NOAA Global Systems Laboratory

Earth-System Prediction: GSL History and The Scientific Method Applied by NOAA Research

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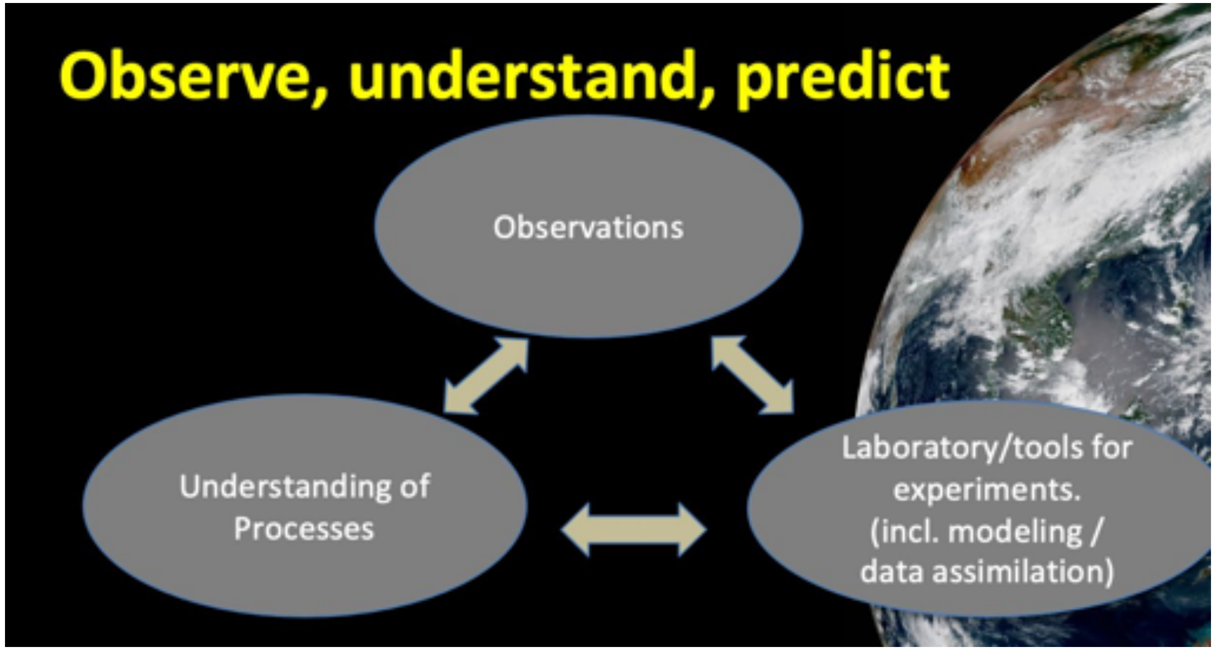
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
Global Systems Laboratory

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

NOAA's mission: Science, Service, Stewardship

→*Hypotheses* for earth-system research to improve prediction



Our responsibility across NOAA Research and in Global Systems Laboratory

- 1974, 2011 – US tornado outbreaks
- 1976 – Big Thompson, CO flood
- 1980s – poor aviation forecasts
- 2005-2015 –lake-effect snow events
- 2013-2020 – heavy rainfall flood events (e.g., CO, Harvey, WV)
- 2012 – Mid-Atlantic derecho
- 2015-2020 – significant US smoke
- 2010-2021 – increased use of renewable energy – wind and solar

GSL's Historical Impact on US NWP

- Rapidly updating models –
  - First hourly updated model (RUC), first hourly updated CAM-scale model (HRRR)
- New observations to initialize models
  - First assimilation of radar reflectivity (2008), commercial aircraft (1994), GPS-met
  - First assimilation of cloud data (METAR, satellite)
- Far higher resolution
  - Ex: MRMS radar availability →quick GSL radar DA and testing HRRR
- Integrated model/DA development
  - Leading physics development, *integrated* PBL/cloud/cumulus/land-snow suite
- Extending from weather to earth system
  - Coupling to land/snow, aerosols, lakes. First land cycling, HRRR-smoke, GEFS-Aerosols
- Community engagement – development for WRF, GSI, UFS, CCPP

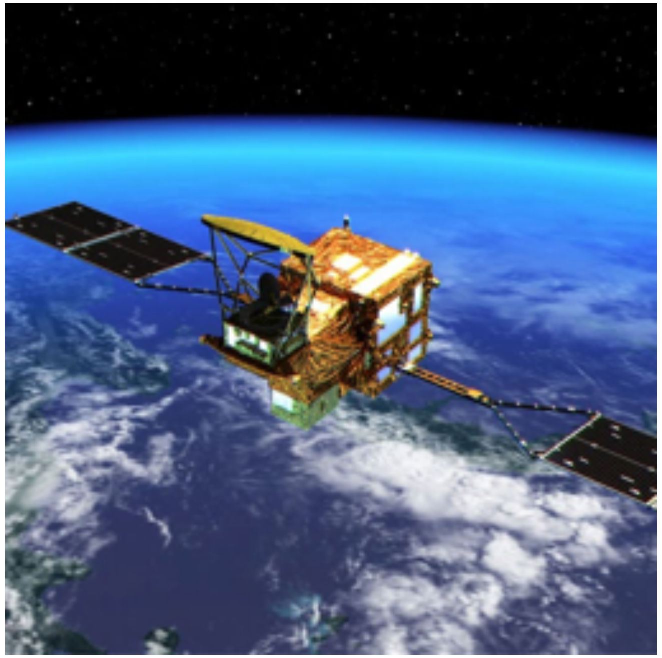
2015 Recommendations for GSL on NWP

- Identify core competencies
  - High-resolution earth-system modeling,
  - High-resolution DA
  - Community-enabling role, e.g., CCPP, DTC, UFS
- Develop a convection-permitting ensemble
  - HRRR Ensemble
- Contribute to NGGPS (now UFS)
- Prioritize GSL NWP via user needs
  - Energy, severe weather, aviation
- Collaborate with National Water Center
  - HRRR = near-term QPF for National Water Model, project for cycling with NWM

Our upcoming GSL modeling story

- Modeling
- Data assimilation
- Improvements to prediction across scales
- Community engagement

A 100-km view overview



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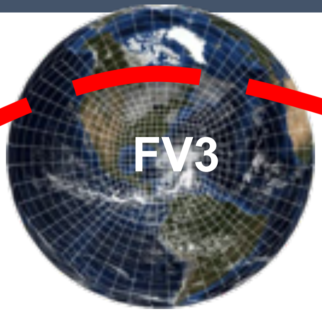
Earth System Prediction: Modeling to improve the Prediction of Weather, Air Quality, and Climate

Georg Grell
Division Chief, Earth Prediction Advancement Division

Global Systems Laboratory

Overview of Activities in Modeling

Advance understanding and modeling of the environment



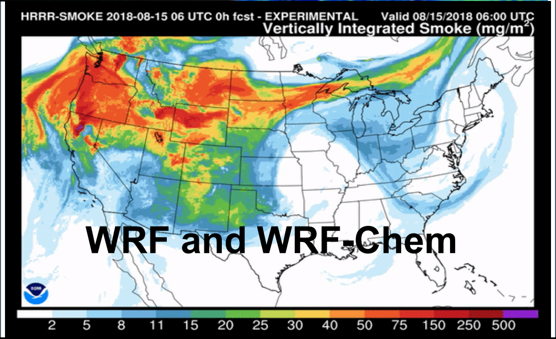
Improve operational forecasting of weather and air quality on all scales

Physics and Chemistry Development

- Boundary layer
- GWD drag
- Convection
- Land surface
- Atmospheric composition
- Scale awareness

Developmental Testbed Center (DTC)

- Infrastructure for development of parameterizations
- Assessment of physics innovations
- Hierarchical tests



Inline coupling

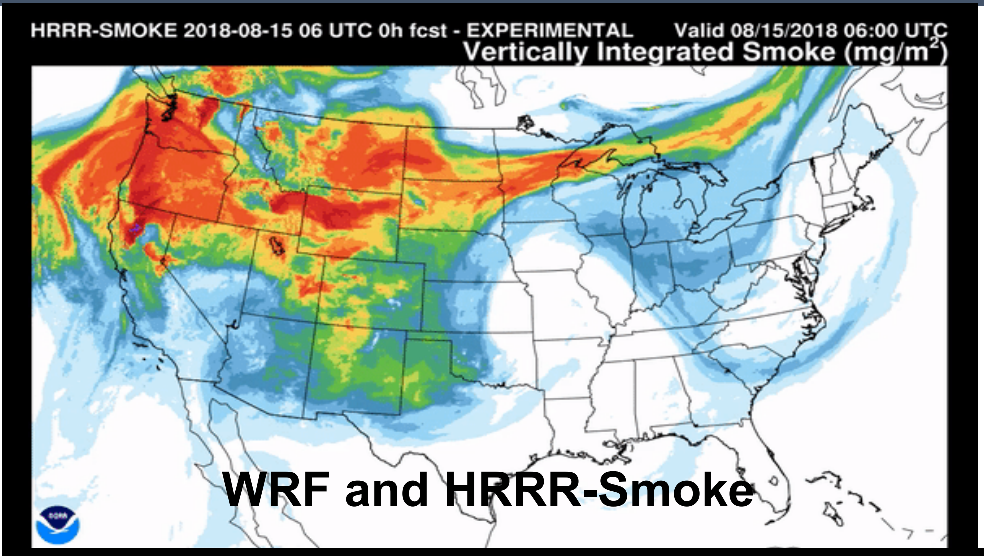
- SubX FIM
- WRF-Chem
- RAP-Chem
- HRRR-Smoke
- UFS
- Chemical data assimilation

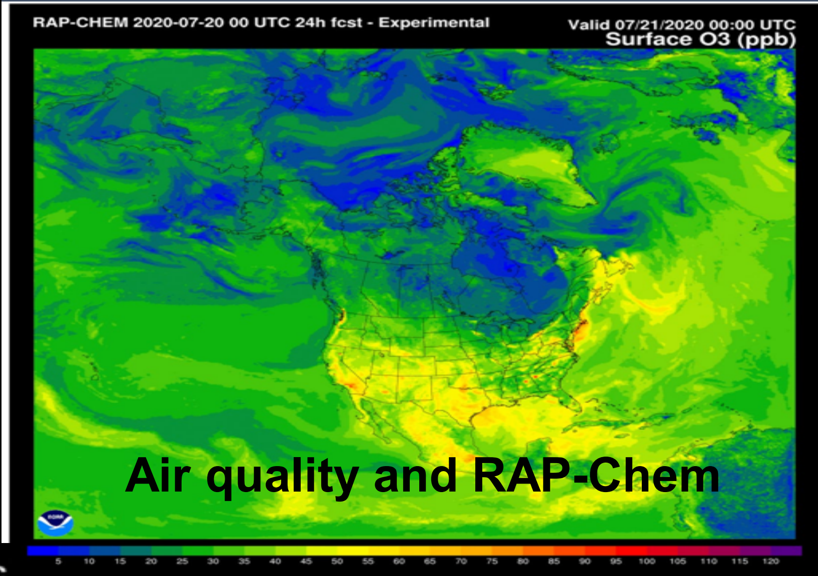
Coupling with tools

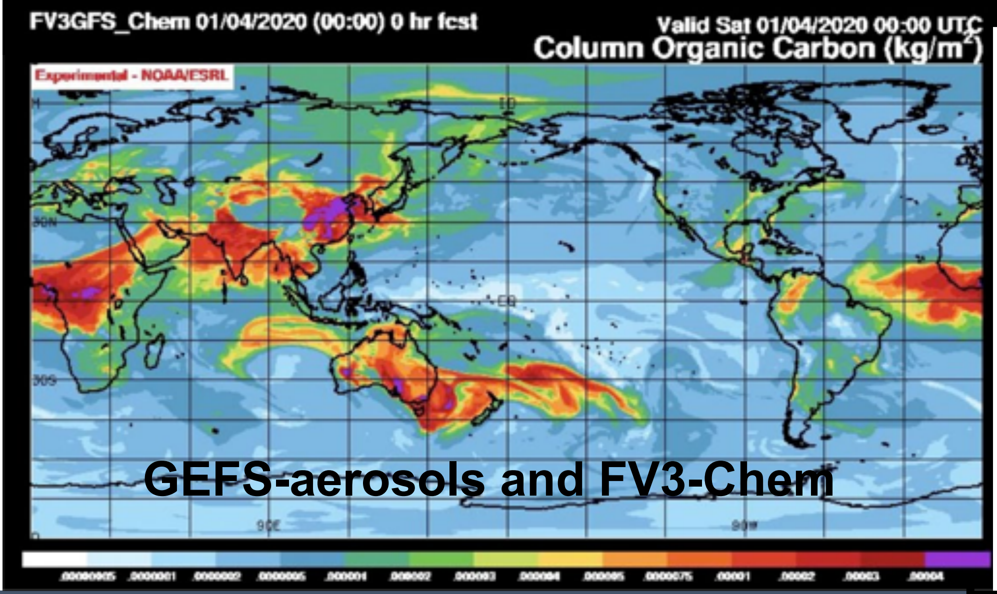
- GEFS-aerosols (ESMF)
- FV3-Chem with CCPP
- FV3-CMAQ and RRFS-aerosols

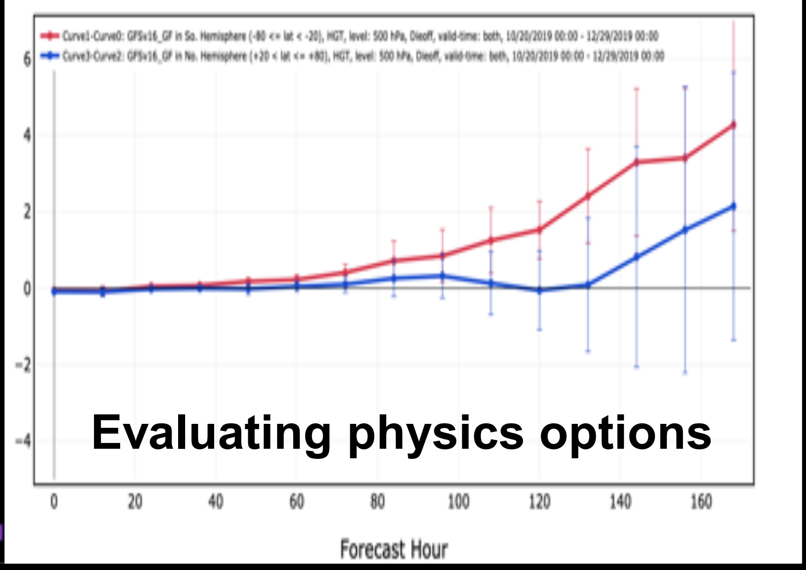
Collaborations with OAR labs (CSL, ARL, PSL, GLERL), NWS, NCAR, DOE, national and international community

