NOAA’s 3-km Rapid Refresh Weather Forecasting Models and Renewable Energy Forecasts

Dave Turner
Senior Scientist / Global Systems Laborory
Manager, NOAA’s Atmospheric Science for Renewable Energy Program

Motivation

- Climate change is real; action is needed to reduce emissions – 5th National Climate Assessment
- Energy needs continue to grow!

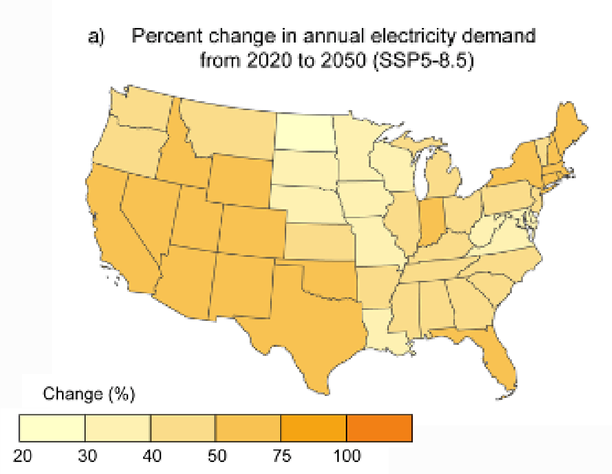

Figure 5.2. Due to climate change, electricity demand is projected to increase over this century.

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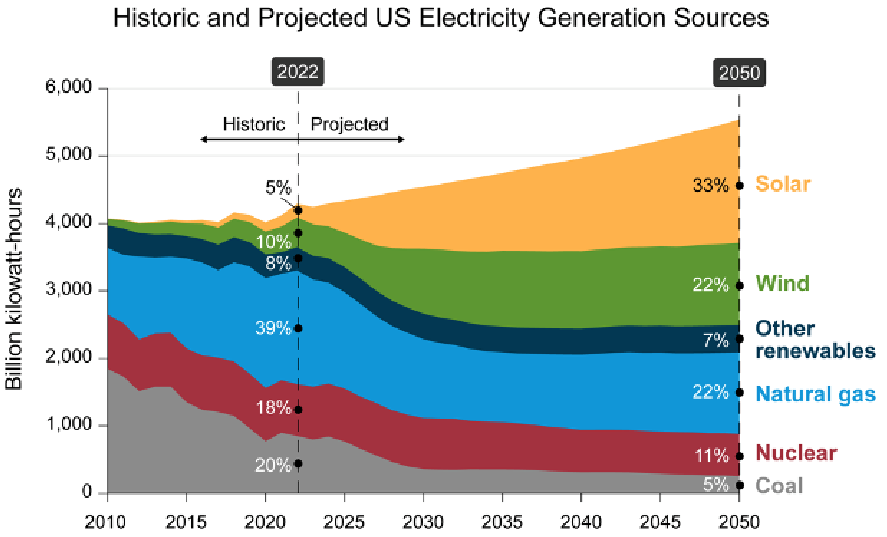

Figure 5.7. The Nation's electricity grid continues to expand use of clean energy technologies.

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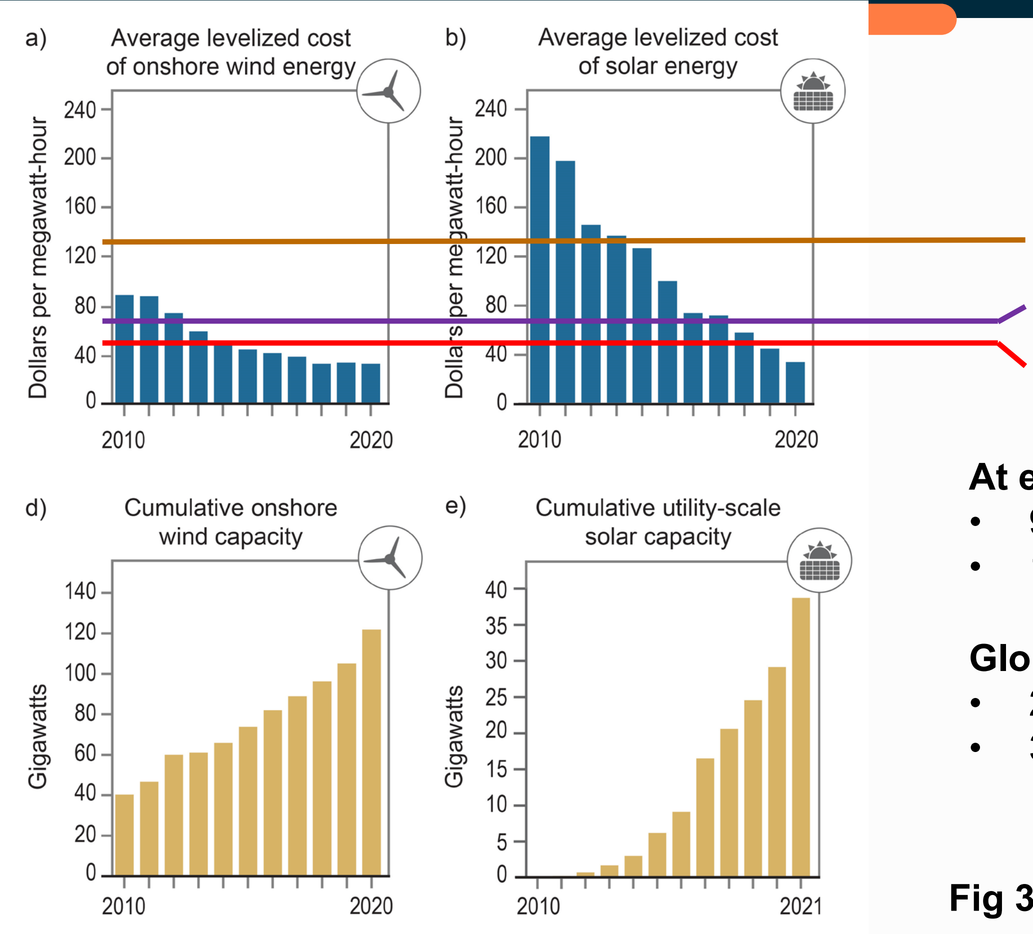
Evolution of cost and capacity for wind and solar in the US



(Levelized costs from Lazard in 2021)

Nuclear: $131 / MWh

Coal: $65 / MWh

Combined cycle gas turbine: $45 / MWh

At end of 2022, the global capacity is

- 900 GW for wind (US fraction is 13%)
- 1050 GW for solar (US fraction is 4%)

Global growth between 2020 and 2022

- 21% more wind generation
- 38% more solar generation

Fig 32.8

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Motivation

- Administration priorities:
  - 30 GW of offshore wind generation installed by 2030
  - 45% of total electiricty in US from solar generation by 2050
- Renewable energy generation is very dependent on the weather!
- Better weather forecasts make the electric grid more:
  - Efficient, resilient, and prepared (for climate change)

- NOAA provides foundational weather forecasts for the RE community
  - Decisions about mixture of generation (e.g., "how much energy from gas?")
  - Decisions about energy demand (complicated by "behind-the-meter" generation)
- Need to improve treatment of:
  - Boundary layer (winds, turbulence, thermodynamics)
  - Clouds and wildfire smoke
  - Precipitation (esp. hail and graupel)

- ASRE is a multi-NOAA laboratory program that:
  - Conducts fields campaigns and analysis
  - Improvements to NWP modeling systems
  - Transfers these improvements to the NWS every apprx 2 y

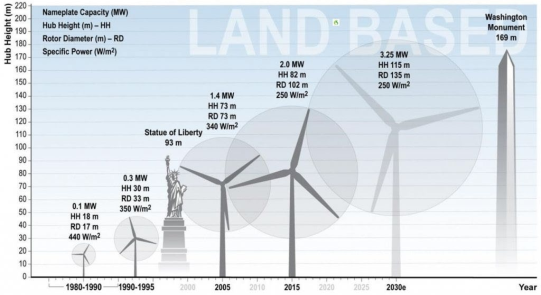
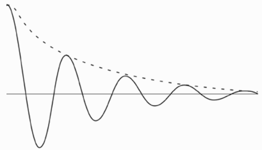


Figure 1. Expected Growth in Land-Based Turbine Size in North America

Four time-scales for RE forecasts / predictions

- **Seconds-to-hours**: keep power/voltage supply stable
  - Nowcast improvements result in a **more stable** voltage on the electric grid



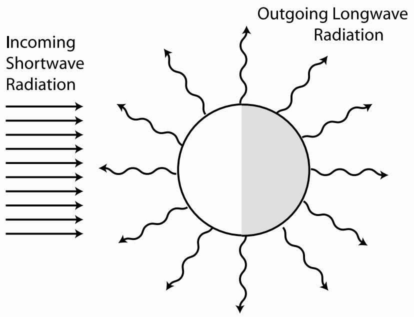
- **Hours-to-days**: improved short-term weather forecasts enables more accurate forecasts of the amount of energy generated from wind and solar resources
  - Significant cost savings (many 10s of $Ms)
  - Improvements at this timescale make the electric grid **more efficient**

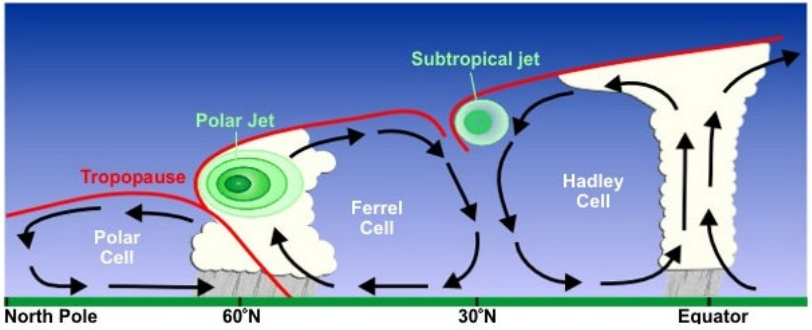
- **Days-to-months**: improved medium-term to sub-seasonal forecasts enable:
  - Identification of renewable energy “droughts”
  - Identification of periods when repair/maintenance would be more ideal
  - Improvements at this timescale make the electric grid **more resilient**

