NATIONAL WEATHER SERVICE

On the Development of NOAA Unified Forecast System -- Reducing Extreme Weather Forecast Biases with Improved Model Physics

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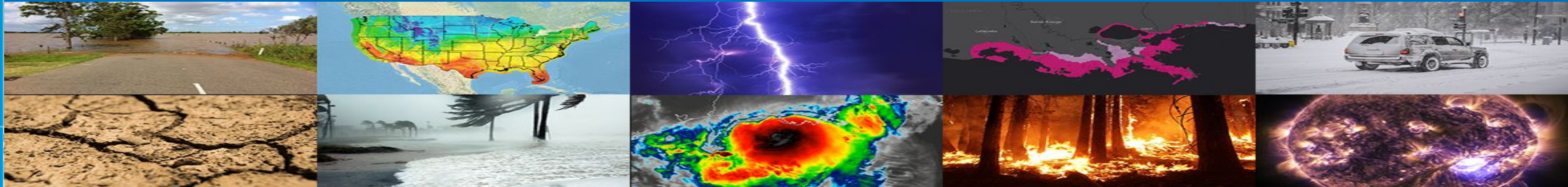
International workshop on “Stratosphere-Troposphere Interactions and Prediction of Monsoon weather EXtremes” (STIPMEX) at IITM, Pune during 3-7 June 2024.



Outline

- Current NOAA NCEP Operational Systems
- Unified Forecast System Applications
- Development of UFS Physics to Improve Extreme Weather Forecasting

Acknowledgements to UFS Active Developers

Atmospheric Physics

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Coupled Model Component Development

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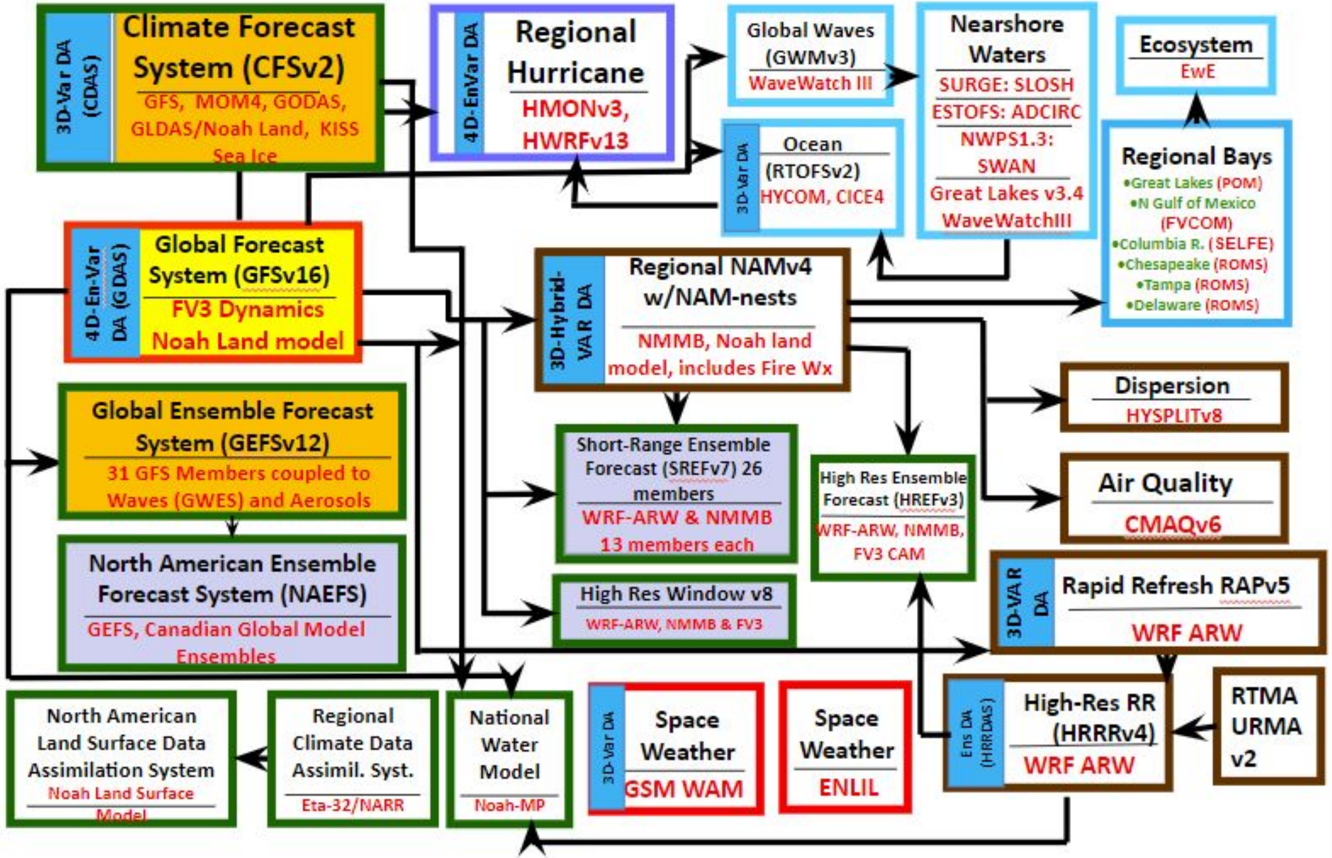
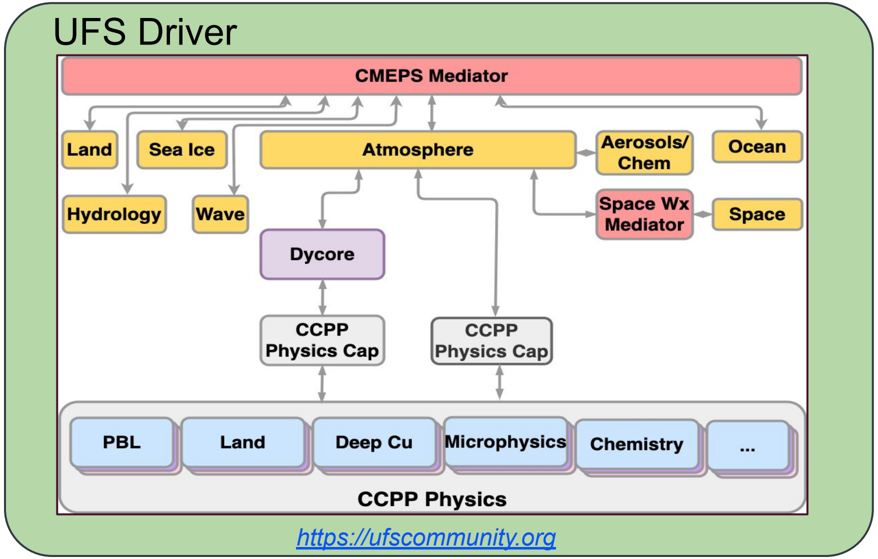
Current State of NCEP Production Suite



- NCEP operates more than 38 distinct modeling systems to meet the stakeholder requirements
- Quilt of Models developed to meet the service needs over a long period of time
- Simplification of NCEP Production Suite is critical to reduce redundancy and improve efficiency

NOAA is collaborating with the US weather and climate science community to develop the next generation fully coupled earth system modeling capability for both research and operational forecast applications across different temporal and spatial scales.

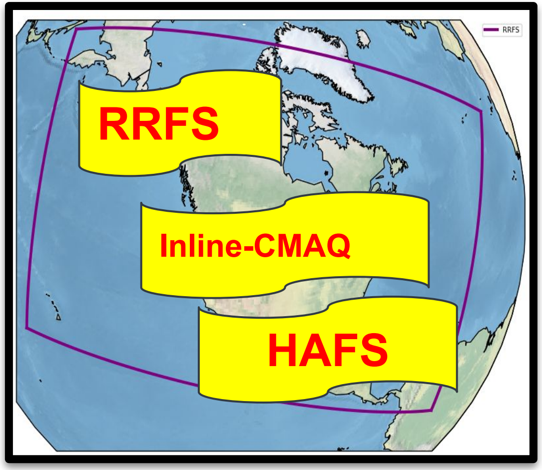


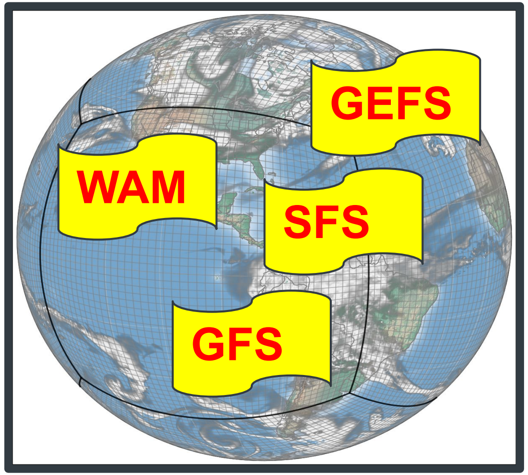
- CMEPS mediator
- FV3 dycore
- CCPP physics
- MOM6 ocean
- Noah-MP LSM

- WAVEWATCH III wave
- CICE6 sea-ice
- GOCART aerosols
- CMAQ air quality

UFS Applications:

SRW/CAM





MRW/S2S

Regional:

HAFS - **Hurricane Analysis and Forecast System (parent 4km; nest 2km)**

RRFS - **North America Rapid Refresh Forecast System (3km)**

Online-CMAQ - **North American Air Quality Model (12km)**

Global:

GFS - **Medium-Range Deterministic Weather Forecast Model (9km)**

GEFS- **Global Ensemble Sub-Seasonal Forecast System (25km)**

SFS - **Seasonal Forecast System (??)**

WAM - **Whole Atmospheric Model (up to 500 km; 50km)**

On Physics Development for UFS Applications:

- Develop and improve physics parameterizations for UFS applications to **reduce model systematic biases,** ***improve forecast of extreme weather and climate events*****, and maximize model prediction skills**.
- **Unify physics parameterizations** for all applications across different spatial and temporal scales to speed up the R2O transition of physics innovations and to reduce the cost of operational systems maintenance.

