Reconstructing high-resolution in-situ vertical carbon dioxide profiles in the sparsely monitored Asian monsoon region

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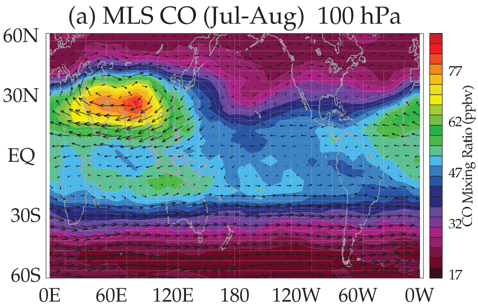
JÜLICH Forschungszentrum

Kathmandu in Nepal summer 2017

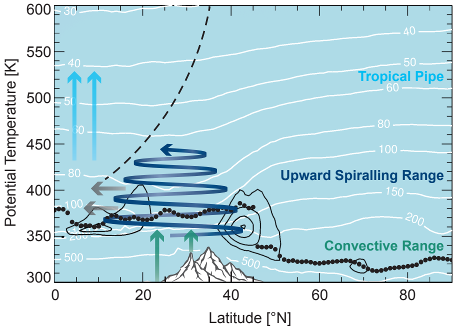
courtesy of Armin Afchine

Pollutants and greenhouse gases are transported from the surface into the lower stratosphere in the Asian monsoon region

Asian monsoon anticyclone (AMA): Vertical transport



Park et al., JGR, 2007



Vogel et al., ACP, 2019

- Pronounced circulation pattern in summer with enhanced substances of tropospheric origin (pollution, aerosol,..)
- convective range: fast uplift up to ≈360 K (within hours)
- upward spiraling range: slow uplift by diabatic heating superimposed by the anticyclonic flow up to ≈460 K (within a few months)
- the tropical pipe: upward transport into the middle stratosphere by large-scale circulation (within ≈ one year)

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Evaluation of vertical transport in ERA5 and ERA-Interim reanalysis using high-altitude aircraft measurements in the Asian summer monsoon 2017

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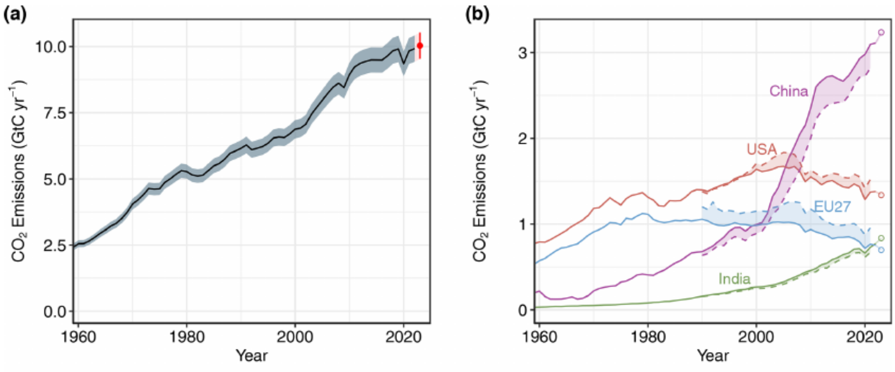
Fossil CO_2 emissions

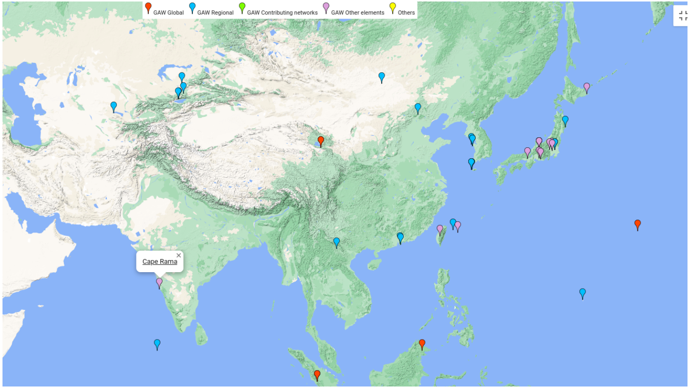


Friedlingstein et al., 2023, Global Carbon Budget 2023

(a) Fossil CO_2 emissions for the globe
(b) Territorial (solid lines) and consumption (dashed lines) emissions for the top country emitters (USA, China, India) and for the European Union