Overview of Activities in Modeling









Real Time applications for weather and air quality

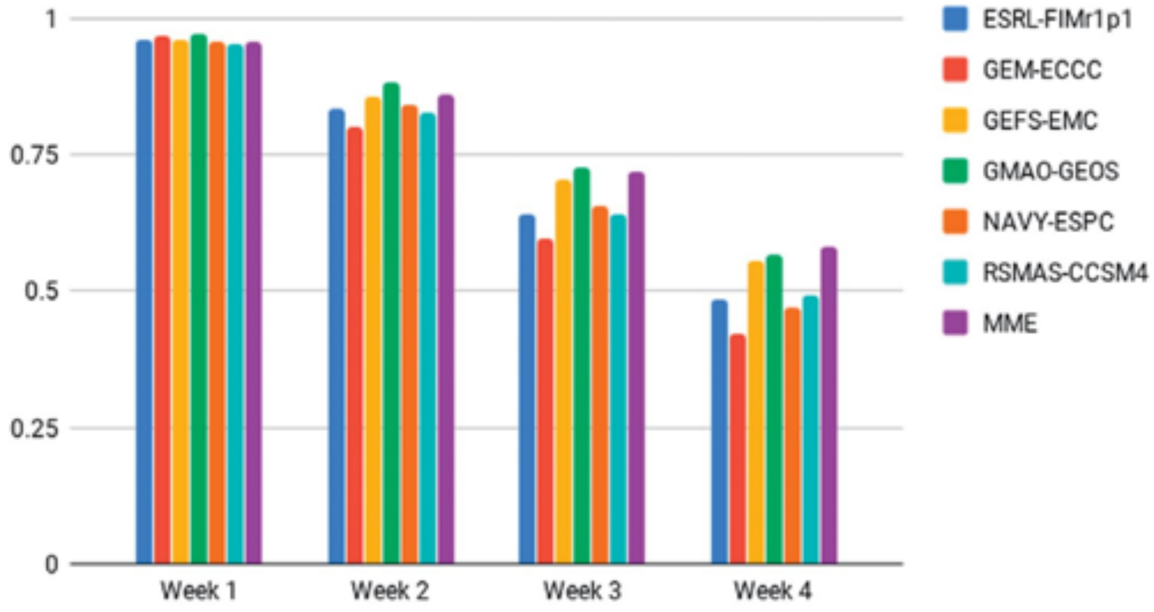
- Weather forecast and dispersion applications (RAP/HRRR/HRRR-Smoke)
- Aerosol and chemistry modules in global models (GEFS-aerosols)
- Air quality forecasting (RAP-Chem, FV3-CMAQ)
- Evaluating different physics options (GSL suite in RAP, HRRR, and FV3)

Speakers in This Talk

Physics:
Joseph Olson

Model coupling:
Shan Sun

Atmospheric Composition:
Ravan Ahmadov



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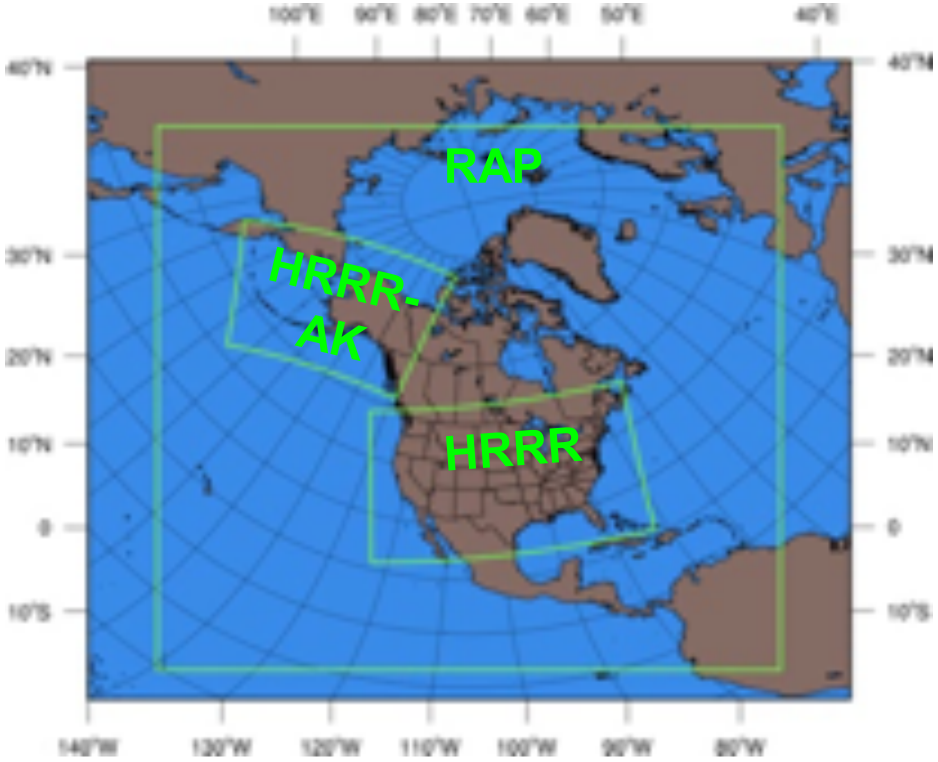
Physics

Joseph Olson
Model Physics Branch Chief
Earth Prediction Advancement Division

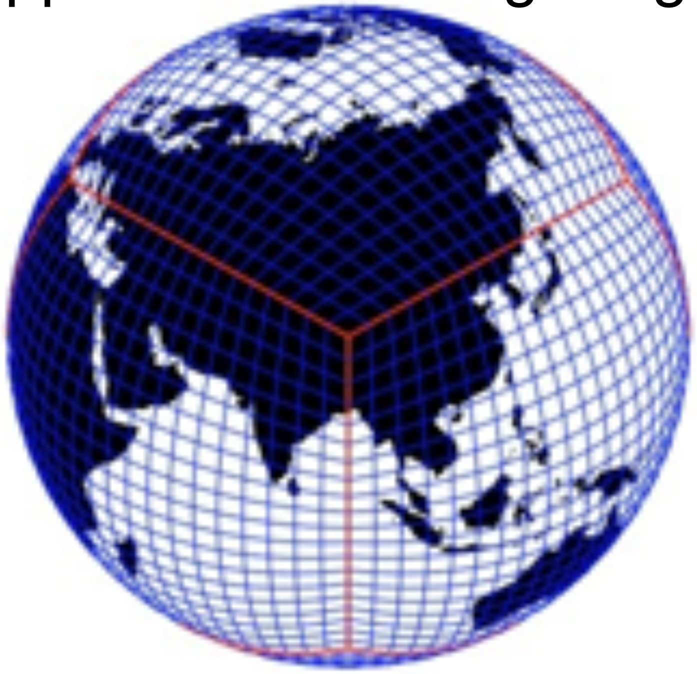
Global Systems Laboratory

Motivation

Past 5+ years:
Developing short-range regional models



Present and Future:
Develop short-range regional models **+** global applications for long-range prediction



- Need to develop a comprehensive physics suite that can be useful for all applications
- Transition suite/schemes/subcomponents/ideas to improve the operational suite

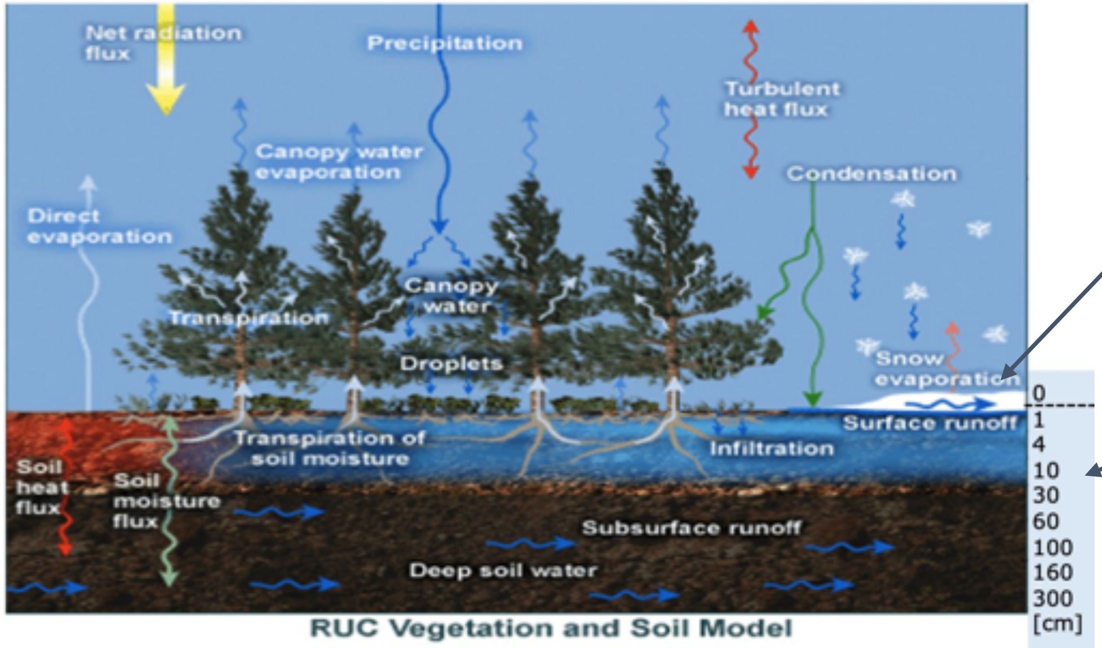
Overview of GSL Physics Development

Component	Scheme	Primary Developers
Land-Surface:	RUC/Snow model	Tanya Smirnova (GSL), Siwei He (GSL)
Surface Layer:	MYNN	Joseph Olson (GSL), Tanya Smirnova (GSL)
PBL:	MYNN-EDMF	Joseph Olson (GSL), Jaymes Kenyon (GSL), Wayne Angevine (CSL), John Brown (GSL)
Convection:	Grell-Freitas	Hannah Vagasky (GSL), Haiqin Li (GSL), Saulo Freitas (NASA), Georg Grell (GSL)
Drag:	GSL Suite	Michael Toy (GSL), Valery Yudin (GSL[1])
Radiation:	ML Emulator	Dave Turner (GSL), Ryan Lagerquist (CIRA)
Microphysics:	Thompson Aero	Greg Thompson (UCAR), John Brown (GSL), Hannah Vagasky (GSL), Tanya Smirnova (GSL)

[1]Recently left for a position at NASA

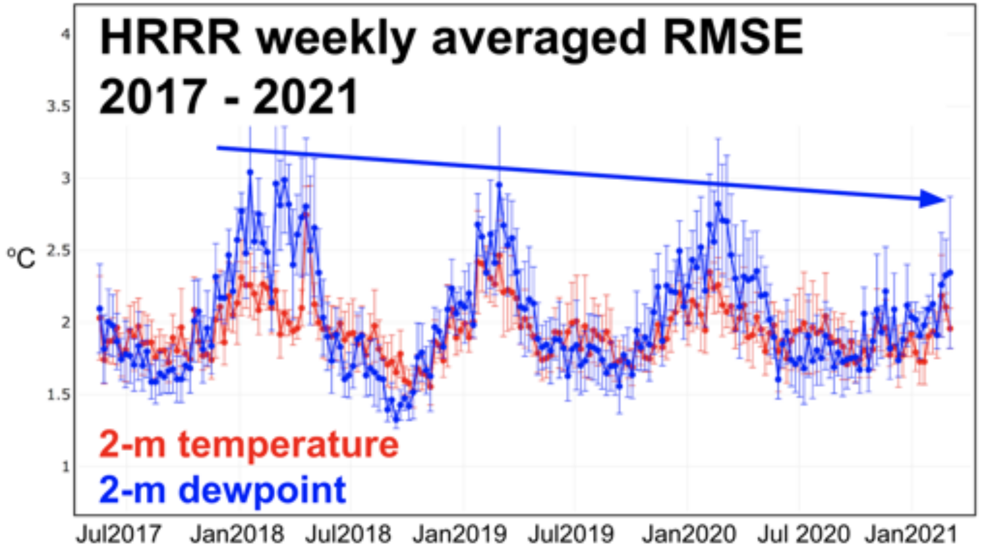
RUC Land-Surface Model

RUC LSM has been used as the land surface component in RAP/HRRR since 2014



Publication: Smirnova et al. 2016 (MWR)

- Implicit solver for energy and moisture balance
- Two-layer snow model
- Subgrid-scale heterogeneity (snow/landuse)
- Sea-ice model
- High vertical resolution in soil model



Boundary-Layer Clouds and Turbulence

- **MYNN Eddy Diffusivity-Mass Flux (EDMF) scheme**:

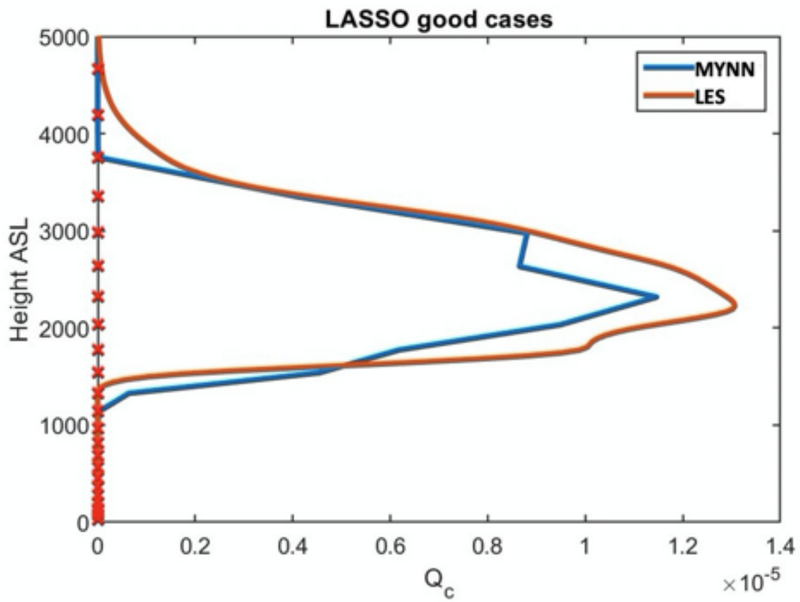
$$\overline{w'\phi} = -K\frac{\partial\bar{\phi}}{\partial z} + M(\phi_u - \bar{\phi})$$

