsoon 2020. Over South Asia, India experienced one of the wettest monsoons since 1994. August was wettest on record since last 44 years. West coast of India experienced wettest in over 60 years. Withdrawal of monsoon was delayed by about two weeks. Over East Asia, China recorded the longest rainy season and highest precipitation since 1961. Korea experienced its third wettest summer and rainy season was longest since 1973. Highest precipitation since 1946 recorded in one Japan's province. Rainy season ended later than usual over Korea and Japan. We demostrate that one possible cause could be the considerable reduction in aerosols due to COVID-19 lockdown regulations . By comparing recent monsoons during 2020-2023, we further demonstrate that the North Pacific Subtropical High could be one feature which can explain the in-phase as well the out-of-phase extreme monsoon rains over South and East Asia.

Role of the Himalaya-Tibetan Plateau in Moistening the Tropopause as Inferred from the Model Simulations

Abhishek Anand[1], Shipra Jain[2], Vaibhav Kumar[3], Saroj Kanta Mishra[4]

[1]Regional Meteorological Centre, India Meteorological Department, Kolkata 700027, India
[2]Institute for Risk and Disaster Reduction, University College London, London, UK
[3]Department of Geomatics, National Cheng Kung University, Tainan City 701401, Taiwan
[4]Centre for Atmospheric Sciences, IIT Delhi, Hauz Khas 110016, India

This study utilizes a General Circulation Model to investigate the roles played by the Himalaya-Tibetan Plateau (HTP) in moistening the tropopause during the boreal summer. Numerical simulations validate that approximately half (about 50-55%) of the seasonal increase in water vapour near the tropopause can be attributed to the elevated terrain of the plateau. The moist convection occurring over the HTP emerges as a significant factor contributing to this rise. The high altitude of the plateau serves as a source of mid-tropospheric moisture through surface evaporation, which is subsequently transported into the upper troposphere and tropopause within the Asian summer monsoon anticyclone (ASMA). Additionally, the plateau acts as a geographical barrier to moisture originating from the Indian subcontinent, thereby reinforcing vertical transport through the mountain uplifting process. The elevated nature of the plateau is also identifiedas influencing the location and intensity of the ASMA, which, in turn, affects the location and strength of the observed moistening phenomenon.

Keywords: Upper Troposphere and Lower Stratosphere, UTLS, Tropospheric-Stratospheric Exchange, Tropopause Processes, Upper-Level Asian Anticyclone, Himalaya-Tibetan Highland.

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QBO Impacts Asian Summer Monsoon Precipitation by Modulating the Walker Circulation

Yuanpu Li[1], Christine Shields[1], Jadwiga H. Richter[1], Chih-Chieh Chen[1], Kai Huang[1]

[1] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, 80301, USA

This study investigated the influence of the stratospheric quasi-biennial oscillation (QBO) on the precipitation related to the Asian summer monsoon. Based on the ERA5 reanalysis data after the 1980s, the easterly QBO (EQBO) phase is companied by the wetness on the west side of the Maritime Continent and South India, and dryness on the east side of the Maritime Continent as well as the region north to the Maritime Continent, i.e., Bay of Bengal, Indo-China Peninsular, South China Sea and tropical northwestern Pacific. The rainfall and wind anomalies near the surface corresponding to the weakened tropical easterly jet (TEJ) are generally consistent with the anomalous pattern caused by EQBO, thus we argue that TEJ likely plays an essential role in the mechanism of the QBO teleconnection in the Asian summer monsoon precipitation. The anomalous frequency of the atmospheric river events in the Asian summer monsoon region is consistent with the anomalous precipitation distribution. We proposed a hypothesis that QBO will influence the monsoon wind near the surface and tropical easterly jet in the upper troposphere by modulating the Walker circulation.

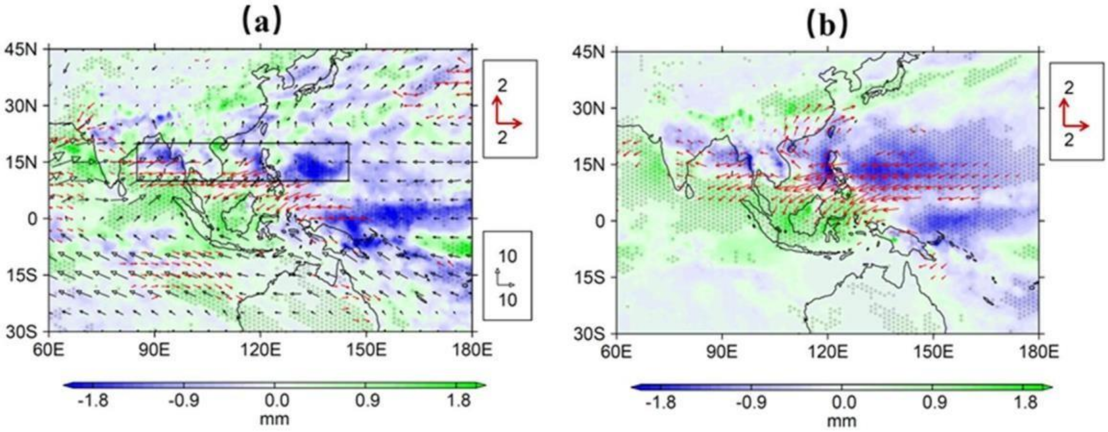

Fig. 1 (a) Differences in precipitation (shading, unit: mm) and wind at 925 hPa (red vectors, only differences in wind significant at the 90% confidence level are shown) between EQBO and WQBO. The black vectors are the climatology wind at 925 hPa. Differences in precipitation above the 90% confidence level under the Monte Carlo test are shown by empty dots. The black box represents the region of 85°E - 145°E, 10°N -20°N. (b) The anomalies of precipitation and wind at 925 hPa regressed to the tropical easterly jet intensity. This graph corresponds to a scenario when the TEJ is weakened. The regions of dots and red vectors are significant at the 90% confidence level according to the F-test.

ECMWF's Journey in Advancing Extreme Weather Prediction

Dr. Estibaliz Gascon

ECMWF, Bonn, Germany

Forecasting severe weather has become a primary objective for The European Centre for Medium-Range Weather Forecasts (ECMWF) in recent years. Severe weather encompasses various phenomena, including windstorms, precipitation, thunderstorms, heat waves, and cold spells, which can lead to flooding, forest fires, and deteriorated air quality. This abstract explores ECMWF's recent initiatives and progress in enhancing extreme weather prediction capabilities within the Integrated Forecasting System (IFS). Recent advances have focused on improving forecast accuracy and lead time for severe weather events such as tropical cyclones, intense convective storms, and heavy precipitation events.

Integration of satellite observations, innovative data assimilation techniques, enhanced ensemble forecasting methodologies, high-resolution model simulations, and advances in machine learning have been instrumental in enhancing the accuracy and reliability of severe weather forecasts. Two noteworthy initiatives, the Destination Earth initiative and the development of the Artificial Intelligence/Integrated Forecasting System (AIFS), have significantly contributed to this progress.

In the Destination Earth initiative (https://destine.ecmwf.int/), ECMWF is constructing the global component of the Extremes Digital Twin, leveraging enhanced earth-system simulations and observations fusion, as well as simulations performed by the IFS at kilometre-scale resolution (2 to 4 km) up to four days ahead. Additionally, the Artificial Intelligence/Integrated Forecasting System (AIFS), while currently operating at relatively coarse resolution, has demonstrated higher skill compared to traditional IFS forecasts for metrics such as 2-meter temperature. This machine learning-based model, along with other ML approaches, has shown promise in predicting certain extreme weather events earlier than deterministic IFS forecasts, thereby enhancing early warning capabilities.

This abstract underscores ECMWF's dedication to advancing weather prediction science and emphasizes the importance of continuous innovation to improve extreme weather forecasts.

Deep learning based downscaling approaches for precipitation extremes: an assessment over India

Pankaj Kumar and Murukesh, M.

Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research, Bhopal, India

Abstract

Deep learning has revolutionized many fields by providing powerful tools for pattern recognition and data analysis. In climate science, deep learning techniques are increasingly being used to address complex problems, such as predicting weather patterns, understanding climate dynamics, and improving climate models. One promising application of deep learning is in the downscaling of climate data, where high-resolution predictions are made from low-resolution inputs, enhancing our ability to study and respond to regional climate changes. Precipitation downscaling is a challenging problem due to its stochasticity and positively skewed distribution. In this study, the performance of a Super-Resolution Generative Adversarial Network (SRGAN), a cutting-edge deep learning-based image super-resolution generative model, is assessed in downscaling and reconstructing high-resolution rainfall data over India from the low-resolution input. SRGAN consists of a generator network that takes information from low-resolution (1°x1°) rainfall data to infer potential high-resolution (0.25°x0.25°) counterpart. The long-term record of gridded rainfall provided by the India Meteorological Department, for the period 1901-2021 is utilized in this study. Bias correction and spatial disaggregation (BCSD), a statistical downscaling method, is also deployed to benchmark deep learning-based downscaling methods. The downscaling methods are comprehensively assessed for their ability to reconstruct distribution, mean, and extreme rainfall during the test period. The results show that the deep learning-based methods has an upper hand over the BCSD method for gridded rainfall downscaling, over the Indian sub-continent.

Keywords: Downscaling, Climate data, Gridded rainfall, Deep learning, SRGAN, Image super-resolution

Related work:

Murukesh, M., Golla, S., & Kumar, P. (2023). Downscaling and reconstruction of high-resolution gridded rainfall data over India using deep learning-based generative adversarial network. Modeling Earth Systems and Environment. https://doi.org/10.1007/s40808-023-01899-9

On the Development and Evaluation of NOAA Unified Forecast System Atmospheric Model Physics Component for NCEP Operational Forecast Applications

Fanglin Yang[1]

[1]NOAA/NWS/NCEP Environmental Modeling Center

NOAA is collaborating with the US weather and climate science community to develop the next generation fully coupled earth system modeling capability for Unified Forecast System (UFS) research and operational applications across different temporal and spatial scales. An overview is given in this presentation of physics configurations employed by UFS-based global and regional models that either are already in NCEP operation or are planned for upcoming operational implementations, including the Global Forecast System (GFS), Global Ensemble Forecast System (GEFS), the Rapid Refresh Forecast System (RRFS), and Hurricane Analysis and Forecast System (HAFS). Performance of individual physics parameterizations was first developed and evaluated in atmospheric-only forecast models in the aforesaid applications and then further evaluated and improved in the integrated earth system modeling applications to reduce model systematic biases and maximize model prediction skills. Significant efforts were made to unify physics parameterizations for all applications to speed up the transition of physics innovations to operation and to reduce the cost of operational systems maintenance. A few samples will be presented to highlight the successes and challenges of unifying physics parameterizations for different NCEP operational forecast applications across a variety of temporal and spatial scales.

East African October to December Rainy Season - Major Drivers, Mechanism and Improved Predictability

Indrani Roy (Indrani.roy@ucl.ac.uk)[1], Alberto Troccoli[2]

[1] University College London (UCL), London, Department of Earth Sciences, WC1E 6BT, UK, [2] World Energy and Meteorology Council (WEMC), Norwich, NR4 7TJ, UK

Monsoon rainfall and year-to-year variability play an important role in Africa's energy, agriculture, and other societal sectors. Within the African continent, east African countries are affected much by higher degrees of variability in seasonal monsoon precipitation. Two large-scale climate drivers, the Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) are studied in this regard. A strong connection starting from a season ahead is identified for early austral summer (Oct-Nov-Dec, OND) monsoonal rain in eastern Africa. This has been examined using various data sources, detrending data beforehand, analysing either recent or earlier time periods - covering two decades each, and using the analyses of regression. Results of compositing also suggested a strong significant anomaly in OND rain covering that region of east Africa (named here as region A: 18˚ S-12˚ N, 25˚E-52˚ E). When IOD and ENSO are both negative in July-August- September(JAS) there is a significant deficit in OND rainfall, while an excess rain when both are positive. The Walker circulation plays a key role via altering descending and ascending branches in two circumstances. Based on this analysis, it is possible to deliver an estimation of cumulative rain in terms of median value, range and distribution, one season in advance, at a point location or average over a region. Results are further verified for recent two years of 2022 and 2023, where drivers were of same sign, either both negative (2022) or positive (2023). Classifications based on two drivers are not only modulating cumulative rain but also influencing onset dates; excess (deficit) rain and early (late) onset are associated with positive (negative) phases of both drivers starting from JAS. Two different onset techniques are compared and found such results are similar. Interestingly, regions of east Africa, south of that box region shows a complete reverse pattern in OND and that pattern continues till Dec-Jan-Feb. In terms of mechanisms, apart from Walker circulation, ocean also plays a key part.

Some results of compositing are confirmed for longer records (1940-2021) too and further classification of drivers, based on a threshold value (+0.4) is tested. In the recent year 2023, as both drivers were strongly positive in JAS, more analyses in such cases are presented. We note if either of the drivers is weak positive and lies in the range of 0 to +.04, the signal in region A weakens substantially on the eastern side of the box. The strongest weakening happens when both the drivers are of low magnitude in JAS (i.e., between 0 to +0.4). Rainfall (OND) variability of region A, at intra- decadal, decadal and multi-decadal scales are studied by applying the method of centered moving averages of 5-year, 11- year and 21-year respectively. A decreasing trend is noted in all situations and major peak/trough years are identified. For multi-decadal analyses, a shift at around 1958 is identified when the trend of OND rain is reversed and switched from increasing to decreasing. Our results have implications for future planning in optimizing energy and agricultural outputs and the livelihood of millions of east Africans will be impacted.

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Interplay of Background Dynamics and Large-Scale Circulations in the Kerala Extreme Rainfall Event of August 2019

Vaibhav Tyagi[1], Saurabh Das[1], Bipasha Paul Shukla[2]

[1]Department of Astronomy, Astrophysics and Space Engineering, Indian Institute of Technology Indore, 453552, India
[2]Atmospheric Sciences Division, Space Applications Centre (SAC), ISRO, Ahmedabad, 380015, India

The southwest monsoon, a vital component of India's annual rainfall, contributing around 75% of country's annual rainfall, significantly influences the weather patterns across the Indian subcontinent. In 2019, the southern-west state of India, Kerala, witnessed unprecedented rainfall from August 6 to August 14, 2019, about 602.2 mm which is 394% more than the normal (122.0 mm) rainfall that resulted in unprecedented and devastating floods and landslides. This affected 1038 villages, causing around 301 casualties and severely impacting sectors like housing, power and agriculture (DDM 2019). The objective of this study is to analyse the synoptic conditions, the influence of background dynamics and large-scale circulation that led to the extreme precipitation event using a variety of observational and reanalysis data. The IMD gridded daily rainfall data is analysed to study the spatial distribution of the rainfall. The peak rainfall was observed on 08 August 2019, when most of the districts of the state received about 250 mm or more rainfall. Synoptic analysis using radiosonde observations revealed a surge in Convective Available Potential Energy (CAPE) values preceding the extreme rainfall event, with CAPE values exceeding 1700 J/kg starting from August 3rd. The SkewT-Log P plots indicate an unstable atmosphere characterized by high CAPE values and low Convective Inhibition (CIN), facilitating convective cloud development. Furthermore, the study investigated the influence of large-scale wind circulations, including the Low-Level Jet (LLJ) and Tropical Easterly Jet (TEJ), on moisture transport and convective activity on August 8th. The LLJ facilitated moisture influx from the Arabian Sea, with wind speeds exceeding 16 m/s over southern India. The analysis also revealed the presence of a strong easterly jet stream, known as the Tropical Easterly Jet (TEJ), at 100 hPa, with wind speeds reaching 35-40 m/s. In contrast, westerly winds at 500 hPa were notably weaker, with speeds of approximately 10-12 m/s. This significant difference in wind speed between the upper and lower troposphere created substantial wind shear, a characteristic atmospheric condition conducive to the vertical development of convective clouds. The atmospheric instability, coupled with significant moisture influx from the Arabian Sea, provided a favourable environment for convective cloud development that resulted in heavy rainfall during that time. These findings highlight the intricate interplay between background dynamics, large-scale circulations, and extreme rainfall events. Understanding these mechanisms is essential for improving monsoon forecasting accuracy and developing effective disaster mitigation strategies.

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Dynamical Aspects of Heavy Rainfall Events Over Southern Peninsular India during Northeast Monsoon Season and its Association with Indian Ocean Warming and Madden Julian Oscillation

Ms. Sreevidya Ravi[1]

[1]CUSAT, Kochi

The Southeastern Peninsular India witnessed heavy rainfall events (HRE) during the recent El Nino year 2015 and La Nina year 2021 in November and early December. Both these events were associated with enhanced easterly wave activity and active MJO over the Maritime continent. The MJO was on the fourth (MJO-4) phase for 15 and 17 days in Nov 2015 and Nov 2021 respectively. A weakening in the positive correlation between El Nino and Northeast monsoon rainfall and a strengthening of the positive correlation between the MJO-4 and HRE have also been observed in very recent years. This study revealed that the unequal changes in sea surface temperature i.e., warming over the eastern Indian Ocean and cooling over the western Pacific Ocean can be a crucial factor for the increased occurrence of MJO-4 and HRE over southern peninsular India. The easterly wind anomalies towards southern BoB and southeastern Peninsular India and westerly wind anomalies over the central equatorial Indian Ocean is significantly correlated with HRE in the recent epoch. Warming in eastern IO brings easterlies from the cool western Pacific and westerlies from the western IO, which helps the MJO to remain active over the maritime continent and inhibit its further eastward propagation. It is also observed that the heavy rainfall events are now associated with the low-pressure system and cyclonic circulation over southern Peninsular India, which brings moisture from the Arabian Sea towards peninsular India. At the same time, the HRE in the early epoch were related with BoB anticyclonic circulation and moisture transport from BoB and the southeastern Indian Ocean. A proposed mechanism for the HRE in the recent epoch is as follows.The SST gradient in the Indo-Pacific Ocean is conducive for the moistening of MJO- 4 centre and is favorablefor the enhanced easterly wave activity and the formation of low- pressure systems, which get strengthened while moving towards southern peninsular India due to the presence of strong equatorial westerlies over the Indian Ocean. Strong ascending wind anomalies over southern Peninsular India and strong descendinganomalies over the Central Indian Ocean, which is associated with the strengthened low-pressure systems produce heavy rainfall events over southern Peninsular India.

A Parameterization for Cloud Organization and Propagation by Evaporation-Driven Cold Pool Edges

Saulo R. Freitas1 , Georg A. Grell2, Angel D. Chovert3, Maria Assunção F. Silva Dias4 , and Ernani de Lima Nascimento5

[1]National Institute for Space Research (INPE), São José dos Campos, Brazil
[2]Earth System Research Laboratory, NOAA, Boulder, CO, USA,
[3]Center for Environmental Studies, Monitoring and Prediction (CEMPA), Federal University of Goiás, Goiânia, Brazil,
[4]University of São Paulo, São Paulo, Brazil, 5Federal University of Santa Maria, Santa Maria, Brazil

When the negatively buoyant air in the cloud downdrafts reaches the surface, it spreads out horizontally, producing cold pools. A cold pool can trigger new convective cells. However, when combined with the ambient vertical wind shear, it can also connect and upscale them into large mesoscale convective systems (MCS). Given the broad spectrum of scales of the atmospheric phenomenon involving the interaction between cold pools and the MCS, a parameterization was designed here. Then, it is coupled with a classical convection parameterization to be applied in an atmospheric model with an insufficient spatial resolution to explicitly resolve convection and the sub-cloud layer. A new scalar quantity related to the deficit of moist static energy detrained by the downdrafts mass flux is proposed. This quantity is subject to grid-scale advection, mixing, and a sink term representing dissipation processes. The model is then applied to simulate moist convection development over a large portion of tropical land in the Amazon Basin in a wet and dry-to-wet 10-days period. Our results show that the cold pool edge parameterization improves the organization, longevity, propagation, and severity of simulated MCS over the Amazon and other different continental areas

A Convection-permitting Model: IITM HGFM to Improve High Impact Weather Prediction

P. Mukhopadhyay[1], R. Phani Murali Krishna[1], Siddharth Kumar[1], A. G. Prajeesh[2], Revanth Reddy[1], Kumar Roy[2], Malay Ganai[1], Radhika Kanase[1], Snehlata Tirkey[1] and Tanmoy Goswami[1]

[1.] Indian Institute of Tropical Meteorology, MoES, Pune, India
[2.] KAUST, Saudi Arabia
[3.] University of Victoria, Canada

The Numerical Weather Prediction has advanced significantly in last few decades since its journey in 1949. The skill of medium-range forecast by NWP model such as the IITM Global Forecast System (GFS) Model has improved by 2 days meaning whatever was the skill for day 3 forecast (or 72-hour lead time) with 27 km resolution model has now been achieved for day 5 forecast with a 12 km GFS model which is a significant progress. However, the effect of climate change is modulating the character of rainfall variability across global tropics vis-a-vis over Indian region. Very heavy rainfall (11 to 20 cm/day) is frequently realized within shorter time span and this as such becomes a new challenge and also a need of the hour for NWP community to resolve. Keeping this in to account, a global convection permitting model has been developed at IITM: IITM High resolution Global Forecast Model. The model is being developed using the cubic octahedral grid in spectral truncation (TCO) and it currently runs at a spatial resolution of 6.5 km over global tropics. The model has been run experimentally since June 2022 and being evaluated for many extreme events. The forecast comparison of HGFM and GFS shows the fidelity of both the models to capture the large scale pattern and the mean monsoon features. However, for the specific events of heavy rain and also the rainfall PDF show the HGFM has better fidelity in capturing heavy rains as compared to GFS. This model will be further tested and eventually be handed over to IMD for operational application. In the near future, the model will be run in ensemble mode along with coupling to ocean and the physics will be modified with AI/ML based approach.

On GPEX and Organized Convection

Prof. Xubin Zeng
University of Arizona, USA

The Global Precipitation EXperiment (GPEX) was launched in October 2023 as a World Climate Research Programme (WCRP) Lighthouse Activity. It takes on the challenge of improving the prediction of precipitation quantity, phase, timing and intensity, characteristics that are products of a complex integrated system.

In this talk, I will first briefly overview the GPEX Science Plan. Its central phase is the WCRP Years of Precipitation for 2-3 years with coordinated global field campaigns focusing on different storm types (atmospheric rivers, mesoscale convective systems, monsoons, and tropical cyclones, among others) over different regions and seasons.

As these storm types are all related to organized convection, I will next overview some of our relevant work, including the environmental conditions leading to the initiation of mesoscale convective systems, hurricane prediction, global monsoon onset and retreat, and atmospheric river effect on snowmelt extreme.

Rain-type Classification and Convective Clustering in Heavy Rain Events: Radar Observations and Numerical Simulation

Harshad S. Hanmante[1,2], Sachin M. Deshpande[1], Subrata K. Das[1], Medha Deshpande[1] and Manisha Tupsoundare[1]

[1] Indian Institute of Tropical Meteorology, Pune, India
[2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, India

Deep convection and the degree of convective organization play an important role in the global circulation regarding moisture fluxes, energy, and momentum transport. During the Indian summer monsoon, deep moist convection is frequent, and it produces widespread and heavy precipitation over Central India. Given its significance, a dual-polarization C-band (CPOL) radar was recently installed at the Atmospheric Research Testbed (ART) Facility of IITM at Silkheda in the monsoon core zone. The high-resolution resolution CPOL radar observations (6 min, 1 km) allow us to investigate the evolution of convective clustering during the life cycle of convective entities and use this as an observational basis to assess how convective clustering is represented in a numerical model.

Radar observations during the two-day heavy rain events from June to September 2022 are used to stratify 3D radar echoes into different rain types: convective, stratiform, mixed, isolated convective core, and isolated convective fringe. Clustering metrics are applied to radar-identified convective echoes to measure the degree of convective aggregation/clustering and their spatial distribution within a radar domain. Two distinct phases of convective clustering are seen, each lasting ~ 24 hours before (Phase 1) and after (Phase 2) the peak rain rate. In phase 1, convective clustering is attended by a rise in convective elements but phase 2 shows the prevalence of a broad area of stratiform along with a decline in convective elements. Composite evolution shows that small convective objects are blended into fewer and larger objects that are more grouped, saying that convective aggregation is occurring. A phase lag association amongst the isolated convective core, convective, and stratiform echoes is noticed.

Next, a convection-permitting simulation is made using the WRF model for an extreme rain event on 20-22 August 2022. Similar techniques were applied to the simulated reflectivity to examine rain-type classification and convective clustering, and the results were compared to radar observations. In general, the reflectivity CFADs for different rain types below 5 km demonstrate a good comparison between radar and WRF, but the frequency distribution is much wider and the WRF reflectivity values are weaker above 5 km. The microphysical quantities and other variables from the simulation (e.g. vertical velocity) are used to explain the observed similarities and differences between the radar and WRF comparison and details will be presented at the conference.

A Machine Learning Based Approach to Predict Extreme Rainfall Events in India's Uttarakhand Region

Aayushi Tandon[1]*, Amit Awasthi[1] and Kanhu Charan Pattnayak[2]

[1]Department of Applied Sciences, University of Petroleum & Energy Studies, Dehradun, Uttarakhand, 248007, India
[2]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom

Extreme events are often unpredictable, and their occurrence can have far-reaching consequences on human lives, infrastructure, economies, and ecosystems. This study evaluates precipitation trends and extreme precipitation indices using the MERRA 2 reanalysis dataset in Uttarakhand, India. Employing statistical methods like the Mann-Kendall test and Sen's slope estimator, we observed a general increasing trend in precipitation from 1984 to 2023 on a significance level of 0.05. Examination of extreme precipitation indices revealed nuanced variations in threshold levels across different return periods. Notably, May, marking the significant increase in rainfall activity (p = 4.83551E-09). June and July recorded the highest cumulative Consecutive Wet Days (CWD), followed closely by August, while November and December exhibited the lowest Consecutive Dry Days (CDD). Moreover, threshold values generally rose with increasing return periods, except for the 30-year and 25-year periods where it remained constant at 31 mm. The dominance of July and August in driving extreme events, particularly evident in the R95PTOT index, underscores the monsoon's pivotal role in shaping rainfall extremes. While Extreme Value Theory (EVT), Generalized Extreme Value (GEV) Distribution, and Peak analysis traditionally inform extreme event analysis, this study seeks to evaluate cutting-edge supervised machine learning (ML) models – specifically Random Forest (RF) and Support Vector Machine (SVM). In our study, we found RF and SVM achieving the accuracies of 84% and 85% respectively which agrees with the other literature on precipitation (Adugna et al., 2022; Kumar & Singh, 2022; Markuna et al., 2023) offering promise in addressing climate change challenges effectively. Furthermore, extending our methodology to analyze global and regional datasets like CORDEX, CMIP, IMDAA can have implications for diverse applications such as climate extreme studies. These insights will aid in better preparedness and mitigation strategies against extreme precipitation events.

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Impact of Western Ghats Orography on the Simulation of Extreme Precipitation over Kerala, India during 14–17 August 2018

V. Yesubabu[1], Biyo Thomas[2], C.V. Srinivas[3], Ghouse Basha[1], Ravi Kumar Kunchala[2]

[1]Weather and Climate Research Group (WCRG), National Atmospheric Research Laboratory, Gadanki- 517 112, Andhra Pradesh, India.
[2]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India
[3]Environmental Assessment Division, Indira Gandhi Centre for Atomic Research, Kalpakkam – 603102, Tamilnadu, India, a CI of Homi Bhabha National Institute, Mumbai.

The state of Kerala, located in southwest peninsular India, has experienced a series of extremely heavy rainfall events in the past few years, resulting in severe flooding and landslides. Among these events, an extremely heavy rainfall episode (50 to 480 mm/day) occurred during 14–17 August 2018 had led to devastating floods along the southwest coast of India. In this study, we have chosen this event as a case study to analyze the role of orography, using a high-resolution (1-km) cloud-resolving WRF model configuration. We conducted four numerical sensitivity experiments to examine the impact of different topographic configurations, ranging from no- mountain to plateau, moderate, and steep mountain terrains, on the simulation of the extreme rainfall event. The results of the mountain sensitivity experiments indicate that as mountain height increases, simulated low-level wind decelerates quickly. This flow blocking is also manifested in parameters such as reduced upper-air wind intensity, increased dynamical convergence, and increase of vertical velocities at the Western Ghat (WG) mountain barriers, which lead to the variations in moist instability and cloud microphysical processes influencing the horizontal and vertical distribution of solid-phase hydrometeors. Furthermore, the results also show that a reduction in the orography of the WGs decreases the vertical extension of low-level jet winds to upper levels, weakens the tropical easterly flow, and decreases the wind shears between the lower and upper troposphere. In addition, the results suggest that large-scale variations in mountain orography in numerical simulations can affect the simulated magnitude and direction of moisture transport, which may have played a role in determining the magnitude and distribution of simulated rainfall over Kerala.

Keywords: Heavy rainfall events, Kerala, Western Ghats, Orography and WRF-ARW model

Understanding the Extreme Precipitating Monsoon Rainstorms over Pakistan

D. C. Ayantika[1], Tiasha Dev[1], Kalik Vishisth[1], R. Krishnan[1], K. M. Sumit[1], and R. Vellore[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India

The recent years were marked by several extreme precipitating events over the arid and semi-arid regions of Pakistan during the summer monsoon months. Many of these events played a significant role in causing some of Pakistan's most devastating and expensive natural disasters, impacting both human lives and resources. While earlier studies have mostly investigated the seasonal patterns that promotes flood causing heavy rainfall over Pakistan, a thorough understanding of the precipitation characteristics and circulation dynamics associated with major rainstorms over the region remains necessary. This study conducts a detailed analysis of the observed severe monsoon rainstorms over Pakistan and north-west India during the period 1980-2023 using CPC Global Unified Gauge-Based Analysis and ECMWF Reanalysis v5 (ERA5). This analysis also usesrainfall characteristics obtained from spaceborne precipitation radars on board TRMM/GPM. The results show noticeable interannual variations in the duration and intensity of monsoon rainstorms over Pakistan and north-west India, indicating the impact of climate modes of variability over the tropical Indian and Pacific Oceans along with a distinct rise since the year 2005. Interestingly we notice that the severe and expansive rainstorms over this dry region is often associated with circulation anomalies resulting from westward propagating monsoon low pressure systems and are characterised by broad stratiform raining areas that are quite unusual for this region. The upper-level large-scale circulation patterns during the intense rainstorms includes profound southward-extending mid-latitude westerly trough, a blocking high-pressure system over western Eurasia or a strengthened Tibetan anticyclone. Our results offer evidence of a shared large-scale circulation pattern linking the extra-tropics and the South Asian monsoon region that is conducive to development of broad and intense stratiform precipitating rainstorms over the arid and semi-arid regions of Pakistan and northwest India.

STI POSTERS

Influence of Major Stratospheric Sudden Warming on the Stratospheric Ozone Intrusions over South Asia

Shubhajyoti Roy[1], Prashant Chavan[1], Satheesh Chandran PR[1], and Suvarna Fadnavis[1]

[1]Indian Institute of Tropical Meteorology Pune, 411008, Ministry of Earth Sciences Delhi, India

Sudden stratospheric warmings (SSWs) are an important indicator of polar variability. Stratosphere-troposphere coupling during the splitting of the polar vortex due to SSWs (split SSWs) strongly influences weather. A significant impact of SSWs is observed on stratospheric ozone concentrations; however, their effects on stratospheric-tropospheric exchange (STE) and upper troposphere-lower stratosphere (UTLS) radiative forcing are poorly understood. In this study, we analysed a strong SSW event in 2018 against climatology from 1960 to 2017 using ERA5 data. Potential vorticity distribution at 10 hPa shows that on 12 February the Arctic vortex splits into two baby vortexes, one centered over North America and another over Russia. Our diagnostic analysis from geopotential and wind shows that the air mass from the Arctic stratosphere descends into the UTLS over the Pakistan-North India region (60–90°E, 10–40°N). It intensifies the Rossby wave breaking (RWB), which leads to the deep intrusion of warm, ozone-rich air from the stratosphere into the troposphere, results in an enhancement of ozone by 20–30 ppb and temperature by 4K at 600 hPa. RWB persists typically for 60 days, with a periodicity of 4–8 days. Rossby Wave moves eastward in the subtropical jet and breaks over the Pakistan and the North Indian region causing ozone intrusions. The ozone enhancement increases total ozone radiative forcing (RF) over the North India region (60–90°E, 10–40°N) by 0.16 W.m^{-2} which may impact the atmospheric circulation and weather. It is important to note that this notable abundance of ozone also has numerous consequences on air pollution, Earth's ecosystems, and human health.

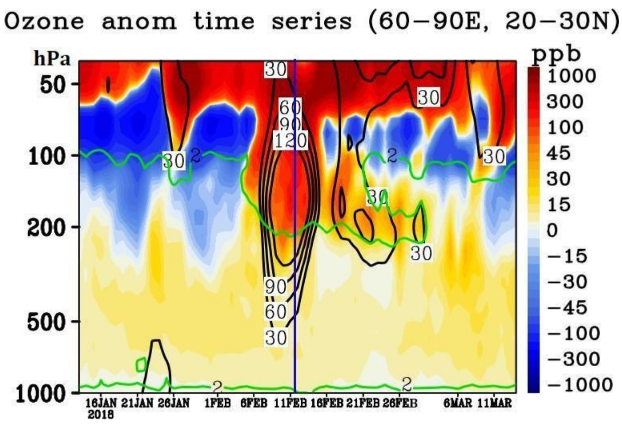

Figure 1: Time series of ozone anomaly during 13 January 2018 – 14 March 2018 averaged over North Indian region (60–90° E; 20–30°N). Black line indicates GPH anomaly and green line indicates PV. Blue straight line indicates polar vortex breaking day (12 February, 2018).

Exploring Atmospheric Gravity Waves Post-Explosive Volcanic Eruptions

Satyamesh H Tiwari[1*] and Mala S Bagiya[1]

[1]Indian Institute of Geomagnetism, Navi Mumbai

*satyamesh.t@iigm.res.in

Explosive Volcanic eruptions occur when pressure inside magma increases and it erupts violently releasing gases and volcanic ash into the atmosphere. The ejected gases like SO_2 can form sulfate aerosols and thus lead to localized heating of the stratosphere and influencing temperature distributions which, in the long term, can alter the overall circulation pattern. The convective region created by the hot gases and volcanic ash gives rise to gravity waves forming the principal form of energy exchange between the lower and upper atmosphere. On breaking into the upper atmosphere, Gravity waves transfer their energy and momentum driving the mean atmospheric circulation and hence influencing tropospheric weather and climate patterns. Despite the importance of gravity waves in upper atmospheric dynamics, very little is known about upper-level gravity wave characteristics which might be because of the lock of high-resolution observations. It is now known that volcanic eruptions are also a potential source for the generation of gravity waves and observing them at different altitudes can help us in understanding gravity wave characteristics. Still, there are only very few observations of Gravity waves after explosive volcanic eruptions. This study presents the observations of stratospheric and mesospheric gravity waves after large explosive volcanic eruptions and discusses their possible generative mechanism.

Influence of Synoptic-scale Rossby Wave Breaking on Extreme Weather Events over the Indian Subcontinent

Biyo Thomas[1], Ravi Kumar Kunchala[1,*], Bhupendra Bahadur Singh[2], and Kondapalli Niranjan Kumar[3], and Viswanadhapalli Yesubabu[4]

[1]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, 110016, India
[2]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, 411 008, India
[3]National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, Noida, 201309, India
[4]Weather and Climate Research Group (WCRG), National Atmospheric Research Laboratory, Gadanki517 112, Andhra Pradesh, India

The weather of the subtropical Indian region can be significantly affected by dynamical changes in the atmosphere triggered by Rossby Wave Breaking (RWB). However, there is still a lack of comprehensive understanding on how extreme weather events modulated or triggered by RWB over this region. To address this gap, we explored the relationship between the occurrence of extreme events and RWB in this study. We utilize a Potential Vorticity (PV) contour searching algorithm, adapted from existing literature but with additional constraints specific to the Indian subcontinent, to detect RWB events. Based on this algorithm, we identified and analyzed 513 RWB events during the period from 1979 to 2021 allowing us to gain insights into the climatology and variability of RWB over the region. Further, we extend our analysis on the co-occurrence of RWB on extreme weather events such as rainfall and heat waves. Our analysis shows that RWB promotes extreme rainfall by generating instability in the atmosphere allowing enhanced moisture influx over the region ahead of the streamer. However, the weather conditions in the west of the PV streamer can lead to the formation of heat waves. By using the regression analysis, we further explore the triggering mechanism of the extreme weather events that occur due to RWB over the study region. Moreover, these findings could have practical applications in climate investigations, particularly concerning extremes within the context of a warming climate.

Does the Tropical Atmosphere Support Doppler Shifted MRG Waves?

