An Overview of Physical Parameterization Development for the Unified Forecast System

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Outline

Goals:

1. Overview the primary model physics development in support of NOAA's Unified Forecast System (UFS)
2. Convince the audience that a robust holistic effort is ongoing to improve the representation of physics and reduce systematic model errors
3. Working towards a skillful forecast model that can also be useful for scientific research

Today's Topics:

- Our approach to the development of the UFS
- LSM, PBL, Convection, Microphysics, Radiation, GWD, and Atmospheric Composition
- Tentative test plans
- Summary

Approach to Physics Development

- **Full adoption of the Common Community Physics Package (CCPP)**
- **Development is typically performed within defined CCPP suites**
  - Specific scheme intercomparisons are performed within GFS/RRFS suites
- **Working towards unified physics suite for all scales and applications**
  - In some cases, like GWD, complementary subcomponents are easy to unify
  - In other cases, like LSM and microphysics, target schemes have been chosen and subcomponents from other sources will be added
  - In yet other cases, like PBL and convection, outstanding science questions still need to be resolved before the final design is known
- **Physics development adopts a two-stream approach:**
  - Focus some development on improving the current operational schemes
  - Spend some time researching/designing longer-term scheme/suite features

Overview of PBL Schemes

Scheme	Primary Developers	Type/Features
TKE-EDMF	Jongil Han (EMC), Chris Bretherton (UW)	• TKE-L • Scale-Adaptive • Uses separate ShCu scheme • Used in GFS
MYNN-EDMF	Joseph Olson (GSL), Jaymes Kenyon (GSL), Wayne Angevine (CSL), John Brown (GSL)	• TKE-L (level 2.5, 2.6, 3.0) • Scale-Adaptive • Integrated ShCu physics • Used in RAP/HRRR
TKE-Epsilon	Chunxi Zhang (EMC)	• TKE-epsilon • Scale-Adaptive
SHOC	Peter Bogenschutz (NCAR), Steve Kreuger (Utah), Alexei Belochitski (EMC)	• TKE-L (diagnostic HOMs) • Scale-Adaptive

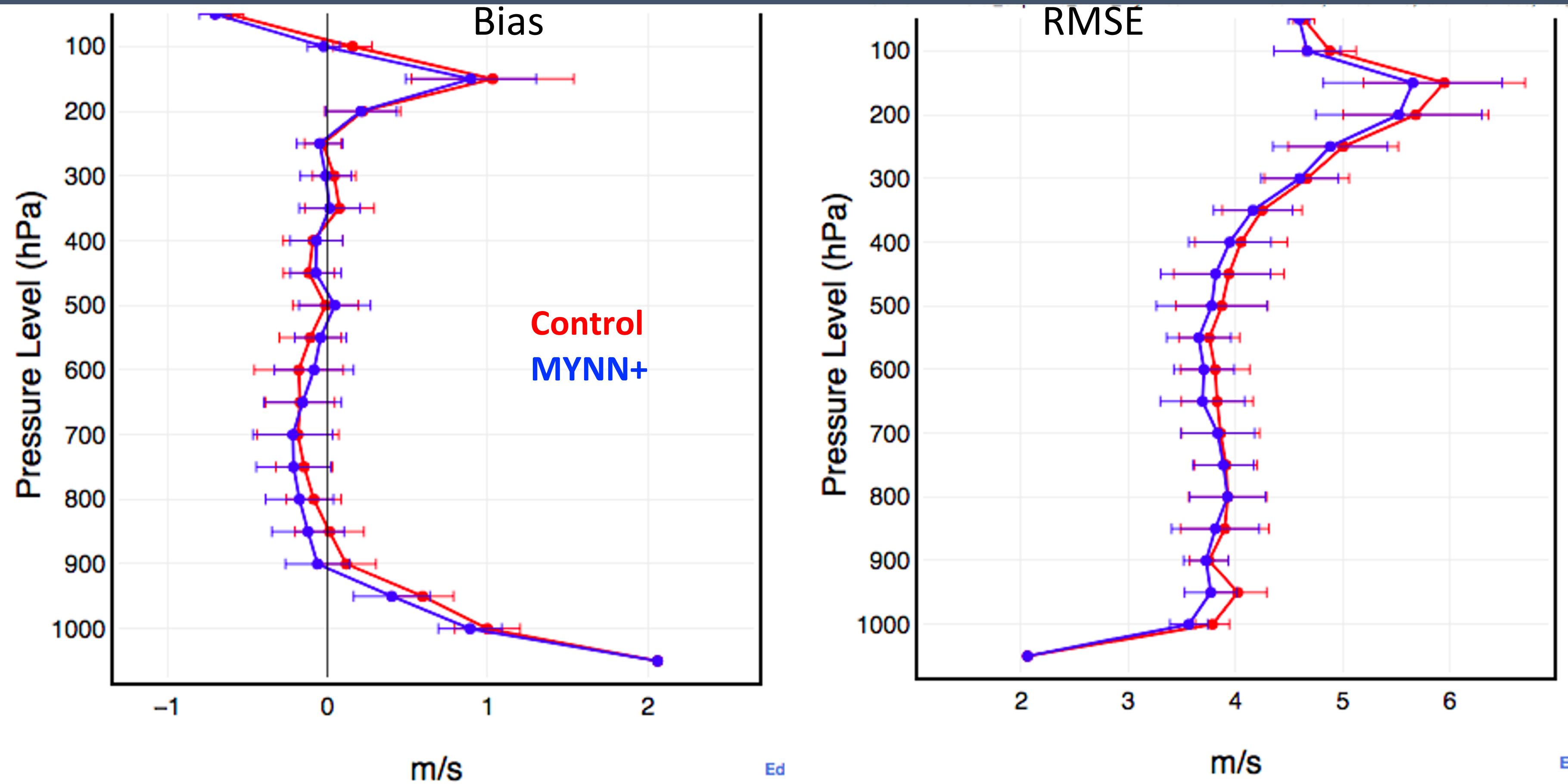
Recent modifications to the MYNN-EDMF

- Reduced numerical noise isolated in the stability functions
  - Only use level 2.5 S_H and then specify $S_M = Pr\ S_H$
  - Specifies Prandtl number, *Pr*, according to Esau and Grachev (2007, WindEng), but slightly modified to honor the original MYNN in the unstable limit:

