Atmospheric Model Physics for the NOAA Unified Forecast System Applications Across Scales

NATIONAL WEATHER SERVICE

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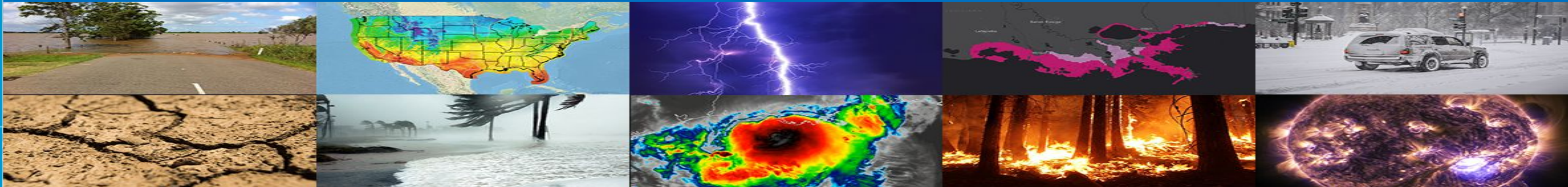
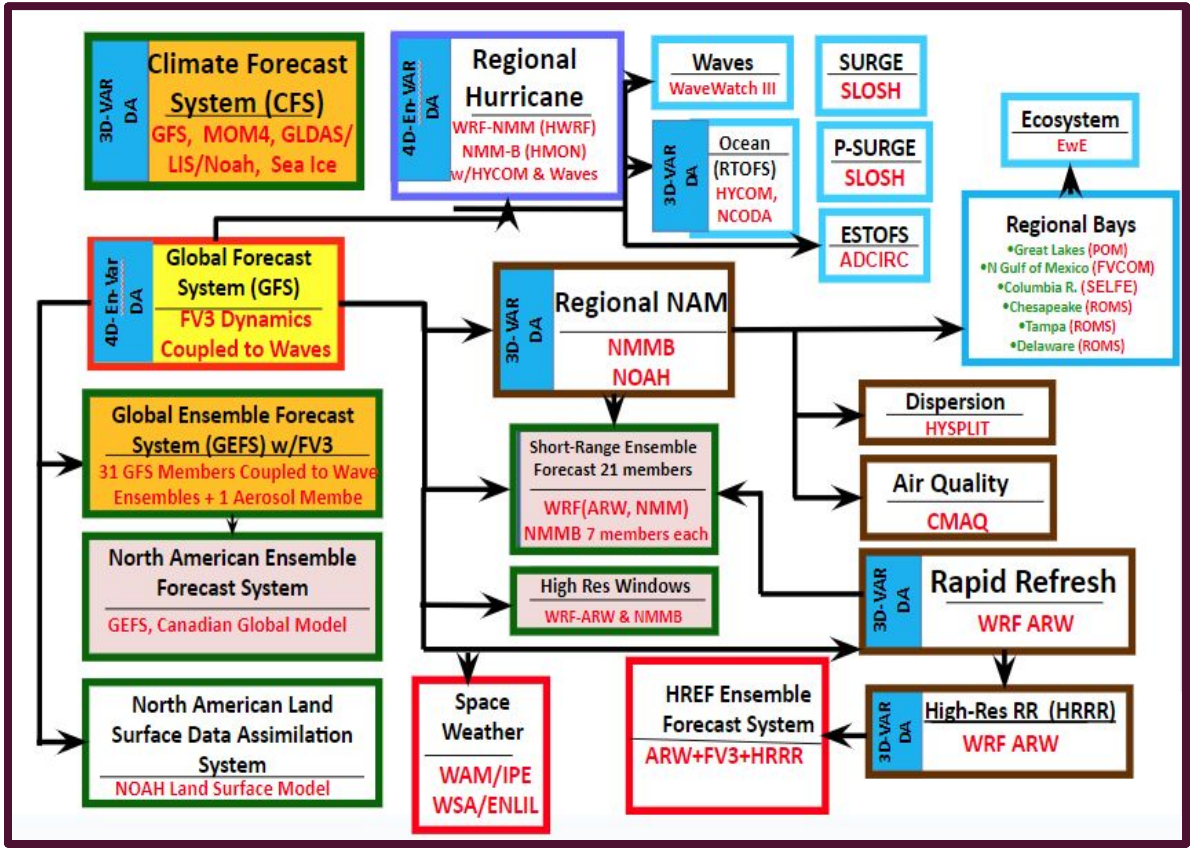
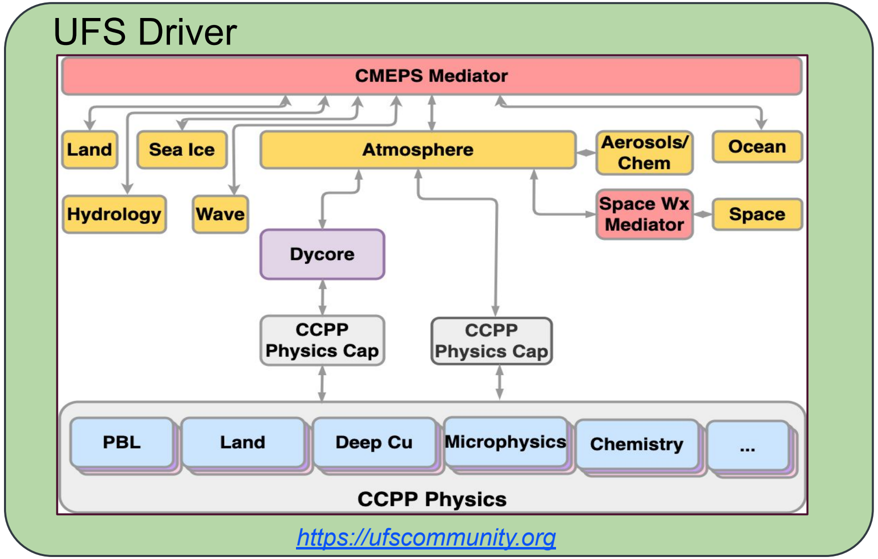