Shreya Keshri[1], Vishal Ranjith[2], and Suhas Ettammal[1]

[1]Indian Institute of Science Education and Research, Pune, 411008, India
[2]University of Cambridge, CB2 1TN, United Kingdom

MRG waves belong to one of the major synoptic scale modes of tropical atmospheric variability and they exhibit the properties of both slowly evolving Rossby and quickly evolving gravity type wave disturbances. Since the MRG waves bridge the gap between the low-frequency and high frequency modes of variability, it is crucial to understand the underlying dynamics of the MRG waves to improve the tropical weather and extended range forecasts. Many previous studies reported the observation of Doppler shifting of MRG waves in the western Hemisphere (e.g. Yang et al. 2003, Yang and Hoskins 2016). Nevertheless, a comprehensive study of eastward propagating Doppler shifted MRG (E-MRG) waves and their frequency of occurrence relative to the westward propagating MRG waves is missing. In this study, we investigate the E- MRG wave events at 200 hPa pressure level using the wave fitting and Empirical Mode Decomposition (EMD) based wave event identification methodology. We have found 743 E-MRG wave events for the period 1979-2022 and a large fraction of them occur in the westerly duct during boreal winter seasons. It is noteworthy that E- MRG wave events account for 33% of the total MRG wave events in the western Hemisphere during boreal winter seasons. As expected from the linear wave theory, 75% of the E-MRG wave events occur when the background winds are westerly. On the contrary, a notable fraction of the E- MRG events occur when the background winds are easterly. Detailed analysis reveals that the westerly phase of the large-scale Kelvin waves setup the conducive environment for MRG wave events to be Doppler shifted and explain more than 75% of the E-MRG wave events that occur when the background winds are easterly. In addition to that, the observation of a strong link between the intrusion of eastward propagating extratropical disturbances and the E-MRG wave events support the extratropical-tropical interaction theory of Hoskins and Yang (2016). The study underscores the importance of multi-scale interactions and its realistic representation in the climate andnumerical weather prediction models.

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Characteristics and Long-term Trend in Tropopause Parameters Obtained from US High-resolution Radiosonde Data

K. P. Aathira.1*[1], M. Pramitha[1]

[1] Indian Institute of Science Education and Research, IISER Thiruvananthapuram, Kerala, India

*aathirakp23@iisertvm.ac.in, pramitha@iisertvm.ac.in

Tropopause is the boundary between evenly mixed troposphere and stably stratified stratosphere. Along with stratification, potential vorticity and chemical constituents such as water vapor, Ozone varies in this region and is important for stratosphere-troposphere exchange processes (STE). Based on latitudinal variation, tropopause altitude can be used to measure the width of the tropical belt, which is also an indicator of climate change. There exist different definitions of tropopause based on its chemical, dynamical, and thermal properties. In the present study, SPARC- US high-resolution radiosonde temperature profile data (6 sec) which is interpolated to 50m altitude has been used to study extratropical thermal lapse rate tropopause (LRT), multiple tropopause and tropopause inversion layer (TIL). There are96 US stations, with data available from 1998, from which the stations which have more than 85% of the month's data have been selected for the present work. LRT temperature and altitude, TIL, and Multiple tropopause have been identified for the different stations, in which LRT altitude varies between 10 - 15 kmbased on season. Seasonally LRT altitude is maximum during the Summer Season (JJAS) compared to winter (DJF). A tropopause-based averaging technique is used to redraw the temperature and pressure profiles and calculate the Brunt–Väisälä frequency(N) from them.TIL is found to be having a width of 300m to 4 km. Further, Multivariate linear regression is applied to the monthly mean tropopause altitude/ temperature by incorporating solar Cycle, Quasi-Biennial Oscillation, and El Nino Southern Oscillation, and the long-term trend in the LRT has been identified. The tropopause altitude is showing an increasing trend while tropopause temperature is showing a decreasing trend. The altitude and temperature is showingopposite trends as expected in 68% of the stations. The TIL height is found to be in the range 13-14 km

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Vertical Interactions of Atmospheric Layers under Different QBO and ENSO Phases

Anastasia Golovko[1], Andrey Koval[1], and Tatyana Ermakova[1]

[1]Saint Petersburg State University, Saint Petersburg, 199034, Russian Federation

The investigation purpose is to assess the influence of tropical oscillations on the middle and upper atmosphere of high latitudes. The influence of the quasi-biennial zonal wind oscillation in the equatorial stratosphere (QBO) and El Niño– Southern Oscillation (ENSO) on the dynamics of the stratosphere, mesosphere and lower thermosphere in the Northern Hemisphere winter was studied. Ensemble runs were carried out using the nonlinear general circulation model of the middle and upper atmosphere “MUAM” for January–February. The modeling results made it possible to estimate the sensitivity of the zonal wind, temperature fields, residual meridional circulation (RMC), and wave activity to different combinations of ENSO and QBO phases. The temperature anomaly and oscillations of the zonal wind component are different, and the strengthening/weakening of the RMC branches shifts in height depending on the combination of phases. It is shown that the greatest temperature increase in the stratosphere and cooling in the mesosphere, as well as a weakening of the stratospheric polar night jet stream are simulated under the conditions of El Niño and the easterly QBO, while the maximum weakening of the meridional flow from the summer to the winter pole is noted at an altitude of 80-90 km. The opposite situation is observed during the negative phase of La Niña and the westerly QBO: the zonal wind component is maximum in the stratosphere of middle latitudes, at a minimum temperature above the pole. As a result of this different manifestation of tropical oscillations at middle and high latitudes, their impact on the frequency and intensity of sudden stratospheric warming events is evident. These events can lead to extreme cold waves in the troposphere over Eurasia, as well as the formation of ozone holes.

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Variability of the UTLS Ozone over India during Future EL-Nino and La-Nina

Chaitri Roy[1], Archana Sagalgile[1], and Suvarna Fadnavis

[1]Indian Institue of Tropical Meteorology, Pune, India
[*]Corresponding author: suvarna@tropmet.res.in

Ozone fluctuatuations in the upper troposphere and lower stratosphere (UTLS) significantly modulate Earth's radiative balance. The interplay of El Niño and La Niña phenomena across the Pacific Ocean can exert notable effects on UTLS ozone during the Asian Summer Monsoon (ASM) through atmospheric dynamical alterations. Employing the global Chemistry-Climate Model ECHAM6-HAMMOZ, we investigate the projected UTLS ozone variations during El Niño and La Niña years under the future Shared Socioeconomic Pathway (SSP) scenario. We identified eight El Niño years and six La Niña years within the timeframe of 2020-2050. Our analysis reveals a substantial increase in ozone concentration at 100 hPa over India, ranging from 8-20 ppb during June to September (JJAS) during the El Niño years in the future, contrasting with minimal changes, less than 3 ppb, observed during La Niña years. This pronounced ozone surge in the UTLS during El Niño is primarily attributed to stratospheric ozone intrusions over the Indian subcontinent. Furthermore, the UTLS ozone fluctuations exert a significant influence on regional temperature and heating rates over India in future.

Unveiling Lightning NO_x Emissions and its Impact on Air Quality over India

Subhojit Ghoshal Chowdhury[1], Dilip Ganguly[1], and Sagnik Dey[1, 2]

[1]Centre for Atmospheric sciences, Indian Institute of Technology Delhi, India
[2]Centre of Excellence for Research on Clean Air, Indian Institute of Technology Delhi, India

Lightning modifies middle and upper tropospheric trace gas composition by producing significant Nitric oxide (NO), disassociating O_2 and N_2 at high temperatures. Freshly formed NO immediately oxidizes to NO_2; the combination ($NO+NO_2$) is known as Lightning NO_x (LNO_x). Lightning contributes up to 10% of the global NOx emission annually. It also influences the production of ozone (O_3) and hydroxyl (OH) radicals, which leads to changes in the oxidative potential of the atmosphere and perturbs the radiative balance of the climate system. Increase in convective activity across the globe, makes lightning a potentially important factor responsible for changes in atmospheric composition and climate through chemistry-climate interaction from troposphere to stratosphere. In the present study we investigate the impact of LNOx on tropospheric NOx vertical column density, tropospheric column O_3 and OH production at different altitudes focusing on northwest Indian region.

We use the Weather Research and Forecasting coupled with chemistry (WRF-Chem) model combined with satellite, ground-based observations for our research. First, we identified lightning days over our study region using Lightning imaging sensor high-resolution dataset (10kmX10km). As Lightning is more dominant during premonsoon (MAM) & Monsoon (JJAS) seasons, these seasons are chosen for our study period. Further, we use OMI level 3 daily gridded data (0.25°×0.25°) of total and tropospheric NO_2 vertical column density to analyze lightning induced variations in atmospheric NO_2. Our results show that, total NOx emission is enhanced by (10-15) % during lightning days from surface to upper troposphere. In addition, total columnar ozone is also significantly increased by (6-8) DU during lightning events. Moreover, OH concentration is also markedly modulated by lightning strokes. As the the oxidative potential of the atmosphere gets significantly perturbed due to lightning and this in turn affects the lifetime of various air pollutants in the troposphere, it is important for us to take in to account these changes while formulating effective mitigation strategies for combating the menace of air pollution in north India. More results with greater detail on the impact of LNO_x on the tropospheric chemistry and air pollution will be presented.

Research Mapping and Trend Analysis on Stratosphere Troposphere Exchange during Monsoon Weather Extremes

Arnab Chakraborty[1], Shompa Das[2]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India
[2] Indian Institute of Tropical Meteorology, Pune, 411008, India

Stratosphere and troposphere interaction has great significance regarding weather patterns in monsoon. An in-depth understanding of STI helps better track monsoon variability and weather extremes. Further studying different patterns of STI helps in having a comprehensive perception of regional weather patterns, climate change and improved weather forecasts. As a result, the scientific community working in this domain are also very keen on studying STI and its role in monsoon weather extremes. This is a comprehensive analysis of the current state of scientific inquiry into STI and monsoon weather extremes, focusing on mapping research performance, identifying multidisciplinary approaches, delineating emerging trends and understanding the multifaceted challenges of studying Stratosphere-Troposphere interaction (STI) and monsoons.

WoS database and statistical and data visualisation tools like Biblioshiny, Vos-viewer, and Ms-Excel are used to collect and interpret data and make appropriate inferences visually. Using proper keywords and suitable filtering, 544 articles were found in English, with an annual growth rate of 10.64% and an international co-authorship rate of 43.04%. By analysing all the author keywords, we have observed that the Asian Tropopause Aerosol Layer (ATAL), Upper Troposphere-Lower Stratosphere (UTLS), stratosphere- troposphere coupling, Asian summer monsoon, anticyclone, etc, are emerging research areas. In contrast, areas like arctic oscillation, gravity waves, ozone layer, Quasi-Biennial Oscillation (QBO), and Mesospheric Stratospheric Tropospheric Radar (MST-Radar) have already contributed much to the domain. Co- authorship is one of the dynamic metrics that help to understand the integration of different authors from multiple disciplines and research on STI, and monsoon weather has a co-authorship rate of 5.82, and only 12 single-authored papers in total, 544 papers prioritise the importance of approaching the subject from a multidisciplinary perspective. It has also highlighted two essential journals, namely “Atmospheric Chemistry and Physics” and “Journal of Geophysical Research-Atmosphere”, which contribute most to this topic and indicated that most research articles are concentrated in a minimal number of periodicals.

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Understanding the Physical Mechanism Behind Extreme Weather Episodes in Nepal

Damodar Bagale, Deepak Aryal and Madan Sigdel

Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu 44613, Nepal;

***** Correspondence: damu.bagale@gmail.com

Precipitation along 107 meteorological stations was analyzed to examine the characteristics of rainfall over Nepal from 1977 to 2018. Based on the observational and reanalysis data, El Niño/La Nina associated with the Nepalese monsoon droughts/floods are investigated. Summer monsoon of Nepal (JJAS) is the mainly rainy season in Nepal. During the last four decades, eight large deficit (drought) and eight excess (flood) events were identified. The intense summer drought was identified in 1992 and 2015; similarly, extreme flood was obtained in 1986 and 1998. The large excess (deficit) episodes precipitation 19.21 % above (below 19.29 %) from long-term climatology 1977-2018. There is large temporal and spatial variability of precipitation in extreme episodes. In El Nino (La Nina) episodes was observed approximately 9 % below (above) precipitation was observed than the average precipitation of summer season. This study has examined possible forcing factors behind the occurrence of extreme summer events using re-analysis dataset. The upper air circulations during dry years seem weak due to low convection near the source regions. In contrast, these circulations phenomena marked strong due to high convection near source regions in the La Nina years. Furthermore, the increasing/decreasing of sea surface temperature (SST) in the Indian and Pacific Ocean is the cause of decreasing/increasing precipitation in Nepal.

Keywords: Atmospheric circulations, Extreme episodes, El Nino and La Nina, Precipitation

Comparison of Temperature and Wind fields from Reanalysis with Radiosonde at Nainital in the Southern Himalayas during the Monsoon Season

Satheesh Chandran P R[1], Suvarna Fadnavis[1], Sunil Sonbawne[1], Archana Sagalgile[1], Manish Naja[2], and Rolf Müller[3]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India
[2]Aryabhatta Research Institute of Observational Sciences, ARIES, Nainital, India
[3]Forschungszentrum Jülich GmbH, IEK-7, Jülich, Germany

Reanalysis datasets are often used in model simulations of the past history. Because in situ and satellite observations which are assimilated into reanalysis systems, reanalysis datasets differ. Hence it is imperative to validate these reanalysis data products against observations. Any biases in meteorological data can cause significant errors and uncertainties in both prognostic and diagnostic variables. Here, we performed an intercomparison study for temperature and wind data in the troposphere and lower stratosphere (TLS) region at Nainital (29.38°N,79.45°E) in the Southern slopes of the Himalayas in August 2016 and 2023. We compared temperature and wind from ERA5, MERRA2, JRA-3Q and IMDAA reanalysis against measurements by Väisälä-RS41. The elevated topography of the Himalaya plays an important role in the Asian monsoon circulation. Our diagnostic analysis reveals a fair agreement in temperature across reanalysis datasets but notable discrepancies in wind components. A mean temperature difference of <0.8 K is observed in the TLS region, with a standard deviation of less than 1 K in the troposphere and more than 1.5 K in the stratosphere. In the troposphere, ERA5, JRA-3Q and IMDAA showed a very good agreement with the observation as compared to the MERRA2, they are within a standard deviation of each other. Meanwhile, near the tropopause region, IMDAA exhibited a large overestimation of temperature by 1K.

On the other hand, the zonal component of wind shows a large variability of >50-100% in the troposphere and <10% in the stratosphere. IMDAA showed a better agreement with the zonal component of wind in the troposphere, which is not the case for the stratosphere. The meridional component of wind shows 50-100% deviation in the TLS region. The large variability in wind is observed in the altitude region with wind speed <5m/s. Our findings emphasize the importance of in-situ observations in the summer monsoon region for a better representation of the meteorology in models and (re)analyses.

Response of the Rainfall of Western Half of the Indian Sub-continent to the Large-Scale Stratospheric Circulation

Busnur Rachotappa Manjunatha[1]

[1]Department of Marine Geology, Mangalore University, Mangalagangothri-574 199, India

Numerous recent investigations indicate that the stratospheric circulation tends to be rather stronger and wider coverage than the tropospheric zonal and meridional circulations. The former circulation seems to be induced not only influenced by natural variability, but also impacted by anthropogenic activities. From these investigations, it is quite clear that the atmospheric pollutants are transported to polar region through the stratospheric circulations and eventually sink to the polar region thereby causing an amplified climatic impacts (such as arctic amplification, enhance ozone hole), that would again boomerang on the lower latitude climate of the temperate and tropical regions. In this study, an effort has been made to unravel the response of the rainfall of the western half of India to the stratospheric-tropospheric interactions. The Principal Component Analysis (PCA) of the satellite data available since 1979 has been analyzed along with the IITM rainfall data. The PCA-1 indicates that it has been positively loaded with the Dipole Mode Index (DMI), Azores High, North Atlantic temperature anomaly are positively loaded with the All India Summer Monsoon Rainfall (AISMR), and other meteorological subdivisions along the western half of India, for instance, Central North East India, Peninsular India, Western Rajasthan, Saurashtra, Konkan-Goa, Coastal Rainfall of Karnataka and Kerala, however, negatively loaded with the ozone anomaly, Polar Vortex suggesting the deleterious impact of the stratospheric-tropospheric interaction on the rainfall of the study area. Similarly, the Arctic sea ice and its thickness during the slower sea ice formation month/season indicate that these have been negatively loaded, however, positively loaded with DMI, global temperature anomaly, global sea surface temperature (SST). In PCA-3, also there is a demarcation can be seen between the stratospheric and tropospheric interactions, such as stratospheric ozone anomaly is negatively loaded, but Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Odisha and western Rajasthan rainfall.

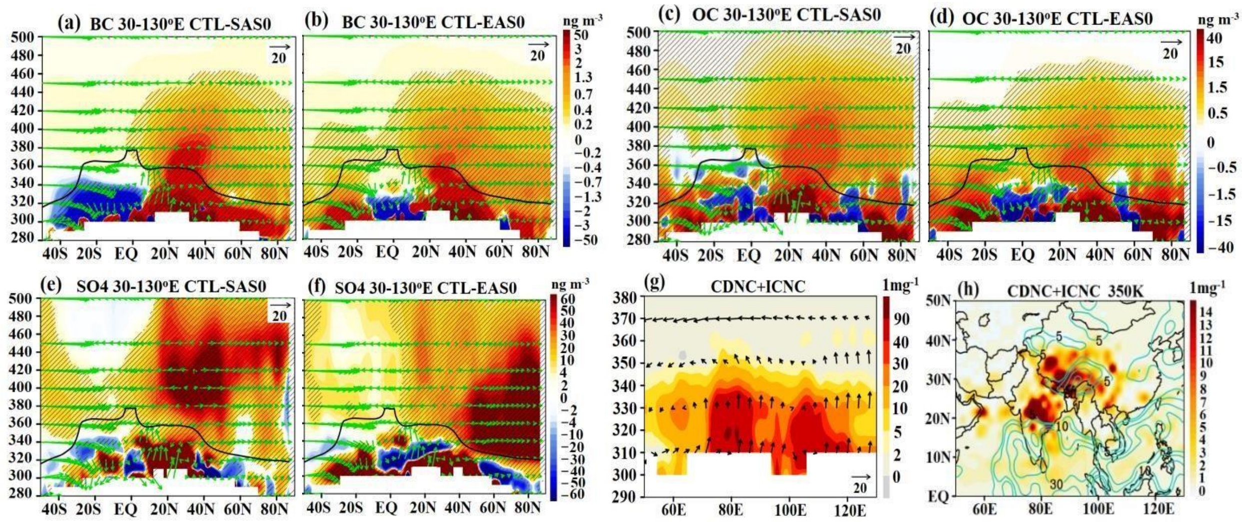
In the PCA-4, the El Niño-Southern Oscillation (ENSO), stratospheric ozone anomaly, and the Polar Vortex are negatively loaded, but other climatic data are positively loaded (AO, Arctic Sea Ice, Niño 3.4, global average SST. In the final PCA-5 , the stratospheric ozone anomaly shows a high positive loading along with Polar Vortex, and Suns spots North Atlantic temperature , however, negative with all India summer monsoon rainfall and many other meteorological subdivisions rainfall of India (North Western India, West Central India, Peninsular India, Western Rajasthan, Konkan –Goa and Tamil Nadu. All this information suggests an inverse relationship of the stratospheric circulations on the tropical ones which is initiated in the Arctic region, spreads later to the Mid-latitude regions and ultimately affects the tropical region.

Long Range Transport of South and East Asian Anthropogenic Aerosols Counteracting Arctic Warming

Suvarna Fadnavis[1], Sunil M. Sonbawne[1], Anton Laakso[2], Felix Ploeger[3], Mian Chin[4], Alexandru Rap[5], Bernd Heinold[6], and Rolf Müller[3]

Indian Institute of Tropical Meteorology, Centre for Climate Change Research, MoES, Pune, India,
[2]Finnish Meteorological Institute, Kuopio, Finland
[3]Forschungszentrum Jülich GmbH, IEK-7, Jülich, Germany
[4]Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, U.S.A
[5]School of Earth and Environment, University of Leeds, Leeds, UK,
[6]Leibniz Institute for Tropospheric Research (TROPOS), Germany

The large-scale convection during the Asian summer monsoon plays an important role in the rapid transport of boundary layer aerosols into the Asian summer monsoon anticyclone. Here, using the state- of-the-art ECHAM6–HAMMOZ aerosol-chemistry-climate model, we show that these aerosols are further transported to the Arctic along isentropic surfaces by the Brewer-Dobson-Circulation (BDC) during the monsoon season. Our model simulations show that larger amounts of East Asian anthropogenic aerosols are transported to the Arctic therefore causing a reduction of solar radiation reaching the surface (-0.82 W m-2), compared to those from South Asia (-0.55 W m-2). Over the Arctic, the East Asian aerosols cause an estimated seasonal mean radiative forcing (RF) at the top of the atmosphere (TOA) of -0.017 ± 0.008 W m-2 and a surface cooling of -0.56 K, compared to the South Asian aerosols (seasonal mean RF at TOA: -0.015 ± 0.01W m-2, surface cooling: -0.043 K). Overall, the long-range transport of East Asian aerosols cools the Arctic, therefore playing an important role in counteracting the rapidly rising Arctic temperatures and the associated snow and ice melting.



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Unveiling the Influence of Troposphere-Stratosphere Interaction on Groundwater Hydrology: A Novel Multi-Scaler Assessment

Akash Tiwari[1], Dr. Manish Kumar[1], Dr. Swati Thakur[2], and Jahnavi Singh[1]

[1]Central University of Haryana
[2]Dyal Singh College, University of Delhi

Global climate system is primarily driven by the interaction between the troposphere and stratosphere which is furthermore important in the shaping of atmospheric dynamics, affecting weather patterns, and influencing climate variability. This climatic variability leads to uneven distribution of the rainfall, which profoundly influenced the groundwater hydrology. In the atmospheric science troposphere-stratosphere interaction is widely studied, but its integration with groundwater has been provided a novel dimension to present study. In the present study, MERRA-2 reanalysis datasets of temperature, humidity, and precipitation were utilized to examine the troposphere-stratosphere interactions and major atmospheric patterns over India. Subsequently MODFLOW hydrological model was used to simulate the process of groundwater recharge under the varying atmospheric conditions. Statistical analysis using Geographical Weighted Regression (GWR) analysis was performed to quantify the relationship between troposphere-stratosphere interactions and groundwater dynamics. Understanding of the interlinkages between troposphere-stratosphere interactions and groundwater hydrology is crucial for the improvement of ability to forecast hydrological extremes, and sustainable water resource management. The development of integrated atmospheric-hydrological modeling frameworks, groundwater management strategies, and policies for adapting to climate change are all impacted by this study. Through understanding the complex connection between atmospheric dynamics and groundwater hydrology, this research adds to an improved understanding of Earth's hydrological cycle and how it reacts to both natural and human impacts.

Keywords: Stratosphere, Troposphere, Groundwater, Oscillation, Climate Change

Teleconnections between the Stratospheric – Tropospheric Interactions on the Seasonal and Annual Rainfall of the Peninsular India and, its Western Ghats and Coastal Region

Poornachandra R[1], Sudha[1] and SA Ahmed[2]

[1]Department of Physics, Kuvempu University, Shankaraghatta, Shivamogga, Karnataka 577451, India
[2]Department of Applied Geology, Kuvempu University, Shankaraghatta, Shivamogga, Karnataka 577451, India

The Quasi-Biennial Oscillation (QBO) has been identified as an inter-annual mode of shifting of the easterly westerly zonal winds in the tropical stratosphere, affecting the planetary circulations and associated climate change. In order to know the impact of the QBO on the seasonal and annual rainfall of the Peninsular India and the monsoon-windward side of the Western Ghats and the adjacent coastal tract, the Principal Component Analysis (PCA) has been carried out for the annual and seasonal data along with the possible teleconnecting forces, such as data pertaining to Arctic Oscillation (AO), North Atlantic Oscillation (NAO), El Niño- Southern Oscillation (ENSO), Niño 3.4 , global temp anomaly, Sun's spots, Dipole mode index Standard, Island low, Azores high, NE Atlantic temperature, Atlantic Multi-decadal Oscillation (AMO) and the Quasi- Biennial Oscillation (QBO) spanning over 69 years from the year 1948.

Intense research being carried out on the North Atlantic Climate system since three decades indicates that the temperature increase in the Arctic Circle is three-to-four-fold higher than the global average, not only suggesting the fragile nature of the former climatic system, but it has implications to the temperate and tropical regions. Apparently, the rainfall, barring the summer season, along the coastal Karnataka appears to be regulated principally by teleconnections, such as, the global temperature, global sea surface temperature (G.SST), as well as the Indian Ocean and Pacific Oceans SST, the remote influence of the North Atlantic Regions climatic systems, like the Western Disturbances (WD), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO) forms a secondary influence of the rainfall of the study area. The profound impact of the stratospheric-tropospheric interactions can be best understood by the phenomenon – Arctic Amplification results in strengthening the Polar Vortex thereby affecting the mid- and low-latitudes climate systems. Such an impact has been identified from this study as there is a negative relationship among the QBOand the summer monsoon rainfall patterns of the Peninsular India. Conversely, the teleconnections from the AMO, NAO and AO found to favour the rainfall of the study area. Although the ENSO links appear to be rather robust, the impact of the stratospheric-tropospheric connected circulations on the rainfall of the study area cannot be ignored.

CALIPSO Observed Persistent Aerosol Layer over the Indian Region: Implications on Heating Rates and Radiative Forcing

Rohini Bhawar*[1], Suvarna Fadnavis[2], Vinay Kumar[3], P.R.C. Rahul[2], Jennifer Griswold[4], and Simone Lolli[5]

[1]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India
[2]Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune, India
[3]Department of Atmospheric Science, Environmental Science and Physics, University of the Incarnate Word, San Antonio, Texas, USA
[4]Atmospheric Sciences Department, University of Hawai' Manoa, Honolulu, USA
[5]National Research Council (CNR), Institute of Methodologies for Environmental Analysis, Italy

A rising trend in aerosol pollution over South Asia is of great concern due to its impact on human health and the hydrological cycle. Here, using Cloud and Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) vertical aerosol profiles during 2007-2017, we explore the seasonal variation of dust and smoke aerosols and radiative forcing over the Indian region. Our diagnostic analysis reveals that a persistent layer of aerosols occurs in the lower troposphere (0-5km) over the Indian region throughout the year. The observed aerosol layer is attributed to a continuous supply of aerosols from the neighboring region throughout the year in addition to the local sources, i.e., dust from west Asia during pre-monsoon and monsoon seasons and smoke particles from the Indo-China region during winter and post-monsoon seasons. The higher amount of smoke from local sources thickens the layer over the Indo-Gangetic Plains (IGP). CALIPSO observations also show accumulation of dust over the Arabian Sea during pre-monsoon and monsoon seasons due to the transport from West-Asia and smoke aerosols over the Bay of Bengal during winter and post-monsoon seasons due to transport from the Indo-China region.

These accumulated aerosols generate heating over the Indian region throughout the year with pronounced high over IGP (~ 0.2 $K.day^{-1}$). The aerosol layer produces negative surface radiative forcing over the Central India and IGP (-5. 7 to -7.5 $W.m^{-2}$) counteracting global warming effect.

Interestingly, the aerosol layer is thicker during El-Niño years than normal years producing a higher negative radiative forcing than normal years over the Central India and Indo-Gangetic Plain land-mass (-5.66 to -8.8 $W.m^{-2}$). During the monsoon season, the smoke aerosols are transported to the upper troposphere by large-scale convection generating heating of 0.08 $K.day^{-1}$ in the free troposphere, which has implications for monsoon-circulation and precipitation over the Indian region.

Exploring the Influence of Troposphere-Stratosphere Interaction on Air Pollution and its Impact on 15-49 Years Age Group Population in India: A Multi-Dimensional Analysis

Jahnavi Singh[1], Dr. Manish Kumar[1], Dr. Swati Thakur[2], Akash Tiwari[1]

[1]Central University of Haryana
[2]Dyal Singh College, University of Delhi

India is the world second largest populous country where gradual deteriorating air quality has become a major problem. Decreasing air quality could lead to several adverse effects on public health, ecosystems and economic productivity. Understanding of the interaction between troposphere- stratosphere plays an important role in the shaping of the atmospheric dynamics, influencing weather patterns. But its interactions with the air quality is poorly understood particularly in India. To understand the troposphere-stratosphere interactions, MERRA-2 reanalysis datasets of temperature, humidity, wind and precipitation datasets were utilized. Air pollutants data for PM10, PM2.5, SO2, and NO2 were collected from Central Pollution Control Board (CPCB), India. Inverse Distance Weightage (IDW) geostatistical method was used for the interpolation of the air quality parameters. Fuzzy-AHP based method was utilized for the preparation of the comprehensive air quality map of India. Correlation analysis was performed to assess the statistical importance among the air quality parameters. Health related dataset between 15-49 years age group were obtained from the Global Burden Diseases (GBD) dataset of India. Understanding the intricate relationship between troposphere-stratosphere interaction and air quality pollution in India is critical for formulating educated policies and strategies to control air pollution and protect the air pollution triggered public health. By combining atmospheric dynamics, stratospheric processes, pollution dynamics, and health this study contributes to a better understanding of the variables that drive air quality variability and high pollution occurrences in the region. The study's findings have implications for improving air quality forecasts, strengthening pollution control measures, and encouraging sustainable development practices in India to offset the negative effects of air pollution on human health and the environment.

Keywords: Stratosphere, Air Quality, Correlation, CPCB, Fuzzy-AHP

Impact of Arctic Stratospheric Warming on Extreme Winter Weather in North India

Athira K S[1] and Raju Attada[1]

[1]Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Mohali, Punjab – 140306
Email: ph20044@iisermohali.ac.in

Sudden stratospheric warming events are occurrences where the temperature in the stratosphere above the Arctic suddenly rises, disrupting the usual *polar vortex* circulation pattern. The polar vortex is a large area of low pressure and cold air that typically resides over the polar regions during winter. When sudden warming events happen, they weaken the polar vortex, which can have cascading effects on weather patterns in lower latitudes. The study aims to understand how warming in the stratosphere of the Arctic affects winter extreme temperatures in north India. Our analysis highlights that a significant contributor to Arctic warming is the reduction in sea ice concentration over the Barents-Kara Sea. This reduction exposes more Barents-Kara Sea water, which absorbs more sunlight, leading to increased warming in both the surface and stratosphere of the Arctic. The loss of sea ice in the Barents-Kara Sea not only contributes to surface warming but also influences stratospheric warming through the propagation of upward planetary waves. These waves are large-scale atmospheric disturbances that can transfer energy and momentum vertically in the atmosphere, contributing to stratospheric warming. As the Arctic warms, we observe a weakening of the polar vortex. This weakening, in turn, reduces the speed of the polar night jet—a high-altitude, moving wind belt encircling the polar region. As a result, the jet stream tends to meander more. This meandering can lead to the intrusion of cold Arctic air into lower latitude regions, causing extreme cold conditions. Hence our study reveals that the warming of the Arctic stratosphere induced by the loss of sea ice in the Barents-Kara Sea disrupts the polar vortex, leading to extreme cold wave conditions in north India.

Keywords: Sudden stratospheric warming, Polar Vortex, Barents-Kara Sea ice loss, north India, extreme cold wave

An Assessment of Surface Reaching Solar Radiation in India: Impacts of Clouds and Atmospheric Aerosols

Ashwin Vijay Jadhav[1], P. R. C. Rahul[2], Vinay Kumar[3], Umesh Chandra Dumka[4] and Rohini Lakshman Bhawar[1, *]

[1]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University (SPPU), Pune, India
[2]Indian Institute of Tropical Meteorology (IITM), Pune, India
[3]Department of Atmospheric Science, Environmental Science and Physics, University of the Incarnate Word, San Antonio, Texas, USA
[4]Aryabhatta Research Institute of Observational SciencES (ARIES), Nainital, India

Surface solar radiation (SSR) is a crucial climate variable and the fundamental energy source for forging path towards an equitable and sustainable future. Meteorology induced variability increases uncertainty in SSR, making its intermittent nature a limitation on reliability. This variability depends on several meteorological factors, including cloud cover, atmospheric gases and water content, aerosol concentrations, and other factors that remain partially understood. This research investigates the detailed impact characteristics of clouds and aerosols on SSR across Indian regions. Utilizing high-quality and finely resolved satellite data along with reanalysis retrievals, the research covers the period from 1993 to 2022. Aerosols contributed to an average attenuation of ~ 13.33% on SSR, while clouds showed much stronger impact, with an attenuation of ~ 30.50%. The research reveals an increasing cloud impact on SSR in the recent decade, with significant increase rate of ~ 0.11% year^{-1}. The trend of aerosol impact also indicates a positive pattern, signifying average increase of ~ 0.24% year^{-1} across all Indian regions. The findings underscore the importance of considering climatic variables while studying the growing solar dimming. Our findings also will assist policymaker's and planner's in better evaluating the solar energy resource across India in the years to come.

Keywords: surface solar diming; solar energy potential; cloud impact; aerosol impact.

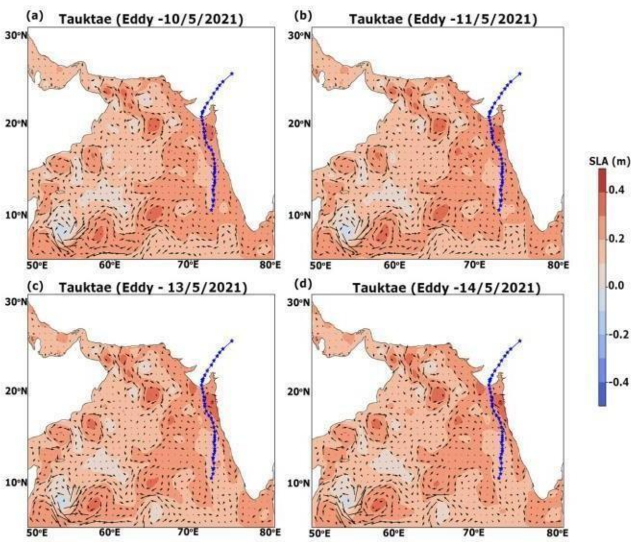
Warm Oceans and Cyclone Tauktae: Genesis and Intensification Dynamics

Athira P Ratnakaran[1] and Abish B[1]

[1]Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies, Kerala, India, 682506

email: athiathi26nov@gmail.com

The study focuses on comprehending the factors contributing to the formation and intensification of the extremely severe cyclonic storm 'Tauktae' in May 2021, marking the strongest occurrence in the Arabian Sea since Kandla in 1998. This cyclone underwent rapid intensification due to favorable warm ocean conditions. Rapid intensification of 'Tauktae' was facilitated by notably high sea surface temperature anomalies (ranging from 0.8 to 1.6°C) and elevated tropical cyclone heat potential (120–140 kJ/cm^2) at both the tropical cyclone genesis point and along its track. These conditions significantly contributed to the cyclone's intensified development. Comparatively, the accumulated cyclone energy of 'Tauktae'surpassed the climatological mean, with the combination of high sea surface temperature and tropical cyclone heat potential playing a crucial role. During the period of rapid intensification from a very severecyclone to an extremely severe cyclonic storm on May 16 to 17, 2021, warm core eddies were observed inthe region. The coexistence of high sea surface temperature, tropical cyclone heat potential, and warm-coreeddies created a conducive environment for continuous energy transfer, involving sensible and latent heatflux from the ocean surface to the atmosphere. The analysis underscores the indispensable role of excessively warm ocean conditions, alongside favorable atmospheric factors, in the genesis and intensification of tropical cyclone 'Tauktae.' As the Arabian Sea continues to experience warming trends, ongoing monitoring and understanding of its impact on tropical cyclone dynamics become imperative.



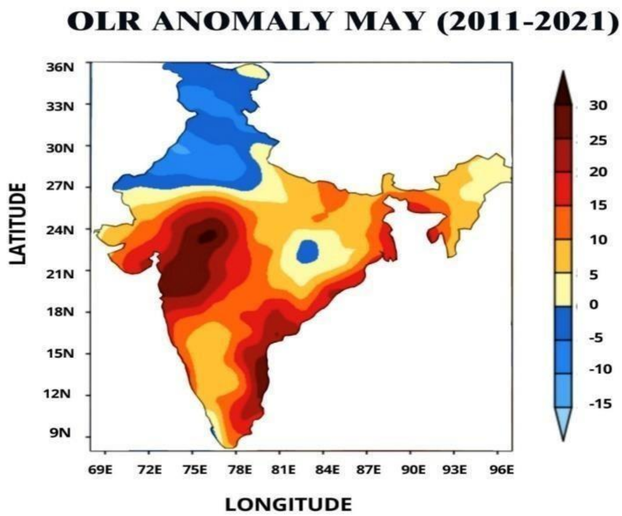
Track of Tropical cyclone 'Taukate' with eddies in the background. Vector denotes the geostrophic currents.

Analysing Intensifying Heat Waves in India in Recent Years

Neethu C S[1] and Abish B

Department of Climate Variability and Aquatic Ecosystems, Faculty of Ocean Science and Technology Kerala, University of Fisheries and Ocean Studies (KUFOS), Kochi, Kerala,682506.
Presenting Author : csneethu0@gmail.com

India has severe heatwaves from March through June. Under a warming climate in India, heatwaves that cause catastrophic harm have increased and are expected to occur more frequently. A heat wave is a period of unusually high temperatures and high humidity. From a statistical point of view, a small change in the mean value of a climate variable (such as temperature) corresponds to large changes in weather, which means a small shift in the mean of the temperature distribution implies a sizeable change in the frequency and intensity of temperature extremes. In this paper, the observed patterns and statistical analyses of the temperature variability across India are discussed. For the base period of 1981–2022, the anomaly of 2 metre temperature, outgoing longwave radiation, and vertical velocity is computed. The heat wave was identified using the criteria given by the India Meteorological Department (IMD), i.e., a heat wave is recognised when the daily normal maximum temperature of a station is less than or equal to (greater than) 40 °C, and it will be considered a heat wave if the daily maximum temperature exceeds the daily normal maximum temperature by 5 °C (4 °C). The analysis was confined to the three summer months of March, April, and May. The standard deviation of daily temperature for May over the years 1981–2022 shows large values extending from the north to the interior peninsular, apart from the coastal regions facing the Indian Ocean. The temperature anomalies show positive departures in those regions. The vertical velocity shows anomalous sinking over the Indian landmass due to the anomalous anticyclone over the region. The sinking motion causes positive OLR anomalies, resulting in heatwaves over the region.