Ground-based CO_2 measurement sites in Asia

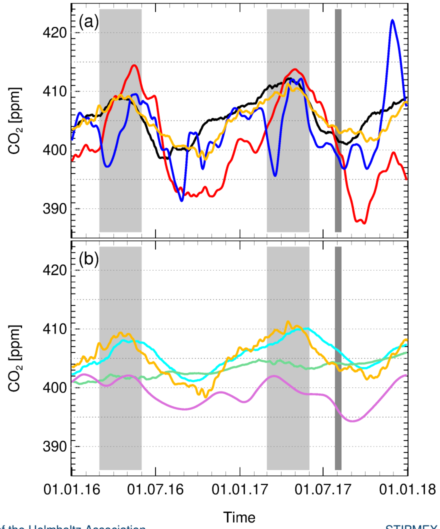
World Data Centre for Greenhouse Gases (WDCGG)

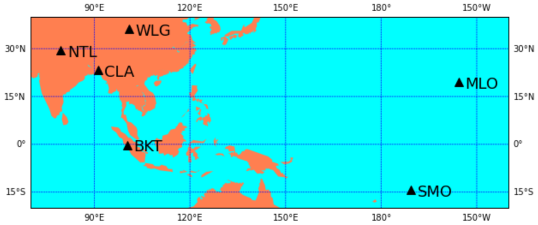


`https://gaw.kishou.go.jp`

➥ Only a limited number of continuous ground-based measurements of CO_2 and of other Greenhouse Gases are available in South Asia, in particular on the Indian subcontinent.

Ground-based CO_2 measurements in Asia





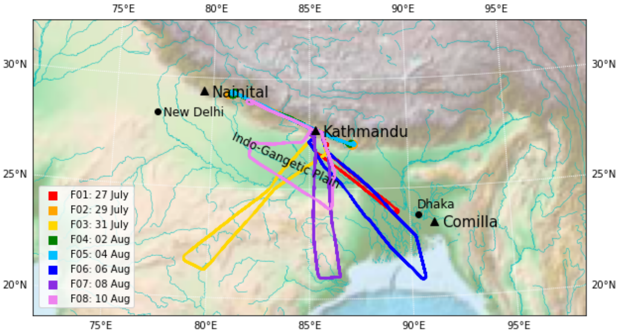
Nainital (India)
Comilla (Bangladesh)
Mt. Waliguan (China)
GOSAT Indian subcontinent
Mauna Loa (Hawaii)
Cape Matatula (Samoa)
Bukit Kototabang (Indonesia)

GOSAT-L4B: mean value between 20–30°N and 75–95°E at 975 hPa

Nomura et al., ACP, 2021; World Data Center for Greenhouse Gases

StratoClim aircraft measurement campaign

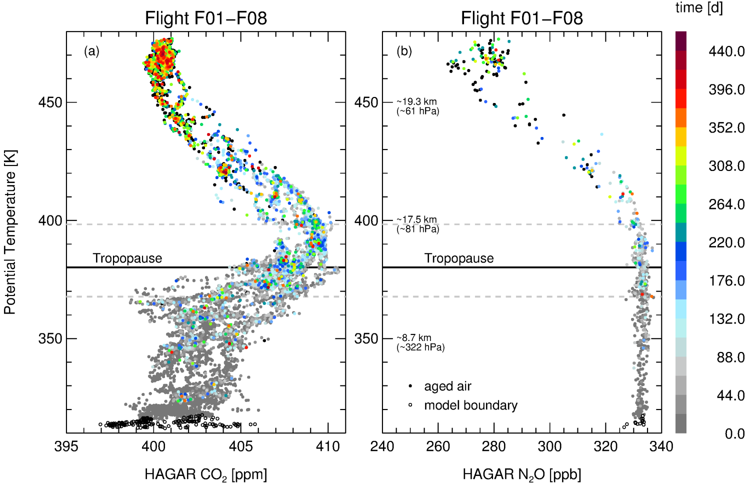
in Kathmandu (Nepal) in summer 2017



High-altitude aircraft Geophysica

➥ The StratoClim measurements constitute a unique data set in the Asian monsoon region up to ∼ 20 km (∼55 hPa or ∼475 K)