Current State of NCEP Production Suite



- NCEP operates more than 38 distinct modeling systems to meet the stakeholder requirements
- These systems use a variety of different physics packages. Model development to meet service requirements takes long time and extraordinary efforts
- Simplifying NCEP Production Suite is critical to reduce redundancy and improve efficiency

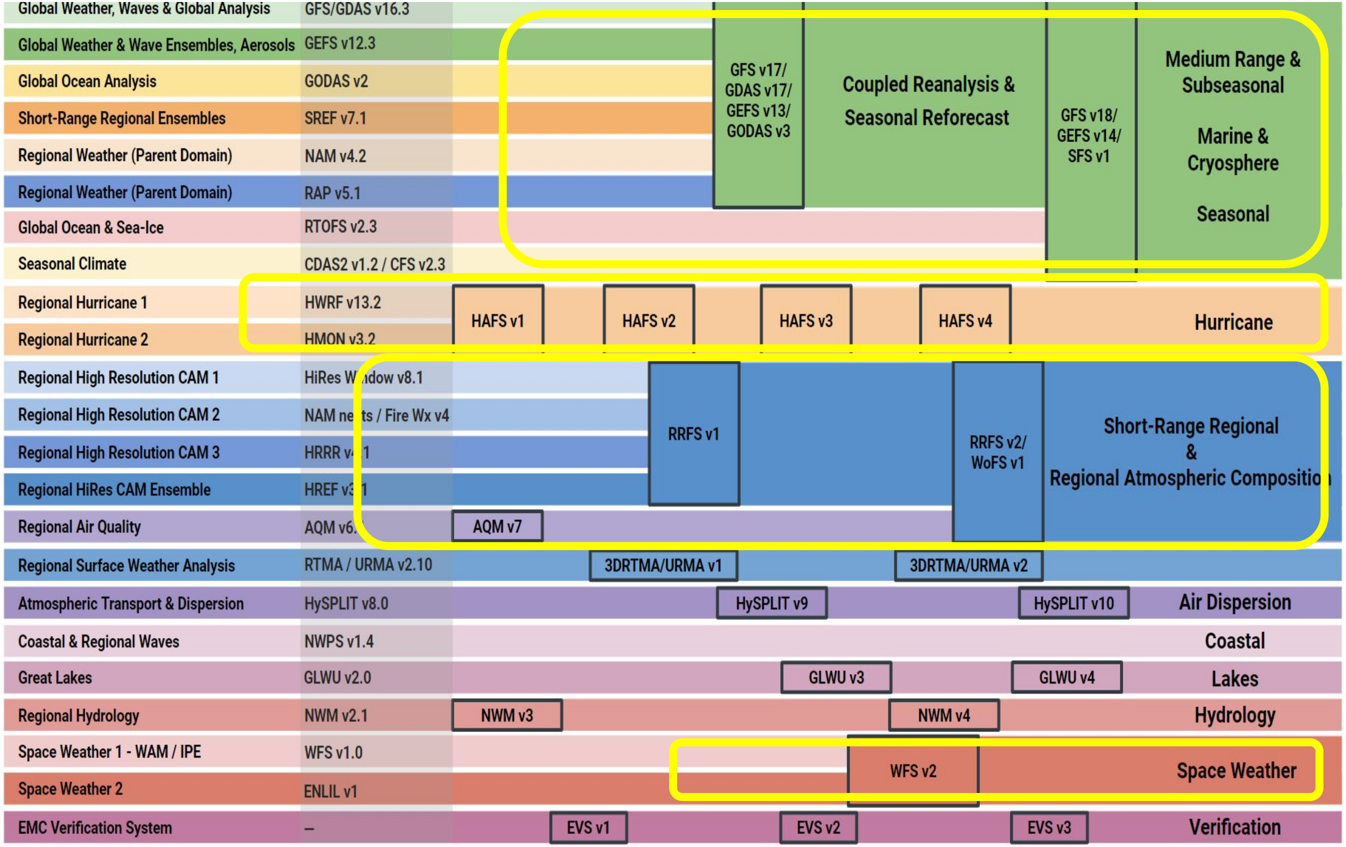
NOAA is collaborating with the US weather and climate science community to develop the next generation fully coupled earth system modeling capability for both research and operational forecast applications across different temporal and spatial scales.