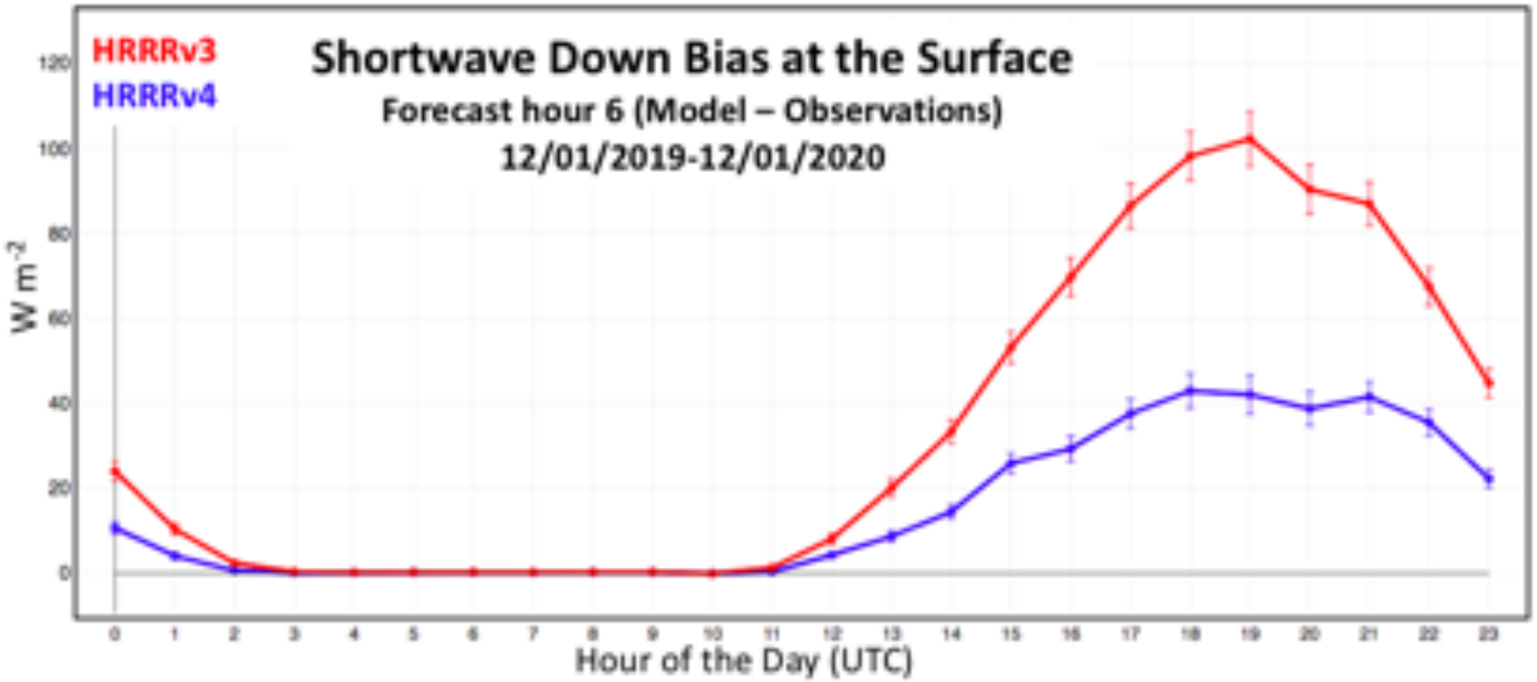
  - **Eddy Diffusivity**: turbulent kinetic energy (**TKE**)-**based** with option to run at **level 2.5, 2.6 or 3.0 closure**
  - **Mass Flux**: Spectral multi-plume model
- **Moist-turbulent mixing scheme**:
  - Uses two cloud PDFs to consistently represent **subgrid-scale (SGS) clouds** (stratus and convective clouds), their **impact on turbulent mixing,** and the same SGS clouds are **coupled to the radiation scheme**
- **Scale-adaptive**
  - Tested and developed down to sub-km scales

Documentation: Olson et al. 2019a (NOAA Technical Memorandum), Olson et al. 2019b (BAMS)

Improved MYNN-EDMF Subgrid Clouds

Average of 12 cases from the 2018 LASSO study, comparing MYNN-EDMF against LES:

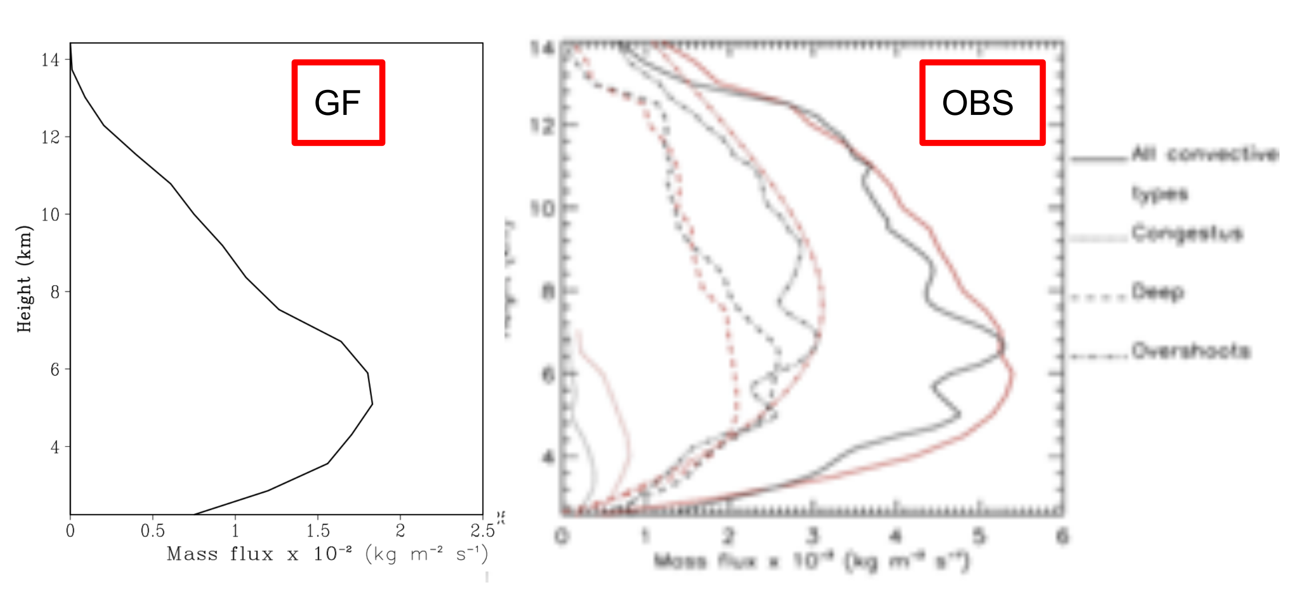




MYNN-EDMF reproduces cloud base, cloud top, and liquid water path very well.

Grell-Freitas Convective Parameterization

- GF is scale-aware using Arakawa's 2011 approach
- Three PDFs to characterize the statistically averaged vertical mass flux
- PDFs used to derive entrainment and detrainment rates
- Double moment microphysics tendencies
- Ensemble of closures
- Option to include memory impacts
- Atmospheric composition treatments included

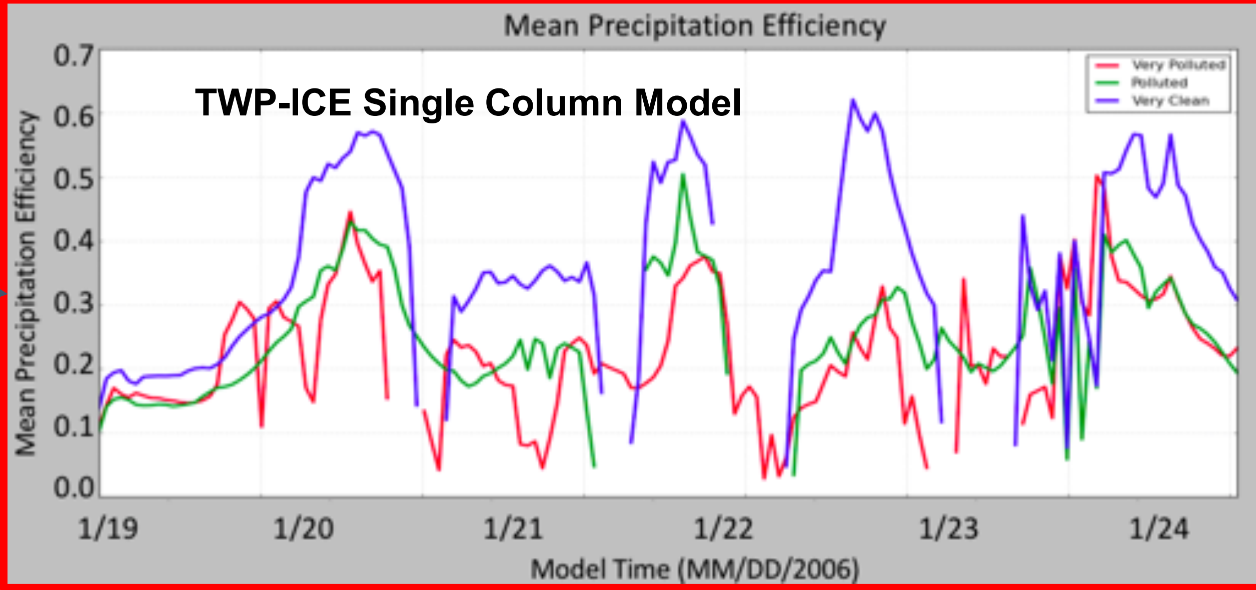


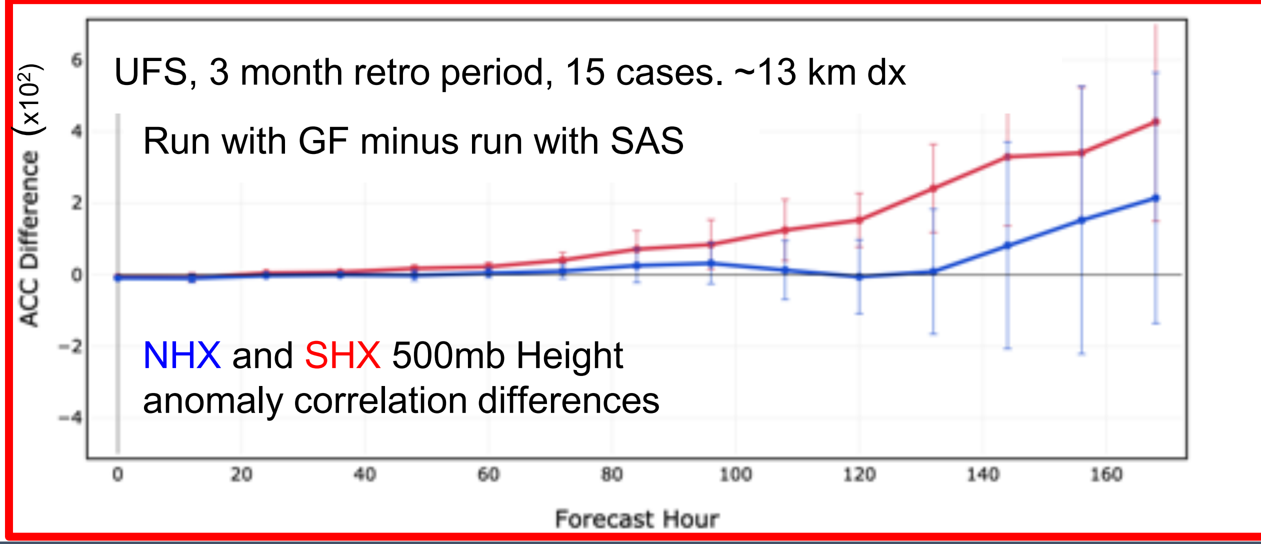
Derived vertical mass flux distribution (left) from PDFs for deep convection compared to observations (from **wind profiler** and **CPOL data**, Kumar et al, 2019). Compare predicted deep convection to observations (dashed red and black).

Publications: Grell/Freitas 2014 (OAR outstanding scientific publication award in 2017), Freitas et al. 2021 (award for "possibly the most significant skill improvement in the history of the GEOS modeling system")

Grell-Freitas Scheme: Ongoing Research

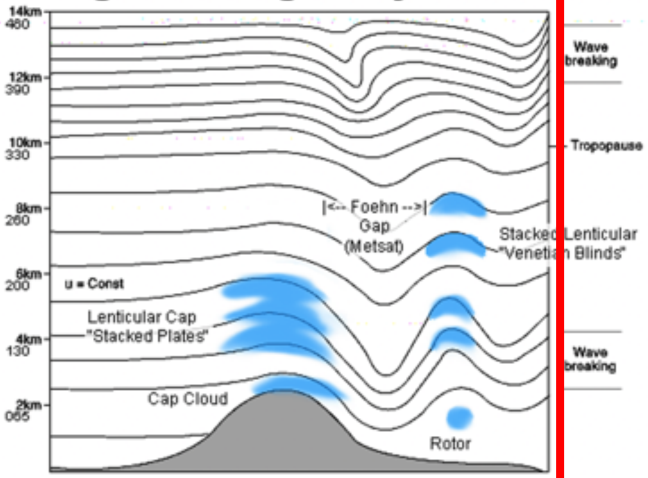
- Improve scale-awareness
- Validate and train closure assumptions
- Evaluate full aerosol interactions
- Use stochastics in the vertical mass flux PDFs
- Implement different chemistry options
- Explore Machine Learning (ML) algorithms
- Incorporate the movement of convective clouds as well as downdraft cold pools