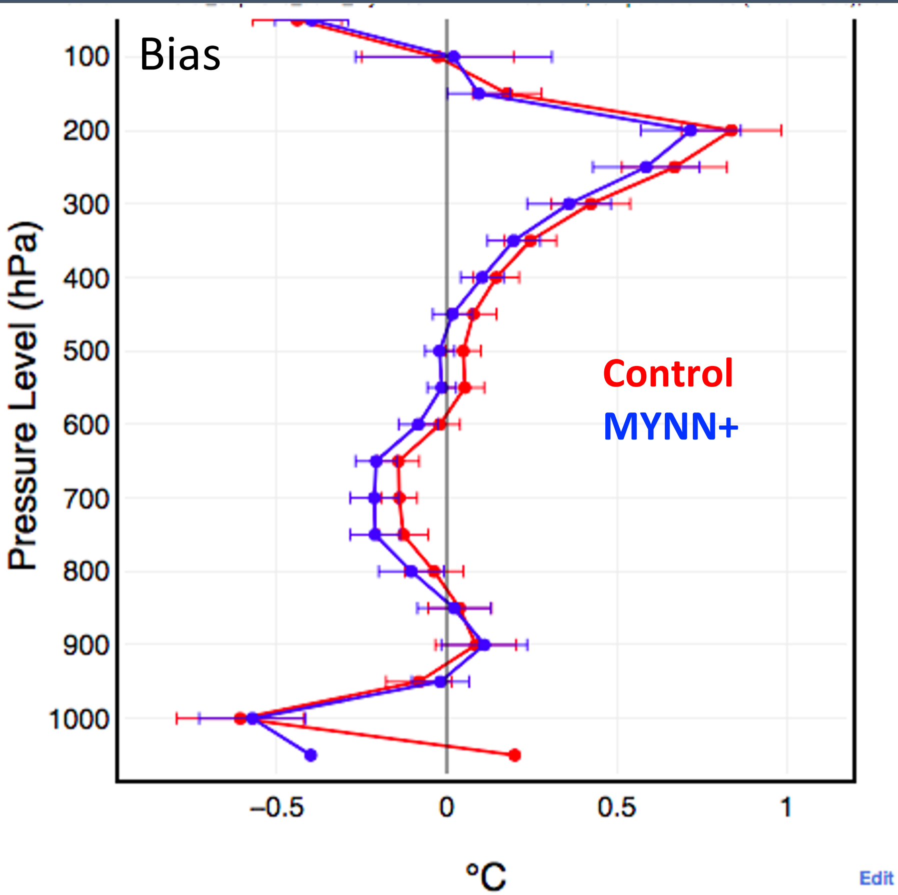
$$Pr = Pr_0 + c\,Ri_g$$

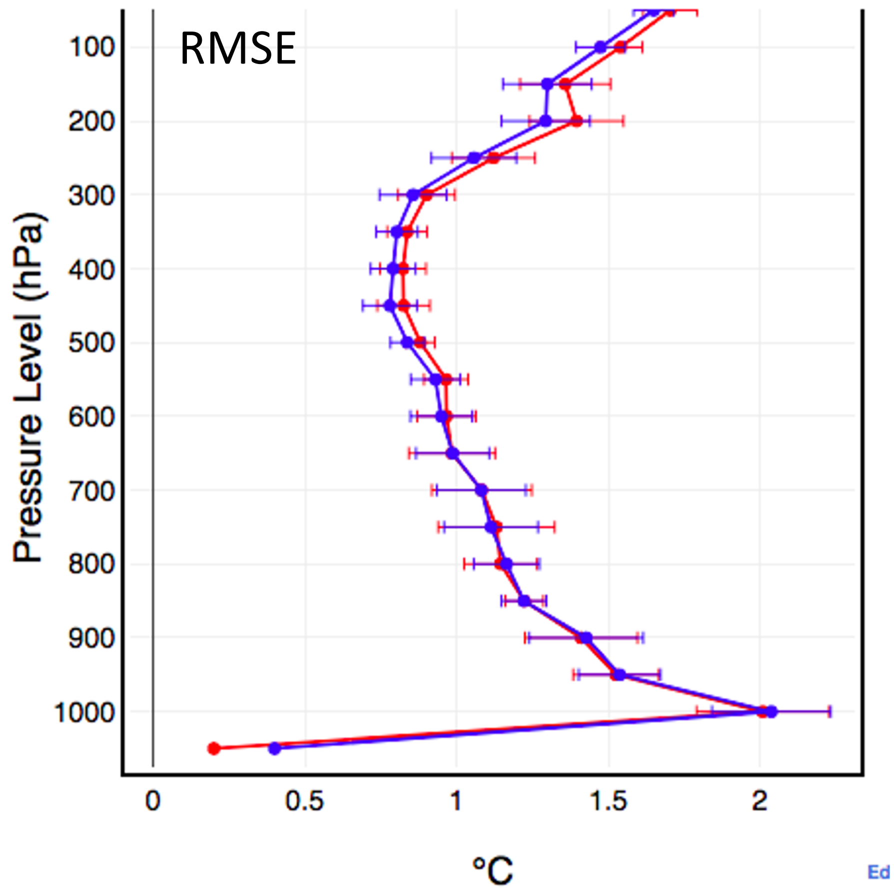
  - Where $Pr_0 = 0.80$, $c = 3.0$, and Ri_g is limited to a lower bound of -0.013, which results in a *Pr* of 0.76 in the unstable limit.
- Modified mixing lengths to minimize the noise-impact of clouds and precipitation on the buoyancy length scale.
  - Changes to the specification of length scales in the PBL were small, mostly impacts free atmosphere.

RRFS Retro (04-12 Sep 2020): Wind Speed, fhr 12



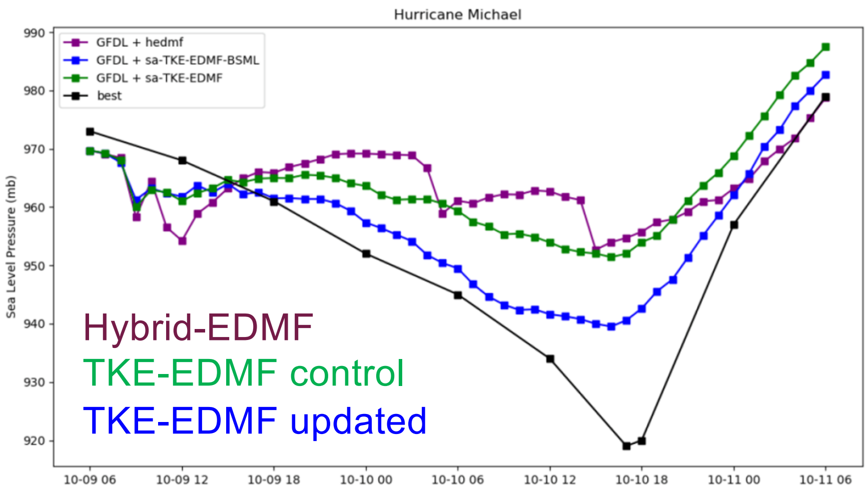
RRFS Retro (04-12 Sep 2020): Temperature, fhr 12





Updated TKE-EDMF PBL scheme for GFSv17

- Include wind shear effect in characteristic mixing length calculation, reducing the mixing length in strong shear environment such as hurricane.

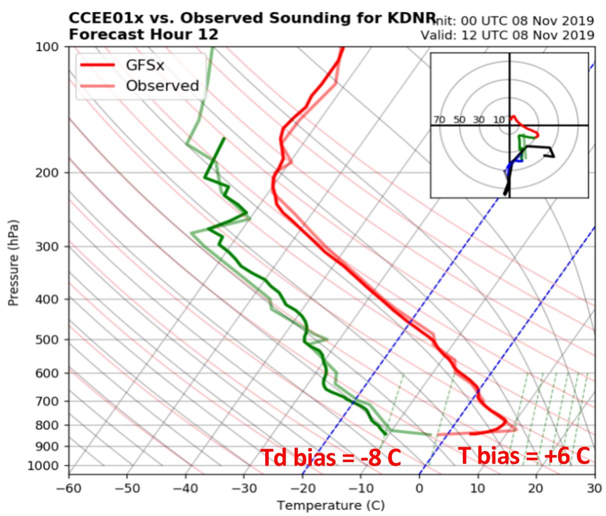


- To suppress too much PBL growth, the PBL updraft overshoot is limited by bulk Richardson number-based-PBL depth.
- To improve the simulation of strong stable layers, the background diffusivity (K_0) in the inversion layers is reduced as a function of surface roughness and green vegetation fraction.

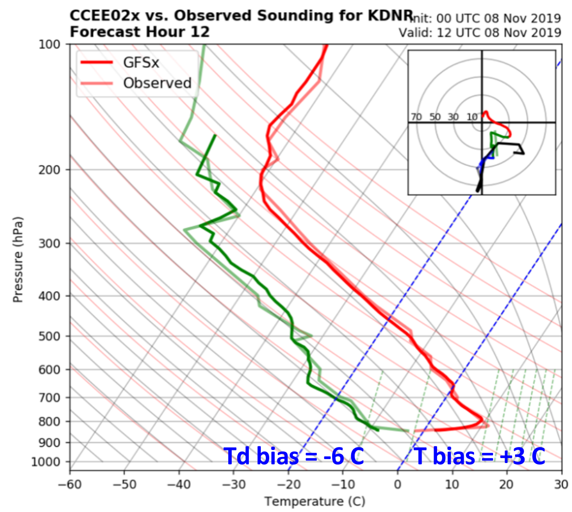
Improved surface-based stable layers

Updated background diffusivity (K_0) in the inversion layers improves the surface inversion prediction

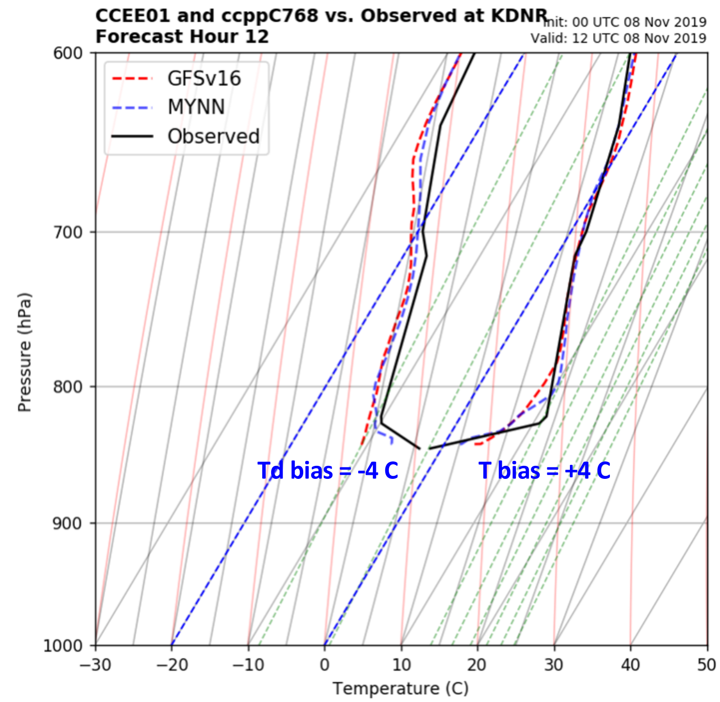
GFSv16



Updated K_0



GFSv16 and MYNN



Denver, CO (00Z8Nov2019, FH=12)