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

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

Transition to UFS Applications



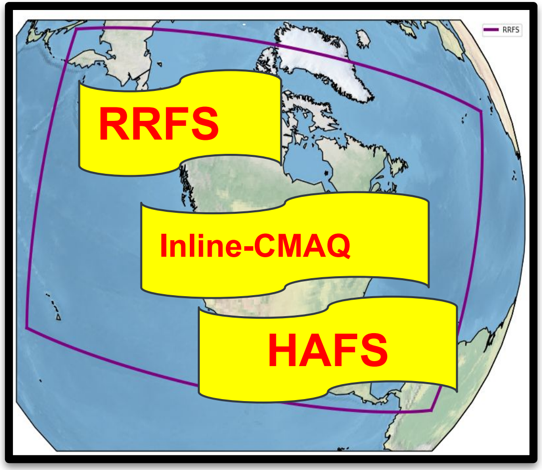
Applications in yellow boxes all use the CCPP for atmospheric physics

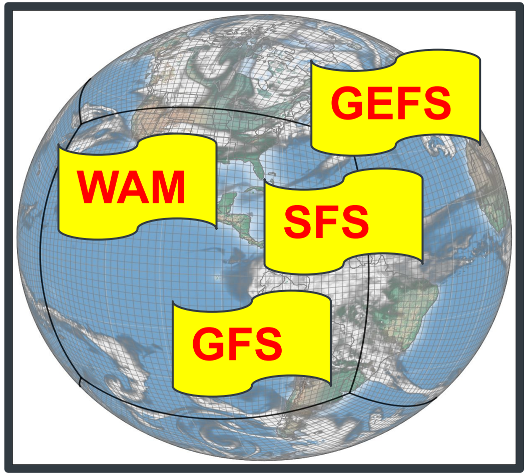
The simplification of NCEP production suites presents an opportunity and also a challenge to simplify and unify, to the extent possible, physics packages used by different UFS-based applications

Guidance for Atmos Physics Development 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.

SRW/CAM





MRW/S2S

Atmos Physics Parameterizations in UFS Applications: Current Status

	GFSv17 (13km) & GEFSv13 (25km)	RRFSv1 (3-km) (single physics ensemble)	HAFSv1 (6/2 km)	AQMv7 (12km) aka Inline-CMAQ
Deep Convection	sa-SAS	GF ?	sa-SAS	sa-SAS
Shallow Convection	sa-SAS	MYNN-EDMF	sa-SAS	sa-SAS
Microphysics	Thompson MP	Thompson MP (aerosol aware)	A: GFDL MP B: Thompson MP	GFDL MP
Radiation	RRTMG	RRTMG	RRTMG	RRTMG
Surface Layer	GFS	MYNN	GFS	GFS
PBL	sa-TKE-EDMF	MYNN-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	uGWPv0
SS-GWD & TOFD	Yes	Yes	Yes	No
Aerosol-radiation	MERRA2 Clim & GOCART	MERRA2 Clim	MERRA2 Clim	OPAC Clim

Atmos Physics Parameterizations:
Unify or not to unify in the "next" UFS Applications

HAFS.v2: there is a desire to use different physics options in HAFS-A and HAFS-B to increase diversity.