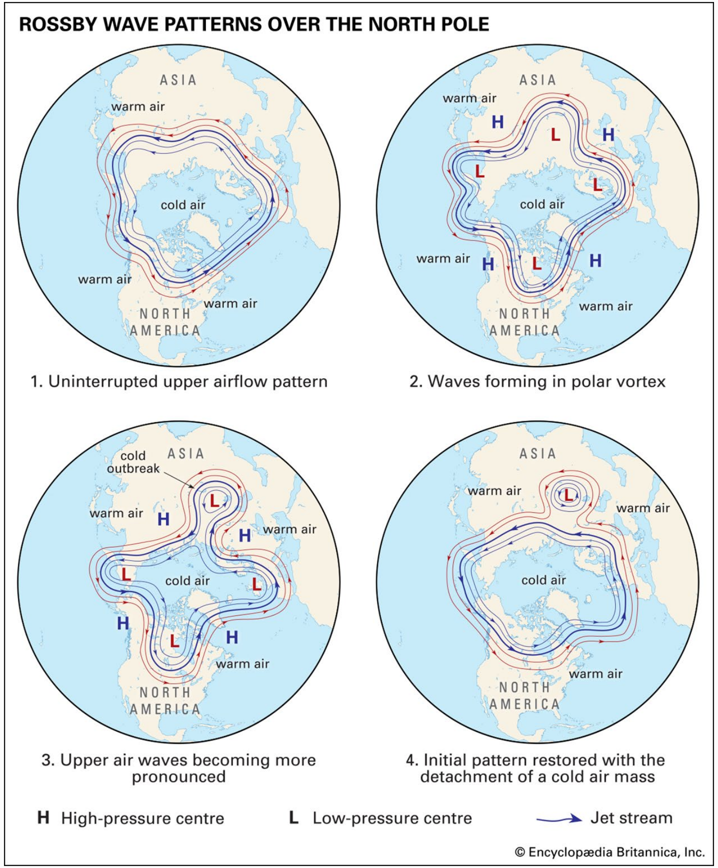
- **Seasonal-to-decadal**: improved predictions needed to understand:
  - How the renewable resource might change with climate change
  - How damaging weather events might change with time
  - Improvements at this timescale enable **better decisions on infrastructure**

Numerical weather prediction

- Weather is driven by differential heating of the earth; the atmospheric can be considered is a rotating fluid on a sphere

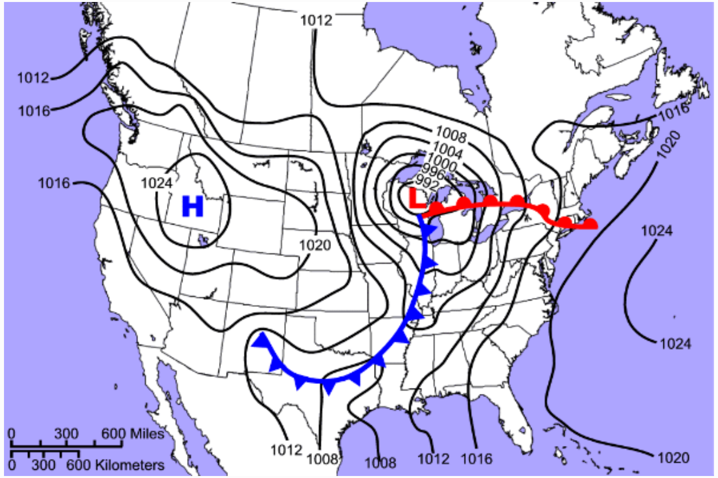


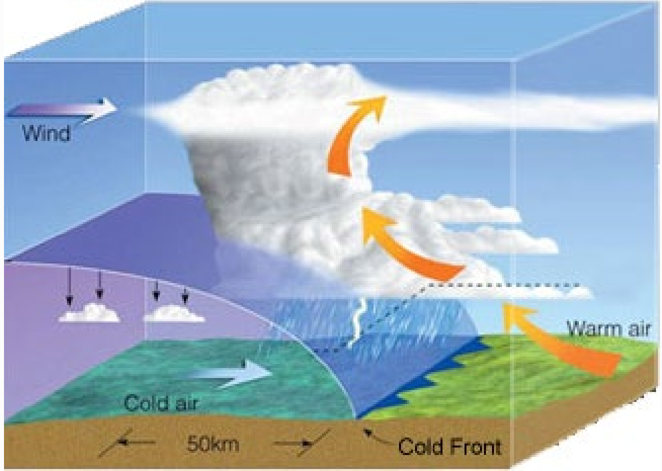


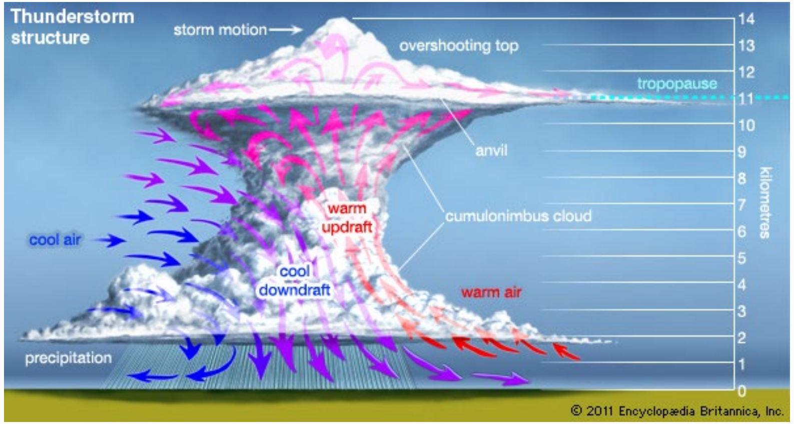


Weather is temperature gradients driving waves

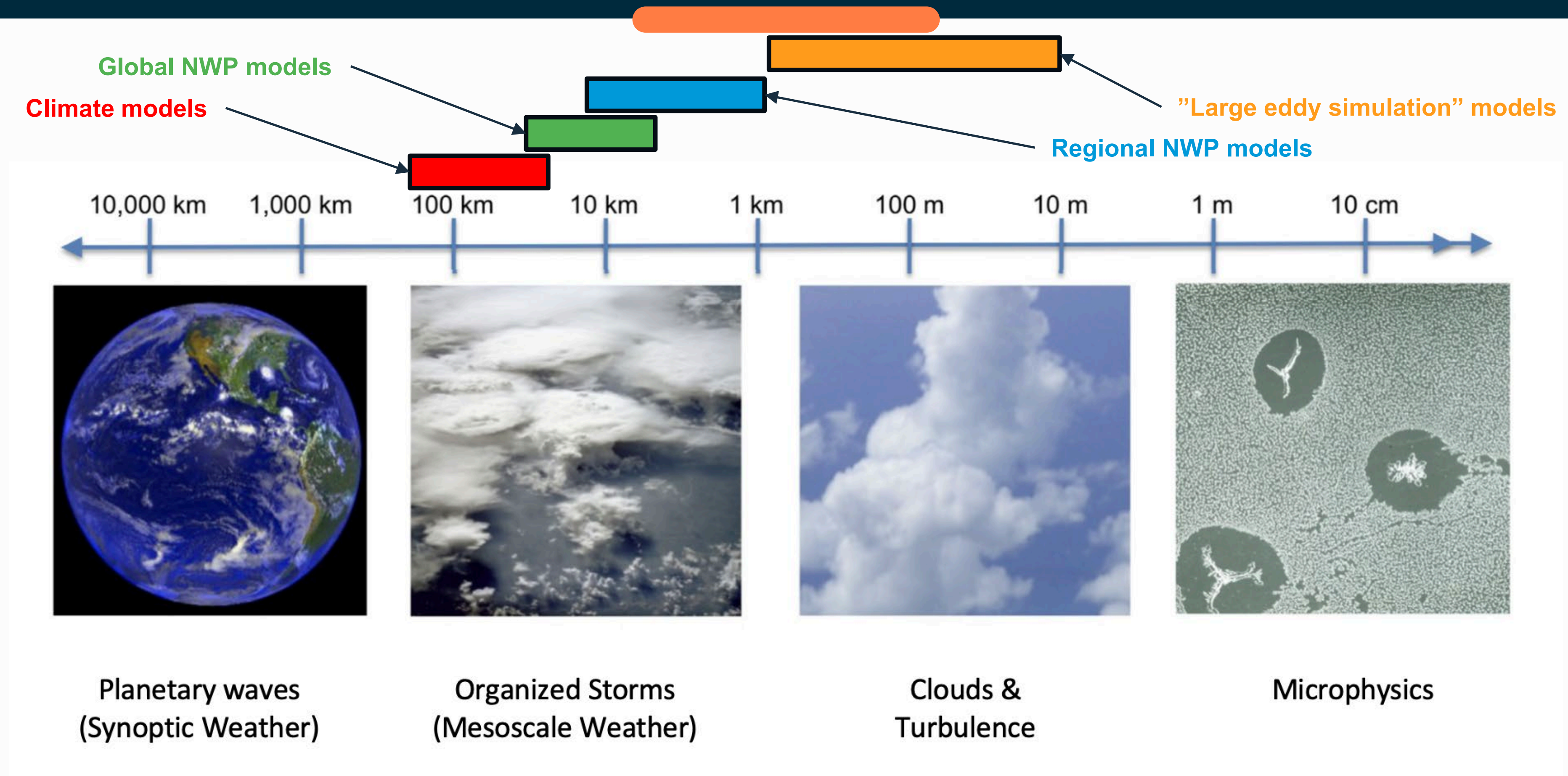
- “Big whirls have little whirls, that feed on their velocity; And little whirls have lesser whirls, and so on to viscosity.” – Lewis Fry Richardson







NWP must handle a huge range of scales



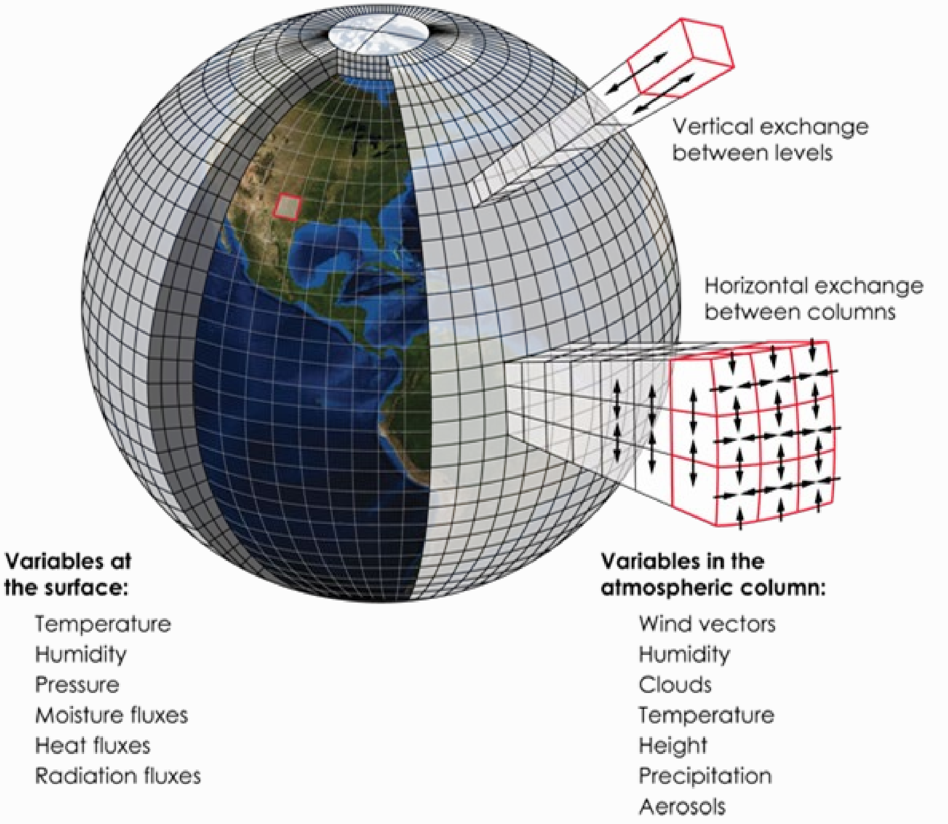
Numerical weather prediction (NWP) modeling

- Break the globe (or region) into boxes
  - Horizontally and vertically

- Need to specify many variables in each of these boxes (e.g., temperature, humidity, clouds, precipitation, ...)