CO_2 and N_2O aircraft measurements and transport time



- HAGAR = multi-tracer in situ instrument (University Wuppertal)
- high-resolution CO_2 measurements (3–5 seconds)
- CO_2 profiles reflect CO_2 variability at ground level
- N_2O profiles above 400 K indicates mixing with older stratospheric air
- transport time from CLaMS back-trajectories to 1 June 2016 driven by ERA5 reanalysis

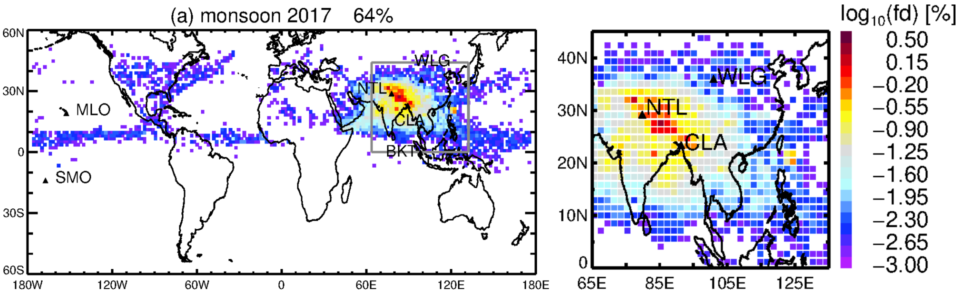
Time periods and age of air of considered seasons

on Indian subcontinent

Season	Time period	Start Time	Age of air
Monsoon 2017	June–September 2017	1 June 2017	$\sim$ 2 months
Pre-monsoon 2017	March–May 2017	1 March 2017	$\sim$ 2-5 months
Winter 16/17	December 2016 – February 2017	1 Dec 2016	$\sim$ 5-8 months
Post-monsoon 2016	October–November 2016	1 Oct 2016	$\sim$ 8-10 months
Monsoon 2016	June–September 2016	1 June 2016	$\sim$ 10-14 months
Aged air	older than 1 June 2016		$>$ 14 months

- Time when CLaMS back-trajectories driven by ERA5 (started along the flight tracks) reach the model boundary layer (BL) ($\sim$2-3 km above surface) corresponds to the age of air of measured air parcels.
- 90% of the air is younger than 1 June 2016, the other 10% is aged air

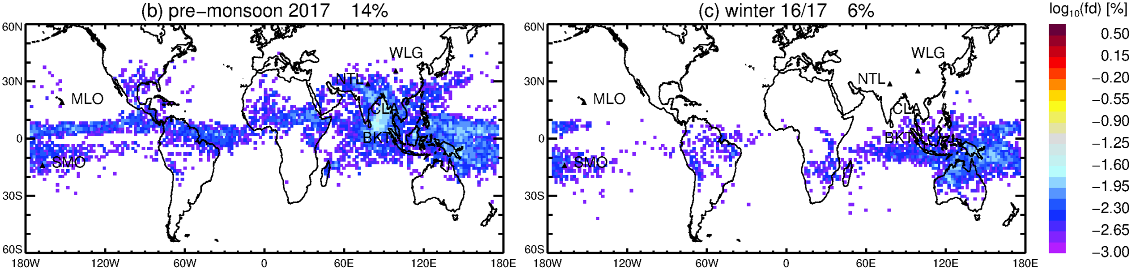
Air mass origin at Earth's surface during monsoon 2017



Frequency distribution (fd) of the air mass origins at the model boundary layer using CLaMS ERA5 back-trajectories

- Most air parcels were released at the model BL during monsoon 2017 (64%)
- from the northern part of the Indian subcontinent, the Tibetan Plateau, Bay of Bengal and eastern China

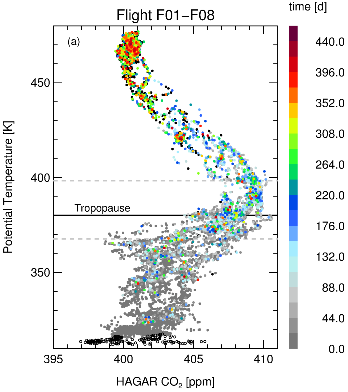
Air mass origin at Earth's surface during pre-monsoon 17 and winter 16/17