Significant OLR (W/m^2) anomalies for the period 2011-2021 for May month

Remote Influence of Madden Julian Oscillations on the Genesis of Mixed Rossby-Gravity Wave Events

Mehak[1] and E. Suhas[1]

[1]Indian Institute of Science Education and Research Pune, India

Mixed Rossby-Gravity (MRG) waves are westward propagating synoptic scale equatorial disturbances which play a crucial role in modulating the major modes of tropospheric and stratospheric variability eg., MRG waves are considered to be critical for the genesis of the Madden-Julian Oscillation (MJO) and Quasi-Biennial Oscillation (QBO). MJO is the most energetic subseasonal mode of tropical variability. In this study we explore the dynamic response of diabatic heating associated with the MJO over the Maritime continent (MC) in the genesis of MRG wave events exciting within the westerly duct in the upper troposphere during boreal winter. We find that about 60% of the MRG wave events associated with the intrusion of stratospheric extratropical disturbances occur when MJO is convectively active over the MC. We observe characteristic differences between the genesis of MRG wave events associated with the convectively active phase of MJO over MC as compared to when it is inactive over MC. Dynamic response associated with the convectively active phase of MJO over MC makes the central eastern Equatorial Pacific atmosphere more barotropically unstable and provides a conducive environment for the MRG wave seeding. Further the intruding stratospheric extratropical disturbances interact resonantly with the MRG wave seeds. Whereas in the case when MJO is inactive over the MC, we find that, insitu convective processes seed the MRG waves in the upper troposphere. The observation of contrasting convection circulation coupling strength for the two MRG event regimes corroborates the differences in the MRG wave genesis mechanism.

Impact of Volatile Organic Compounds on Ozone Distribution in Asian Summer Monsoon Anticyclone

Annada Padhi[1], Prashant Chavan[1], Satheesh Chandran PR[1] and Suvarna Fadnavis[1]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, (MoES) India-411008

One of the most noticeable circulation patterns in the upper troposphere and lower stratosphere (UTLS) during summer in the northern hemisphere is the Asian summer monsoon anticyclone (ASMA). The convective uplift of surface pollutants and their subsequent confinement by the ASMA act as an efficient transport pathway to the UTLS. The elevated pollutants affect the composition of ASMA. In this study, we investigated the potential impact of VOCs on the distribution of UTLS ozone using the state-of-the-art chemistry-climate model ECHAM6-HAMMOZ. It is a known fact that NOx and VOCs play a crucial role in tropospheric ozone production, and there are studies investigating the sensitivity of NOx emission to UTLS ozone. Nevertheless, limited research has been conducted to determine the effect of VOC emissions on UTLS ozone. In this regard, we performed model sensitivity experiments by doubling the VOCs emissions (i.e., DVOCS) globally during the period 1998 to 2020 from the present level (CTL) to understand the impact of VOC emissions on ozone distribution within the ASMA region. Our simulations showed that negative ozone trends inside the ASMA (-30 ppb/year) changes it sign and magnitude by 122 ppb/year due doubling of VOCs. This ozone enhancement and its radiative effects will have repercussions on climate change.

Seasonal Variation of UTLS Water Vapour over Indian Monsoon Region using MLS data

Anila Alex[1]and Jikku Joy[2]

[1]Centre for Water Resources Development and Management, Kozhikode, 673571, India
[2]Institute of Climate Change Studies, Kottayam, 686001, India

Spatial and temporal variation of the water vapour mixing ratio (WVMR) in the upper troposphere and lower stratosphere (UTLS) was examined using water vapour mixing ratio data from MLS satellite. Specific pressure levels corresponding to UTLS region have been studied in order to portrait the distinct traits of each sector of UTLS region. An analysis of the WVMR at different pressure levels reveals that the troposphere's water vapour (WV) movement is quite fast up to a level of about 147 hPa. Above tropopause level only minor amount of water vapour is transported and it encounters horizontal advection rather than following a vertical flow; accounts for the time lag in WVMR peak over higher altitudes. It has been shown that the monsoon dynamics (circulation patterns over UTLS) and deep convective activity is closely correlated with seasonal variation of WVMR across the tropical lower stratosphere (TLS).

If you include a figure or table, please paste it above and replace this text by the caption.

Time series of WVMR at 147 and 100 hPa levels along with the time series of 13-day running mean OLR for the period of 1 January 2007–31 December 2010 over Indian monsoon region.

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Stratospheric Impacts of an Extreme Australian Bushfire Event: A Multi-Satellite Analysis

Srinivasan Prasanth[1,2,] Narayana Sarma Anand[3], Kudilil Sunilkumar[2], Subin Jose[4], Kenath Arun[1], Sreedharan K. Satheesh[2,5,6], and Krishnaswamy K. Moorthy[5]

[1]Department of Physics and Electronics, Christ University, Bengaluru, Karnataka, India
[2]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, Karnataka, India
[3]School of Earth, Environmental and Sustainability Sciences, Indian Institute of Science Education and Research Thiruvananthapuram, Kerala, India
[4]Department of Physics, Newman College, Thodupuzha, Kerala, India
[5]Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru, Karnataka, India
[6]DST-Centre of Excellence in Climate Change, Indian Institute of Science, Bengaluru, Karnataka, India

Correspondence: Prasanth S. (prasanthphy57@gmail.com)

An extensive investigation of the stratospheric impacts of the emissions of aerosols and gases by the extreme Australian bushfire widely known as the Black Summer event is made using multi-satellite data. This event injected large amounts of bushfire aerosols and gases into the atmosphere, a significant part of which entered the stratosphere, initiating a series of sub- events. During Austral autumn of 2020, an analysis of the Nitric acid (HNO_3) mixing ratio from a microwave limb sounder revealed that there has been enhanced hydrolysis involving dinitrogen pentoxide, resulting in a remarkable increase in gas phase HNO_3 due to these aerosols, in the high-latitude (60°S to 90°S) lower stratospheric region (20 to 30 km altitude). In addition, the smoke plumes from the Black Summer event carried moist air from the troposphere and resultedin a significant increase in water vapor at the altitude of ~17 km. The consequences of this modified stratospheric chemistry in lower stratosphere are discussed in detail. These findings contribute substantially to our understanding of the impact of extreme wildfire events on stratospheric chemistry and dynamics.

Role of Solar Forcing in Alteration of Indian Summer Monsoon Through Tropospheric- Stratospheric Circulations

Vasundhara Barde[1], Jayashree Bulusu[1], and A.P. Dimri[1,2]

[1] Indian Institute of Geomagnetism, Mumbai, India, 410218
[2] School of Environmental Science, Jawaharlal Nehru University, New Delhi, India, 110067

Indian Summer Monsoon (ISM) is a part of climate system and it's interaction with other component/ process, viz., atmosphere-ocean-land-cryosphere, proves it to be a complex phenomenon. ISM affects and gets affected by large-scale and local scale processes, and because of this, higher order complexities are present for complete understanding of formation, onset, progression and dispassion of ISM. One of them is forcing from upper atmosphere and especially solar forcing. The direct and indirect effect of solar forcing are considered in this study. For ISM, Tropical Easterly Jet and Low level Jets are important. During years of maximum solar activity, a strong Somali jet stream is observed, and during years of minimum solar activity, a strong Tropical Easterly Jet is observed. Also, the area of influences is also different for maximum and minimum solar activity; during maximum solar activity, North India receives reasonable amount of rainfall; however during minimum solar activity South India received more rainfall than North India. In addition, the large scale circulations such as PDO, Niño 3.4, QBO, IOD, and AMO are important for ISM rainfall variability as their pre- monsoonal and monsoonal conditions affects ISM. To understand the impact of solar forcing through high latitude, stratospheric winter (November to March) time North Polar Region (60N to 90N) temperature anomalies is considered. 11-years moving mean of stratospheric temperature anomalies and sunspot number shows significant positive correlation. Empirical orthogonal function (EOF) and correlation analysis of stratospheric (10hPa) temperature with various climate indices and associated circulation pattern are checked for winter season, followed by the pre-monsoon and monsoon season.

Key words: ISM, Sun Spot Number, Low level Jet, large scale circulation

Spatial and Temporal Variation of Aerosols Optical Depth and Ångström Exponent four different altitudes of Uttarakhand, India

Amar Deep[1*], Alok Sagar Gautam[2], Karan Singh[2], and Tushar Kandari[3]

[1*]Department of Physics, Dhanauri P. G. College, Dhanauri, Haridwar, 247661, Uttarakhand, India
[2]Department of Physics, H N B University, Garhwal (A Central University) Srinagar (Garhwal), 246174 Uttarakhand, India
[3]Department of Physics, M.P.G. College Mussoorie, 248179, Uttarakhand, India

This study delves into a comprehensive analysis of Aerosol Optical Depth (AOD) and Ångström Exponent (AE), crucial parameters for discerning ambient aerosol concentrations over the upper (Uttarkashi and New Tehri) and foothill (Dehradun and Haldwani) regions of the Himalaya in Uttarakhand, India. Leveraging data from the Moderate Resolution Imaging Spectrometer (MODIS) onboard satellites spanning 2017 to 2023, our investigation explores aerosol properties at monthly, seasonal, and annual scales. The monthly maximum value of MODIS-derived AOD and AE were determined to be 0.796 and 1.767 at Dehradun. The monthly minimum value of MODIS-derived AOD and AE were determined to be 0.044 and .844 at Dehradun during the study period. Seasonal variations revealed peak AOD values of 0.32 ± 0.07 (MODIS) in the pre-monsoon season, contrasting with the minimum values (0.099 ± 0.021) observed in the post-monsoon season at Dehradun. Observations unveiled the presence This research provides critical insights into the climatic ramifications of atmospheric aerosols in the Himalayan region of Uttarakhand, India.

Keywords: AOD, AE, CALIPSO, and MODIS.

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Understanding the Impact of Stratosphere-Troposphere Exchange on Ozone Distribution and Climate Dynamics

Surat Dewan[1] and Anita Lakhani[1]

[1]Department of Chemistry, Dayalbagh Educational Institute, Dayalbagh, Agra-282005, UP, India

The current ozone distribution and future projections are greatly influenced by the interaction between stratosphere-troposphere exchange (STE) and large-scale climate patterns like the El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO). According to studies, Brewer-Dobson Circulation accelerates with climate warming, which is expected to raise surface and mid-tropospheric ozone concentrations. Forecasts point to a significant increase in the amount of stratospheric ozone entering the troposphere, which highlights the significance of comprehending the mechanisms underlying stratospheric ozone loss. An essential element of STE occurrences, tropopause folds allow ozone-rich stratospheric air to be transported downward into the troposphere, changing the amount of ozone in the troposphere. This study provides an extensive view of the complex interrelationships among STE, climate trends, and ozone distribution. It is essential to comprehend these dynamics for estimating future ozone levels with accuracy and evaluating the effects on human health, air quality, and climatic variability. Further investigation and understanding of the mechanisms behind STE and its interactions with climatic patterns are crucial for well-informed policy creation and decision-making as we work to minimise the effects of climate change.

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Study of gas to particle conversion in new particle formation over clean environment of western Himalayan region, Uttarakhand, India

Karan Singh[1], Alok Sagar Gautam[1], Jeni Victor[2] and Kaupo Komsaare[3]

[1]Atmospheric and Space Physics Laboratory, Department of Physics, Hemvati Nandan Bahuguna Garhwal University, Uttarakhand – 246174, India.
[2] Indian Institute of Tropical Meteorology, Pune – 411008, India.
[3] Institute of Physics, University of Tartu, Tartu - 50090, Estonia.

New particle formation is the physical process in which the tiny particles, especially nanometer size, are produced through coagulation scavenging and condensation growth via gas- to- particle conversion (Kulmala et al., 2013; Kamra et al., 2015). In this study, we have done the observation of particle number size distribution ranged from 10 to 420 nm measured with TSI Nano SMPS 3090 at a high-altitude location Swami Ram Teertha Campus (30.34 N, 78.40 E, 1706 m AMSL), Hemvati Nandan Bahuguna Garhwal University Tehri Garhwal from 1 January 2020 to 31 December 2021. We have observed 53 NPF events out of 143 observation days. The shift of mode diameter from 14 nm to 25 nm during NPF by the particle number size distribution illustrates the particle growth remains between ~1.25 to ~5 nm/hour. Most of these events occurred in the pre-monsoon season during the hottest months (March-April-May) of the year. We have observed the maximum coagulation sink $3.55 \pm 2.84 \times 10^{-5}$ s^{-1} during winter season and lower $1.19 \pm 1.1 \times 10^{-5}$ s^{-1} in Monsoon season. Also, the maximum condensation sink 0.12 ± 0.06 s^{-1} measured in pre-monsoon season and minimum 0.06 ± 0.02 s^{-1} in monsoon season. The presence of pre-existing large particles at clean environment of western Himalayan region suppressed the formation rates and growth rates. The relatively lower ambient relative humidities may weaken the coagulation sink and higher solar radiation, higher temperature facilitates the occurrence of new particle formation (Kanawade et al., 2014).

Keywords: Nucleation, Growth rate, formation rate, coagulation sink, condensation sink and western Himalayan region.

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Biomass Burning and SO_2 Emissions in Uttarakhand's Himalayan Region

A. S. Gautam[1], S. Kumar[1], and K. Singh[1]

[1] Atmospheric and Space Physics Laboratory, Department of Physics, Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar Garhwal Uttarakhand
E-Mail: phyalok@gmail.com, as.gautam@hnbgu.ac.in

The SO_2 played a significant role in atmospheric chemistry and was attributed in the form of toxic fog, acid rain, new particle formation, socio-economic impacts, etc. (Gautam et al. 2018). The variation of SO_2 strongly depends upon local metrological parameters such as temperature, humidity, wind speed, wind direction, solar radiation and precipitation during 2007-2009 (Rogalski et al. 2014). The variation of SO_2 concentration combinedly depends upon local and long-range transport of pollutants from industrial areas mainly located in the Indian Gangetic Plan (IGP) region . The Himalayan region is covered by a dense forest of Chir, Pine and Oaks at different elevation ranges (Vadrevu et al. 2012). Generally, residents burn the litters and pastures of pine and agricultural waste to clear the field for upcoming agricultural activities in Mar to May of each year which may result in a potential forest fire that affects the water, ecology, air quality and economic system of the Uttarakhand. The forest fire activities in the Himalayas region lead to degrading the air quality in Uttarakhand and nearby states. In the past, several relevant studies have been carried out in the foothill of the Himalaya (Dehradun, Haridwar and Rishikesh) to estimate the SO_2 concentration using a respirable dust sampler (Resolution: 24 hours) although they failed to provide a continuous and fine resolution (5 minutes) data of SO_2 concentration. The prime goal of this study is to conduct a comprehensive and continuous ground-based observation of SO_2 levels in the Srinagar Garhwal Valley (SGV) in Uttarakhand, India. By filling the existing data gap and exploring SO2 in detail, our objective is to understand the diurnal and seasonal variations of SO_2 in the region, identify potential sources of SO_2 emissions, and analyze the influence of meteorological parameters on its levels. Additionally, we aim to investigate the impact of forest fire emissions on the concentration of SO_2 over SGV, a critical area located in the Himalayas. Through this research, we hope to enhance our understanding of SO_2 dynamics in the region and contribute valuable insights for air quality management and environmental conservation efforts in Uttarakhand.

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The impact of Quasi Biennial Oscillation on Indian Summer Monsoon Subseasonal variability

Shubham Waje[1,2], Susmitha Joseph[1], M.K.R. Phani[1], and A. K. Sahai[1]

[1]Indian Institute of Tropical Meteorology, Pune- 411008, India
[2]Savitribai Phule Pune University, Pune- 411007, India

The stratosphere has been identified as an important source of predictability for a range of processes on sub-seasonal to seasonal (S2S) time scales by various pathways. One of them is an equatorial pathway in which the QBO (Quasi Biennial Oscillation) is a dominant phenomenon. The QBO has a downward propagating easterly and westerly zonal wind pattern dominant in the lower and middle stratosphere bounded vertically (between 100 hPa and 10 hPa) and meridionally (between 10 N and 10 S), which has approximately 28 months of periodicity. The QBO phase influences the Boreal Wintertime convections of eastward propagating ISO (Intra-seasonal Oscillations) called MJO (Madian Jullian Oscillations). MJO is found to be more organized and persistent during the Easterly phase of the QBO. Even MJO prediction skill is enhanced by a couple of days in the easterly phase of the QBO. This study evaluates to what extent the QBO impacts the Indian monsoon in perspective of the northward propagating ISO called MISO (Monsoon Intra-seasonal Oscillations) during Boreal summer.

Investigation of PM Bound Aromatics during the Spring Season in Bengaluru, Silicone Valley of India

Durga Prasad Patnana[1] and B.P. Chandra[1]*

[1]Department of Chemistry, Sri Sathya Sai Institute of Higher Learning, Prasanthi Nilayam Campus, Puttaparthi, Andhra Pradesh – 515134, India
[*] Corresponding author. Tel: +91 9491485589; E-mail address: bpraphullachandra@sssihl.edu.in

Several studies have shown that the organic species bound to the ambient particulate matter (PM) governs cloud condensation and ice nucleation activity. Organic compounds bound to the suspended particulate matter are known to have both local (e.g. toxicity, health hazards) and global (e.g. climate change) impacts. However, due to the complexity of their chemical nature, the significance of organic constituents bound to PM in driving physical and chemical atmospheric processes is poorly understood. Field experiments have shown that the CCN activation efficiency can often be better predicted in the background atmosphere rather than urban atmosphere. This is likely due to the PM bound organic constituents which have the largest uncertainty and are not fully chemically understood. Hence, in this study, we aimed to characterise the various aromatic compounds bound to the inhalable fraction of PM during the spring season in Bengaluru. Seven carcinogenic polycyclic aromatic hydrocarbons (PAHs) (benzo[a]anthracene, benzo[b]fluorenthene, benzo[k]fluorenthene, benzo[a]pyrene, dibenzo[ah]anthracene, benzo[ghi]perylene, and indeno[1,2,3-cd]pyrene); five derivatives of PAHs (1,4 naphthoquinone, 9 fluorenone, 9 nitroanthracene, 9,10 phenanthroquinone and benzanthrone) and seven phthalic acid esters (PAEs) - endocrine disruptors (dimethyl phthalate, diethyl phthalate, benzyl butyl phthalate, dibutyl phthalate, bis (2-ethyl hexyl) phthalate, bis(2-ethylhexyl) adipate, di-n-octyl phthalate) were characterised using the LC-MS/MS. Observed concentrations of PAHs, derivatives of PAHs and PAEs are in the range of 0.06 – 3.82 ng/m^3, 0.05 – 10.47 ng/m^3 and 0.11 – 5.38 ng/m^3, respectively during the sampling period in Bengaluru. The results of this study could help to improve the understanding of CCN activity and impacts of organics especially in metropolitan cities like Bengaluru by better parameterization of CCN in climate models.

Generation of Equatorial Waves due to Extratropical Influence

S. Sridharan[1] and Sandhya, M[2]

[1]NARL, Gadanki, India
[2]NCMRWF, New Delhi, India

Space–time spectral analysis of ERA-interim winds and temperature at 200 hPa for December 2012–February 2013 shows the presence of eastward propagating waves with a period near 18 days in mid-latitude meridional winds at 200 hPa. The 18 day waves of k = 1–2 are dominantly present at latitudes greater than 80°, whereas the waves of k = 3–4 are dominant at 60° of both the Northern and Southern Hemispheres. Though the 18-day wave of smaller zonal wavenumbers (k = 1–2) is confined to high latitudes, there is an equatorward propagation of the 18-day wave of k = 4 and 5. The wave amplitude of k = 5 is more dominant than that of k = 4 at tropical latitudes. In the Northern Hemisphere (NH), there is a poleward tilt in the phase of the wave of k = 5 at mid-latitudes, as height increases indicating the baroclinic nature of the wave, whereas in the Southern Hemisphere (SH), the wave has barotropic structure as there is no significant phase variation with height. At the NH subtropics, the wave activity is confined to 500–70 hPa with moderate amplitudes. It is reported for the first time that the wave of similar periodicity (18 days) and zonal structure (k = 5) as that of extratropical wave disturbance has been observed in tropical OLR, a proxy for tropical convection. We suggest that the selective response of the tropical wave forcing may be due to the lateral forcing of the eastward propagating extratropical wave of similar periodicity and zonal structure.

Understanding the Impact of Stratospheric Water vapor Injection by Hunga-Tonga Volcano on Brewer-Dobson Circulation

Veenus Venugopal[1,2] and Siddarth Shankar Das[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, 695022, India
[2]Department of Physics, University of Kerala, Thiruvananthapuram, 695034, India

The eruption of the Tonga submarine volcano served as a natural laboratory for studying the effects of large-scale water vapor injection into the stratosphere. This eruption injected significant amounts of water vapor that influenced the dynamics of the stratosphere and global climate patterns. Our research focuses on analysing the temperature changes, and wind patterns following the volcanic eruption. The changes in the stratosphere will result in variations in the meridional circulation, the Brewer-Dobson circulation, which in turn will influence stratosphere-troposphere exchange. These changes will be reflected in the stratospheric distribution of ozone. The present study evaluates the impact of the event using the observations from Aura Microwave Limb Sounder and ERA5 reanalysis. Changes in the stratospheric composition of ozone and the meridional circulation were observed. Detailed results will be presented in the upcoming workshop.

Modulation of Stratospheric Circulation by Quasi-Biennial Oscillation: Implications on Ozone and Water vapor Distribution

Veenus Venugopal[1,2] and Siddarth Shankar Das[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, 695022, India
[2]Department of Physics, University of Kerala, Thiruvananthapuram, 695034, India

The tropical upper-troposphere lower stratosphere region's air is carried to higher altitudes by the Brewer-Dobson circulation (BDC), a stratospheric circulation that extends towards the poles. Momentum deposited by breaking planetary waves is the driving force for the circulation. The propagation of these waves and, consequently, the intensity of the circulation, are modulated by the different atmospheric conditions in the stratospheric zonal wind oscillation; the Quasi-Biennial Oscillation (QBO). QBO is linked to alternate descending zonal wind patterns in the stratosphere that regulate the region where the planetary wave breaks, causing variations in the stratosphere's meridional transport. Using ERA5 reanalysis data and the Aura Microwave Limb Sounder observations, the current work investigates BDC changes caused by QBO and the resulting stratospheric temperature structure, as well as ozone and water vapour distributions. Eliassen-Palm flux divergence and meridional residual velocities are used to evaluate the circulation. The study analyses the changes in relation to climatological patterns by examining the responses of the circulation. The wave dissipation in the QBO's eastward and westward phases differs noticeably. The distribution of ozone and water vapour is altered as a result of the subsequent modifications in meridional transport. The detailed results will be presented and discussed in the upcoming workshop.

Synoptic-scale Methane Events over the Indian Subcontinent

Yogesh K. Tiwari*[,1] and Ramesh K. Vellore[1]

[1]Indian Institute of Tropical Meteorology, Pune, Ministry of Earth Sciences, Govt of India

Methane (CH4) emissions play a crucial role in the Earth's atmospheric chemistry and climate system. A comprehensive understanding the dynamics and distribution of CH4 events is essential for environmental management suitable for the Indian subcontinent. Satellite data serves as a valuable resource for passive CH4 concentration observations over large spatial domains. In this study, we employ advanced data processing techniques and statistical tools to distill meaningful information from the satellite retrievals of XCH4 (column-averaged dry-air mole fraction of methane) to understand the synoptic scale CH4 variability during the Western Disturbance (WD) passages. We intend to provide insights into spatial and temporal patterns, trends, and underlying drivers for CH4 variability suitable for the Indian subcontinent. The findings of this study provide better understanding of CH4 dynamics from the Indian context not only towards mitigation strategies for methane emissions, but also offers suggestions for improved monitoring and modelling exercises.

Exploring Thunderstorm-Induced Muon Events: Observations by the Ooty Muon Telescope and their Correlation with Atmospheric Electric Field Fluctuations

Pranaba K Nayak[1]

(for GRAPES-3 Collaboration)

[1]Tata Institute of Fundamental Research, Mumbai 400005, India

The Ooty muon telescope records short-term variations in muon intensity during major thunderstorms, referred to as thunderstorm-induced muon events (TIMEs). As part of the GRAPES-3 experiment, the telescope detects approximately one and a half trillion muons each year [1]. Its excellent angular resolution validates the TIMEs with small directional variations. Ground-based electric field measurements during fair weather and thunderstorms are crucial parameters for global electric circuit investigations. The variation of the atmospheric electric field is measured using four electric field mill sensors for Ooty and its outskirts [2]. We examine the variations of the near-surface electric field and meteorological parameters during both fair weather and thunderstorms, for the continuous years of 2021 and 2022 on a standalone basis for each season. Minimum values are observed during the monsoon season, and maximum values are observed during winter and spring. According to the results from the muon telescope, the majority of TIMEs occur in the spring and autumn seasons, with fewer occurrences during the summer monsoon period [1]. In 2021, the muon telescope detected 46 TIMEs, compared to 54 in the subsequent year, while the number of events for large- scale electric field changes remains at 105. The important characteristic of TIMEs with their variable features concerning time-correlated electric fields will be extensively discussed. This study exemplifies the interplay between atmospheric science and experimental astroparticle physics.

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Mass and Light Absorption Properties of Atmospheric Carbonaceous Aerosols over the Outflow Regions of Indo-Gangetic Plain

Ashish Soni, Abhijit Chatterjee, Binoy K Saikia, and Tarun Gupta*

*Corresponding Author: Prof. Tarun Gupta, tarun@iitk.ac.in

The uncertainty associated with carbonaceous aerosols in climate models becomes an obstacle to evaluating their harmful environmental effects. Brown Carbon (BrC) has recently become an eye-catching carbonaceous aerosol in ambient air because of its strong light absorption properties. The optical properties of soluble BrC are well studied in South Asia, one of the largest emitters. However, the absorption property of strong light-absorbing insoluble BrC is highly uncertain because of their complex mixing. Besides, the simultaneous apportionment of light-absorbing carbonaceous aerosol constituents as a function of wavelengths is seldom explored. The present study aims to study mass as well as apportionment of absorption properties of Black Carbon (BC) and different BrC chromophores using a multi-wavelength thermal-optical carbon analyzer over the least explored Eastern part of India to fill the knowledge gap. The output suggested that the primary emission sources dominate the carbonaceous aerosol mass; thus, the primary emission reductions will be helpful in improving the local air quality. The BrC is the dominant light-absorbing carbonaceous aerosol in the ultraviolet wavelengths. Besides, significant light absorption by BrC chromophores in near- infrared wavelengths (up to ~50% of total aerosol absorption) suggested the absorption by BrC in longer near-infrared wavelengths cannot be neglected. The insoluble fraction of BrC (Tar- BrC), which has a property identical to BC, contributes significantly to light absorption and is more than 50% of total absorption by aerosols in shorter ≤635nm wavelengths. The present study also revealed that the contribution of Tar-BrC is more pronounced in the Indo-Gangetic Plain (IGP) outflow region than in the IGP emission source regions.

Keywords: Carbonaceous Aerosols; Tar-BrC; Light Absorption Properties; Thermal-Optical Carbon Analyzer; South Asia

Moisture Intrusion in the Lower Stratosphere Related to High Gravity Wave Energy during a Severe Convective Event: A Test Case of Cyclone Aila

Soumyajyoti Jana[1]

[1]Indian Institute of Tropical Meteorology, Dr. Homi Bhaba Road, Pashan, Pune 411008, India

This study investigated the influence of a severe convective event cyclone Aila (became a Severe Cyclonic Storm on May 23, 2009; Dissipated: May 27, 2009; Landfall: May 25, 2009) on gravity wave energy (*Et*) and related specific humidity intrusion within the lower stratosphere (LS). Analyzing data from the ECMWF 91 model level, the research revealed a significant increase in *Et* within the LS (18-25 km) during Aila. This finding aligns with previous studies by Chane-Ming et al. (2010) and Pramitha et al. (2016), which demonstrated the upward movement of gravity wave (GW) energy in the LS due to cyclones. The study also observed an atypical tropopause height reaching 17.5 km compared to the typical 17 km, influencing the chosen LS analysis range (18-25 km). Investigating the profile of *Et* variations across the cyclone-affected region's latitudes and longitudes, the research identified an enhancement of energy also in the upper LS (around22-23 km) during Aila. Hodograph analysis was employed to understand the energy propagation direction within the LS (18-25 km) during Aila. The predominantly clockwise rotation of the hodograph curve indicated upward energy movement within the LS. This upward propagation of GW is linked to deep convection, which,as shown by the ECMWF 91 level data (obtained from the web portal of Stratosphere- troposphere ProcessesAnd their Role in Climate (SPARC); http://www.sparc-climate.org/data-center/data- access/sparc-ipy/), is responsible for the increased specific humidity (moisture content) observed within the LS during Aila. Furthermore, spectral analysis using the Lomb-Scargle method investigated the dominant vertical wavelengthresponsible for Et enhancement in the LS. The analysis revealed that vertical wavelengths in the range of 2.5-
3.2 km, corresponding to 2-3 cycles/km of wave number, were dominant for GW within the LS.

A crucial finding of the study is the co-occurrence of water vapor intrusion from the troposphere into the LS alongside the upward energy propagation during Aila's strong convection. This intrusion of water vapor into the LS, as highlighted by Kirk-Davidoff et al. (1999) and Shindell (2001), is a major concern due to its potential to contribute to ozone depletion. Specific humidity measurements from the ECMWF 91 model level data over the cyclone-affected region during Aila (Figure 1) confirmed this observation. The figure demonstrates an increase in specific humidity within the LS, particularly near the landfall region where high gravity wave energy was identified. The upward energy propagation, as confirmed by the hodograph analysis, is linked to deep convection, which transports water vapor from the upper troposphere to the LS, leading to the observed enhancement in specific humidity.

In conclusion, this study sheds light on the interconnectedness between severe convection, gravity waves, and water vapor intrusion within the LS. It highlights the potential impact of convective activities on upward energy transport and subsequent water vapor intrusion, raising concerns about potential ozone depletion. A modeling study will be performed to quantify the impacts of the deep convection on such troposphere stratosphere exchange processes.

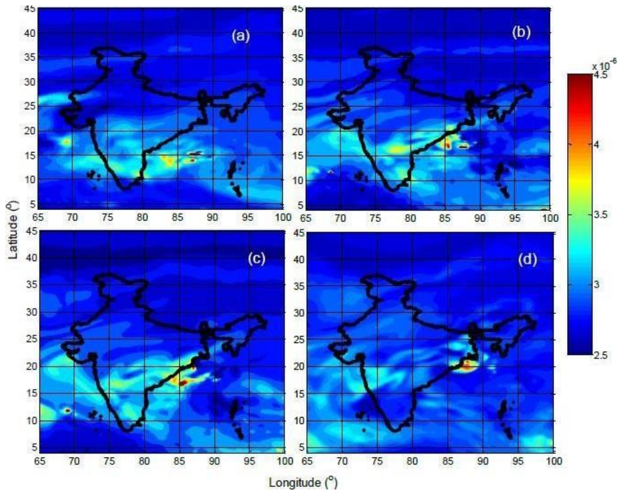

Figure 1. Contour plots on average specific humidity in the heights range 18-25 km during the tropical cyclone Aila: (a) 23 May 2009, (b) 24 May 2009, (c) 25 May 2009, and (d) 26 May 2009.

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The Tropospheric Pathway of QBO for Modulation in the Global Monsoon System

Vinay Kumar[1] and Shigeo Yoden[2]

[1]Radio and Atmospheric Physics Lab., Rajdhani College, University of Delhi, Delhi-110015, India
[2]Institute for Liberal Arts and Sciences, Kyoto University, Kyoto-606-8501, Japan

The modulation in the global monsoon system will be an interesting subject for “external” stratospheric dynamical forcing such as the equatorial stratospheric Quasi-biennial oscillation (QBO). Monthly-mean data of ERA-5 reanalysis for precipitation, OLR, and SST are investigated during 44 years (1979–2022) to reveal the modulation in global monsoon dynamics by the QBO. Only neutral ENSO period is considered, as it is also a major source for the inter-annual variability in some regional monsoon, especially Asian summer monsoon. After introducing eight QBO phases based on the two leading principal components of the zonal- mean zonal wind variations in the equatorial lower-stratosphere, the statistical significance of the composite difference in precipitation and tropospheric circulations is evaluated for the opposite QBO phases. The composite differences show significant modulations in some regional monsoon systems, dominated by zonallyasymmetric components, with the largest magnitudes for specific QBO phases corresponding to the traditionalQBO index at 20 and 50 hPa. Along the equator, significant QBO modulation is characterized by the modulation of the Walker circulation over the Western Pacific. In middle latitudes during boreal summer, fora specific QBO-phase, the statistically significant modulation of low-pressure cyclonic perturbation is obtained over the Northern-Hemisphere western Pacific Ocean, which is associated with statistically significant features of heavier precipitation over the eastern side of the cyclonic perturbation and the opposite lighter precipitationover the western side. During boreal winter, similar significant low-pressure cyclonic perturbations were found over the Northern-Hemisphere eastern Pacific and Atlantic Oceans for a specific QBO phase.

Deciphering East Atlantic Low-Pressure System Formation: Exploring the Nexus of Tropical Jet Stream and Extreme Precipitation

Vinay Kumar[1], Dipak Kumar Sahu[2], Ktelyn Simonsen[1], Sabrina Gonzalez[1], and Christian Schnell[1]

[1]University of the Incarnate Word, San Antonio, TX-78209, USA
[2]India Meteorological Department, C S M I Airport, Mumbai-400099, India

The Tropical Easterly Jet (TEJ) induces upper level diffluence, crucial for the development of low-pressure systems (LPS) in the Eastern Atlantic Ocean, adjacent to West Africa. Despite its significance, the precise impact of the intensified TEJ and diffluence on cyclogenesis remains inadequately understood. The strengthening TEJ and subsequent diffluence branching off the African coast contribute to heightened extreme precipitation occurrences across the Indian subcontinent and Africa. Recent observations spanning from 2019 to 2023 reveal a delayed correlation between LPS formation in the Eastern Atlantic Ocean (within 10N-20N, 15W-30W) and TEJ activity over the Indian subcontinent (approximately 3 days later) and Africa (approximately 1 day later). This correlation is intricately linked to the bifurcation of diffluence at the 200mb level. Furthermore, ongoing investigations are exploring the roles of the Saharan Air Layer and easterly waves in the formation of LPS.

A Model-based Investigation of the Effects of Stratospheric Sulphate Aerosol Geoengineering on the Global and Tropical Precipitation Patterns: Sensitivity to Latitudinal and Altitudinal Distribution of Aerosols

Govindasamy Bala[1] and Usha K H[1]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore 560012, India

Solar geoengineering, also known as Solar Radiation Management (SRM), is proposed as a potential strategy to mitigate the effects of global warming caused by greenhouse gases. This approach involves reflecting solar radiation away from the Earth by increasing the planet's albedo, resulting in global cooling. Stratospheric aerosols geo-engineering (SAG) is one of the several SRM options, where reflective aerosols like sulphates are injected into the stratosphere. Previous studies indicate that both SAG and reduction of solar insulation would lead to a decrease in global mean precipitation if the surface temperature rise caused by greenhouse gas warming is offset exactly. Our SRM modelling research at the Indian Institute of Science (IISc) focuses on the sensitivity of global and tropical precipitation to the latitudinal and altitudinal distribution of sulphate aerosols in the stratosphere. For our research we have been using the CESM global climate model and our simulations use the HPC resources provided the Supercomputing Education and Research Centre (SERC) at IISc

In our first SAG modelling research in 2017, we showed that placing aerosols in the Arctic to cool the Arctic regions could shift the latitudinal position of the Intertropical Convergence Zone (ITCZ) to the south, alter the meridional heat transport at the equator, disrupt the tropical monsoon systems, and reduce the summer monsoon rainfall over India.

In a recent investigation (2022) , we evaluate the impact of aerosol injection latitude on global and Indian monsoon precipitation through single-point injections at latitudes 30° S, 15° S, the equator, 15° N, and 30° N. Results show that while summer monsoon precipitation decreases in the hemisphere of aerosol injection, but increases in the opposite hemisphere, with changes of more than ±10% when the aerosol optical depth (AOD) difference between the hemispheres exceed 0.2.

In a subsequent study (2023), we conduct stylized simulations with various meridional distributions and amounts of volcanic sulphate aerosols prescribed in the stratosphere, quantifying the sensitivity of tropical monsoon precipitation to SAG in terms of two parameters: global mean aerosol optical depth (GMAOD) and interhemispheric aerosol optical depth difference (IHAODD). Similar sensitivity assessments are made for changes in global mean and interhemispheric differences in effective radiative forcing and surface temperature. This study clearly demonstrates that the precipitation in the tropical monsoon regions for SAG can be characterized by just two parameters: the global mean and interhemispheric differences in AOD.

In a more recent study (2023), we investigate the sensitivity of the tropical water cycle to the altitude of the stratosphere aerosol layer. This study is motivated by previous modelling studies which indicate that SAG could weaken the tropical circulation due to radiative heating of the aerosol layer in the lower stratosphere. It is also suggested that the efficacy of the cooling via SAG increases with altitude of the aerosol layer. Therefore simulations are carried out, where we prescribe volcanic sulphate aerosols at three different altitudes (22 km, 18 km and 16 km) and assess the sensitivity of the global and tropical mean precipitation to the altitude. Although cooling efficacy increases with aerosol layer altitude, we find that global and tropical mean precipitation are less sensitive to it due to offsetting responses between slow and fast precipitation adjustments to aerosol altitude. An analysis based on atmospheric energy budget is presented to explain the limited sensitivity of the hydrological cycle to the altitude of the stratospheric sulphate aerosol layer.