RRFS: single physics ensemble vs multiple physics ensemble ?

SFS.v1: project begins in Q1FY24. Will start with GFSv17/GEFSv13 physics package

Components that can be unified:

- Land: NOAH LSM and RUC ==> NOAH-MP
- Radiation: RRTMG ==> RRTMGp
- GWD: uGWDv0 ==> uGWDv1

Components that will likely remain diversified

- Microphysics: Thompson MP, GFDL MP, NSSL MP, MG3 or PUMAS ...
- Deep/Shallow Convection: sa-SAS, Grell-Freitas, *Tiedtke*, *C3*, *CLUBB*, *SHOC*, *UNICON* ...
- PBL: TKE-EDMF, MYNN-EDMF, Hybrid-EDMF, SHOC ...
- Aerosols (radiation): MERRA2 climatology for GFS
  GOCART for GEFS (TBD)
  RRFS-SD or CMAQ for RRFS.v2 ?
  ?? for SFS

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 convection, PBL, and GWD needs further development to become truly scale aware

Challenge for Unification: Taking Thompson Microphysics As an Example

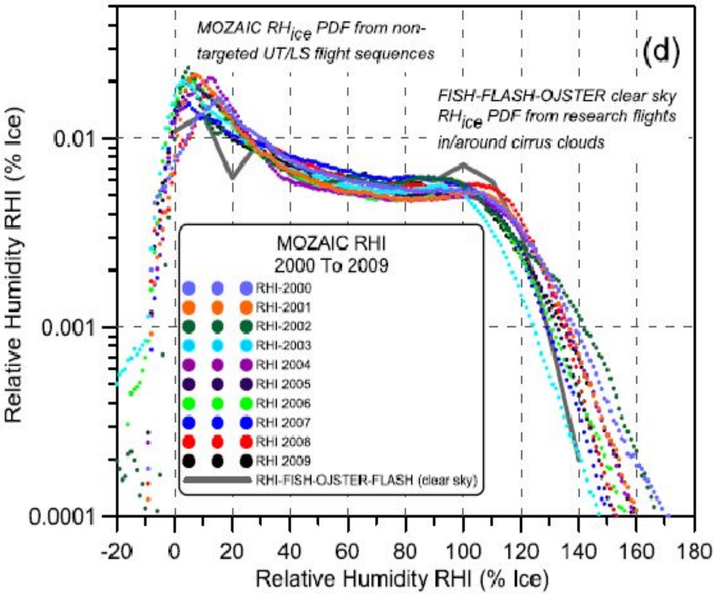
- In current NCEP operation, GFS &GEFS ==> GFDL MP; RAP & HRRR ==> Thompson MP; NAM ==> Ferrier-Aligo MP. FA was also used by HWRF before HAFS implementation.

- 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).

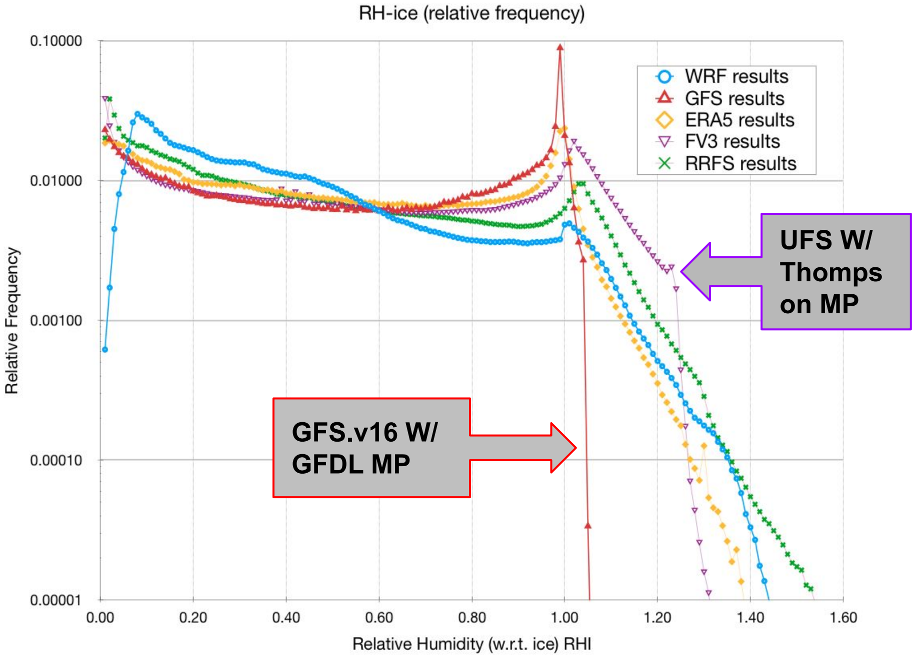
- Thompson MP has been widely used in the WRF community for regional model applications. Adapting it for NCEP global model applications has proved to be challenging.