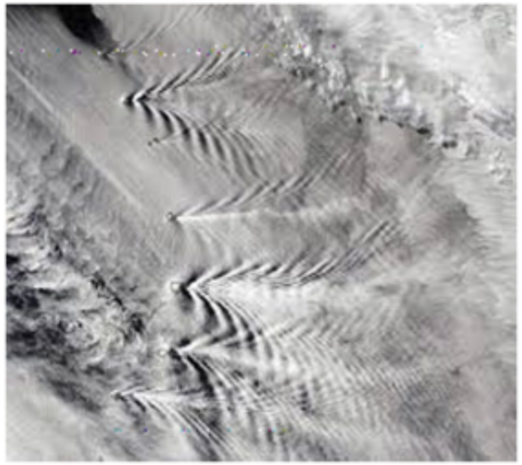


Drag Suite

Large-scale gravity waves



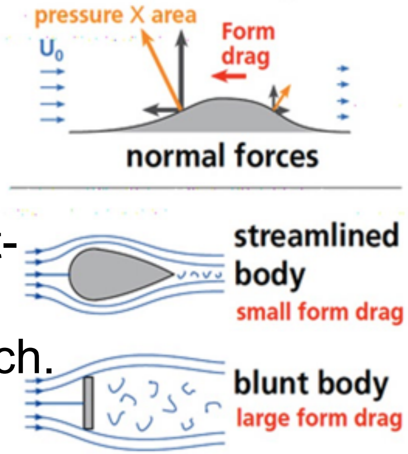
Small-scale gravity waves



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

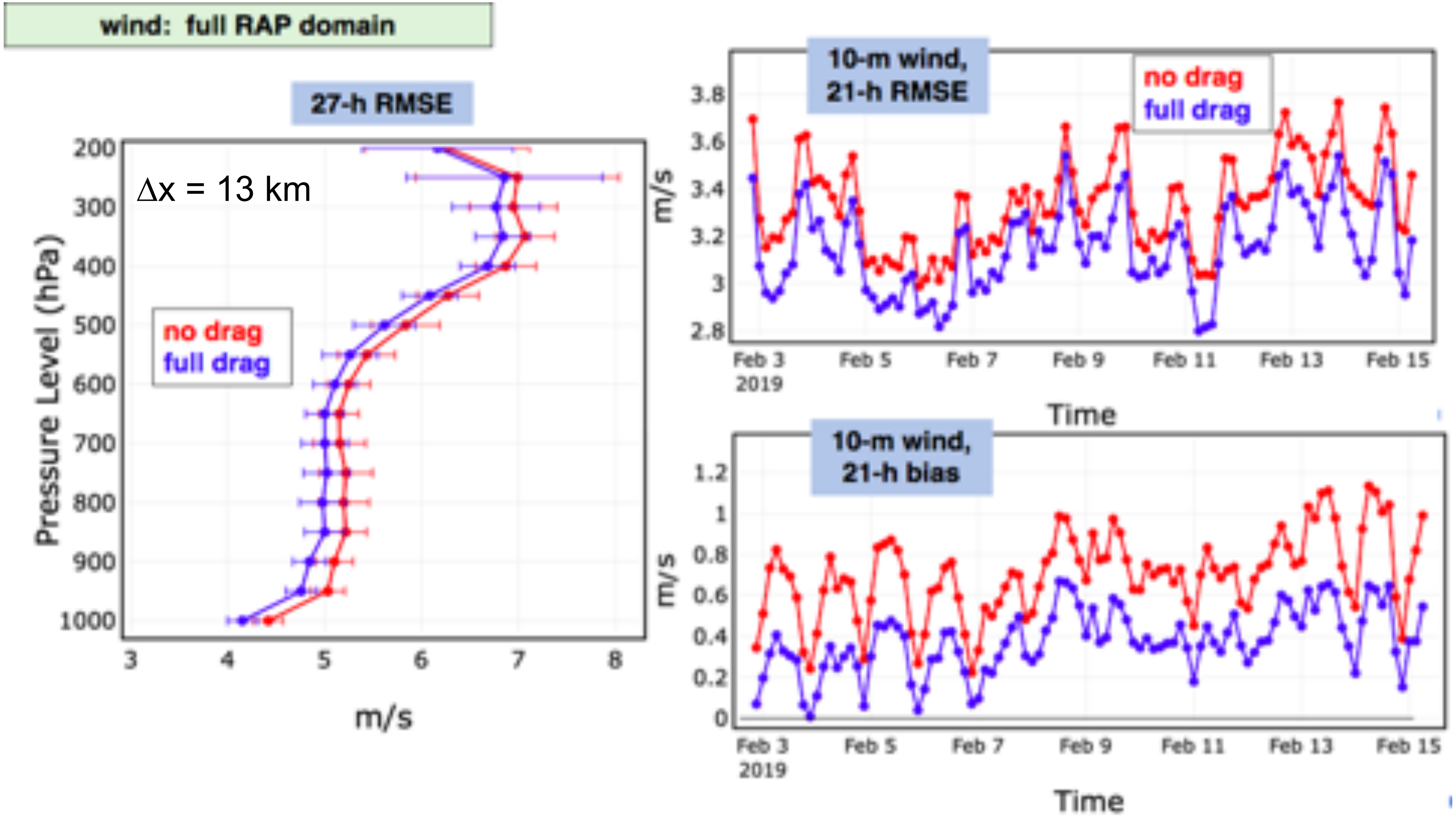
New components:

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

Future Work:

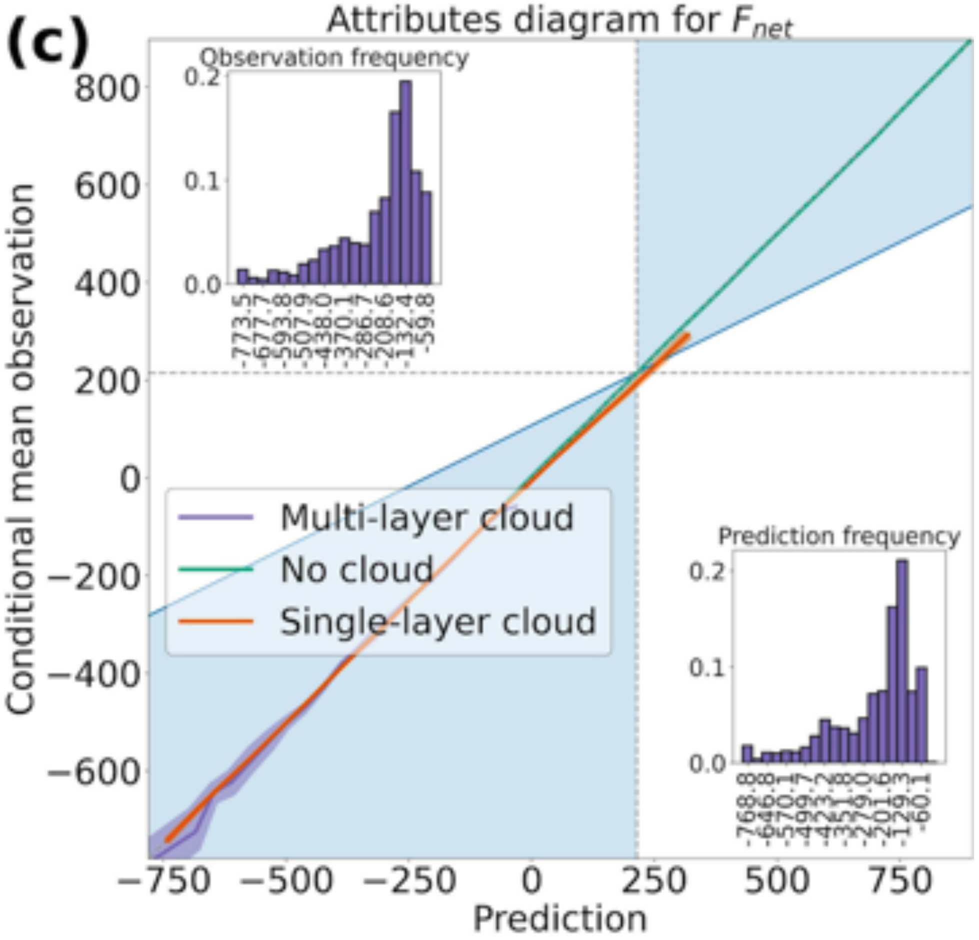
- Merge small- and large-scale GWD with Fourier (multi-scale/wave) formulation

Improvements with GSL Drag Suite



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



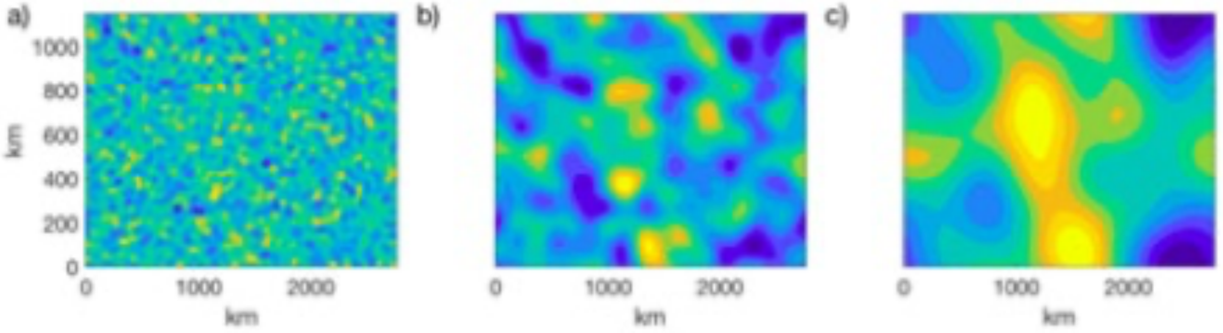
- Has near perfect reliability and low bias
- Is over 1,000 faster than RRTM

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

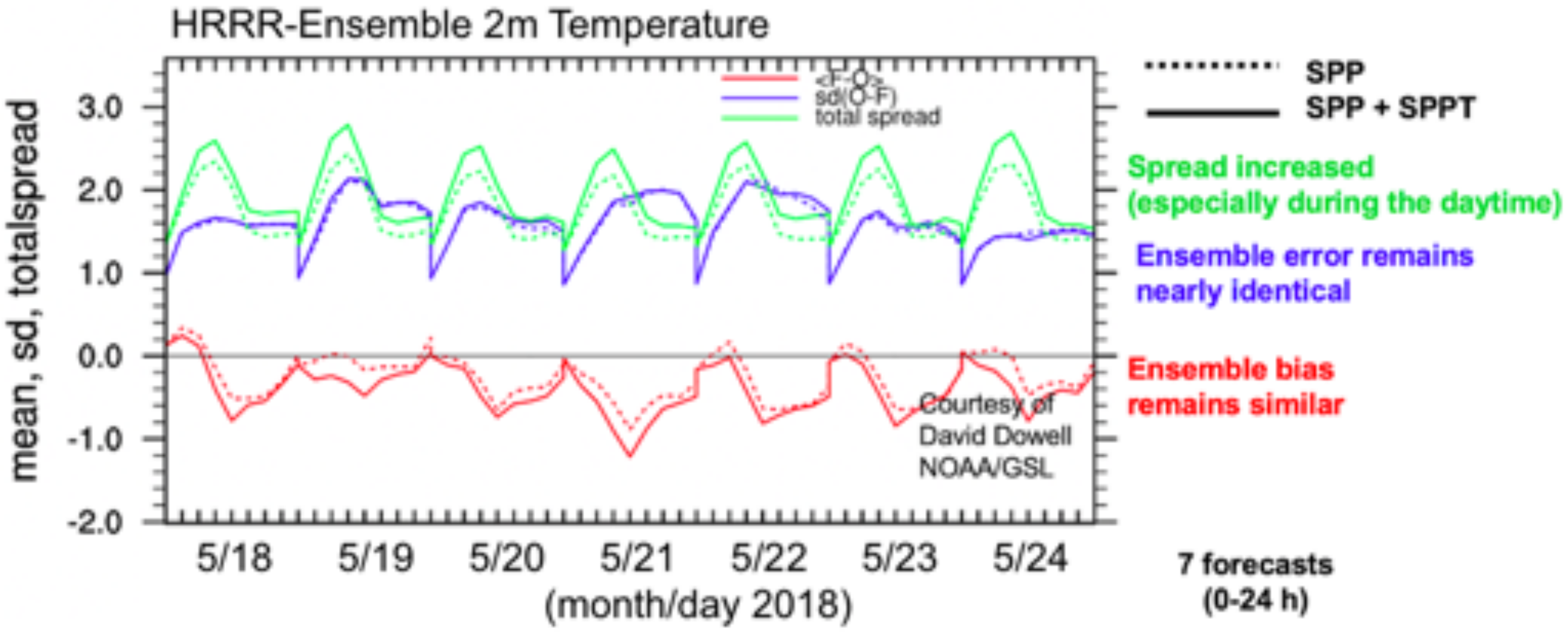
Including Stochastic Physics

Approaches Employed:

- **Stochastically Perturbed Parameterizations (SPP):** Perturbations added to LSM, PBL, Surface layer, Convection, GWD, microphysics, and radiation schemes.
- **Stochastically Perturbed Physical Tendencies (SPPT):** Perturbation of temperature, moisture, and wind tendencies from various schemes.



Example of Randomly-Generated Spatial Perturbation Patterns



Summary

- We have expanded our scope from being primarily short-term regional to include **all time and spatial scales for all applications.**
  - Generalize physical parameterizations
  - Provide improvements for the UFS
- Future development emphasis will be on **moist-turbulent physics** (PBL, microphysics, and convection):
  - Efforts include machine learning, integrating atmospheric composition, and LES comparisons
- We currently lead cross-institutional model development groups for PBL, Convection, and GWD scheme advancement for the UFS.
- We continue to leverage expertise at a variety of institutions (CSL, PSL, GML, NASA, UCAR/NCAR, NRL, DOE, GLERL, ARL).

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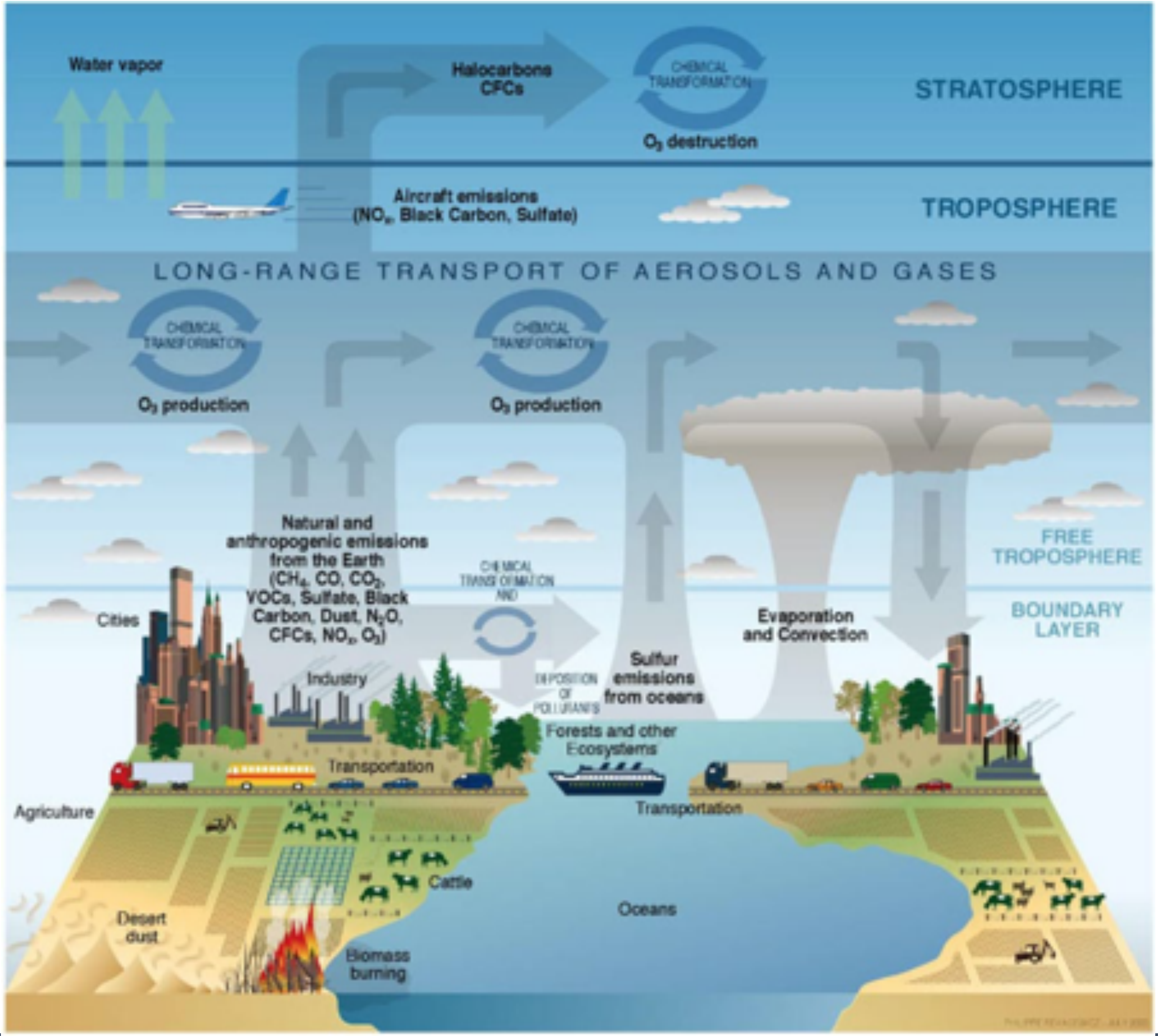
Atmospheric Composition

Ravan Ahmadov
Atmospheric Composition section lead
Earth Prediction Advancement Division

Global Systems Laboratory

Atmospheric Composition Modeling



https://www.globalchange.gov/browse/reports/us-climate-change-science-program-vision-program-and-highlights-scientific-strategic

Our Primary Air Quality Model: WRF-Chem

- WRF-Chem is a coupled meteorology-chemistry model
  - Many different physics/chemistry options from simple to very complex
  - Used worldwide for weather and air quality forecasting
  - Applied for research towards understanding complex processes essential for climate change
- Latest release of V4.3 in April 2021. GSL continues to coordinate the developments through the Github repository, in collaboration with NCAR, DOE, and many other model developers.
- Current use of WRF-Chem for air quality research and forecasting at GSL
  - **RAP/HRRR-Smoke and RAP-Chem**
  - **GEFS-Aerosols** (inherited the chem_driver with some simple bulk aerosol modules)
  - **Research** on impacts of aerosol on weather forecasting (storm scale to S2S)

WRF-Chem paper has been cited **>1600** times. There are more than 284 WRF-Chem related publications since 2020. The WRF-Chem paper was awarded the Haagen-Smit prize in 2017.