PBL Summary

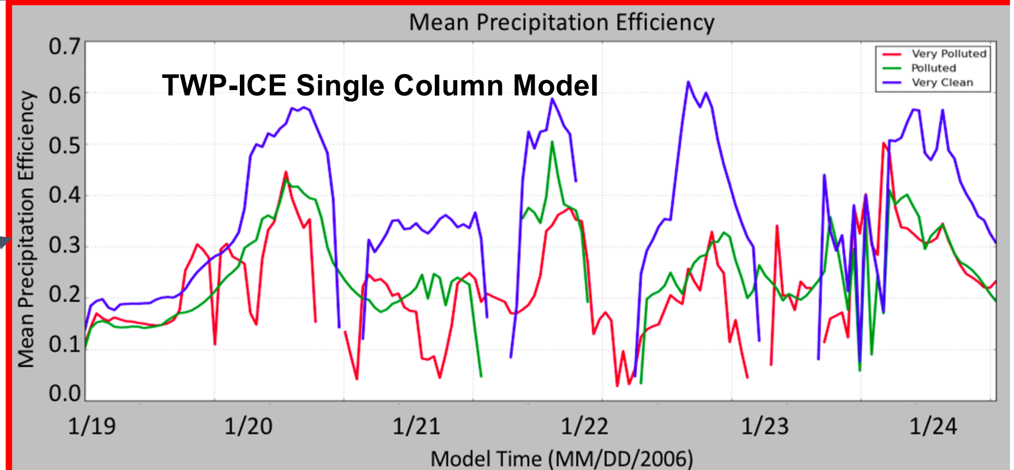
- Yet to determine the “optimal” design/framework to address the full set boundary-layer-related forecast challenges:
  - TKE-*L*, TTE, or TKE-ε, other?
  - Mass-flux scheme or a higher-order closure?
- Still assessing and developing at dx = 12 and 3 km grid spacing
- Significant improvements have been made for both MYNN-EDMF and TKE-EDMF
  - Hurricanes, stable layers, and wind speed & temperature profiles
- Code universalization under way (led by Laura Fowler, NCAR):
  - MYNN-EDMF will be universalized for CCPP, WRF, and MPAS
  - Easier code management and more frequent updates will be possible

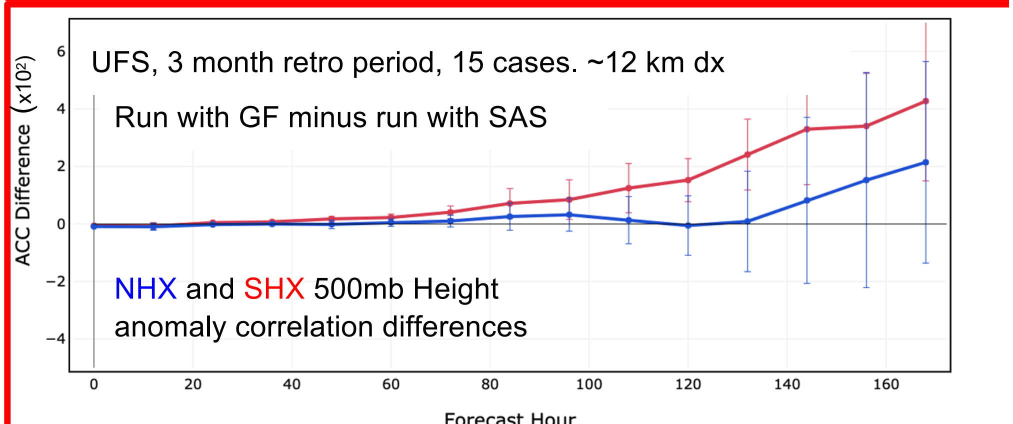
Overview of Convective Schemes

Scheme	Primary Developers	Type/Features
Scale-Aware SAS	Jongil Han (EMC)	• Quasi-Eq Arakawa-Schubert • Deep and shallow cumulus • Scale-aware
Grell-Freitas	Hannah Vagasky (GSL), Haiqin Li (GSL), Saulo Freitas (NASA), Georg Grell (GSL)	• Multi-closure ensemble • PDF mass-flux profiles • Arakawa-Wu scale-aware • Aerosol-aware
Chikira-Sugiyama	Minoru Chikira and Masahiro Sugiyama (Research Institute for Global Change, JAMSTEC)	• Prognostic CKE closure • Arakawa-Wu scale-aware • Spectral cloud representation
RAS	Shrinivas Moorthi (EMC)	

Grell-Freitas Scheme Development

- Double moment microphysics tendencies - improved coupling
- Atmospheric composition treatments included
- Evaluate full aerosol interactions
- Ongoing Work
  - Implement different chemistry options
  - Explore Machine Learning (ML) algorithms
  - Refine scale-awareness to improve convective evolution at dx = 3 km.





sa-SAS Convection changes for GFSv17

Goal: To reduce the existing biases in GFSv16 such as:

(1) underestimated CAPE,

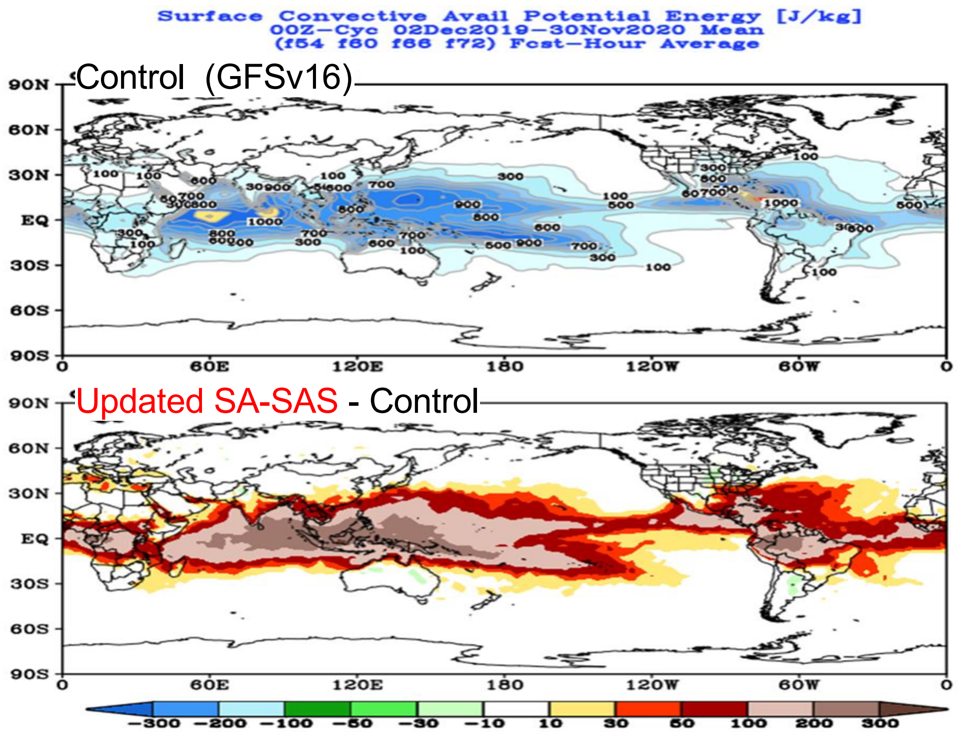
(2) cold bias in tropospheric profiles, and

(3) improve the propagation of tropical kelvin waves

- **More strict convection trigger** (which helps to enhance CAPE)
  - No triggering if sub-cloud mean RH is less than a threshold value (set to 75%).
  - Updraft parcel starts from lower 20% of PBL depth only for trigger to avoid a spurious convection triggering due to rapid surface heating in the morning.
  - About 30% reduced entrainment rate below cloud base to reduce false alarm storms.
- **Reduced rain evaporation with removal of wind shear dependency** (reduces the cold bias in the Tropics).
- **Include a stochastic parameterization of organized convection using cellular automata** (Lisa Bengsston NOAA/PSL) (improves kelvin waves).

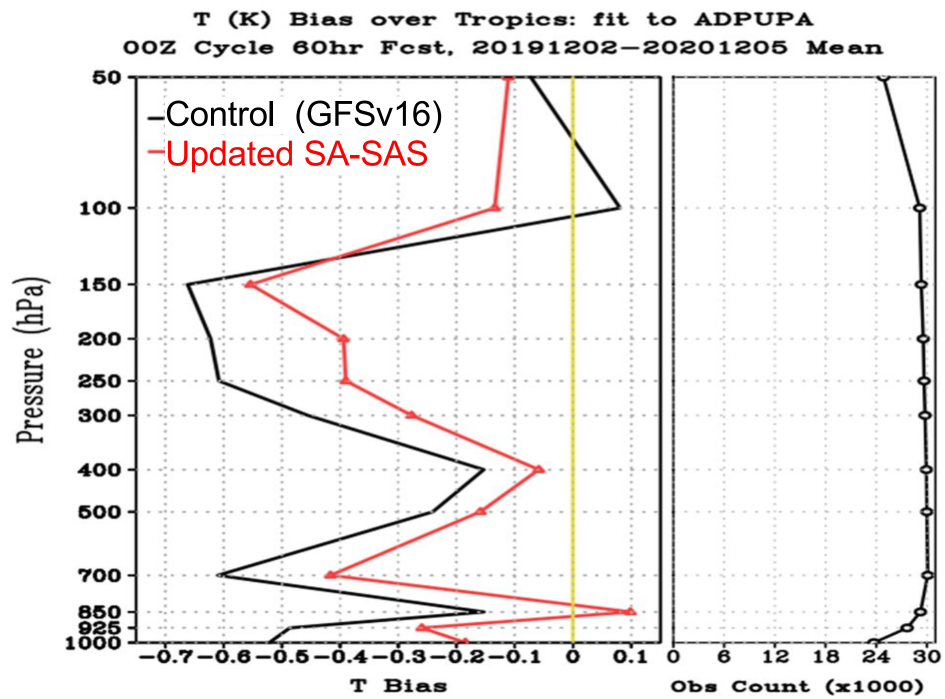
Example of improvements

CAPE



More strict convection trigger helps to enhance CAPE

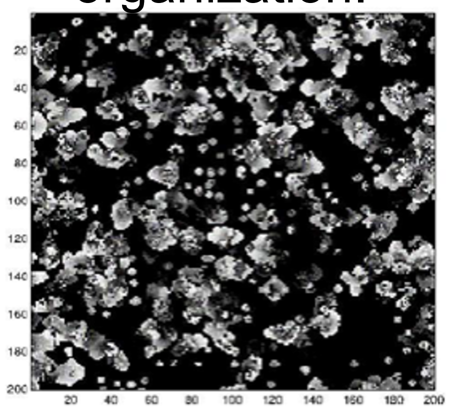
Temperature bias over Tropics



Reduced rain evaporation helps to reduce cold bias in tropospheric temperature profile especially over Tropics.