- 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.



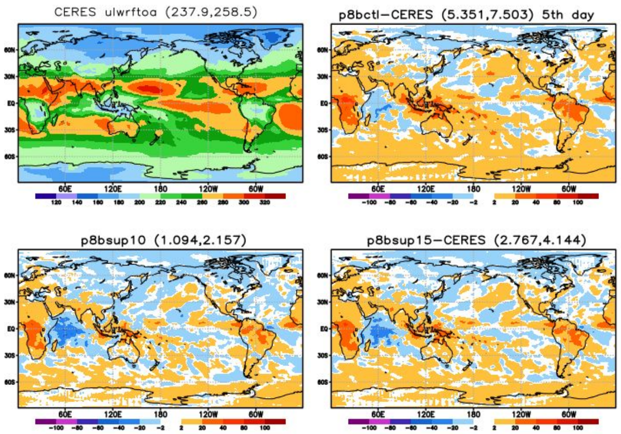
RHI PDF from various models (Credit: Greg Thompson). **Supercooled cloud water is a hazard to aviation !**

UFS Microphysics Development -- Challenges

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

g/m2	GFSv16 GFDL MP	GFSv17 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

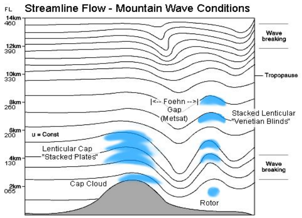


UFS p8b experiment: OLR varies with RHic for supersaturation

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

Also see Talk 1.3 by M. Toy

Challenge for Unification: Gravity-Wave Drag



Large-Scale Orographic GWD

Low-level flow blocking

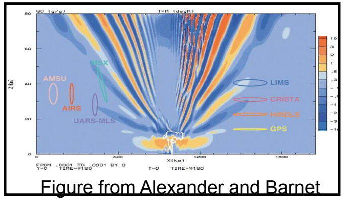
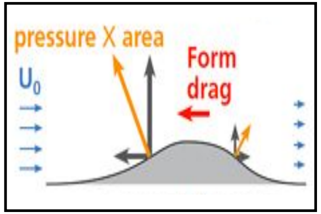


Figure from Alexander and Barnet (JAS,2007)

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

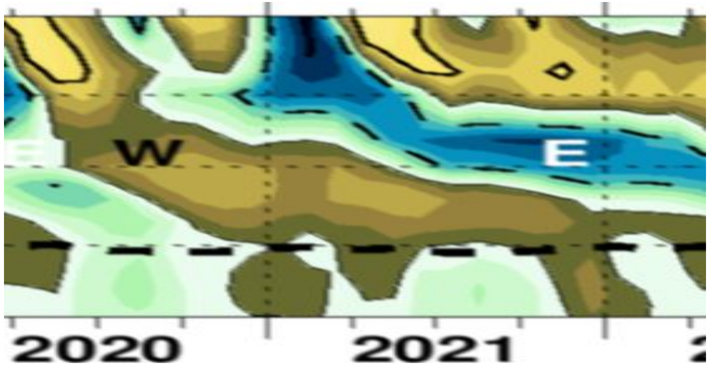
Different scaling factors need to be tuned and applied for different model grid resolution.