The Impacts of Wildland Fire Smoke

San Francisco skyline during the Camp fire, November 2018

Smoke and air quality alerts

Visibility

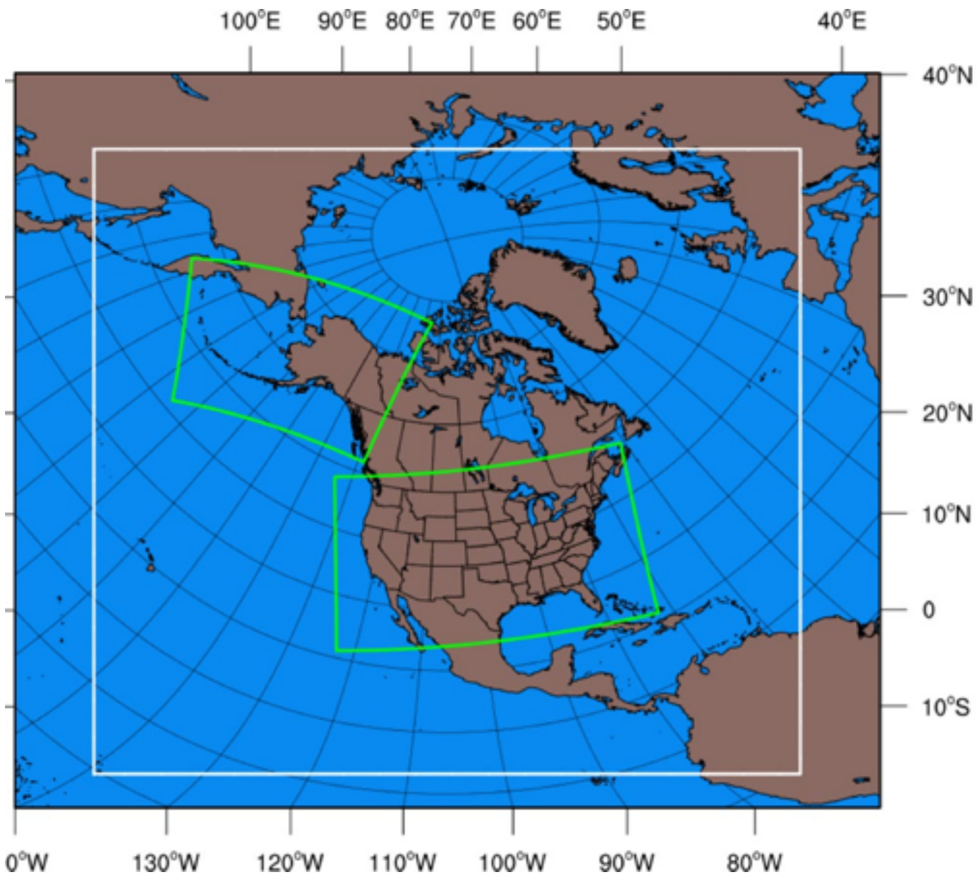
Smoke impact on weather

Solar energy production


Fatal accident caused by a fire smoke on Interstate 40 in Arizona, October, 2016

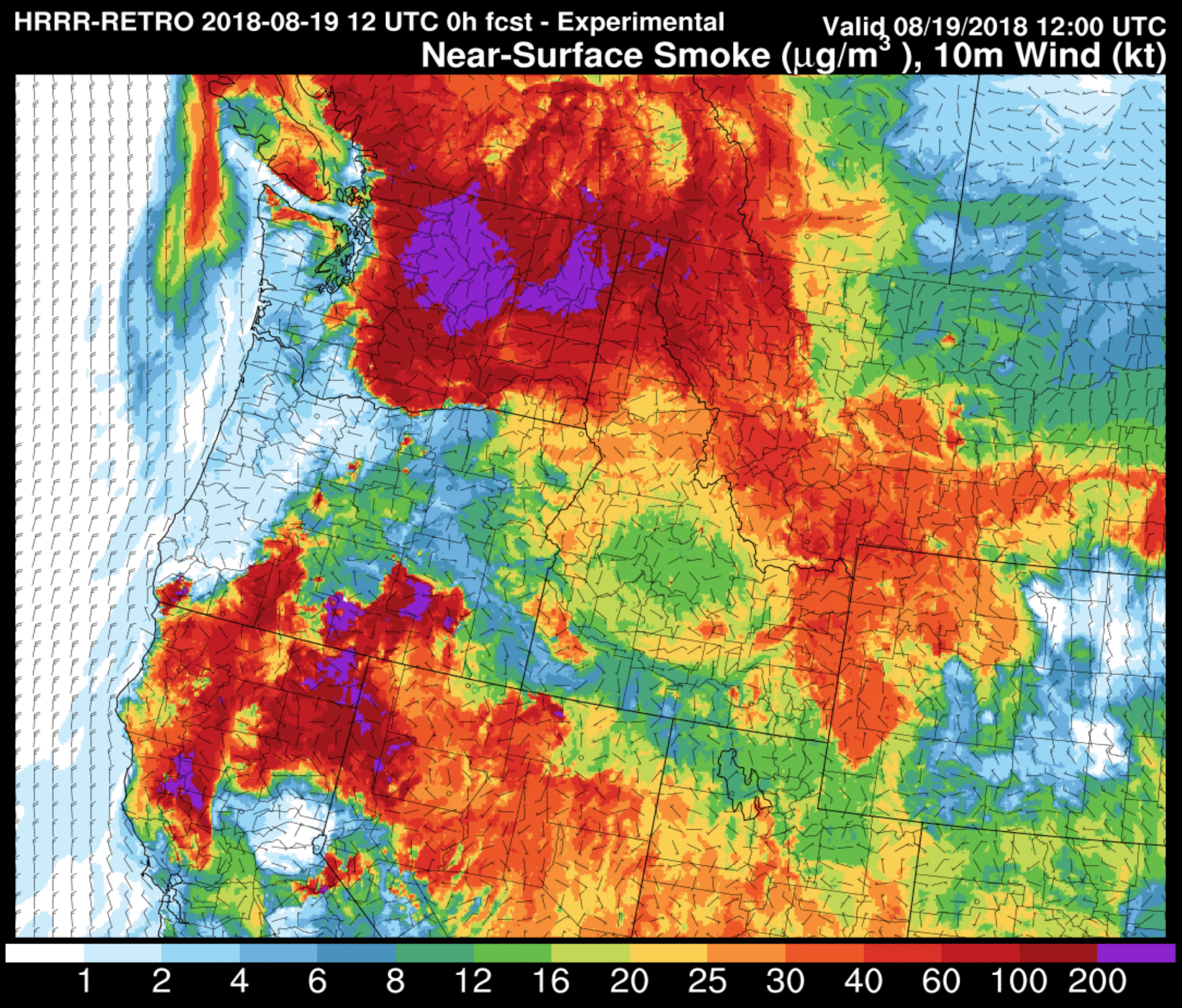
NOAA’s Operational RAP/HRRR-Smoke Models

- A **smoke tracer** is added to the RAP/HRRR weather forecast models (*using the WRF-Chem framework*)
- The satellite FRP data are used to estimate the fire emissions and heat flux in real time
- The HRRR-Smoke (3km) model is able to capture the mesoscale flows and smoke transport in complex terrain
- Smoke feedbacks on radiation and visibility are also included in these models
- The smoke forecasting capability was transitioned to the operational RAPv5/HRRRv4 systems in 2020



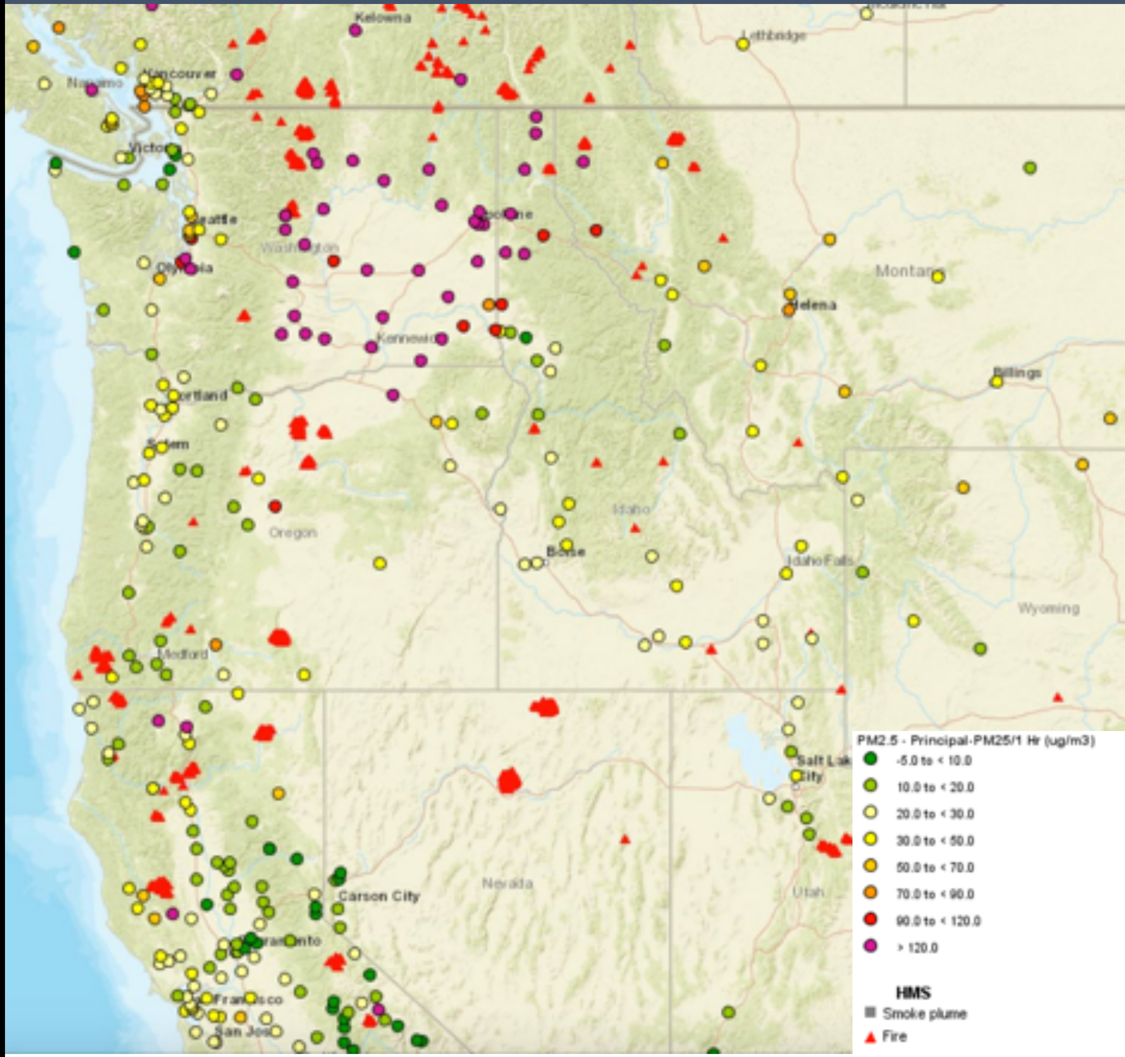
RAP-Smoke (white), 13.5 km resolution
HRRR-Smoke model domains (green), **3 km** resolution
(https://rapidrefresh.noaa.gov/)

Smoke forecasting over the NW US



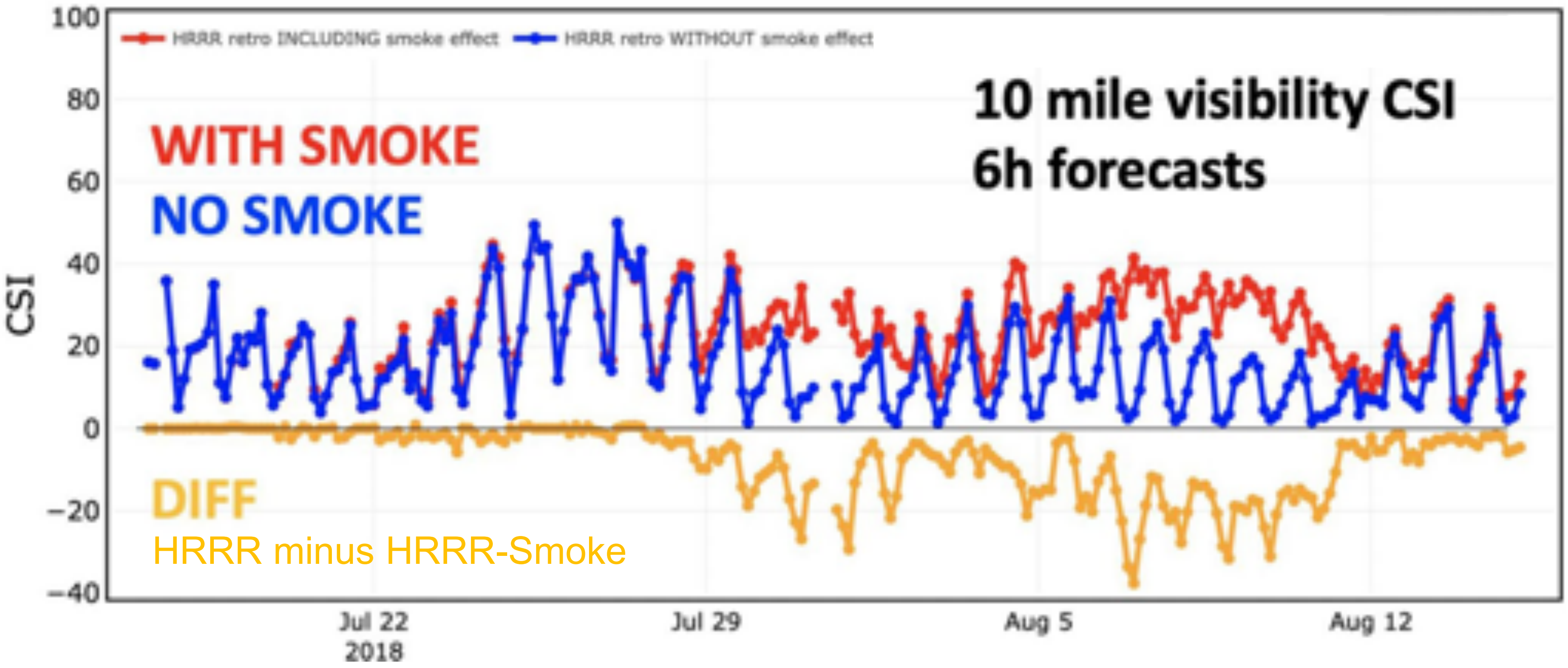
Numerous wildfires in the western US and Canada during summer, 2018

