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On the Development and Evaluation of Atmospheric Model Physics for the Unified Forecast System Applications Across Scales

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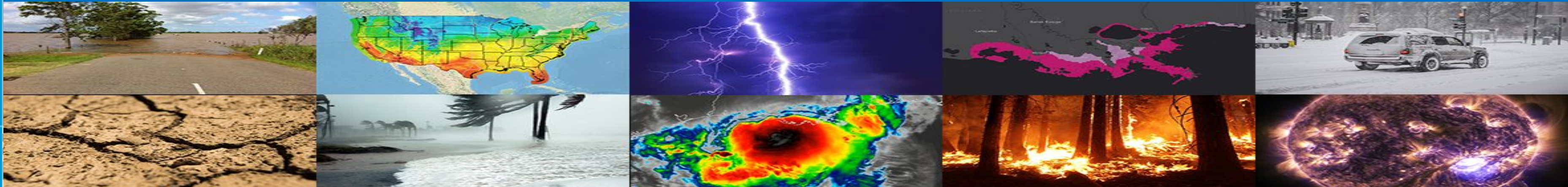
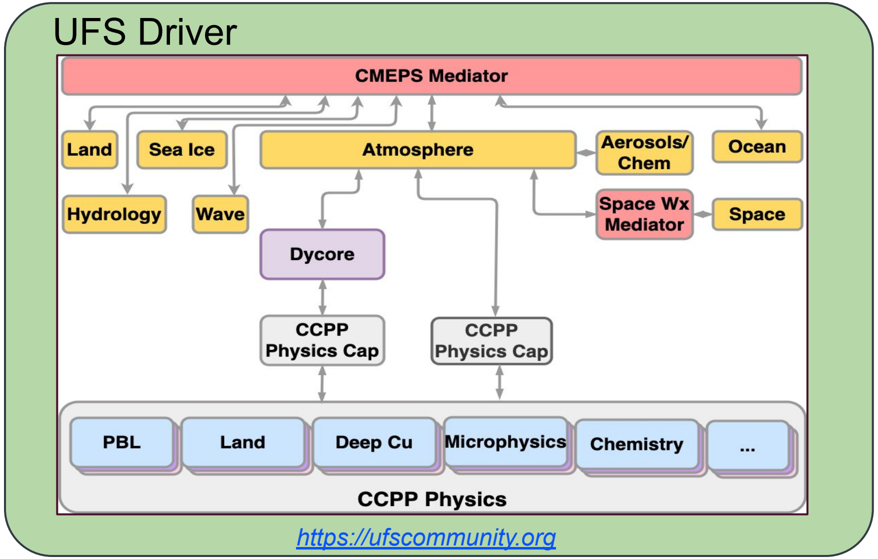


NOAA is collaborating with the US weather and climate science community to develop the next generation fully coupled earth system modeling capability for both research and operational forecast applications across different temporal and spatial scales.



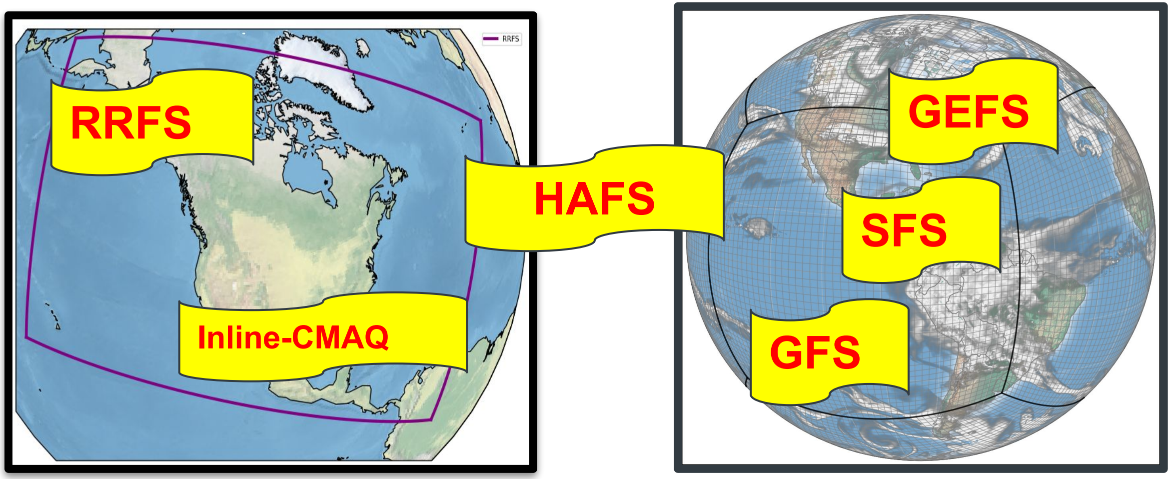
- CMEPS mediator
- FV3 dycore
- CCPP Physics
- MOM6 ocean

- WAVEWATCH III wave
- CICE6 ice
- GOCART aerosol
- Noah-MP land

Physics for UFS Applications:

- Develop and improve physics parameterizations for UFS applications to reduce model systematic biases 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.

CAM/SRW



MRW/S2S

Physics Updates for MRW/S2S Prototype #7

	GFS.v16	UFS
Cumulus Convection (Shallow & Deep)	sa-SAS	Positive definite mass flux; stochastic convective organization; Improved CAPE
Surface Layer	GFS	Sea spray; optimization
PBL	sa-TKE-EDMF	Positive definite tracer advection; optimization
Non-orographic GWD	uGWP v0	uGWP.v1 (Yudin et al., 2021)
Orographic Gravity Wave Drag Small-scale gravity-wave drag (new) Turbulence Form drag (new)	Kim & Arakawa (1995)	uGWP.v1 Kim and Doyle (2005) Tsiringakis et al. (2017) Beljaars et al. (2004)
Land	Noah LSM	NOAH MP and VIIRS veg type
Aerosol	OPAC	MERRA2
Fractional grid	N/A	compositing albedo and emissivity; fractional grid enabled surface cycle; z_bot calculation for coupling stability etc

Updated

New

Physics Updates for MRW/S2S Prototype #8

	GFS.v16	UFS
Microphysics	GFDL MP	**Thompson MP** ● improve computational stability (inner-loop), ● optimize cloud cover and radiative fluxes ● use Semi-Lagrangian sedimentation for rain and graupel ● develop cloud-aerosol interaction scheme
Radiation (LW &SW)	RRTMG	RRTMGp *(pending on improvement in computational efficiency)*
Ice climatology	CFSR (model)	IMS-NIC (observation & retrievals)
land/sea/lake masks	MODIS	VIIRS