- Need to determine how the variables "move" from one box to another

- Need to determine how the variables evolve within each box



NWP language: Mathematics

Numerical Weather Forecast Model (governing equations)

Momentum equations

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial x} + fv$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial \rho}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial y} - fu$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

Thermodynamic equation

$$\frac{\partial \theta}{\partial t} = -u\frac{\partial \theta}{\partial x} - v\frac{\partial \theta}{\partial y} - w\frac{\partial \theta}{\partial z} + \dot{Q}$$

Mass continuity equation

$$\frac{\partial \rho}{\partial t} = -u\frac{\partial \rho}{\partial x} - v\frac{\partial \rho}{\partial y} - w\frac{\partial \rho}{\partial z} - \rho\nabla\cdot\vec{V}$$

Moisture equation

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} - w\frac{\partial q}{\partial z} + micro(q)$$

Ideal gas law

$$p = \rho RT$$

Cloud equations

$$\frac{\partial \theta_l}{\partial t} = -\frac{\partial(u_i\theta_l)}{\partial x_i} + \upsilon_{\theta_l}\frac{\partial^2\theta_l}{\partial x_i^2} + Q_{\theta_l}$$

$$\frac{\partial q}{\partial t} = -\frac{\partial(u_i q)}{\partial x_i} + \upsilon_q\frac{\partial^2 q}{\partial x_i^2} + Q_q$$

$$Q_{\theta_l} = \left(\frac{\partial \theta_l}{\partial t_i}\right)_{\mathrm{rad}} + \left(\frac{\partial \theta_l}{\partial t}\right)_{\mathrm{prec}}$$

$$Q_q = \left(\frac{\partial q}{\partial t}\right)_{\mathrm{prec}}$$

Precipitation

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{\mathrm{prec}} = \begin{cases} -(\bar{q}_l - q_{lt})\tau; & \bar{q}_l > q_{lt} \\ 0; & \bar{q}_l \le q_{lt} \end{cases}$$

$$\left(\frac{\partial \bar{\theta}_l}{\partial t}\right)_{\mathrm{prec}} = -\frac{L}{c_p}\frac{\theta}{T}\left(\frac{\partial \bar{q}}{\partial t}\right)_{\mathrm{prec}}$$

$$\bar{q}_l = 0.05\ \mathrm{gkg}^{-1}$$

Radiation equations

$$\left(\frac{\partial \bar{\theta}_l}{\partial t}\right)_{\mathrm{rad}} = -\frac{\theta}{T}\frac{1}{\rho_0 c_p \Delta z}\left[\Delta F(z^+) - \Delta F(z^-)\right]$$

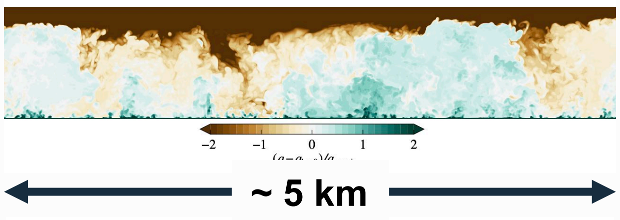
$$\Delta F = F_\uparrow - F_\downarrow$$

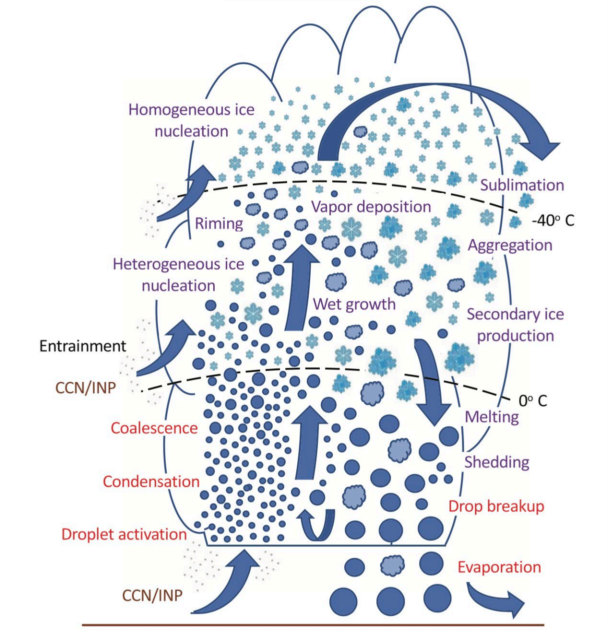
$$F_\uparrow(z) = B(0) + \varepsilon_\uparrow(z,0)(B(z) - B(0))$$

$$F_\downarrow(z) = F_\downarrow(z_{\mathrm{top}}) + \varepsilon_\downarrow(z, z_{\mathrm{top}})(B(z) - F_\downarrow(z_{\mathrm{top}}))$$

Parameterizations

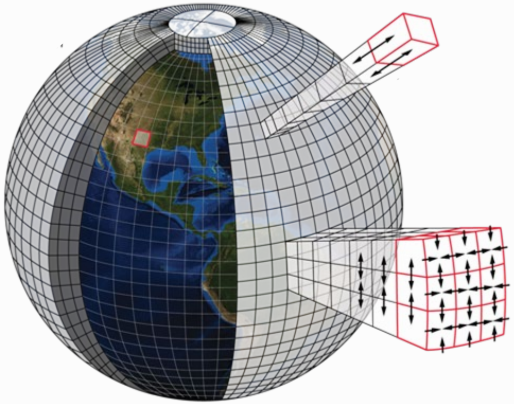
- Many atmospheric processes work at scales much finer than the model grid resolution (also true in ocean, ice, land, etc!)
- Examples:
    - Turbulent mixing of energy, mass, and momentum
    - Clouds and microphysics
    - Convection
    - Radiation
    - Interactions between atmosphere and surface
- Even though we don't "resolve" these, we still need to represent their impacts
- "Parameterizations" are simplifications of physical processes
- Continually working to improve parameterizations
- Increasing model grid spacing helps, but is expensive
    - Doubling the grid resolution makes the model $2^4 = 16$ times more computationally expensive!

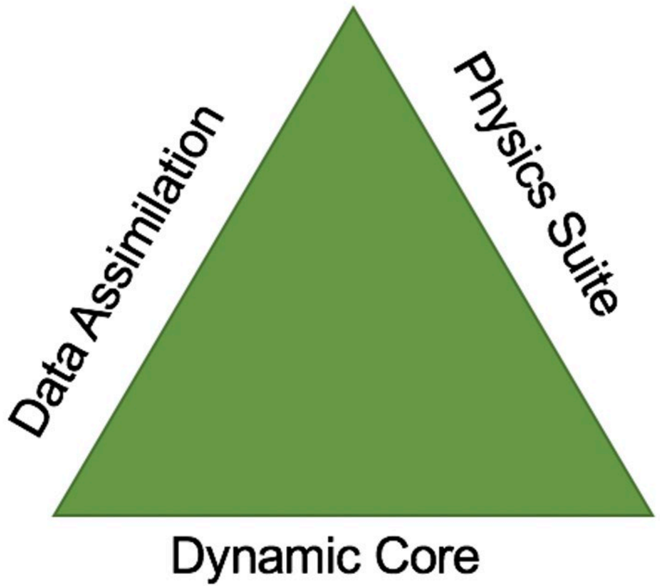




Components of a NWP system

- Dynamic core (to move the air around)
- Data assimilation system (to initialize the model with the current weather conditions)
- Physics package (to represent clouds, precipitation, radiation, turbulence, interactions with the land and ocean, and more)

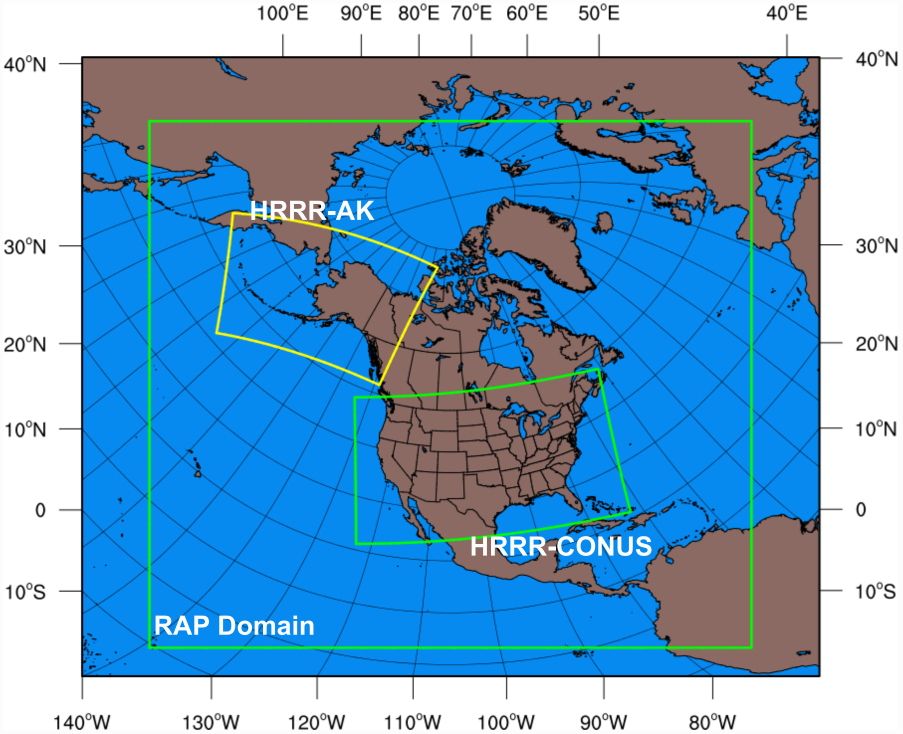




Observations (of as many variables as possible) are essential for both evaluating (improving) NWP models and initializing them