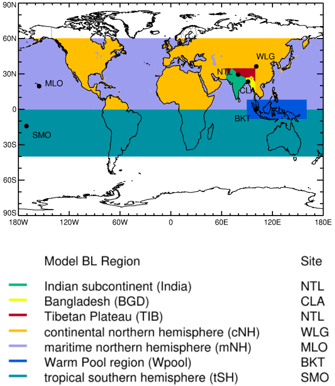


Frequency distribution (fd) of the air mass origins at the model boundary layer using CLaMS ERA5 back-trajectories

- Pre-monsoon 2017 (14%) and winter 16/17 (6%)
- During pre-monsoon 2017 the origins are shifted towards the tropics to the northern Inter-Tropical Convergence Zone (ITCZ)
- During winter 16/17 to the southern ITCZ

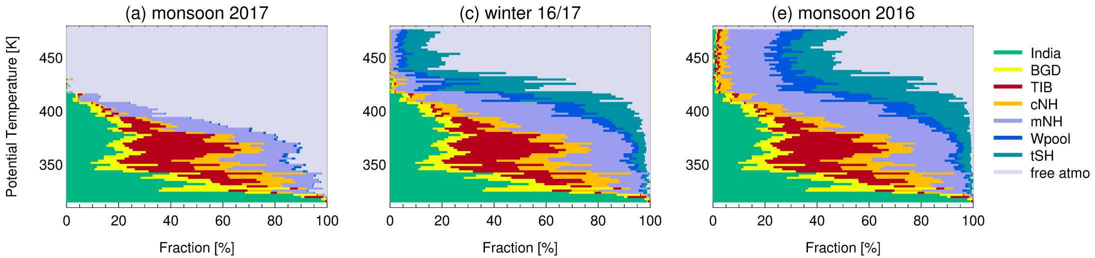
CO_2 reconstruction from observation sites

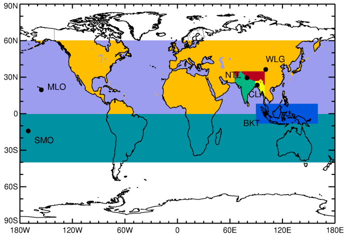




- CO_2 is chemically inert in the troposphere and stratosphere and can be used as an age tracer
- Reconstructed CO_2 from ground-based measurements
- CO_2 mixing ratios from ground-based measurements are prescribed at the time when each trajectory reach the model BL

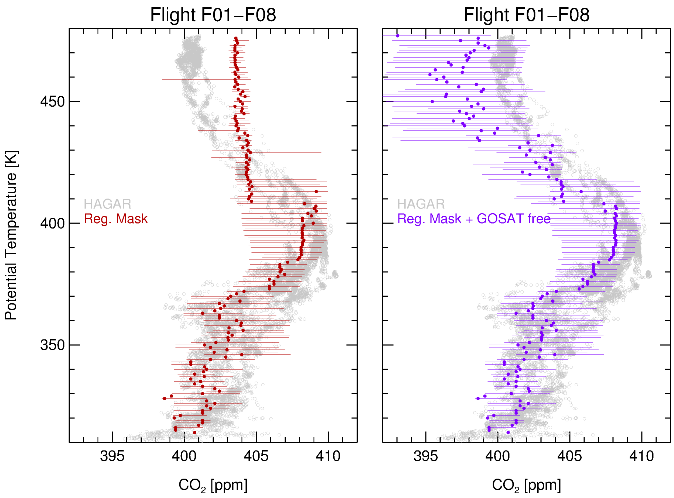
Accumulated fractions of air





- more than 90% air from the model boundary layer up to 410 K (winter 16/17)
- above 410 K air masses from the free atmosphere (aged air) have to be included

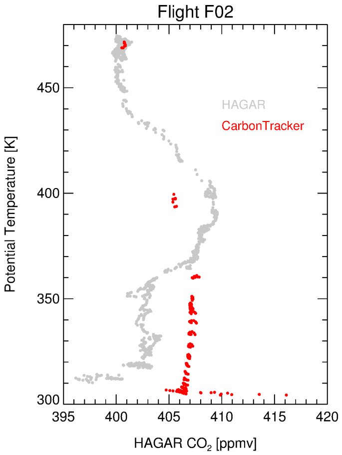
Reconstructed CO_2 using back-trajectories until 1 Dec 2016