Physics Parameterizations in Major UFS Applications

	GFSv17 (13km) & GEFSv13 (25km)	RRFSv1 (3-km) (multi-physics ensemble)	HAFSv1 (6/2 km)	AQMv7 (12km) aka Inline-CMAQ
Deep Convection	sa-SAS	GF and sa-SAS	sa-SAS	sa-SAS
Shallow Convection	sa-SAS	MYNN-EDMF	sa-SAS	sa-SAS
Microphysics	Thompson MP	Thompson MP & NSSL MP	A: GFDL MP B: Thompson MP	GFDL MP
Radiation	RRTMG	RRTMG	RRTMG	RRTMG
Surface Layer	GFS	MYNN & GFS	GFS	GFS
PBL	sa-TKE-EDMF	MYNN-EDMF & TKE-EDMF	sa-TKE-EDMF	sa-TKE-EDMF
Land	NOAH-MP	RUC	NOAH LSM	NOAH LSM
oro and non-oro GWD	uGWP v1	N/A	uGWP.v0 (oro)	uGWP.v0
SS-GWD & TOFD	Yes	Yes	Yes	No

P6 (C384) — P7(C384) — P8 (C384) — HR1 (C768) — HR2 (C768) — HR3 (C768 & C1152)

P6

Land: **Noah**
PBL: **TKE-EDMF**
Microphysics: **GFDL MP**
Deep convection: **saSAS**
Shallow convection: **saMF**
Radiation:**RRTMG**
Gravity wave drag: **uGWDv0**

GFS.v16 Physics Package

P7

Land: **Noah-MP** +
Compositing surface layer variables, albedo/emissivity
PBL: **TKE-EDMF**
Reduced background diffusivity, limit PBL updraft overshoot.
Microphysics: **GFDL MP**
Deep convection: **saSAS**
Stricter trigger criteria, reduced entr. rate, reduced rain evap. rate
Shallow convection**: saMF**
Radiation:**RRTMG**
MERRA2 aerosols
Gravity wave drag: **uGWDv0**

P8

Land: **Noah-MP**
Tuning, use CICE albedo in atm, new ice climatology, VIIRS based land/lake mask, spun up land IC's.
PBL: **TKE-EDMF**
Positive definite mass flux scheme, reduced entrainment rate
Microphysics: **Thompson MP** +
Semi-Lagrangian Sedimentation + refined ice microphysics
Deep convection: **saSAS**
Cellular automata convective org scheme.
Positive definite mass flux scheme
Shallow convection: **saMF**
Positive definite mass flux scheme
Radiation:**RRTMG**
Gravity wave drag: **uGWDv0**

HR1

Land: **Noah-MP**
Bug-fixes
PBL: **TKE-EDMF**
Microphysics: **Thompson MP**
Improve radiative fluxes and cloud cover
Deep convection: **saSAS**
Prognostic closure
Shallow convection: **saMF**
Prognostic closure
Radiation:**RRTMG**
Couple convective cloud to radiation
Gravity wave drag: **uGWDv0**

HR2

Land: **Noah-MP**
Bug-fixes
PBL: **TKE-EDMF**
wind shear effect and TKE dependent entrainment.
CONUS CAPE enhancement
Microphysics: **Thompson MP**
Reduce stratus and downwelling rad. fluxes
Deep convection: **saSAS**
wind shear effect and TKE dependent entrainment
Shallow convection: **saMF**
Radiation:**RRTMG**
Gravity wave drag: **uGWDv0**

HR3

Land: **Noah-MP**
PBL: **TKE-EDMF**
Microphysics: **Thompson MP**
Deep convection: **saSAS**
Shallow convection: **saMF**
Radiation:**RRTMG**
Address excessive large net SW net to ocean at low sun angles
Gravity wave drag: **uGWDv1**

UFSR2O physics/dynamics development coordination
Fanglin Yang, Lisa Bengtsson

Acknowledgement to ALL UFS coupled/infrastructure/physics/dynamics/DA developers, application/project leads , and evaluators!

Physics Development for the Global Model: GFSv16/GEFSv12 --> UFS-based GFSv17/GEFSv13

Items highlighted in blue color had also been included in HAFS.v1

Introduced

- a **two-moment cloud microphysics** scheme (GFDL MP --> **Thompson MP**)
  - Improved the cloud radiation interaction capabilities
  - Introduce Semi-Lagrangian Sedimentation for improved stability and cost
- a **new land model** (NOAH LSM --> NOAH-MP LSM)
- **new small-scale gravity wave** and **turbulent orographic form drag** parameterizations
- a **new** parameterization for **convective organization**, and a new **Prognostic**-Stochastic and Scale-Adaptive **Cumulus Convection Closure**
- **new stochastic physics** in the ocean, land-surface and the atmosphere
- a **new positive definite tracer advection (TVD)** scheme in convection and PBL
- new capability for **coupling between aerosols and physics**
- **new land/ocean/lake masks, new ice climatology, and surface composites over fractional grid**

Improved

- **cumulus convection** schemes and **boundary layer** schemes to address model systematic biases
- **gravity wave drags and mountain blocking**
- **coupling of the land model and surface layer** schemes.

Example: Updating Thompson Microphysics For Global Applications

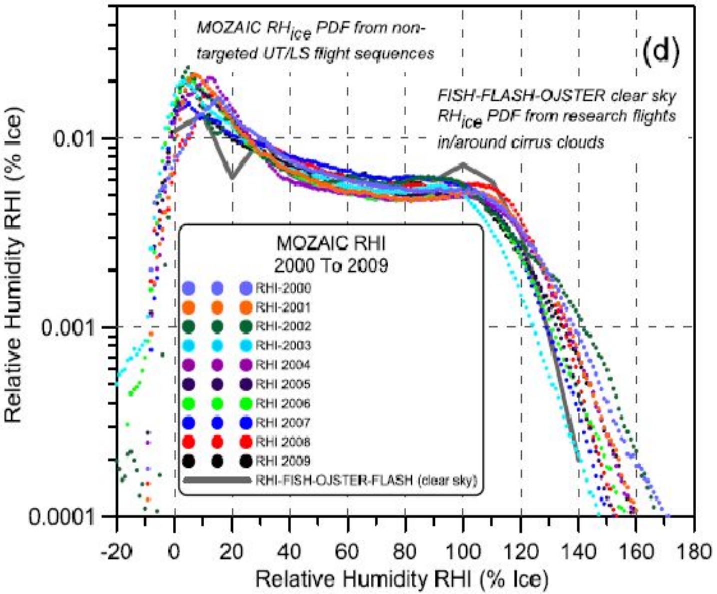
- In current NCEP operation, GFS &GEFS ==> GFDL MP; RAP & HRRR ==> Thompson MP; NAM ==> Ferrier-Aligo MP. FA was also used by HWRF before HAFS implementation.

- In 2020 after GFSv16 was finalized for operation, a decision was collectively made by EMC and the UFS Physics WG to **adopt Thompson MP for all UFS-based applications** (except for HAFS-B).

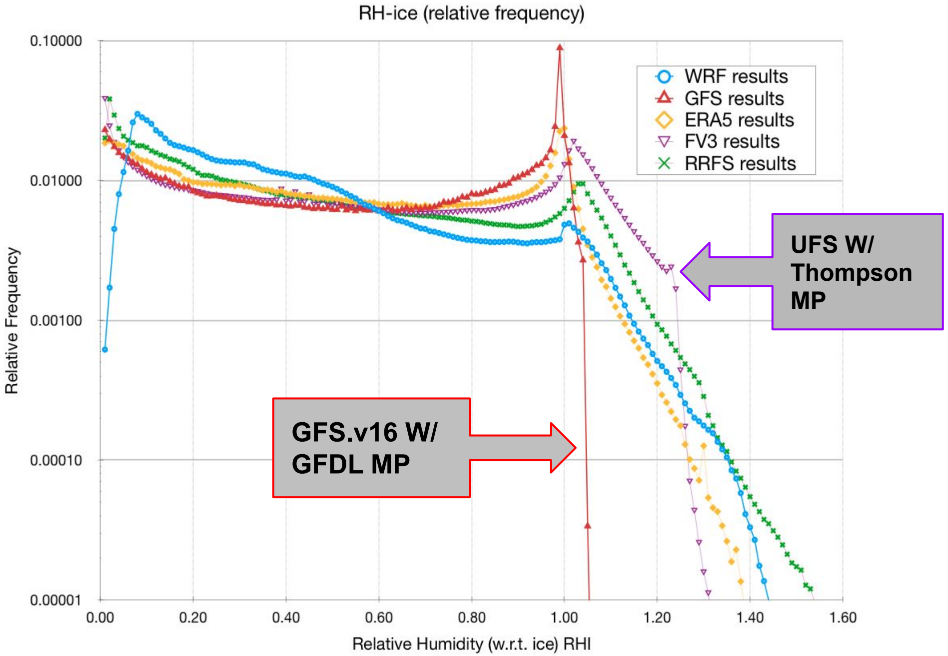
- Thompson MP has been widely used in the WRF community for regional model applications. Adapting it for NCEP global model applications has proved to be challenging.

- Significant efforts have been made 1) to **eliminate computational instability of Thompson MP** in global models which have larger physics time steps than regional high-res models. **Subcycling microphysics and semi-Lagrangian sedimentation** for rain and graupel were both developed to maintain computational instability; 2) to **improve simulation of ice clouds in the tropics** to achieve better radiation and energy balances.

Supersaturation and Supercooled cloud water



Observed frequency distribution (PDF) of RH relative to ice (RHI) from MOZAIC flight-level obs.



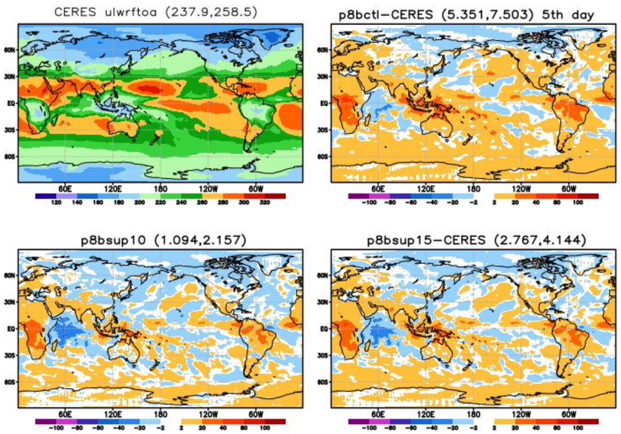
RHI PDF from various models (Credit: Greg Thompson). **Supercooled cloud water is a hazard to aviation !**

Microphysics Hydrometers and TOA Energy Balance

Integrated hydrometeors (global, tropical:30S-30N)

g/m2	GFSv16 GFDL MP	GFSv17 Prototype Thompson MP	IFS
Cloud liquid	(77.6, 57)	(54,45.14)	(54.6, 50.13)
Cloud ice	(35.47, 23.82)	(8.67,12.32)	(20.17,15.14)
Snow	(17.57,13.75)	(54.3,40.97)	(49.63,43.14)
Ice + snow	(53.04,37.57)	(62.97,53.29)	(69.8,58.28)
Ice + snow + cloud liquid	(130.64, 94.57)	(117.42,98.43)	(124.4,108.41)

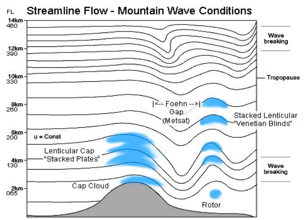
These difference in hydrometer loadings affect radiative heating and energy balances



UFS p8b experiment: OLR varies with RHic for supersaturation

UL: CERES obs
UR: RHi=125% (default)
LR: RHi=115% (final for GFSv17)
LL: RHi=110%

Unified Gravity-Wave Drag Parameterization



Large-Scale Orographic GWD

Low-level flow blocking

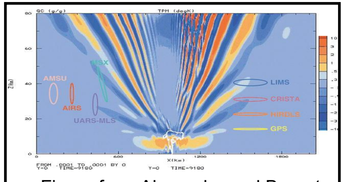
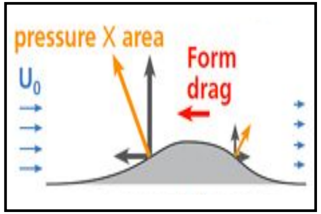


Figure from Alexander and Barnet (JAS,2007)

Non-stationary GWD

Small-scale GWD



Turbulent orographic form drag

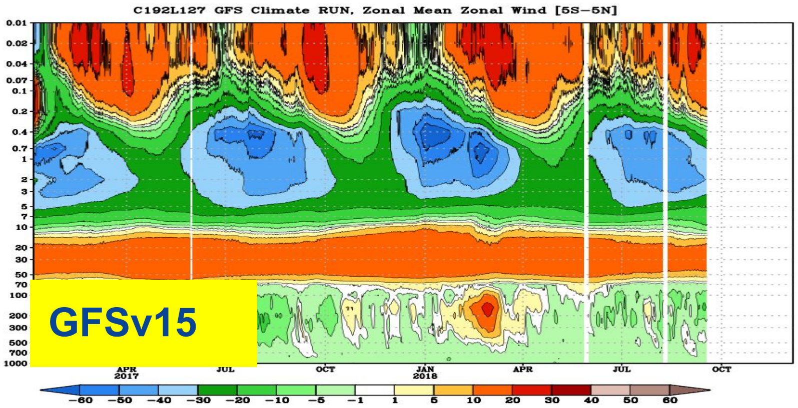
uGWD.v0 in current ncep operation:
Kim & Arakawa (1995) O-GWD & Block,
Yudin et al (2020) N-GWD

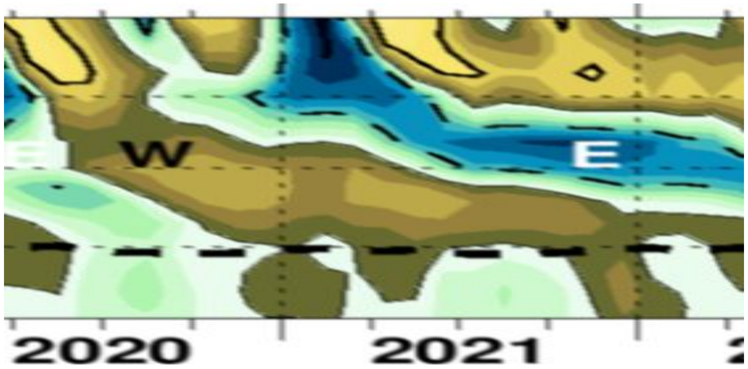
Different scaling factors need to be tuned and applied for different model grid resolution.