NOAA's Current Rapid Refresh NWP models

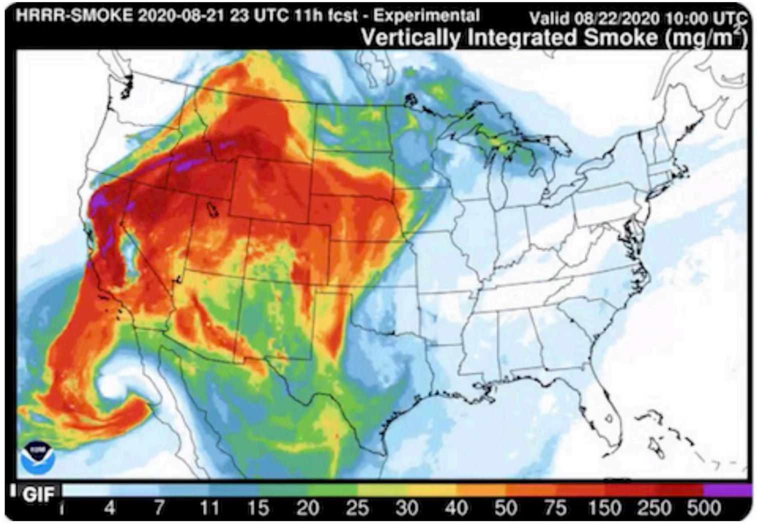
- What is "rapid refresh"?
  - Re-initialize model hourly to use most recent obs
  - Data assimilation is computationally expensive!
- Rapid Refresh ("RAP")
  - 13-km horizontal spacing
  - 953 x 834 x 50 points (300 MB / Fx hour)
  - Forecasts to 51h 4x daily; 21h otherwise
- High-Resolution Rapid Refresh ("HRRR")
  - 3-km horizontal spacing
  - Domains over CONUS and Alaska
  - 1799 x 1059 x 50 points (800 MB / Fx hour)
  - Forecasts to 48 h 4x daily; 18 h otherwise
- Model output is on the cloud (NODD) and open to everyone at no cost

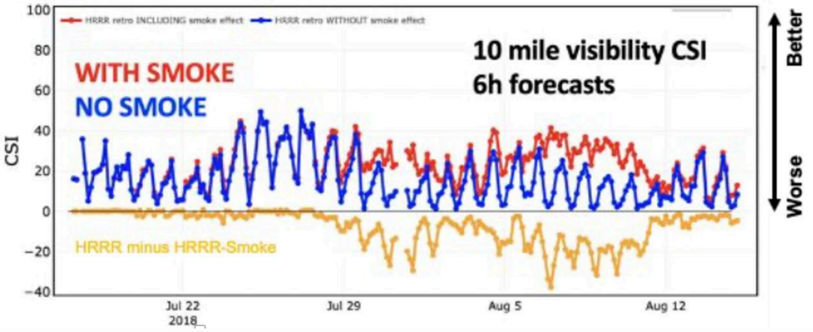


Addition of smoke to the forecasts

- RAP and HRRR first operational NWP models to include predictions of smoke
- Fires identified in satellite obs from MODIS and VIIRS
- Intensity of the fire used to:
    - Predict how much smoke mass to inject
    - Height of the injection
- Smoke is cycled from one run to the next
- Smoke interacts with the solar radiation
- Smoke is not allowed to interact with clouds
- Smoke leaves atmos via deposition and scavaging

- Including smoke resulted in improved T2m forecasts
- Really important for renewable energy, air quality, and aviation stakeholders!

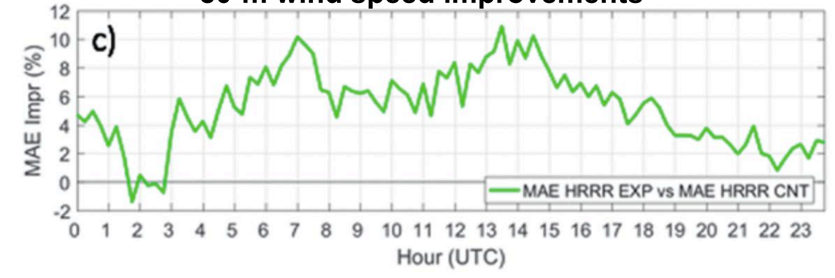




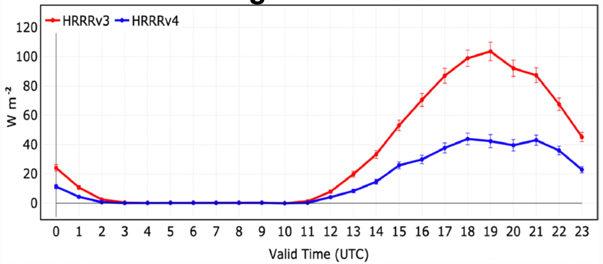
Major Recent Improvements to the HRRR

- Extended maximum forecast lengths to 48 h
- Storm-scale ensemble data assimilation
- Smoke emission / transport from wildfires
- Local mixing lengths improvements
- Non-local mixing via mass flux improvements
- Improved treatment of subgrid-scale clouds
- Large reduction of shortwave radiation bias
- Implementation of small-scale gravity wave drag
- New vertical advection scheme
- Improved conversation of variables
- Improvements to stability functions
- Coupled atmospheric model to a wave model

80-m wind speed improvements

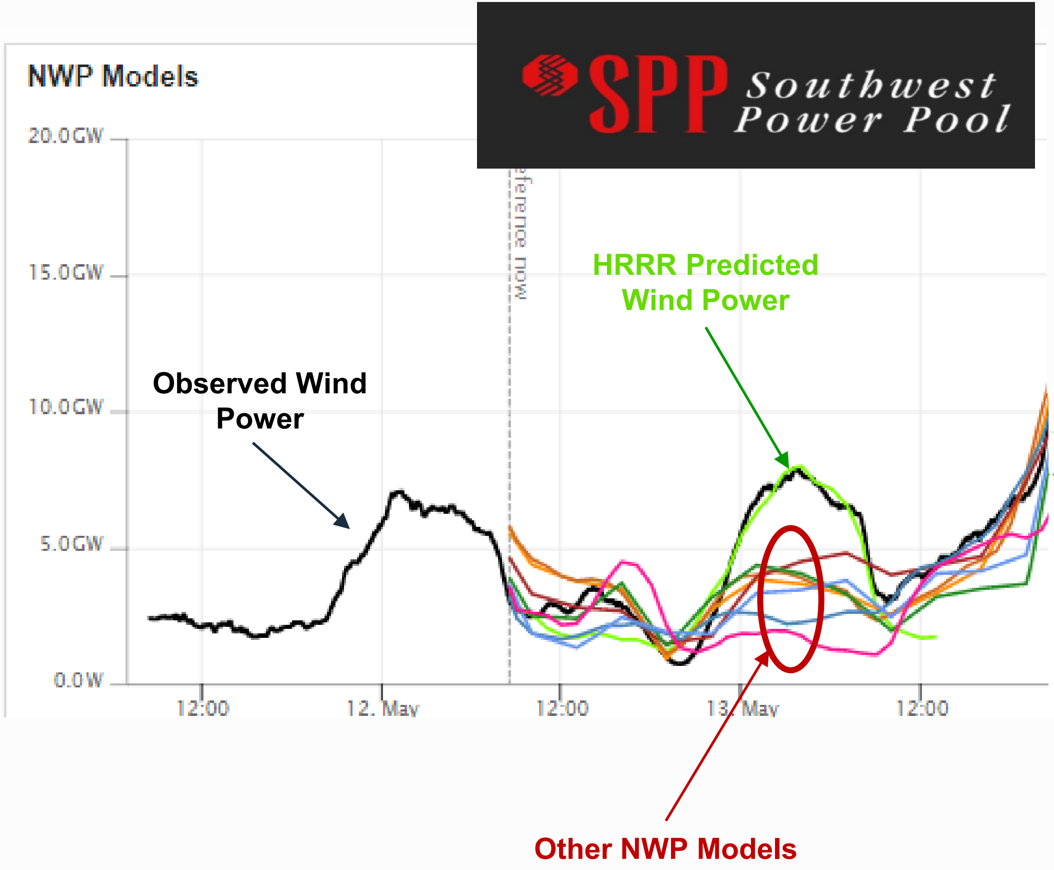


Downwelling Solar Radiation Bias



Taking a unified approach to improve the model (wind and solar, all seasons and locations, regional and global, etc) which is resulting in marked forecast improvements

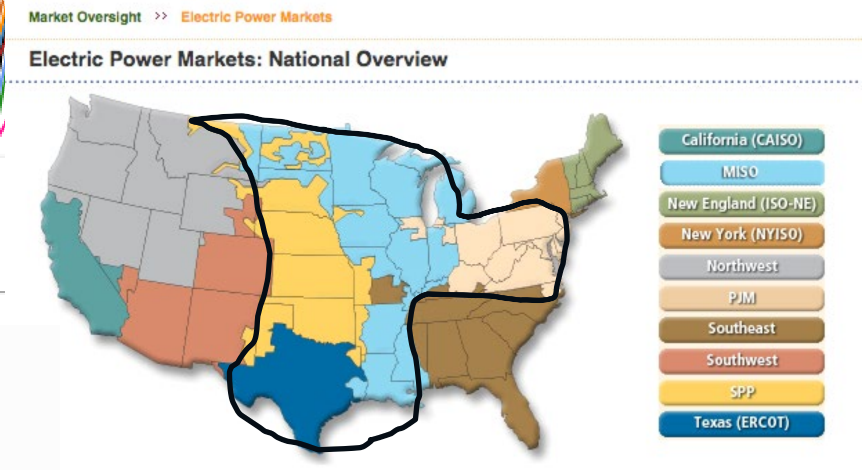
"Ramp Events" – So Important to Capture



29 Nov 2018 – "SPP/ERCOT/MISO/PJM switched short-term forecast to HRRR today.

It is now main weight for forecasting our 21,000MW of wind power in the Midwest! SPP went from not using HRRR in July 2018 to full weight implementation in 4 months because it performed so well, especially on AM/PM ramps. "

- Gunnar Shaffer – Southwest Power Pool, Little Rock, AR. 25



Economic Impacts via Improved Wind Forecasts

- Evaluated the economic impacts of improved wind on the U.S. electricity sector
- Compared two different versions of the HRRR (version X and X+1)
- Considered both:
  - Overprediction: model forecasts too much wind (need to purchase/acquire power)
  - Underprediction: model forecasts too little wind (using more fossil fuel than needed)
  - Costs for the two conditions are not symmetric!

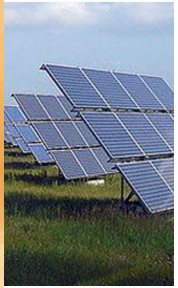
- Evaluated using different economic analysis regions
- Many assumptions about how decisions are made
  - Assumed decision was based purely upon the HRRR forecast
- Savings using HRRR.v2 vs HRRR.v1: $500M / year
- Savings using HRRR.v3 vs HRRR.v2: $230M / year

Jeon et al. *Journal of Renewable and Sustainable Energy*, 2022

Solar Power: Demand vs Generation

- Private solar energy generation are becoming increasing common
- Continue to see the growth of utility scale solar
- The challenge: “big weather event” like cloud deck, smoke, or dust can strongly impact solar energy
- Demand goes up, but ability to meet the demand goes down!