New

- Convection, PBL, Noah-MP, GWD parameterizations included in P7 are further updated to improve their performances for both coupled and uncoupled models at C384 and C768 resolutions.
- **Some of the schemes are also tested and evaluated in RRFS and HAFS for physics unification.**

Physics Planned for RRFS.v1

Physics	SCHEME	REFERENCE
PBL/Turbulence	MYNN-EDMF	Olson et al. (2019)
Surface Layer	MYNN	Olson et al. (2021)
Microphysics	Thompson-Eidhammer	Thompson and Eidhammer (2014)
Climatological Aerosols	Thompson-Eidhammer	Thompson and Eidhammer (2014)
Smoke and Dust	RAVE fire data, FENGSA scheme for dust	Ahmadov et al., Freitas et al., 2010
Shallow Convection	MYNN-EDMF	Olson et al. (2019) Angevine et al. (2020)

Gravity Wave Physics	Small Scale and Turbulent Orographic Gravity-Wave & Form Drag	Beljaars et al. (2004) Tsiringakis et al. (2017) Toy et al. (2021)

Land Model	Noah-MP	Niu et al. (2011)
Large Lakes	FVCOM	Fujisaki-Manome et al. (2020)
Small Lakes	FLake/CLM Lake	Mironov (2008)/Subin et al. (2012), Mallard et al. (2015)
Near-Surface Sea Temperature	NSST	Fairall et al. (1996), Derber and Li (2018)
Long and Short Wave Radiation	RRTMG	Iacono et al. (2008), Mlawer (1997)

Model Physics for 2022 HAFS Real-Time Experiments

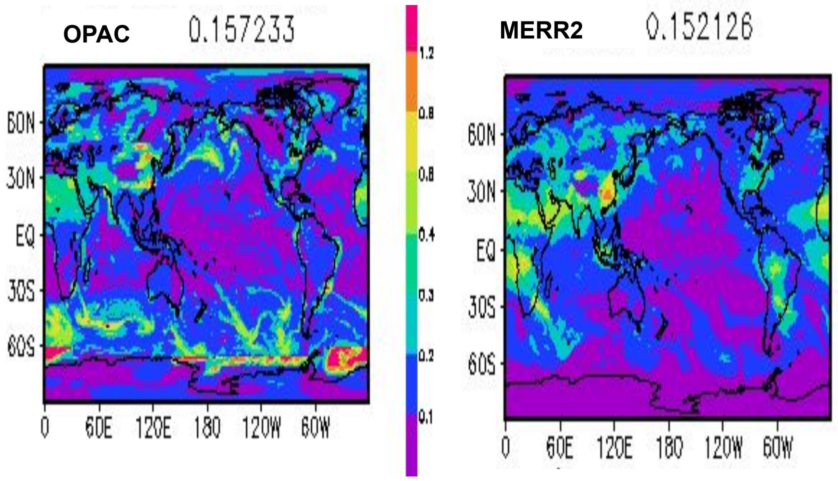
	Suite 1	Suite 2
Cumulus Convection (Shallow & Deep)	sa-SAS: Positive definite mass flux; Stochastic convective organization; Optimization for CAPE	sa-SAS: Positive definite mass flux; Stochastic convective organization; Optimization for CAPE, TC-specific tuning
Surface Layer	GFS: Sea spray, optimization	GFS: Sea spray; optimization,TC-specific tuning
PBL	Modified sa-TKE-EDMF: Positive definite tracer advection; TC-Specific tuning	Modified TKE-EDMF: Positive definite tracer advection; optimization, TC-Specific tuning
Gravity Wave Drag	Orographic/Convective: On/Off	Orographic/Convective: On/Off
Land Surface Model	Noah LSM	NOAH MP and VIIRS veg type
Microphysics	GFDL MP	Thompson MP (requires ~10% more resources)
Radiation (LW & SW)	RRTMG (30 min)	RRTMG (30 min)

For unification, physics options (Thompson MP, NOAH MP, uGWPv1) planned for GFS.v17/GEFS.v13 are also evaluated in HAFSv0.3 Suite 2 configuration.

Aerosols: OPAC versus MERRA2

	OPAC	MERRA2
Horizontal resolution	5 by 5 degree	0.5 by 0.625 degree
Vertical levels	5 regimes (One layer/two layers)	72 (Surface to 1 Pa)
Aerosol types	10 (1 inso, 1 so, 2 ss, 4 mineral, 1 su)	15 (5 du, 5 ss, 2 oc, 2bc, 1su)
Stratosphere volcano	Background (1.e-4)	Assimilated SS and SU
Data Collected	Before 1998	2003-.

Total aerosol optical depth (0.55 mu)



Sulphate aerosol, dust, sea Salt, black carbon, organic carbon

- OPAC has been used in NCEP operational models for more than 20 years.
- MERRA2 is now active in the UFS Prototypes, RRFS and HAFS for computing aerosol direct radiative forcing.
- Development is underway to take into account interaction of aerosols with clouds

Microphysics: GFDL MP vs Thompson MP

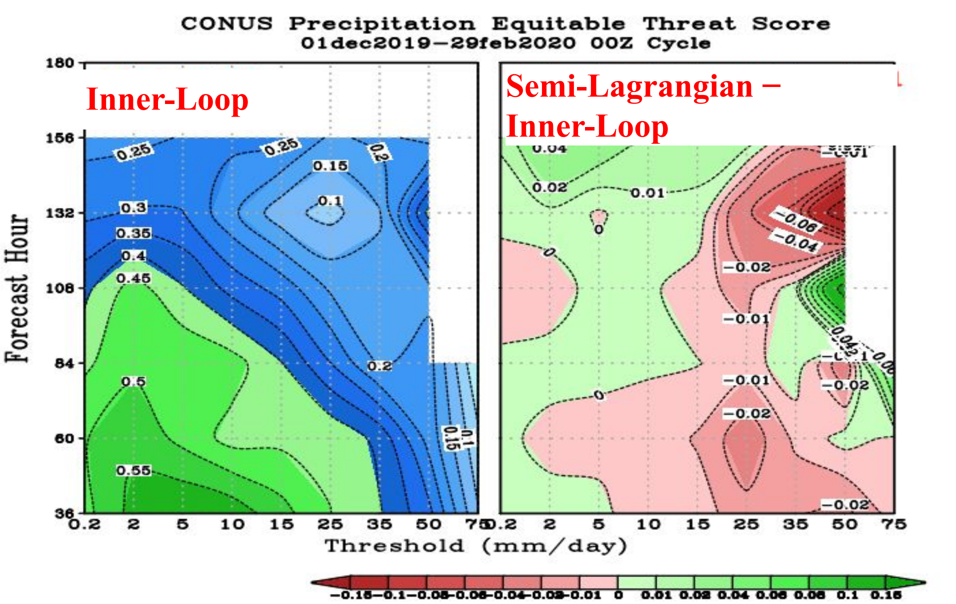
	GFDL MP (single moment)	Thompson 2008/2014 (double)
prognostic variables	qv, ql, qi, qs, qr, qg	qv, ql, qi, qs, qr, qg, ni, nr (2008) + nc, nwfa, nifa (aerosol-aware)
condensation and evaporation	Lin, et al (1983)	Yau and Austin (1997), Thompson and Eidhammer(2014)
mixed-phase clouds	yes	yes
precipitation sedimentation	qi, qr, qs, gq sediment vertically	qi, qr, qs, qg sediment vertically (ql)
assumed PSD	exponential	generalized gamma