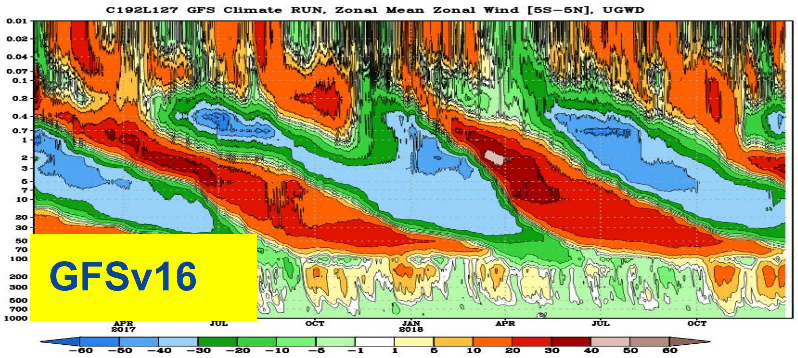
uGWDv1 (aka the GSL suite) for the UFS:
Kim and Doyle (2005) O-GWD & Block
Yudin et al (2021) N-GWD
Tsiringakis et al. (2017) SS-GWD,
Beljaars et al. (2004) TOFD

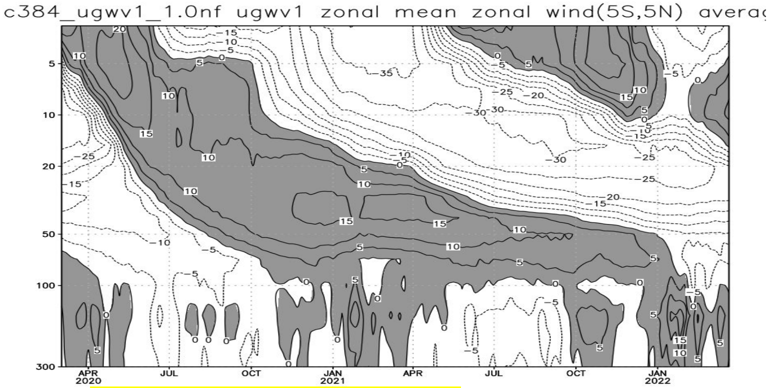
O-GWD & Block have been optimized to match COORDE intercomparison benchmark. Source functions for triggering N-GWD still need to be set differently for models with different resolutions

Improved forecasts of the QBO with improved GWD parameterizations









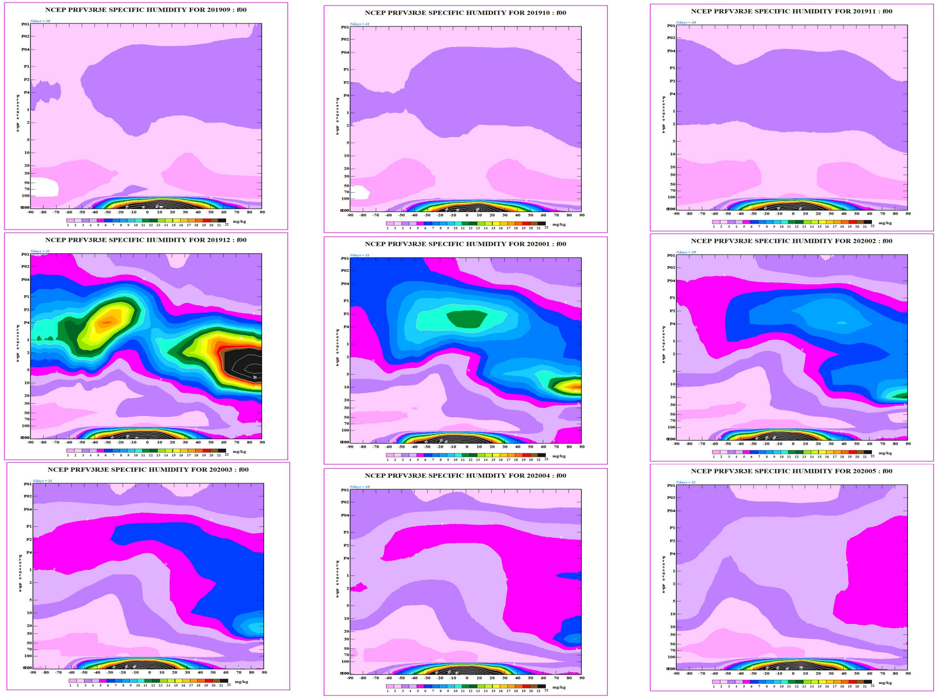
GFSv17 Prototype

Improving Water Vapor in the Stratosphere

09/2019

12/2019

03/2020



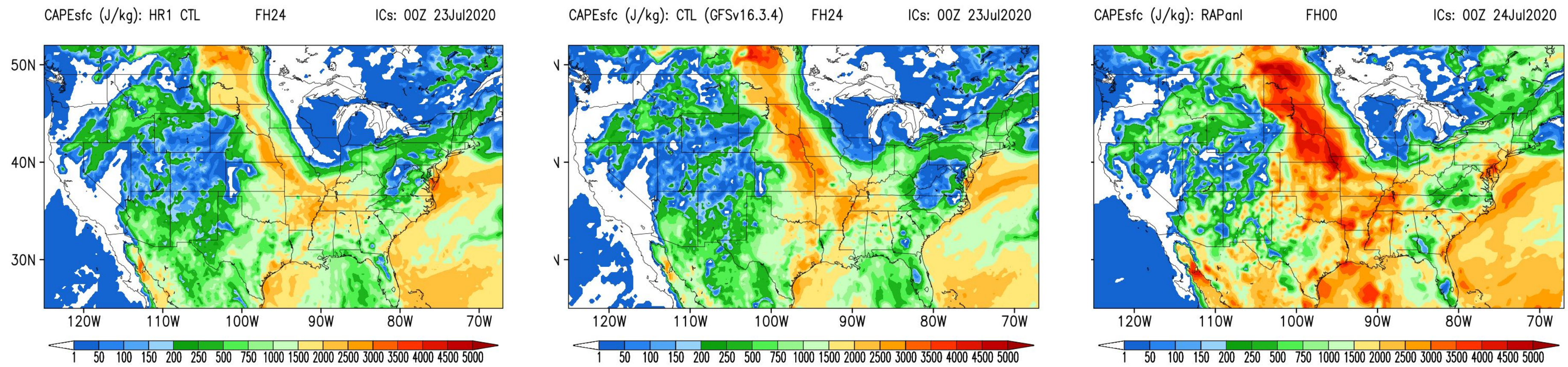
Compared to GFSv15, GFSv16 Captured well water vapor seasonal cycle in the stratosphere verified against UARS HALOE observations (no shown), attributed primarily to a higher model top and new Parameterization of middle atmospheric water vapor photochemistry (McCormack et al. 2008).

The same verification will be done for GFSv17

Improving CAPE for GFS.v17

Addressing Forecasters' Concerns

CAPE (J/kg) **Valid: 00Z 24 JUL 2020**



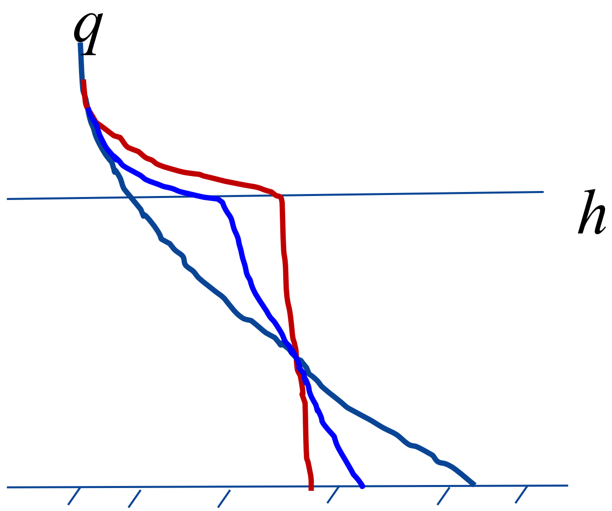
GFSv17 atmos-only Prototype

GFS.v16

RAP ANL

GFSv17 is less than Ops GFS.v16, and both are much less than RAP analysis

Sensitivity of CAPE to entrainment enhancement in TKE-EDMF PBL scheme



Dark Blue: no non-local mixing
Red: a full non-local mixing
Blue: reduced non-local mixing by enhanced entrainment rate

- Increase entrainment rate in updraft to reduce PBL mixing (1.3 c_ε --> 2.0 c_ε)
- Further adjust entrainment rate in updraft as a function of vegetation fraction (σ_f) and surface roughness length (z_0)

$$\varepsilon_u = c_\varepsilon \left[\frac{1}{z + \Delta z} + \frac{1}{(h - z) + \Delta z} \right]$$

$$f_1 = \frac{\sigma_f - 0.1}{0.9}, \quad f_2 = \frac{z_0 - 0.1}{0.9}$$

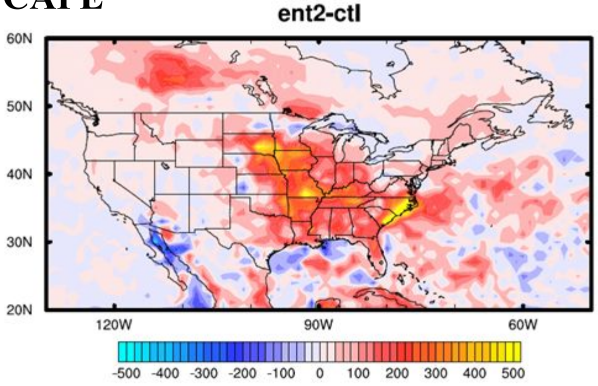
$$c_\varepsilon' = \left(1 + \sqrt{\min(\max(f_1, 0), 1)}\right)\left(1 + \min(\max(f_2, 0), 1)\right) c_\varepsilon$$