Extremely important to be able to forecast these events, so the energy companies can plan to have other generation methods available!



Wind Forecast Improvement Projects

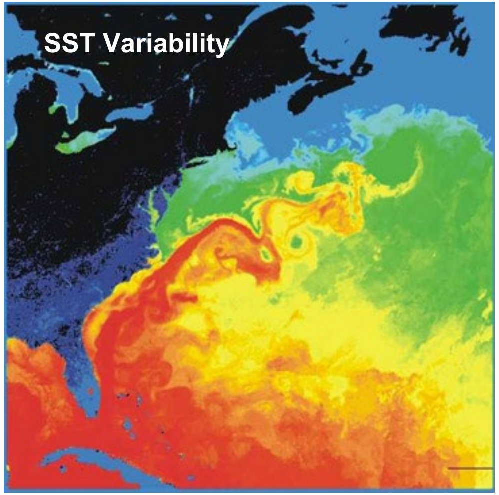
- WFIPs are collaborative NOAA / DOE / private partnerships
- Have previously conducted two WFIP campaigns
    - WFIP-1 (2011-2012) focused on model initialization
    - WFIP-2 (2016-2017) focused on complex terrain physics

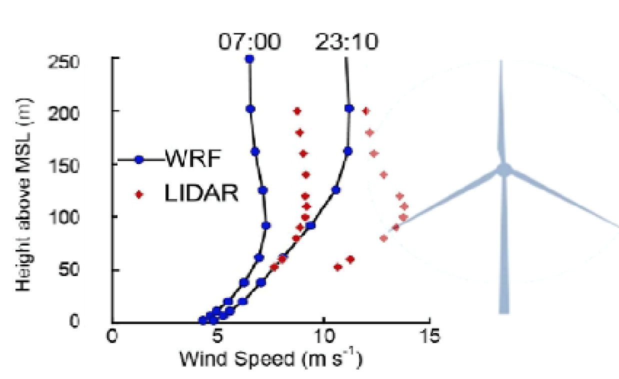
Wind Energy Technologies Office

- WFIP-3 is targeting offshore wind energy characterization
- WFIP-3 objectives:
    - Improve understanding of atmos & oceanic physical processes that directly affect wind resources on US east coast
    - Incorporate this new understanding into foundational NWP forecast models to improve wind energy forecasts
- Field campaign: 18-month coupled atmos-oceanic study (2024-2025)
- Goal: evaluate current and improve future forecasts for OSW

WFIP-3 Key Science Issues

- US east coast offshore wind energy environment is much different than the European offshore areas
  - Much warmer summer (colder winter) upstream air mass leads to very stable (unstable) atmos boundary layer
  - Stable BLs produce low level jets with substantial variations in wind speed, which is not captured well by current models
  - Larger SST gradients can lead to internal boundary layers and local circulations

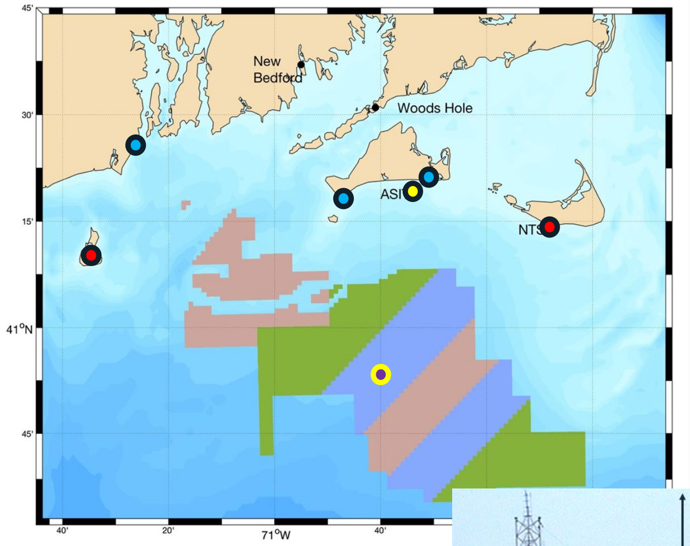


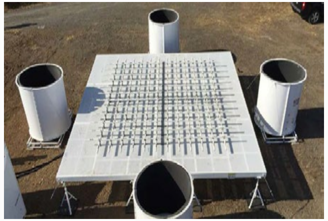


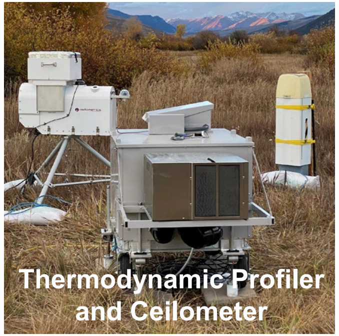
- Complex coastline can modulate offshore wind patterns
- Interactive coupling between ocean and atmosphere (e.g., wave impacts on winds)
- Challenging weather: sea-breeze, coastal upwelling, nor'easters, hurricanes, precipitation, …

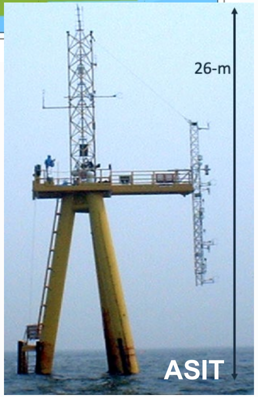
WFIP-3 Sites and Instruments

- Instrumented barge
  - Requested a NOAA ship for winter time
- WHOI Air-Sea Interactions Tower (ASIT)
- Multiple island sites
  - Block Island and Nantucket sites (NOAA)
  - Two sites on Martha's Vineyard
  - Rhode Island
- Sentinel and Doppler lidar buoys
- Many different remote sensing instruments
- Instruments from NOAA, DOE, WHOI, universities…

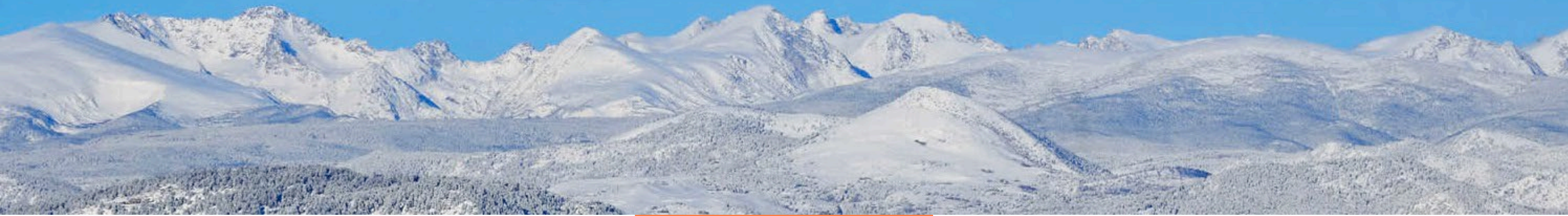



Radar Wind Profiler





An Overview of the Rapid Refresh Forecast System (RRFS)



Simplifying NOAA's Operational NWP Forecast Suite

Storm-scale Numerical Weather Prediction Models

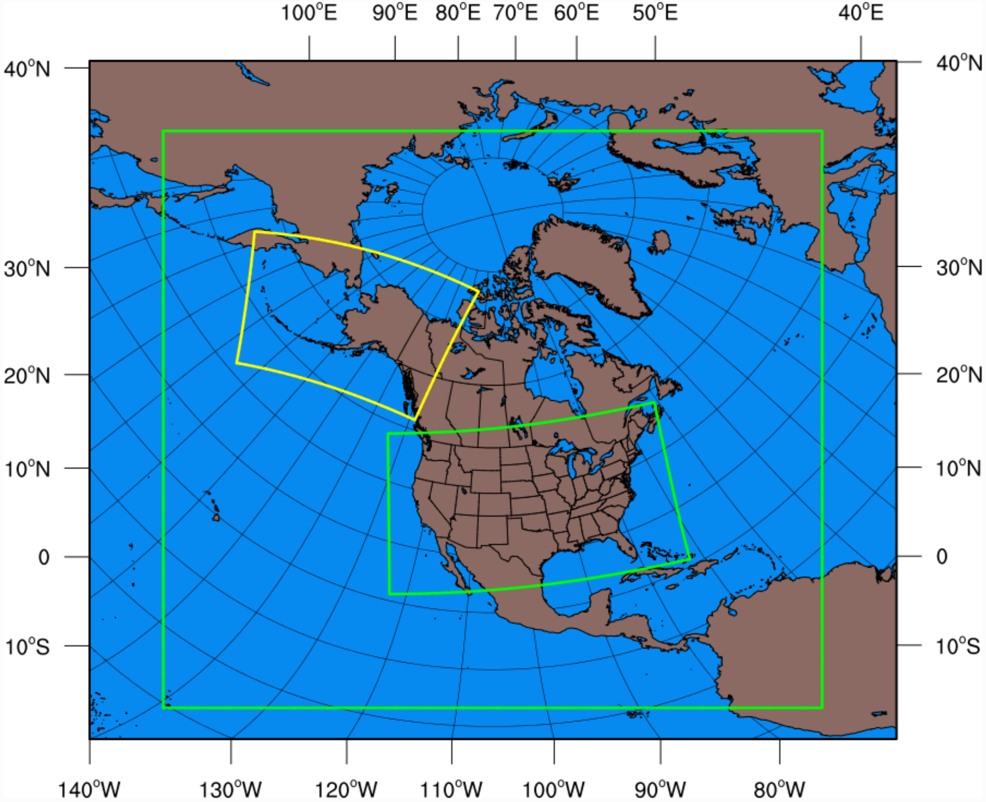
- Seven different systems currently operational
  - Different physics, different DA approaches, different domains, different forecasts lengths…
  - Desire of the Unified Forecast System (UFS) philosophy to simplify the production suite
  - Goal: only one storm-scale (~4 km grid) model system