- GFDL MP has been used in operational GFS and GEFS since 2019.
- Significant effort has been put into **eliminating computational instability of Thompson MP** in both global and regional models. **Subcycling microphysics and semi-Lagrangian sedimentation** (applied to rain and graupel) techniques have been developed and successfully tested and evaluated in these models.
- Thompson MP without aerosol awareness is currently running in **RRFS, HAFS Suite-B, and UFS Prototype 8**.

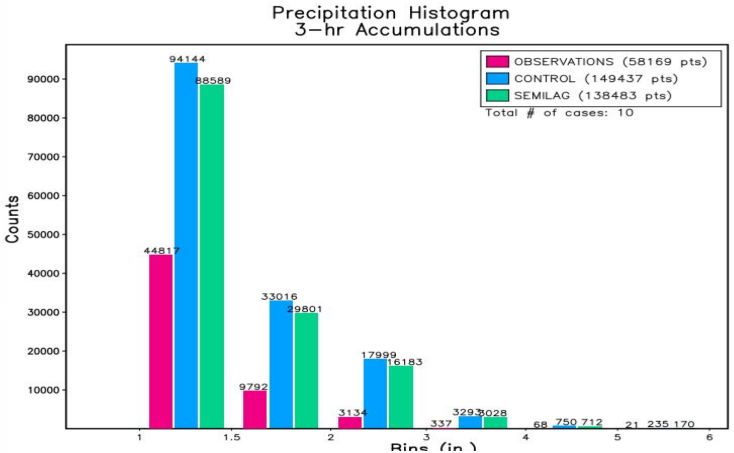
UFS Microphysics Development

The Semi-Lagrangian sedimentation of rain and graupel has been implemented in the Thompson MP scheme to improve its accuracy and **computational efficiency (> 12% reduction)**. It has been extensively tested and incorporated into the most recent UFS prototype configuration.

Impact on 13-km Global Model Precipitation

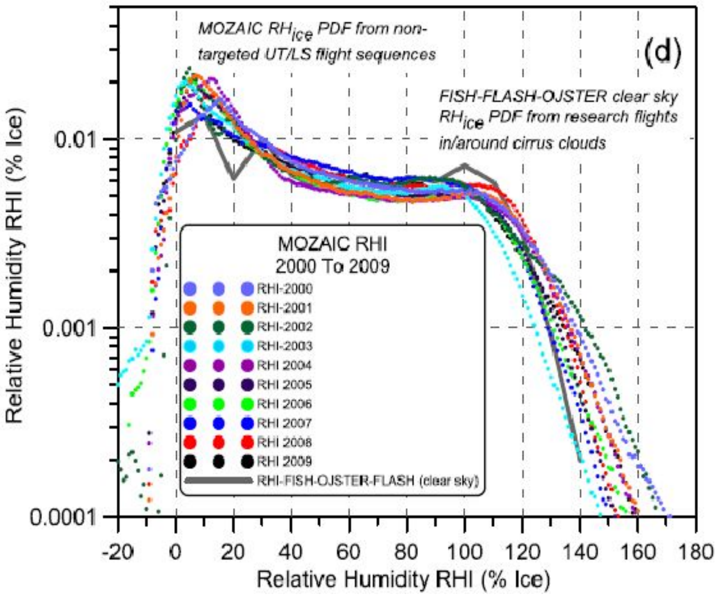


Impact on 3-km RRFS

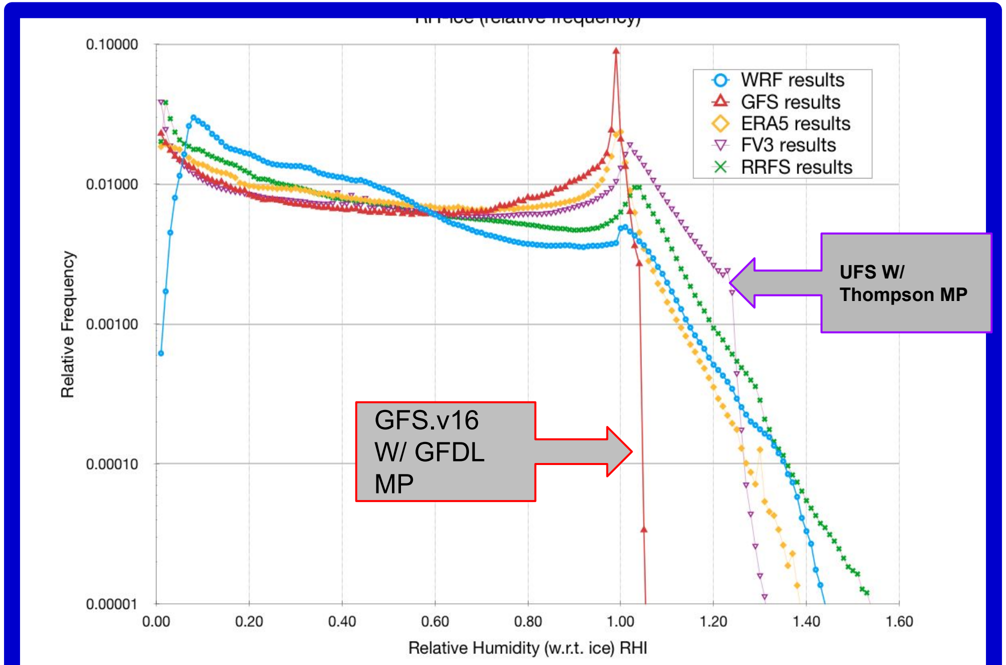


reduces the high biases in the 3-h accumulated **precipitation rates < 2.5 inches**

UFS Microphysics Development -- Challenges



Observed frequency distribution (PDF) of RH relative to ice (RHI) from MOZAIC flight-level obs. (Krämer et al.,2009)