In summary, our SRM research at IISc underscores the complex interplay between aerosol distribution, altitude, and their impacts on global and tropical precipitation patterns, highlighting the need for further research and nuanced understanding before potential implementation.

Chemistry of Cloud Water During Indian summer Monsoon at a High-Altitude Location in West India

Ranjeeta D. Gawhane[1], Krishankant B. Budhavant[2,3], Vinayak V. Waghmare[1], Subrata Mukherjee[1], B. Padmakumari[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune-411008, India
[2]Divecha Centre for Climate Change, Indian Institute of Science, Bangalore-560012, India
[3]Maldives Climate Observatory-Hanimaadhoo, Maldives Meteorological Services, Hanimaadhoo-02020, Maldives

This study focuses on the chemistry of clouds and rainwater of southwest monsoons, which provides information on various pollutants in the atmosphere. Understanding the summer aerosol regime is essential for the monsoon system of South Asia. The study collected data (2016-2017) from ground-based cloud- water and rainwater collector systems intercepted at a high-altitude mountain station in Sinhagad. This site in the western part of India can be a reference site as it is away from industrial and urban areas, and the monsoon clouds almost touch the hilltops.

The average pH of cloud-water samples was 6.1, with about 18% of the values below 5.6. High concentrations of SO^{2-} and NO^{-} were observed in the cloud water samples; despite this, these samples were not more acidic than rainwater samples (average pH 6.6). This study differs from most other studies, which have reported higher acidity in cloudwater than in rainwater. The cloud-water samples were slightly alkaline (pH>5.6), mainly due to the dominance of soil-derived calcium carbonate, which neutralizes the acids or their precursors. The back trajectory analysis of the cloud-water data revealed that samples in air masses that spent the last few days over the Indian sub-continent were generally more acidic (due to an increase in anthropogenic emissions and aerosol-cloud interactions) than those collected during days with air masses of marine origin. A high correlation between Ca^{2+}, Na^{+}, NO^{-}, and SO^{2-} makes it difficult to estimate the contribution of SO_4 from different sources, as anthropogenic sulfur emissions and soil dust both make significant contributions.

This study of cloud chemical properties and air mass transport analysis identifies compositional source regimes with implications for the monsoon build-up, climate variabilities (such as ENSO), ecosystems, agriculture, and climate change.

Comparison of Dust Aerosols Transport in Asian Monsoon Anticyclone Using Reanalysis and Chemistry-Climate-Model Data

Archana Sagalgile[1,2], Suvarna Fadnavis[1] and Satheesh Chandran P R[1]

[1]Indian Institute of Tropical Meteorology (IITM), Pune, India
[2]Centre for Ocean Atmospheric Science and Technology, Amity University Rajasthan, Kant Kalwar, Jaipur, India

The dust aerosols are abundant over Asia which can modulate the clouds and precipitation over this region. During the monsoon season, strong convection can uplift boundary layer dust into the Asian summer monsoon anticyclone (ASMA) region (60-120°E; 15-40°N). in the Upper troposphere and Lower Stratosphere (UTLS.) Also, during the monsoon season, westerly winds transport dust from west Asia to the Himalayas through the lower and mid-troposphere, which is further uplifted into the ASMA. Considering the large impacts of dust on the radiation budget, monsoon circulation, and rainfall, understanding of the variability of dust aerosols in the ASMA region is important. However, dust amounts vary with models, reanalysis, and satellite data sets.

In this study, we compare dust aerosol in the troposphere and the UTLS over the ASMA region during the Indian Summer Monsoon season (JJAS) from the ECHAM6-HAMMOZ global chemistry-climate model, and two global reanalyses datasets (MERRA-2 and CAMS) for the period 2003–2018. One-way analysis of variance (ANOVA) test shows significant differences in dust loading among these data sets. All three data sets show similar spatial distribution of dust while the amount of dust loading differs. In the lower troposphere, MERRA-2 shows a higher dust aerosol loading compared to CAMS (by 200-500 kg/kg) and the ECHAM6- HAMMOZ simulation (by 300-700 kg/kg) in the mid-troposphere (CAMS by 20-100 kg/kg; ECHAM6-HAMMOZ simulation by 40-100 kg/kg) and in the UTLS (CAMS by 3-5 kg/kg; ECHAM6-HAMMOZ simulation by 6-9 kg/kg). Our analysis shows that dust aerosols, an important driver of monsoon circulation, are not consistent even in reanalysis data sets and chemistry-climate models. For better prediction of monsoon rainfall, accurate simulation of dust is important.

Keywords: Dust Aerosol, ASMA, MERRA-2, CAMS, ECHAM6-HAMMOZ

Response of Low and Mid Latitude Climate to Arctic Amplification in the Intermediate General Circulation Model

Satyaban B. Ratna[1,2], Timothy J. Osborn[2], Manoj Joshi[2]

[1]Climate Research and Services, India Meteorological Department, Pune, 411005, India
[2]Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, United Kingdom

Arctic surface air temperatures rose between two and four times as fast as the global average in recent decades, a feature known as 'Arctic amplification'. This study compares the impact of low and high amounts of Arctic amplification on temperature, precipitation and atmospheric circulation using the Intermediate General Circulation Model, version 4 (IGCM4). Changes in sea surface temperatures (SST) were first diagnosed from Coupled Model Intercomparison Projects of Phase 5 and 6 (CMIP5 and CMIP6) projections. Two composite patterns of SST change were created for a global warming level of 2 degrees Celsius from those models with either high or low amounts of Arctic amplification. The high and low amplification SST patterns were used to force two configurations of IGCM4: L20 with limited representation of the stratosphere and L35 that resolve the stratosphere. High Arctic amplification CMIP5 and CMIP6 models simulate similarly enhanced warming over the Arctic that peaks in boreal winter but reduced surface warming in the low and mid latitudes, compared with the low amplification models. The IGCM4 responds to these different SST forcings with significant warming throughout the globe but the High Amplification forcing drives greater warming across most extratropical NH landmasses during boreal winter compared with Low Amplification forcing. The precipitation response is most sensitive to the amount of Arctic amplification during boreal winter, with High Amplification forcing causing strong changes over the North Atlantic (wetter near the sea ice margin, drier over the main storm track, wetter over the Azores high region). These changes are almost the same for the L20 and L35 model configurations, demonstrating that a stratospheric pathway is not playing a key role in shifting precipitation patterns. These changes arise from weakening and equatorward movement of the tropospheric jet during boreal winter, and these changes are more pronounced with High Amplification forcing but do not depend on the model's representation of the stratosphere.

Exploring the Link Between Upper Tropospheric Humidity and Lightning Frequency Over the Tropics

Devika M V[1] and Ajil Kottayil[1]

[1]Satellite Remote Sensing and Applications, Advanced centre for Atmospheric Radar Research, Cochin University of Science and Technology, Cochin, India-682022

As water vapour is the most potent greenhouse gas, an increase in its concentration in the atmosphere will amplify the effect of global warming. Water vapour in the upper troposphere than in the lower troposphere significantly impacts the greenhouse effect and, thereby, the Earth's Energy Budget (EEB). In addition to the effect as a greenhouse gas, water vapour also influences EEB indirectly through the interaction with clouds. This study aims to understand the link between Upper Tropospheric Humidity (UTH) and lightning frequency. The analysis incorporates UTH datasets from microwave sounders onboard NOAA and MetOp-A polar-orbiting satellites. Lightning data from publically available global datasets will be used in the analysis. It is widely recognized that deep convection can trigger lightning and also increase upper tropospheric humidity. This study examines how the relationship between upper tropospheric water vapour and lightning activity evolves across tropical regions within the context of climate change.

Exploring the Vertical Structure of the QBO as a Predictability Source for Indian Summer Monsoon Rainfall

Suneeth K.V.[1] and Prasanth A. Pillai[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, 411008, India

While several studies have recognized the potential of the stratospheric Quasi Biennial Oscillation (QBO), as a predictor of the Indian summer monsoon rainfall (ISMR), their relationship still remains complex and uncertain. It is believed that, in comparison to other altitudes, the zonal wind at the 15 hPa level during the preceding winter is the most reliable predictor of late ISMR in August/September [1]. At the same time, the predictability of early ISMR is still remains uncertain. A recent study emphasized the importance of examining the vertical structure of the QBO instead of focusing on its index at specific levels. This approach provides a more comprehensive understanding of the link between secondary circulations and rainfall patterns [2]. In this study, we investigate further on the predictability of ISMR by analyzing the vertical structure of QBO during the preceding winter/spring. Furthermore, we explore the influence of QBO phases on the upper troposphere – lower stratospheric (UTLS) region and the variability of tropical easterly jet (TEJ). The study also found that the influence of the previous season's QBO mainly contributes to the June month rainfall. The influence of QBO on the ISMR is found to be independent of the El Nino Southern Oscillation (ENSO) and thus, the previous season's QBO can serve as an independent predictor for the boreal summer monsoon over India. In this aspect, the study further examined the relationship in different QBO-resolving CMIP6 models and seasonal prediction models. These models are able to capture the simultaneous relationship with rainfall variability associated with westerly and easterly phase of the QBO. However, the predictability from the previous season to the monthly rainfall is not evident in many models. Also, the independent relationship in the absence of ENSO is also not adequately represented in the models. It seems that the models need to bettercapture the vertical structure of QBO in order to accurately simulate any predictive signal of ISMR from QBO.

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Uncovering the Peculiarities Behind the December 2023-January 2024 Cold Wave Conditions over the North Indian Region

Sreyasi Biswas[1], Charu Singh[1] and Anjana VS[1]

[1]Atmospheric Sciences Department, Marine and Atmospheric Sciences Group, Indian Institute of Remote Sensing (IIRS), Indian Space Research Organization (ISRO), Dehradun, Uttarakhand, India

The winter of 2023-2024 has been unusual for the Northern Indian states. A series of cold wave (CW) and severe cold wave events were reported in the Indo-Gangetic belt including the Northern Indian states of Himachal Pradesh, and Uttarakhand from late December 2023 until late January 2024. Dense fog conditions prevailed in the above regions typically between 5:30 to 8:30 in the morning. This resulted in a limited amount of sunlight reaching the ground and triggering a low surface temperature. Precipitation too was abnormally less in these states, with 89% deviation from the normal between the 4th to 10th of January 2024. The Himalaya was snow-starved at the beginning of 2024 and the temperature was very low. This study has attempted to understand the unusual winter experienced. A Strong El Nino during this period resulted in Type 2 Cold Waves where lower than normal temperatures are associated with the North-western Indian region. The negative phase of the Arctic Oscillation (AO) was strong which was associated with a very weak Stratospheric Polar Vortex (SPV). A peak in the stratospheric temperature was recorded on the 5th of January 2024. The weak SPV is associated with a weak Polar Vortex (PV). The weak PV meandered to reach the lower latitudes and thus enhanced the winter all across the Northern Hemisphere, especially in the mid-latitudes. The 2 m temperature estimated during this period showed a prominent seepage of very low-temperature air into Northern India from the higher latitudes. More details will be presented during the workshop.

Keywords: CW, AO, SPV, PV

Extreme Rainfall over Indian Core Monsoon Zone and Their Ingredients Revealed by Radar and Reanalysis Measurements

U. V. Murali Krishna[1], Subrata Kumar Das[1], Yogesh K. Kolte.[1] and Govindan Pandithurai[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India

Heavy rainfall events are challenging for the forecast community due to their vide variety of rainfall intensities and time durations. These heavy rainfall events not only produce destructive weather and damage, but also play a major role in stratosphere-troposphere exchange (STE). The Indian core monsoon zone is a moisture rich environment that aids the development of heavy rainfall during summer monsoon. The present study aims to understand the characteristics of extreme rainfall, like frequency, intensity and structure, etc. using dual-polarization Doppler weather radar measurements. A Lagrangian storm tracking algorithm, TINT (TINT is not TITAN) is used to track the convective storms and to identify its characteristics. The radar derived convective storms revealed that the storms associated with the extreme rainfall are moderate intense and congestus in nature. Apart from the predominance of congestus storms, the other modes are also present in the extreme rainfall. The spatial occurrence is nearly same such that there is no dominant regions within the radar domain that exhibit higher frequency. A pronounced diurnal variability with two peaks, one in the afternoon and a secondary in the morning hours is noticed. To further explore the ingredients for these extreme rainfall, the European reanalysis data, ERA5 has been utilized.

This study will focus mainly on:

1. Monitoring the convective storms associated with extreme rainfall over India's core monsoon zone using Doppler weather radar.
2. What are the observed temporal patterns of extreme rainfall and how they differ from monsoon convection?
3. What are the major contributing factors for the observed extreme rainfall over central India.

Overview of Remote Sensing of Aerosols in the UTLS Region

B. Padmakumari[1]

[1]**Indian Institute of Tropical Meteorology (IITM), Ministry of Earth Sciences, Pune – 411 008, India**

Atmospheric aerosols/pollutants are widely distributed both horizontally as well as vertically and play a major role in atmospheric chemistry and climate change by directly scattering and absorbing the incoming and outgoing radiation as well as through modifying cloud properties. The increasing aerosol loading, contributed by both regional sources and long range transport, changes in cloud microphysics due to aerosol- cloud interactions and the warm oceans surrounded by peninsular India play a significant role on Indian monsoon variability.

In the recent decades, the presence of distinct aerosol layers aloft called elevated layers is consistently observed with various observational/remote sensing techniques. Hence, as compared to aerosol optical depths, aerosol vertical profiles give more insight on aerosol impacts on climate change such as aerosol warming on the thermal structure and stability of the atmosphere, and stratosphere- troposphere exchange. Over India, the vertical distribution of aerosols was studied from in situ probing using rocket and balloon-borne instruments, and ground-based, air-borne and space-borne lidars. However, observations of upper troposphere and lower stratosphere (UTLS) are very sparse over the tropical region. Vertical distribution of atmospheric aerosols was also studied using a simple passive remote sensing technique called twilight sounding method in terms of logarithmic gradient of twilight sky intensity. This method is used to retrieve aerosols in the UTLS region and is an efficient technique to study the stratospheric aerosol layer variability not only during volcanic eruptions but also during volcanically quiescent periods. This technique was also utilized for the first time in the tropical latitudes to understand the influx of extraterrestrial dust in the upper atmosphere and its subsequent descent to stratospheric altitudes. Hence, continuous monitoring of UTLS aerosol properties is crucial especially during monsoons. The methodology and the variability of aerosol vertical distribution at different altitudes with case studies will be presented.

The Tropopause QBO over the Indian Summer Monsoon Region: A Revisit

N. Koushik[1], K. Kishore Kumar[1], and Shailendra Kumar[1]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India-695022

The stratospheric Quasi-Biennial Oscillation (QBO) is the leading mode of variability in the tropical stratosphere characterized by descending easterly and westerly wind regimes that alternate with an average period of 28 months. The stratospheric QBO has been observed to affect the tropical tropopause region by modulating the temperature structure of the tropopause via thermal wind balance. In this study, we reexamine the QBO signal in the tropical tropopause over the Indian Summer Monsoon (ISM) region using the Indian Monsoon Data Assimilation and Analysis (IMDAA) reanalysis datasets. Emphasis is given to

(i) studying the seasonal dependence of the tropopause QBO and (ii) identifying the zonal asymmetry in the QBO temperature signal. QBO characteristics of the tropopause region obtained using IMDAA are compared with those obtained using the Modern Era Reanalysis for Research and Applications version 2 (MERRA 2) and zonal asymmetries are quantified. Further, the behavior of tropopause QBO temperature signal during strong and weak phases of the Madden Julian Oscillation (MJO) are investigated.

Assessment of Temperature Trend at 100 hPa from ERA5, AIRS and Radiosonde Datasets over Indian Region

Piyush Kumar Ojha[1] and Krishan Kumar[1]

[1]School of Environmental Sciences, Jawaharlal Nehru University, Delhi, 110067, India

Atmospheric convection is a major source of hazardous weather in different parts of the world. India also witnesses large number of convective events especially over the coastal region because of its proximity to ocean, which is a major source of water vapour. Coastal region of India, particularly, experiences a number of convective events every year owing to the favourable conditions for atmospheric convection over the Bay of Bengal, and Arabian Sea. ERA5 datasets have proved to be useful in the study of atmospheric convection. However, recent studies have reported there are some spatio-temporal uncertainties between the trends of atmospheric variables obtained from the observation and model based reanalysis (ERA5) datasets. Many studies observed that temperature in upper atmosphere (especially at 100 hPa) plays an important role in intensifying the atmospheric convection. In this study, we have examined the trends of temperature at 100 hPa from 2001-2021 over the entire Indian region using observation, model as well as satellite datasets. Observation data includes the twenty-four balloon based radiosonde stations which is fairly spread across the Indian region and model data includes ERA5 datasets whereas satellite data is taken from AIRS. Our study finds the significant decreasing trend in the temperature at 100 hPa from radiosonde observations whereas ERA5 data shows the significant increasing trend over the Indian region from 2001-2021. Non-significant decreasing trend is observed from satellite based AIRS datasets.

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Detection of Multiple Tropopause and Stratospheric Intrusions using VHF Radar over the Central Himalayan Site

Aditya Jaiswal[1,2], and Subrata K. Das[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune 411008, India
[2]Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, 263001, India

High altitude subtropical Himalayan region is prone to downward transport of the stratospheric airmass into the troposphere. Such downward transport processes can significantly affect the tropospheric ozone levels, especially over the Himalayan regions, which are relatively devoid of anthropogenic emissions. Past investigations over this region have inferred that the downward intrusion occurs as a dynamic response triggered by the breaking of the orographic/convectively generated gravity and Rossby waves (Phani Kumar et al. 2017). Multiple tropopauses are known to occur frequently at the edge of subtropical jet streams, which controls the excursions of stratospheric airmass into the troposphere. This may also lead to the existence of the secondary ozone peaks at the mid tropospheric level (Ojha et al., 2017). Therefore, it is crucial to probe the mesoscale nature of these structures.

Ground based VHF radars have been proven to be an indispensable tool for studying the mesoscale dynamics of the upper troposphere and the lower stratosphere (UTLS) region. Vertically propagating VHF radiowaves are strongly scattered by the stable thermal inversion around tropopause, causing sharp gradients in the refractivity structure constants. This property can be utilised to monitor the tropopause structure continuously. In this context, we have utilised the 206.5 MHz ARIES Stratosphere Troposphere Radar (ASTRAD) being operated at the high altitude site of Nainital located in central Himalayan foothills (29.4ºN, 79.5ºE, ~1.8 km amsl) to study the multiple tropopause structures in conjunction with the STE processes. We considered the lapse rate tropopause definition and determined its altitude using the gradient method with signal-to-noise ratio (SNR) profiles from the 206.5 MHz wind profiler radar. The tropopause altitude derived from the ST radar is validated against tropopause obtained from colocated GPS radiosonde measurements, showing a good agreement between the two methods. Several case studies will be presented regarding the detection of the multiple tropopause, downward transport of stratospheric airmass and their underlying dynamics using VHF radar complemented with satellite and reanalysis datasets. This study will serve as a valuable diagnostic to detect the ozone intrusions by using mesoscale nature of tropopause as precursor and will aid in the monitoring of the air quality and mass/momentum flux transport budget in the UTLS region.

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Evaluation of Atmospheric Thermodynamic Parameters on Lightning over Indian Region

Swati Tyagi[1] and Arun Srivastava[1]

[1] School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, 110067, India

Lightning is one of the natural disasters that cause significant financial losses and even fatalities. Therefore, it is necessary to understand the characteristics of lightning and related factors to take appropriate preventive and mitigation measures. Globally lightning activity has been increased drastically and it is directly associated with different thermodynamic parameters. Recent studies reported the increasing trend in the lightning activityover the Indian region. In this study, we have examined the influence of atmospheric thermodynamic factors on lightning activity over the Indian region using Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) from 1998-2013. Furthermore, datasets of atmospheric thermodynamic parameters are taken from the fifth-generation ECMWF atmospheric reanalysis (ERA-5) as well as from the Modern Era Retrospective Analysis for Research and Applications version 2 (MERRA-2). Our result shows the increasing trend of lightning strikes in the western, south western, southern and north eastern part of India. The study also observed the increasing trend of convective available potential energy (CAPE) over almost entire part of the Indian region except central region. The probable reason of high lightning activities over these regions corresponding to the distribution pattern of aerosols. An increase in CAPE and aerosol concentration trend along with specific humidity could be the probable reason to increase in the lightning activity over the study region.

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An Advanced Review on the Gaseous Composition in Asian Summer Monsoon Anticyclone (ASMA) and their Impacts on the Tropopause and Atmosphere

Suresh Aluvihara[1,2], T.E. Weerawardena[2], H.D.A.K. Gunaratne[2]

[1]Department of Chemical and Process Engineering, University of Peradeniya, Peradeniya, 20400, Sri Lanka

[2]Soil Science Division, Central Research Station, Department of Export Agriculture, Matale, 21000, Sri Lanka

*Email: sureshaluvihare@gmail.com, sureshaluvihare24@gmail.com

The Asian Summer Monsoon Anticyclone (ASMA) is a leading atmospheric process with some distinguished features because of the topography of the region covered by the monsoon system, natural processes and some anthropogenic activities are being progressed in such region. The impacts of such monsoon anticyclone on the global climatology are significant because of its impacts on the upper troposphere, lower troposphere and tropopause in the northern hemisphere especially during the summer season. In the case of the theoretical concern of such incident, the convection principle is the foremost principal of upward transportation of the most of gases up to the level of stratosphere since the cyclone/ monsoon system is generated due to huge pressure differences in between two locations of the atmosphere while having vertical and horizontal transport of air. In the considerations of the gaseous compositions of such air masses, mainly there were identified the presence and transportation of carbon monoxide (CO), sulphur dioxide (SO2), hydrogen cyanide (HCN), water vapor (H2O), ethane (C2H6), acetylene (C2H2), methyl chloride (CH3Cl), ammonia (NH3), carbonyl sulphides (OCS) and small dust particles (PM2.5, PM10) in the upper tropospheric region and ozone (O3), nitrogen compounds (NOX), nitric acid (HNO3) and hydrochloric acid (HCl) in their gaseous forms. When considering the impacts of such gases, most of them are considered as the boundary layer pollutants. The impact of those gases on the atmosphere can be found and discussed at various stages namely as the ground level, dispersion process and boundary layer. The lifespans of those gases play an important role in the consideration of their impacts on the climatology and weather conditions. In the consideration of gaseous form of ammonia (NH3), it is considered as an essential component especially in the formation of aerosols in the atmosphere which is also identified as a secondary pollutant. In addition, some acidic gases play a role of the formation of acid rains such as SO2 and NO2 and also the depletion of ozone and the deduction of ozone concentration due to the reaction of NO2 and O3 is a critical factor regarding boundary layer process. Also, the increasing of particulate matter concentration (PM2.5, PM10) causes some dust layers/ clouds which are able to regulate the incident of sunlight on the surface of earth through the tropopause.

Keywords: Asian Summer Monsoon Anticyclone (ASMA)**,** Chemical composition, Tropopause, Northern hemisphere

PMWEX POSTERS

Identifying Vulnerable Hotspots of Weather Extremes in Bangladesh, Pakistan, and Nepal

Shaukat ALI[1]

[1]SickKids Centre for Global Child Health, The Hospital for Sick Children, Toronto, Ontario, Canada

This study is part of the APN project, "Towards Robust Projections of Climate Extremes and Adaptation Plans over South Asia" focusing on generating local-scale (5 km) reference and future (CMIP6) climate data, as well as analyzing weather extremes in Pakistan, Bangladesh, and Nepal. The research aims local information on climate extremes and identify vulnerable hotspot regions in these three countries. In the initial phase, we conducted quality control on station data using both objective and subjective techniques. ERA5 data is corrected for biases by incorporating observational data. A 5km horizontal resolution grid dataset was obtained by combining observed data with regularly spaced data through kriging. ERA5 data were excluded in regions with available observation stations to prioritize the more reliable station data. For temperature adjustments in areas with limited observed data particularly in mountainous regions with complex topography. We considered the estimated average of the Lapse Rate of Temperature (LRT). This adjustment also factored in the topography using a high-resolution digital elevation model specifically the Global 30 Arc-Second Elevation (GTOPO30) from the U.S. Geological Survey (USGS).

In the second step, we validated 40 CMIP6 models and selecting the best 5 models. These selected models were downscaling/bias correction using spatial disaggregation quantile delta mapping (SDQDM). This method addressed the issue of stationarity in data and preserved the trend in future climate signals.

This study is part of the APN project titled "Towards Robust Projections of Climate Extremes and Adaptation Plans over South Asia", which aims to prepare local-scale (5 km) reference, future (CMIP6) data and weather extremes in three countries Pakistan, Bangladesh, and Nepal. This research study seeks to provide local information on climate extremes and identify vulnerable regions.

In last step, we analyzed the weather extreme and identify vulnerable hotspot regions in Pakistan, Bangladesh and Nepal.

Keywords: 5km Climate Data, CMIP6, Pakistan, Bangladesh, Nepal, Weather extremes, Hotspot

Long Term Changes in Tropical Easterly Jet- Observational and Multi-model Approach

Karthika P P[1], M. Roja Raman*[1] and M. Venkat Ratnam[2]

[1]Centre for Remote Sensing and Geoinformatics, Sathyabama Institute of Science and Technology, Chennai – 600119, Tamil Nadu, India.
[2]National Atmospheric Research Laboratory (NARL), Dept. of Space, Gadanki, India.
E-Mail: ramansvu@gmail.com

Indian Summer Monsoon (ISM) consists of several elements that are inter-linked. Any change in one element will reflect on the other and finally on the rainfall characteristics. In the changing climate, several changes have been reported in these elements. Two important elements that directly affect the ISM are the Monsoon Low Level Jet (MLLJ) and Tropical Easterly Jet (TEJ). The long term changes in the characteristics of TEJ features during ISM months (June, July, August and September) has been investigated using sixteen years of high resolution GPS radiosonde observations over NARL, Gadanki is reported in the present study. Further, Availability of more than four decades of high resolution reanalysis data sets over the Asian monsoon region are used to monitor the changes in spatial extent and strength of TEJ. The bias in estimating the TEJ characteristics with reference to the high resolution radiosonde and radar wind profiler is quantified. The detailed characteristics of horizontal wind fields like TEJ peak strength, height and width over a given grid/location is estimated daily during monsoon months and then averaged for peak monsoon months July and August to represent the seasonal mean. The seasonal mean time series of TEJ characteristics are subjected to multi-variate regression analysis to extract the dominance of natural variabilities like QBO, ENSO and solar cycle. The residual time series is then subjected to linear regression to estimate the long term trend in TEJ strength and spatial extent. In addition, the forward moving regression is performed to find the point of origin that make the change in trend. The relation between TEJ characteristics and monsoon rainfall and tropical cyclones is delineated. Finally the future projections in TEJ characteristics are examined with the help of CMIP model outputs.

Keywords: Indian Summer monsoon**,** Tropical Easterly Jet, GPS radiosonde, Reanalysis data, Climate Projections.

Heavy Rainfall and Thunderstorms in South Interior Karnataka

Chanabasanagouda S Patil[1,2], Kamsali Nagaraja[1] and Shaik Darga Saheb[1]

[1]Department of Physics, Bangalore University, Bengaluru - 560056
[2]India Meteorological Department, Bengaluru -560001
Email: csgoudapatil@gmail.com (Patil); kamsalinagaraj@gmail.com (Nagaraja)

This study aims to conduct a synoptic and thermodynamic analysis of significant rainfall events that happened during the break monsoon season. During the investigation of meteorological events, it was observed that the monsoon trough at mean sea level passed along the foothills of the Himalaya. On August 31, 2023, there was a cyclonic circulation observed in the northeast Bay of Bengal as well as adjacent areas, reaching an altitude of 5.8 kilometers above mean sea level. This circulation tilted southwestward with height. During the period of September 1-3, 2023, there was a persistent phenomenon that occurred inside a particular geographical area. This phenomenon extended up to a height of 4.5 km above mean sealevel and exhibited a south-westward tilt as the altitude increased. On August 31, 2023, the Convective Available Potential Energy (CAPE) was measured to be 2153 J/kg, whereas the Convective Inhibition Energy was recorded as 0 J/kg. INSAT satellite image showed a cloud top temperature of -40 °C to -60 °C. The doppler radar pictures also showed convective clouds to support this phenomenon. The synoptic and thermodynamic indices indicate a high likelihood of significant precipitation occurring over Bengaluru and its surrounding regions.

Key words: Heavy rainfall, Synoptic situations, Thermodynamic indices

Oceanic Influence on Large-Scale Atmospheric Convection during Co-occurring La Niña and IOD events

Supriya Ovhal[1,2], Mujumdar M[1]*, Swapna P[1], Sreenivas P[3], Sandeep N[1], M. Ravichandran[4]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Ministry of Earth Sciences (MoES), Pune 411008, India
[2] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, 411007, India
[3] University of Hyderabad, Telangana 500046, India
[4]Ministry of Earth Sciences (MoES), New Delhi, India

The Indian Summer Monsoon Rainfall (ISMR) profoundly impacts the lives of over a billion people across the region. Historically, its extremes have been linked to the El Niño/Southern Oscillation (ENSO) and modulated by the Indian Ocean Dipole (IOD). Notably, the monsoon rainfall during June to September 2022 displayed intriguing spatial patterns: above-normal precipitation over the south peninsula and central India, normal over Northwest India, and below-normal over East and Northeast India. In 2022, La Niña conditions associated with a negative Indian Ocean Dipole (nIOD) (hereafter co-occurrence years), were prevalent over the equatorial Pacific and Indian Ocean. This study investigates the often-overlooked Oceanic subsurface contribution to large-scale atmospheric convection over the tropical Indian Ocean. By undertaking a comprehensive analysis of the observed and reanalysis datasets, we find that strong equatorial westerly wind anomalies prevailed over the equatorial Indian Ocean during co-occurring years generating eastward propagating downwelling Kelvin waves which deepens the thermocline in the eastern equatorial Indian Ocean. The Kelvin waves then propagates into Bay of Bengal and gets reflected from southern tip of India as westward propagating Rossby waves deepening the thermocline and causing low level wind convergence in the northern Arabian Sea. We identify two centres of low-level wind convergence, one over Northern Arabian Sea and another over Maritime Continent during co-occurrence years. These wind convergence centres play a pivotal role in channelling moisture towards their core, in addition, significantly deepen the oceanic thermocline, increase the Ocean heat content and thus maintaining warmer SSTs over area of conversions. Together, these interrelated factors create an environment that is conducive for enhanced convective activity over the zone of convergence, enhancing and sustaining the convective conditions. This study underscores the significant contribution of ocean dynamics in shaping large-scale atmospheric convection during the co-occurrence years. Beyond the conventional focus on SST, our findings highlight the significance of considering broader Oceanic variables in comprehending and forecasting monsoonal variability.

Keywords: ISMR, ENSO, La Niña, IOD, thermocline, Ocean heat content.

Extreme Monsoon Assessment using Sentinel-1A SAR Data, AP, India

Jayaraju N[1] and Kiran Dasari[2]

[1]Department of Geology, Yogi Vemana University, Kadapa, AP, India
[2]Dept of Electronics and communication, MLR Institute of Technology, Hyderabad, India

India is one of the most flood-prone countries in the world and one-eighth of the country's geographical area is subjected to floods. As a matter of fact, one of the most important problems associated with flood monitoring is the difficulty to determine the extent of the flood area as even a dense network of observations cannot provide such information. The flood extent information is used for damage assessment and risk management, and benefits to rescuers during flooding; it is also very important for calibration and validation of hydraulic models to reconstruct what happened during the flood and determine what caused the water to go where it did. During floods the cloud coverage is more, thus very difficult to acquire and obtain information using earth observation satellites suing optical sensor . To overcome the limitation, SAR sensors can acquires the ground information even in cloud cover. Therefore risk management can be performed as early as possible. Handling of SAR information is valuable for this situation since typical optical satellite pictures will be prevented by mists and is difficult to plan water bodies. Yet, with SAR pictures we can notice the landscape despite the fact that there are numerous obstructions like mists dust and so on as it is Radar Tech dissimilar to optical one. Curtailed type of open source PC vision library which upholds python, c++, and java interfaces. It is essentially intended for accomplishing computational productivity and furthermore to give emphasis for ongoing applications. This bundle enjoys an additional benefit that is multicore handling. Picture handling library essentially centered around ongoing PC vision with application in wide scope of regions like 2D and 3D highlights toolboxs, facial and motion acknowledgment.

Keywords: Python, Hyper text markup language, command style sheets, Online trial room, Open CV

Long-term Characteristics of Thunderstorm Activities and its Influence on Atmospheric Composition over Bengaluru: A Urban Location in South Peninsular India

Shaik Darga Saheb[1] and Chanabasanagouda S Patil[1,2]

[1]India Meteorological department, KIAL, Bengaluru, India
[2]Department of Physics, Bangalore University, Bengaluru, India

The study examines the long-term analysis of thunderstorm and lighting activities and their impacts on local meteorology and atmospheric pollutants over Bengaluru using ground and spaceborne observations from 2011-2023. The diurnal thunderstorm events mainly occur in the late evening hours (1900–2100 IST) and on monthly, the maximum thunderstorms occurred in the month of May while minimum in January. Annually there are 41 thunderstorms and 157 lighting events observed over Bengaluru and showed a significant (95%) increasing trends with a rate of 3.41% and 3.3% per year respectively during 13 years period (2011-2023). Local temperature's combined with abundant moisture supply from the southwest/Northeast monsoon creates a favourable condition for the initiation of thunderstorms over the region. This study also focused on the trend analysis of meteorological parameters and atmospheric compositions, a rising trend was found for rainfall (1.44 mm year–1), RH (0.74% year–1) & pressure (0.03 hPa year–1) whereas a slight declining trend for temperature (-0.06 0C year-1) & wind speed (-0.02 ms-1 year–1) was observed. Meteorological variations are indicating that even though the temperature changes are small, the associated RH changes are significant over the years. Since heat and moisture availability are two main requirements for thunderstorm occurrence and hence the probability of occurrence of severe thunderstorms may increase in future. The AOD, NO_2 & O_3 showed a significant ($p < 0.01$) increasing trend while no trend for SO_2. The Pearson correlations showed the AOD, NO_2 & SO_2 concentrations are significant negatively correlated with wind speed but positively correlated with atmospheric pressure while AOD and O_3 positively correlated with temperatures. A further study indicated a significant impact of thunderstorm on the air pollutants has been quantified and it is observed that PM2.5 concentration gradually decreases after the commencement of thunderstorm while quick increasing response (below1 hour) was in O_3 and delayed response (after 2:30 hours) in NO_2 was observed which may attributed due to mature phase of the thunderstorm and linked to lighting activities. The results reveal that thunderstorms are may influence the local meteorology as well as atmospheric pollutants and vice-versa in regional to global.

Keywords*:* Thunderstorms, Lightning, Meteorology and Air pollutants, LIS, MODIS

Mechanisms Governing Rainfall over India during Monsoon Onset and Post Onset Phases

Sujatra Bhattacharyya[1] and Arindam Chakraborty[1,2]

[1]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, India
[2]Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru, India

Observations show that the statistical correlation between rainfall during the onset phase (June) and the post-onset phase (July to September) is very weak. This study aims to understand the governing mechanisms that might be associated with June and the rest of the season's rainfall. For the first time, without pre- assuming any of the intra-seasonal features such as Onset, Intra-seasonal oscillations, synoptic variabilities and extremes, etc., the connection between Inter-annual and monthly variations of rainfall is established using a seasonal cycle perspective. Inter-annual variations lead to perturbations to the mean seasonal cycle which in turn results in monthly variations of rainfall on top of the mean seasonal cycle. These monthly variations are considered for this study. Analyses in this study show that the June rainfall which is related to the onset of the Indian Summer Monsoon is majorly governed by Madden-Julian Oscillation activities along with mean background precipitable water which in some years can alone result in onset by intensifying HF-ISO and synoptic events over Kerala and Central India respectively. On the other hand, the rest of the season's rainfall is majorly explained using an evolving ENSO mode which has a negligible effect on June rainfall, increasing from July and having maximum effect on September rainfall.

Keywords: Seasonal Cycle, Madden Julian Oscillation, ENSO

Soil Moisture Revamps the Temperature Extremes in a Warming Climate over India

Naresh G. Ganeshi[1,2], Milind Mujumdar[3], Yuhei Takaya[2], Mangesh M. Goswami[3], Bhupendra Bahadur Singh[3], R Krishnan[3] & Toru Terao[4]

[1]University of Tokyo, Kashiwa, Japan
[2]Meteorological Research Institute, Tsukuba, Japan
[3]Indian Institute of Tropical Meteorology, Pune, India
[4]Kagawa University, Kagawa, Japan

Soil moisture plays a crucial role in altering climate extremes through complex land–atmosphere feedback processes. The present study investigated the impact of soil moisture perturbations on the characteristics of temperature extremes over India based on soil moisture sensitivity experiments using the model MRI-AGCM3.2 for the historical period (1951–2010, HIST) and future (2051–2100, FUT) under the 4 K warming scenario. Our findings show that more than 70% area of the Indian landmass has experienced significant changes in the characteristics of temperature extremes due to soil moisture perturbations. In particular, it is noted that soil moisture perturbations exert substantial control on the near-surface temperature variability over north-central India (NCI), a hotspot for soil moisture-temperature (SM-T) coupling, by altering the surface energy partitioning between sensible and latent heat fluxes, and soil moisture memory.