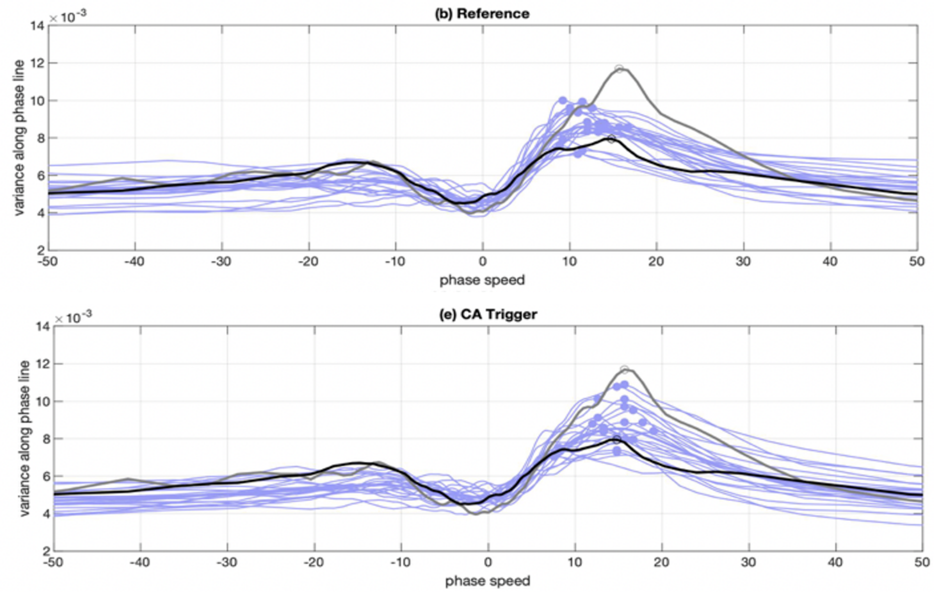
CA stochastic convective organization scheme

- Uses a stochastic cellular automaton to address stochasticity, horizontal communication, and memory in convection parameterization.
- In UFS coupled to saSAS to parameterize feedback associated with sub-grid and cross-grid convective organization.



The cellular automaton exhibits self-organizing behavior and is used within the convection scheme to address sub-grid convective organization.

Bengtsson, L., et al (2021). A stochastic parameterization of organized tropical convection using cellular automata for global forecasts in NOAA's Unified Forecast System. *Journal of Advances in Modeling Earth Systems*



Radon projection plot of **precipitation variance** vs **wave phase-speed.** Observations (grey) show a peak variance along 15 m/s (Kelvin wave propagation). Blue lines show ensemble members for Reference and CA scheme. Black line is control member. CA scheme enhances wave propagation to better match observed speeds.

Convection Summary

- Another good example of our two-stream approach:
  - Continuing to improve the current operational scheme (sa-SAS) in the GFS
  - Experimenting with improved coupling to aerosols (GF scheme)
- Chipping away at systematic biases in the GFSv16 with the sa-SAS
  - Reduced cold bias in Tropics
  - Reduced the low CAPE bias
  - Improved propagation of Kelvin waves with Cellular Automata
- GF improvements:
  - Improved coupling to double-moment microphysics schemes
  - Improved coupling to aerosols
  - Results in improved ACC scores

Overview of Microphysics Scheme Development

Scheme	Primary Developers	Type/Features
GFDL	Linjiong Zhou (GFDL), S-J Lin (GFDL), Lucas Harris (GFDL)	● Single-moment ● Descendent of the Lin Scheme ● Can create partial-cloudiness in subsaturated grid cells ● Currently used in GFSv16
Thompson Aerosol-Aware	Greg Thompson (UCAR), Trude Eidhammer (NCAR), Anders Jensen (NCAR), Ruiyi Sun (EMC)	● Double-moment in qc, qi, qr ● Ice & water friendly aerosols ● Updated aerosol emissions ● Runs stable with new sub-timestepping capability ● Currently used in RAP/HRRR

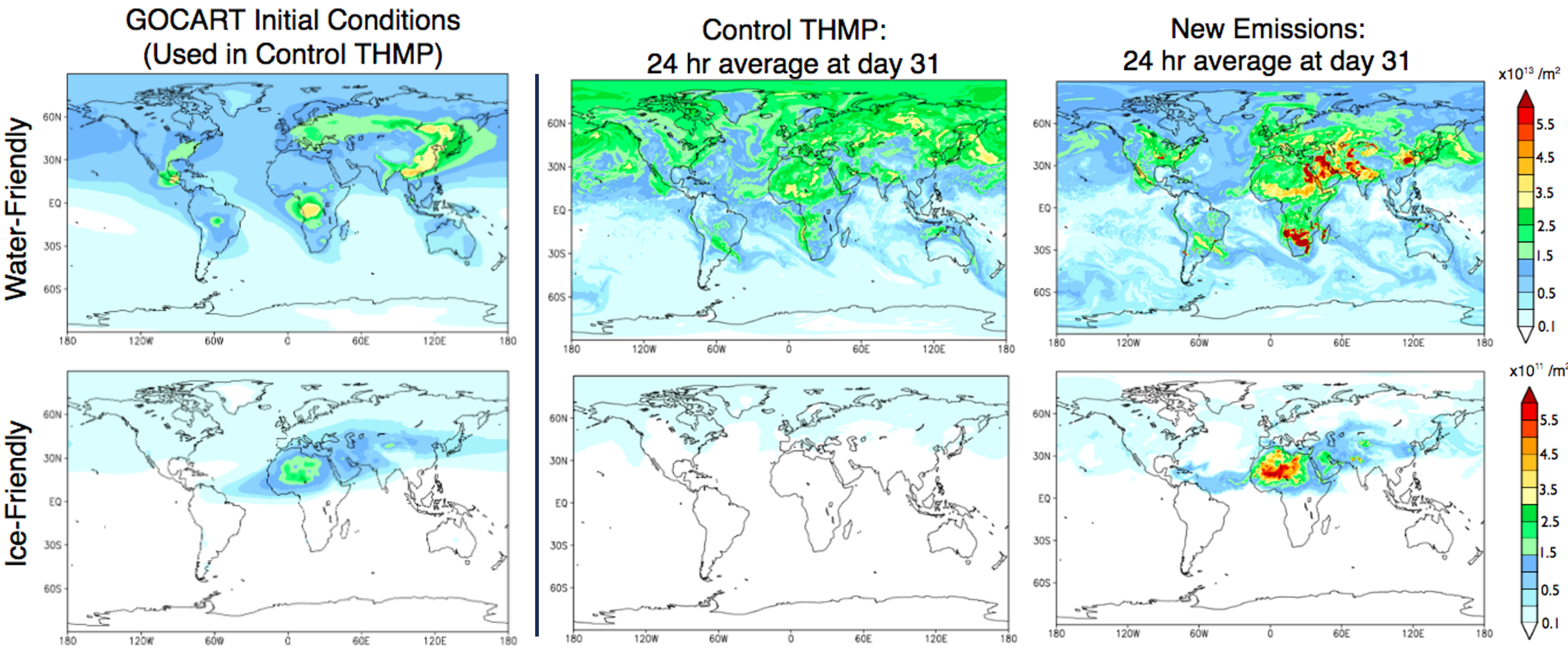
Updated Development of the Thompson Scheme

Currently used operationally for regional applications, now being tested and developed for global applications.