- Adopted the FV3 dynamic core for both global and regional applications

- Good progress already made with GFS and GEFS

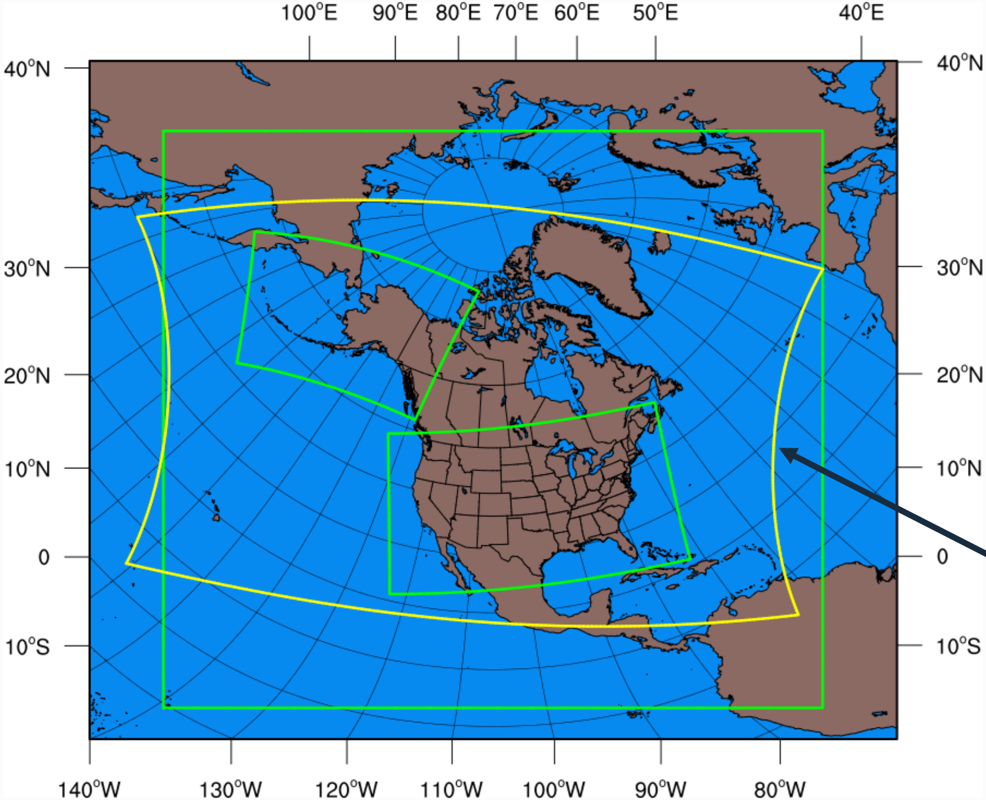
- Regional application: Rapid Refresh Forecast System (RRFS – "rufus")
  - Development started in 2020
  - Collaborative effort between GSL, EMC, and NSSL
  - Will use the physics from the Rapid Refresh / High-Resolution Rapid Refresh (RAP/HRRR)
  - Larger domain to cover CONUS, Alaska, and many OCONUS areas

Current RAP / HRRR Domains



- RAP (13-km)
  - Rotated lat-lon grid
  - 953 x 834 x 50 points
  - 300 MB / 3d native file (i.e., 1 Fx hour)
- HRRR-CONUS (3-km)
  - Lambert Conformal
  - 1799 x 1059 x 50 points
  - 800 MB / 3d native file
- HRRR-Alaska (3-km)
  - Polar Sterographic
  - 1299 x 919 x 50 points
  - 500 MB / 3d native file

The RRFS Domain



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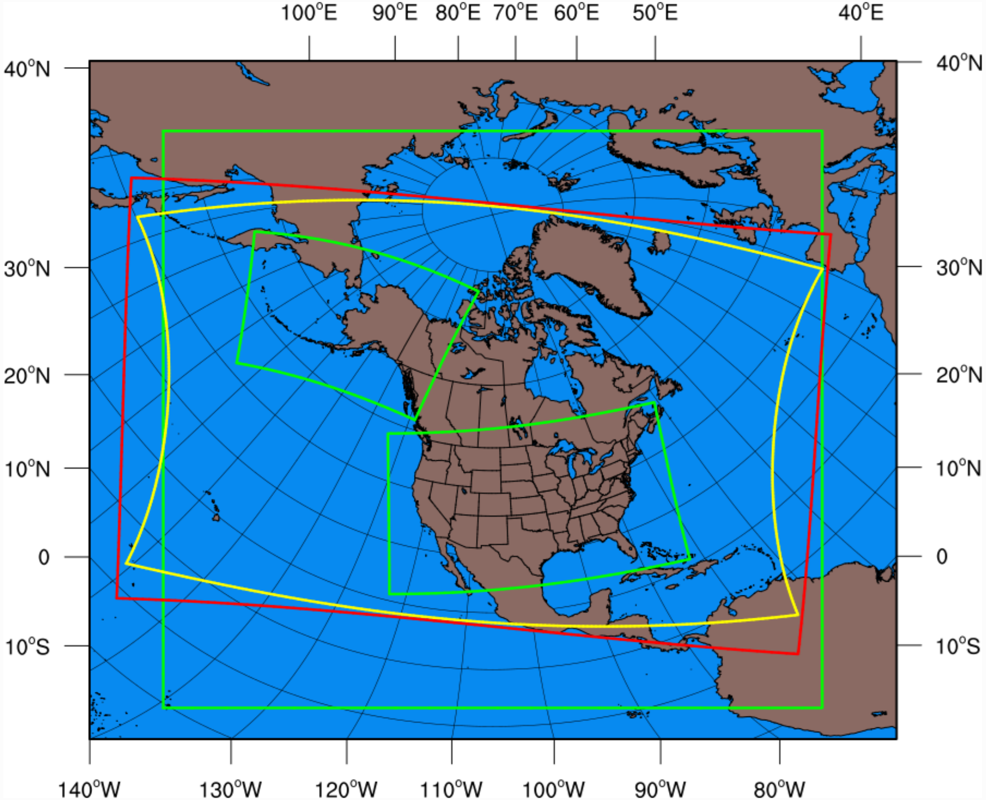
- Large RRFS domain to:
  - Reduce number of domains being run
  - Provide operational NWP support over Hawaii and Carribean
  - Better guidance for hurricanes, atmospheric rivers, Arctic airmasses…

The RRFS Domain



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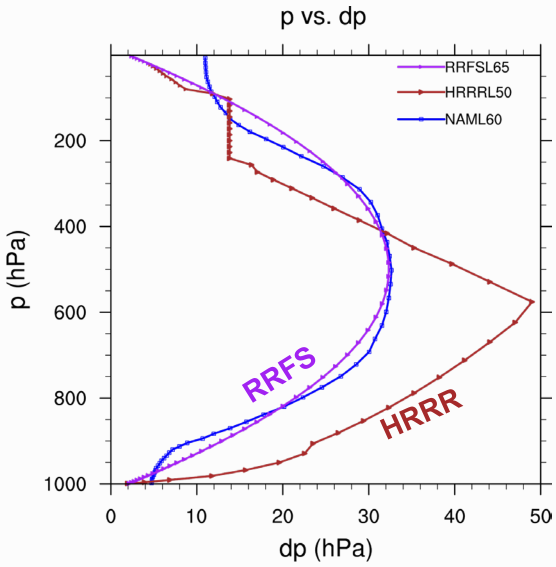
  - 1299 x 919 x 50 points
  - 500 MB / 3d native file
- FV3 is a cubed sphere configuration
- Its "ESG" grid gets finer near the boundaries
- Will project data on an easier-to-use grid
  - Rotated lat-lon grid
  - 4881 x 2961 x 65 points
  - 10 GB / 3d native file
  - 9.7x more 3d points than HRRR

RRFS Design Elements

- Large domain
  - GFS → RAP → HRRR: 3 distinct integration domains
  - GFS → RRFS: 2 distinct integration domains
- Vertical grid
  - 65 vertical levels instead of 50
  - First vertical level is still ~8 m
  - Higher model top (2 mb for satellite DA)
  - Twice as much vertical resolution in the PBL
- Model physics
  - Largely the HRRR physics (much updated!)
  - Modified to use the CCPP interface (UFS standard)



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)
Aerosols	Thompson-Eidhammer	Thompson and Eidhammer (2014)
Shallow Convection	MYNN-EDMF	Angevine et al. (2020)

Physics	SCHEME	REFERENCE
Gravity Wave Physics	UGWP.v1: Small Scale and Turbulent Orographic Form Drag	Toy et al. (2021)
Land Model	RUC	Smirnova et al. 2016
Land Use	VIIRS	-
Large Lakes	FVCOM	Fujisaki-Manome et al. (2020)

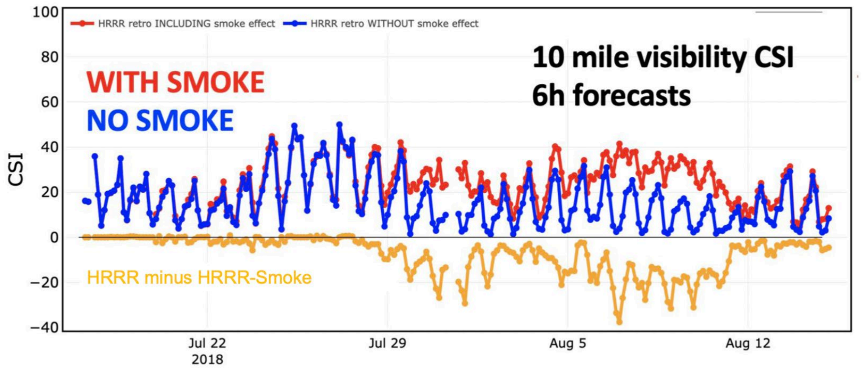
Physics	SCHEME	REFERENCE
Small Lakes	CLM lake model	
Near-Surface Sea Temperature	SST (once per day)	
Long and Short Wave Radiation	RRTMG[2]	Iacono et al. (2008), Mlawer (1997)

Smoke within RRFS

- Smoke forecasts added to HRRRv4; became operational in Dec 2020
- Smoke treated as a single tracer (computationally efficient)
  - Does not allow smoke to evolve chemically
  - Smoke does interact with radiation
  - Smoke does not interact with clouds
  - Deposition and scavaging included
  - Smoke fully cycled
- Use LEO obs from VIIRS & MODIS to identify fires
- Fire-radiative power (FRP) used to parameterize intensity of the fire, which controls:
  - Injection height of the plume
  - Amount of mass injected
- Provide profiles of smoke mass, total column, and PM2.5 at the surface
- Improvements to RRFS include how FRP changes over time with conditions in forecasts

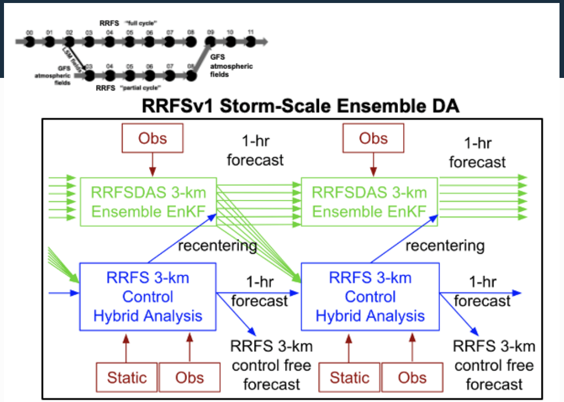
- Also include dust (both fine and coarse mode) as two additional tracers for visibility / AQ purposes