PM2.5 measurements 8pm PDT, August 19, 2018



https://www.airnowtech.org/navigator/#

Verification of the Surface Visibility Forecasting by HRRR-Smoke over Western US



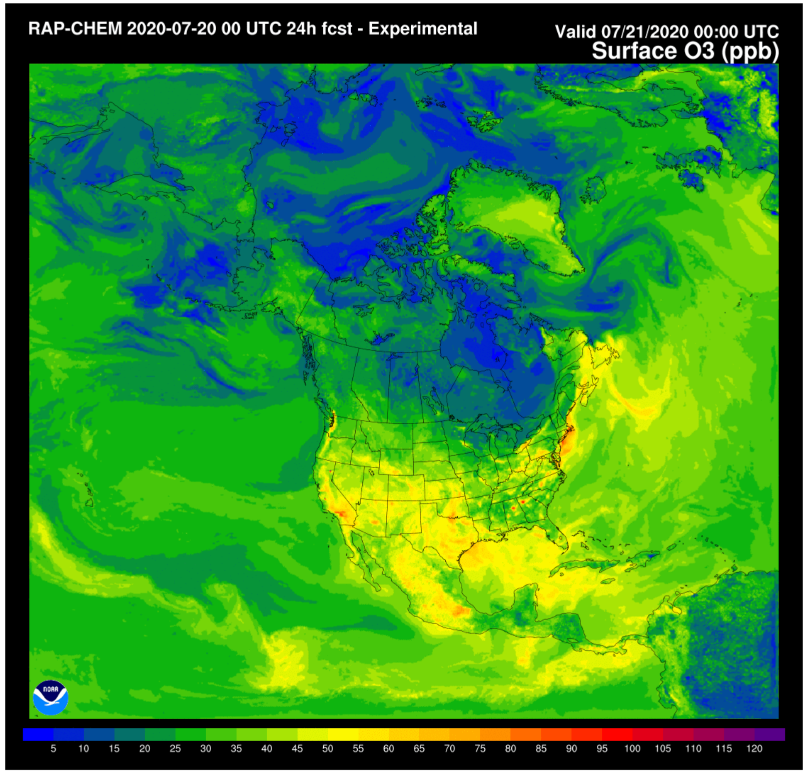
HRRR-Smoke is the first NWP model in the US to include the interactive aerosols and their impact on radiation and the visibility diagnostics.

CSI - critical success index (%)

The measurements from over 400 weather stations are included in this verification

Experimental Air Quality Forecasting using WRF-Chem

- Daily air quality forecasts over North/Central Americas with a lead time of 48 hours
- COVID-19 adjusted emissions developed by CSL
- The meteorological input data come from the RAP weather forecast model
- The chemical mechanism includes gas and aerosol chemical species, and new SOA treatment
- Online emissions: dust, sea salt, biogenics, and biomass burning
- Photolysis and radiation include aerosol direct effects
- **The new chemistry scheme may be a candidate for future implementation within UFS**



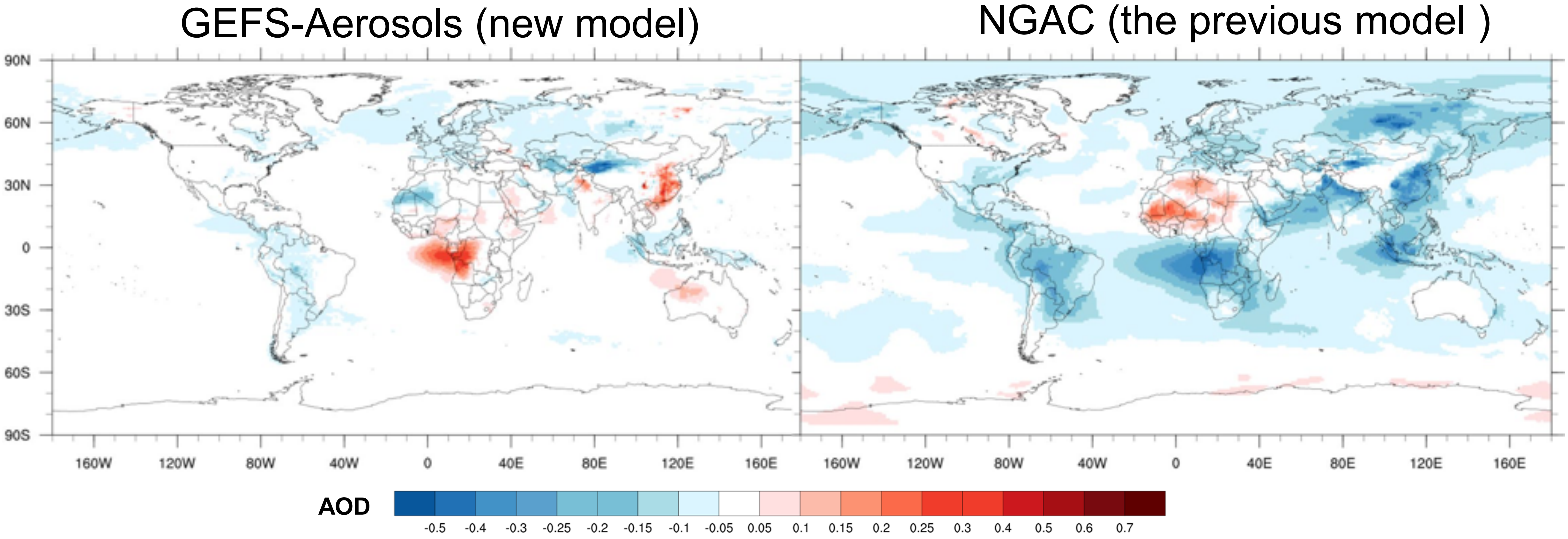
URL: rapidrefresh.noaa.gov/RAPchem/
Surface ozone forecast (**13.5 km** resolution)
Some parts of the US were impacted by the smoke pollution during summer, 2020.

NOAA’s Operational Global GEFS-Aerosols Model

The GOCART aerosol scheme from WRF-Chem was coupled to the global FV3 model. Anthropogenic, dust, fire and sea salt emissions are included in the model.

Saharan dust transport to North America

GEFS-Aerosols vs. NGAC



The bias is calculated taking the difference between the model AOD and MERRA2 analysis. The figures show an average over a five-month period.

Future Plans

- Transition the simple aerosol capability including emissions to the UFS
- Assimilate the satellite AOD data into the UFS models
- Apply machine learning techniques to biomass burning emission forecasting
- Inline coupling of tracer transport and removal within the physics schemes
- Moving more WRF-Chem capabilities into CCPP to be useful for UFS
- Study aerosol-physics interactions using parameterizations with different levels of complexity for applications in next-generation air quality, seasonal and climate prediction models

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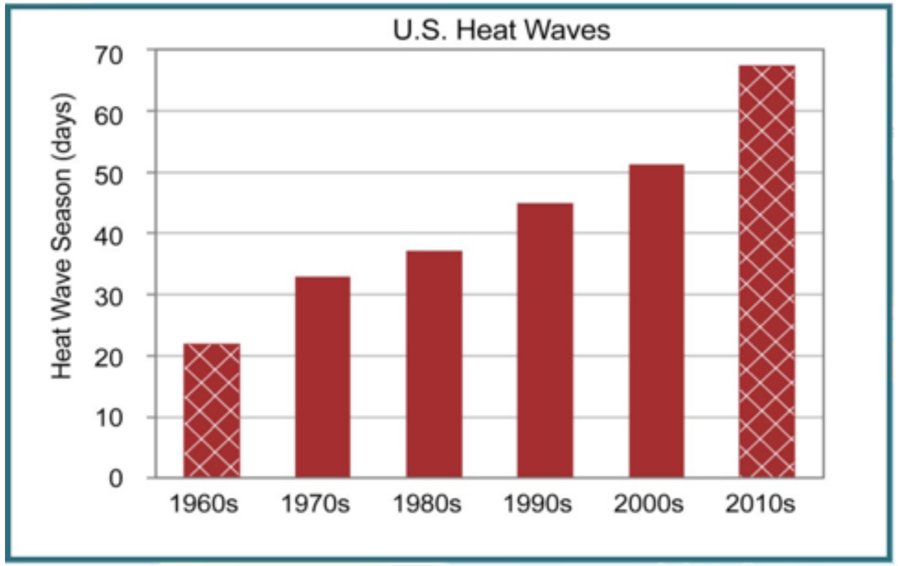
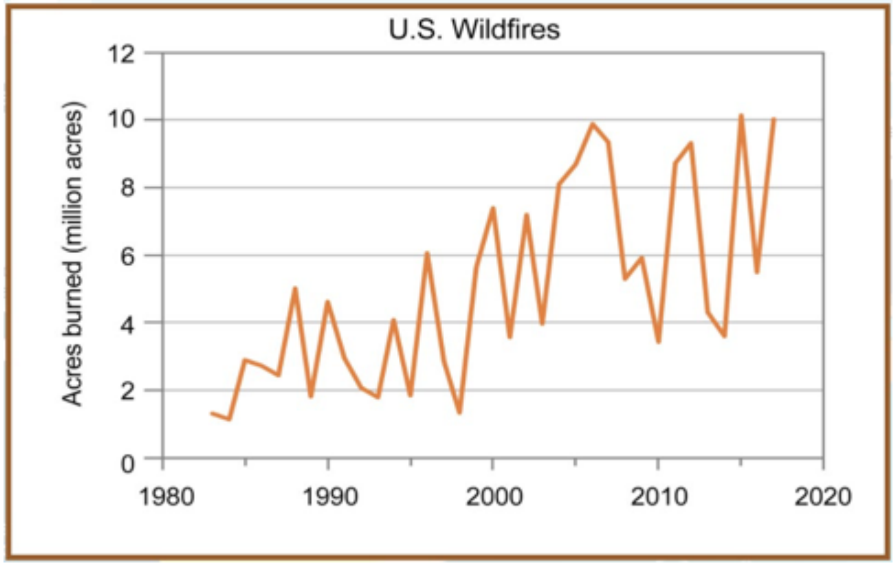
S2S Prediction and Short-Range Cycling with Coupled Atmosphere-Chemistry-Ocean-Ice-Lake Models

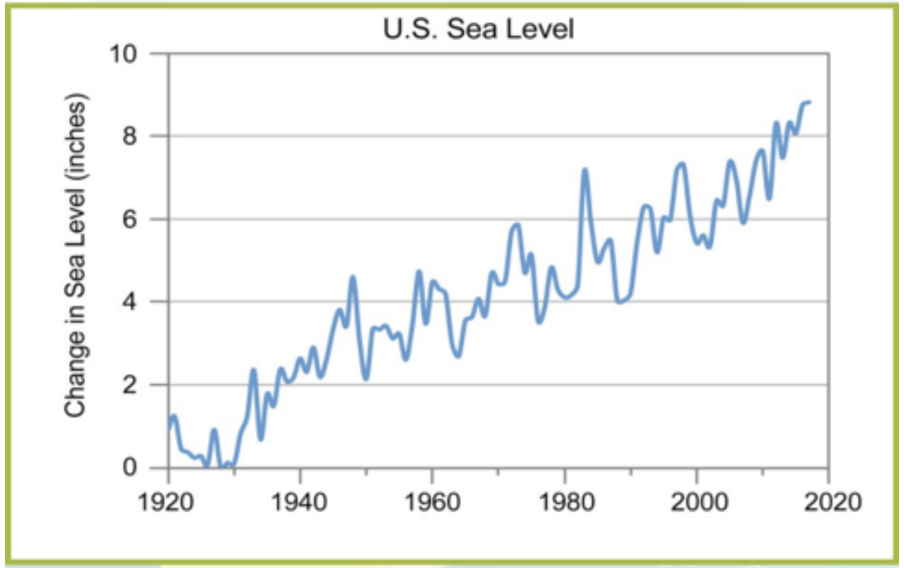
Shan Sun
Chief, Global Earth/Chem Modeling Branch
Earth Prediction Advancement Division

Global Systems Laboratory

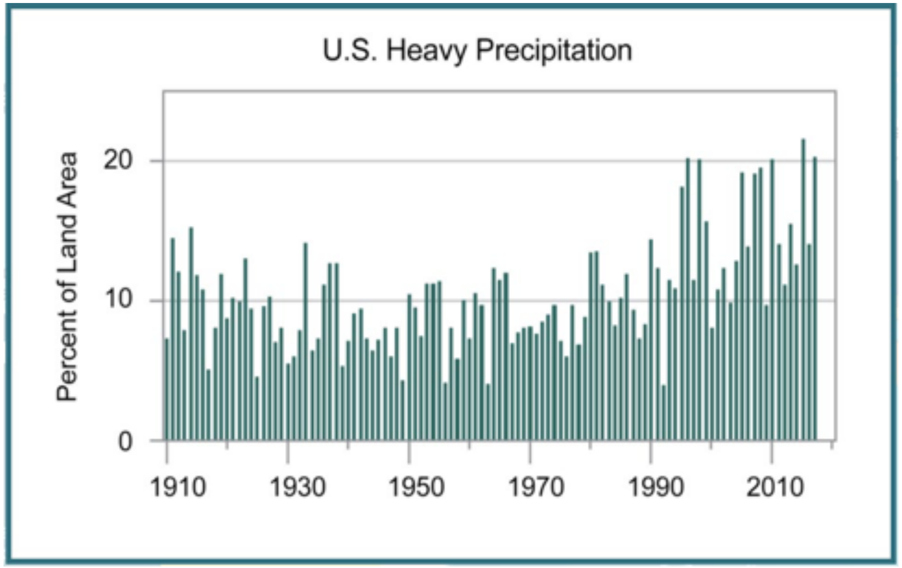
Increasing Frequency of Extreme Weather Events