- Improve computational stability and efficiency
  - Constraints on phase-change processes
  - New ability to sub-timestep as scheme in CCPP
  - Semi-Lagrangian sedimentation
  - Treat fast and slow processes differently (integration into dynamical core)
- Improved surface aerosol emissions:
  - Bug was removed which over-amplified the surface emissions of water-friendly aerosols
  - We have taken a step further to improve the specification of emissions:
    - Go away from evolved atmospheric climatological values
    - Specify directly from surface emission observations (GOCART)

INITIAL THOMPSON AEROSOL-AWARE MICROPHYSICAL SIMULATIONS

AEROSOL NUMBER CONCENTRATIONS [m^{-2}]

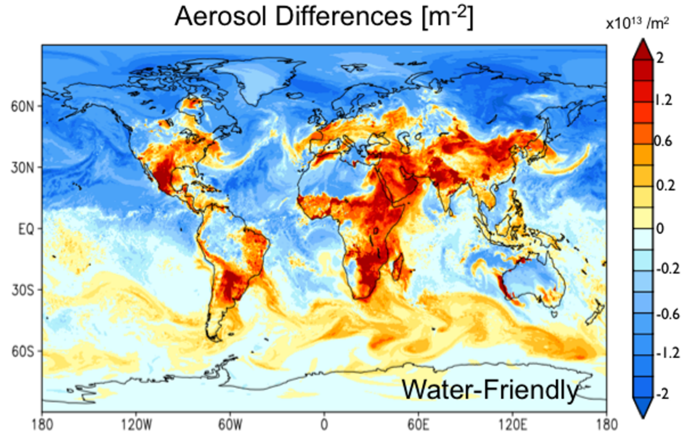


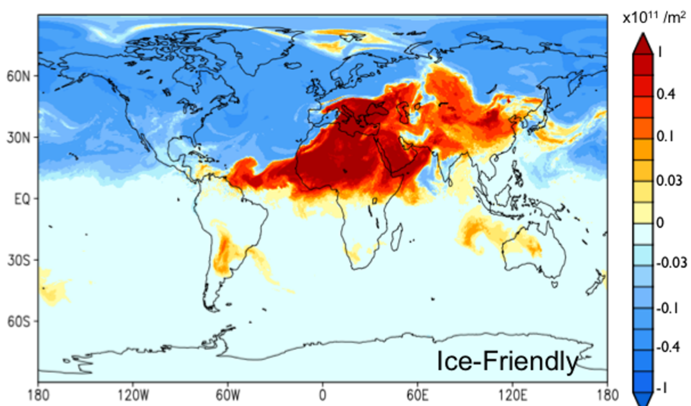
Simulation and figures from Haiqin Li

INITIAL THOMPSON AEROSOL-AWARE MICROPHYSICAL SIMULATIONS

DAY 31 RESULTS

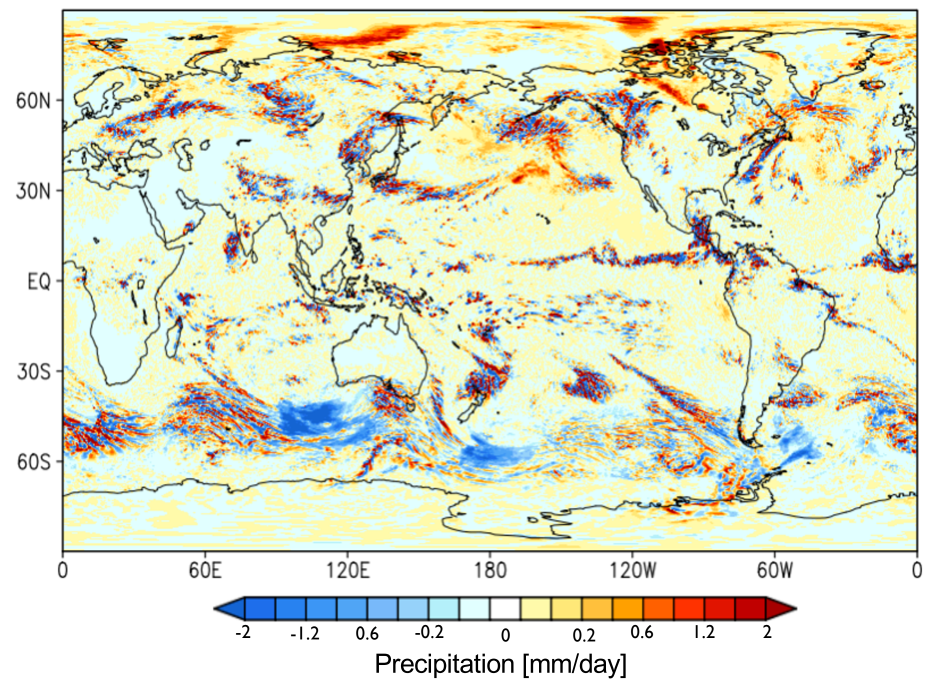
Aerosol Differences [m^{-2}]





Simulation and figures from Haiqin Li

24 hr Average of Large-Scale Precipitation Differences

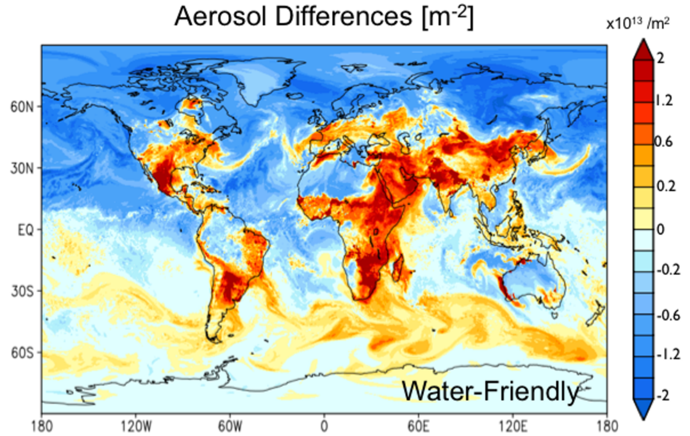


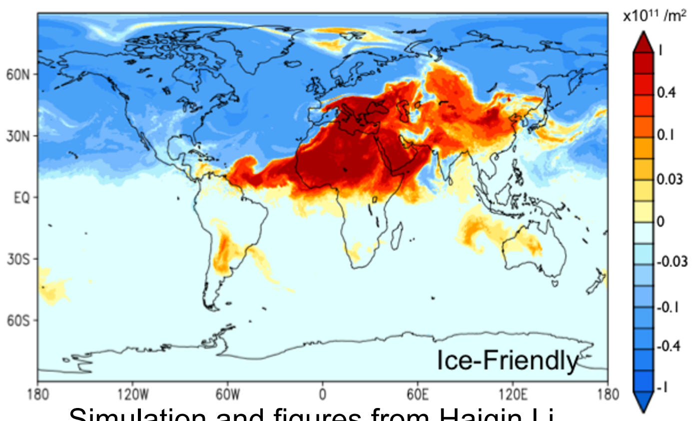
Large-scale precipitation increases (decreases) where water-friendly aerosols decreases (increases).

THOMPSON AEROSOL-AWARE MICROPHYSICAL SIMULATIONS

DAY 31 RESULTS

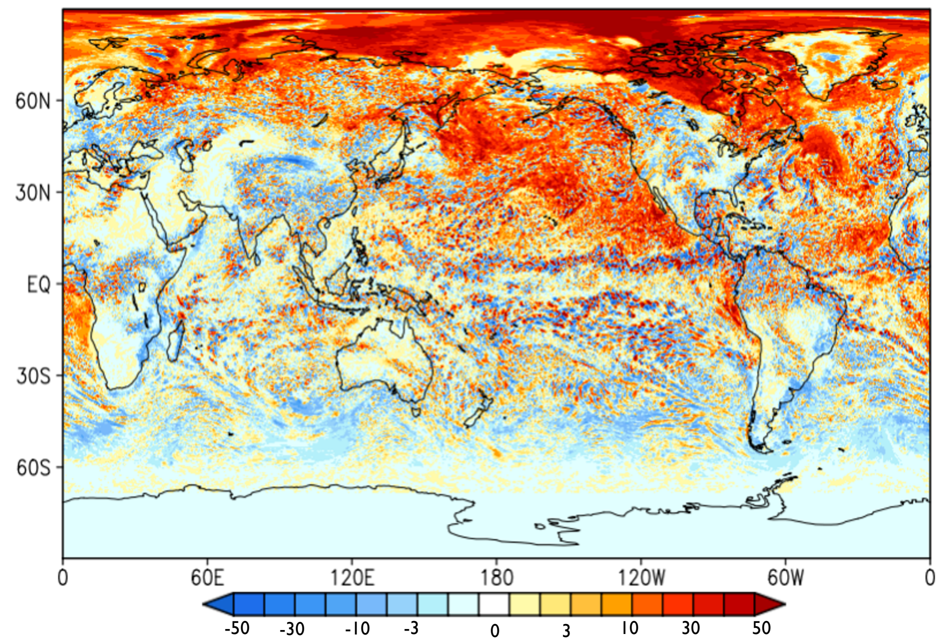
Aerosol Differences [m^{-2}]





Simulation and figures from Haiqin Li

24 hr Surface Downward Short-Wave Differences



Notable increase in downward shortwave radiation in the northern hemisphere where there is a decrease in aerosols.

Summary for Microphysics

- Promising results for improving the computational stability for longer timesteps (not shown).
  - These proposed modifications are still being evaluated - will not be considered for the next upgrade of the GFS.
- Surface aerosol emissions have been improved:
  - Specifying emissions from observations (GOCART).
    - Results do impact precipitation and radiation; may require further tuning.
- Near-term plans are to use the prescribed MERRA2 aerosol climatology for radiation interactions for both deterministic and ensemble applications.
  - New GOCART-derived emissions are under consideration for the single chemistry member of the GEFS ensemble system.

