On the Development and Bias Reduction of Atmospheric Model Physics for the NOAA Unified Forecast System Applications

Fanglin Yang

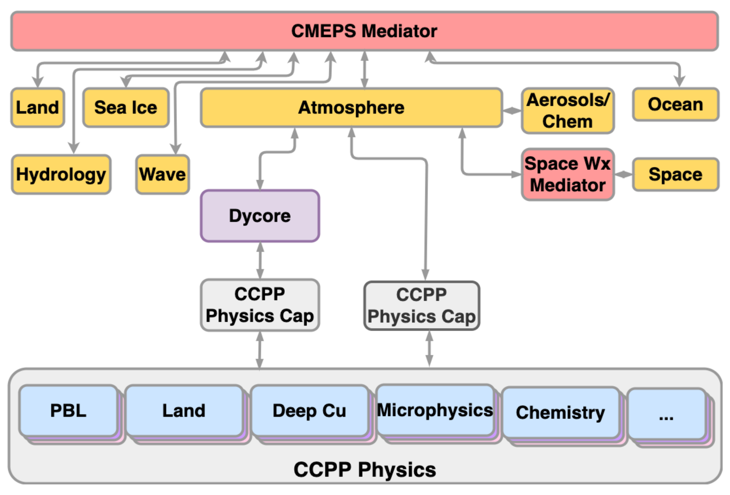
NOAA/NWS/NCEP Environmental Modelling Center

6th WGNE Workshop on Systematic Errors in Weather and Climate Models, ECMWF, Reading, 31 October 2022 to 4 November 2022

Summary

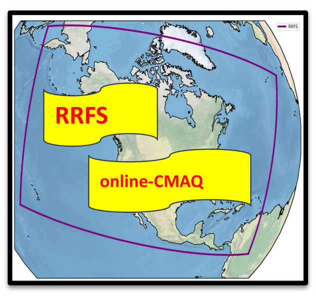
NOAA is collaborating with the US weather and climate science community to develop the next generation fully coupled earth system modeling capability for both research and operational forecast applications across different temporal and spatial scales. This presentation will first introduce major changes and updates of atmospheric model physics which are targeted for both the global and regional models for short and medium-range weather forecasts and subseasonal to seasonal predictions. Strategies are developed to first test individual physics parameterizations in atmospheric-only forecast experiments in the aforesaid applications and then to further evaluate and improve the parameterizations in the integrated earth system modeling applications to reduce model systematic biases and improve model prediction skills. Significant efforts are made to unify physics parameterizations for all applications to speed up the transition of research to operation (R2O) and to reduce the cost of operational systems maintenance. A few samples will be presented to highlight the success and challenges of introducing new physics parameterizations into the UFS forecast systems.

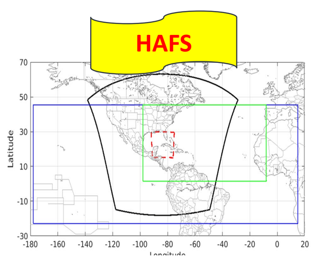
A. NOAA Unified Forecast Systems

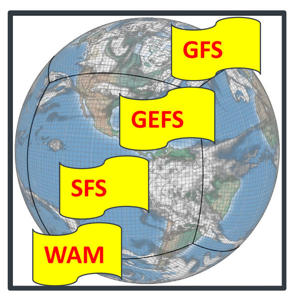


- CMEPS mediator
- FV3 dycore
- CCPP Physics
- MOM6 ocean

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







RRFS: Regional Rapid Refresh Forecast System
HAFS: Hurricane Analysis and Forecast System
CMAQ: Community Multiscale Air Quality Modeling System

GFS: Global Forecast System
GEFS: Global Ensemble Forecast System
SFS: Seasonal Forecast System
WAM: Whole Atmospheric Model

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.

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.