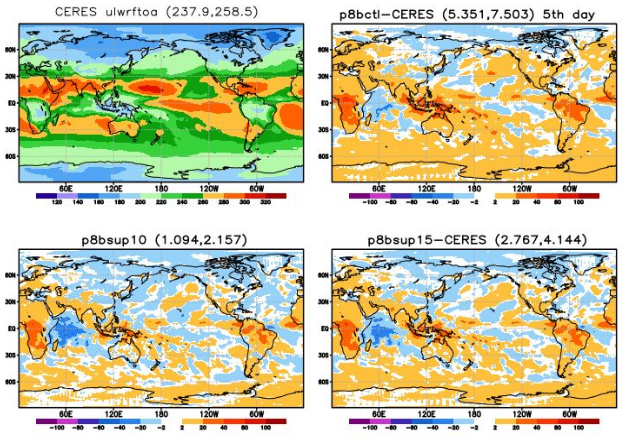
RHI PDF from various models (Credit: Greg Thompson). **Supercooled cloud water presents a hazard to aviation !**

UFS Microphysics Development -- Challenges

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

g/m2	GFSv16 GFDL MP	GFSv16 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 radiative balances



UFS p8b experiment: OLR varies with RHic for supersaturation

UL: CERES obs
UR: RHi=125%
LR: RHi=115%
LL: RHi=110%

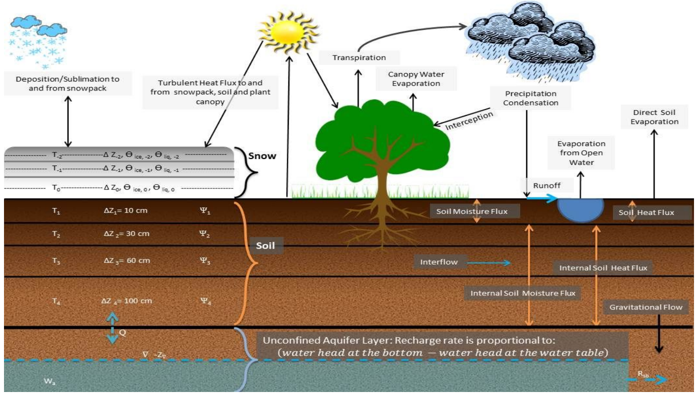
Further Development of Thompson MP

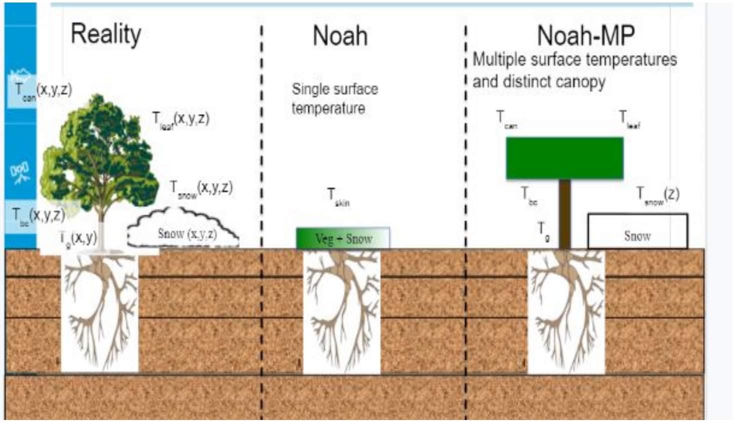
- Improving cloud cover and radiative balances in global model
- Improving storm structure and precipitation in regional model

- **Develop Aerosol-cloud-radiation interactions with a hierarchical approach**
    - MERRA2 aerosol climatology, without aerosol chemistry, emission, physics (deposition and scavenging), and transport.
    - Thompson-Eidhammer double-moment scheme, with MERRA2 climatology for initialization and including in model integration aerosol emission, deposition and scavenging, and transport.
    - Thompson-Eidhammer double-moment scheme, including only water friendly and ice friendly aerosols, with emissions included (OAR/GSL).
    - Coupled to aerosols predicted by the online-GOCART aerosol module.

Land Surface Model: Noah vs Noah-MP LSM

https://www.jsg.utexas.edu/noah-mp/





Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes (courtesy of Mike Barlage)

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover

- NOAH LSM has been used in NCEP operational models since mid 2000’s
- NOAH-MP is now running in the UFS couple model prototypes (for GFS/GEFS/SFS).
- Currently actively tested in RRFS and HAFS.
- Recent updates include calling GFS and MYNN surface layer inside NOAH-MP, updating snow physics, using VIIRS veg type and land/lake masks, and developing land spin-up process etc

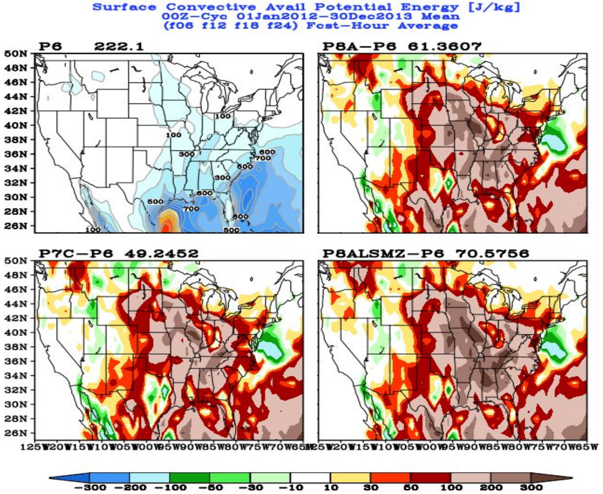
Land Model Development, Evaluation, and Application

EMC land and ensemble team

Develop/refine Noah-MP code

A series of mini PT tests have been carried out to test each land surface upgrade to address some land-related biases found in P7 and P8, An option of the **thermal roughness length scheme** was added to the model. The canopy height dependant scheme was selected to reduce the warm bias of the minimum 2-m T. **Snow compaction** was adjusted to improve snow forecast