Overview of Radiation Scheme Development

Scheme	Primary Developers	Type/Features
RRTMG	Eli Mlawer (AER), Mike Iocono (AER)	• LW - 16 bands • SW - 14 bands • Uses McICA to represent unresolved clouds
RRTMGP	Robert Pincus (CU/PSL), Eli Mlawer (AER) Dustin Swales (CU/PSL - CCPP coupling)	• Conceptually similar to RRTMG • Correlated k-distribution for absorption by gases • McICA for small scale cloud structure
SW Emulator	Dave Turner (GSL), Ryan Lagerquist (CIRA)	• Machine Learning-based • Modified U-net • Computationally efficient

Updated Features with RRTMGP

Improved physics

- Clouds scatter longwave radiation
- Approximate heating rate response to surface temperature between radiation calls

Improved data

- Modern spectroscopic data, especially more absorption of sunlight by water vapor
- Spectral data provided at runtime; enables a range of cost/accuracy tradeoffs

Improved software

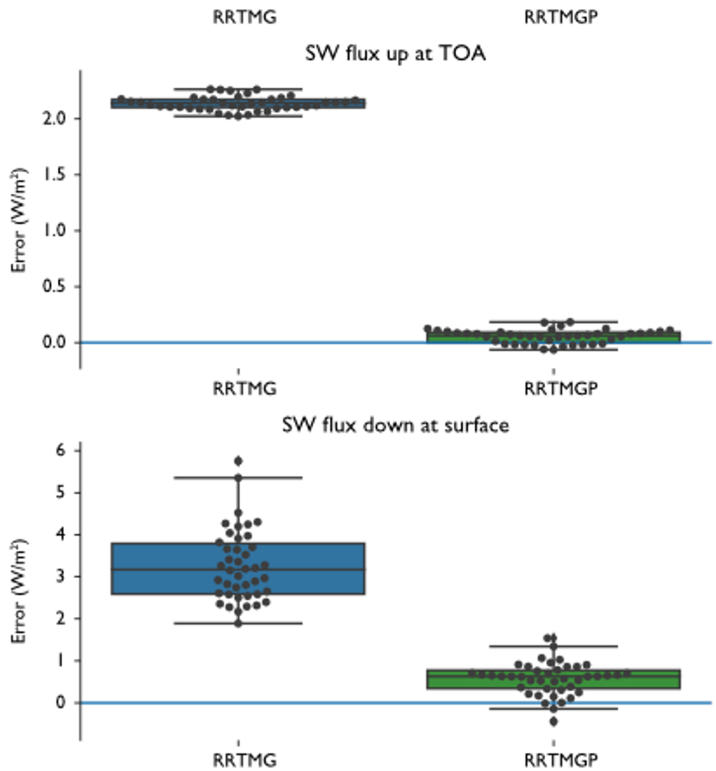
- Clear conceptual divisions allow for precise and flexible cloud/radiation coupling
- GPU-ready using OpenACC or OpenMP compiler directives (6-8x speedup)

Computational performance

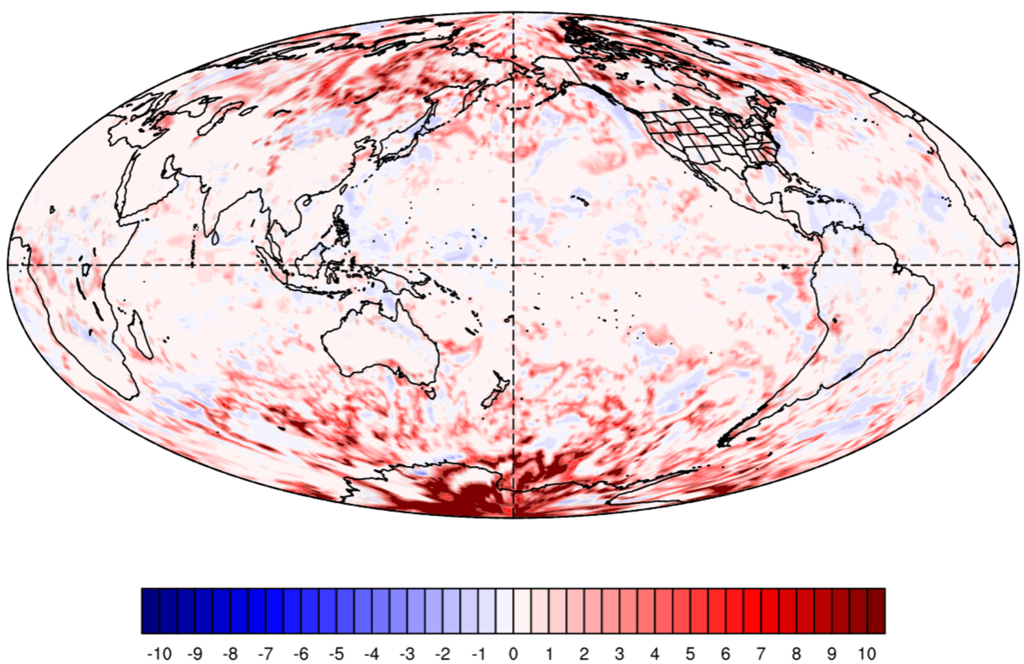
- RRTMGP remains slower than RRTMG due to different memory patterns
- Reduced-resolution spectral data are nearly complete; will improve
- Refactoring is ongoing

Improvements with RRTMGP

The importance of updated spectroscopic data:



The impact of physics innovations:



Change in UFS (v16) instantaneous downwelling longwave flux at the surface (Wm-2) when including scattering by clouds.

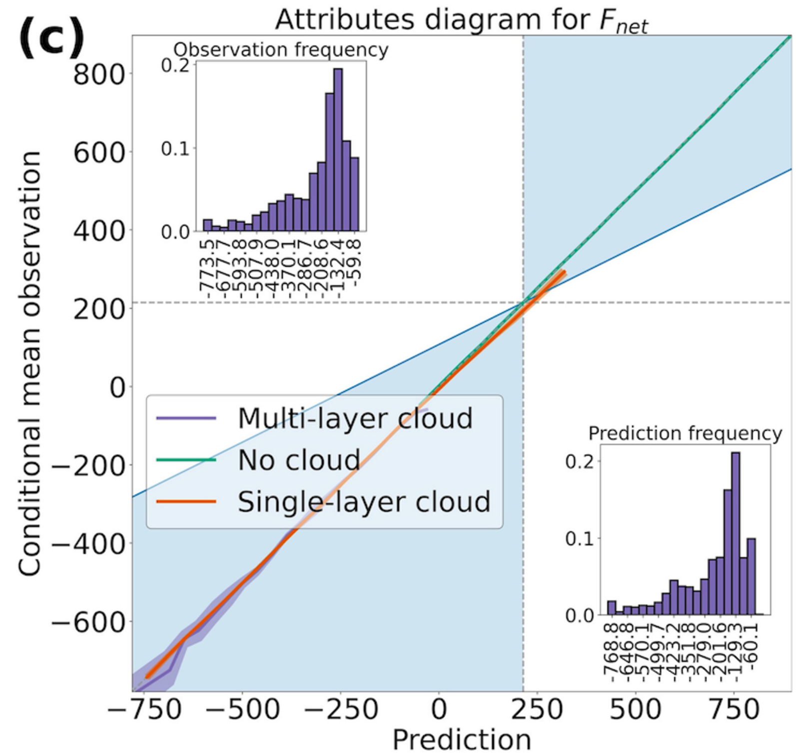
Figure credit: Dustin Swales (NOAA/PSL)

Emulating the Radiation Scheme with ML

- Radiation schemes are computationally expensive; called every ~10 time steps
- Developed a Machine Learning (ML) algorithm to mimic the shortwave parameterization RRTM Shortwave Scheme

- Has near perfect reliability and low bias
- Is over 1,000 faster than RRTM

- Current / future work:
  - Making emulator vertical grid agnostic
  - Incorporating aerosols and precipitation
  - Building a complementary longwave emulator
- Will be tested in the Unified Forecast System
- Paper in review at JTECH



Summary for Radiation Scheme Development

Development has been largely two-streamed:

- Updating to the more contemporary **RRTMGP scheme**
  - Improved physics: LW scattering, Surface temperature impacts
  - Improved data: modem spectroscopic data
  - Improved software: flexible cloud-radiation coupling, GPU-ready
  - Still working on improving computational efficiency
- Experimenting with **machine learning-based emulators**
  - Much computationally faster than “traditional” approaches
  - May eventually be able to incorporate impacts of:
    - 3D effects
    - Cloud overlap assumptions
  - Not yet available in CCPP

Overview of Unified GWP Scheme Development

Goals:

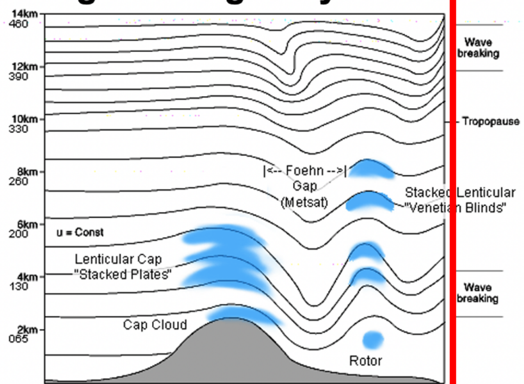
- A unified drag parameterization in the FV3GFS, which includes the effects of both orographic and non-stationary gravity waves (GW), and turbulent orographic form drag
- A “scale-aware” scheme for horizontal grids from ~100km to ~1km

Objectives:

- Incorporate the **GSL orographic drag suite** and **UGWP.v1** into the CCPP Unified Drag Suite.
- Perform extensive testing of the suite

GSL Orographic Drag Suite

Large-scale gravity waves

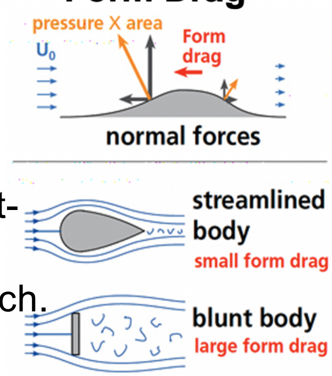


Small-scale gravity waves

Adapted from original version provided by Gert-Jan Steeneveld, Delft Univ. of Tech.