Our findings suggest that a 20% increase of soil moisture perturbation applied on the HIST and FUT experiments, tends to decrease the frequency and duration of extreme temperature events over NCI by nearly 60–70% and 20–30%, respectively. Conversely, a 20% decrease of soil moisture perturbation applied on the HIST and FUT experiments, tends to increase the frequency and duration of extreme temperature events over NCI by nearly 60–100% and 15–40%, respectively. In other words, it turns out that the impact of soil moisture perturbations on the frequency and duration of extreme temperature events over NCI becomes less prominent in the future (FUT) 4 K warming scenario as compared to the historical (HIST) climate. We note that this reduced impact of soil moisture perturbations on temperature extremes in FUT, as compared to HIST experiment, is related to the increase of precipitation and soil moisture over the Indian region which causes a decrease in the temperature difference between the surface and near-surface atmosphere (i.e. 2 m air temperature), decrease of Bowen ratio and decrease of sensible heat flux from the surface to the atmosphere. These findings are useful to better understand the impact of land-atmosphere interaction on climate extremes in a warming climate.

Understanding the Characteristics of Mesoscale Convective System Associated with the Sub-seasonal Variability over the Indian Summer Monsoon Region

Silpamol D S[1], Ajil Kottayil[1], Prince Xavier[2] and Tesna Maria[1]

[1]Satellite Remote sensing and applications, Advanced centre for Atmospheric Radar Research, CUSAT, India.
[2]Met Office UK, Exeter, United Kindom.

Mesoscale convective systems (MCSs) are organized clusters of convective storms span several hundred kilometers. They generate widespread convective and stratiform precipitation and are often responsible for intense rainfall events in the tropics. Models possess inherent limitations when accurately simulating the characteristics of MCSs, which can consequently introduce biases in their precipitation estimates. Alternately, MCS can be detected from observations. In this study, we track the MCS in the Tropical Rainfall Measuring Mission (TRMM) daily precipitation data from June to September 2000-2023 over the Indian monsoon region. The characteristics of convective systems, such as area, orientation, shape, etc., for various threshold values of precipitation will be estimated. The derived features of the precipitating system will be linked to various phases of major monsoon sub-seasonal variability, such as boreal summer intraseasonal oscillation (BSISO). The long-term changes in the characteristics of MCS related to the BSISO will also be investigated in this study.

Indian Summer Monsoon Rainfall Response to Two Distinct Features of the La Niña and Performance of Seasonal Forecast Models

Tanu Sharma[1,2], Satyaban B. Ratna[1], D.S. Pai[3]

[1]Climate Research and Services, India Meteorological Department, Pune 411005, India
[2]Savitribai Phule Pune University, Pune 411007, India
[3]India Meteorological Department, New Delhi 110003, India

This study shows the asymmetry in the Indian Summer Monsoon Rainfall (ISMR) response over all-India and its four homogeneous regions to two distinct types of temporal evolution in La Niña, by analyzing the sea surface temperature (SST) and large-scale dynamics over the tropical Indo-Pacific region for the period 1951- 2022. We have identified two types of La Niña episodes during the monsoon season (June-September) based on whether it evolved from El Niño or La Niña from the previous boreal winter season (December-February). India received more (less) rainfall during the La Niña years when it was preceded by El Niño (La Niña) in the preceding winter. When the La Niña years were preceded by El Niño in the winter, the positive surface pressure anomaly over the west-north Pacific, persistent low-level westerlies and moisture transport favored the rainfall over the south peninsula and west-central India. Whereas moisture divergence associated with anomalous lower-tropospheric anticyclone over the west-north Pacific suppressed the rainfall over the Indo- Gangetic plains. However, when the La Niña years were preceded by La Niña in the winter, the absence of westerlies and weak moisture transport subdued the rainfall over the south peninsula and west-central India. This study also evaluated the performance of the ensemble forecasts of eight Copernicus Climate Change Service (C3S) models for the period 1993–2016 for ISMR response to two types of La Niña episodes using the model forecasts of April initial conditions. The results indicate that some of the seasonal forecast models were able to capture the spatial pattern of SST anomaly over the Indo-Pacific Ocean as well as the associated ISMR for the two types of La Niña.

Cloudburst Prediction in the Indian Himalayas

B Sudarsan Patro[1,2], Prashant P. Barttake[1]

[1]COEP Technological University, Pune, Shivajinagar, Pune-411005, Maharashtra, India
[2]India Meteorological Department, Pune, Shivajinagar, Pune-411005, Maharashtra, India

Forecasting cloudbursts in the Indian Himalayas poses significant challenges due to the region's distinctive geographical and meteorological features. The complex terrain, marked by steep slopes and high altitudes, exacerbates the difficulty of predicting abrupt and intense rainfall events, influenced by the intricate interplay of these geographical characteristics. The scarcity of real-time data, particularly from remote and inaccessible Himalayan areas, is a primary challenge, impeding the development and calibration of models crucial for accurate cloudburst forecasting. Additionally, the unpredictable nature of these events occurring in isolated pockets further complicates establishing a comprehensive forecasting system. The Indian Himalayas exhibit unique atmospheric dynamics, with moist air masses interacting with complex topography, introducing additional complexities. Convectional processes triggered by orographic features play a crucial role in cloudburst initiation and intensification, posing challenges for meteorologists and researchers in understanding and modelling these intricate atmospheric interactions. The rapid and unpredictable nature of cloudbursts complicates timely warnings to downstream vulnerable communities, emphasizing the urgency of improving forecasting accuracy. Flash floods resulting from cloudbursts can lead to devastating consequences. To overcome these challenges, advanced modelling techniques are essential for accurately simulating the complex atmospheric processes specific to the Indian Himalayas. Furthermore, enhancing observational infrastructure through the deployment of weather stations in remote areas is crucial for collecting real-time data. Addressing the complexities of forecasting cloudbursts in the Indian Himalayas necessitates a multidisciplinary approach, combining advanced modelling techniques, improved observational infrastructure, and a deeper understanding of local meteorological intricacies to enhance accuracy and mitigate associated risks effectively.

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On the Association of the Arctic Oscillations and Winter Precipitation Extremes over the Indian Region

S. D. Sanap[1], M. Mohapatra[2], D.R. Pattanaik[2]

[1]Climate Research and Services, India Meteorological Department, Pune-05
[2]Office of the Director General of Meteorology, India Meteorological Department, New Delhi

The prolonged positive phase of the Arctic Oscillation (AO) and associated quasi- stationary equivalent barotropic Euro-Atlantic blocking high (EABH) and the Siberian high (SH) existed during January 2020. The presence of the persistent quasi-stationary barotropic high resulted in higher (lower) than normal surface temperatures in most parts of northern (southern) Eurasia. The large-scale analysis suggests the detouring of the mid-latitudinal westerlies from EABH and the formation of the west-east trough from East Atlantic to Northwest Pacific across North Africa, the Middle East, North India and China. The analysis reveals a convergence of moisture and positive convection anomalies along the trough region. Against the backdrop of these extensive circulation anomalies, central and north Indian regions experienced higher than normal precipitation, accompanied by thunderstorms and hailstorm events. The variations in the AO index (AOI) and EABH were found to be in concurrence with the precipitation anomalies over the Indian region. The detailed analysis of a selected thunderstorm/hailstorm cases suggests that the lowering of the $0^{o}C$ isotherm due to the intrusion of mid-latitudinal westerlies and the development of atmospheric instability with moisture supply from the adjacent seas facilitated the occurrence of the thunderstorms/Hailstorm events during January 2020. The winter precipitation patterns and its association with the phase of the AO on a climate scale will also be discussed.

Verification and Usability of Medium-range Weather Forecast for Kullu Valley of North-west Himalayas

Abhay Sharma[1*], Devina Vaidya[1], BS Thakur[1], SK Bhardwaj[2], Joginder Singh[1], Vijay Kumar[1] and Disha Thakur[1]

[1]Regional Horticultural Research & Training Station, Bajaura-175 125, Kullu, Himachal Pradesh, India
[2]Department of Environmental Science, Dr. YS Parmar University of Horticulture and Forestry, Nauni-173 230, Solan, Himachal Pradesh, India

Weather forecasts issued by IMD for AMFU-Seobagh present in mid hills of Kullu district of Himachal Pradesh from March 2020 to February 2022 have been analyzed and verified for accuracy. Analysis of the verification of the forecast data was carried out on a seasonal and annual (March-February) basis using various verification techniques *viz*., Ratio Score (RS), Critical Success Index (CSI), Heidke Skill Score (HSS), Hanssen and Kuipers Score (HK), Root Mean Square Error (RMSE) for rainfall, and RMSE for other parameters (*viz*., maximum and minimum temperature, morning and afternoon relative humidity). The ratio score of rainfall was highest during post-monsoon (85.87) and winter seasons (84.75) as compared to pre-monsoon (60.87) and monsoon seasons (51.64), indicating the higher performance of forecast prediction in post-monsoon and winter months than in the other two seasons. In post-monsoon, the forecasting performance in terms of usability of rainfall was excellent whereas poor in Monsson months during all years. Also, the forecast found within quite a usability range for most of the parametersbut improvements are still needed. The correlation analysis showed that there was a high correlation between forecasted and observed values of weather parameters over the years during the different seasons.Hence, the forecast was found widely applicable among different user groups and farming community.

Modification of Cloud-Aerosol Interacting Microphysics for the Tropical Monsoon Region

K.S. Apsara[1], A. Jayakumar[2], Saji Mohandas[2], Paul Field[3], T. J. Anurose[2], Thara Prabhakar[4], and V.S Prasad[2]

[1]Indian Institute of Science Education and Research, Tirupati, India
[2]National Centre for Medium-Range Weather Forecasting, Noida, India
[3]Met Office Exeter UK
[4]Indian Institute of Tropical Meteorology, Pune, India

Introduction of double moment cloud microphysical scheme (CASIM: Cloud-Aerosol Interacting Microphysics) in the operational convection permitted model of National Centre for Medium-Range Weather Forecasting (NCUM-R) is targeted for the improvement in the tropical prediction. CASIM development by the UK Met Office started with an objective of enhanced cloud-aerosol interaction and is employed here for the advancement of extreme weather events predictions. Comprehensive understanding of the nature of DSD distribution of the CASIM is evaluated using the Bulk parameters like Mass weighted mean Diameter (Dm) and Normalized number concentration parameter (Nw), against Joss-Valdvogel Disdrometer (JWD) and the Global Precipitation Mission - Dual Frequency Precipitation Radar (GPM-DPR). The past study inferred the limitation of the droplet growth and presence of large concentration of smaller drops during the convective stage of monsoon precipitation. The warm rain physics, encompassing self-collection, auto-conversion, and accretion, is reassessed in CASIM utilizing realistic droplet distribution information during convective stages. Revised scheme is tested for the case study of the heavy precipitation and high lightning events. The improved predictability in the probability distribution of precipitation and the lightning number from the case study encouraged for the further optimization of CASIM for the tropical settings.

Transport of Water Vapor Associated with Monsoon Rainfall over Bangladesh

Sakia Shabnam Kader[1]

[1]Daffodil International University, Dhaka, Bangladesh.

Atmospheric water vapor transport is the most important part of the atmospheric branch of the water cycle. Advection of water vapor plays the most significant role to form precipitation in the monsoon season. The parameter for this study is focused on the spatial analysis of the vertical integral of the water vapor flux which presents the horizontal rate of flow of water vapor over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. Very few researches have been carried out on the transport of water vapor over Bangladesh in monsoon for the longer time scale. This study covers the long-term variation in the transportation of water vapor flux in monsoon season for 30-year from 1990 to 2019 and its contributions to the total rainfall over Bangladesh. Global moisture budget monthly data from 1990 to 2019 has been derived from ERA-5 reanalysis data generated by European Centre for Medium-Range Weather Forecasts (ECMWF) having horizontal resolution of 0.25°x 0.25° are used in this study. The influence of advection of water vapor on the rainfall has been investigated.

Keywords: Water vapor, Advection, Rainfall, Monsoon.

The Role of Mixed Rossby-Gravity Wave Dynamics in Enhancing the Prediction Skill of Indian Ocean MJO Convection Initiations in S2S Model Reforecasts

Daniel Simon[1], Neena Joseph Mani[1], and Suhas Ettammal[1]

[1]Indian Institute of Science Education and Research, Pune, 411008, India

Understanding the initiation of Madden-Julian Oscillation (MJO) is a challenging problem in tropical Meteorology. Recent studies highlight the important role of the dynamics of Mixed Rossby-Gravity (MRG) waves in initiating the convectively active phase of the Madden-Julian Oscillation (MJO) in the Indian Ocean. In this study, we explore whether the occurrence of MRG wave events several days prior to the initiation of MJO convection initiation is crucial for improving the prediction skill or not using four (CMA, UK MetOffice, ECMWF and NCEP-CFS) S2S model reforecasts. Boreal winter Indian Ocean MJO convective events and their initiations are identified using out-going longwave radiation (OLR) MJO index (OMI) for the period 1979-2021. MRG wave events in the lower and upper levels are identified by applying the Empirical Mode Decomposition (EMD) method on the meridional winds for the same time period. We find that 39% of Indian Ocean MJO initiations were linked to preceding MRG wave events. It is noted that all the model reforecasts initialized with MRG wave events realistically capture the horizontal structure and other properties of the MRG waves. Estimation of MJO convection initiation prediction skill at different lead times (5 days, 7 days and 9 days) consistently reveals significant enhancement in three out of four models (ECMWF, UKMO, and NCEP) when the MJO events precede MRG wave events to its west. We speculate that these models ability to simulate realistic MJO and MRG wave events might be the main reason behind their better performance. The results obtained from the study underscore the importance of scale interaction and the need for realistic simulation of high frequency equatorial waves in improving the prediction skill of the MJO initiation.

Deciphering Precipitation Microphysics and Atmospheric Anomalies in India's Capital City during Intense Downpour, July 2023

Gargi Rakshit[1], Kaustav Chakravarty[2], K.C. Sai Krishnan[1]

[1]India Meteorological Department, Ministry of Earth Sciences, Government of India, New Delhi, India
[2]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India

The present multi-technique investigation deals with the extreme rainfall episodes experienced in New Delhi (28.62°N, 77.17°E), the capital city of India during the monsoon season from July 5 to 15, 2023. Joss–Waldvogel disdrometer (JWD, Distromet RD-80) operated at the Indian Institute of Tropical Meteorology (IITM) in New Delhi revealed a total monsoon rain accumulation of approximately 543 mm in this region during the June to September period. Remarkably, a significant amount of this total, approximately 241 mm, occurred within the ten days of July 5-15, 2023, constituting nearly 45% of the entire monsoon rainfall. The repercussions of this extreme weather event included disruptions to social life, school closures, waterlogging, traffic jams, and vehicle breakdowns. The focus of this study is on the variability of precipitation microphysics and associated atmospheric anomalies that characterized this extreme downpour over Delhi. Despite minimal variation in the mean raindrop diameter between the extreme event days (July 5-15, 2023) and the overall monsoon period (June-September, 2023), a significant difference was observed in the raindrop size distribution (DSD) in terms of the liquid water content of the raindrops (Rakshit et al., 2024). The DSD during the extreme event days featured a higher mean liquid water content (LWC) of 0.48 g/m^3, significantly surpassing the monsoon mean of 0.26 g/m^3. Furthermore, Nw (m^{-3}mm^{-1}), the normalized intercept parameter indicative of higher LWC, was elevated during the extreme downpour days. Analysis of a fourteen-year (2009-2023) ERA-5 dataset revealed positive specific humidity anomaly over Delhi during the extreme rainfall episodes during July 5-15, 2023. Figure 1 (a) shows the occurrence of positive specific humidity (kg.kg^{-1}) anomaly that prevailed over the surrounding region of Delhi (indicated by red filled dot). The specific humidity (kg.kg^{-1}) anomaly is estimated at 850 hPa to reveal the enhanced moisture incursion for the extreme downpour. The study implicates the vertically integrated moisture transport (VIMT) up to 300 hPa, an atmospheric river phenomenon originating from the Arabian Sea, as a probable cause for the substantial influx of moisture over the Delhi region (Roxy et al. 2017). This urged us to investigate VIMT phenomena during the extreme downpour days. Figure 1 (b) reveals the signature of vertically integrated moisture transport surrounding the study location as obtained from the ERA- 5 dataset on 8 July 2023, as a representative case.

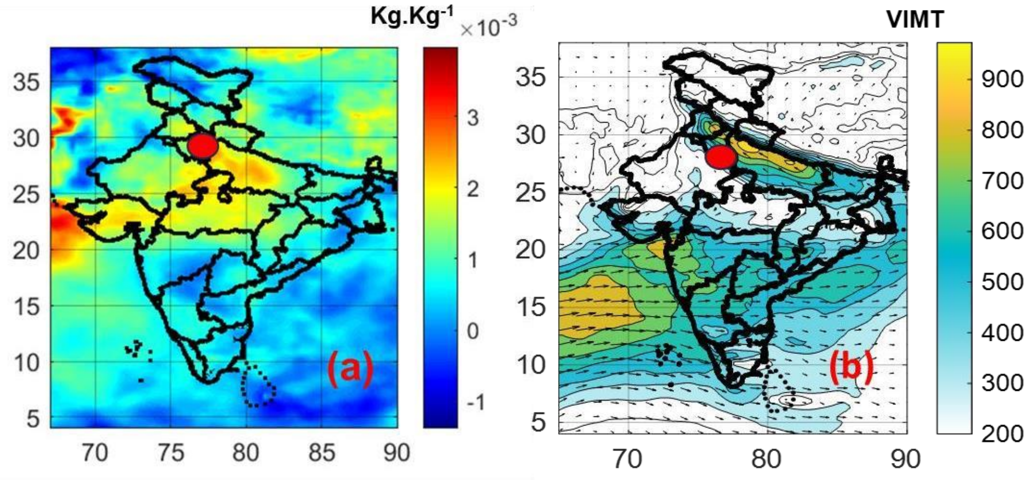

Fig. 1. (a) Spatial distribution of specific humidity ($kg.kg^{-1}$) anomaly at 850 hPa during intense downpour days (5-15 July) with respect to the monsoon period from 2009 to 2023. Here, a positive (negative) anomaly in specific humidity represents enhanced (decreased) moisture content. (b) Vertically integrated moisture transport ($kg \cdot m^{-1} s^{-1}$) up to 300hPa on 8 July 2023. The location of Delhi is indicated by a red-filled circle.

In conclusion, this investigation sheds light on the intricate interplay of precipitation microphysics, atmospheric anomalies, and moisture transport during the extreme rainfall events in Delhi, providing valuable insights for understanding and potentially mitigating the impacts of such extreme weather occurrences in the future. This study holds significance in contributing to the development of a regional climate model, specifically incorporating the associated atmospheric parameters linked to extreme precipitation episodes over a heavily polluted metropolis like Delhi, the capital of India.

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Multi-input Multi-output LSTM Model for Meteorological Parameters Prediction

Tanushree Roy[1], Uma Das[1], Oishila Bandyopadhyay[1], Dalia Nandi[1]

[1]Indian Institute of Information Technology Kalyani, Kalyani-751235, West Bengal, India

Extreme weather events include heat or cold waves, heavy precipitation and tropical cyclones, which causes damage to life and result in economic losses. In recent times, heavy and dense fog is also causing huge losses in the aviation sector as well as for other modes of transportation during winter time. Indira Gandhi International airport Delhi alone suffered economic losses of approximately 248 million Indian rupees due to a total of 653 hours of dense fog between 2011 and 2016. Road accidents only due to foggyand misty weather increased by 18% from 2021 to 2022, according to a report of the Ministry of Road Transport and Highways. In this work, we propose a deep learning model to predict foggy weather in winterover Northen India. A two- layer deep Long Short Term Memory (LSTM) model is developed to predict meteorological parameters that affect fog formation. India Meteorological Department (IMD) dataset for 2014-15 collected at Delhi (Safdarjung) station has been used for this work. From 8 different features in the dataset, 3 most important features - relative humidity, dry bulb temperature and vapour pressure – are chosen based on information gain and predicted for the short term. LSTM is a specially designed ANN forworking with sequential time series dataset. The proposed sequential model has two different layers of LSTM with different numbers of memory cells in it. Thus, during training of the model with all the important features, two levels of information and dependencies abstraction among the features from a smalldataset has occurred. After 100 epochs of training, the model is able to predict the previously mentioned parameters for next 9 hours with an average accuracy of 90% and average R^2 score of 80% with a noticeablelower mean absolute error (MAE). It is then verified whether these meteorological conditions are conducive for fog formation. The main challenge for fog prediction is it mainly depends on very short period changes in meteorological parameters that have non-linear dependencies. So, machine learning anddeep learning methods are proving valuable for such operational requirements.

Seasonal Characteristics of Convective Variables over the Indian Region

Athira Sasikumar[1] and Dr . Veena Suresh Babu[2]

[1] PG Department of Physics and Research Centre, MG College, University of Kerala, Thiruvananthapuram, 695004, Kerala, India.
[2] PG Department of Physics, All Saints' College, University of Kerala, Thiruvananthapuram,695007,Kerala,India.

The study explores the dynamic nature of atmospheric variables such as pressure, equivalent temperature, level of free convection and CAPE, emphasizing their relevance in understanding weather patterns and associated risks. Rising temperatures pose significant threats to human health, agriculture, and ecosystems due to increased heatwaves, water scarcity, and intensified meteorological events like floods andcyclones. The latitudinal variation of convective parameters refers to how certain atmospheric conditionssuch as temperature, humidity, and wind patterns change with latitude. Monitoring CAPE variations is crucial for predicting severe weather, issuance of warnings, and preparedness measures. The height of theLFC affects convection intensity, with higher LFC causing weaker updrafts and lower LFC resulting in stronger, more vigorous updrafts, contributing to more intense thunderstorms. In this perspective we havemade an attempt to analyse the seasonal variation of these parameters over the Indian region. In the present study we have made use of the data collected from Wyoming University archive for four stationsover Indian region (Chennai, Nagpur, New Delhi, and Kolkata) during the year 2022. Over the Indian region, latitudinal variation is influenced by geographical location and diverse topography.

It reveals that CAPE peaks during the monsoon and decreases in winter, while LFC peaks in post- monsoon in Chennai and Nagpur , and during the monsoon in New Delhi and Kolkata. Equivalent temperature peaks during the monsoon and declines in winter across all stations. The study highlights the counterbalance effect between CAPE and LFC during the monsoon, with increased CAPE indicating potential for severe weather events. Additionally, it suggests that local forcing plays a more significant role in Indian Surface Air Temperature (SAT) variability compared to remote impacts like ENSO(Elnino southern oscillation).

Identifying Thresholds of Thunderstorm Indices for Predicting Lightning Events Across India with WRF-ARW Model and ERA5 Reanalysis Datasets

Unashish Mondal[1], S. K. Panda[1], Anish Kumar[1,2], Devesh Sharma[1], and Someshwar Das[3] 1

[1]Department of Atmospheric Science, School of Earth Sciences, Central University of Rajasthan, Bandar Sindri, Kishangarh, District: Ajmer, State: Rajasthan, India (305817)
[2]Institute of Meteorology, Leipzig University, Leipzig, Germany
[3]South Asian Meteorological Association (SAMA), New Delhi, India

This study examines the utilization of various thunderstorm indices to predict the intense thunderstorms in Odisha on June 24, 2020, and Hooghly on June 7, 2021, during monsoon season in India. The Weather Research and Forecasting (WRF) model, utilizing the NSSL-17 double moment 4-ice microphysics scheme, has been operational for a period of 30 hours. The investigation analyses fifteen thunderstorm indices obtained from both the ERA5 reanalysis datasets and model-simulated datasets. The effectiveness of the forecasts relies on identifying the most suitable thresholds for each index. By incorporating thunderstorm indices with skill scores such as the Heidke Skill Score (HSS), Equitable Threat Score (ETS), and True Skill Statistic (TSS), the accuracy of severe thunderstorm predictions is enhanced. The study highlights the need of utilizing numerous indices instead of depending solely on a single metric to forecast severe thunderstorms. The Energy Helicity Index (EHI), Significant Tornado Parameter (STP), and Supercell Composite Parameter (SCP) are effective in predicting severe thunderstorms since they heavily depend on wind shears. The EHI (>1), and SCP (>=3.5), STP (>=1.2) along with low Storm Relative Helicity (SRH) at 3 km (100 m2/s2) has been utilized to predict the severe category of thunderstorms. In contrast, simplistic indices like Convective Available Potential Energy (CAPE), K Index (KI), and Virtual Total (VT) Index show strong forecasting skills for thunderstorms that are not in the severe category. The research evaluates the reliability of the numerical prediction model through the examination of model skill scores. The model performance demonstrates accuracy levels ranging from 60 to 80 percent. The integration of various thunderstorm indices by meteorologists enhances the accuracy of their forecasts, thereby enhancing the protection of individuals and assets. Further exploration in this area has the potential to enhance the precision and dependability of severe weather prediction models.

Keywords: Thunderstorm Indices, WRF-ARW, ERA5, Optimal Threshold, Model Skill Score

Dynamics of Extratropical-tropical Interactions: Eddy Feedbacks, Monsoonal Rainfall, and Extended Range Forecasting

Mahesh Kalshetti[1], Rajib Chattopadhyay[1,2], R Phani[1], Susmitha Joseph[1], and AK Sahai[1]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India
[2]India Meteorological Department, Pune, 411005, India

The interaction of two dynamically different regimes, i.e., extratropics and tropics, can alter mean-flow modulation mediated by transient eddies. The transient heat and momentum flux transport eddies introduce high- frequency forcing on relatively lower-frequency tropical mode. The resultant bidirectional transport can be interpreted as regional eddy forcing on the local time-averaged flow; such transport also causes regional departure from zonally symmetric large-scale circulation like Hadley-type circulation. This study discusses a primary quantification of spatial extent and temporal properties of extratropical transient eddies. A case study based on the 2013 Uttarakhand extreme rainfall event explores the interplay between anisotropic eddy shapes, meridional propagation, and their feedback on rainfall intensity, utilizing an E-vector approach. Findings reveal that extratropical Rossby wave intrusions and local factors like orography and moisture convergence enhance heavy rainfall. The general study adopts extratropical-tropical transport indices to quantify intrusion episodes over northern India. During the Indian summer monsoon, especially over the north Indian region, ~60% of rainfall events show no influence of extratropical intrusions, while ~40% of rainfall events are associated with the transient eddy feedbacks between MISO phases (tropical mode), and the zonal transport of wave number 7-8 pattern (extratropical mode). At 1-week lead periods, ERPAS and GloSea5 models are capable of forecasting the rainfall in northern India under the influence of extratropical transient eddies, but beyond that, their accuracy declines.

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Atmospheric Stability and Cloud-rain Characteristics during Pre-monsoon Precipitating Events Analysed using Ground-based Observations of a High-altitude site in Western Ghats, India

Leena P P[1], Resmi E A[2], Dhwanit J Mise[3], V Anilkumar[1], Arun V S[1], Rohit P Patil[1], and G. Pandithurai[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pashan, Pune 411008, Maharashtra, India
[2] National Centre for Earth Science Studies, Ministry of Earth Sciences, Thiruvananthapuram 695011, Kerala, India
[3] Department of Atmospheric & Space Sciences, Savitribai Phule Pune University, Pune 411007, India

The Indian subcontinent frequently experiences severe thunderstorms during the pre-monsoon season i.e., March, April, and May. Thunderstorms cause lightning, heavy precipitation, wind gusts, etc., affecting satellite launch operations, air transport, public life, etc. Thus, understanding its thermodynamic characteristics, cloud types and formation mechanism, precipitation etc. is essential as convection is often associated with these aforesaid processes. In this study, various characteristic features of pre-monsoon precipitating events over a high-altitude site, Mahabaleshwar (17.92ºN, 73.66ºE, 1348m above mean sea level) in Western Ghats, India have been analysed using co-located ground-based observations. Initially thermodynamic state of atmosphere during non-precipitating and precipitating event has been examined where rainfall or rain intensity (RI)=0 mm hr^{-1} as non- precipitating, 0 mm hr^{-1} >RI<10mm hr^{-1} as weak and RI> 10mm hr^{-1} for consecutive 10 min as strong precipitating day has been considered. Based on this criteria 26th March 2021 as non- precipitating, the 23rd of March 2021 a weak (01 mm rainfall) and 06th May 2021 a strong (23 mm rainfall) precipitating day is selected. Estimated various stability indices from the vertical profiles of temperature (T) and relative humidity (RH) from ground-based microwave radiometer (MWR) in addition to direct products such as vertical profile of vapour and liquid. A remarkable difference in the meteorological parameters (T and RH), equivalent potential temperature, stability indices (KI, TTI, HI), moisture (MR and vapour), and liquid are noticed from non- precipitating to a precipitating day. Though higher values in the stability indices were noticed during non- precipitating case there was a weak low level moisture convergence. During strong precipitating case clear changes in the meteorological parameters and most of the stability indices was noted in addition to strong low-level moisture convergence. Detail analysis of strong precipitating event using rain intensity from impact disdrometer, and radar reflectivity profile of micro rain radar confirmed that the event was a convective storm where the rain intensity > 20 mm hr^{-1} and reflectivity > 40 dBz was noted from 16:16 to 16:48 IST of 06th May 2021. Analysis of INSAT 3D brightness temperature showed (a) evolution and dissipation of clouds and (b) signatures of deep clouds over and nearby areas of the study region. Quantitative analysis of strong precipitating events (using 08 cases) showed higher moisture convergence and clear variation in the meteorological parameters. Sharp changes in most of the thermodynamic indices before, during and after the events was also noticed. Clouds with low bases was noted from Ceilometer observations just before the events. Cloud layer statistics extracted from ceilometer showed single-layer clouds of ~8% (20%) and double layer of ~ 42% (26%) before (after) the event. This study suggests that continuous monitoring of these indices can provide a good indication of convective activity and help in the operational forecasting of severe weather and thunderstorms.

A Study on the Thermodynamical Features of Precipitating Systems during Southwest Monsoon over Coastal station

Anusha Andrews[1,2], Sumesh R K[1,2], Resmi E A[1*], Nita Sukumar[1], Sumit Kumar[2,3]

[1] National Centre for Earth Science Studies (NCESS), Akkulam, Thiruvananthapuram - 695011, Kerala, India.
[2] Department of Atmospheric Sciences, Cochin University of Science and Technology, Kochi - 682016, India
[3]Indian Institute of Tropical Meteorology, Pune-411008
E-Mail: anusha.andrews@gmail.com

We examine the dynamical conditions for the formation of shallow, bright band and non-bright band precipitating systems formed at the coastal site, National Centre for Earth Science Studies (NCESS) (8° 31' 23.58" N, 76° 54' 34.32" E, 20 m above Mean Sea Level (MSL)) in Thiruvananthapuram using in- situ observations during the monsoon months (June-July) of 2022. The radar reflectivity and fall-velocity profiles from the micro rain radar and surface rain rate from disdrometer observations, are used to classify the precipitation as shallow, bright band (BB) and non-bright band (NBB) precipitating systems. It is found that shallow precipitating systems are identified throughout the season. The accumulated rainfall contributed by the BB is much greater than that of other precipitating systems. Analysed the variation of relative humidity, liquid water path (LWP), integrated water vapour (IWV) and cloud base height (CBH) before, during and after the precipitation using microwave radiometer. Shallow systems are mostly associated with low level clouds (0-2 km) and the BB and NBB precipitating systems are associated with mid-level clouds (2-4 km). The average IWV for before (during) shallow, BB and NBB is around 50 kgm^{-2} (60 kgm^{-2}), 80 kgm^{-2} (85 kgm^{-2}) and 55 kgm^{-2} (80 kgm^{-2}) respectively. BB systems are identified with precipitation lasting 30 minutes or more duration that was supported by humidity (> 80%) between 4 to 8 km, as well as high values of LWP and IWV in the atmosphere. The radar reflectivity profiles of both the BB and NBB extend over the melting layer, suggesting that both warm and cold rain processes are involved in rain formation. Systematic analysis on the role of upper tropospheric dynamical condition is important to the formation of BB and NBB precipitating systems.

Keywords: Relative humidity, Liquid water path, Integrated water vapour, Cloud base height.

Characteristics of Raindrop Size Distribution for Precipitating Systems over a Coastal region

Gadha Gopan[1], Resmi E.A[2], Sumesh R.K[2], Nita Sukumar[2] and Lekshmi Anilkumar[1]

[1] Kerala Agricultural University, Thrissur, 680656, India
[2] National Centre for Earth Science Studies, Thiruvananthapuram, 695011, India

An attempt has been made to classify stratiform, stratocumulus, and convective at a tropical coastal site based on (Zeng et al., 2020) method. The study utilizes four-year (2019–2022) observations of a 1-min, PARSIVEL disdrometer installed on the rooftop of NCESS, Thiruvananthapuram. Four-year data are categorized into three different seasons, namely: Pre-monsoon, Monsoon, and Post-monsoon. For the process of identification of the raindrop spectrum over the location, a modification was made to the methodology (Zeng et al., 2020). For each minute of data, the total number of raindrops should be greater or equal to 10 and the rain rate (R) >= 0.5mm/h for continuous-time (CT) of 10 minutes, is considered as one precipitation event. Mean rain rates and standard deviations were computed for each precipitation event. (i) The mean R $\geq$5 mm/hr and SD > 1.5 (ii) and R $\leq$5 mm/hr and SD < 1.5 are categorized as convective and stratiform rain respectively. All other events should fall under the category of stratocumulus rain. The drop size spectra for each type of rain were averaged to obtain composite drop size spectra. Classified events were compared with Micro Rain Radar (MRR) observations to validate the classification. To identify the deep convective systems over the coastal region rain rate is greater than or equal to 10mm/hr for a continuous time of 15 minutes or more considered a rain event and the total accumulated rainfall should exceed 10 mm, such events fall under the category of deep convective system. The study revealed that convective rain contributed the most rainfall across all the seasons and stratocumulus produced the least. Stratiform rain events produced more rain during the monsoon season. In all events, raindrop spectra are greater than 1 m^{-3} mm^{-1}, and the composite spectra display similar one-peak distributions. The maximum diameters of raindrops are approximately 3.25 mm for convective, 2.75 mm for stratocumulus, and 2.37 mm for stratiform clouds. Climate, atmospheric, and topographical variations cause noticeable temporal and spatial fluctuations in DSD (Tokay and Short,1996) and is important for understanding the microphysical characteristics of precipitating systems.

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Precipitation Microphysics and Variability during Tropical Cyclone over Southern India

Lekshmi Anilkumar[1], Resmi E. A[2], Sumesh R.K[2] and Nita Sukumar [2]

[1]College of Climate Change and Environmental Science, Kerala Agricultural University, Thrissur, 680656, India
[2]National Centre for Earth Science Studies, Trivandrum, 695011, India

A notable trend in Rapid Intensification (RI) of Tropical Cyclones (TCs) over the basin has been seen since 2000. The post-monsoon season has more RI (63%) and rapid decay (90%) cases (Nadimpalli et al., 2020). The majority of TCs achieve RI onset during their initial stage. The microphysics precipitation during the tropical cyclones in the pre-and post-monsoon seasons are studied. We have considered 12 cyclones formed in the Indian Ocean (Arabian Sea and Bay of Bengal) for the period 2017-2022. To examine the rain microphysics associated with the cyclone, rainfall from parsivel disdrometer installed at the coastal site (NCESS & ACARR) and elevated terrains (HACPO and BRM) are utilized. It has been noted that the maximum rainfall from the cyclones over the above-mentioned study locations received from the outer rainbands (approx. >500km) especially in the premonsoon season. The peak rainfall has been observed during Nisarga (86.91 mm) at the NCESS station in the pre-monsoon whereas cyclone Ockhi is registered with 173.89 mm at Braemore station in the post-monsoon season. Pre-monsoon cyclones are found to give more intense rainfall, nearly 3% more than post-monsoon cyclones for a shorter duration of time. The diurnal variation of DSD during the peak rainfall day of the cyclone indicates clear variations between elevated and coastal observations. The uniformly decreasing concentration from smaller-sized drops (0.3-0.6 mm) to larger drops is more evident in the elevated terrains (HACPO). The peaks in DSD concentration are mainly observed between the 0.4-0.6 mm diameter range in the elevated observation centres. Quantifying and analyzing the rainfall events during an extreme weather event like a tropical cyclone is crucial for representing the microphysical processes in mesoscale models and that helps for accurately predicting the rainfall evolved by tropical storms.

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Elevation-dependent Characteristics of Widespread Rainfall Extremes along the Western Ghats

Several recent studies have focused on understanding the rainfall trends over the Western Ghats (WG), situated along the west coast of India. However, there has been less emphasis on examining the spatial characteristics of atmospheric features linked to widespread and elevation-dependent extreme rainfall events in this region. This study aims to provide insights into this aspect. This study observes a rising trend in extreme rainfall events over the WG from the 1979–2020 period, consistent with earlier investigations. The extreme rainfall events on the windward side located below and above 500 m above sea level exhibit different background circulation signatures, such as mean wind speeds of low-level jets and moisture convergence. The extreme rainfall events seen below [above] 500 m above sea level occur in the backdrop of mesoscale [large-scale] monsoon circulation. The Froude number analysis revealed the significance of the topography of the WG foothills in enhancing the development and spatial distribution of extreme rainfall events. Therefore, the interaction of dynamics with the topography results in the induction of spatial segregation of extreme rainfall over the windward side of the WG.