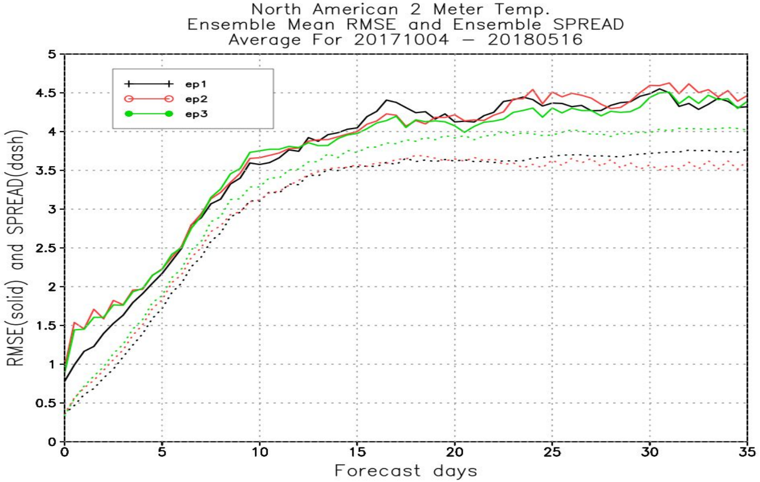
Surface CAPE [J/kg] Day 1 Mean Mini-prototype Cases



Issue: CAPE too low, especially over central US

Solution: improve surface coupling with Noah-MP, **increase latent heat flux**

GEFS tests with updated NOAH-MP

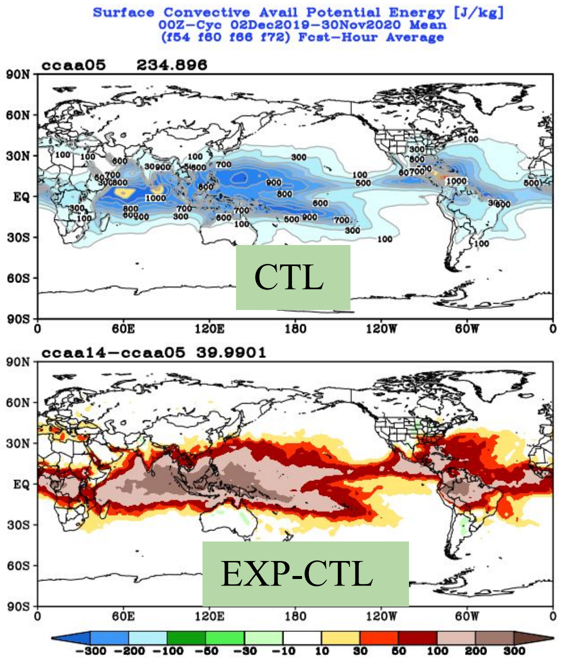


Ensemble forecasts made with the latest p8 physics suite (EP3) showed much improved T2m ensemble spread in cold seasons. We are still working towards understanding how the various physics updates contributed to this improvement, in particular the feedback between cloud microphysics and NOAH-MP.

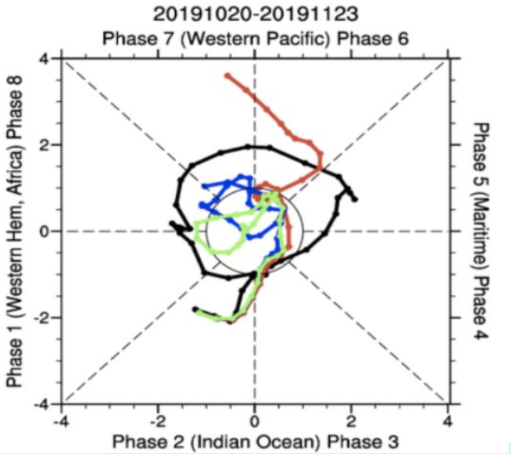
Updated Convection and PBL Schemes

- **Updated sa-SAS cumulus convection, TKE-EDMF PBL and GFS surface layer scheme** to improve CAPE and to reduce cold bias in the tropical troposphere found in GFSv16, and to improve surface temperature forecasts. (link)
- Added a positive definite **TVD** (Total Variance Diminishing) mass-flux scheme to remove negative tracers in the PBL and cumulus convection parameterizations.

CAPE



- Added A stochastic parameterization of organized tropical convection using **cellular automata** (Bengtsson et al. 2021) to improve MJO.



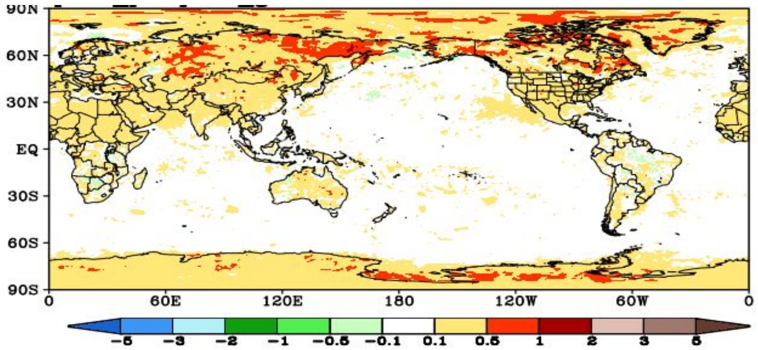
Challenges of Implementing RRTMGp in the UFS

- **RRTMGp is more computationally efficient than RRTMG in offline RTM calculations, but is still two to three times more expensive in the UFS after certain optimization and with halved spectral bands.**

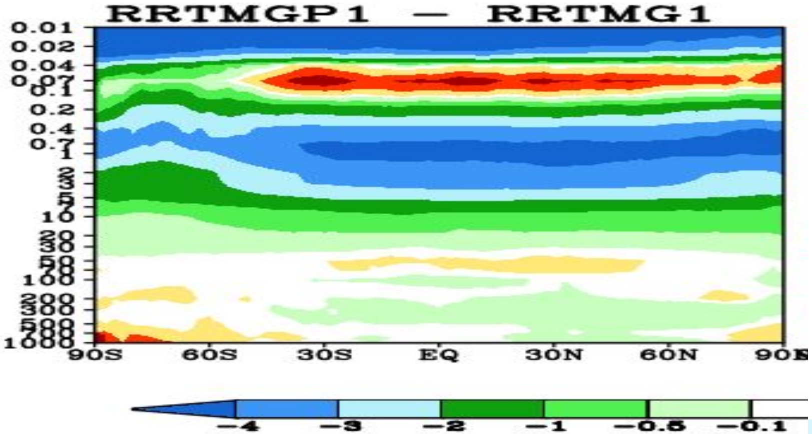
- **Much colder temperature in the upper atmosphere.**