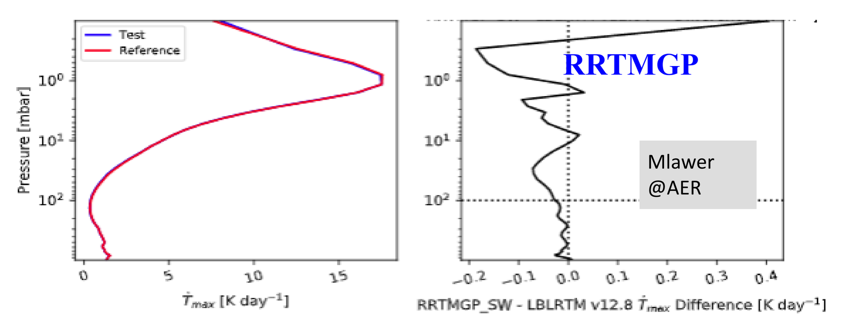
B. Physics options in latest UFS applications planned for operations in 2023 to 2024

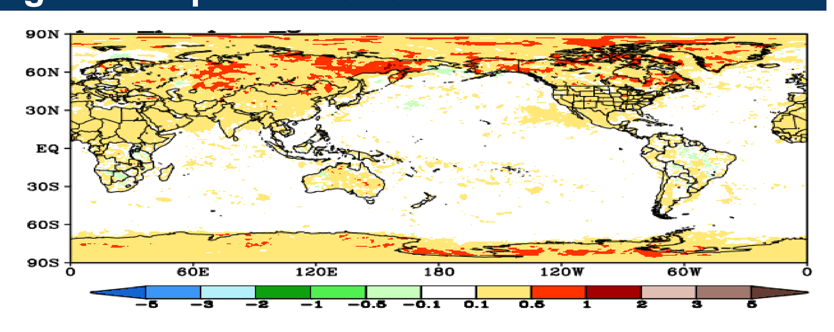
	GFS.v17/GEFS.v13	HAFS.v1 Suite A	HAFS.v1 Suite B	RRFS.v1
Shallow & Deep convections	sa-SAS: Positive definite mass flux; Stochastic convective organization; Optimization for CAPE	sa-SAS: Positive definite mass flux; Stochastic convective organization; Optimization for CAPE	sa-SAS: Positive definite mass flux; Stochastic convective organization; Optimization for CAPE, TC-specific tuning	MYNN
Surface Layer	GFS sfc, with Sea spray	GFSsfc, with Sea spray	GFS sfc with Sea spray,TC-specific tuning	MYNN sfc
PBL	Modified sa-TKE-EDMF: Positive definite tracer advection	Modified sa-TKE-EDMF: Positive definite tracer advection; TC-Specific tuning	Modified TKE-EDMF: Positive definite tracer advection; optimization, TC-Specific tuning	MYNN
Gravity Wave Drag	Orographic-GWD & Mountain Block; non-stationary GWD; SS-GWDW ; TOFD	Orographic-GWD & Mountain Block; non-stationary GWD	SSW ; TOFD	SS-GWD ; TOFD
Land Surface Model	NOAH MP and VIIRS veg type	Noah LSM	NOAH MP and VIIRS veg type	RUC ➔ NOAH MP
Microphysics	Thompson MP (non-aerosol aware)	GFDL MP	Thompson MP (non-aerosol aware)	Thompson MP (aerosol aware)
Radiation (LW & SW)	RRTMG	RRTMG	RRTMG	RRTMG
land/sea/lake masks	VIIRS	MODIS	MODIS	MODIS ➔ VIIRS

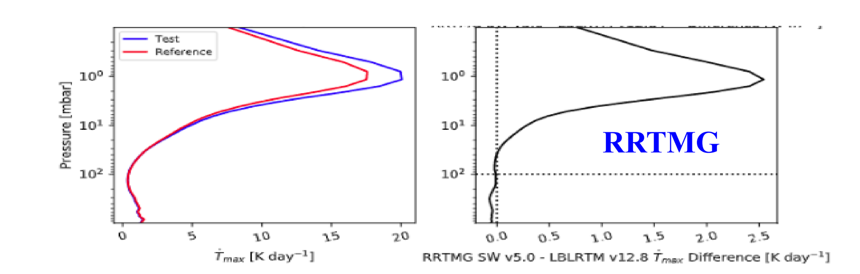
Colored texts represent recently added new and/or updated physics parameterizations