Navigating Monsoon Extremes: Advancements in Weather Prediction

Mohd Akbar Ali[1] and Sudhir Kumar Singh[2]

[1]University of Allahabad, Prayagraj, 211002, India
[2]University of Allahabad, Prayagraj, 211002, India

The monsoon, a seasonal atmospheric phenomenon crucial for various regions worldwide, presents both life- sustaining rains and devastating weather extremes. As our understanding of the complex interactions between the stratosphere and troposphere deepens, advancements in weather prediction have become paramount. This abstract delves into the strides made in navigating monsoon extremes through cutting-edge prediction methodologies.

Drawing upon interdisciplinary research, this abstract showcases the fusion of atmospheric science, meteorology, and data analytics to forecast monsoon weather with unprecedented accuracy. Through the utilization of sophisticated numerical models, coupled with satellite observations and ground-based monitoring systems, researchers have honed their ability to anticipate the onset, intensity, and duration of monsoon extremes.

Furthermore, this abstract explores the role of emerging technologies such as machine learning and artificial intelligence in enhancing monsoon weather prediction. By harnessing vast amounts of data and leveraging computational power, these innovative approaches empower forecasters to discern subtle patterns and drivers of monsoon variability, thereby improving the lead time for extreme weather events.

Additionally, the abstract underscores the importance of international collaboration and data-sharing initiatives in advancing monsoon prediction capabilities. By fostering partnerships among meteorological agencies, research institutions, and policymakers, a global framework for monitoring and forecasting monsoon extremes is being forged, mitigating risks and enhancing resilience to weather-related disasters.

In conclusion, "Navigating Monsoon Extremes: Advancements in Weather Prediction" highlights the transformative impact of scientific innovation on our ability to anticipate and mitigate the impacts of monsoon weather extremes. Through ongoing research and collaboration, we strive towards a future where communities are better equipped to withstand the challenges posed by the dynamic nature of the monsoon climate.

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Understanding the Variabilities in Regional Hadley Cells

Pratiksha Priyam Baruah[1] and Neena Joseph Mani[1]

[1]Indian Institute of Science Education and Research, Pune, 411008, India

Several studies have reported a poleward expansion of the global HC in recent decades, which is attributed to global warming and natural variability. However, there is an apparent lack of consensus regarding whether the HC is strengthening or weakening. These observed changes in HC have the potential to induce substantial alterations in the global climate system, as observed in the poleward movement of jet streams, storm tracks and subtropical dry zones which leads to modifications in precipitation patterns, water availability in the subtropics and expansion of desert areas. Most of these studies have concentrated on studying the variability and trends in the strength and extent of the global mean HC, which may not often reflect the region-to-region differences in the HC. There are several unanswered questions pertaining to the characteristics of the various regional Hadley Cells. The present study aims to provide a comprehensive analysis of the regional Hadley Cells across six geographic domains.

Our analysis reveals very weak correlations among the different regional HCs, indicating a lack of synchronization and emphasizing the need to study the HC from a regional perspective. We have found that the Western Pacific HC and Indian Ocean HC exhibit the highest intensities and most poleward extent in both hemispheres. On the other hand, the Eastern Pacific HC and Atlantic HC shows lowest intensity and smaller extent. In the Indian Ocean, East Pacific, and Atlantic regions, the respective regional HCs tend to be considerably stronger in boreal summer (JJA) compared to boreal winter (DJF) , while for South America and West Pacific, the boreal winter (DJF) HCs are stronger than the boreal summer (JJA) HCs. This could be a reflection of the association with the regional monsoons. Surface temperature, convection and meridional temperature gradients were identified as the primary factors contributing towards the regional diversity and seasonality of HCs. Furthermore, the Madden-Julian Oscillation (MJO) alsoemerged as significant contributors to the interannual variability of regional HCs.

Spatiotemporal Variations of Recycled Precipitation over the Indian Sub-continent during Summer Monsoon

Rupali Bhangale[1] and Anandakumar Karipot[1]

[1] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, 411007, India.

The precipitation over a region contributed by the local evaporation/ evapotranspiration from the same region is known as recycled precipitation. It is often expressed as the recycling ratio, which is the fraction of the recycled precipitation to the total precipitation in the same region. The recycled precipitation has been reported as an important component of the continental precipitation, in several studies globally. The Indian summer monsoon season (JJAS) rainfall is primarily contributed by the moisture transported from the oceans surrounding the subcontinent. However, local evapotranspiration also plays an important role in modulating the subcontinental precipitation. The Indian subcontinent has large spatiotemporal variations in the rainfall during summer monsoon, due to varying topography and surface characteristics. The spatial rainfall patterns has also been reported to be varying in the recent decades, in association with the changing climate. The present study explores the characteristics of the recycled precipitation across the different regions of the Indian subcontinent. The dynamical recycling model (DRM) and the 2 Layer DRM are used for the calculation of recycling ratio. The datasets used for the study includes ERA5 and MERRA2 reanalysis datasets and IMD high resolution rainfall. The study also presents the role of land-surface and boundary layer processes in precipitation recycling and its spatial and temporal variations

Characteristics of Spectral Energetics During the Contrasting Indian Summer Monsoon Rainfall Years

Dhishana P R[1] and Sarvesh Kumar Dubey[1]

[1]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India

More than 80% of annual precipitation in India occurs during the southwest monsoon, which spans from June to September (JJAS). Significant spatial and temporal deviations from the seasonal mean rainfall, such as severe droughts (deficient rainfall) and floods (excess rainfall), have a major impact on agriculture, quality of life, and the economy of India. Also, Indian Summer Monsoon Rainfall (ISMR) variability (intra-seasonal, inter-annual, and inter- decadal) arises from nonlinear energy interactions among various atmospheric systems. This study so far explored the precise nature of complex nonlinear energy interactions of Low Pressure Systems (LPSs) and Intraseasonal Oscillations (ISO) with the seasonal meanflow and all other scales excluding the meanflow.

The analysis was conducted using high-resolution ERA-5 reanalysis daily data spanning from 1950 to 2021. This study focuses on the Monsoon Core Zone (15°-28°N, 67°-88°E) of the Indian subcontinent. We examined how these exchanges vary during the contrasting summer monsoon rainfall years. We found that the baroclinic conversion of Available Potential Energy (APE) to Kinetic Energy (KE) is the primary source of KE for the monsoon mean flow and LPS. On the other hand, the primary source of KE for ISO (30–60 day mode) comes from the meanflow. Furthermore, LPSs are modulated by the KE interaction with meanflow (0.61 W/m^2) and the baroclinic conversion of APE to KE (0.95 W/m^2) from the LPS scale. Also, ISO modulates meanflow by giving the KE which is received from all other scales. Overall, this study provides a comprehensive understanding of how the complex non-linear energy interactions are regulating the strength of the monsoon circulati

Representation of Cloud Cover and Precipitation along the Indian Region in Future Projections/Scenario's using CMIP6 Models

Praneta Khardekar[1], Rohini Bhawar[1, 2] , Hemantkumar S. Chaudhari[3], and Anupam Hazra[3]

[1]Department of Physics, Savitribai Phule Pune University, Pune, India
[2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India
[3]Indian Institute of Tropical Meteorology, Pune, India

The recent advancements in coupled ocean-atmosphere dynamical models mark a new era in seasonal prediction and the development of current-generation coupled models. Despite developments in CGCM's (Coupled General Circulation Models), depiction of clouds and Indian Summer Monsoon Rainfall (ISMR) along the South Asian region remains a grand challenge. The Climate Model Intercomparison Project Phase 6 (CMIP6) models offer a valuable opportunity to assess the performance of coupled models, both retrospectively and in future scenarios. This evaluation aims to enhance our understanding of the escalating warming and its implications for cloud dynamics, thereby influencing precipitation patterns. Best 10 models from CMIP6 historical simulations were selected on the basis of their ability to represent the annual cycle of rainfall, coefficient of variation along the ISM region. The pattern correlation, as determined, aligns with the observational dataset. Notably, the multi-model ensemble provides a more accurate estimation of total cloud cover compared to individual models. This observation has prompted us to anticipate diverse cloud covers, particularly high and low cloud covers, using CMIP6. In pursuit of this objective, models were selected based on their availability to represent distinct cloud covers, specifically low and high cloud covers. Within CMIP6, the depiction of high cloud cover in the Indian region during the Indian Summer Monsoon (ISM) is more accurate compared to low cloud cover. To understand the potential impact of these scenarios on cloud cover, different Shared Socio-economic Pathways (SSPs) were selected and analysed whose primary focus is on sustainability and reducing dependence on fossil fuels. The findings suggest an anticipated increase in total cloud cover in a future warming world, particularly along the coastal regions of India. This increase poses a potential threat, serving as a warning for future populations regarding water management challenges and associated crises.

Microphysics of Extreme Rainfall over Southern India Determined using the GPM-DPR

Amit Kumar[1,2,3, *], D. R. Pattanaik[1]

[1]India Meteorological Department, New Delhi
[2]Department of Geophysics, Banaras Hindu University, Varanasi, India
[3]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, New Delhi, India
[corresponding author: **amitkumar.jrf@tropmet.res.in**]

Indian monsoon season advances with the large-scale circulation, evidently affecting rainfall distribution over India. However, the dynamics and microphysical properties of extreme rain events in different seasons are still not clear. In this present study, we examined more than 1000 extreme rain events that occur in different seasons using the dual-frequency spaceborne precipitation radar observations installed on the Global Precipitation Measurement (GPM) Satellite. The extreme rain events defined based on the rain rate (R>10 mm/hr). The study period is from 2015 to 2021, and area of study is South India, consisting of the eastern and western coastal regions of India. The precipitation microphysics is determined using the precipitation efficiency index (PEI). The analysis shows both spatial and temporal variation in near-surface R, reflectivity (Z), and mass-weighted mean diameter (D_m) with PEI with respect to the topography and season. The mean of R and Z is larger for the convective precipitation than stratiform in each season. The concentration of bigger rain droplets (large D_m) is more in the case of convective precipitation, increasing with the PEI values. The number of extreme rain events is higher around the wind ward side of the Western Ghats than the Eastern Ghats of India. The mean value of D_m at near-surface increases with PEI and storm top height. High PEI values indicate a larger Z value and a significant concentration of bigger rain droplets. The contribution of the microphysical process above and below the bright band is distinct. Below the bright band, the break-up process is the primary microphysical process during the small PEI values. Meanwhile, at the time of large PEI value, the collision-coalescence process acts as a principal microphysical process. Further, it is observed that the contribution of various microphysical processes during extreme rain events varies with cloud type, topography, and season. The thermodynamic and dynamical properties have considerable influence on precipitation microphysics. The value of convective available potential energy (CAPE) and wind shear is different at times of extreme rain events in each season.

Keywords: GPM-DPR, extreme rain events, monsoon, microphysics

Precipitation Characteristics of Atmospheric Rivers using the Dual-frequency Precipitation Radar

Abhishek Gupta[1*], Amit Kumar[1,2,3], and Shivsai Dixit[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India
[2]Department of Geophysics, Banaras Hindu University, Varanasi, India
[3]India Meteorological Department, New Delhi, India
[*corresponding author: abhishek.gupta@tropmet.res.in]

Many studies point toward the significance of atmospheric rivers (AR) in maintaining accumulated rainfall at the regional level and global water cycle distribution. It is challenging to understand the complex processes of water vapour fluxes happening in the ARs over the oceanic region. Here, we study the precipitation microphysics of ARs over the Northern Indian Ocean during the monsoon season. Gridded rainfall data from the India Meteorological Department (IMD) and reanalysis datasets were used to find the ARs over the oceanic region. The dynamical and microphysical characteristics of the ARs around the study region are evaluated using the radar reflectivity from the dual-frequency space borne precipitation radar mounted on the Global Precipitation Measurement (GPM-DPR) satellite along with thermodynamical and kinematical properties using reanalysis datasets. The accumulated rainfall and frequency are predominated by the deep convective and stratiform precipitating clouds, respectively. The occurrence of shallow convective precipitation is equivalent to deep convective precipitation, while its mean intensity is notably low. It is also noticed that extreme rainfall is generally correlated with elevated storm top height, particularly during convective precipitation. The contour frequency with altitude profiles of radar reflectivity and drop size distribution (DSD) parameters varied across differences in precipitation intensities and cloud types (stratiform / convective precipitation). Furthermore, the relationship between the ARs total and large-scale circulation is determined by employing the Poisson regression model. The analysis revealed a significant positive (negative) dependency between AR occurrence and the Indian Ocean Dipole (IOD) & El-Niño (Southern Oscillation Index: SOI). A high frequency of AR events is linked to the larger IOD and El-Niño, while smaller SOI values are related to higher AR occurrences. The investigation demonstrated the significant influence of dynamical and microphysical processes on the evolution of AR.

Keywords: Atmospheric River, GPM-DPR, Northern Indian Ocean, precipitation

Synoptic and Large-Scale Drivers of Non-monsoonal Extreme Precipitation Events in the Indian Himalayan Region

Nischal Sharma[1], Raju Attada[1*], Kieran M. R. Hunt[2,3], and Mathew Barlow[4]

[1]Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Mohali, Punjab, India
[2]Department of Meteorology, University of Reading, UK
[3]National Centre for Atmospheric Science, University of Reading, UK
[4]Environmental, Earth & Atmospheric Sciences, University of Massachusetts Lowell, Lowell, MA, USA

E-Mail:nischalsharma@iisermohali.ac.in

Non-monsonal (wintertime) precipitation extremes over the western Himalayas (WH) induce widespread damage to life, infrastructure, environment, and agriculture. In the present study, we investigate the synoptic and large-scale drivers of these extreme precipitation events (EPEs; surpassing the 95th percentile threshold), primarily associated wih intense western disturbances (WDs). The findings indicate that the interplay of pronounced Rossby waves sinking over the region, coupled with regional orography, significantly contributes to occurrence of winter EPEs. Employing clustering analysis, we observed that the strongest EPEs are linked to anomalous vorticity in the upper to middle troposphere, together with deep convection via highly strengthened WDs, suggesting a potential role of large-scale influences. We further looked into the role of large-scale connections and EPEs through quasi-resonant amplification (QRA) analysis in the WH. The findings unveil the association of QRA with notably magnified, quasi stationary mid-latitude planetary waves characterized by wavenumbers ramging from 6 to 8 (notably baroclinic waves), contributing to precipitation extremes. Remarkably, distinct fingerprints of meridional temperature gradients, indicative of QRA, are linked to extreme events. Furthermore, this investigation discerns distinctive QRA patterns associated with varying clusters of extreme event intensities. Overall, our results emphasize the crucial role of QRA in amplifying planetary waves and promoting extreme precipitation in the WHR, underscoring the region's vulnerability to evolving climate conditions and providing insights into the underlying physical mechanisms.

Keywords: Precipitation Extremes, Quasi-resonant amplification, western Himalayas

Establishing a Multi-Hazard Early Warning System for Managing Foggy Winters to Thunderous Monsoons

A. K Mishra[1], C. N Prabhu[1,] Will Cheng[2], Stefano Alessandrini[2], and R. Kumar[2]

[1]Bihar Mausam Sewa Kendra, Patna, 800025, India
[2]National Center for Atmospheric Research, Boulder, 80307, USA

Bihar, characterized by its distinct geomorphic and climatic features, has been a region highly vulnerable to various hydro-meteorological hazards viz. floods, droughts, thunderstorms, heat waves, cold waves, fog etc with varied intensity. The analysis of historical weather data shows that Bihar is subjected to one or more Hydro-met hazards every month during a calendar year (Fig 1). However, the climate dynamics over Bihar is yet to be understood at micro-scale because the available historical data is too coarse in spatiotemporal resolution and insufficient coverage. As a result, there has been a large uncertainty in foreseeing the extreme weather events and its adverse impact on the state.

Now, Bihar has taken a big leap towards monitoring, forecasting, and generating early warning about any extreme event in the state. A multi-hazard early warning system supported with dense weather monitoring stations network up to Block / Panchayath level (cluster of villages), Multi-Model Ensemble (MME) weather forecasting system and Information and Communication Technology (ICT) enabled Information dissemination platform with last-mile connectivity. The high spatiotemporal resolution weather data collected through the network (96 data points / station /day form 534 Automatic weather Station (AWS) and 8298 Automatic Rain Guage (ARG)) is helping to understand the weather dynamics at both Macro and Micro- level, identify and map vulnerable areas with varied intensity. The indigenously developed AI-ML based web- applications for data and analysis and forecasting has enabled to foresee the extreme weather events with enhanced accuracy.

The paper will discuss about the novel Analog ensemble based (An-En) fog forecasting system developed and operationalised in Bihar. The system has been developed by training the model for 1 season and testing for 2 seasons. The efficiency of fog forecast system, tested during the winter 2023-24 in Bihar (Fig 1), is promising (probability of detection: improved by more than 75% by using An-En against default WRF) and would help in mitigating the hazardous impact of the winter fog in the entire Indio-Gangetic belt and elsewhere.

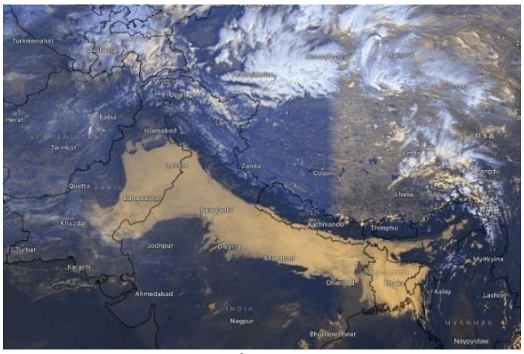

Fig 1: Winter Fog Observed on 14th Jan 2024 (source: EUMETSAT)

Variations in Large-Scale Circulations over the Indo-Pacific Region and Their Connection to the 2018 Kerala Extreme Rainfall Event

Roja Chaluvadi[1,2*], Hamza Varikoden[1], Milind Mujumdar[1] S. T. Ingle[2] and J.Kuttippurath[3]

[1]Indian Institute of Tropical Meteorology, Pashan, Pune-411008, India.
[2]Kavayitri Bahinabai Chaudhari North Maharashtra University, Jalgaon-425001, India.
[3]CORAL, Indian Institute of Technology Kharagpur, India
*rojachaluvadi.jrf@tropmet.res.in

In the present study we have investigated characteristics of extreme rainfall event (ERE) in Kerala (south western regions of peninsular India) during the month of August 2018. The changes in large scale circulations over the Indo-Pacific domain and their association with regional circulations, which results the extreme rainfall in Kerala are analysed. It has been observed that this ERE is accompanied with two extreme spells of rainfall during 8-10 and 14-17 August 2018 that made severe floods in Kerala. During this ERE, Kerala experiences excess rainfall of more than 80-100 mm day^{-1}, especially in the southern parts of Kerala. The triad (average of three days) analysis of vertical velocity at 500 hPa and moisture convergence at surface reveals the dynamic and thermal natures of the regional convective activity. The thermodynamic nature of the regional patterns of convection is modulated by large-scale circulations over the Indo-Pacific domain. A remarkable eastward shift of cross equatorial flow over the Indian Ocean produces an intense offshore vortex which induces more moisture towards Kerala, especially towards the southern regions. The west Pacific subtropical high (WPSH) is one of the large-scale circulations over the Indo-Pacific region, which shifts northward and the centre of WPSH extended towards western flank resulting cyclonic circulation over the northwest Pacific during the 2018 Kerala flood episode. The eastward shift of cross-equatorial flow over the Bay of Bengal, outflow from regional high over East Asian are mainly feeding to maintain the low-pressure system over the Bay of Bengal. The prominent cause of the extreme flood over Kerala in August 2018 is the deep moisture convergence through the offshore vortex, intense intrusion from subtropics and out flow from low-pressure system over the Bay of Bengal.

Severe Small-scale Storms in the Tropics and Subtropics

Achintya Paliwal[1,2], Vishal Dixit[1], and Martin Singh[2]

[1]IDP in Climate Studies, Indian Institute of Technology Bombay, Mumbai, 400076, India
[2]School of Earth Atmosphere and Environment, Monash University, Melbourne, Victoria, 3800, Australia

Severe convective storms are characterized by lightning, hail, gust fronts, and heavy precipitation, which can result in fatalities and property damage. A significant amount of literature involving observations, theory and modelling exists on storm characterization for the mid-latitude regions but a similar characterization for the tropics is currently lacking. The CMIP5- climate models typically run at resolutions (~100km) that cannot resolve small-scale storms (~10km). Using a high-resolution ERA5 dataset in this study we identify background environmental conditions (BECs) favouring the occurrence of severe storms over India. We study the seasonality of BECs and their association with the severity of storms. The accepted indicators of severe storms in the mid-latitudes namely convective available potential energy (CAPE) and vertical wind shear show skill in capturing the storm severity but do not capture the seasonality. Furthermore, we find that the definition of vertical wind shear-index needs to be modified to capture the seasonality in wind-shears during monsoons. The co-occurrence of lightning, hail, andprecipitation is also found to be critical to the severity of storms in the tropics.

Annual Climate Trends in North-East India: A Multisite Analysis

Rohit Gautam[1,2], Arup Borgohain[2], Binita Pathak[1], S.S. Kundu[2], and S.P. Aggarwal[2]

[1]Department of Physics, Dibrugarh University, Dibrugarh, Assam 786004, India
[2]North-Eastern Space Applications Centre, Umiam, Meghalaya, 793103, India

This study investigates the annual climate trends across 21 study sites in North-East India and contiguous areas. Using reanalysis datasets from the Indian Meteorological Department (IMDAA), we examine precipitation, temperature extremes, and related events. The study employs the Expert Team on Climate Change Detection and Indices (ETCCDI) criteria, analyzing trends at 5% and 1% significance levels using the Mann-Kendall (MK) and modified M-K (mMK). Additionally, change point analysis is conducted with CUSUM charts. Minimum temperatures exhibit significant annual increases across most locations. Maximum temperatures show a less pronounced trend. Indices related to warmer nights display greater significance. Annual precipitation generally showed declining trend, except for one location. Change points related to temperature shifts outnumbered those for precipitation. Indices such as SU25, TR20, TNx, TX90p, TN90p, TXn, and TNn shift from negative to positive, indicating a warming scenario. Conversely, indices like TXx, TX10p, TN10p, and DTR shift from positive to negative, suggesting warming dominance. Notably, precipitation extremes' patterns exhibit shifts, as seen in the case of CWD. The evolving climatic pattern may significantly impact human and natural ecosystems in the region.

Spatial Variation of Planetary Boundary Layer Height in Association with Rainfall over the Himalayan State Uttarakhand: A Study using IMDAA Reanalysis Dataset

V S Anjana[1] and Charu Singh[1]

[1]Marine and Atmospheric Sciences Group, IIRS, ISRO Dehradun, 248001, India

Himalayan foothills region is a topographically complex region which often experiences frequent extreme as well as heavy rainfall events during the south-west monsoon season. Topography of the region has a direct influence on various atmospheric parameters including Rainfall. Current study investigates the influence of Planetary boundary layer height (PBLH) on the observed distribution of rainfall over the Himalayan state Uttarakhand extending from the latitude 28° N to 32° N and longitude 77 °E to 82° E. Study analyses the seasonal and monthly climatology of PBLH in relation with Rainfall during monsoon season using IMDAA reanalysis data having a spatial resolution of 12 km and a temporal resolution of 1 hour for the period of 1989 to 2020. To find the influence of PBL height on rainfall distribution, study analyses the correlation between PBLH and rainfall using Pearson correlation coefficient. Study also analyses the diurnal pattern of rainfall and PBLH and their inter-relationship to understand about the Peak rainfall timings and the effect of PBLH on the formation of such peaks. Seasonal climatology shows low values of PBLH over the foothills region of Uttarakhand during monsoon season. Monthly climatology shows comparatively low values of PBLH during active monsoon months July, August, and September as compared to June. Peak rainfall locations are found to coincide with low PBLH. Correlation studies show significant negative correlation between PBLH Rainfall at 95 % confidence level over majority of the state. Diurnal pattern of PBLH and rainfall shows a negative phase relationship. Diurnal peaks of rainfall are mainly found over the locations where PBLH is low.

Keywords: Planetary Boundary Layer Height, Peak rainfall, Correlation coefficient, Diurnal pattern, Topography

An Investigation on the Prediction of Extreme Rainfall Events over Indian Peninsular Region during North-East Monsoon 2023

Shravan Kumar Muppa[1], D R Pattanaik[1], Pradeep Mishra[1], Satendra Kumar[1], and Mohapatra Mrutyunjay[1]

[1]India Meteorological Department, Mausam Bhawan, Lodhi Road, New Delhi - 110003, India

Extreme rainfall events occur over the south-eastern Indian peninsular region during the North-East monsoon season (October to December). These events are becoming quite common, especially over the state of Tamil Nadu in the recent years. These are also responsible for the loss of lives, livestock and cause extensive damage to the local infrastructure and economy. These extreme rainfall events need to be well predicted in advance to reduce the causalities and manage the economic losses. Two extreme rainfall case studies during the North-East monsoon of 2023 have been investigated in this study. In the first case, two districts of Tamil Nadu state, namely, Coimbatore and The Nilgiris have received extremely heavy rainfall of 370 mm and 240 mm respectively on 22nd November 2023. Several other stations in the districts of Ramanathapuram and Erode also reported heavy rainfall of 150 mm each for this case. This extreme rainfall event was associated with a Cyclonic Circulation over interior Tamil Nadu and adjoining Kerala in the lower tropospheric levels during this period. We also investigated the medium range operational weather forecast model from India meteorological department global forecast system (IMDGFS, T1534L64, 12 km) model forecasts and its performance for this case. While IMDGFS model forecasts indicated early signs of rainfall up to 170 mm for Day 3 and Day 4 forecasts respectively, the intensity got reduced to lessthan 100 mm for Day 1 and 2 forecasts. However, the peak extreme rainfall of above 200 mm was totally missing from the IMDGFS model forecasts in this case.

The Second case study was on 17th December, where the peak point rainfall in the districts of Thoothukudi and Tirunelveli was 950 mm and 610 mm respectively on a single day. A total of 39 stations have received rainfall of more than 200 mm for this case. Similar to previous case, IMDGFS has predicted extremely heavy rainfall of around 352 mm for Day 3 (72 hour forecast). Again, the intensity got reduced for day 2 and day 1 rainfall forecasts with 173 mm and 127 mm respectively. The above results suggested that IMDGFS model has underestimated the peak and intensity of rainfall for both the cases and also, as the lead-time for the extreme event approaches nearby, the model under-estimated the observed rainfall. However, the IMDGFS model rain forecasts for Day 3 and Day 4 were in better comparison with the observations than Day 1 and Day 2, which needs further more investigation. The dynamical aspects of reduction in model skill for day 1 and day 2 have been examined and will be presented.

Tropical Cyclone Track Prediction using a CNN-LSTM Model

Soumyajit Pal[1], Uma Das[1], Oishila Bandyopadhyay[1]

[1]Indian Institute of Information Technology Kalyani, Kalyani-751235, West Bengal, India

Climate change has increased the frequency of extreme weather events. These can be short-lived events like tropical cyclones (TC) and cloudbursts or long-duration events like temperature extremes leading to droughts. TC is the most destructive extreme weather event in terms of loss of lives and economic damage. Although climate change cannot be reversed, effects of cataclysmic events like TC, which are enhanced by climate change, can be minimized. This is possible if the movement of the TC path can be predicted with higher accuracy. With the increased availability of open-sourced satellite images from Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC), maintained by the Indian Space Research Organization (ISRO), under the aegis of the Government of India, deep learning (DL) techniques are being increasingly applied to the track prediction problem. The proposed work investigates the feasibility of predicting the track of TC with longer lead times, up to 72 hours, using satellite images. A hybrid Convolution Neural Network (CNN) – Long Short-Term Memory (LSTM) model is proposed for this purpose. The dataset consists of 62 storms spanning the period from 2013 to 2022. The CNN extracts spatial features while the LSTM extracts temporal features of the storms. This hybrid model is found to give good results in predicting the path of the TC. Further work is needed to improve the forecasts for longer lead times. This would truly establish DL models, such as the one proposed in this work, as powerful surrogates to the existing weather forecasting system and enable better management of the disaster.

Study of Satellite-Observed Extreme Lightning Events over Uttarakhand

Sanjeev Kumar[1*], Alok Sagar Gautam[1*], Karan Singh[1], Sunil D Pawar[2], A K Kamra[2], and Devendraa Singh[2]

[1] Atmospheric and Space Physics, Laboratory, Department of Physics, Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar Garhwal- 246174, Uttarakhand, India
[2] Indian Institute of Tropical Meteorology, Pune 411008, India
*E-Mail:sk8190179@gmail.com/phyalok@gmail.com

The spatial and temporal distribution of lightning events is crucial due to their potential to inflict damage on agriculture, forests, power networks, property, and lives (Zhang et al., 2011). We examined extreme lightning events in Uttarakhand using high-resolution Tropical Rainfall Measuring Mission Lightning Imaging Sensor (TRMM LIS) data during 1998 to 2013. The Standardized Lightning Index (SLI) was calculated to identify lightning hotspots. Moderate hotspots (SLI, 1-2) have observed in Uttarkashi, Dehradun, southern Pauri, and Nainital, while mild hotspots (SLI, 0-1) emerged in the middle Himalayan region, encompassing Chamoli, Haridwar, Almora, and Bageshwar. These findings underscore the concentrated lightning activity in the foothills of the Himalayas and the north-western region of Uttarakhand. The study highlights the significance of investigating topography's role in extreme lightning events and understanding lightning dynamics within the region. Western disturbances contributed 93% to lightning in the Himalayas, while Eastern India played a major role (43%) in tropical cyclonic storms (Unnikrishnan et al., 2021). This research enhances understanding of lightning in Uttarakhand, guiding the development of strategies to mitigate risks and improve safety.

Keywords: Standardized Lightning Index, hotspots, TRMM LIS, Uttarakhand

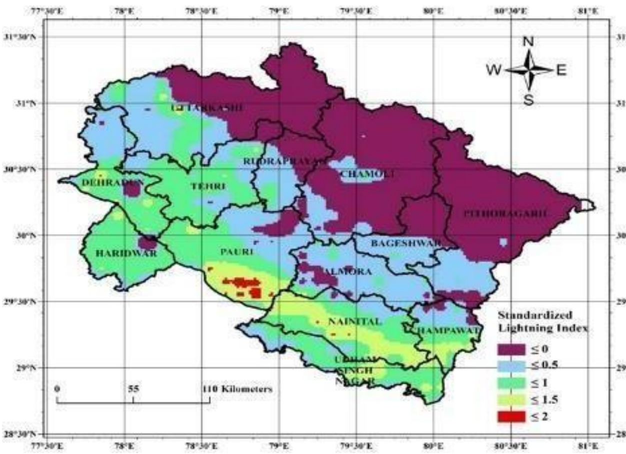

Fig. 1: The spatial variation of Standardized lightning index (hotspot) over Uttarakhand.

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Identification of Extreme Weather Event using Machine Learning and Artificial Intelligence Approaches over the Himalayan Region of Uttarakhand

Yasti Panchbhaiya[1], Alok. Sagar Gautam[1], Karan Singh[1], Sanjeev Kumar[1]; Aman Deep Vishwkarma[1]

[1]Atmospheric and Space Physics Laboratory, Department of Physics, Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar Garhwal, Uttarakhand -24746, India
E-mail:phyalok@gmail.com, panchbhaiyayasti@gmail.com

This study conducts a comprehensive examination of extreme weather phenomena in Uttarakhand, India, addressing the challenges arising from its intricate topography and irregular distribution of rain gauges. Weather data encompassing temperature, precipitation, wind speed, humidity, and atmospheric pressure play a crucial role in weather prediction and the training of machine learning models. Decision trees, random forests, and neural networks are employed to identify patterns associated with extreme weather events, with a particular emphasis on the unprecedented June 2013 rainfall event in the Western Himalayas (Kanga et al., 2022). Emphasizing the hydrological implications of such events, the study underscores the significance of precise rainfall predictions derived from satellite observations. Machine learning techniques, including neural networks and Support Vector Machines (SVM), are utilized to analyze various weather parameters and propose an artificial intelligence-based approach to predicting storm characteristics. Specifically, the Gated Recurrent Unit (GRU) model is employed to forecast storm characteristics such as wind speed, pressure, humidity, temperature, and wave height, with evaluation metrics attesting to its efficacy. The study highlights the effectiveness of the GRU model and SVM classifier in predicting storm characteristics, indicating the growing utilization of machine learning and deep learning models in forecasting extreme weather events (Frifra et al., 2022). It further explores the broader application of artificial intelligence in meteorological studies, emphasizing the continuous evolution and impact of cutting-edge technologies in enhancing predictions and understanding meteorological phenomena.

Keywords: Metrological Parameters, Deep learning, Machine learning, Gated recurrent unit, Support vector machines, Decision making

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Low Clouds over the Subtropical Indian Ocean and its Associations with Heavy Rainfall Events over India during the Indian Summer Monsoon

Gokul.T[1, 2], R.K. Vellore[1, 2], D.C. Ayantika[1, 2], R. Krishnan[1, 2], M.J.K. Reji[1, 2]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, 411008, India
[2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, 411008, India

Observational and reanalysis datasets show that periods of excess low clouds over the Subtropical Indian Ocean are associated with enhancements in the cross equatorial moisture transport and an active type large scale monsoon circulation over the Indian sub-continent on sub-seasonal time scales. The vertical profile of diabatic heating associated with the low clouds generates a dipole like structure in the Potential Vorticity field which thermally reinforces the Mascarene High. A component of cross equatorial flow enhancement that arises out of this reinforcement drives moisture transport from the subtropical south Indian Ocean through the Arabian Sea and Bay of Bengal towards the monsoon trough region which provides a favourable large scale set up that enhances the synoptic scale activity which is associated with heavy rainfall events in the vicinity of the monsoon trough region. This study shows that large scale moisture transport enhancements associated with excess low cloud periods plays a sizable role in modulating a component of the large scale moist circulation in the Indian monsoon region.

Study of Extreme Weather Events in the Central Himalayan Region through Machine Learning and Artificial Intelligence: A Review

Aman Deep Vishwkarma[1*], Alok. Sagar Gautam[1], Yasti Panchbhaiya[1], Sanjeev Kumar[1] , and Karan Singh[1]

[1]Atmospheric and Space Physics Laboratory, Department of Physics, Hemvati Nandan Bahuguna Garhwal University (A Central University), Srinagar Garhwal, Uttarakhand -24746, India
E-mail:phyalok@gmail.com, amandeep212241@gmail.com,

This review study focuses on various machine learning approaches for analysing extreme weather events in Uttarakhand, India, based on meteorological data and aerosol properties. Unforgettable major extreme weather events have been reported in Uttarakhand, such as the Kedarnath flash flood in 2013, and the Chamoli incident in 2020 (Pandey 2021; Naithani et al., 2011). We aim to acquire a comprehensive understanding of the incidents and attributes of extreme weather events in the central Himalayan Region. We employ cutting-edge methodologies, including Random Forest, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and General Regression Neural Networks (GRNN), specifically, we implemented a Random Forest model to predict rainfall events in the Srinagar Garhwal region, utilizing parameters such as temperature, humidity, wind direction, and wind speed. This model serves as an early warning system for environmental management and disaster preparedness. The model's efficacy was assessed through rigorous evaluation metrics, including the Mean Absolute Error (MAE), Coefficient of Determination (R^2), and Root Mean Square Error (RMSE). The Srinagar rainfall model, with 100 trees, demonstrated a delicate balance between complexity and performance, excelling with RMSE 2.74, MAE 1.39, and R^2 0.57. However, increasing the number of trees to 1500 reduced the performance and increased the errors (RMSE 3.02, MAE 1.54 & R^2 0.46). In future work, we plan to incorporate more ground-based and satellite meteorological data, including parameters such as solar radiation, pressure, dew points, and higher data resolution (1 minute) to enhance model efficiency. Additionally, we aim to apply SVM, ANN, and GRNN to further study extreme weather events over Uttarakhand. This interdisciplinary approach provides valuable insights into extreme weather patterns in Uttarakhand, contributing significantly to the understanding of extreme weather events in the central Himalayan Region. It supports efforts for sustainable environmental management and disaster resilience.

Keywords: Metrological Parameters, Central Himalayan Region, Random Forest Model, RMSE, MAE, FFNN, Learning models

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Unravelling the Dynamics of Boundary Layer Deepening: Insights into Rapid Intensification of Tropical Cyclone TEJ

Ravi Shankar Nemani[1], Sanjeev Kumar Singh[1], and Yogesh Kant[1]

[1]Indian Institute of Remote Sensing, Indian Space Research Organisation, 4-Kalidas Road, Dehradun, Uttarakhand - 248001, India

Rapid intensification (RI) of tropical cyclones (TCs) poses significant challenges for forecasters and disaster preparedness efforts due to its sudden and often unpredictable nature. The process of RI is closely linked to the deepening of the boundary layer, a critical component of TC dynamics. This research investigates the physical processes driving boundary layer deepening and its role in facilitating RI event in recent extremely severe cyclonic storm TEJ over Arabian Sea. Through a combination of observational analysis and numerical modelling, we elucidate the mechanisms responsible for the rapid enhancement of surface winds and pressure gradients within the TC boundary layer. Special attention is given to factors such as sea surface temperature anomalies, convective organization, and atmospheric stability, which can influence boundary layer dynamics and contribute to RI. This study aims to improve our understanding of the physical processes underlying boundary layer deepening, improve the prediction and mitigation of RI events, ultimately enhancing societal resilience to the impacts of extreme tropical cyclones.