Improved CAPE and Q2m

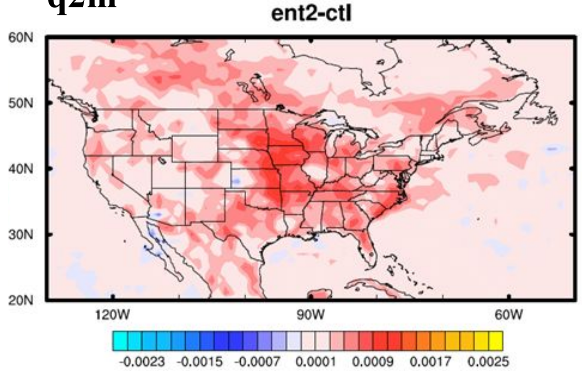
5-Day Fcst 20200716-20200830

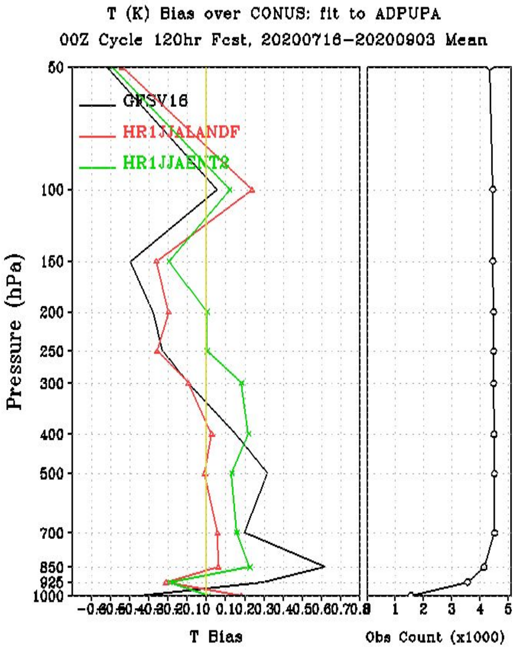
Improved T and Q profiles over CONUS

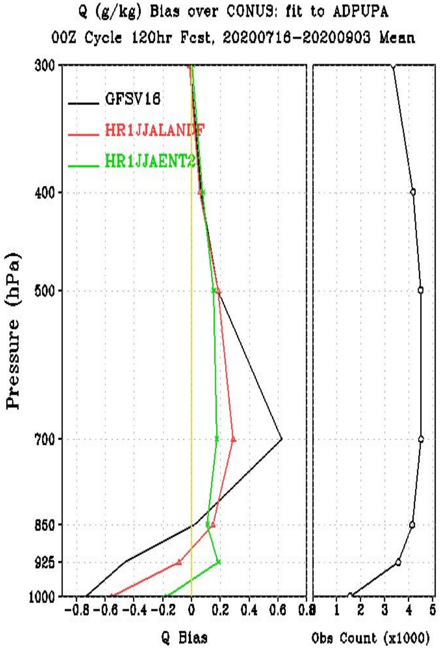
CAPE



q2m





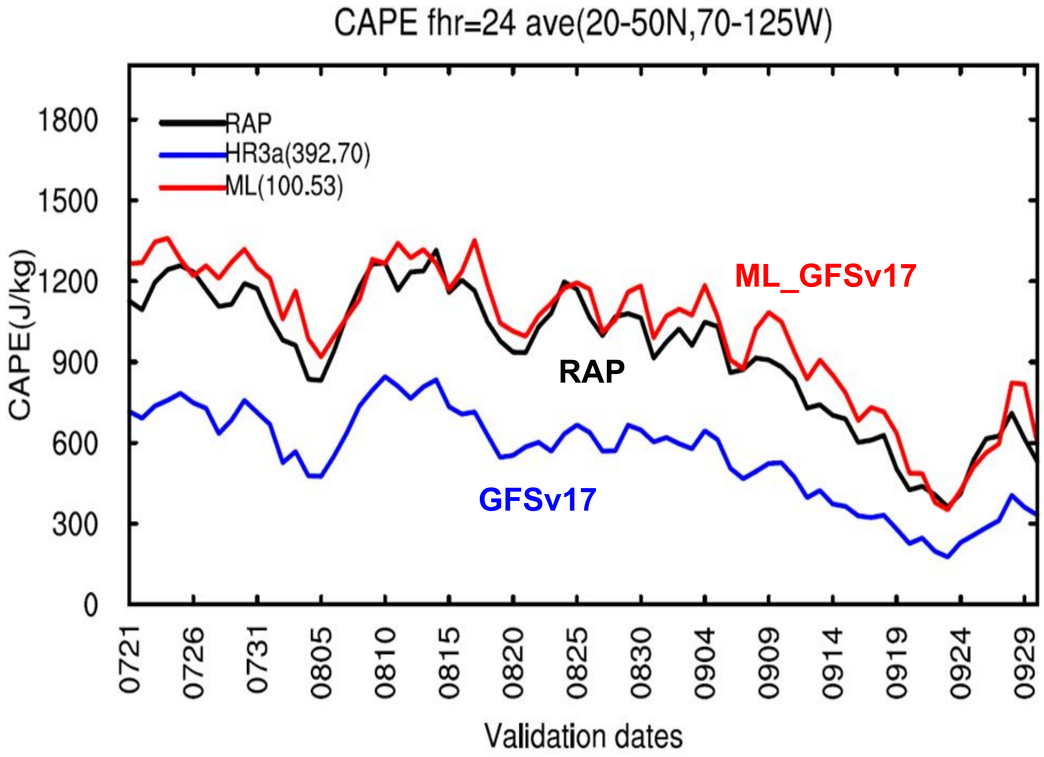


HR1JJALANDF: Control

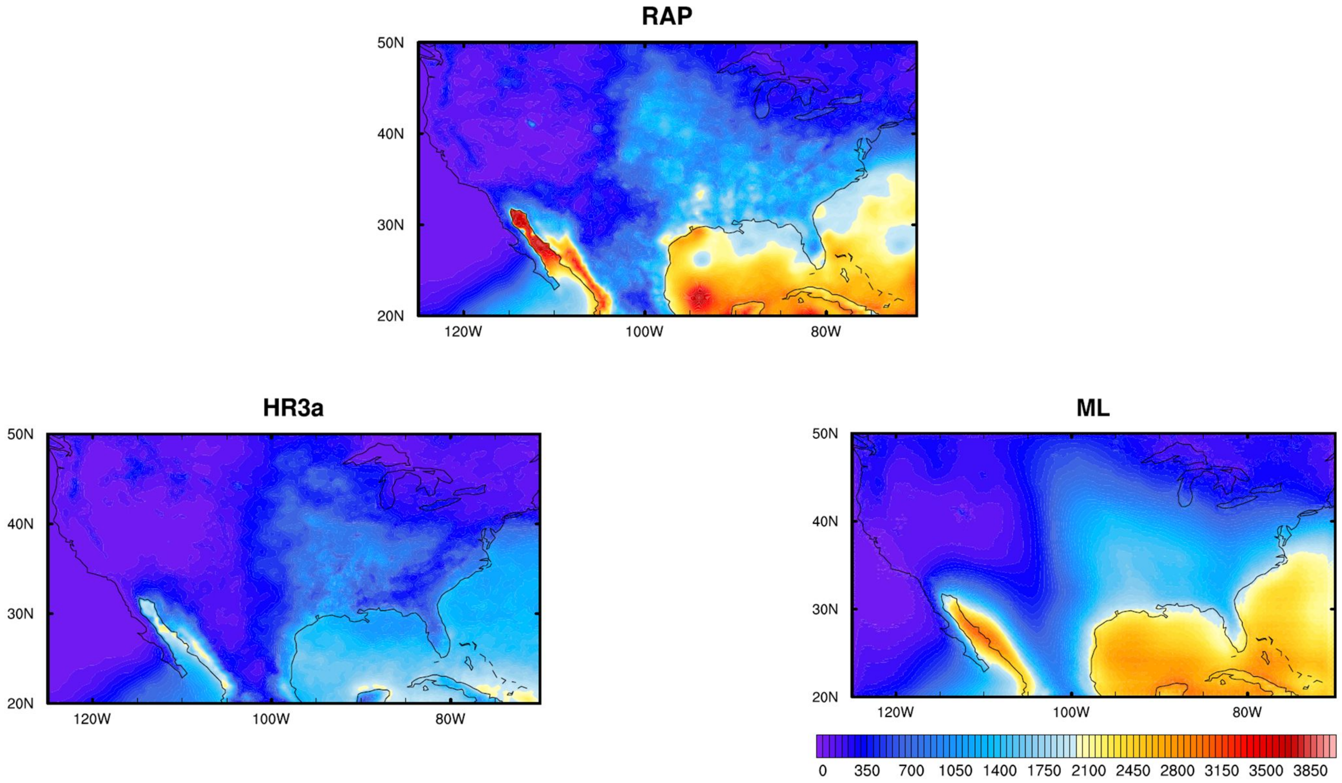
HR1JJAENT2: increased entrainment rate

Use Machine Learning (Unet) to Predict/Correct GFSv17 CAPE
fhr=24, 20200720-20200930

- **Training data:** CAPE + land sea mask from **GFSv16** forecast at F024
- **Ground truth:** CAPE from **RAP**
- **For each date only 00Z is used (no RAP f00 data for other initial time)**
- **Training parameters**
  - training data: 20210323-20230323 (730 samples shuffled, 90% training 10% validation)
  - epochs=50
  - learning rate= 0.001
  - batch size=32
  - (Hera) CPUtime: ~26 mins/epoch
  - (Hera) GPU time: ~0.4mins/epoch



CAPE fhr=24 ave(IC=20200720-20200930)



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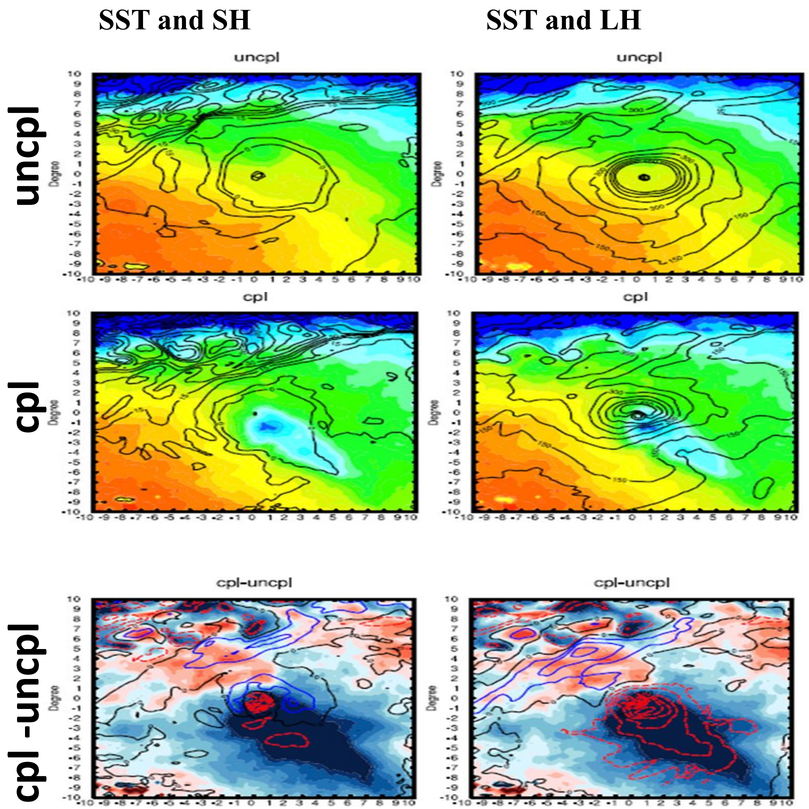
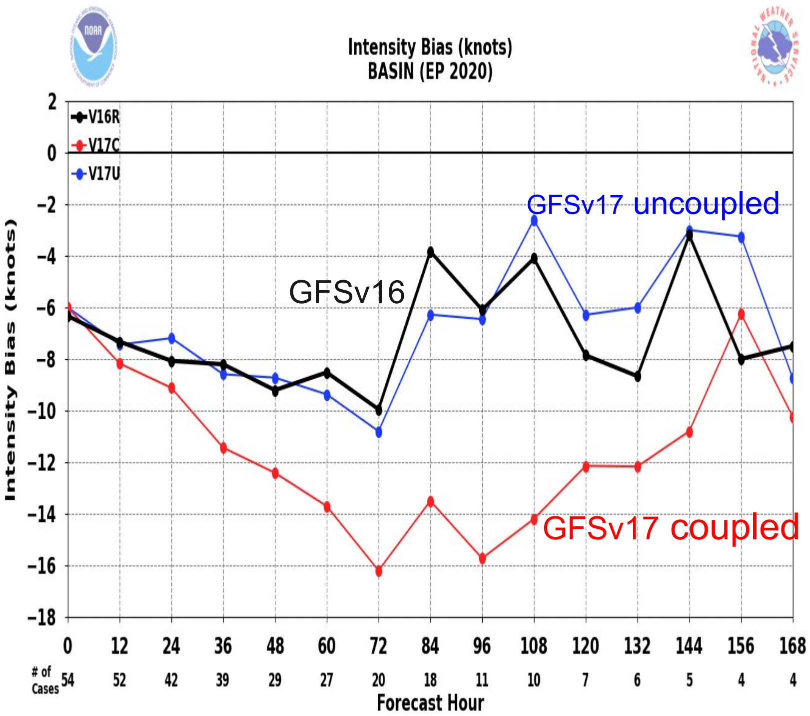
Weakening Hurricane Intensity in Coupled Model (GFSv17, 13-km)