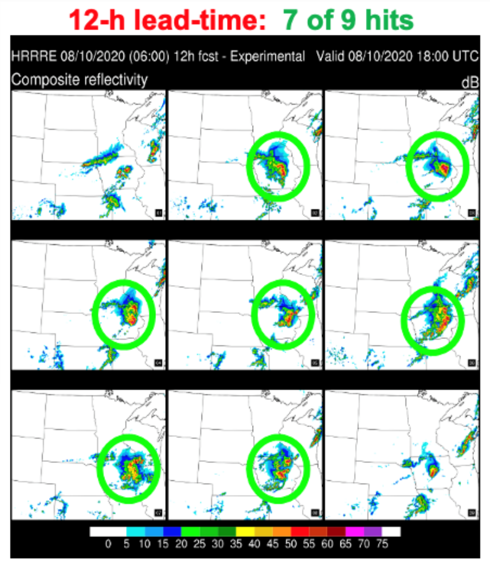
20 June to 14 Aug 2018 Smoke event over Western CONUS

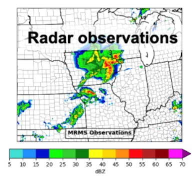


More RRFS Features

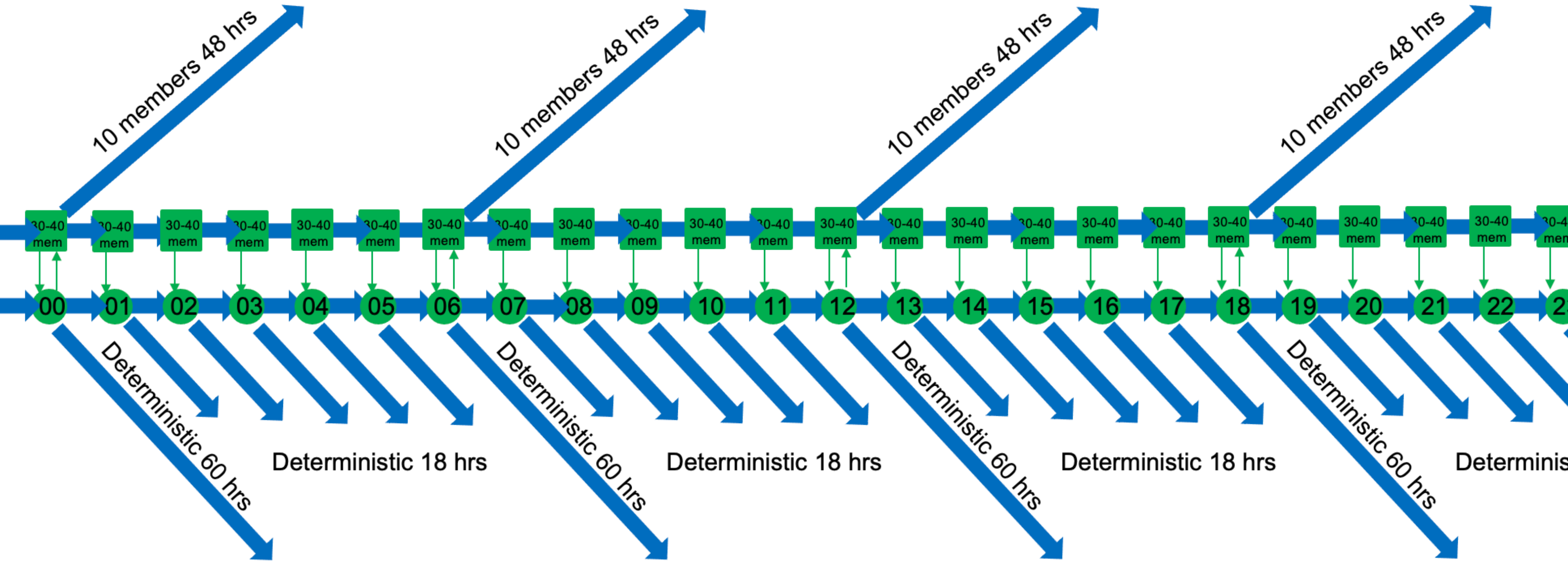
- Assimilates many different types of observations
  - Profiles (radiosondes, aircraft, profilers)
  - Radar and lightning
  - Surface (land-based and from buoys/ships)
  - Satellite
- Improved storm-scale ensemble DA method
- Land-surface “moderately coupled” DA
- Cloud DA (non-variational currently; working to improve)
- Post-processing diagnostics (e.g., wind gust potential)
- Ensemble predictions
  - 10-members, each doing 48-h forecasts
  - Will be evaluating these for wind/solar energy Fx



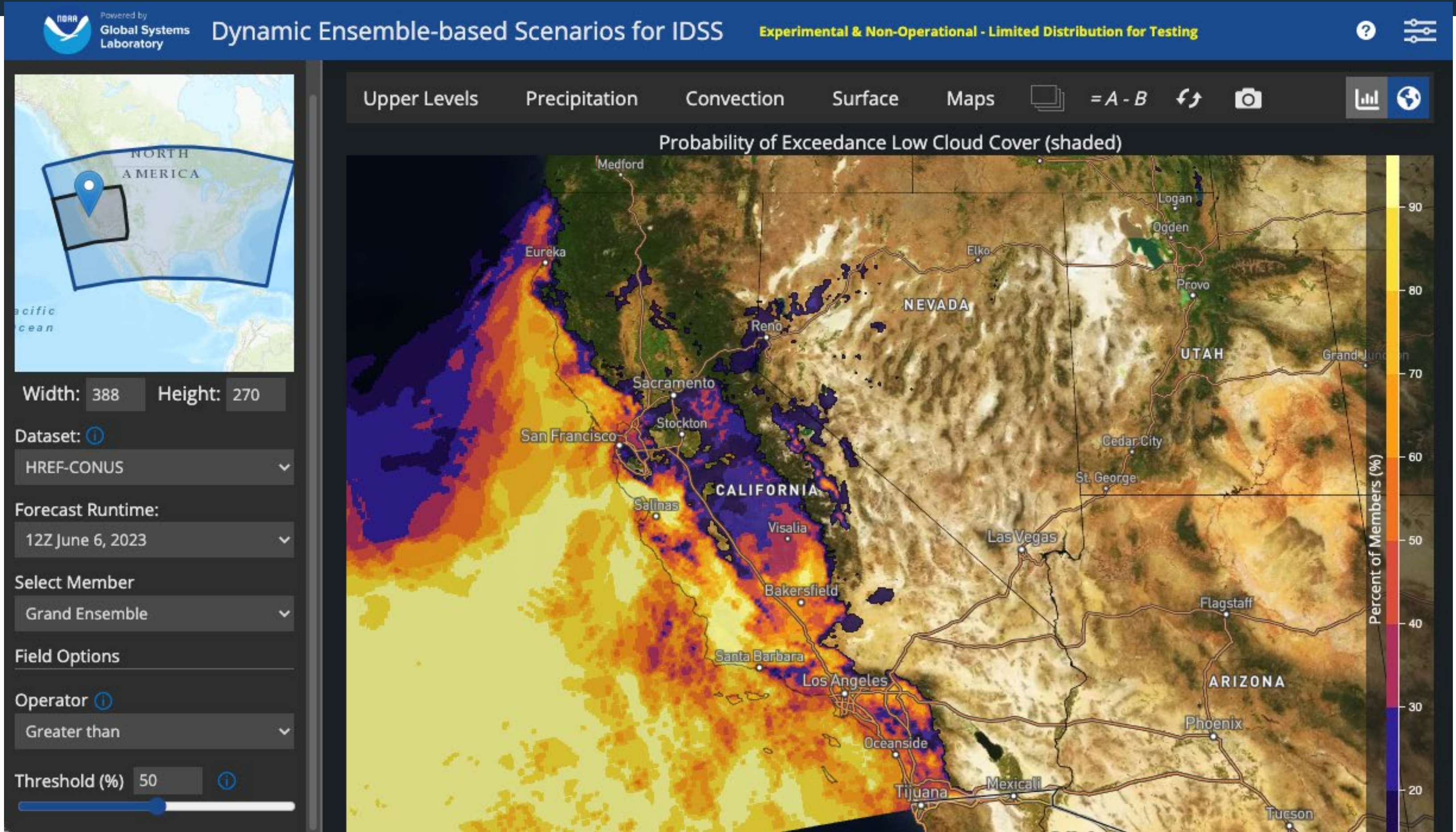




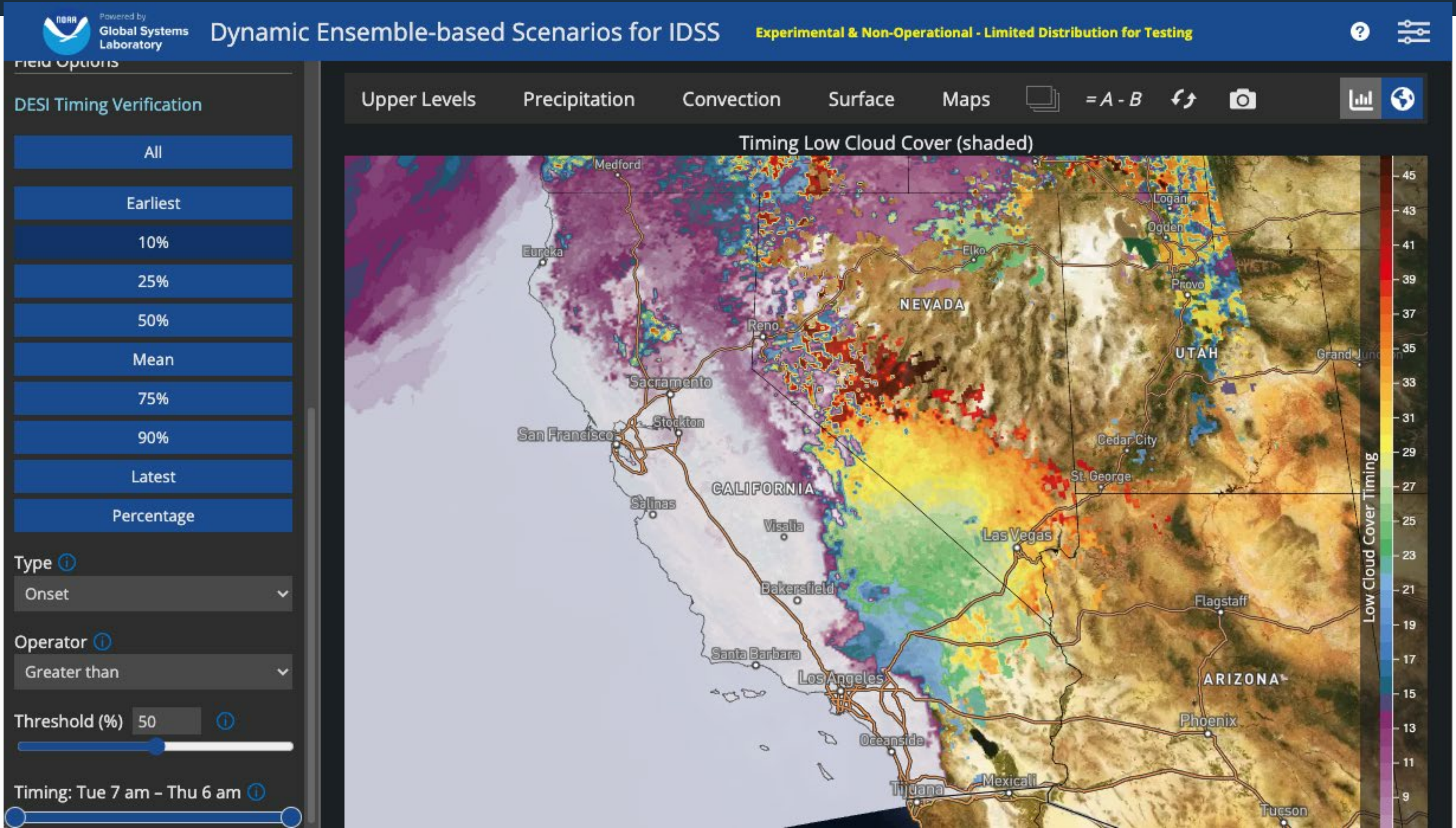
RRFS is an ensemble DA and forecast system