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Characteristics and Projected Changes in Daily Maximum Precipitation Across the Globe

Nishant Uchale[1,2] and Bhupendra Bahadur Singh[2]

[1,2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University (SPPU), Pune-411007, India
[2]Indian Institute of Tropical Meteorology (Ministry of Earth Sciences), Pune-411 008, India

Research indicates a notable rise in extreme precipitation events across the globe in association with a warmed climate. A considerable chunk of such assessments focuses either on global land areas or specific regions, and have often been reported on an annual basis. However, it is crucial to note that significant monthly variations occur in the precipitation regimes, especially during seasonal transitions. This research evaluates the statistical characteristics of extreme precipitation globally in observations and Coupled Model Intercomparison Project Phase 6 (CMIP6) model projections. Our assessment focuses on daily maximums on an annual, seasonal, and monthly scale globally for both historical and future climate in the21st century. The historical assessment is conducted based on 1980-2014 period whereas the future climateis sectioned into, termed as Near Future (2040-60) and Far Future (2070-2090) focusing on two emission scenarios: SSP245 and SSP585. Monthly assessments of daily maximum precipitation indicate an expansion in the probability density curve's width starting from boreal winter season going into the peak- to-late summer season both in observations and model simulations. Future projections assessed based on multi-model mean, reveal a substantial rise in 1-day maximum precipitation in a warmer climate, particularly under the SSP585 scenario. The increase in daily maximum precipitation in both scenarios (SSP245 and SSP585) as compared to historical climate outweighs the decrease by about a factor of 1.5. Additionally, land regions are expected to exhibit more pronounced intensification in future, whereas the decline is mostly confined to sub-tropical oceanic regions.

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Role of North Tropical Atlantic in Modulating the ENSO-Indian Summer Monsoon Teleconnections

Ajinkya M. Aswale[1,2,*], Sooraj K P[1], Swapna P[1], Pascal Terray[3], Sandeep N[1,2]

[1] Centre for Climate Change Research, Indian Institute of Tropical Meteorology (IITM), Pune 411008, India
[2] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune 411007, India
[3] LOCEAN/IPSL, Sorbonne Universités (UPMC, Univ Paris 06)-CNRS-IRD-MNHN (Campus Université Pierre et Marie Curie), 4 Place Jussieu, BP 100, 75252 Paris cedex 05, France
* Corresponding author email id: ajinkya.aswale@tropmet.res.in

Recently, the North Tropical Atlantic Sea Surface Temperature (NTA SST) anomalies have received great importance as a prominent contributing factor to El Niño Southern Oscillation (ENSO) variability, thus emerging as a key-driver of the whole ENSO-Indian Summer Monsoon (ENSO-ISM) system. Against this backdrop, the current study aims to conduct a comprehensive analysis using observations, reanalysis, and long-term numerical simulations from the IITM Earth System Model (IITM-ESM), to have deeper insights on the role of the NTA SST variability on the ENSO-ISM teleconnections. Our results distinctly demonstrate the pronounced biennial nature of the NTA-ENSO-ISM system thus suggesting a crucial role of NTA SSTs in the biennial ENSO-ISM system. The ensembles of short coupled sensitivity experiments, by imposing observed warm (cold) SST anomalies over NTA, further highlight the key role of NTA SSTs in the reversal of the ENSO conditions through their capacitor effect. It further illustrates the nonlinear characteristics of this system as the cold NTA SST perturbations are more influential than warm NTA SSTs. This non-linearity brings up new perspectives on the NTA-ENSO-ISM system as it is further reflected in the asymmetric response in the simulated ENSO-ISM. These results have larger implications in a global warming future scenario, as the climate variability over NTA region is projected to intensify in the future

Understanding the Structural Changes and Inner Core Processes Involved in the Rapid Intensification of Amphan Super Cyclone using WRF Model Simulation

Ganadhi Mano Kranthi[1,2], Medha Deshpande[1], Emmanuel R[1,2], and S. T. Ingle[2]

[1]Indian Institute of Tropical Meteorology, Pune, Ministry of Earth Sciences, India
[2]School of Environmental and Earth Sciences, KBC North Maharashtra University, Jalgaon, Maharashtra, India

Rapid intensification is a pivotal process driving the development of intense tropical cyclones, yet understanding the associated structural changes remains a critical research gap, particularly over the North Indian Ocean. This study employs satellite data and the non-hydrostatic Weather Research and Forecasting (WRF) model at a cloud-permitting resolution (3 km) to investigate the intensification of Super Cyclonic Storm Amphan. Amphan originated as a depression on May 18th, rapidly (explosively) intensifying into an Extremely Severe Cyclonic Storm at 2100 UTC on May 17th, and eventually reaching Super Cyclonic Storm around 0600 UTC on May 18th, 2020. The cyclone exhibited the development of concentric double eyewalls during rapid intensification and experienced an eyewall replacement cycle from May 18th to 19th, 2020.

The simulated tropical cyclone track and maximum intensity reasonably match the IMD best track data. The model slightly overestimated the intensity and the intensification rate, particularly in the initial 48 hrs. The structural changes simulated by the model during the intensification are compared with CIMSS microwave brightness temperature data. Brightness temperature exhibits well-captured spatial structures in the model. Structural analysis of the simulation reveals that the tropical cyclone rapidly intensified during the formation of the eye and primary eyewall, followed by the development of a secondary concentric eyewall. The cyclone further intensified, reaching its lifetime maximum intensity as a super cyclonic storm. Subsequently, the primary eyewall dissipated, and the secondary eyewall radius decreased, leading to the replacement of the primary eyewall and eventual weakening of the cyclone.

These structural changes in the simulation qualitatively align with features visible in microwave satellite images. Future research endeavors will explore the role of inner core microphysical processes during these structural changes, contributing to a comprehensive understanding of the structural changes with intensification mechanisms of the Amphan cyclone in the North Indian Ocean.

Keywords: tropical cyclone Amphan, rapid intensification, eyewall replacement cycle, weather research forecast model, satellite data

Study of Himalayan Glaciers using Remote Sensing and Climate Model Projections and Associated Disaster

Protyusha Mukhopadhyay[1], T. P. Sabin[2], Swagata Payra[1] and A. P. Krishna[1]

[1]Birla Institute of Technology, Mesra, Ranchi, Jharkhand
[2]Indian Institute of Tropical Meteorology, Ministry of Earth Science, Pune

The Himalayan glaciers serve as pivotal indicators of the rapid escalation in global mean temperatures and the consequential impacts of global warming. This study elucidates the intricate dynamics governing these glaciers, characterized by the complex synergy between snow accumulation and glacier melt, which reverberates throughout the landscape, destabilizing the foundational aspects of regional stability. Recent disruptive events, including Glacial Lake Outburst Floods (GLOFs), underscore the vulnerability of populations inhabiting these rugged terrains, accentuated by the absence of predictive or early warning mechanisms.

Against this urgent backdrop, the study embarks on a meticulous expedition to unravel the temporal and spatial intricacies of Himalayan glaciers. Leveraging state-of-the-art remote sensing satellite data, the research scrutinizes three emblematic glaciers: Gepang Gath (lat: 32°31’7.13” N lon: 77°13’45.91” E) in the Western Himalaya, Gangotri Glacier (lat: 30°47’54.06” N lon: 79°9’15.21” E) in the Central Himalaya, and South Lhonak Glacier in the Eastern Himalaya. Through rigorous analysis, the study reveals a stark reality: Gepang Gath has experienced a retreat of 969 meters, Gangotri Glacier by 542 meters, and South Lhonak Glacier (lat: 27°55’36.17” N lon: 88°12’23.02” E) by a substantial 1209 meters over the past three decades (1990-2020).

Of particular concern are Gepang and South Lhonak Glaciers, where the presence of glacier lakes exacerbates vulnerability to the relentless impacts of climate change. Employing the predictive capabilities of CMIP6 model projections, the The study predicts an intensification of glacier melting and an elevated risk of GLOFs in the future. Such findings underscore the urgent necessity for comprehensive monitoring, predictive analytics, and robust warning systems to mitigate the escalating threats posed by Himalayan glacier dynamics.

Microlevel Study of an Assessment of Dry spell and Wet spell Analysis of Pune District Region, Maharashtra, India

Dr. Sapana Sasane[1]

[1]Department of Geography, Savitribai Phule Pune University, Pune, 411007. India.

The economy of Maharashtra is highly dependent on agriculture. Most of the annual precipitation is received through the Indian summer monsoon (Gadgil and Gadgil, 2006). Thus, Rainfall is an important factor that needs serious attention as Indian agriculture is drastically affected due to changes in rainfall patterns (Devdatta V. Pandit, 2016). Knowledge of the trend and variability of rainfall is essential to working out the supplemental water requirement of different crops during their critical growth periods. Changes in climate over the Indian region, particularly the SW monsoon, have a significant impact on agricultural production, water resources management, and the overall economy of the country. Any variation in climatic variables affects the crop growth stages thereby degrading the yield stability and quality. For the Pune district region, the daily rainfall data have been collected from the Indian Meteorological Department, Pune. Daily rainfall data archived for 13 tehsils (13 stations) for 41 years from the year 1980 to 2021. To characterize the rainfall variability pattern in Pune District Maharashtra, The study attempted to understand the rainfall initial probabilities of dry spells and wet spells and the Conditional Probability of dry spells and wet spells over the Pune district region during the study period (1980- 2021). The study also emphasized the advancement of SW Monsoon and the weekly distribution of rainfall crops and varieties needs to be selected by considering the probabilities of getting wet weeks in the future.

Keywords: Rainfall variability, Initial and conditional probability, suitable crop planning

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Investigations of Atmospheric Clouds and Boundary Layer using PRL's Indian Lidar Network (ILIN) Program: A Novel Perspective

Som Sharma[1]

[1]Physical Research Laboratory, Ahmedabad-380009, India
Email: somkumar@prl.res.in and sharmasomkumar@gmail.com

Atmospheric clouds are one of the vital components of the hydrological cycle and play important role on modulating Earth's radiation budget and also play an important role in the weather and climate of the earth-atmosphere system. Understanding of the vertical distribution of clouds, their properties, and temporal evolution are essential for understanding the origin and impact of clouds and their feedback on the above-mentioned processes and their parameterization in weather and climate models for improving forecast. Atmospheric Boundary Layer (ABL) characteristics lies in their direct and indirect influence on living beings and the environment and it work like packing volume of most of the pollutants. Understanding ABL characteristics, and ABL-clouds interactions along with pollutants is essential for improving weather forecasting, air quality management, climate modeling, and many more atmospheric processes. This study deals with the investigation of Cloud characteristics, ABL dynamics and pollutants using lidars operating under the Physical Research Laboratory's Indian Lidar Network (ILIN) Program over the Indian region. Ground- based observations using ceilometer lidar show a prominent diurnal variation of ABL, with summer boundary layer height (BLH) exceeding the winter BLH by 1-1.5 km. The substantial variation in surface fluxes during the two seasons drives these differences. During the onset of monsoon, the ABL is thicker compared to active monsoon. The seasonal variation of BLH is crucial for several environmental aspects. Further, we have investigated the role of dust storms on the Clouds and ABL over an urban location in Western India. The characteristics of cloud base height and modulations in the ABL over a hilly remote station in northeast India are also investigated. The accuracy of reanalysis datasets in representing the boundary layer over the Western- Indian region has been assessed using observations from ILIN. The reanalysis datasets show less than 1 km differences from the ground-based lidar observations. However, the performance of reanalysis in representing BLH has a seasonal dependency. Satellite observations overestimated the observed BLH. Therefore, it is essential to monitor the Clouds and ABL using ground-based instruments continuously covering different regions and seasons. A good network of ground-based lidar observations of clouds and ABL along with other atmospheric parameters provides ground-truth inputs for weather and climate models. This will further help in improving weather forecasting, air quality management, and climate predictions over the India region.

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Influence of Southern Hemispheric Upper Troposphere Potential Vorticity Intrusion Events on the Southwest Monsoon Rainfall

Sandhya, M[1,2,3], and S. Sridharan[1]

[1]NARL, Gadanki, India
[2]Providence Women's College, Calicut, India
[3]Now at NCMRWF, New Delhi, India

The possible influence of potential vorticity (PV) intrusion events in the southern low-latitude upper troposphere over the longitude region 0-90°E during June-September on the southwest monsoon rainfall (SWMR) over India is investigated using ERA-interim potential vorticity data and high resolution gridded IMD (India Meteorological Department) rainfall data. It is found that unlike in the northern hemisphere, the PV intrusion events are more frequent in the southern low-latitudes in the longitude region 0-90°E during June-September and they are present irrespective of the phase of the El Nino Southern Oscillation (ENSO). More PV intrusion events into the southern hemispheric low-latitude upper troposphere are observed during the negative SWMR anomaly years. The cross-equatorial flow is observed to be weak during intrusion events. The deep penetration of PV into the lower troposphere in southern hemisphere reverses low-level wind direction from north to south during or the next day of the PV anomaly events. This reversal of low-level wind leads to a break in the SWMR, which can be inferred from the positive time mean removed OLR (>10 W/m^2) during high PV event days. It is suggested that the reversal of low-level wind induced by PV intrusion event may have prevented moisture transport to India, resulting in break spell and hence reduced rainfall.

Simulation Studies on Hydro-meteorological Response of Extreme Monsoon Rain Events over Elevated Region of Western Himalaya

P Priya[1], R Krishnan[1], M Mujumdar[1], T P Sabin[1], T Pascal[2], R Houze Jr[3,4]

[1]Indian Institute of Tropical Meteorology, Pune, India
[2]Institut Pierre Simon Laplace (IPSL), Sorbonne Universites, France
[3]University of Washington, USA
[4]Pacific Northwest National Laboratory, Richland, Washington

The present study investigates regional and global circulation patterns, long-term changes, and hydrological repercussions associated with heavy monsoon rain events over northwest India. Initially, a series of high-resolution Atmospheric General Circulation Model experiments were conducted to comprehend the influence of tropical sea surface temperature anomalies on the occurrence of heavy monsoon rain events over the India-Pakistan region during 2010. Our analysis reveals the prominent role of intrinsic Indian Ocean variability in amplifying and sustaining heavy rainfall events over the northwest India-Pakistan region, against the backdrop of modulated Walker circulation due to prevailing La Niña conditions over the East Pacific. Further analysis, using historical rainfall records, indicates an increase in the occurrence of heavy monsoon rain events over elevated regions of northwest India. Our investigation using multiple datasets, elucidates the combined effect of weakened monsoon circulation, increased transient trough activity over the region, and enhanced moisture supply from the Arabian Sea as the causative factors for the occurrence of these events. Additionally, ensemble hydrological model simulations were also conducted using the macro-scale Variable Infiltration Capacity hydrology model to understand the hydrological response of these events at the river basin scale. While heavy monsoon rain events were responsible for the 2010 Pakistan flood conditions, our results also emphasize the importance of regional surface air temperature in seasonal river discharge over the region.

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Study of the Driving Mechanism of the Flash Drought in the Indian Region

Arya V.B.[1], Prasanth A Pilla[1]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India

Flash drought, a relatively recent extreme phenomenon, is often viewed as a component of seasonal drought occurrences. The primary drivers behind the rapid development of flash droughts are an abnormalrise in temperature and insufficient precipitation. Various approaches and indicators have been employed to examine flash droughts in India. The association between soil moisture and temperature, known as land-atmosphere coupling, has been recognized as a crucial element that affects the severity of flash droughts. These droughts may potentially escalate in magnitude in the face of anticipated climate warming. Flash droughts exhibit rapid intensification immediately following their initiation, leading to significant short-term consequences for agricultural activities and the wider ecosystem. However, the factors that contribute to the occurrence of sudden and severe flash droughts in India, particularly those associated with atmospheric conditions; have yet to be thoroughly investigated. In the present investigation, we analyze various observation-based reanalysis datasets and climate model data to identify flash drought occurrences during both the summer monsoon (June-September) and non-monsoon seasons (October-May). Moreover, we will examine the atmospheric variables that instigate the onset of flash droughts in India. Our findings indicate that the majority of flash drought occurrences during the monsoon breaks take place during the summer monsoon season. Conversely, only a small proportion of the total flash droughts are observed in the non- monsoon season. This work will elucidate the seasonal dynamics and atmospheric mechanisms driving flash droughts. Our study indicates that along with the changes in precipitation and temperature, atmospheric circulation induced dynamical processes are also plays major role in the flash drought during monsoon season. These dynamical processes can lead to predictability signal for these events also. The findings of this research are of utmost importance as they provide valuable insights for enhancing the ability to predict flash droughts in climate models. Additionally, these insights can contribute to the development of effective strategies for mitigating the impact of flash droughts and managing resources in India.

Insights into Extreme Weather Patterns: Exploring Precipitation Dynamics in the Central Himalayan Region Through Radar Observations

Samaresh Bhattacharjee[1], Manish Naja[1] and Kishan Singh Rawat[2]

[1]Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, Uttarakhand, India
[2] Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India

Several extreme weather events have been observed in the Himalayas, including of heavy precipitation. These heavy precipitations are also strongly influenced by the complex topography in the Himalayas, leading to localized weather systems. When moist air encounters a mountain barrier, orographic lifting forces it to ascend, leading to condensation cloud formation and prolonged and intense precipitation. Mountains can also disrupt prevailing wind patterns, causing air masses to converge and rise and enhancing precipitation. Additionally, atmospheric circulation patterns influenced by mountains can amplify precipitation intensity by converging moisture-laden air masses. This study presents the atmospheric processes behind extreme weather events from 2020 to 2022 due to heavy precipitation in Nainital, Uttarakhand, during the pre-monsoon, monsoon, and post-monsoon periods. We utilize the atmospheric wind data from ARIES Stratosphere Troposphere Radar (ASTRAD), situated at ARIES, Nainital (29.4N, 79.5E, approximately 1800 meters above sea level) in the central Himalayas. With its 588-element active phased array installed on a rooftop, this radar system is the first of its kind in the central Himalayas, operating at a frequency of 206.5 MHz in the VHF band. Its sensitivity to Bragg and Rayleigh scattering enables it to provide high-resolution data on wind patterns and precipitation components across all weather conditions. Nainital, located within the central Himalayan region and in the northern part of the monsoon trough, experiences low-level southeasterly winds during the monsoon while encountering western disturbances in the winter and spring months. In addition to the wind data, the Automatic Weather Station (AWS) measurements are used to understand ground conditions during such events. During the monsoon events in August 2020 and July 2022, dominant southeasterly and easterly winds were identified at 8-10 km altitudes, with speeds averaging 8-10 m/s. Sudden updrafts and downdrafts observed during the July event coincided with heightened afternoon solar radiation. The turbulent motion extended up to approximately 15 km altitude, with updraft speeds reaching ~1 m/s and downdraft speeds hitting 3.5 m/s. Analysis of the wind patterns preceding heavy precipitation events in 2021, during pre-monsoon (May) and post-monsoon (October) periods, revealed consistent dominance of southwesterly winds and interaction between upper-tropospheric westerly and lower-tropospheric easterly winds. HYSPLIT back-air trajectory analysis traced the origin of this air mass. Additionally, analysis of the Doppler spectra (Rayleigh) of precipitation pinpointed a notable change in velocity at ~ 5.5 km altitude, characteristic of the stratiform region associated with widespread precipitation. Understanding these intricate, atmospheric processes is vital for predicting and mitigating the impacts of such events in the Himalayan region, where cloud bursts and severe damage are frequent. Detailed results will be presented in the upcoming conference.

Assimilation of Weather and Ecological Responses to Explore the Extreme Weather events

Sanjeev Kimothi[1*], Sameer Rawat[1], and Asha Thapliyal[2]

[1]Department of Physics, Graphic Era deemed to be University, Dehradun, 248002, India
[2]Uttarakhand Space Application Centre (USAC), Dehradun, 248001, India

Weather Research and Forecasting (WRF) models based on a numerical weather prediction (NWP) and atmospheric simulation methods are highly sophisticated and its performance relies on the spatial and temporal resolution datasets. In the proposed study Stochastic and Radiative transfer (RT) approaches have been employed to assimilate the weather and ecological responses in different temporal and spatial resolution. The time series data for both vegetation indices, i.e., NDVI and EVI, is acquired from MODIS Terra and Aqua satellite data. The climate parameters are collected using several GEE datasets for the period of 40 years from 1980 to 2022. The data with different temporal scales is then transformed into monthly scales. The processing phase of this research uses the JavaScript programming language. The weather variables i.e., Air temperature (T), Precipitation (Pr), Wind velocity (W), and Relative humidity (Rh) are critical parameters to identify and forecast the extreme weather events over a spatio-temporal resolution. The weather indices i.e Hurst coefficient (H), predictability (PI), and Fractal dimension (FD) are estimated on different temporal and spatial resolution with Multifractal approach. The responses of H, PI, and FD are observed with ambiguities with NDVI, EVI, and UHI and weather parameters are found within predictable ranges and are indicates towards increasing heat indices under studied spatial resolution. This increasing heat index indicates warming trend with decreasing NDVI and EVI which may cause heat-waves and hence affect the weather pattern in long-term. Examined physical approaches demonstrated strong correlation of weather and ecological parameters that can be highly effective in long term weather events predictions. The spatial-temporal consequences of the changing climate during the past 40 years in the Himalayan region are examined using the MFDFA. A multifractal exponent correlation analysis revealed that there was a positive association and a negative correlation between LST and NDBI and NDVI, EVI and NDBI, respectively. Over the past three decades, the vegetation profiles have decreased, as indicated by the NDVI pattern. Both climatic variables and topographical modifications have an impacton the spread of UHIs and hence may impact on local weather conditions. More proof of the changes in the forest and landscape pattern can be seen in the region's irregular precipitation pattern. On the basis of ambiguities among the self symmetric patterns and long term behaviours the extreme weather events are marked successfully. The multifractality among wind patterns and land surface air temperature shows a positive association during these weather extreme events.

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South Asian Summer Monsoon under Stratospheric Aerosol Intervention

A. Asutosh [1,2] and Simone Tilmes[2]

[1]Indian Institute of Technology, Bhubaneswar, Odisha, India
[2]Atmospheric Chemistry, Observations, and Modeling Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

The South Asian summer monsoon (SAM) bears significant importance for agriculture, water resources, economy, and environmental aspects of the region for more than 2 billion people. Understanding monsoon variability is essential for sustainable development and disaster preparedness in South Asia. The continuing global warming trend due to climate change will likely lead to more irregular precipitation patterns with an increasing risk of flooding and drought. To minimise the impacts of global warming, Stratospheric Aerosol Intervention (SAI) might lower temperatures by reflecting some percentage of solar energy into space. However, the effects of SAI on SAM, especially on hydrology, are still very uncertain and demand more research. Using multi-ensemble members from the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) datasets, we have investigated the possible changes in SAM and associated mechanisms. For this study, we use the period 2010–2030 (referred to as CTRL) with two future scenarios (for the period 2070–2090) referred to as RCP8.5 (business as usual scenario) and SAI (Stratospheric Aerosol Intervention). Our study reveals a reduction in mean and extreme summer monsoon precipitation for SAI compared to RCP8.5 and CTRL. SAI results in a weakening of the northern hemispheric subtropical Jetstream by heating the lower tropical stratosphere. The effects further translate to the change in upper tropospheric wave activities. We observe a strong relationship between the SAI-induced phase of wave activities, geopotential height anomalies, the strength of the Asian Monsoon Anticyclone, lower atmospheric pressure, and wind circulations. All these changes play a decisive role in lowering summertime SAM rainfall over the core monsoon region. The local change in dust, which is important for SAM rainfall variability and climate change, seems to play a minor role in SAI. Results from similar model experiments using a newer model version also support our findings.

Keywords: Monsoon, Stratospheric Aerosol Geoengineering, Jet stream, Wind circulation, extreme precipitation

Rainfall Amplification over Western India in a Warming Climate: An Indian Ocean Dipole Perspective

Sumit K. M.[1,2], Ayantika D. C.[1,2], R. Krishnan[1], and R. Vellore[1]

[1] Indian Institute of Tropical Meteorology, Pune, 411008, India
[2] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, 411007, India

Over the past few decades, the Indian summer monsoon (June–September) has been exhibiting a prominent increase in deep convection and extreme rainfall in its western sector. Using observational datasets and Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations, we explore the coupled large-scale ocean-atmospheric associations favourable for the development of heavy precipitating systems over Western India in a warming climate. Our analysis reveals an uptrend in heavy rainfall days across Western India since the late 1990s, largely coinciding with positive Indian Ocean Dipole (pIOD) years. Notably, the year 2019 witnessed the highest instances of heavy rainfall in a century over Western India during the monsoon season (Ayantika et al., 2024). Analysis of station rain gauge data from Gujarat and western Maharashtra illustrates that widespread heavy rainfall in this region primarily came from three intense rain episodes in the backdrop of intense pIOD conditions evolving at the equatorial Indian Ocean since late June. The continual top-heavy stratiform heating from the organized convective systems reinforced high mid-tropospheric potential vorticity with the maximum over western India and an associated giant cyclonic vortex stretching across South and Southeast Asia. The pIOD-induced strong zonal sea surface temperature (SST) gradient at the equatorial Indian Ocean forced anomalous cross-equatorial moisture transport and was vital in fostering deep convection and heavy precipitation in western India. Upon Helmholtz's decomposition of moisture flux anomalies, we note that the area of intense divergence over the southeast equatorial Indian Ocean feeds excess moisture to western India during the pIOD years. We find a 25% increase in the spatiotemporally aggregated rainfall over western India contributed by the heavy rainfall events for the pIOD seasons as compared to the non-pIOD seasons in the past sixty years. Projections from selected CMIP6 models indicate a pIOD-like future SST warming pattern in the tropical Indian Ocean and a marked increase in projected monsoonal rainfall over Western India in the late 21st century following the Shared Socioeconomic Pathway 5-8.5 (SSP585) scenario. This anomalous SST gradient-driven enhanced cross-equatorial moisture transport triggers stronger deep convective ascent along the Indian west coast leading to the increase in heavy precipitation. This study highlights the repercussions of intense pIOD manifestations in the increasing occurrences of hydrological extremes in Western India in the 21st century.

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Role of Equatorial Waves in Rainfall Extremes over Southern Peninsular India: South Tamil Nadu (A Case Study)

Piyush Ahire[1], Medha Deshpande[1], Emmanuel Rongmie[1, 2], and Ganadhi Mano Kranthi[1, 2]

[1]Indian Institute of Tropical Meteorology, PUNE, 411008, India
[2]KBC North Maharashtra University, JALGAON, 425001, India

Extreme rainfall events cause tremendous damage to the livelihoods of people in the area. Convectively coupled equatorial waves are known to play a major role in organizing mesoscale convective systems (MCS) that lead to these extreme rainfall events. Accessing the impact made by these waves on extreme rainfall events is crucial for predicting these events and taking the necessary measures. This intrigues us to explore the role of Equatorial waves on extreme rainfall events for the case 17-18 December 2023 (TN Extreme Heavy Rainfall Event) that records 932 mm of rain in 24 hours by rain gauge station Kayalpattinam. This event contribute 4.5 times the rainfall as categorized by IMD as Extremely heavy rainfall (i.e., rainfall is equal to or greater than 204.5 mm in 24 hours). During this time, the Northeast monsoon (October - December) is in its active phase with the presence of ITCZ. In past studies, it has been well-established that NWP models have difficulties simulating convective parameters, i.e., rainfall. In contrast, NWP models have better skill in simulating dynamic parameters such as wind, temperature, or geopotential height. In this study, an attempt has been made utilizing IMDAA/NGFS reanalysis data to derive equatorial waves using dynamic parameters and compare that with the waves derived from OLR and rainfall (convective parameters). We also investigated the role of waves in modulating MCS leading to these extreme events. In future we will evaluate the skill of the operational GFS in predicting the equatorial waves and associated extreme rain events.

Midlatitude Role in Decadal See-saw of East-West Dipole in Indian Summer Monsoon

Shikhar Srivastava[1] and Arindam Chakraborty[1,2]

[1]Centre for Atmospheric and Oceanic Science, Indian Institute of Science.
[2]Divecha Centre for Climate Change, Indian Institute of Science

The Indian Summer Monsoon Rainfall (ISMR) exhibits prominent spatio-temporal variability ranging from the diurnal to the centennial timescales. During recent decades, ISMR has shown preferred variationsin two of the most populous regions of our country. While the regions close to the Himalayan foothills show a sharp decline, the regions over west-central India are experiencing more than average rainfall. Here,we identify this observed rainfall pattern as the second leading mode of rainfall variability over India (8°N-30°N, 70°E-90°E) with the dipole of opposite polarity sitting over Gujarat and Central north-east India (CNE). The observed spatial pattern exhibits a significant decadal cycle. The physical mechanism leading to the observed dipole pattern is a prominent decadal variation in the temperature over the midlatitude regions of central Europe and Asia. Strong barotropic atmospheric heating at these locations weakens the upper-level jet stream and shifts it southward of its climatological location at its eastern flank. This forces a low-level anti-cyclonic circulation over CNE, which inhibits the intrusion of the low-level monsoon jet towards central India. This, along with significant low pressure over the north Arabian Sea, creates favourable conditions for monsoon rainfall over Gujarat and persistent below-average rainfall over CNE. Our study shed light on the role of inherent low-frequency climate variability in driving the observed trend in rainfall over these two regions.

Keywords: Indian Monsoon, Decadal climate variability, Tropical-extratropical interaction.

Abrupt Global Warming, Warming Trend Slowdown Thereafter and Associated Indian Summer Monsoon Behaviour

Indrani Roy (Indrani.roy@ucl.ac.uk)[1]

[1] University College London (UCL), London, Department of Earth Sciences, WC1E 6BT, UK

This study addresses abrupt global warming in later two decades of the last century and a slowdown thereafter that happened in first two decades of the current century. It separated the role of anthropogenic CO2 led linear trend to that from natural factors (volcano and the sun). It segregates a period 1976–1996 where two explosive volcanic eruptions occurred in active phases of strong solar cycles and also the period covers two whole solar cycles. That same period coincided with abrupt global warming. This study suggests that domination of a particular type of ENSO, the Central Pacific (CP) type ENSO and related feedback from water vapour played a crucial role. A plausible mechanism was proposed that could be triggered by explosive volcanos via a preferential North Atlantic Oscillation (NAO) phase. It modulates the CP ENSO via extratropical Rossby wave and affects the Aleutian Low. From that angle, it is possible to explain the disruption of ENSO and Indian Summer Monsoon teleconnection during the abrupt warming period and how it recovered subsequently afterward. Interestingly, individual models and also the CMIP5 model ensemble fails to agree with the observation. This study further explores important contributions due to natural drivers those are missed by models.

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Structure and Evolution of Mesoscale Convective Systems and Embedded Storms in the Monsoon Core Zone using Satellite and 3D Radar Data

Manisha Tupsoundare[1, 2], Sachin M. Deshpande[1], Zhe Feng[3], Subrata K. Das[1], Medha Deshpande[1], and Harshad Hanmante[1]

[1]Indian Institute of Tropical Meteorology, Pune, India
[2]Savitribai Phule Pune University, Pune, India
[3]Pacific Northwest National Laboratory, Richland, WA, USA

Mesoscale convective systems (MCSs) are the largest type of deep convective storms. They form when convection aggregates and expands upscale, interacting with many storms to produce unique mesoscale circulations. MCS can be categorized into leading-line/trailing stratiform and disorganized structures based on the arrangement of storms within them. Thus, storms play an important role in MCS organization. During summer monsoon, synoptic-scale weather systems move through the monsoon core zone (MCZ) of India, causing frequent deep moist convection and significant precipitation. Despite its importance, studies highlighting the mesoscale organization of convection over MCZ are lacking.

The 3D structure and evolution of MCSs and their embedded storms in the MCZ are studied during a monsoon season (June-September 2019) by applying a Lagrangian cloud-tracking algorithm to three high-resolution data viz. geostationary satellite IR brightness temperature, GPM IMERG precipitation, and IMD S-band Doppler radar reflectivity (at Bhopal). As a consequence of this identification and tracking, 93 distinct MCSs have been located across a radar domain (90,000 km^2). For all MCS cases, embedded storm structures are identified by applying a storm classification method for objectively stratifying 3D radar echo into five dynamically and physically based types: convective, convective updraft, precipitating stratiform, non-precipitating stratiform, and ice-only anvil. In this manner, all MCS tracks and the various storms they comprised were recorded to study the evolution of storms concerning the stages of MCS lifespan.

The composite result (of 93 MCSs) shows that convective and stratiform areas reached their peak sizes, during the developing stage and then decreased slowly at the mature and dissipation stages of MCS. The anvil cloud area, on the other hand, expanded more slowly during the developing stage, peaked at the end of the mature stage, and then started to decrease during the dissipating stage. Convective and stratiform clouds cover an average of 17% and 34% of the total area, respectively, whereas anvil clouds cover 54% of the area. Regression analysis shows that the areal coverage of an anvil is strongly correlated with the size of the convective core and stratiform area. Next, the diurnal cycle of MCS occurrence showed a decrease in midnight, and then reached maxima in the afternoon (~1600 LT). Distinct structures of reflectivity CFADs are observed for the convective, stratiform, convective updraft, and anvil components of MCSs. The findings of this observational study on monsoonal-MCSs, embedded storm structures, and MCS lifecycle development are useful for evaluating high-resolution model simulations of MCSs.

Unraveling Physical Processes during the Tropical Cyclone Genesis at Convection Permitting Scale Utilizing Model Prediction Across Scale (MPAS-A)

Emmanuel R[1, 2], Medha Deshpande[1], Phani Murali Krishna[1], Ganadhi Mano Kranthi[1,2] and S. T. Ingle[2]

[1]Indian Institute of Tropical Meteorology, Pune, Ministry of Earth Sciences, India
[2]School of Environmental and Earth Sciences, KBC North Maharashtra University, Jalgaon, Maharashtra, India

Predicting cyclone genesis is still a challenge considering the multiscale interaction taking place during the process. The recently developed Model Prediction Across Scales (MPAS) provides a tool to simulate these processes across the scale. The primary aim of this research is to explore the process leading to the aggregation of Mesoscale Convective Vortices (MCVs) within a quasi-closed circulation (QCC) leading to the cyclone genesis. This study employs reanalysis, satellite data and the non-hydrostatic global MPAS-A at a convection permitting scale (3 km) to investigate the processes within QCC. The experiment is done for a severe cyclonic storm Mora originated as a low on 25 May 2017 over Bay of Bengal, later intensified as depression on 28 May 2017 and made landfall over Bangladesh on 30 May 2017.

Experiments were conducted with different initial conditions (May 18, 19, 20, and 23), two microphysical parameterization schemes and also with and without Sea Surface Update (SST). Out of total, nine experiments, two experiments could simulate the genesis. The experiment with the Thompson microphysics parameterization scheme initialized on 20th May with updated SST produced a vortex on May 22, six days prior to the depression event. It could also replicate the track and intensity of the depression, comparable with IMD best track data. Thus we investigated this simulation to understand how the genesis takes place. We found the presence of multiple eddies vertically extended upto 500 hPa, within the QCC, which later coalesced to form a depression. Analysis of model-simulated brightness temperature indicated the presence of Vertical Hot Towers (VHTs), persisting for more than a day. These simulation experiments demonstrate how such physical processes within the QCC led to the formation of the depression.

Keywords: tropical cyclone Mora, genesis, vortical hot towers, MPAS

Field-Scale Investigation of Temporal Dynamics in Soil Moisture and Temperature Profiles in Response to Rainfall Events

Aju C.D[1], Milind Mujumdar[1*], Bhupendra Bahadur Sing[1], Mangesh Goswami[1], Madhusudan Ingale[1], Naresh Ganeshi[2]

[1] Center for Climate Change Research, Indian Institute of Tropical Meteorology, Pune
[2]Department of Atmosphere, Ocean and Earth System Modelling Research, Meteorological Research Institute, Tsukuba, Japan
*Corresponding author email address: mujum@tropmet.res.in

Understanding the dynamics of soil moisture and temperature profile in response to precipitation is pivotal for hydrological modelling, weather prediction, and climate change studies. This field-scale study conducted extensive gravimetric analysis of soil samples across various depths from June 2022 to November 2023, alongside measurements of soil temperatures at corresponding depths at a site located in the core-monsoon zone of India. Analysis of soil moisture, soil temperature, and rainfall reveals a positive correlation between soil moisture and rainfall that diminishes with depth. Seasonal analysis demonstrated similar trends in mean soil temperature during pre-monsoon and monsoon seasons, ranging from 27 to 28 degrees, contrasting with decreased temperatures of 23 to 23.5 degrees during post-monsoon and winter seasons. Soil moisture exhibited high variations across the seasons, with the lowest mean in pre-monsoon and the highest in post-monsoon. Depths of 5 cm and 15 cm displayed heightened responsiveness to seasonal changes in both temperature and moisture. Notably, the standard deviation of soil temperature below 45 cm indicated stable conditions across seasons, while the standard deviation of soil moisture decreased below 45 cm during monsoon and post-monsoon, reversing in winter and pre-monsoon. This could be attributed to the textural homogeneity of the soil profile. This study underscores the complex interplay of soil moisture and temperature profiles across seasons, stressing the importance of taking these factors into account when conducting modelling and hydrological research studies.