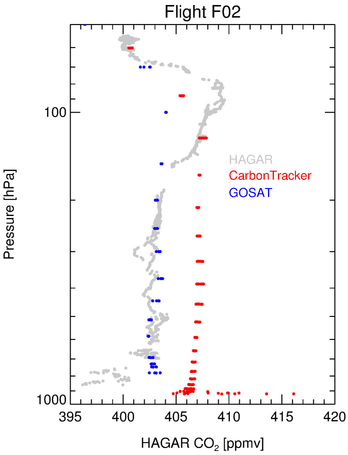


- Reconstructed CO_2 profiles reflect CO_2 variability at ground level
- Reconstructed CO_2 is shown as median calculated from all trajectories
- Bars indicate the range between the 25 and 75 percentile
- CO_2 reconstructed by using a regional mask (observation sites)
- GOSAT-L4B CO_2 data used for stratospheric background
- The statistic treatment represents mixing between different air masses

Comparison with CarbonTracker and GOSAT-L4B

Research Flight F02





- CarbonTracker (CT2019B) is a CO_2 measurement and modeling system

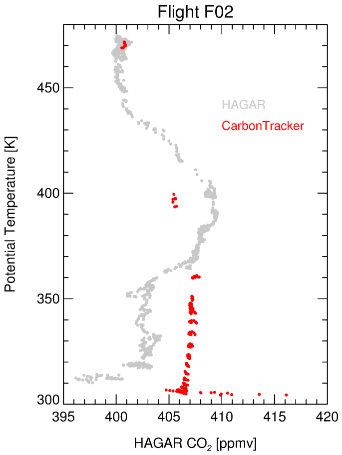
  `https://gml.noaa.gov/ccgg/carbontracker`

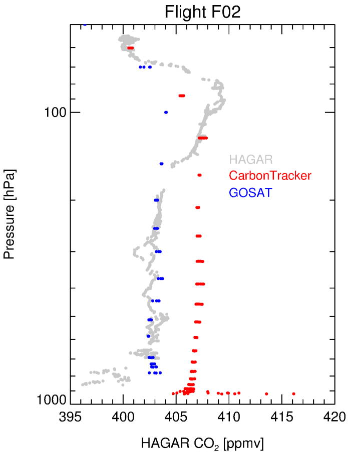
- GOSAT-L4B product is a model simulation using CO_2 surface fluxes inferred from column-averaged satellite measurements

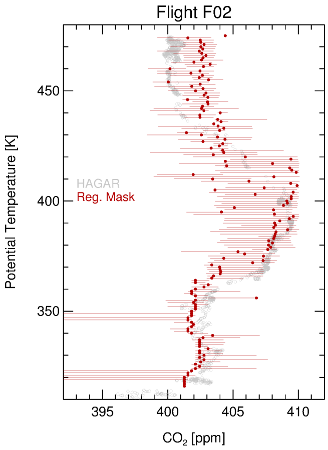
  `https://data2.gosat.nies.go.jp/index_en.html`