C. Success and Challenges

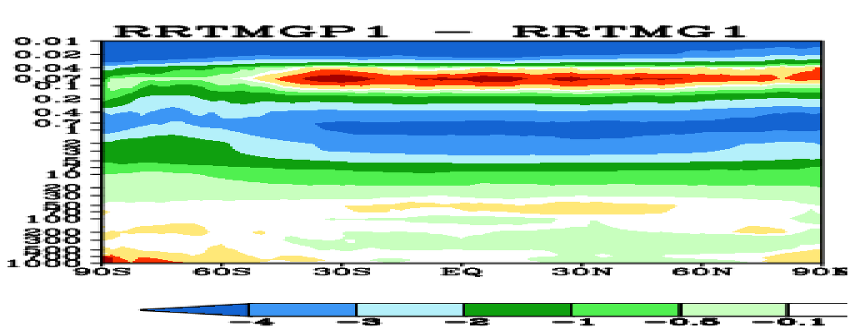
Challenges of Implementing RRTMGp in the UFS







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.



- RRTMGp is completely rewritten with modern Fortran language and has more spectral bands and improved accuracy.
- RRTMG was developed at AER ~ 20 years ago. The full radiation spectrum is divided into 16 bands for LW and 14 band for SW.
- RRTMG has a large warm bias (higher HRs than the reference calculations) in the upper stratosphere / lower mesosphere.

- 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

Microphysics: GFDL MP vs Thompson MP

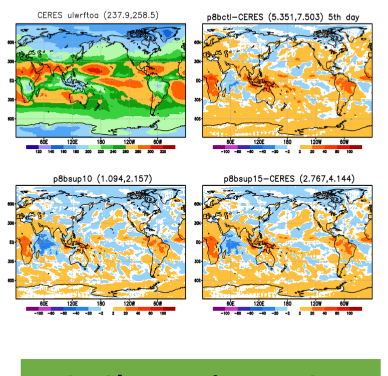
	GFDL MP (single moment)	Thompson 2008/2014 (double)
prognostic variables	qv, ql, qi, qs, qr, qg	qv, ql, qi, qs, qr, qg, ni, nr (2008) + nc, nwfa, nifa (aerosol-aware)
condensation and evaporation	Lin, et al (1983)	Yau and Austin (1997), Thompson and Eidhammer(2014)
mixed-phase clouds	yes	yes
precipitation 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**.
- Development is underway for fully coupled cloud-radiation-aerosol interactions

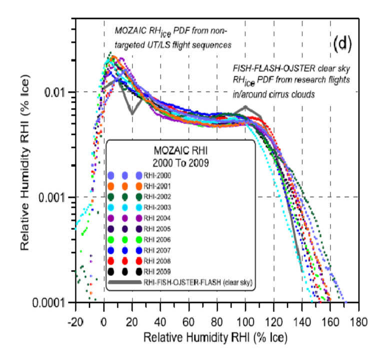
Integrated hydrometeors (global, tropical:30S-30N)

g/m2	GFSv16 GFDL MP	GFSv16 Thompson MP	IFS
Cloud liquid	(77, 57)	(54, 45)	(54, 50)
Cloud ice	(35, 23)	(8, 12)	(20, 15)
Snow	(17, 13)	(54, 41)	(50 ,43)
Ice + snow	(53, 37)	(62, 53)	(70, 58)
Ice + snow + cloud liquid	(130, 94)	(117, 98)	(124, 108)

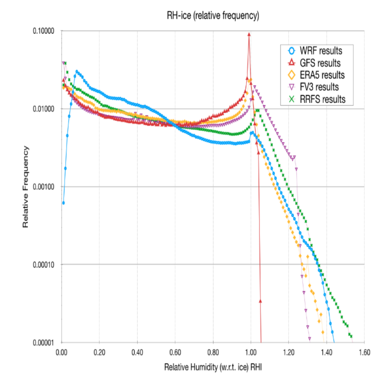
These difference in hydrometer loadings affect radiative heating and radiation balances



UFS p8b experiment: OLR varies with RHic for supersaturation
UL: CERES obs;
UR: RHi=125%
LR: RHi=115%; LL: RHi=110%