Flow blocking

Form Drag



Adapted from Beljaars et al. (2004)

Traditionally used components

- Large-scale GWD and flow blocking drag taper off by Δx = 5km

New components:

- Small-scale GWD and form drag can be used down to Δx = 1 km

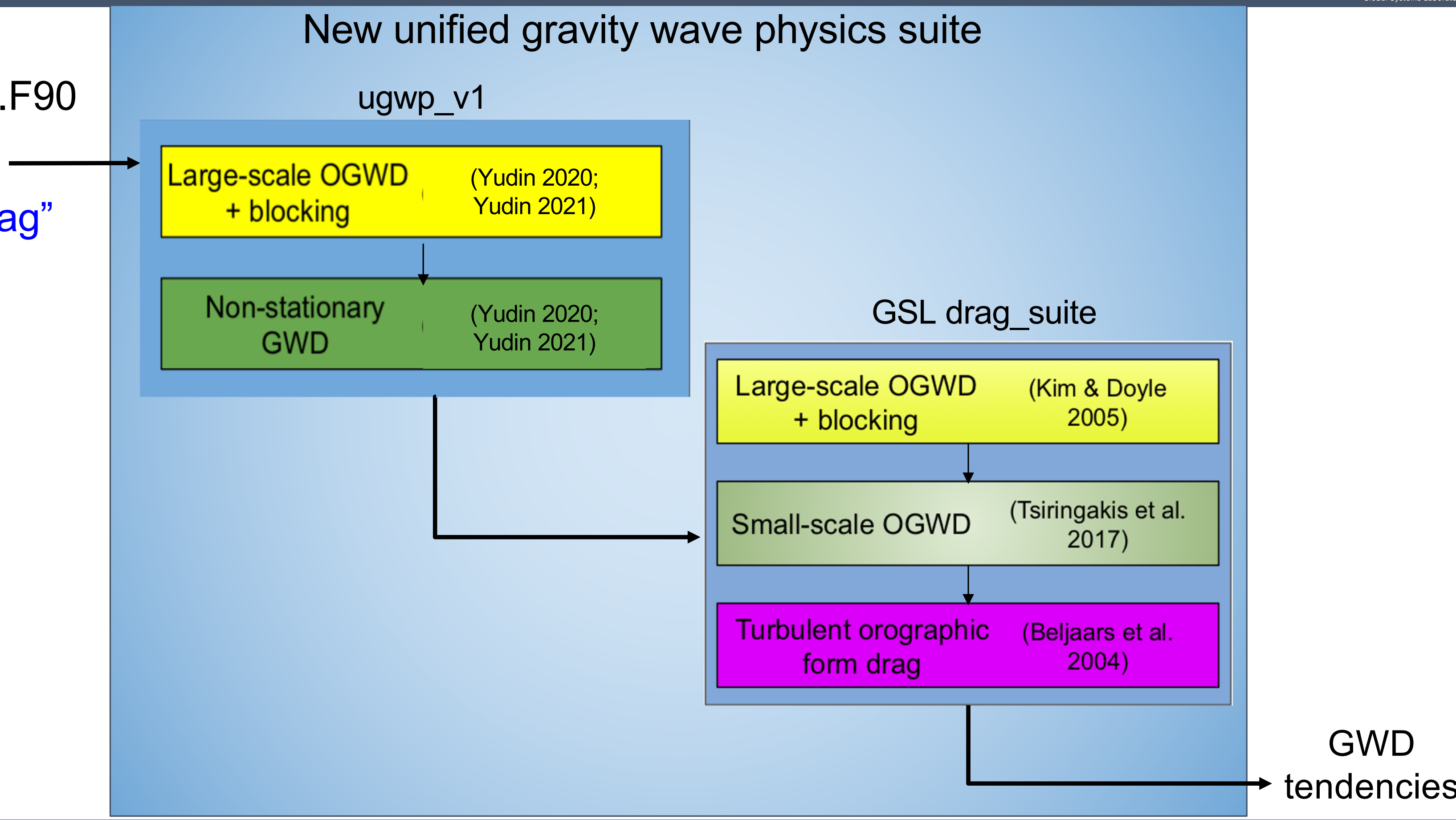
Future Work:

- Merge small- and large-scale GWD with Fourier (multi-scale/wave) formulation

CCPP GWD scheme flow charts

ugwpv1_gsldrag.F90

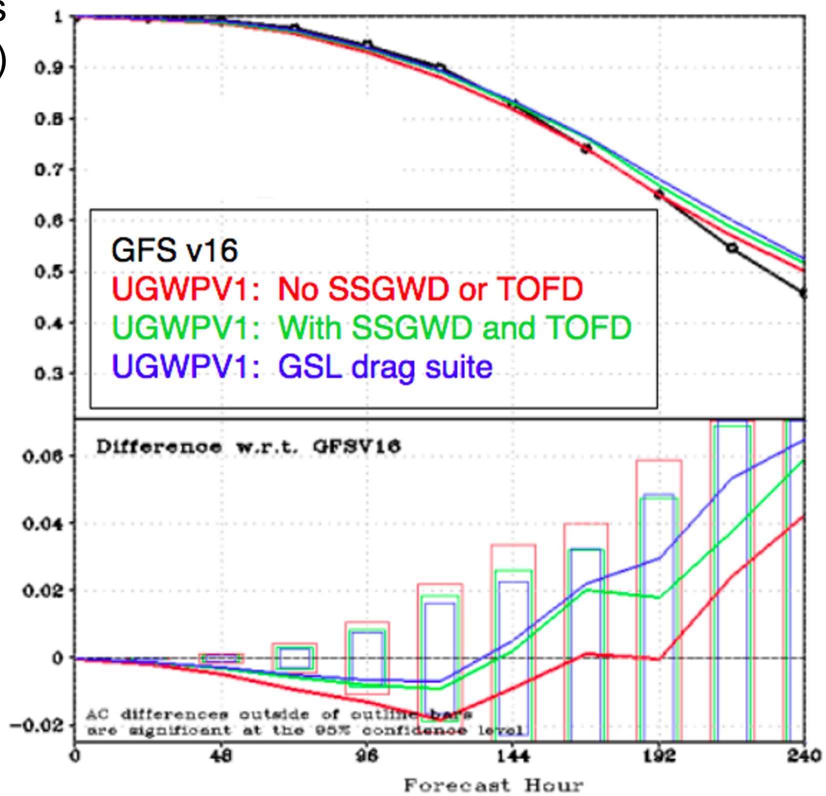
CCPP "ugwpv1_gsldrag" scheme



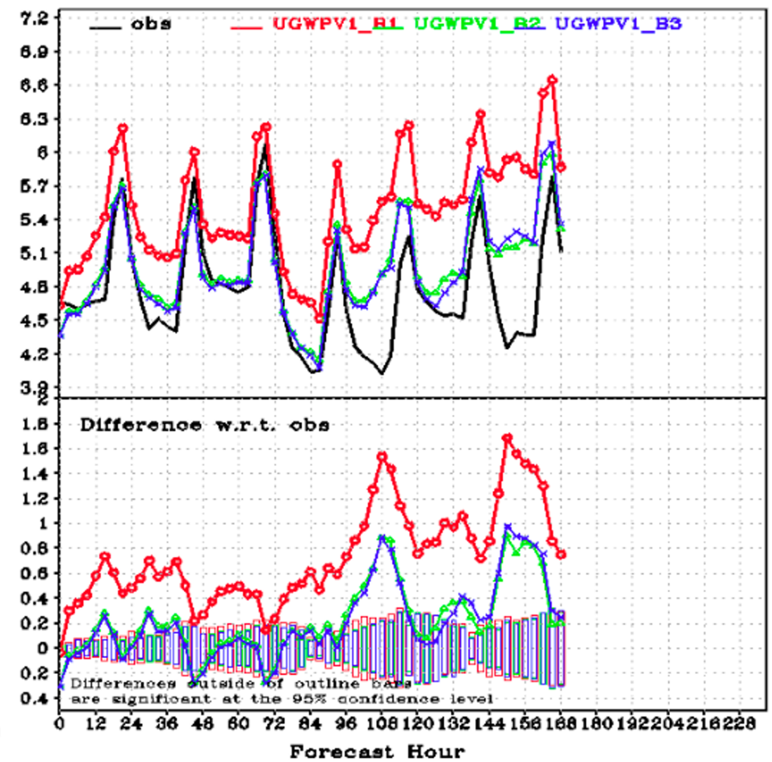
Global FV3GFS Tests (Δx ~13km, 127 levels)

Seven 10-day forecasts initialized every 5 days (01 Jan - 31 Jan 2020)