Hurricane Teddy, IC 20200913, 132h Fcst

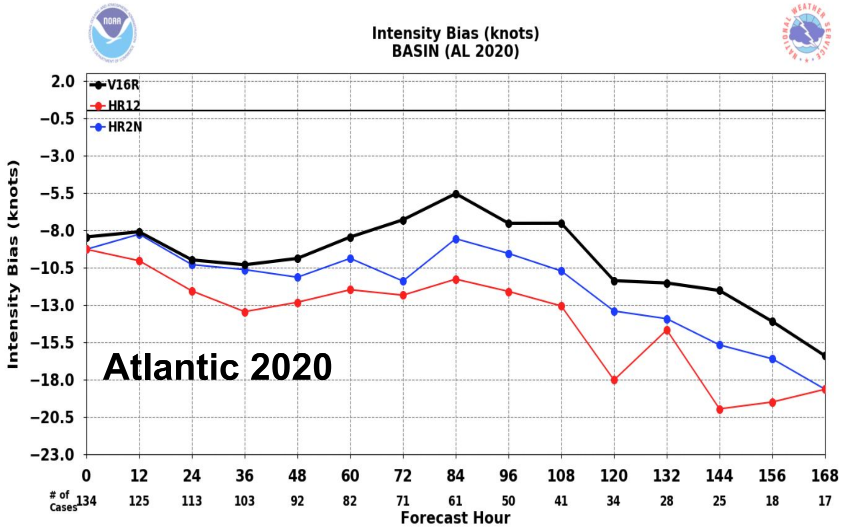


2020 Hurricane Season (Eastern Pacific)

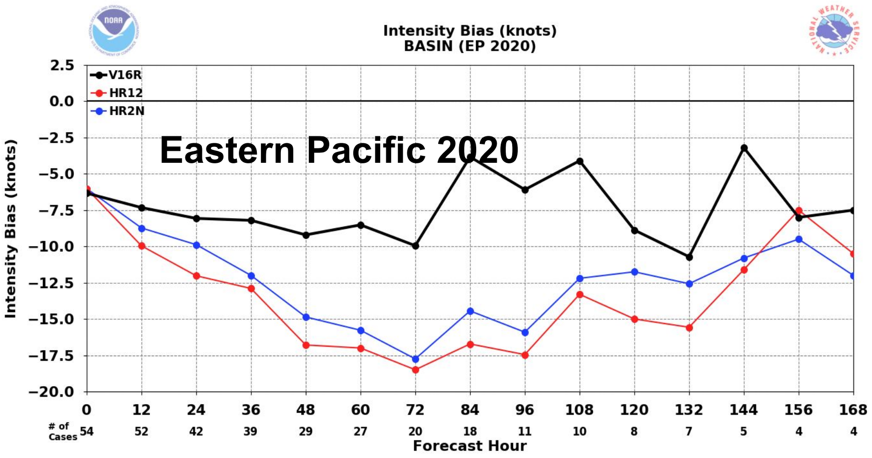


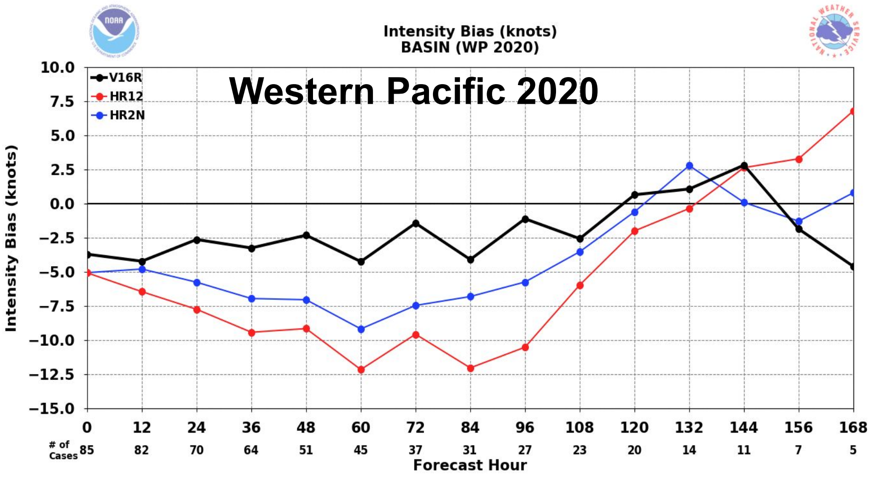
Reduced hurricane intensity biases in coupled GFSv17 by

- introducing environmental wind shear effect on convective updraft and downdraft and TKE-dependent entrainment enhancement
- Update Wave-Atmosphere interaction (ongoing)



V16R--GFSv16; HR12— HR1 coupled; HR2N—HR2 coupled





Improving MJO and Monsoon Forecast in Fully Coupled GFSv17 Prototypes

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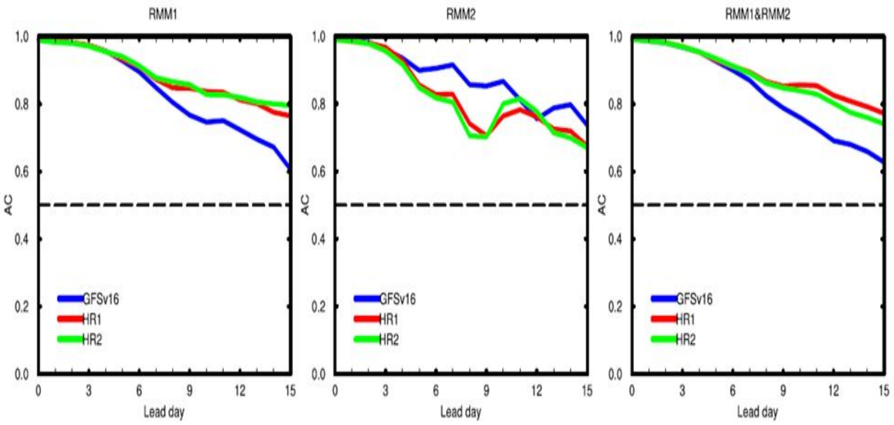
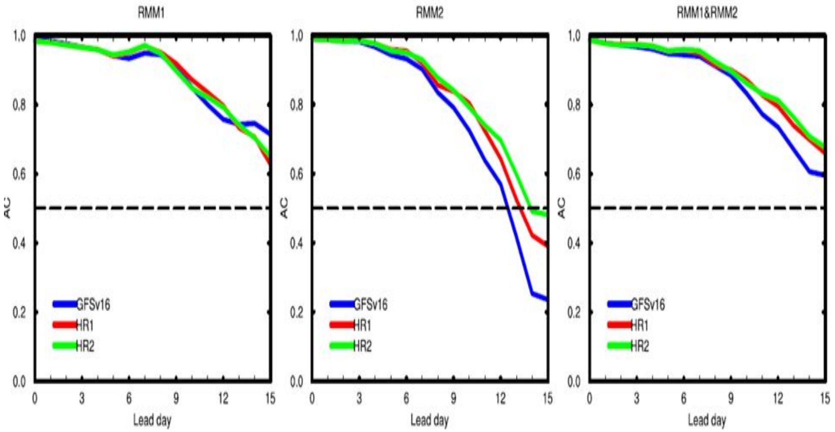
Improving MJO

RMM1 RMM2 RMM1&2



Summer 2020

RMM1 RMM2 RMM1&2



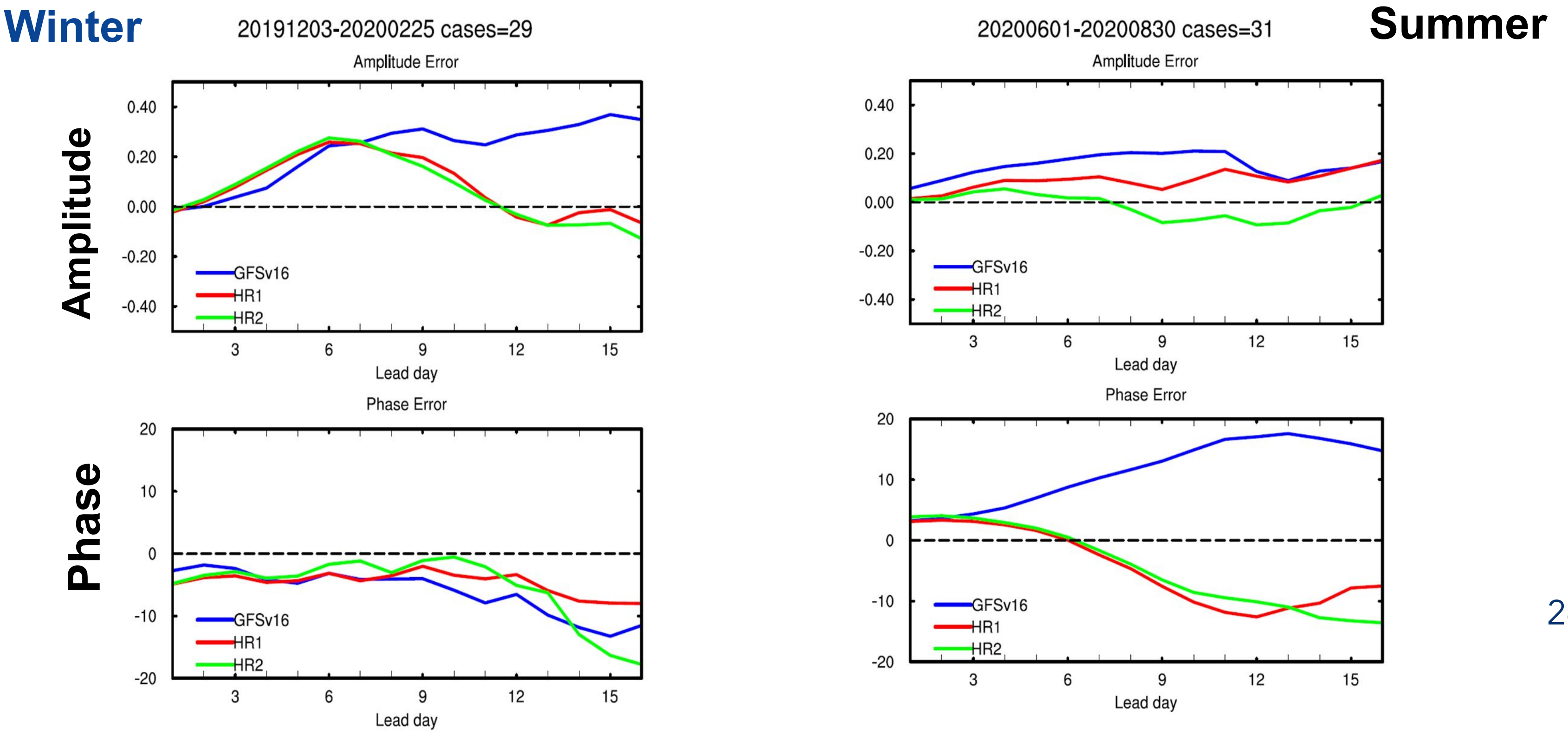
Winter 2019/20

Bengtsson et al, 2013, QJRM

$$\frac{\partial \sigma_u}{\partial t} \int (h_u - \overline{h}) \frac{dp}{g} = L \int \sigma_u \omega_u^* \frac{\delta q_{ca}}{g} + \alpha_{cvg} L \int CVGQ \frac{dp}{g} + \frac{\sigma_{CA} - \sigma_u}{\tau} * \left(\int (h_u - \overline{h}) \frac{dp}{g} \right)$$