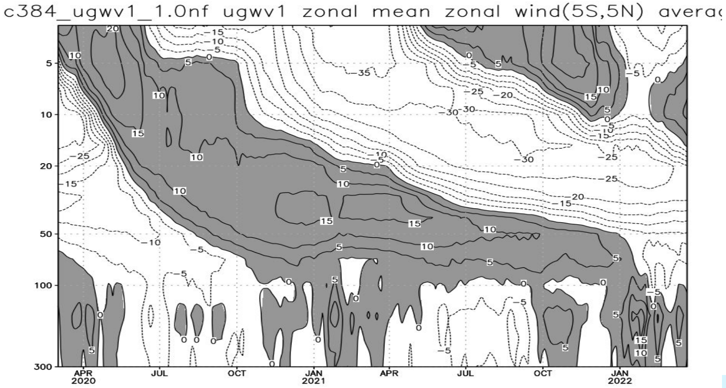
uGWDv1 (aka the GSL suite) for the UFS:
Kim and Doyle (2005) O-GWD & Block
Yudin et al (2021) N-GWD
Tsiringakis et al. (2017) SS-GWD,
Beljaars et al. (2004) TOFD

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

“Best” scaling factors for capturing the QBO and jet streams and for improving overall NWP forecast skills

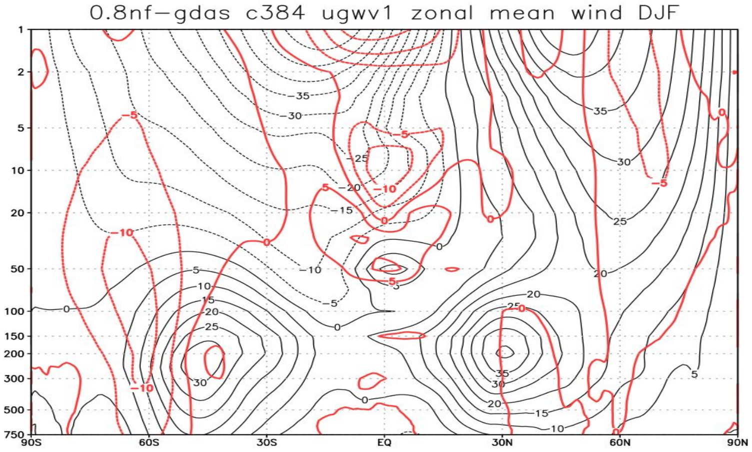
	O-GWD	Blocking	N-GWD
C768	2.5	7.5	0.5
C384	5	5	1.0
C192	10	3.5	1.8





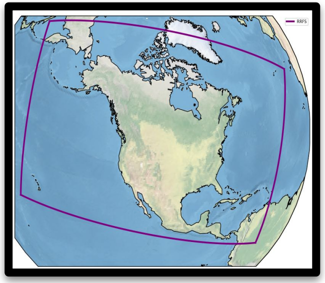
DJF Zonal Mean Zonal Wind

Black: C384 forecast; Red: forecast minus GDAS analysis

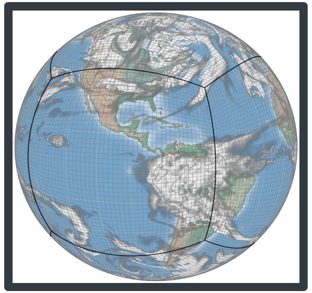


Developing Scale Aware/Adaptive Physics Parameterizations: A Path forward for Unification

- Replaced the Arakawa-Wu convective updraft area fraction in sa-SAS with a prognostic scale-adaptive cumulus convection closure (Bengtsson et al., 2022)
- Unify cloud cover and cloud-radiation interaction through a prognostic cloud scheme where subgrid-scale cloud is treated as a source term (Joseph Olson and Grant Firl, GSL, ongoing).
- Unify aerosol-cloud-radiation interactions for both global and regional models (EMC/GSL, ongoing)
- Develop truly scale-aware stationary and non-stationary GWD parameterizations (GSL/EMC/PSL, ongoing)
- TKE-EDMF and MYNN-EDMF, or a unfiled PBL scheme, for all UFS applications
- Experiment unified PBL, shallow and deep convection schemes such as SHOC (*Bogenschutz and Krueger, 2013*), CLUBB (*Larson and Golaz*, *2005*) and UNICON (Park, 2015)



Thank you



Development Division in the early 1990's at the World Weather Building

NCWCP

EMC in the NCWCP Auditorium in 2017

Backup slides

Recent Achievements -- UFS Prototypes for GEFS.v13 and GFS.v17

	GFS.v16/GEFS	UFS
Cumulus Convection (Shallow & Deep)	sa-SAS	**Positive definite mass flux; stochastic convective organization; prognostic cumulus cloud clouser; TKE dependent entrainment**
Surface Layer	GFS	**Sea spray**; optimization
PBL	sa-TKE-EDMF	**Positive definite tracer advection; wind-shear effect; TKE dependent entrainment**
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)	**Kim and Doyle (2005)** **Tsiringakis et al. (2017)** **Beljaars et al. (2004)**
Land	Noah LSM	**NOAH MP** and VIIRS veg type
Aerosol	OPAC	**MERRA2** or GOCART Prognostic aerosols
Microphysics	GFDL MP	**Thompson MP**
Stochastic physics	SPPT/SKEB	Add CA to convection; add options to perturb individual hydrometeors and cloud fraction for SPPT