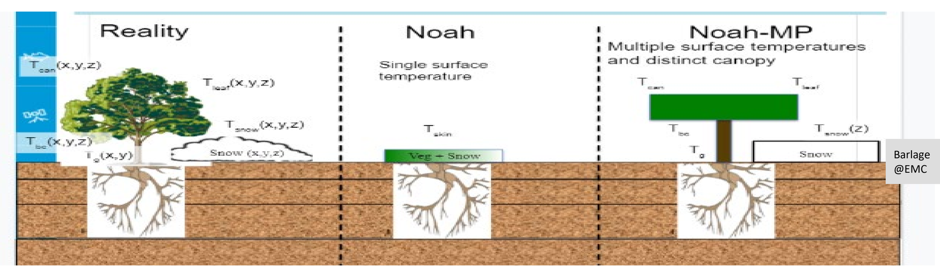


Observed frequency distribution (PDF) of RH relative to ice (RHI) from MOZAIC flight-level obs. (Krämer et al.,2009)



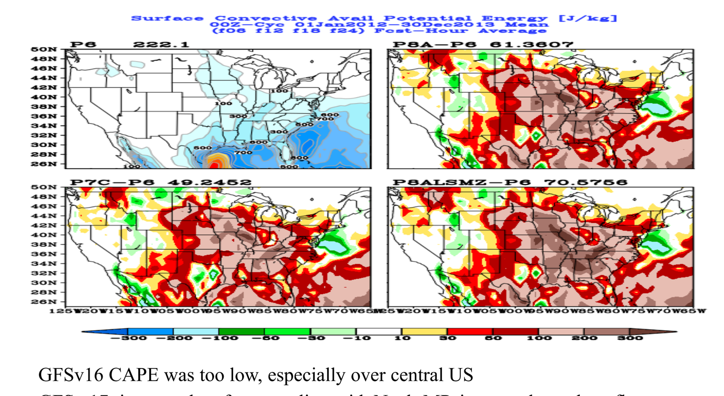
RHI PDF from various models (Credit: Greg Thompson). Supercooled cloud water presents a hazard to aviation !

Land Surface Model: Noah vs Noah-MP LSM

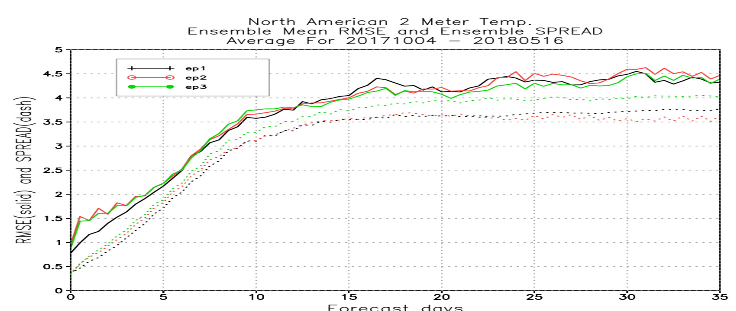


- **Noah-MP** is a land surface model that allows a user to choose multiple options for several physical processes
- **Canopy radiative transfer** with shading geometry
- **Separate vegetation canopy**
- Dynamic vegetation
- Vegetation canopy resistance
- **Multi-layer snowpack**
- Snowpack liquid water 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 improving land spin-up process etc



GFSv16 CAPE was too low, especially over central US
GFS.v17: improved surface coupling with Noah-MP, increase latent heat flux



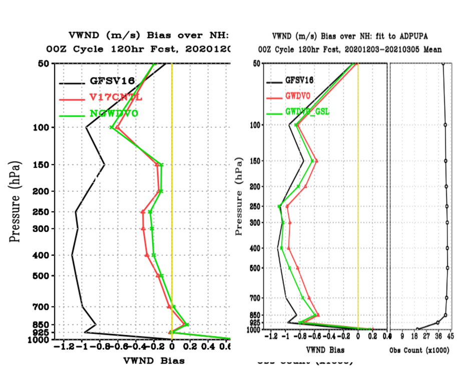
Ensemble forecasts made with the latest UFS physics suite (EP3) showed much improved T2m ensemble spread in cold seasons, presumably due to improvement feedback between cloud microphysics and the land model.