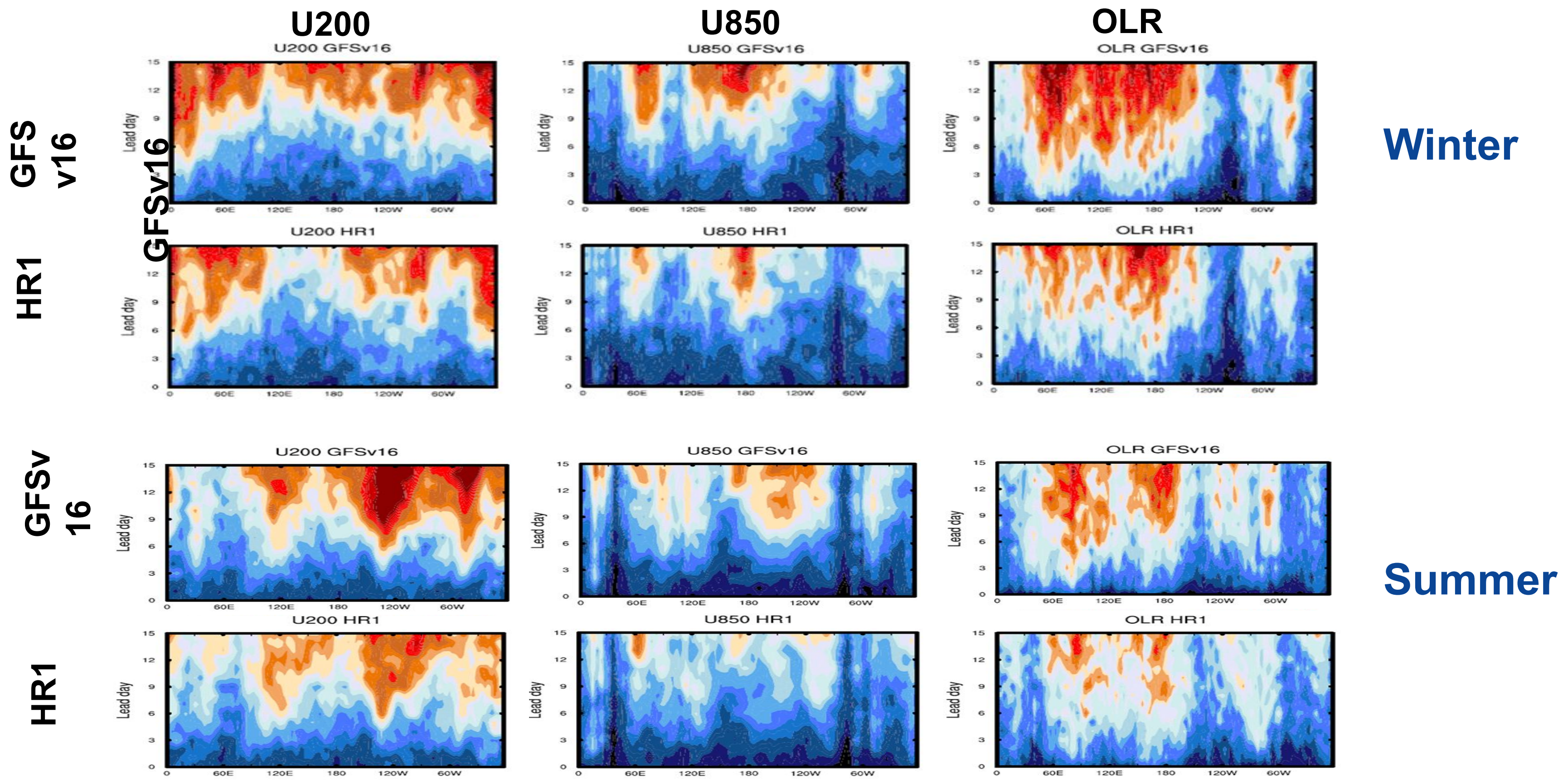
Area fraction = Source (resolved moisture flux convergence) + Sink (moisture -> cloud) + stochastic term

Bias

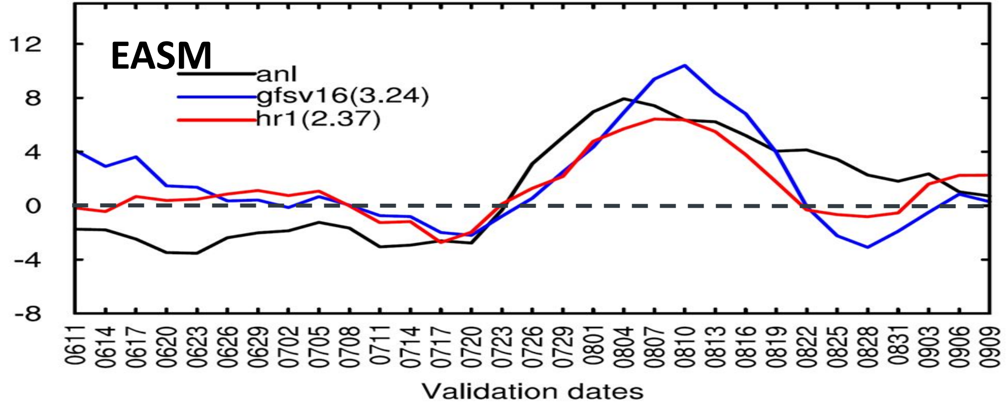

Winter
20191203-20200225 cases=29
Amplitude Error
Amplitude
0.40
0.20
0.00
-0.20
-0.40
GFSv16
HR1
HR2
3
6
9
12
15
Lead day
Phase Error
Phase
20
10
0
-10
-20
GFSv16
HR1
HR2
3
6
9
12
15
Lead day
Summer
20200601-20200830 cases=31
Amplitude Error
0.40
0.20
0.00
-0.20
-0.40
GFSv16
HR1
HR2
3
6
9
12
15
Lead day
Phase Error
20
10
0
-10
-20
GFSv16
HR1
HR2
3
6
9
12
15
Lead day

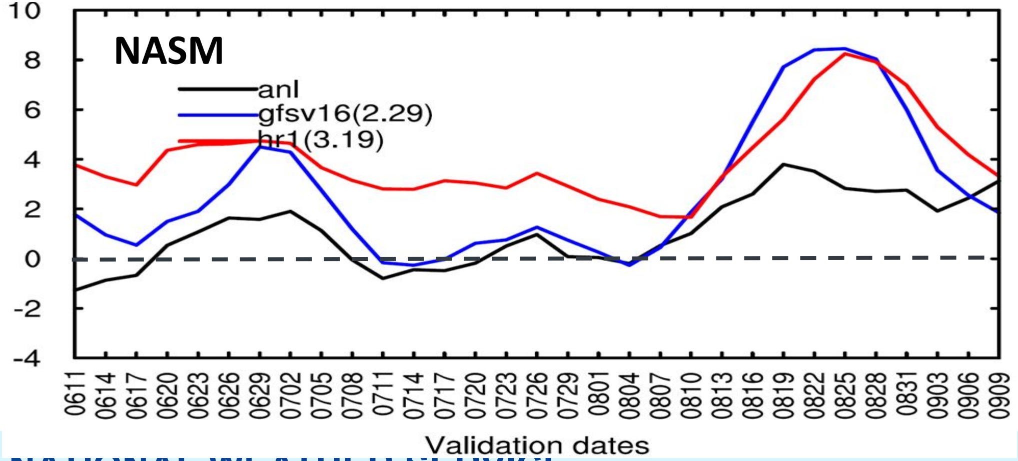
26

Improved MJO Through Reduced Component RMSE



Evolution of monsoon index (lead day=10)





- EASM: Strong/weak bias before/after monsoon onset in the model except peak time in GFSv16
- NASM: Strong bias in the model, especially in HR1

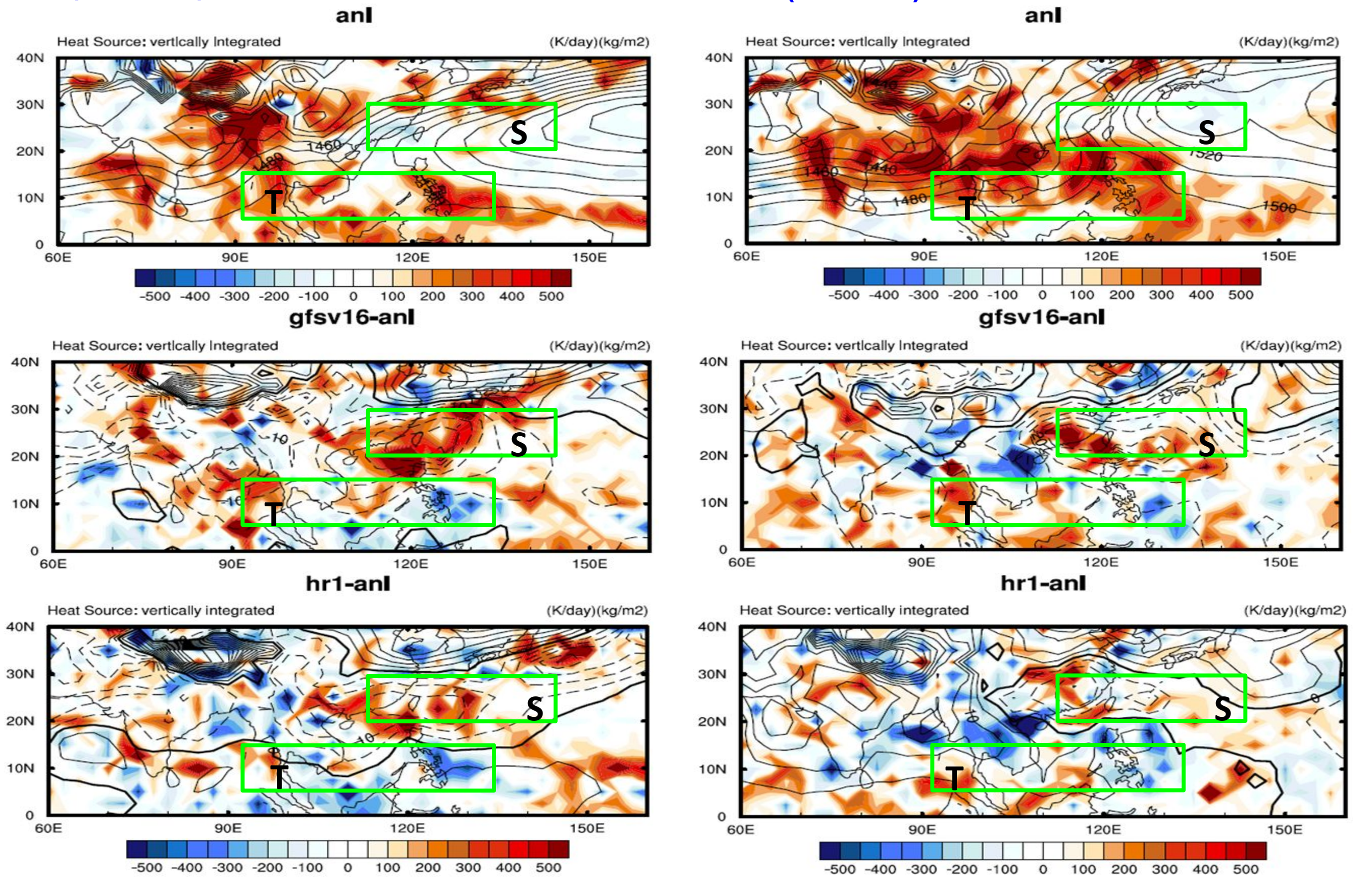
- EASM index= U850(5-15N, 90-130E)-U850(20-30N, 110-140E)