Comparison with CarbonTracker and GOSAT-L4B

Research Flight F02







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ECMWF reanalyses

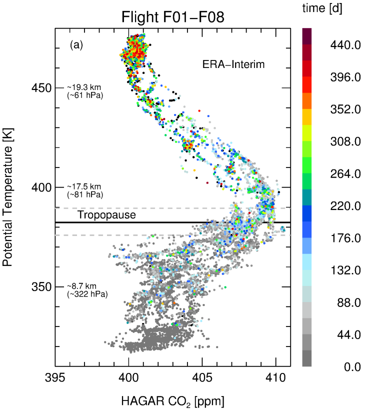
ERA-Interim and ERA5

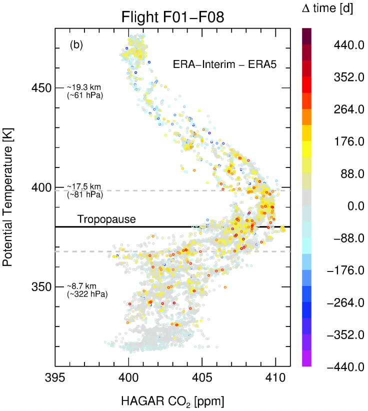
	ERA-Interim	**ERA5**
Horizontal resolution	T_L255 ($\sim$ 79 km)	T_L636 ($\sim$ 31 km)
Horizontal gird	$0.75^\circ \times 0.75^\circ$	$0.3^\circ \times 0.3^\circ$
Vertical resolution	60 levels up to 0.1 hPa	137 levels up to 0.01 hPa
Temporal resolution	6 hours	1 hours
Reference	Dee et al. (2011)	Hersbach and Dee (2016)

provided by the European Centre for Medium-Range Weather Forecasts (ECMWF)

Differences in trajectory-based transport time

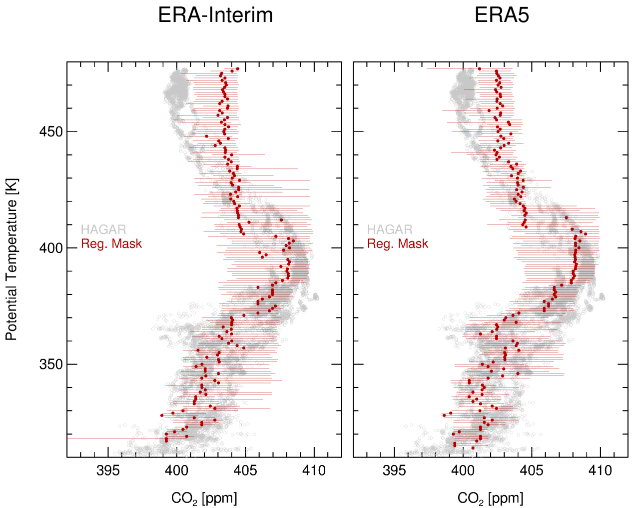
ERA-Interim versus ERA5





- In the stratosphere, ERA-Interim has the tendency to be faster (shorter transport times) than ERA5 (bluish data points)
- In the UTLS, certain air masses are found to experience faster upward transport by convection using ERA5 rather than ERA-Interim (reddish points)

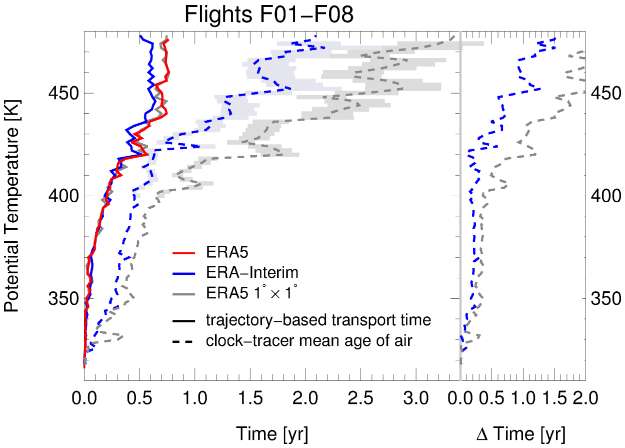
CO_2 reconstruction: ERA-Interim versus ERA5



- trajectories back until 1 June 2016 neglecting the contributions from the free atmosphere
- ERA-Interim vertical velocities are faster between 390 and 420 K $\rightarrow$ stronger dispersion
- convection is better reproduced in ERA5 (low CO_2 at $\approx$ 360 K)

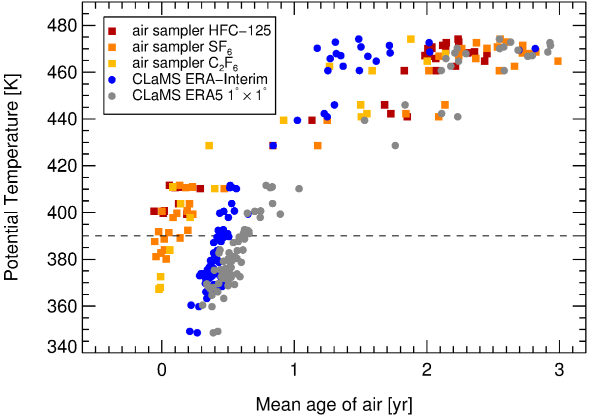
Mean age of air from multi-annual 3-dimensional CLaMS simulations