- **Larger downward LW and warmer surface temperatures**

DJF-2020/21 T2m difference, RRTMGP-RRTMG, UFS



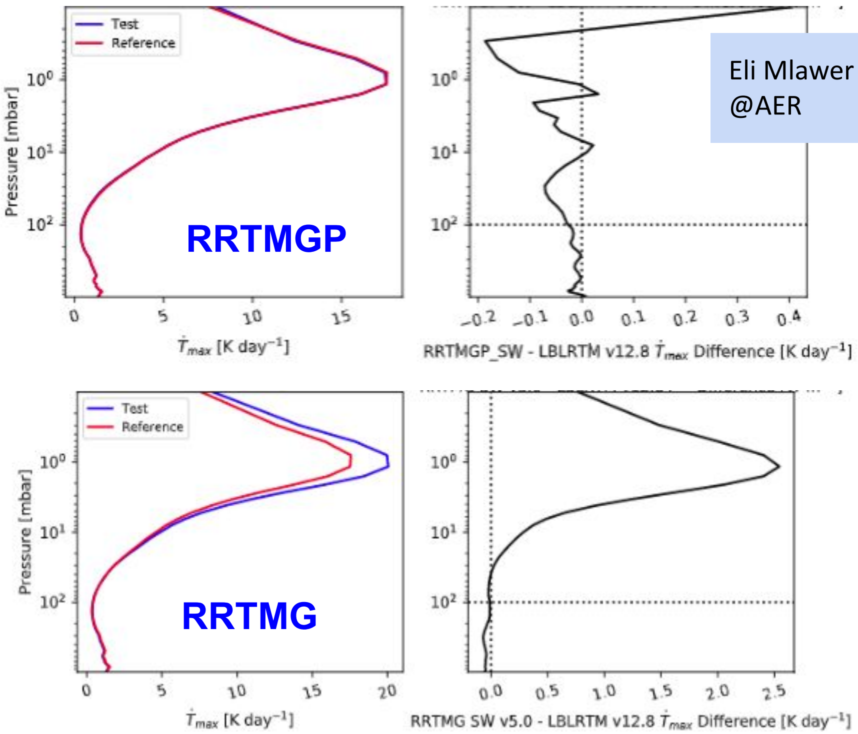
JJAS-2019 Zonal Mean Temperature, UFS



Radiation: RRTMG vs RRTMGp

- **RRTMG was developed at AER ~ 20 years ago. The full radiation spectrum is divided into 16 bands for LW and 14 band for SW.**
- **RRTMGp is completely rewritten with modern fortran language and has more spectral bands and improved accuracy.**

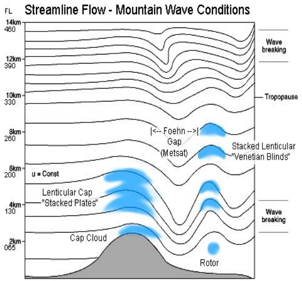
RRTMG has a large warm bias (higher HRs than the reference calculations) in the upper stratosphere / lower mesosphere. RRTMGP has fairly small errors everywhere, some positive and some negative. (Note the different x-axis scales in both the right-hand and left-hand plots.)



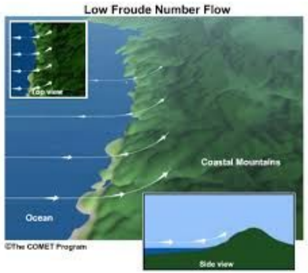
Eli Mlawer @AER

Values on left are average HRs for reference LBL calculations and fast codes for 51 RFMIP atmospheres. Code – reference differences are on right. Top two layers are at 0.28 mb and 0.1 mb.

Gravity-Wave Physics



Large-Scale Orographic GWD



Low-level flow blocking

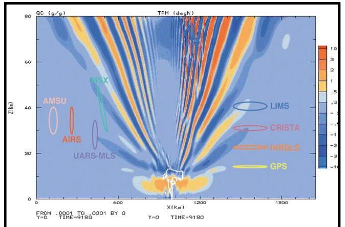
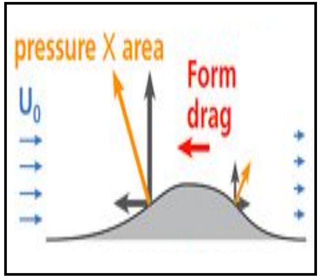


Figure from Alexander and Barnet (JAS,2007)

Non-stationary GWD

Small-scale GWD



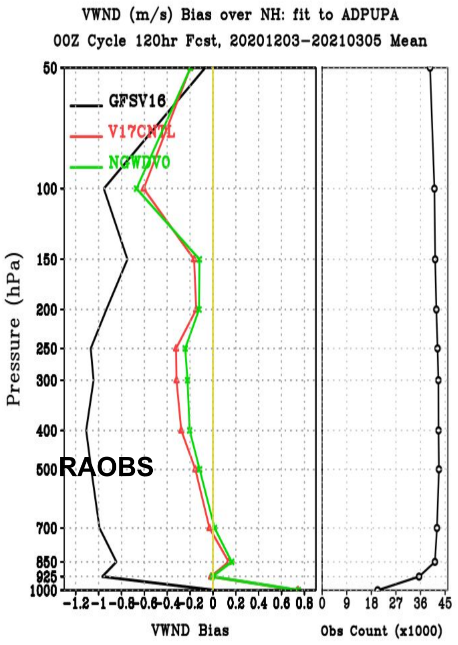
Turbulent orographic form drag

uGWD.v0 used in GFS.v16:
Kim & Arakawa (1995) O-GWD & Block,
Yudin et al (2020) N-GWD

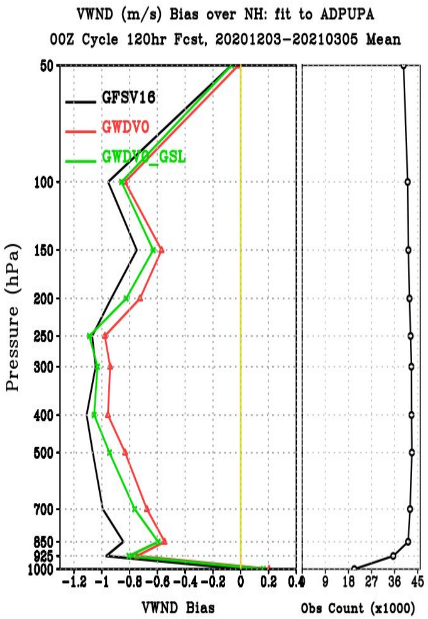
uGWDv1 tested in UFS Prototype 7:
Kim and Doyle (2005) O-GWD & Block
Yudin et al (2021) N-GWD
Tsiringakis et al. (2017) SS-GWD,
Beljaars et al. (2004) TOFD

Challenges of Implementing uGWD.v1 in the UFS

The NEW OGWD: improves tropospheric wind (verified against RAOBS)