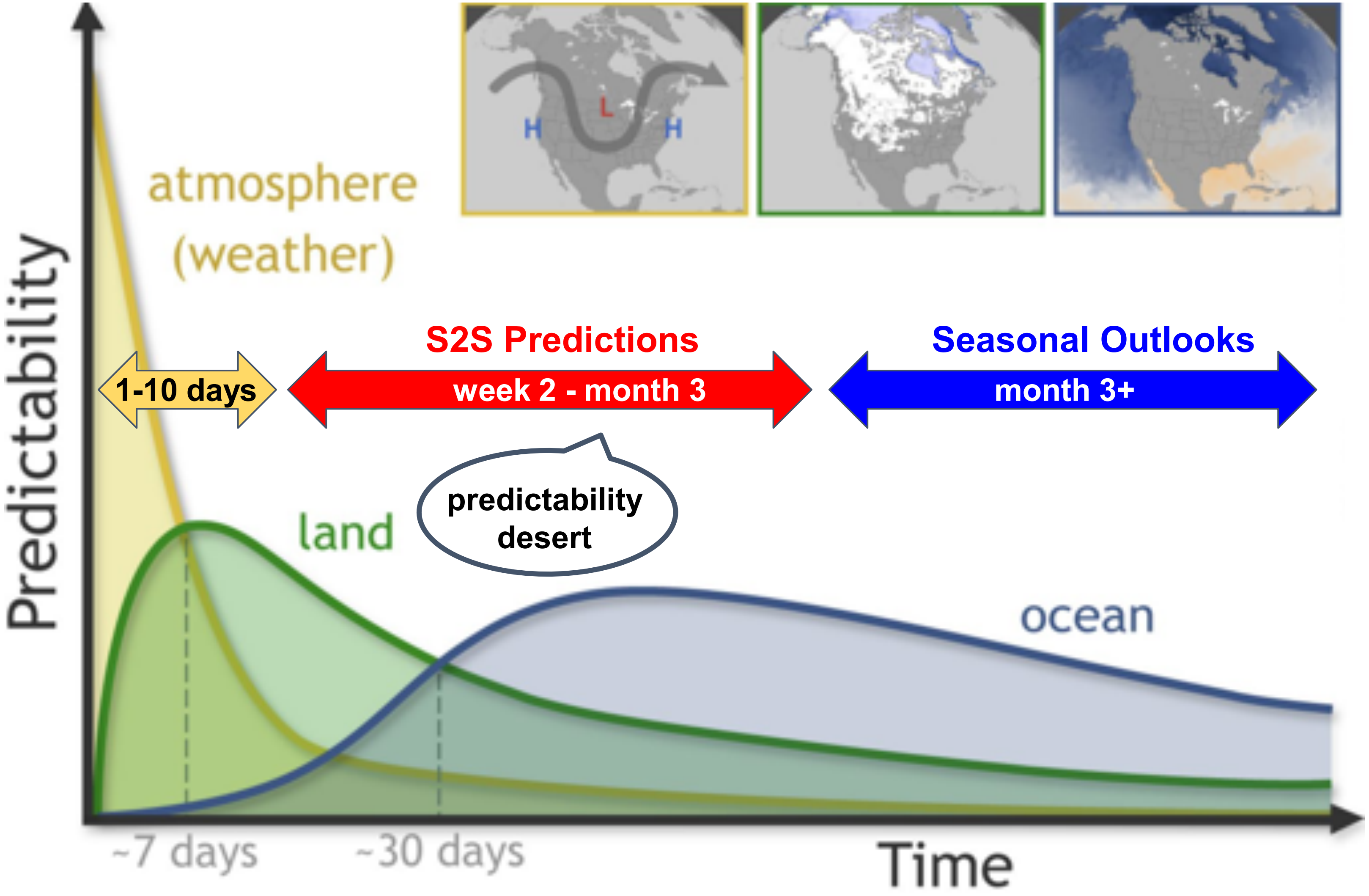




globalchange.gov



Predictability Across Different Lead Times

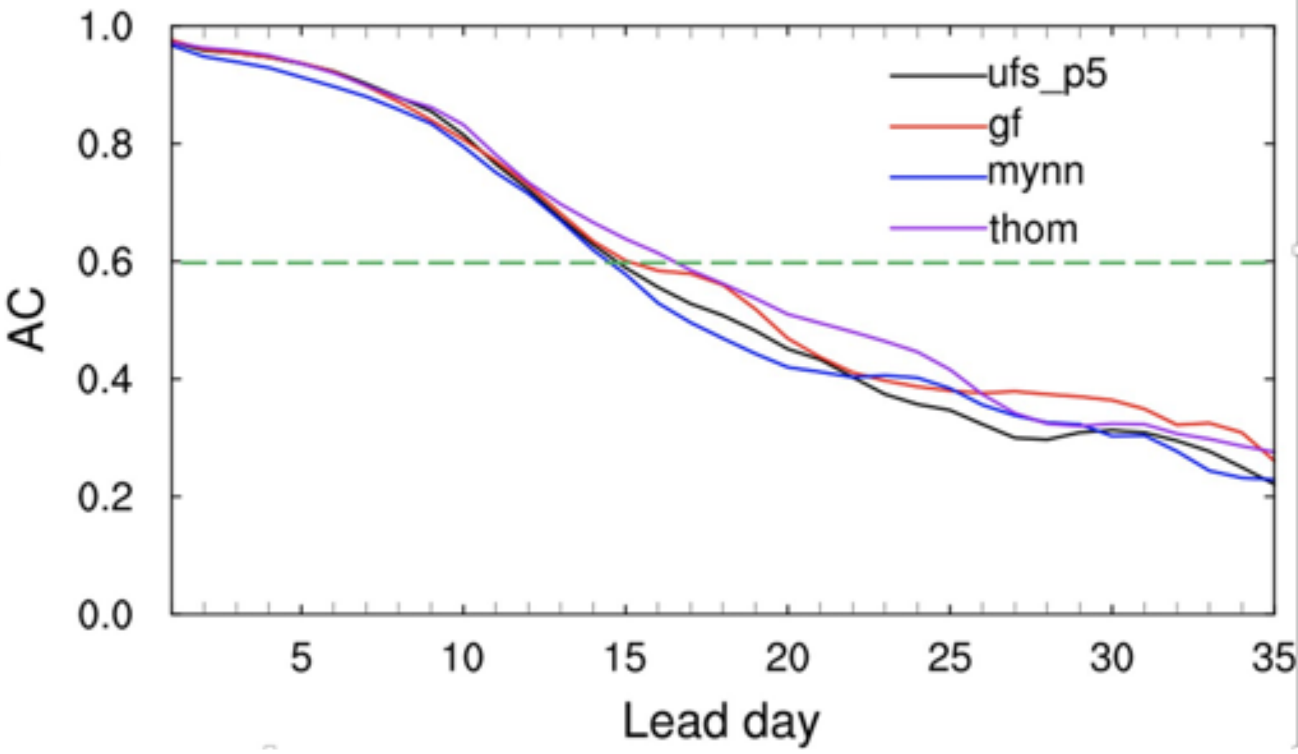


Unified Forecast System (UFS) in S2S Prediction

- Madden–Julian Oscillation (MJO), North Atlantic Oscillation (NAO), sudden stratospheric warming (SSW) and land/ice-related processes are among key sources of predictability. Skill is still low in S2S prediction

- GSL works closely with EMC and PSL on various elements of the coupled UFS, including GSL physics package and air-sea interaction, to improve representation of these processes

MJO Skill: RMM1+RMM2



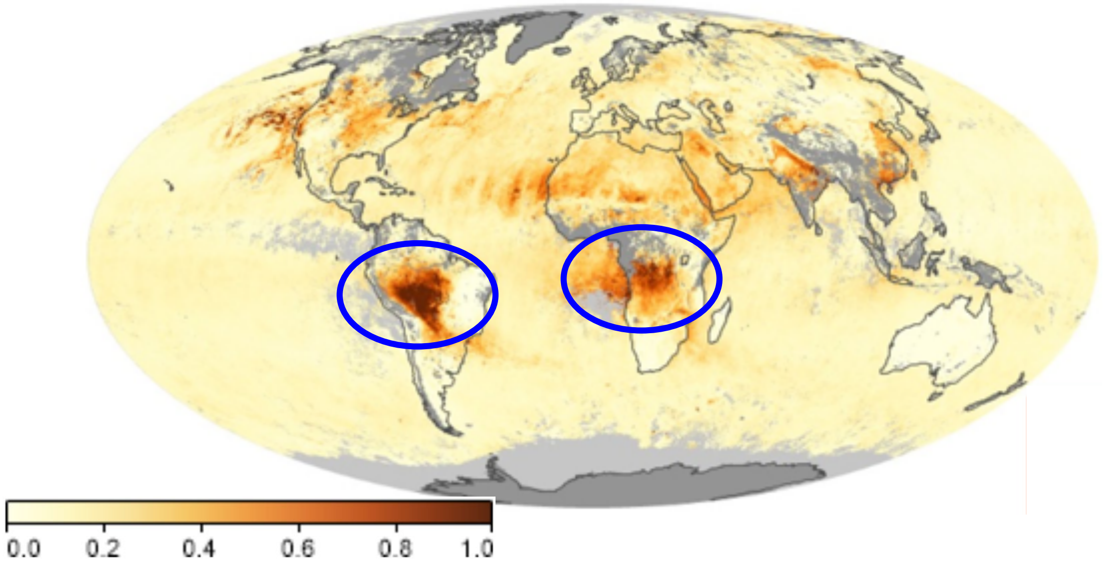
168 cases in each experiment, with S2S P5 prototype.
From Ben Green (GSL) and Eric Sinsky (EMC)

Interactive Aerosols in S2S Prediction

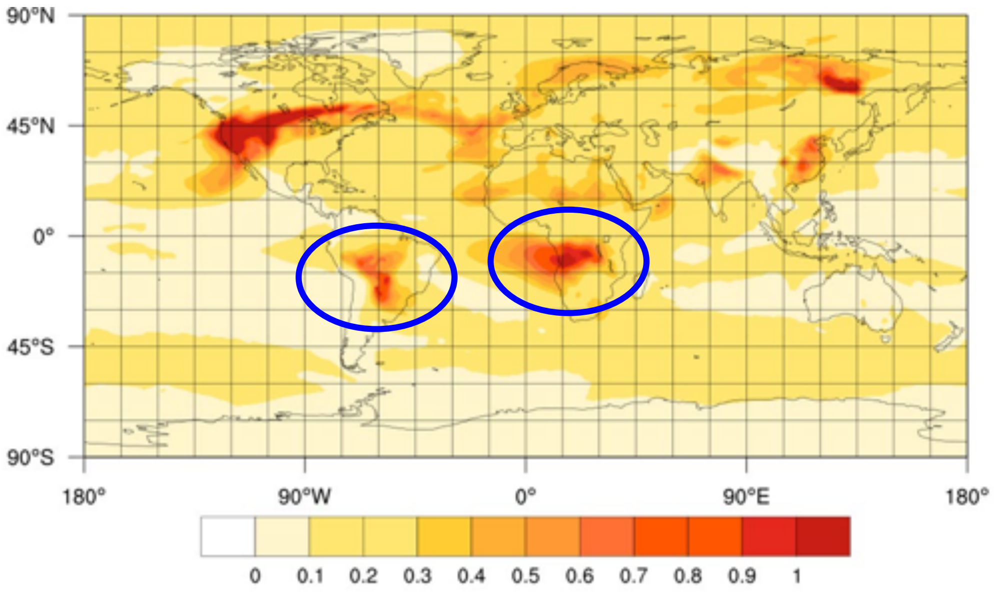
- Studies showed interactive aerosols have the capability of improving S2S prediction
- There is a large uncertainty of aerosol impact on climate
- GSL, with CSL, is adding aerosol prediction capability (using the operational GEFS-Aerosols) to the UFS coupled atmosphere-ocean-ice model for S2S prediction

Aerosol Optical Depth Sept 2020

https://earthobservatory.nasa.gov

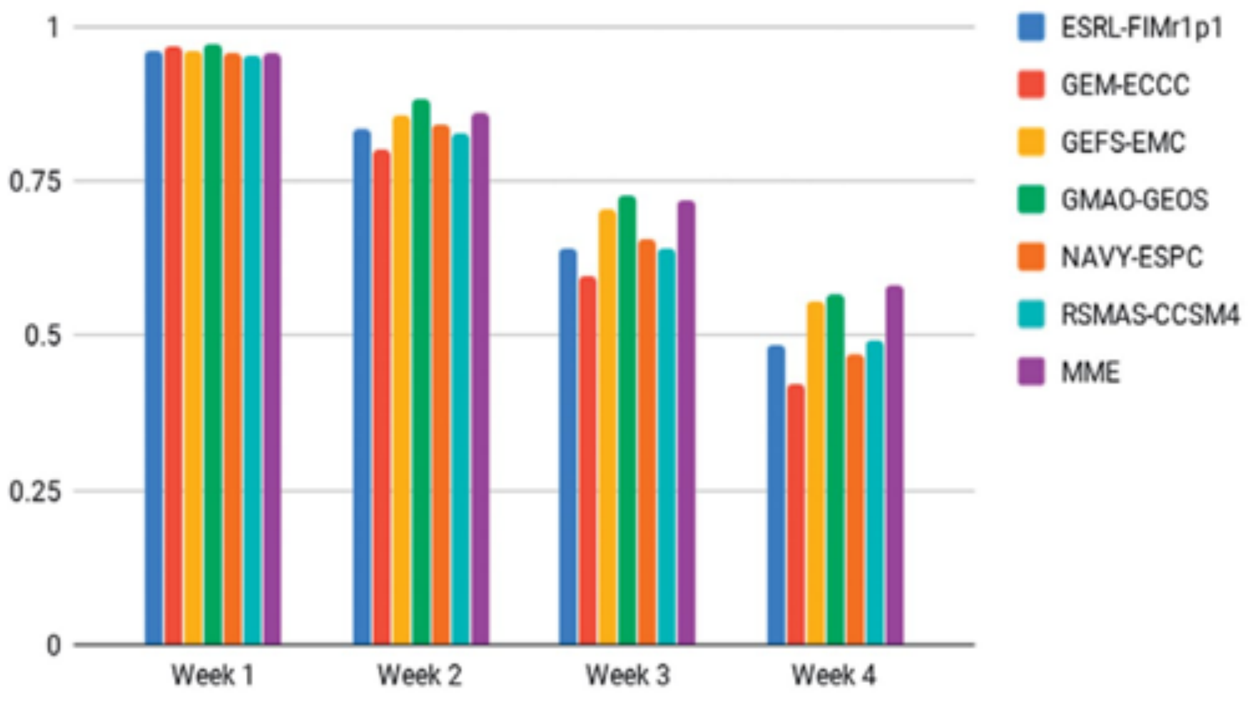


UFS



Ensemble Forecast in S2S Prediction

RMM index skill ACC

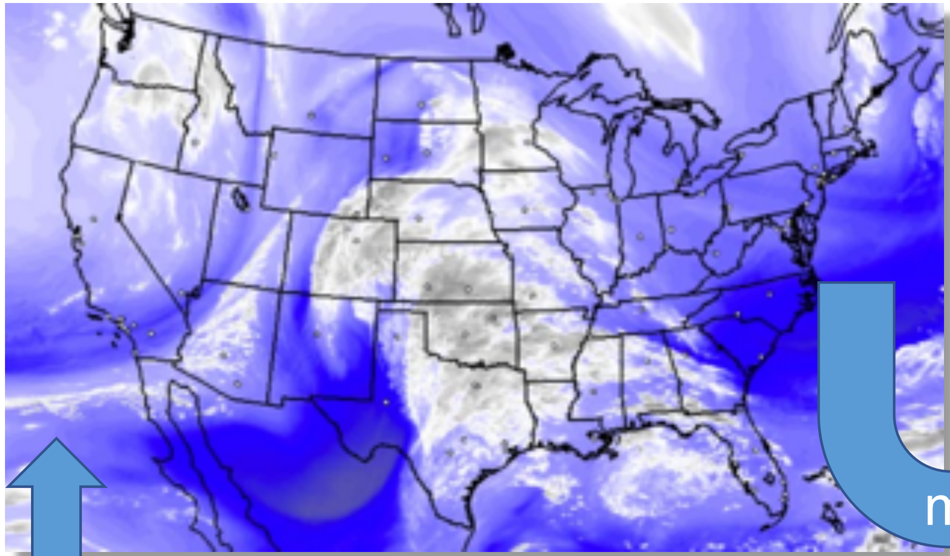


Pegion et al. 2019

- Ensemble forecast targets uncertainties in initial state, physics parameterization, etc.
- GSL ongoing contribution to NOAA real time subseasonal experiment (SubX) used at CPC
- Multi-model Ensemble (MME) has a higher RMM skill than any individual models