  - *CPC monsoon indices: https://www.cpc.ncep.noaa.gov/products/Global_Monsoons/Asian_Monsoons/Figures/Index/*

- NASM index= U850(5-15N, 130-100W)-U850(20-30N, 110-80W)

[Q1]&Z850: EASM (lead day=10)

ave(6.1-6.16), before monsoon onset | **ave(7.22-8.6) after monsoon onset**



- Warm [Q1] bias associated with low Z850 bias
- Opposite [Q1] meridional biases gradient before and after monsoon onset in tropical region
- **Less [Q1] bias in HR1 (eg GFSv17) over subtropical and tropical definition regions**

$$Q_1 = c_p \frac{\partial T}{\partial t} - c_p(\omega\sigma - \mathbf{V} \cdot \nabla T),$$

$$Q_2 = -L\frac{\partial q}{\partial t} - L\mathbf{V} \cdot \nabla q - L\omega\frac{\partial q}{\partial p},$$

[Q1]=[Qr]+LP+SH

[Q2]=L(P-E)

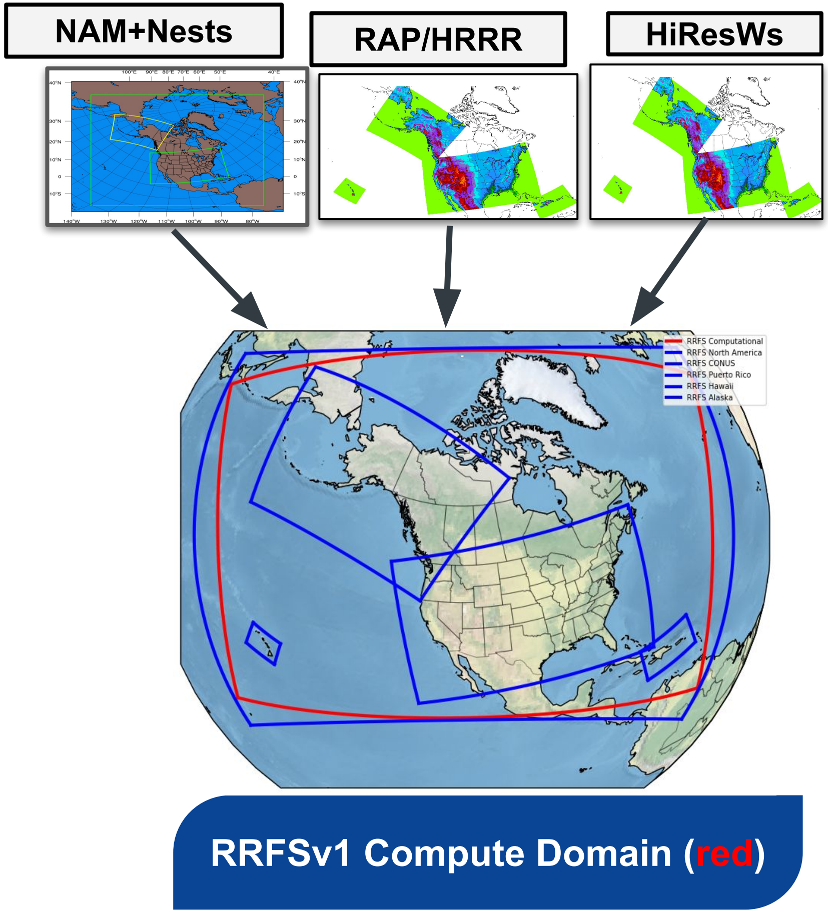
-Yanai etal. (1973, 1998)

-https://www.ncl.ucar.edu/Applications/Scripts/Q1Q2_yanai_1.ncl

RRFS, 3km resolution

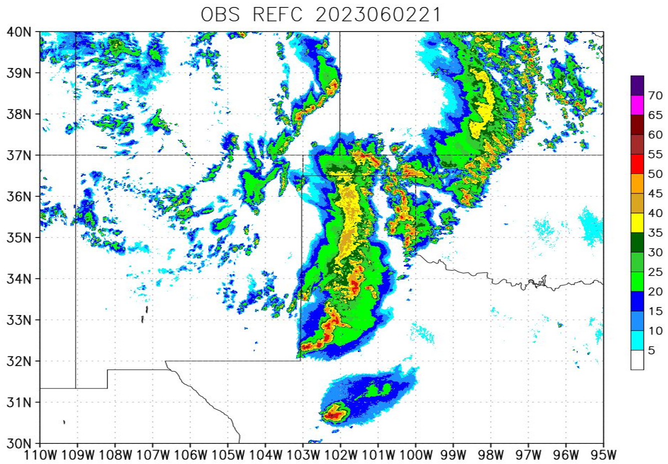
Overprediction of heavy precipitation and radar reflectivity in the regional Rapid Refresh Forecast System in weekly forced convective environment

Sensitivity to parameterized deep convection

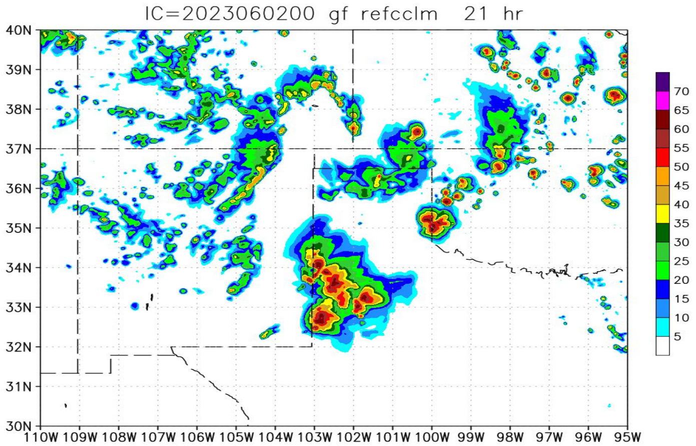


Radar Reflectivity, 2023060221

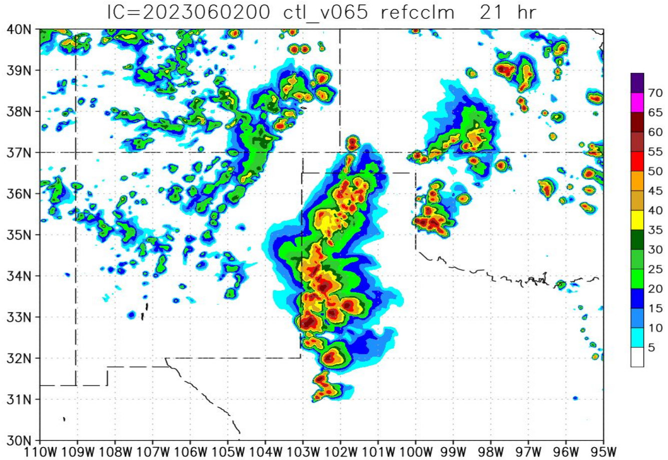
OBS



Grell-Freitas Convection

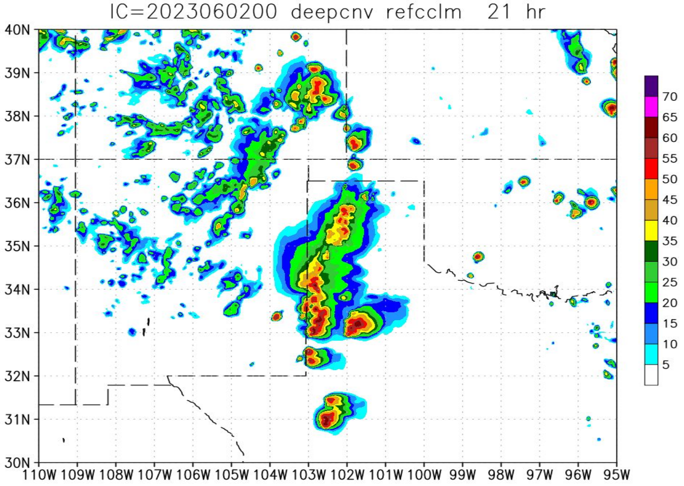


CTL
W/O parameterized convection



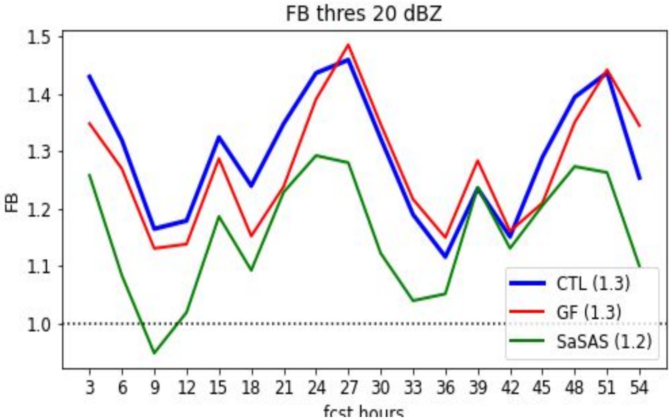
21h Fcst

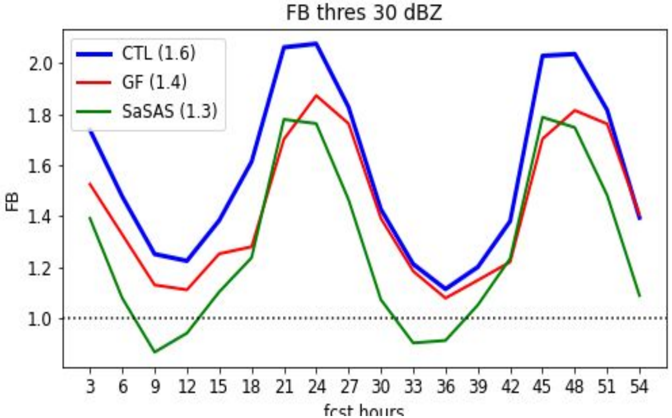
sa-SAS Convection

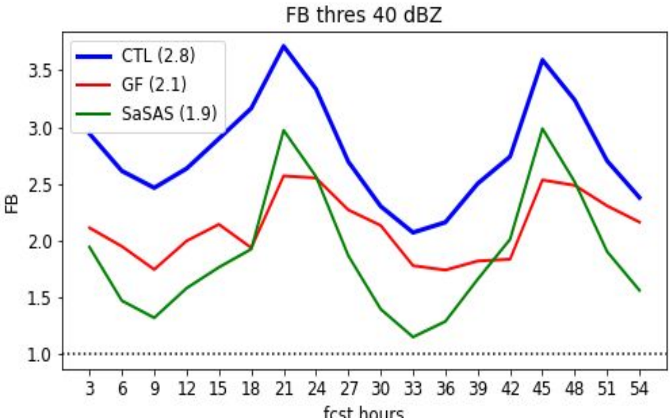


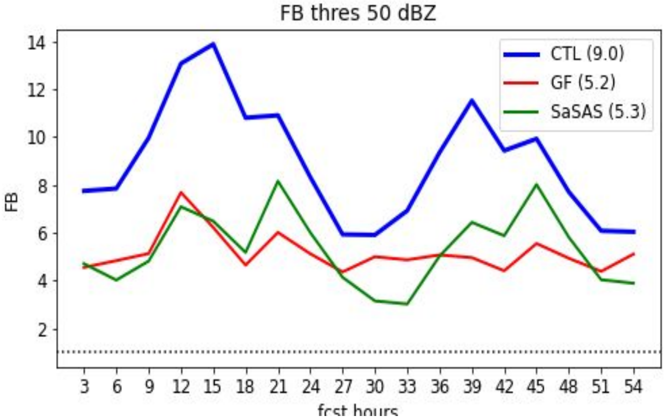
Reduced reflectivity bias with parameterized Deep Convection