Recent Achievements -- HAFS Physics and Dynamics

HAFSv1 uses GFSv16 phys except some TC-related adjustments(underline)

Schemes	HAFSv1-A	HAFSv1-B
Land/ocean Surface	**NOAH LSM VIIRS veg type, HYCOM**	**NOAH LSM VIIRS veg type HYCOM**
Surface Layer	**GFS, <u>HWRF TC-specific sea surface roughnesses</u>**	**GFS, <u>HWRF TC-specific sea surface roughnesses</u>**
Boundary Layer	**Sa-TKE-EDMF, <u>near-surface mixing length tuning</u>**	**Sa-TKE-EDMF, <u>TC-related, model coefficients & mixing length tuning</u>**
Microphysics	**GFDL, single-moment**	**Thompson, double-moment**
Radiation	**RRTMG**	**RRTMG**
Cumulus convection (deep & shallow)	**Scale-aware-SAS <u>calibrated deep convection entrainment rate</u>**	**Scale-aware-SAS**
Gravity wave drag	**Unified GWD (orographic on/convective off)**	**Unified GWD (orographic on/convective off)**
Advection	**Hord=6**	**Hord=6**

Physics Development: from GFSv16 to UFS Global Model Prototypes

- 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)
- 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**
- Introduced a new Prognostic-Stochastic and Scale-Adaptive Cumulus Convection Closure
- 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**

Contributions to UFS physics and dynamics development

For MRW/S2S: Finalized physics suite for the coupled model prototypes, which are targeted for GEFS.v13 and GEFS.v17 implementations

- Replaced GFDL one-moment cloud microphysics with the Thompson two-moment cloud microphysics scheme.
    - Introduced inner-loop and semi-Lagrangian sedimentation to improve computational instability and efficiency.
    - Optimized cloud cover and cloud radiation interaction to improve model energy balance.
- Replaced NOAH LSM with NOAH-MP LSM; Updated the coupling between land and the surface layer and the PBL; Updated vegetation type and land/sea/lake masks using VIIRS dataset. Developed a new tool for spinning up the land model with observations and analysis datasets.
- Included a new more accurate RRTMGp radiation scheme for further evaluation.
- Introduced new ice climatology, and surface composites over the fractional grid
- Added the capabilities of modeling aerosol direct and indirect effects on radiation and clouds.
- Introduced new stochastic physics in the ocean, land-surface and the atmosphere;

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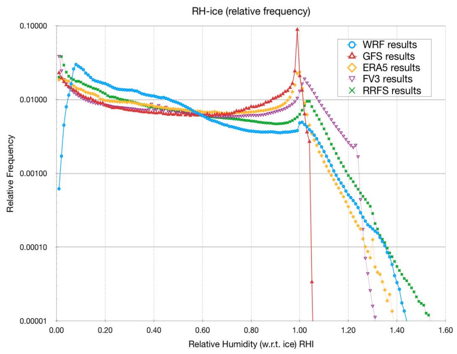
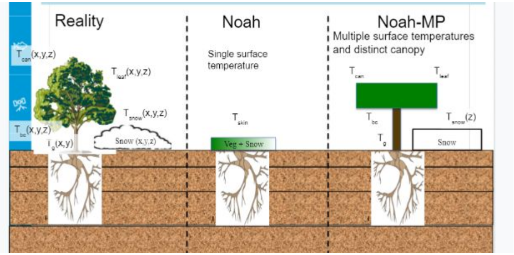