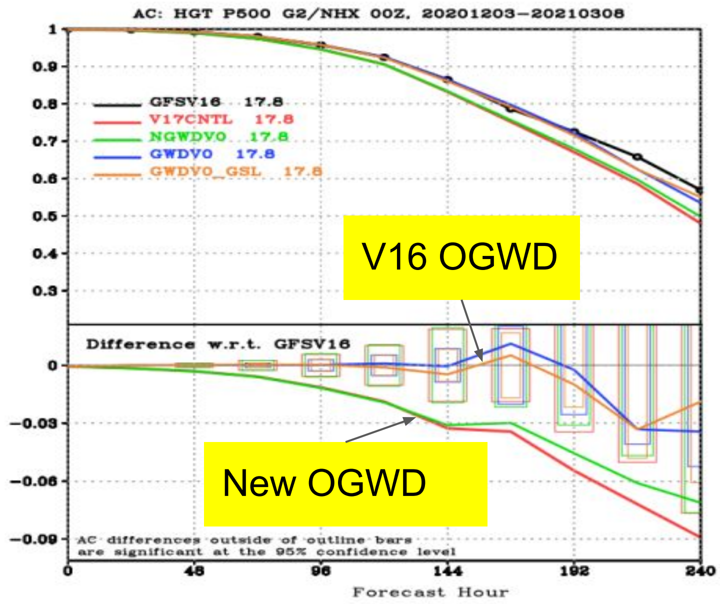


new OGWD



"old" OGWD

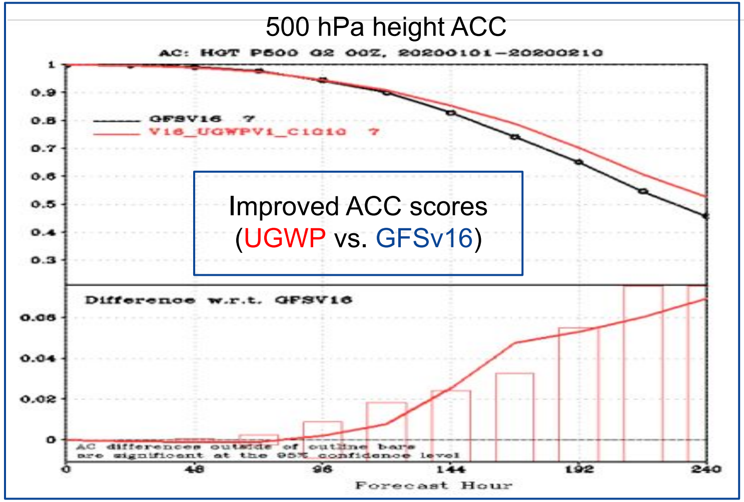
But degraded ACC, and precip (not shown)



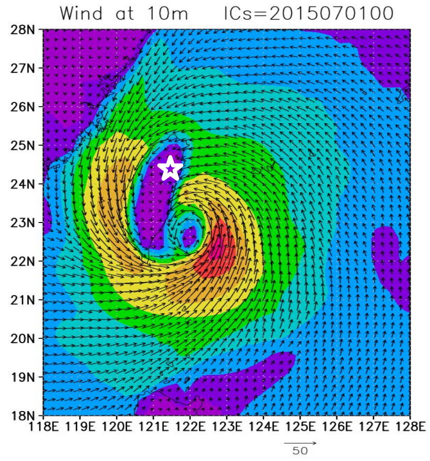
The new N-GWD also made polar night jets too weak (not show here).

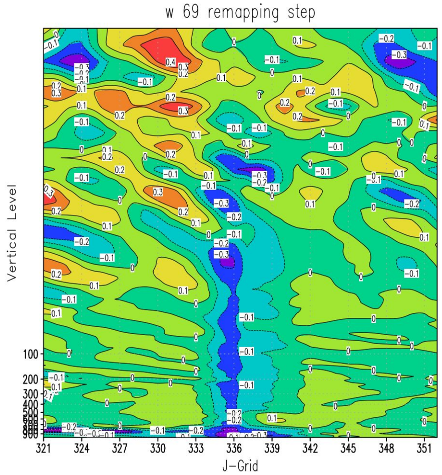
Refine and Develop Unified Gravity Wave Drag

Improvement was made with tuning of large-scale orographic gravity-wave drag and low-level blocking schemes of the Unified Gravity Wave Physics (UGWP) suite.



However, the model still has stability issue over complex terrains with strong surface winds





The investigation is still ongoing. So far the TOFD (turbulence orographic form drag) parameterization has been found to be likely the cause.

Improve Hurricane Track and Intensity for both GFS and HAFS

Jongil Han, Wei Li, Chunxi Zhang, Jiayi Peng (EMC)

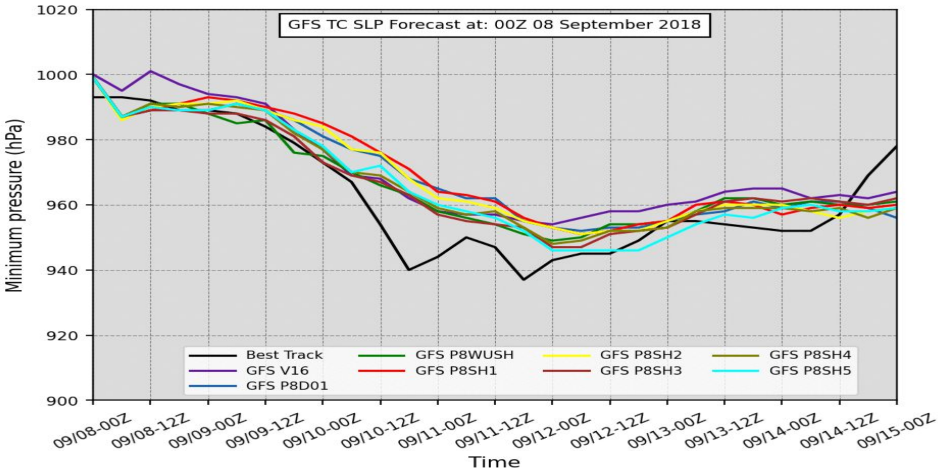
- Significant changes in the GFS cumulus convection, vertical turbulent mixing, and surface layer schemes in the GFS P8B physics updates have been made for potential implementation in the GFSv17, which helped to enhance the underestimated CAPE, to reduce the cold biases in tropospheric temperature profiles over the Tropics, and to reduce the nighttime cold and daytime warm 2m temperature biases over forest regions.
- In the GFS P8B physics updates, a positive definite TVD (Total Variation Diminishing) mass-flux transport scheme and a method for removing negative tracer mixing ratio values have been also implemented into the PBL and cumulus convection schemes.
- Compared to GFSv16 convection schemes, however, the updated cumulus convection schemes tended to reduce the TC intensity in HAFS as well as in GFS, increasing the negative TC intensity biases.
- **It has been found that the cause for the reduction of TC intensity in the P8B physics update is mainly due to the neglect of certain scale-aware features from the GFSv16 convection scheme.**
- In the P8C update of the convection schemes, **the scale-aware cloud base mass flux has been back to the GFSv16 convection version,** which led to a significant improvement in the TC intensity and track forecasts from the P8B in both GFS and HAFS, comparable to GFSv16.
- From the 3-km RRFS experiments, in addition, the current TKE-EDMF PBL scheme tends to overgrow the PBL especially during late afternoon, producing unrealistic widespread popcorn-like precipitation.
- To reduce the PBL overgrowth, in the P8C update the virtual potential temperature at top of the surface layer rather than that at the model first layer is used as near surface virtual potential temperature in the bulk-Richardson number computation, which helps to largely suppress the unrealistic widespread popcorn-like precipitation.
- **To further improve hurricane track and intensity forecasts, a parameterization to include environmental wind shear effect in the cumulus convection and PBL schemes is being developed.**