- 28 Cases from 2023051100 to 2023061100; 00Z only
- ICs: From RRFS real-time parallel DA







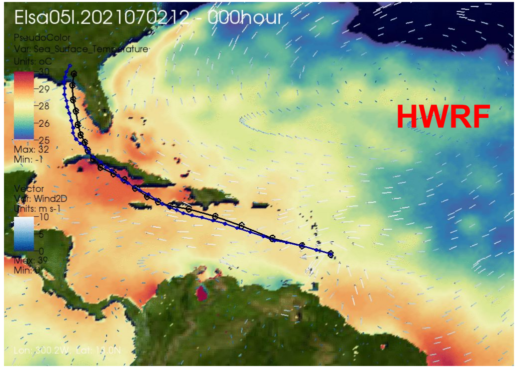


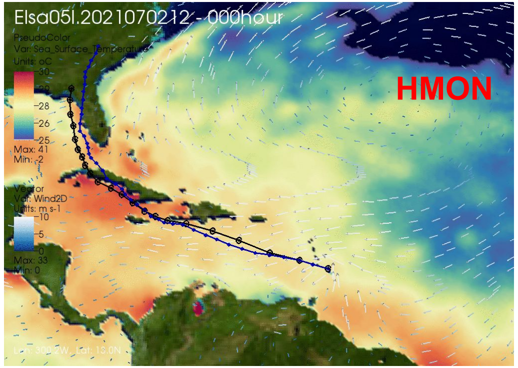
On NOAA’s legacy operational hurricane prediction system (HWsRF/HMON) and the new UFS-based Hurricane Analysis and Forecast System (HAFS)

Slides on hurricanes were provided by Zhan Zhang

Legacy Operational Tropical Cyclone Prediction Models at NCEP

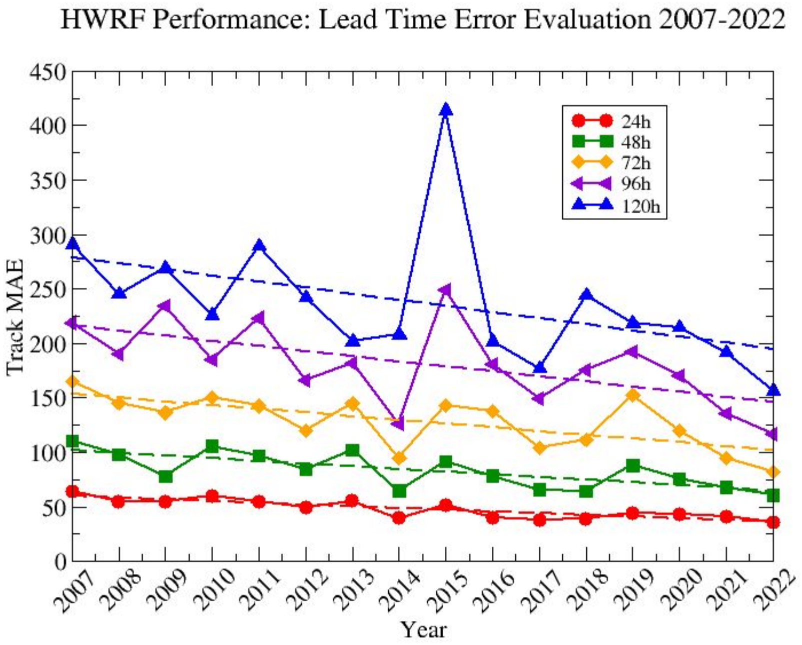
	HWRF	HMON
Dynamic core	Non-hydrostatic, NMM-E	Non-hydrostatic, NMM-B
Nesting	13.5/4.5/1.5 km; 77°/18°/6°; 75 vertical levels; Full two-way moving	18/6/2 km; 75°/12°/8°; 71 vertical levels; Full two-way moving
DA and Initialization	Vortex initialization, Self-cycled hybrid EnKF-GSI with inner-core DA (TDR)	Modified vortex initialization, no DA
Physics	Updated surface (GFDL), GFS-EDMF PBL, Updated Scale-aware SAS, NOAH LSM, Modified RRTM, F-A MP	Surface (GFDL), GFS-EDMF PBL, Scale-aware SAS, NOAH LSM, RRTM, F-A MP
Coupling	MPIPOM for NHC AOR; HYCOM JTWC; RTOFS, WaveWatch-III	HYCOM, RTOFS, No waves
Post-processing	NHC interpolation method, Updated GFDL tracker	NHC interpolation method, GFDL tracker
Operational forecasts	All global basins (NHC/JTWC), max. 7 TCs on-demand	NHC basins, max. 5 TCs, on-demand
Computation Resources	91 nodes in 98 mins	43 nodes in 100 mins

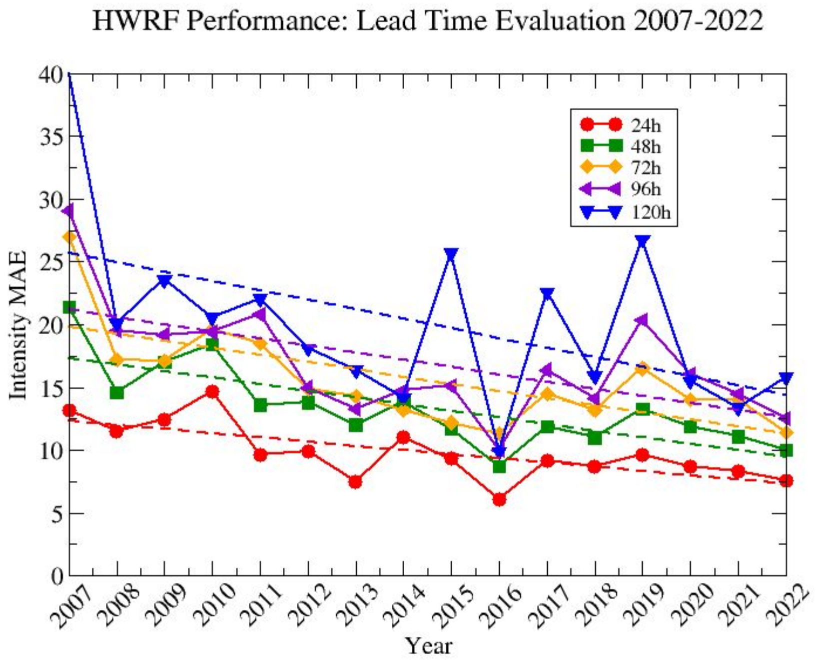




Note: Items in Green are similar/same; Items in Red are different

HWRF Track/Intensity Forecast Error Trend

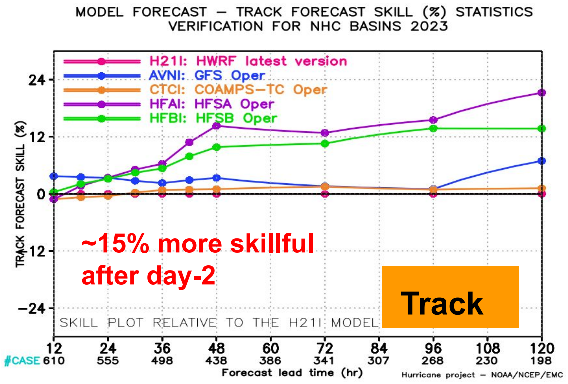


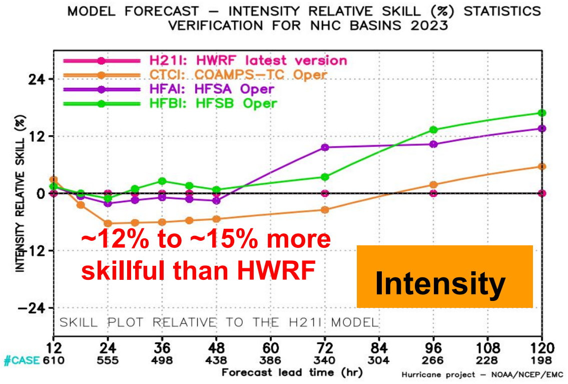


Operational HAFSv1 (Hurricane Analysis and Forecast System)

- **HAFSv1, first major UFS-based hurricane application, was implemented on June 27, 2023**

- **Successful community modeling approach for accelerated transition of research to operations**
  - **Cloud-allowing high resolution moving nest**
  - **Formal vortex initialization and GSI-based data assimilation**
  - **TC-specific physics**
  - **Two-way coupled to Ocean models in all global basins**
  - **One-way coupled to Wave model (WW3) in NHC basins**
  - **Inner-core DA including real-time data from recon missions**



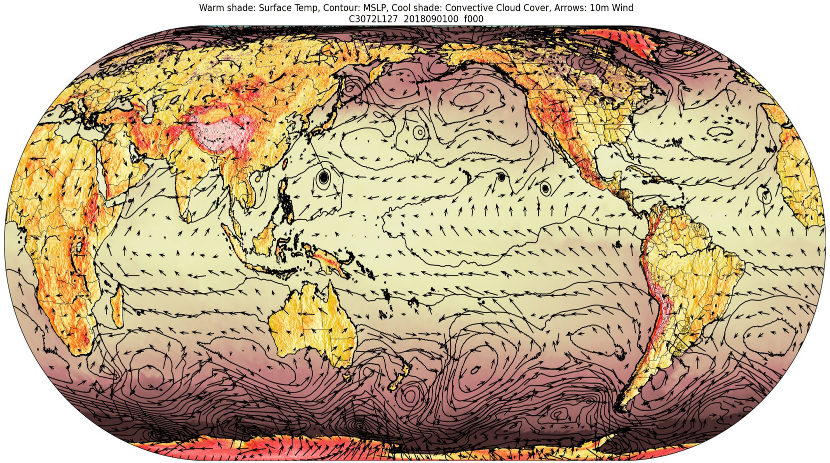


Thoughts on Physics Unification -- Opportunities and Challenges

- **Efforts have been made in the past few years in the UFS and UFS-R2O community to develop scale adaptive physics parameterizations that can be used in UFS applications across different spatial and temporal resolutions, but challenge remains.**
- **Schemes that have been traditionally developed for global models at ~10-km and coarser resolution do not work well out of the box for regional high-resolution models. Likewise, schemes used by regional high-resolution models do not always work well in global models.**
- **To achieve unification, physics parameterizations that have strong dependence on model grid size need to be evaluated in both UFS global and regional applications.**
- **Schemes like microphysics, convection, PBL, and GWD needs further development to become truly scale aware**

Thank you

A fully coupled UFS serves as a foundation for future operational global forecast systems at NOAA/NWS/NCEP ranging from weather to subseasonal to seasonal scales.



UFS Earth System Model Components:

- FV3 (Atmosphere)
- MOM6 (Ocean)
- CICE6 (Sea Ice)
- WW3 (Waves)
- NOAH-MP (Land)
- GOCART (Aerosols)

MRW/S2S: Building a Six-Way Global Coupled Unified Forecast System
For future GFS, GEFS and SFS