Challenges of Implementing uGWD.v1 in the UFS

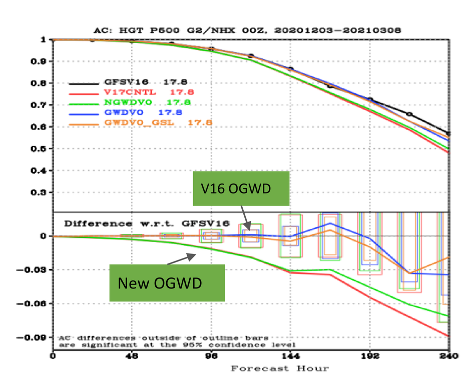
The NEW OGWD: improves tropospheric wind (verified against RAOBS)

But degraded ACC, and precip (not shown)

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



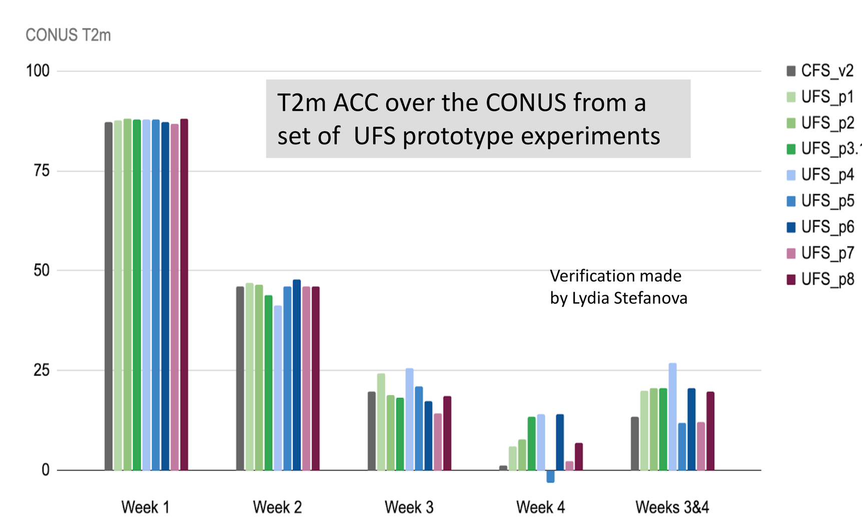
new OGWD "old" OGWD

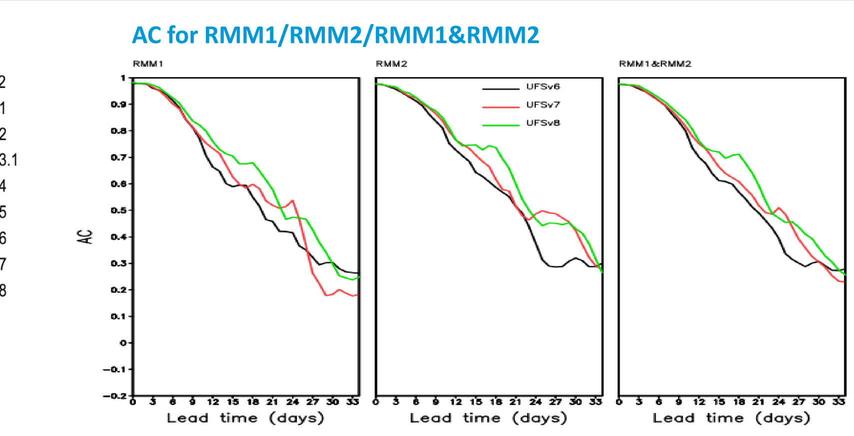


The new N-GWD also made polar night jets too weak (not show here).

uGWDv1 also still suffers numerical instability issues over steep mountains

Successes: Improved Sub-Seasonal Forecast Skill Scores in UFS Prototypes





Progressively Improved MJO forecasts in the UFS prototypes. Including 168 cases (Apr 2011–Mar 2018, 1st and 15th of each month)

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.

Acknowledgment: for contributions made by NCEP/EMC developers Jongil Han, Michael Balarge, Shrinivas Moorthi, Helin Wei, Anning Cheng, Ruiyu Sun, Xiaqiong Zhou, Jili Dong, Eric Aligo, Qingfu Liu, Weizhong Zheng, Rongqian Yang, Yihuya Wu, Wei Li, Bing Fu, Hong Guang, Bo Yang, and community collaborators Lisa Bengtsson, Jian-wen Bao, Michael Toy, Valery Yudin, Shan Sun, Benjamin Green, Tanya Smirnova, Robert Pincus, Dustin Swales, Greg Thompson, Joe Olson, Songyou Hong, Ligia Bernardet, Weiwei Li and Man Zhang. NOAA NWS/STI and OAR/WPO program offices are acknowledged for providing funding support for the UFS development.