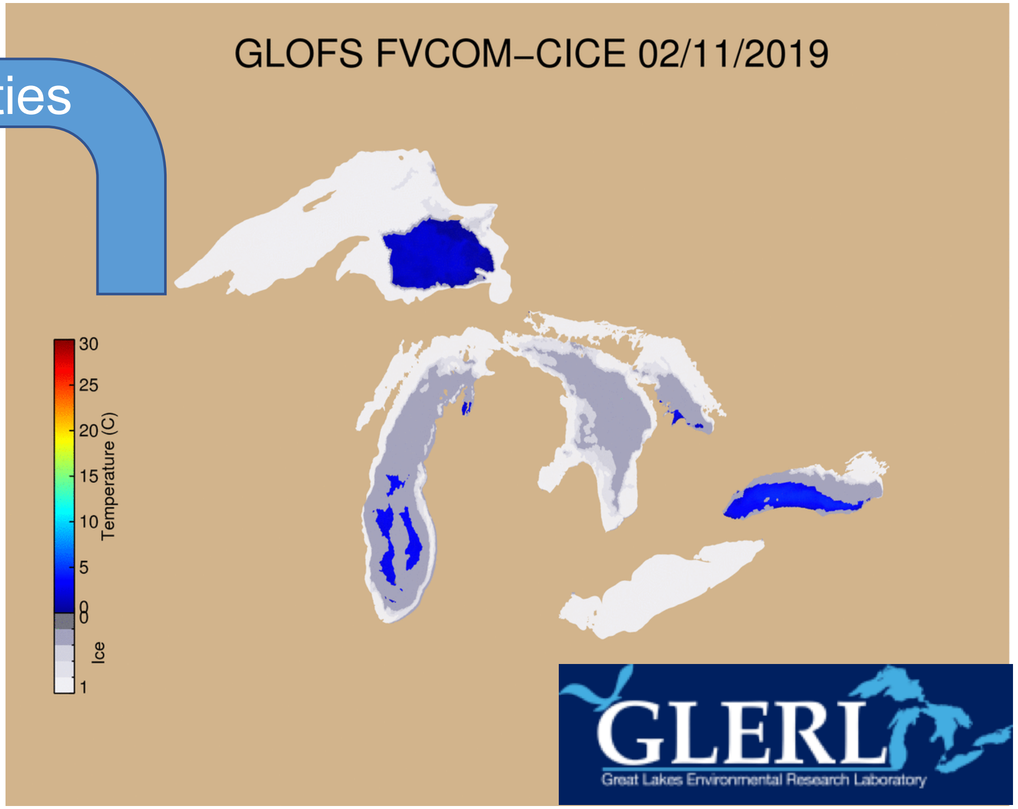
Atmosphere-Water Interaction via Coupling HRRR & Lakes

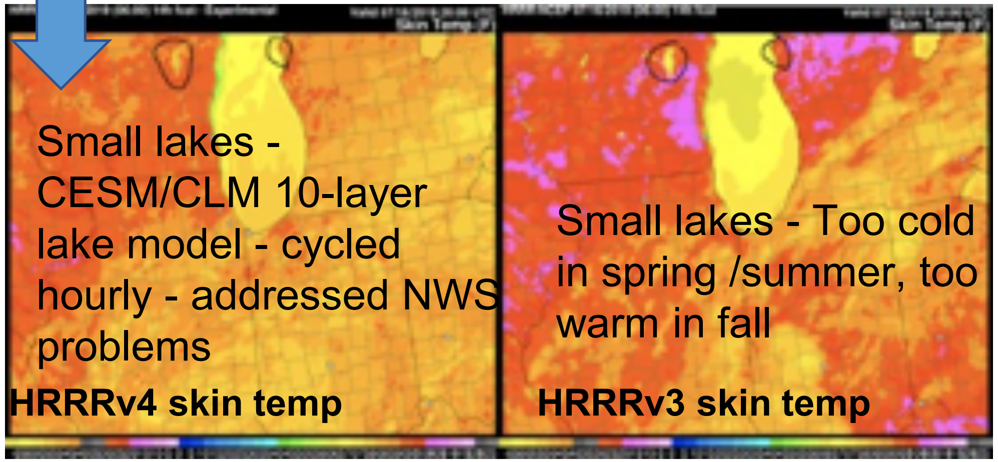
HRRR v4 (Dec 2020 @NCEP)



lake properties

meteorology





Small lakes - CESM/CLM 10-layer lake model - cycled hourly - addressed NWS problems

HRRRv4 skin temp

Small lakes - Too cold in spring /summer, too warm in fall

HRRRv3 skin temp

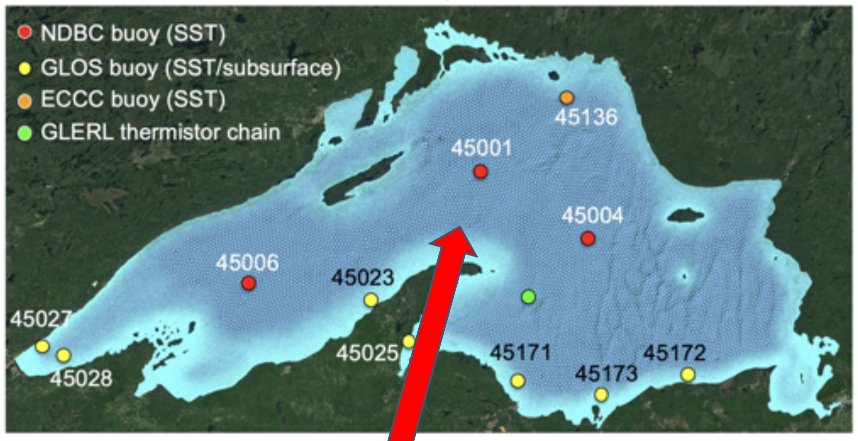
Improved short-term weather and lake forecasts!

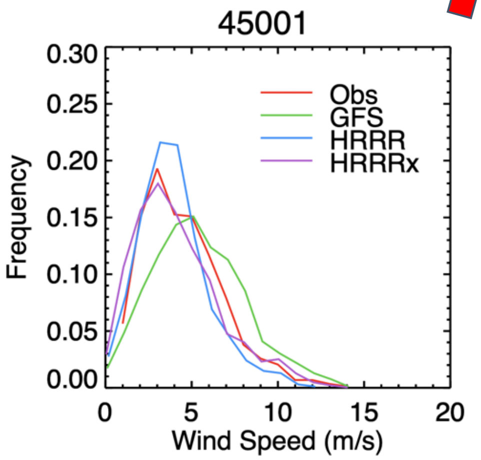
James/Benjamin/Smirnova (GSL), Anderson (GLERL)

Atmosphere-Water Interaction via Coupling HRRR & Lakes

Lake Superior Wind Evaluation

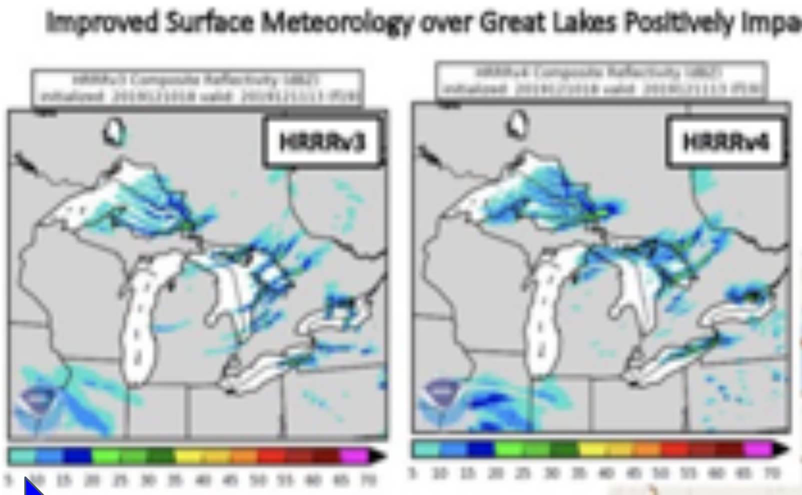
Lake Superior

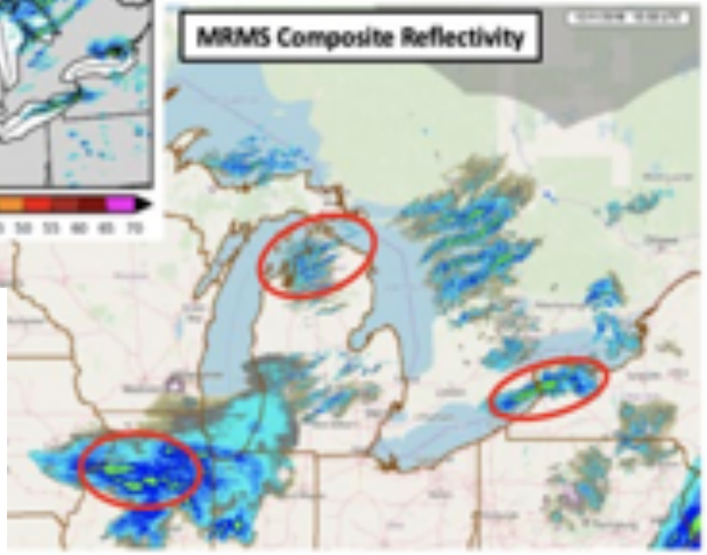




Better lake properties improve surface wind

Improved Forecasts of Great Lakes



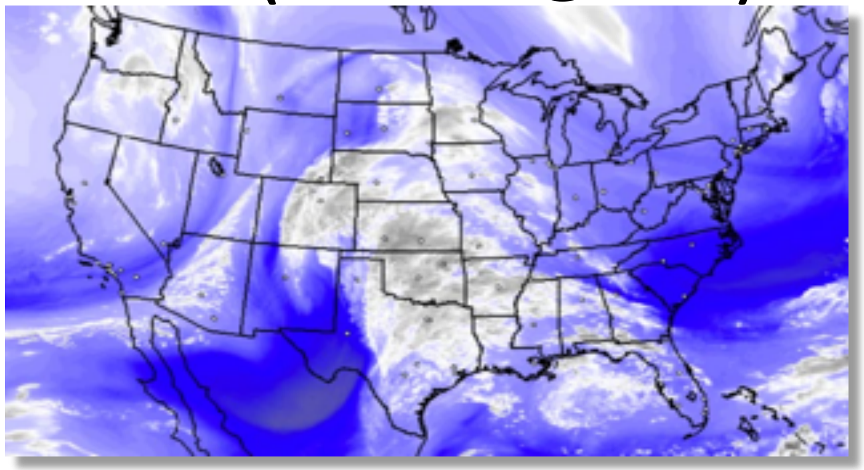


from Great Lakes Environmental Research Laboratory, MEG assessment presentation, 19 Dec. 2019

Better surface wind impacts surface heat flux and improves reflectivity, a proxy for lake effect snow

Courtesy of Joe Olson

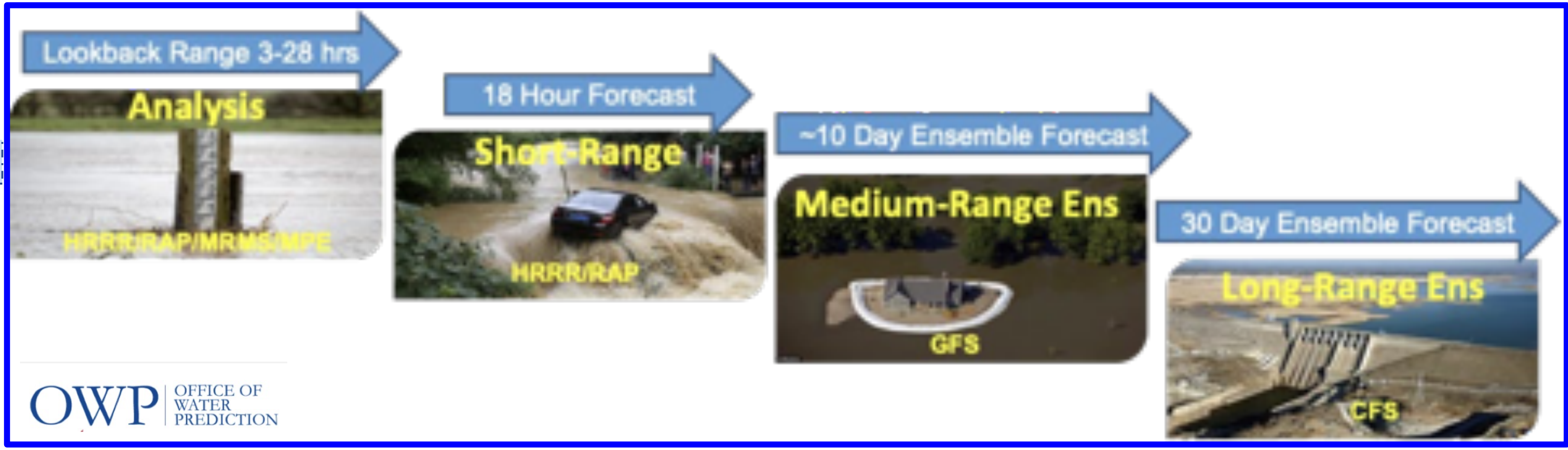
HRRR v4 (Dec 2020 @NCEP)



Future coupled RRFS+NWM systems will include coupled data assimilation

precipitation

2-way coupling soon



Recommendation C4.8

Summary

Finding potential sources of predictability and representing them well in the model are a key for S2S forecast

- Multi-model ensemble seems more skillful than any individual models
- GSL physics package offers a promising alternative ensemble member

Short-range coupling with models in GLERL/OWP

- Cycling between HRRR and lakes (Great and small) improves for both atmosphere and lakes forecast
- Precipitation from HRRR helps prediction of NOAA National Water Model

Future applications

- WGNE: swapping subgrid scale parameterizations to study aerosol impact in the coupled UFS
- Public health: early warnings on extreme weather episodes including heat waves, drought, flooding, etc.

NOAA Global Systems Laboratory

Modeling at GSL: Future Plans and Vision

Georg Grell
Division Chief, Earth Prediction Advancement Division

Global Systems Laboratory

GSL: Scientific Excellence in Modeling

- We have strong expertise in physics
    - Continue to develop and test state-of-the-art physics parameterizations (scientifically and computationally)
    - State-of-the-art physics may be more expensive : GPU usage? Other work on computational efficiency (collaboration with ATD)
- We have strong expertise in atmospheric composition, continue to accelerate transition of WRF-Chem modules into CCPP and UFS
- We have strong expertise in community support and model coupling - continue DTC and infrastructure work
- We are leaders within NOAA on fire weather applications – continue expanding expertise and application areas

GSL: Our Modeling Vision

Use our expertise and sharpened modeling tools to:

- Improve understanding of processes that are important for weather, air quality, and climate modeling
- Lead research advancements of atmospheric composition modules and physics modules using the UFS framework by engaging the community
- Apply the advancements to our Grand Challenge and improve operational applications on all time and space scales

Thank you!