Thompson MP enables the model to simulate supercooled liquid clouds

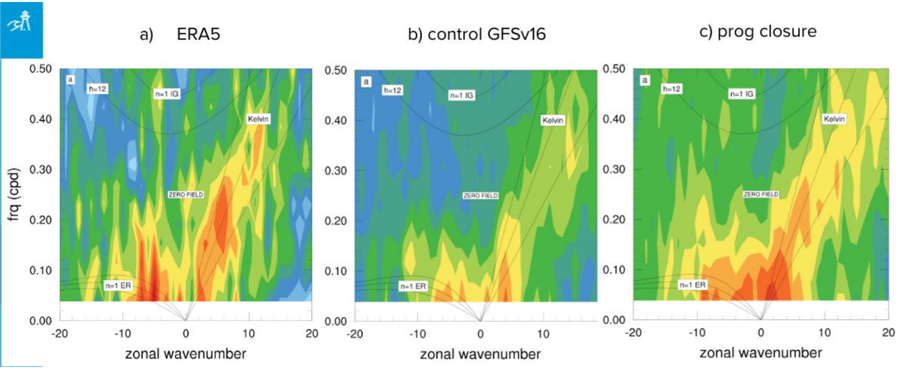


NOAH-MP depicts more realistic the interactions between land, vegetation, snow and the atmosphere.

Contributions to UFS physics and dynamics development

Continued for MRW/S2S: Finalized physics suite for the coupled model prototypes, which are targeted for GEFS.v13 and GEFS.v17 implementations

- ➢ Improved orographic gravity wave drag and mountain blocking; Introduced new small-scale gravity wave and turbulent form drag parameterizations.
- ➢ Updated convection and PBL schemes to improve systematic biases - in particular previously seen low values of CAPE and near surface inversion over CONUS.
- ➢ Introduced new innovations in the convective parameterization to seek improvements in tropical variability: prognostic closure equation in shallow and deep convection, representation of sub-grid convective organization using cellular automata, and stochastic initiation of cumulus convection.
- ➢ Introduced a new positive definitive tracer advection (TVD) scheme to PBL and convection to remove negative tracers and allow for mass conservation when coupling to Thompson MP.
- ➢ Improved collaboration between the DTC T&E activities and physics development across the UFSR2O physics development team



Prognostic closure in convection allows for closer coupling between low level moisture flux convergence and precipitation along tropical wave modes.

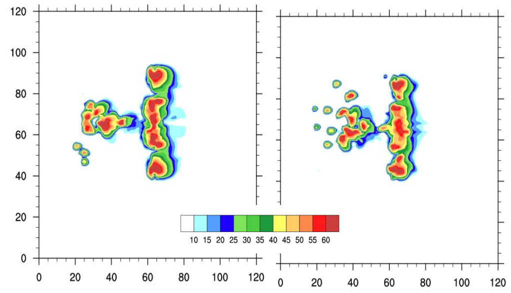
Contributions to UFS physics and dynamics development

For SRW/CAM, attempts were made to reduce RRFS excessive convective precipitation and to improve strom structure:

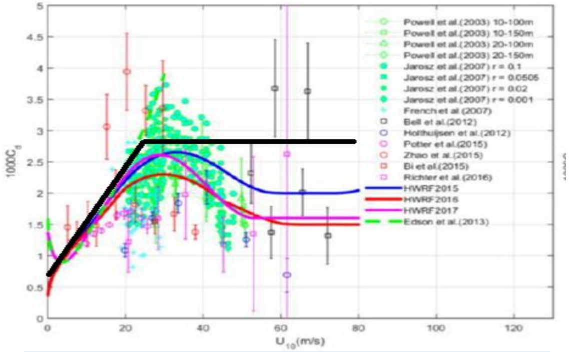
- ➢ Including parameterized deep and shallow convection
- ➢ Inner-looping microphysics and/or semi-lagrangian sedimentation of rain and grapuel
- ➢ Thompson MP parameter changes/updates
- ➢ Update parametric values in the dynamical core pertaining to numerical diffusion, vorticity damping, time-splitting, etc.
- ➢ physics heating at constant pressure instead of constant volume
- ➢ Sensitivity to physics and dynamics time steps

For Hurricane, attempts were made to improve HAFS forecasts of hurricane intensity and track:

- ❖ A parameterization to include environmental wind shear effect in the cumulus convection and PBL schemes was developed and tested in HAFS.
- ❖ Using observations in hurricane environment to constraint parameters of the PBL and surface layer schemes, including mixing length scale, surface roughness etc.
- ❖ Testing sea-spray parameterization, unified GWD and NOAH-MP in HAFS.



RRFS Sensitivity to physics time step; Idealized test case.



HAFS specifies roughness lengths for momentum(z0) and scalar (zt) as a function of wind to match observed drag coefficients (Cd, Ch); Cd decreases with wind speed when wind > 35 m/s