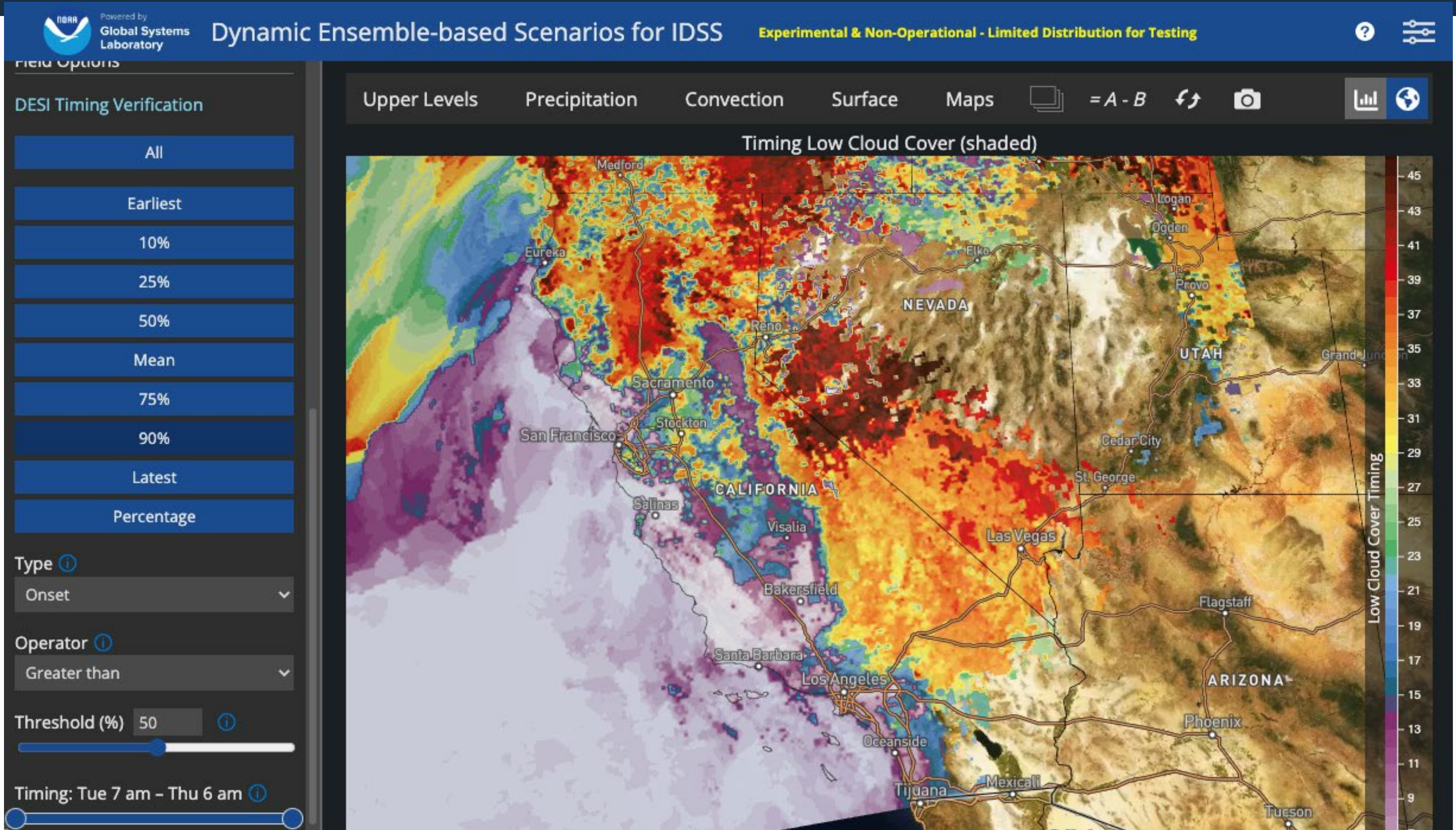
Ensemble: Probability Low Cloud Cover > 50%



Ensemble: Low Cloud Timing (early onset)

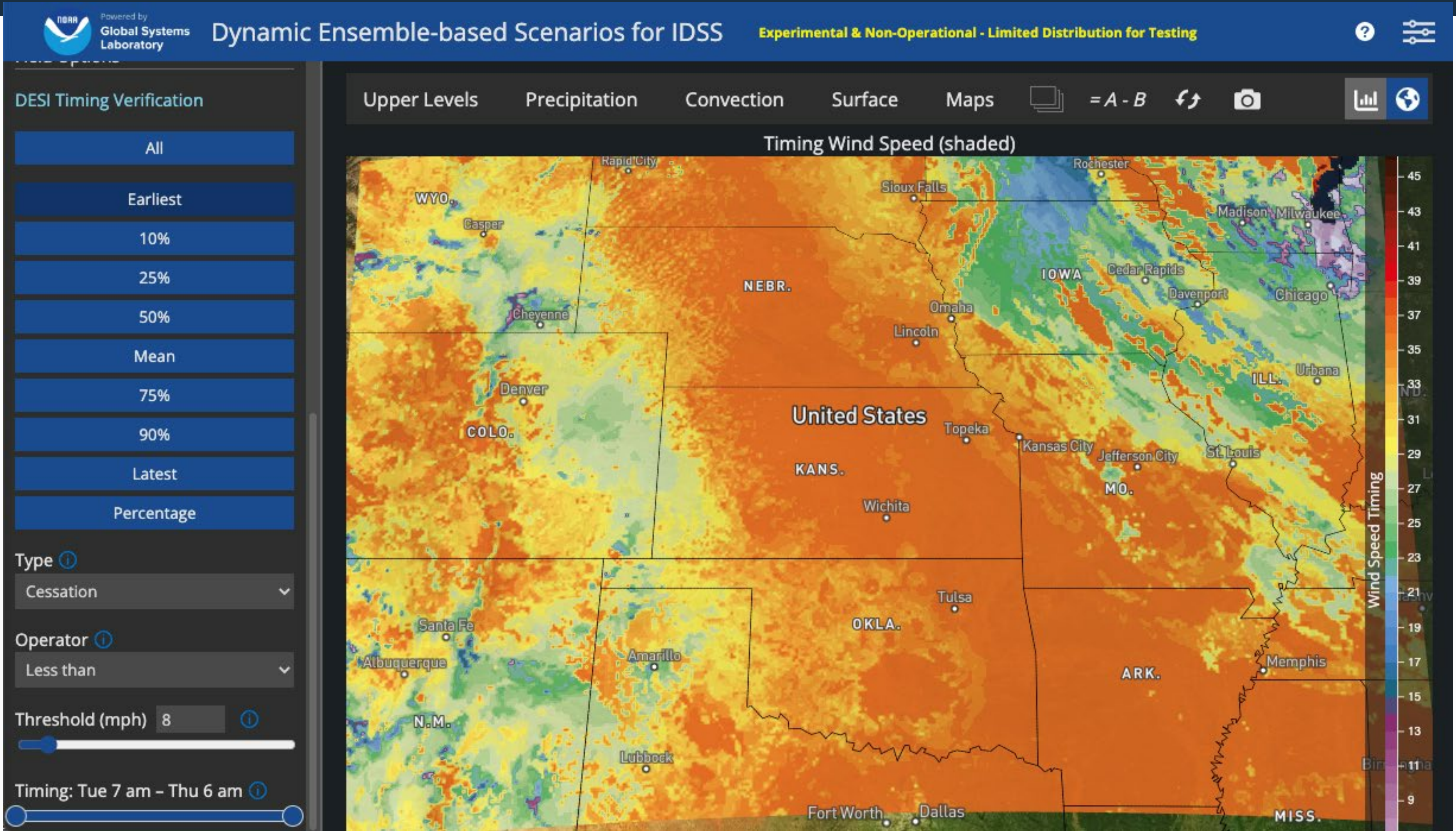


Ensemble: Low Cloud Timing (late onset)



Ensemble: WSPD > CutIn (Mean timing)

Ensemble: WSPD > CutIn (Earliest timing)



RRFS Summary

- RRFS is a major upgrade over the HRRR (larger domain, longer forecast length, ensemble forecasts)
- Deterministic forecasts hourly out to 18 hours; out to 60 h for initializations at 00, 06, 12, and 18 UTC
- Ensemble forecasts out to 48 hours for for initializations at 00, 06, 12, and 18 UTC
- Advanced scale-adaptive physics with many improvements
- Continue to provide smoke forecasts; added dust forecasts also
- Two-way coupled storm-scale ensemble data assimilation
- Most verification statistics match or beat the HRRR verification statistics

- Code freeze in Feb 2024, science evaluation from Mar – Nov, transition to ops at end of year (if passes science and code evaluations) becoming operational in early 2025
  - There are challenges with convective storms and storm structure (not shown here)
  - Traced to dynamic core (FV3) and its behavior at storm-scales
  - Added convective parameterization to provide some mitigation
  - RAP / HRRR (including HRRR-AK) will remain operational after RRFSv1 becomes operational
  - Other regional models will be retired however

Concluding remarks

- NCA5 - Ch5: “An energy system transition emphasizing decarbonization and electrification would require efforts in new generation, transmission, distribution, and fuel delivery”
- NCA5 – Ch32: “A US energy system with net-zero emissions would rely on widespread improvements in energy efficiency, substantial electricity generation from solar and wind energy, and widespread electrification of transportation and heating”

- Accurate predictions of the weather, from a RE perspective, is critical
- High-resolution, rapid-refresh models ideal for the “day-ahead” problem
  - Predicting demand is much complicated due to behind the meter RE generation
  - Informed decisions for including RE into the energy generation mixture
  - Will become increasingly important for energy transmission and “dynamic line rating”
- Global-coupled models ideal for the “week-ahead” challenges
  - Perhaps the largest forecast challenge is accurately predicting time windows for maintenance
- Climate models ideal for the “infrastructure” challenges
  - How will the energy resource change with time
  - How will frequency/intensity of damaging weather change with time?

Dave.Turner@noaa.gov

Questions?