Global 500 hPa Height ACC die-off



West CONUS 10-m wind speed
(black curve = OBS)



GWD Summary

- Components of the GSL drag suite are now integrated into uGWPv1:
  - Overall improvements seen in 500 mb ACC
  - Overall improvements seen in 10-m wind speeds
- Still assessing and developing at dx = 12 and 3 km grid spacing
  - SSGWD and TOFD especially need further assessment at dx = 3 km (just beginning)
- GSL drag suite has now been implemented into WRFv4.3
  - Preprocessing of subgrid terrain fields have also been added (Thanks Michael Duda)
  - We intend to keep updating this suite as it evolves in the UFS
  - Review Michael Toy's presentation for more information (Wed, 09 June 2021)

Tentative Test Plan for GFSv17

- Evaluation of control simulations has been completed
- Goal: Finalize configuration of GFSv17 within 3-6 months
  - Complete RRTMGP/uGWP tests (new schemes)
  - Complete PBL/Convection/Sfc Layer (modified schemes)
  - Complete combined tests and final tuning
- After the atmospheric configuration is known, development/testing will be in coupled mode
- Continue parallel development/testing of experimental candidate schemes

Most experiments: 70 cases over 1 year

uGWP pre-test: 10 cases over NH winter

RRTMGP: 10 cases over 1 year

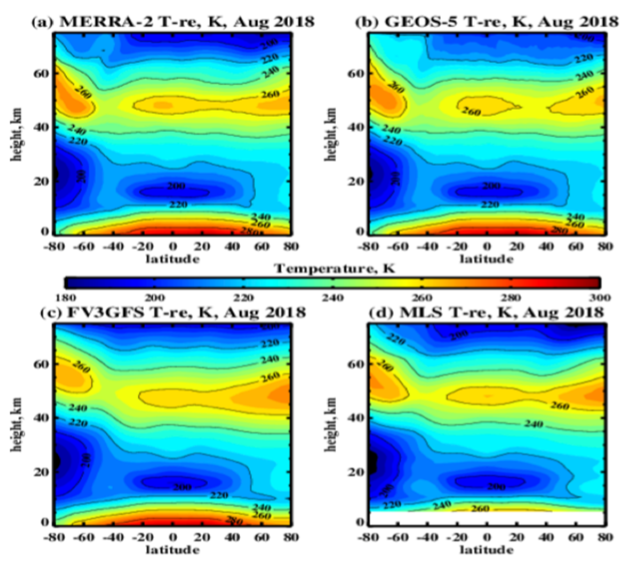
Summary

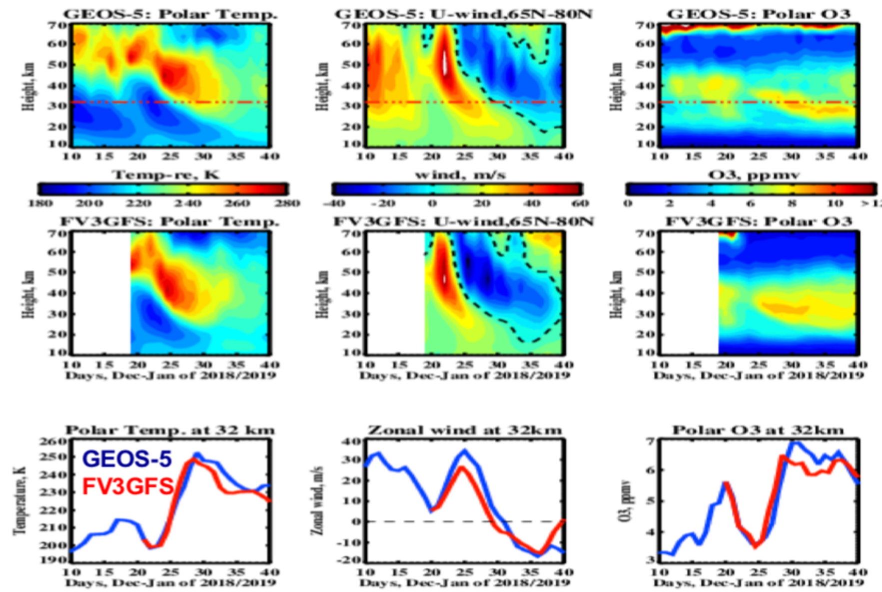
- We have **expanded our scope** from being either regional or global to include all time and spatial scales for any application.
  - Improve current operational physical parameterizations
  - Research and development for longer-term improvements for the UFS
- We are **working towards a unified physics suite** for all scales/applications
  - We commonly test/assess physical parameterizations on a variety of regimes and at different scales
- All components of the model are under intense development
  - Some will be ready for near-future upgrades, some meant for successive upgrades
- Some schemes are already integrated into WRF/MPAS.
  - Scheme universalization and/or CCPP will be the primary mechanism for community collaboration
- We would like to thank our collaborators from a variety of institutions (NSSL, CSL, PSL, GML, NASA, UCAR/NCAR, NRL, DOE, GLERL, ARL, GFDL, AOML...).

Extra Slides

uGWPv1: Non-Stationary Drag Component

uGWPv1: Monthly AUG/2018 (20-day averaged) and 10-day predictions of SSW Jan 1 2019





- Left plate: FV3GFS (c) monthly averaged T-predictions vs MERRA-2 (a), GEOS-5 (b), and MLS data (d)
- Right plate: Predicting (30-day run) the SSW Jan 1 2020 by FV3GFS (10 days before the SSW onset) and GEOS-5 analyses

Moving towards a multi-wavenumber representation of subgrid topography

From linear theory:

$$\tau_x(k,l) = -\frac{1}{2}\rho_0 U^2 \sqrt{\frac{N^2}{U^2} - k^2}\,\frac{k^2}{\sqrt{k^2+l^2}}\left[H(k,l)\right]^2$$

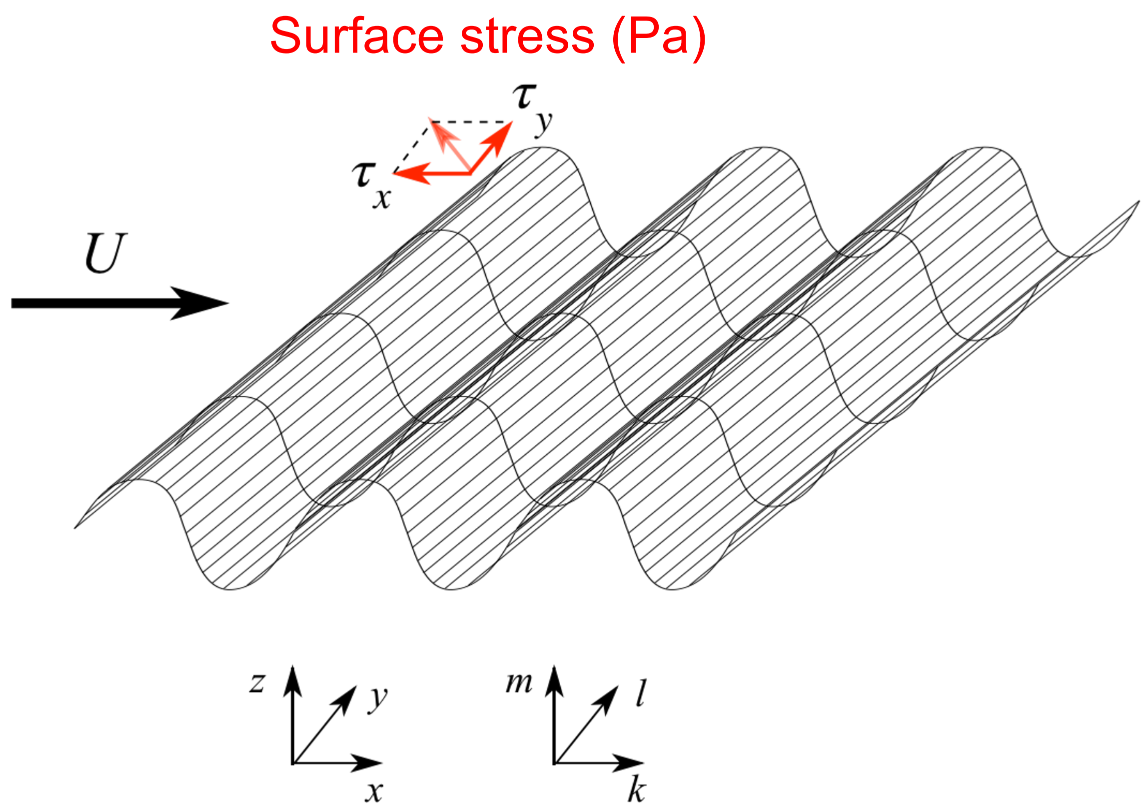
$$\tau_y(k,l) = -\frac{1}{2}\rho_0 U^2 \sqrt{\frac{N^2}{U^2} - k^2}\,\frac{lk}{\sqrt{k^2+l^2}}\left[H(k,l)\right]^2$$

where,

ρ_0 = air density (kg m^{-3})

N = Brunt-Väisälä frequency (s^{-1})

$H(k,l)$ = amplitude of mode (m)



Fourier series representation of 2D ridges

Deplaned topography in vicinity of Mt. Hood, Oregon