Keywords: soil moisture; soil temperature; gravimetric analysis; hydrologic modelling

Projected Changes in the Dry Air Intrusion over India during the Summer Monsoon in a Warming Climate

Rahul Singh[1] and S. Sandeep[1]

[1]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi 110016
*Email: sandeep.sukumaran@cas.iitd.ac.in

The dry air intrusion over India during the summer monsoon break periods is a well-known phenomenon. The monsoon low-level jet (LLJ) transports the unsaturated air over the northern Arabian Sea to northwestern India. The transport of dry air across the northwestern part of India is quantified using a dry air intrusion index. In the historical period, the CMIP6 models are found to have good skill in simulating the observed dry air intrusion. In future projections of a warming climate, the monsoon LLJ exhibit a northward shift over the Arabian Sea. Here, we investigate the projected changes in the LLJ and the dry air advection towards Northwest India using the CMIP6 simulations under the SSP585 scenario. A substantial inter-model variability exists in the projected changes in LLJ over the Arabian Sea. A subset of models shows a poleward shift of the LLJ and a strengthening of the zonal flow over the northern Arabian Sea, while some other models show a slight counter-clockwise turning of the LLJ towards the end of the 21st century. The magnitude of dry air advection differs in these two types of projections. In the case of an enhanced zonal flow, the dry air advection intensifies, while in the latter case, more moist air is being transported from the southern part of the Arabian Sea. This difference in the projected changes in the LLJ is also reflected in the changes in the precipitation pattern over Northwest India, with one set of models projecting a drier and the others a wetter future for this region.

Key words: Monsoon, low level jet, dry air, climate change

Impact of Dust Aerosols on Intensity and Precipitation Structure of Tropical Cyclone: A Case Study

Rama Aslekar [1,2], Medha Deshpande [2], Rohini Bhawar [1] , Sreyashi Debnath [2] Gaurav Govardhan [2,3]

[1] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India
[2] Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India
[3] National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, Noida, India. E-Mail: ramaaslekar@gmail.com

Tropical cyclones are powerful synoptic scale convective systems, which can cause extensive damage on making landfall. The higher the intensity of the cyclone, the greater its destructive potential. Tropical cyclone's intensity is usually measured in terms of the minimum central pressure and maximum wind speed. Factors like SST, vertical wind shear, moisture availability, heat fluxes, etc. affect the intensity of cyclones. Aerosols have the potential to alter the intensity by modulating the wind shear on a large scale. They can also affect heat and moisture fluxes by modifying the cloud microphysics.

During the pre-monsoon period, aerosol loading takes place over the Arabian Sea due to the transport of mineral dust from the Gulf countries. Such dust loading can alter the life cycle of the cyclones generated in or passing through the basin. The aim of this study is to understand such interactions with respect to the cyclone named 'Biparjoy'. We aim to unravel the direct and indirect effects of dust on the intensity and precipitation pattern of the Biparjoy cyclone. For this purpose, sensitivity tests using the regional meteorology-chemistry coupled model WRF-Chem have been conducted. Three experiments were designed: CTRL, is the control run where all aerosols interact with radiation and take part in the cloud-related microphysical processes; DustRad-Off, where just the direct radiative effects of dust have been turned off and lastly the Dust-Off, where the chemistry scheme completely excludes dust aerosol species. Combinations of these experiments will be analyzed and used to obtain the impacts of the direct and indirect effects of dust on the tropical cyclone. The significance of considering dust aerosol impact on theintensity and rainfall prediction of tropical cyclones will be underscored by our findings.

A Deep Learning Algorithm for Classification of a Widespread Precipitation Extremes in the Vidarbha region, India

Arvind Pagire[1,*], Satyaban B Ratna[1], R.Chattopadhyay[1], O. P. Sreejith[1]

[1]Climate Research and Services, Indian Meteorological Department, Pune, India
[2]Savitribai Phule Pune University, Pune, Maharashtra, India
*Email: arvindpagire1995@gmail.com

Extreme precipitation events have increased globally in the recent years, primarily due to global warming. This study explores a convolutional neural network (CNN), a deep learning algorithm to classify widespread extreme precipitation extremes in the Vidarbha region of India. This study utilized NCEP-NCAR reanalysis data such as mean sea level pressure, wind speed (at 850 and 200 hPa) for large-scale processes, and vertical velocity and specific humidity for localized processes as input parameters that normally contributes to widespread extreme rainfall events. To determine widespread extreme rainfall days, we used a connected component algorithm for which at least two stations in the Vidarbha region exceeded the 99th percentile threshold using the daily rainfall data from India Meteorological Department. The CNN model is trained on data from 1951 to 2002, validated for the period from 2003 to 2013, and tested for the period from 2013 to 2022. The analysis of feature importance suggests that wind speed (850 and 200 hPa), vertical velocity and specific humidity are the most significant predictors of widespread extreme rainfall events over Vidarbha. Our analysis of CNN model achieves precision (0.42) and recall (0.34) in detecting widespread extreme rainfall events. Overall, the CNN model is 87.5% accurate in classifying widespread extreme rainfall events. Our study demonstrates that deep-learning algorithms are effective for identifying and analysing complex and non- linear weather patterns in daily rainfall data.

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The Intensity and Structure of Mocha Cyclone with WRF Hydrostatic and Non-Hydrostatic Dynamical Cores

Nahan[1,2], Medha Deshpande[1], Emmanuel Rongmie[1,3], Ganadhi Mano Kranthi[1,3] , and Radhika Kanase[1]

[1]Indian Institute of Tropical Meteorology, Pune, Ministry of Earth Sciences, India
[2]Cochin University of Science and Technology, CUSAT, Kerala
School of Environmental and Earth Sciences, KBC North Maharashtra University, Jalgaon, Maharashtra, India

Advancements in the computational processing power are allowing numerical weather prediction models to resolve the scale permitting the convection. Theoretically, at these resolutions, the model's dynamical core should be non-hydrostatic. Assuming this, we carried out this study to compare the hydrostatic and non-hydrostatic dynamical core available in the weather research and forecasting (WRF) model. We considered the case of tropical cyclone Mocha, which formed over the Bay of Bengal on 9 May 2023, for this study. It moved northeastward, intensifying further on 14 May, crossing north Myanmar-southeast Bangladesh coasts with a maximum sustained wind speed (MSW) of 115 knots and minimum MSLP of 938 hPa. WRF model V4.5, with two domain configurations having the innermost domain at a cloud-permitting resolution (3 km), is used to investigate the intensity and structure of an extremely severe cyclonic storm Mocha. A planetary boundary layer (MYJ) scheme and Cumulus (Grell 3D ensemble) scheme are used for outer domain1, and Cumulus parameterization is off for domain 2. Lateral boundary conditions are updated at every 6-hour interval from 00Z09May to 00Z16May 2023 using ERA5 re-analysis data initial conditions. The model experiment is done with two dynamical cores (hydrostatic and non-hydrostatic) separately. The analysis shows that the hydrostatic dynamical core produced intense storm compared to a non-hydrostatic core. We further investigate the vertical structure of tropical cyclones in terms of dynamic and thermodynamical factors that are responsible for the intense storm of hydrostaticdynamical core than the non-hydrostatic dynamical core.

Keywords: Tropical cyclone, WRF, hydrostatic, non-hydrostatic, vertical structure

Examining the Impact of Atmospheric Chemistry-climate Interaction on the Active and Break Phases of the Indian Summer Monsoon Rainfall

Sreyashi Debnath[1,2], Gaurav Govardhan[1,3], Rajesh Kumar[4], Sachin Ghude[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune-411008, India
[2] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune-411008, India
[3] National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, Noida-201301, India.
[4] National Center for Atmospheric Research, Boulder, CO, 80301, USA

Monsoon intra-seasonal fluctuations, characterized by active-break phases, are intricate phenomena influenced by numerous substantial large-scale factors. However, there exists a notable gap in research regarding the explicit influence of atmospheric chemistry on these dynamic active-break phases. This study attempts to bridge this research gap thorough and comprehensive investigation into the intricate interplay between atmospheric chemistry and monsoon intra-seasonal oscillations. The study aims to offer a detailed exploration of how atmospheric chemical processes contribute to and potentially modulate the observed active-break phases, thereby enhancing our understanding of the complex dynamics underlying monsoon variability.

Using the WRF-Chem model, the atmospheric chemistry-climate interaction on the Indian Summer Monsoon Rainfall (ISMR) is investigated through two sets of simulation experiments spanning a decade from 2010 to 2019. The experiments include (1) a control without atmospheric chemistry and (2) a sensitivity experiment embedding fully coupled MOZART-MOSAIC chemistry. Simulations cover the CORDEX South Asian domain, followed by dynamical downscaling over the Indian sub-continent to consider the impact of long-range emissions transport. Preliminary analysis reveals that the inclusion of atmospheric chemistry predominantly improves the seasonal bias in simulated monsoon rainfall compared to observational data. Over the decade, mean rainfall increases over Central India and the Western Ghats, while drier conditions prevail over the Himalayan foothills and North-east India following the incorporation of atmospheric chemistry. Explicit chemistry also influences inter-annual and intra-seasonal variability in ISMR through modulation of radiative feedback and large-scale circulations. This research has the potential to significantly contribute to a more comprehensive understanding of the intricate relationships between atmospheric chemistry and monsoon dynamics, particularly concerning the monsoon active-break phases. The identified impacts would provide valuable insights into the complex interplay of atmospheric chemistry and monsoon dynamics on a seasonal to inter-annual timescale.

Observed Variation of ITCZ over the Indian Monsoon Domain During ENSO Years

P Kumari[1], B Preethi[1], M Mujumdar[1]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India

The Intertropical Convergence Zone (ITCZ) influences society and climate in tropical regions and contributes around 32% of the world's precipitation. It is a permanent low-pressure feature that marks the meteorological equator where the trade winds laden with heat and moisture from surface evaporation and sensible heating, converge to form a zone of increased mean convection, cloudiness and precipitation. The organized moist convection associated with the monsoon trough may be attributed to a continental ITCZ over the Indian region and an advance in onset of summer monsoon over the southeast Bay of Bengal has been attributed to northward propagation of ITCZ. The variability of the monsoon may be connected to the spatiotemporal variance in the properties of the ITCZ. As Indian monsoon is a manifestation of the seasonal migration of the ITCZ, the understanding of regional characteristics of ITCZ can give more insightinto the variability of Indian Monsoon rainfall in a changing climate. This study discusses about the variability of ITCZ characteristics during different monsoon seasons and its link with Indian Summer Monsoon variability. The results indicate large variability in ITCZ especially during El-Nino and La Niñayears.

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GEFS Model Fidelity in Capturing the Cyclogenesis and Post-genesis Features

Radhika Kanase[1], Snehlata Tirkey[1], Medha Deshpande[1], R. Phani Murali Krishna[1], C. J. Johny[2], P. Mukhopadhyay[1], Gopal Iyengar[3] and M. Mohapatra[2]

[1] Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Dr. Homi Bhabha Road, Pashan, Pune, India
[2] India Meteorological Department, Ministry of Earth Sciences, Mausam Bhavan, Lodhi Road, New Delhi, India
[3]Ministry of Earth Sciences, Prithvi Bhavan, Bhavan, Lodhi Road, New Delhi, India
Corresponding Author: Dr. Radhika Kanase, email: radhikakanase@gmail.com

Tropical cyclone is devastating in nature due to it's strong winds and torrential rains. Over the years remarkable improvements are seen in track and intensity predictions, but it's accurate genesis prediction with longer lead is not yet achieved. The Global Ensemble Forecast System (GEFS T1534) is an operational ensemble prediction system at India Meteorological Department. The present study aims to check the GEFS model fidelity in capturing the genesis of the TC as well as its evaluation for track and intensity of cyclones during year 2021 and 2022. GEFS ensemble tracker is used for tracking the system in pre- genesis and post genesis. Different initial conditions with longer lead hours are analysed for genesis, track, intensity and landfall errors. The model can predict genesis location with error of about 200 km at day 2 lead. From depression till dissipation, the track error for ensemble mean is less than that of the control run. The track error is less than 150 km for ensemble mean till day 3 and is about 220 km on day 4. The model shows northward bias in predicting the track and south-westward bias in predicting the landfall locations.

Quantifying Randomness in Rainfall - Soil Moisture System: Implications for Weather Extremes

Madhusudan Ingale[1], Bhupendra Bahadur Singh[1], Milind Mujumdar[1], Mangesh M. Goswami[1,2], Naresh Ganeshi[1,3], and R. Krishnan[1]

[1]Indian Institute of Tropical Meteorology, Pune-411008
[2]Kavayitri Bahinabai Chaudhari North Maharashtra University, (KBC-NMU) Jalgaon – 425001
[3]Meteorological Research Institute, Japan – 3050052

Hydrometeorological extremes are in general regulated by the rainfall – soil moisture (R-SM) relation. We consider R-SM as a dynamical system and implemented a novel approach of information entropy to understand the variability patterns therein. The study is based on the period of 1980 to 2021 and is carried out over the core monsoon zone of India. Sample entropy is evaluated for the rainfall and SM time series separately for different rainfall conditions and the SM response is observed. Our analysis reveals that SM, in general, exhibits lower entropy than that of the rainfall on different spatial and temporal scales. Higher (lower) entropy indicates increasing (decreasing) degree of randomness. In line of this we found that persisting correlations might be the principal cause of the lower SM entropy. This peculiar SM behaviour is more pronounced during the deficit years where rainfall entropy was found to be increasing. Depending on the rainfall conditions, the persistence period of SM correlation varies. This can be related to the memory of a process and in turn indicates the SM resilience to rainfall variability. Sample entropy, using observations alone, holds the key to quantifying SM memory and therefore might be useful in improving prediction and mitigation measures of the hydrometeorological extremes.

Keywords: Rainfall, Soil moisture, Extremes, Degree of randomness, Sample entropy

Sub Daily to Daily Extreme Precipitation Characteristics using Intensity, Duration, Frequency Curves over the Mumbai Region

K. Sunil Kumar[1], Subrata Kumar Das[1], Chiranjeevi G[1], and G. Pandithurai[1]

[1]Indian Institute of Tropical Meteorology, Pune, India

The extreme precipitation events associated with ISMR has devastating effects in most populate regions such urban cities due to urban sprawl and UHI effect. Having observed recent development in flash flood forecasting, the extreme precipitation events statistics in light of its intensity (I), duration (D), and frequency (F) is an important input for flash flood forecasting. IDF curves are considered as a better proxy to quantify extreme nature precipitation events in terms of intensity (I), duration (D), and frequency (F). The derivation of IDF curves for a specific region essentially needs high spatio/temporal resolution rain fall observation of reliable quality.

MESO scale rain gauge NET work , MESOENT, is established over Mumbai to collect high resolution rainfall observations which are being used for model verification and public information. In this study, IDF curves are derived using 15 minutes resolution rain gauge observations from (MESONET), Mumbai region. The derived IDF curves are used to investigate spatial distribution of short duration extreme precipitation events rainfall intensity and future projections over the Mumbai region.

Spatio-temporal Variations of Tropical Cyclone and Non-Tropical Cyclone Induced Rainfall across India.

Devashis Prakash Singh[1], Shruti Upadhyaya[1,2] , R Maheswaran[1]

[1]Indian Institute of Technology, Hyderabad, 502285, India
[2]Advanced Radar Research Center, University of Oklahoma, USA

The variability of rainfall plays a critical role in the global water cycle and is increasingly affected by climate change, resulting in more frequent and intense climate extremes like floods, droughts, and extreme temperatures. Understanding the dynamics of rainfall patterns, particularly those induced by tropical cyclones (TCR) and non-tropical cyclones (NTCR), is essential for predicting and mitigating the impacts of these events in India.

This study aims to analyze the spatiotemporal variability of TCR and NTCR across the country using the semi variograms, the Mann-Kendall test and the Empirical Orthogonal Function method, leveraging long duration reanalysis precipitation datasets. By investigating the degree of variation in both time and space, the research seeks to provide insights into the changing rainfall patterns. The findings of this study will deepen our understanding of the complex spatiotemporal variations of TCR and NTCR, shedding light on the underlying mechanisms driving these changes. Ultimately, the outcomes of this study can inform adaptive strategies and resilience efforts to mitigate the impacts of extreme rainfall events in India, contributing to enhanced disaster preparedness and climate resilience.

Downscaling of Operational Model Outputs for Detection of Extreme Weather Events Using WRF Model at High Resolution

Revanth Reddy B[1] and Mukhopadhyay P[1]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India

The utilization of Numerical Weather Prediction (NWP) models has become crucial for predicting extreme weather events, enabling early detection of their intensity and location. Noteworthy advancements in physical parameterizations and novel techniques for identifying extreme events have significantly enhanced the accuracy of model predictions. Marked improvements in predicting these extremes were achieved by enhancing resolution in operational weather models. Notably, the Global Forecast System (GFS) model, with a resolution of 12.5 km, failed to anticipate such extreme rainfall events. By downscaling the outputs of the operational model, high resolution model (1 km) simulations employing WRF can be used to replicate such localized extreme events. This study aims to detect the problems leading to simulate the extreme rainfall events over the Indian region by using the operational weather models.

Leveraging Static Topographic Variables to Improve Satellite Rainfall Estimates using Convolutional Neural Networks

Yashraj Upase[1], Abhigyan Chakraborty[1], Vamsi Posimsetti[2], ShrutiUpadhyaya[1,3], Malarvizhi Arulraj[4], and Kishalay Mitra[1]

[1] Indian Institute of Technology, Hyderabad, 502285, India
[2] National Institute of Technology, Karnataka, 575025, India
[3] Advanced Radar Research Center, University of Oklahoma, 73072, USA
[4] Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland, 20740, USA

Skillful precipitation estimation is required for understanding extreme hydrometeorological events and their impacts on society and ecosystems. However, this becomes a challenge in the case of understanding precipitation across orographic regions where ground observations are sparse but the rainfall is highly variable in spatial and temporal scales, such as across India's Western Ghats. Recent advancements in satellite-derived precipitation datasets have improved understanding in challenging terrains, but biases persist in complex geographies. These biases to some extent, can be explained by static topographic variables. The current study aims to test the dependency of topography in satellite-based quantitative precipitation estimates (QPEs). We focus on the commonly used satellite-based precipitation product, Global Precipitation Measurement Mission (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Final run datasets and validate the results using India Meteorological Department (IMD) gridded daily rainfall data obtained from a dense network of rain gauges across India. We report the enhancement of precipitation estimates in such regions by integrating static topographic information extracted from DEM (Digital Elevation Model) such as Elevation, Slope, and Aspect with satellite precipitation retrievals using deep learning, specifically Convolution Neural Networks (CNN). Even though the deep learning model is developed over the Western Ghats, a comprehensive evalua- tion of the methods is performed across India for the Summer Monsoon season from 2014 to 2021. Results suggest that the Bias-adjusted RMSE of IMERG reduced from 23.44 mm to 21.33 mm, and the correlation coefficient improved from 0.39 to 0.51 over the Western Ghats.

Analysing the Current Patterns of Western Disturbances and their Relationship with the Indian Summer Monsoon.

Spandita Mitra[1], Ankit Agarwal[1]

[1]Indian Institute of Technology Roorkee, Roorkee, 247667, India

Western Disturbance (WD) is an extratropical low-pressure system that originates in the Mediterranean Sea and escorts the unforeseen winter precipitation to the North-Western Indian region. WDs are more frequent in the winter season (Dec- Feb) and influence the Indian Winter Monsoon, which rejuvenates the glaciers in the Himalayan Region. Although the frequency of WD events is higher in winter, they mark their presence throughout all the seasons, though at a lower rate. Nowadays, as a backdrop of climatechange, the presence of WD events is increasing in seasons other than the winter season. The present work comprehensively analyses the trend of WD events during the pre-monsoon (March-May) and monsoon seasons (June- September) from 1979 to 2022 using the WD tracking data provided by *Hunt etal. (2018)*. The work also investigates the impact of WD on the Indian Summer Monsoon by focusing onsemi-permanent systems using statistical techniques. The major findings show increasing trends in the pre-monsoon, i.e., MAM (R = 0.354, p-value = 0.02) and monsoon, JJAS (R=0.272, p-value = 0.002) seasons for the study period. A significant increase has been shown in April (R=0.39, p-value=0.001), May (R=0.32, p=0.005) during pre- monsoon and June (R=0.25, p=0.03), and August (R=0.17, =0.03) during monsoon seasons. The correlation between ISM and WD can be an important indicator for the prediction of ISMR. Our findings could serve in addressing the primary drivers of extreme events and enhance understanding for practical implementation, including strengthening climate resilience and aiding policymakers in recovery efforts.

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A Polarimetric Radar Analysis of Pre-monsoon Deep Convective Systems and a Hail-producing Event Observed in the Monsoon Core Zone

Kumar, Abhijeet*[1, 2], Sachin M. Deshpande[2], G. Pandithurai[2]

[1]Atmospheric Research Testbed Facility, Silkheda, Bhopal (IITM-Pune)
[2]Indian Institute of Tropical Meteorology, Pune.
*E-mail: abhijeet.kumar@tropmet.res.in

The pre-monsoon season from March to May significantly contributes to rainfall and exhibits considerable spatial and temporal variations. However, during the pre-monsoon season, the occurrence of thunderstorm activity across central and other parts of India is more, primarily driven by intense and deep convection. These thunderstorms bring heavy rainfall, thunder, lightning, and hailstorms. In this study, we present a composite analysis of 13 deep convective cloud systems and a case study of a hail-producing storm during the pre-monsoon season of 2023 observed by C-band dual-polarization (CPOL) radar at the IITM's Atmospheric Research Testbed (ART) facility in Silkheda, 60 km north of Bhopal. This CPOL radar in the monsoon core zone offers high-resolution Doppler and polarimetric radar measurements, enabling a comprehensive examination of the dynamic evolution of the precipitating convective clouds.

The vertical growth and severity of the observed 13 cases of deep convective systems are assessed by measuring the 35- and 45-dBZ echo top heights (ETHs). The mean heights of the 35-dBZ and 45-dBZ ETHs are around 13 km and 11 km, respectively, indicating an intense and deep convection. The composite contoured-frequency-by-altitude diagrams (CFADs) show that there is a high frequency of smaller values of differential reflectivity (ZDR ~0 dB) and specific differential phase (KDP) above the melting layer. This indicates that intense convective updrafts dominate the pre- monsoon convective systems, causing the riming of hail/graupel particles above the melting layer. The wider distribution or higher values of ZH, ZDR, KDP, and small values of correlation coefficient RhoHV (<0.95) near the surface indicate the presence of a rain-hail mixture.

Next, we provide a case study analysis of a storm that produced hail on April 30, 2023, with cloud tops reaching a height of 14 km. It has been observed that riming is dominated during the evolution of the convection and produces very low values of ZDR and KDP. These features show that the graupel/hail is present above the melting layer between 6 to 10 km, but the high value of RhoHV (~1) at these altitudes suggests that the graupel/hail is dry. The wet hailstones and large raindrops signatures close to the surface are also observed and are characterized by higher values of ZH (> 50 dBZ), enhanced ZDR (~ 3-4 dB), and a depleted RhoHV (< 0.95). Additionally, a KDP exceeding1.8°/km near the surface indicates the process of hail melting/hail coated with water. The results highlight the importance of vertically-resolved polarimetric radar measurements for characterizing the structures of deep convective clouds and related microphysics in the monsoon core zone.

A Comparative Analysis of Polarimetric Radar Observations and WRF Simulations of Lightning-producing Convective Systems over the Monsoon Core Zone

Rupraj Biswasharma[1], Sachin M. Deshpande[1], N. Umakanth[1], Sunil D. Pawar[1] and V. Gopalkrishnan[1]

[1]Indian Institute of Tropical Meteorology, Pune, 411008, India.

Radar observations of deep convective clouds (DCCs) provide critical insights into atmospheric dynamics, microphysics, and lightning parameterizations for numerical weather prediction (NWP). This study investigates three-dimensional structures of lightning-producing DCCs using C-band polarimetric (CPOL) radar, the Indian Lightning Location Network (ILLN), satellite imagery, and WRF model simulations in the Indian monsoon core region. By analyzing 6-minute volumetric scans of CPOL radar, we identify DCCs exceeding reflectivity thresholds and associated lightning flashes. A new method has been implemented to estimate Echo Top Heights (ETHs) and Echo Volumes (EVs) with various thresholds and evaluate their relationships with lightning flashes per convective cell. This spatial-temporal integration of radar and lightning observations has revealed a significant correlation between EVs with lightning flash per cell, with the highest correlation of 0.87 at 35 dBZ (EV35ddBZ) which had ETHs $\geq$ 12 km. These results signify the potential of EV35ddBZ useful for lightning parameterization. Multiple DCCs are considered to see the consistency of the relationships. Furthermore, DCCs were simulated using the convention-permitting WRF model, and subsequently, the ETHs and EVs were calculated. The simulated ETHs and EVs were then used to calculate lightning flashes and compare them with observed lightning. This comparison enables us to assess the accuracy of the simulations in reproducing the important characteristics of real thunderstorms, including their size, intensity, precipitation distribution, and lightning activity. Through quantitative comparison of simulated and observed radar data, we can identify areas where the model needs improvement. There is still a need for more research in this area because it is difficult to forecast lightning accurately with the current lightning parameterization methods (Wang et al., 2018). This study underscores the significance of polarimetric radar observations and high-resolution simulations in advancing our comprehension of thunderstorm dynamics and lightning behaviours within deep convective clouds (DCCs), ultimately enhancing forecasting capabilities.

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Role of Mesoscale Convective Systems In Extreme Rainfall Events During South Asian Monsoon

Vaibhav Pachaulee[1] and Suhas Ettammal[1]

[1]Indian Institute of Science Education and Research, Pune, Pune, 411008, India

Mesoscale Convective Systems(MCS) are responsible for over 50% of rainfall in the tropics[1]. Various studies on MCS have described them as a source of environmental heating[2], leading to enhancement of environmental instability[3]. In this study we systematically investigate the spatiotemporal trends on MCS and analysing their association with extreme weather events during South Asian Monsoon.

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Mesoscale Convective Systems in Convection-permitting Model and its Comparison with Observation over the Monsoon Zone

Sachin M. Deshpande*[1], Manisha Tupsoundare[1], Zhe Feng[2], Medha Deshpande[1], Subrata K. Das[1], and Harshad Hanmante[1]

[1]Indian Institute of Tropical Meteorology, Pune, India
[2]Pacific Northwest National Laboratory, Richland, WA, USA
*Email: sachinmd@tropmet.res.in

Mesoscale convective systems (MCSs) are one of the most significant forms of convection that affect the global water cycle and energy balance, and they produce high-impact weather events. During monsoon, synoptic-scale systems move across the monsoon zone and are responsible for frequently initiating MCSs. MCSs often produce widespread and heavy rain across the monsoon zone. Hence, studies on the structure and evolution of MCSs highlighting the organization of convection are needed for improved understanding of MCS. Compared to global models with parameterized convection, convection-permitting models (resolution ≤ 4 km) can simulate mesoscale and convective processes.

A convection-permitting simulation using the Weather Research Forecast (WRF) model was conducted over the monsoon zone (including Central India and the North Bay of Bengal) for June- September 2015 and we compared WRF MCS population statistics with observed MCSs. Here, we do not expect the model to reproduce individual MCSs at the precise times and locations observed. Instead, we focus on assessing composite MCS properties. To aid this contrast, we applied Lagrangian cloud- tracking to geostationary satellite IR brightness temperature and GPM IMERG surface precipitation to identify and track individual MCS events during JJAS 2015. IMD's S-band radar observations at Bhopal for the same period are used to examine the 3-D structures of storms embedded within the tracked MCSs and analyze the evolution of convective, stratiform, and anvil components of MCSs.

A similar cloud-tracking method is applied to WRF-simulated data (radar reflectivity, IRBT, and precipitation) to identify and track MCS in the model. As a result, the observed and simulated MCSs are consistently identified and tracked, making it possible to compare aspects of MCSs (initiation, size, intensity, lifetime, propagation) and embedded storms (e.g., convective-stratiform areas, convective core length, echo-top heights) between simulation and observations. Although the model underestimated the number of observed MCSs, the composite evolution and frequency distribution of convective area, precipitation amount, and MCS propagation speed produce reasonable agreement with observations but underestimate stratiform areas. Consistent with observations, the simulated MCS properties showed a gradual rise from convective initiation to around 1st half of the MCS lifetime. We observed that an MCS contains multiple precipitation features, particularly during the initial development stage when multiple convective clusters begin to aggregate. Long-duration MCSs (> 60 hrs) are absent in the model. More details on observed MCSs and embedded storm structures, as well as their representation in simulation, will be presented with noted similarities and differences.

Volcanoes Causing Regional Weather Extremes

Amitava Roy [1], A Wong [2], W Yim [3], I Roy [4]

[1] SmartFlow Pneumatics, United Kingdom
[2] Volcanoes Study Group, Hong Kong SAR
[3] University of Hong Kong, Hong Kong SAR
[4] University College London, United Kingdom

Strong volcanic eruptions (submarine, subaerial or mixed) not only can trigger many regional weather extremes, but numerous weather-related global anomalies are associated with it. Following the strength of eruption, sites of origin and eruption timings within the seasonal time of the year, volcanoes can have different regional and global impacts. Various climate modes that control regional weather patterns are perturbed and hence regional teleconnection patterns are modified. Both oceanic and atmospheric circulation patterns are often disturbed. Main mechanisms involved are the reduction of solar radiation, altering cloud distribution via aerosol loading, and altering ozone distribution in the stratosphere among others. Various effects are felt at the time scale of short, medium or longer- term range. In this work, historical records of strong volcanoes are generated and studies using observation, reanalysis product and satellite data, effects of strong volcanic eruptions are examined and time progressions are analyzed case by case. Major interest will be strong eruptions of Pinatubo (June, 1991), El Chichon (March, 1982) and Hunga Tonga in (December, 2021). Situations of regional weather extremes, including floods and droughts are of major interest. Such in-depth analyses to underpin the impact of volcanic eruptions on climate can provide useful guidelines for volcanic risk assessment. It will lead to improved prediction skills of regional climate, alongside mitigating weather-related natural hazard risks.

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Influence of the Adjoining Mountain Ranges on the Indian Summer Monsoon

Abhishek Anand[1], Shipra Jain[2], Saroj Kanta Mishra[3]

[1]Regional Meteorological Centre, India Meteorological Department, Kolkata 700027, India [2]Institute for Risk and Disaster Reduction, University College London, London, UK [3]Centre for Atmospheric Sciences, IIT Delhi, Hauz Khas 110016, India

This study investigates the impact of surrounding mountain ranges on the Indian Summer Monsoon (ISM) through a series of sensitivity experiments using a General Circulation Model (GCM). We systematically removed four major orographic features: the Himalayas and Tibetan Plateau, the African Highlands, the Western Ghats/Deccan Plateau, and the Indo-China/Maritime Continents. Results show that each of these mountain ranges influences temperature, precipitation, and wind patterns over the Indian subcontinent. The most significant impacts are attributed to the Himalayas and Tibetan Plateau, followed by the African Highlands. Their absence weakens the ISM circulation, drastically reduces rainfall, and alters the Somali Jet.

Our findings highlight the critical role of orography in shaping the strength and variability of the ISM. This knowledge has implications for improving monsoon prediction in GCMs, as the accurate representation of mountains and their processes is crucial for simulating the ISM realistically. Additionally, this study may inform assessments of how potential changes in mountain topography due to climate change could further impact regional climate and monsoon patterns.

Keywords: Indian Summer Monsoon, Himalaya-Tibetan Highland, Deccan Plateau, Somali Jet

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Diurnal Changes in Boundary Layer Height Turing Thunderstorm Evolution: Comparison from VHF Radar and Model simulations

Angel Anita Christy[1] and Manoj M.G[1]

[1]Cochin University of Science and Technology, Cochin, 682022, India

Due to land-sea interactions, the height of the atmospheric boundary layer (ABL) varies along the west coast. There are significant daily variations over land when surface temperatures peak and upper-level clouds are absent. Convection is promoted by warm, humid air in the lower atmosphere, and elevated moisture levels in the boundary layer indicate higher Convective Available Potential Energy (CAPE) for air parcels that have been raised. A specific radar campaign experiment investigated the properties of ABL during a post-monsoon thunderstorm in 2022. On November 13, 2022, cumulonimbus clouds developed and brought rain between 14:30 and 18:30 IST. The maximum ABL height as calculated with the help of the VHF radar was observed to be 2.75 km. Concurrently, the convective mass flux within the ABL contributed significantly to the development of the storm. Further, the thunderstorm was simulated using the Weather Research and Forecasting (WRF) model with four nested domains. The Quasi-Normal Scale Elimination (QNSE) boundary layer scheme significantly enhanced the event simulation, indicating a maximum ABL height of 2.15 km that closely matched with the observation. A comparison of ABL heights from the MERRA2 and ERA5 datasets revealed significantly underestimated ABLHs (maximum heights of roughly 600 and 700 metres, respectively). Due to the complicated dynamics and unique topography, accurate prediction of thunderstorm is difficult over this location. However, the radar shows promise as a tool for exploring the significant temporal variation in ABLH and associated dynamics over this uneven terrain.

Keywords: ABL, Thunderstorm, Diurnal Variability, Radar, WRF Model

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Effect of Arabian Sea Cyclones on the Northward Propagation of Monsoon

Rona Maria Sunil[1] and M. G. Manoj[2]

[1]Advanced Centre for Atmospheric Radar Research
[2] Cochin University of Science and Technology, Cochin 682022, Kerala, India

The onset of the Indian summer monsoon (ISM) over Kerala triggers significant atmospheric changes across the Indian subcontinent, characterized by shifts in large-scale circulations and heightened moisture levels over the Arabian Sea (ARB). Concurrently, distinct cyclonic seasons influence monsoon dynamics. This study leverages historical data (2000-2023) to categorize years as cyclone-accompanied or non-cyclone and investigates precipitation propagation. Findings indicate that during cyclone years, fast shear propagation leads to an accelerated northward propagation of precipitation (OLR). Horizontal wind profiles from the 205 MHz wind profiling radar at Cochin University of Science and Technology, India, aid in identifying the core speeds of the Low-Level Jet (LLJ) and Tropical Easterly Jetstream (TEJ), while calculating shear at the onset location. This research enhances comprehension of monsoon-cyclone interactions, contributing to enhanced prediction models.

Seasonal and Regional Differences in the Lightning Activity over the East and West Coasts of India

N. Umakanth[1], Rupraj Biswasharma[1], D.M. Lal[1], S. D. Pawar[1], and V. Gopalakrishnan[1]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune - 411008, India

Lightning is a significant natural phenomenon that causes severe losses to humans and infrastructure. Its occurrence frequency is strongly correlated with various meteorological parameters. This study aims to examine the monthly and seasonal variations of lightning activity over the east coast and west coast regions of India using Lightning Imaging Sensor (LIS) satellite data for a 20-year period (1995-2014). We have considered four regions for our study: two regions, R1 and R2, on the west coast, and R3 & R4 on the east coast. All regions were analyzed with a 50 X 50 grid resolution. It is observed that lightning activity is highest during the pre-monsoon season, while the lowest activity was observed during the winter season. During the pre-monsoon season, regions R4 and R2 displayed higher lightning activity compared to regions R1 and R4. Monthly variations of various meteorological parameters have been investigated from 1995 to 2014. These parameters include rainfall, cloud top temperature (CTT), Convective Available Potential Energy (CAPE), Lifted Index (LI), K-index (KI), and Total Totals Index (TTI). On the West Coast, higher CAPE was observed in April, while in May, the East Coast displayed higher CAPE thresholds. From 1995 to 2014, the R2 region (Kerala coast) exhibited high lightning activity on the west coast, whereas the R4 region (West Bengal & Orissa coast) showed the highest lightning activity on the east coast. The R3 region (Tamil Nadu & Southern Andhra Pradesh coast) exhibited significant lightning activity in the post-monsoon season. The R1 region (Maharashtra & Goa coast) showed the lowest lightning activity.

The study reveals that westerly winds are pushing moisture towards the R4 region, which contributes to intense lightning activity. Additionally, the results indicate that northeasterly winds feedingmoisture trigger lightning occurrences over R2 & R3 during the post-monsoon season. Continuous and close monitoring of lightning activity over coastal regions is necessary for current scientific research.

Understanding the Soil Water Dynamics during the Excess and Deficit Monsoon: The Role of Surface and Subsurface Soil Moisture

Mangesh Goswami [1], Milind Mujumdar [2], Bhupendra Badhadur singh [1], Madhusudan Ingale [1], Naresh Ganeshi [1], SN. Patil [2], and R krishanan [1].

[1]Indian Institute of Tropical Meteorology, Pune - 411008
[2]Kaviyatri Bahinbai Chaudhari North Maharshtra University, Jalgaon - 425001

Field observations soil moisture (SM) conducted between 2000 to 2001 during periods of excess and deficit monsoon seasons provide a unique opportunity to gain insights into the soil water dynamics (SWD) over the core monsoon zone (CMZ) of India. This study aims to analyze SWD by investigating the SM variability, SM memory (SMM), and the coupling between the surface and subsurface SM levels. Particularly intriguing are instances of concurrent monsoonal extremes, which give rise to complex SWD patterns. Usually, it is noted that a depleted convective activity and persistence of higher temperatures during the pre-monsoon season leads to lower SM; while monsoon rains and post-monsonn showers support the prevalence of higher SM conditions. The long persistence of wet (dry) spells during the excess (deficit) monsoon years reduces (enhances) the Bowen ratio (BR) due to the dominance of latent (sensible) heat flux. This enhancement or reduction in BR is due to evapotransipration (ET) which influences the SWD by modulating the surface-subsurafce SM coupling. SM variations and persistence timescales serve as SMM indicactors, evaluated across both surface and subsurface SM observation levels. Evidently, subsurface SM exhibits remarkably prolonged memory timescales-approximately twice than that of surface SM. Furthermore, we dissect SWD linked to wet and dry extremes by analysing annual soil water balance. Our findings reveal augmented (diminished) ET during (excess) years, accompanied by a higher (lower) number of break events. In essence, our study underscores the significance of surface-subsurafce SM observations in unraveling the intricate tapestry of SWD.

Keywords: Soil moisture, Core monsoon zone, Soil water dynamics, Soil moisture memory, Infiltration, Evapotranspiration