driven by ERA-Interim and ERA5



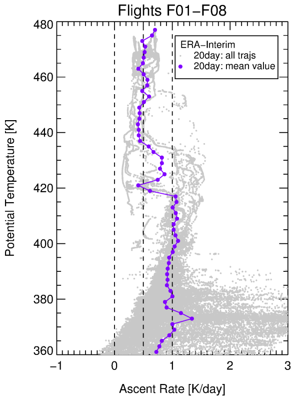
- ERA5 with lower resolution = ERA5 1° × 1° a computing-time-saving alternative for multi-annual CLaMS simulations
- Mean age of air is interpolated along the Geophysica flight tracks
- strong difference between ERA-Interim and ERA5 (more than one year at 470 K)

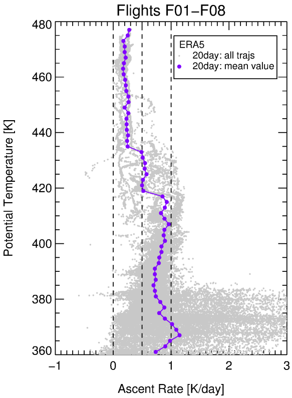
Observation-base mean age of air from StratoClim

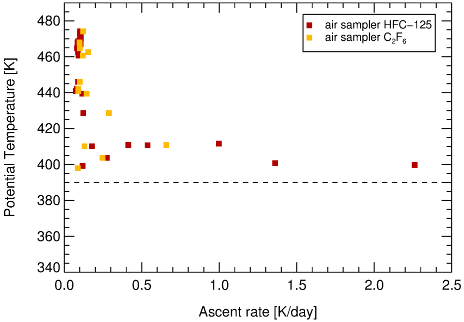


- observation-based mean age of air inferred from long-lived trace gases such as C_2F_6, HFC-125, SF_6 collected with the whole-air sampler of Utrecht University
- In the Asian monsoon region above 430 K, the mean age of air driven by ERA-Interim is too young, whereas the mean age of air from ERA5 ($1^\circ \times 1^\circ$) is too old but somewhat closer to the observations

Mean ascent rates







- Effective ascent rates calculated as difference in potential temperature along backward trajectories driven by ERA-Interim and ERA5
- Observation-based mean ascent rates above 390 K derived from trace gas measurements of air samples collected with the whole-air sampler of Utrecht University

Conclusions

- Atmospheric concentrations of CO_2 have increased substantially because of human activities, however their sources in South Asia are poorly quantified.
- Lagrangian model simulations successfully reconstruct vertical CO_2 profiles obtained by high-resolution aircraft measurements up to 20 km during the Asian summer monsoon 2017.
- Reconstructed CO_2 profiles reflect CO_2 variability at ground level.
- Ground-based CO_2 signals rapidly propagate to approximately 13 km with slower ascent above.
- In situ aircraft measurements indicating a better representation of Asian monsoon transport in the newest ECMWF reanalysis product ERA5.
- A greater number of continuous ground-based measurements of CO_2 and also other GHGs in South Asia, in particular on the Indian subcontinent, would be a great asset for atmospheric and climate modeling.

Vogel et al., 2023, Communications Earth & Environment; Vogel et al., 2024, ACP

Network for the Detection of Atmospheric Composition Change (NDACC)

https://ndacc.larc.nasa.gov

Measurement Stations

Select a station on the map or in the list to access its public data.

Filter By:

Hemisphere

- Northern Hemisphere
- Southern Hemisphere

Latitudinal Band

- Subtropics and Tropics
- Mid Latitude
- High Latitude

Instrument Status

- Active
- Inactive
- Campaign

Instrument

- Brewer
- Dobson
- FTIR Spectrometer
- Lidar
- Microwave Radiometer
- Sonde
- UV/Visible Spectrometer
- UV Spectroradiometer

Working Group: Theory & Analysis

Sarah A. Strode, GESTAR-II, Goddard Space Flight Center, USA
Bärbel Vogel, IEK-7, Research Centre Jülich, Germany

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- the NOAA Earth System Research Laboratory for providing Carbon-Tracker
- the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing ERA-Interim and ERA5 reanalyses