Improve Hurricane Track and Intensity for both GFS and HAFS

Jongil Han, Wei Li, Chunxi Zhang, Jiayi Peng (EMC)

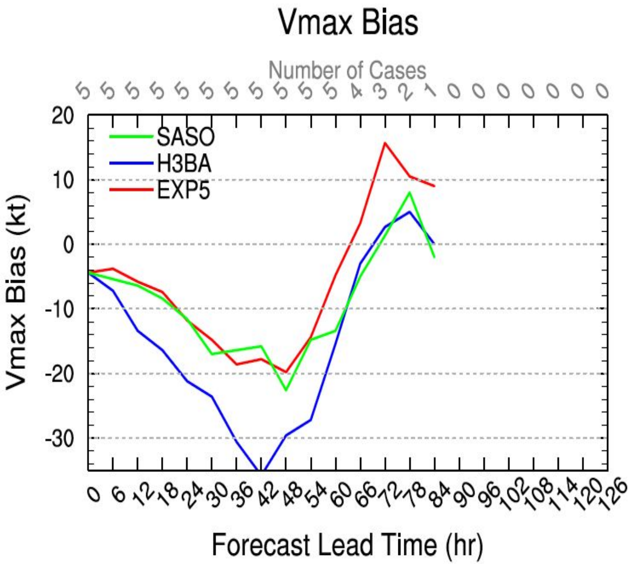
13-km GFS for hurricane Florence

(IC: 00Z 10/06/2018)



Best-Track (black), GFS V16 (purple) : GFSv16 run, GFS P8D01 (blue): GFS run with the latest P8 physics update, GFS P8DWUSH & GFSP8DSH*: Same as GFS P8D01 but with wind shear effect in PBL & convection. Overall, including wind shear effect enhances the hurricane intensity by reducing the momentum mixing.

3-km HAFS for hurricane Ida: 2021082706 - 2021082806



SASO (green): HAFS with GFSv16 convection
H3BA (blue): HAFS with GFS P8B physics update
EXP5 (red): HAFS with GFS P8C convection and PBL physics update

Physics R2O Processes For MRW/S2S Applications

- Develop, test and evaluate each new, or updated, physics scheme by individual developers
- Run **atmos-only experiments** using either GFS.v16 or the latest UFS prototype as the control
- For most of the time, experiments are run at both the C384L127 and C768L127 resolutions, and for both winter and summer seasons
- Verification made against GFS.v16 analyses, satellite retrievals, surface and rawinsonde observations

No surprises !

Decision to move each scheme to the UFS coupled model prototypes are made based on

- Maintain GFS.v16 headline scores, including but not limited to 500-hPa ACC, CONUS precip ETS and bias scores, T2m, surface Winds, tropical winds etc
- check almost all forecast variables; causes for large or unexpected differences from the control experiment must be explained and understood
- Check **computational stability, cost efficiency, restart reproducibility**, compliance of UFS code standard; pass Regression Tests

UFS Prototypes: ... p6, P7a, 7b, 7c, p7.2, p8a, p8b, p8c

based on coupled model evaluation and community feedback, certain scheme is send back to developers for further update and evaluation

Physics Development with the Community
Beyond GFS/GEFS/RRFS/HAFS Prototypes and 2022

- Optimize the physics schemes included in the UFS Prototypes for GFS.v17 and GEFS.v13 to reduce model biases and improve forecast skills
- Finalize RRFS.v1 and HAFS.v1 physics configurations and improve forecast skills.
- Update and test online-CMAQ (~13-km NA Domain) physics packages
- Update PBL and surface-layer schemes to improve PBL inversion and surface weather sensitive elements
- Prognostic aerosols and their interactions with microphysics and radiation
- Unification of sa-SAS and GF convection schemes. Improving tropical waves and mid-latitude CAPE.
- Optimize NOAH-MP to reduce forecast biases. Develop land as a component model.
- Include lake models (e.g. FLAKE, FVCOM etc) in the UFS.
- Further test and evaluate the unified gravity-wave physics package (uGWD.v1).
- Further test and evaluate RRTMGp. Adopt advanced cloud and hydrometeor overlap schemes. Include non-LTE LW radiation and other minor solar UV bands.
- Improve representation of deep convection at grey-zone scales(<10km), including development of a prognostic closure.
- Improve consistency between clouds, radiation and microphysics through the development of a prognostic cloud fraction.
- Continued process level evaluation of new advanced physics processes descriptions in GFSv17, including tropical variability, microphysics/sea ice coupling over the Arctic regions, surface layer processes, etc.

Thank You

https://www.weather.gov/careers/physical-science

From UFS Prototype 6 (GFSv16 physics suite) to the final coupled model Prototype 8 the following physics updates have been made by the UFSR2O community.

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

Introduced a **new land model** (NOAH LSM --> NOAH-MP)

Included **a new more accurate radiation scheme** for further evaluation (RRTMG -> RRTMGP)

Introduced **new small-scale gravity wave** and **turbulent form drag** parameterizations

Improved orographic gravity wave drag and mountain blocking

Introduced a **new** parameterization for **convective organization**, and **stochastic convective initiation**

Improved **cumulus convection** schemes and **boundary layer** schemes to address systematic biases

Introduced **new stochastic physics** in the ocean, land-surface and the atmosphere

Introduced a **new positive definite tracer advection (TVD)** scheme in convection and PBL

Improved the **coupling of the land model and surface layer** schemes.

Introduced **new land/ocean/lake masks, new ice climatology, and surface composites over the fractional grid**

Introduced new capability for **coupling between aerosols and physics** (UFSR2O atmospheric composition team/EMC)