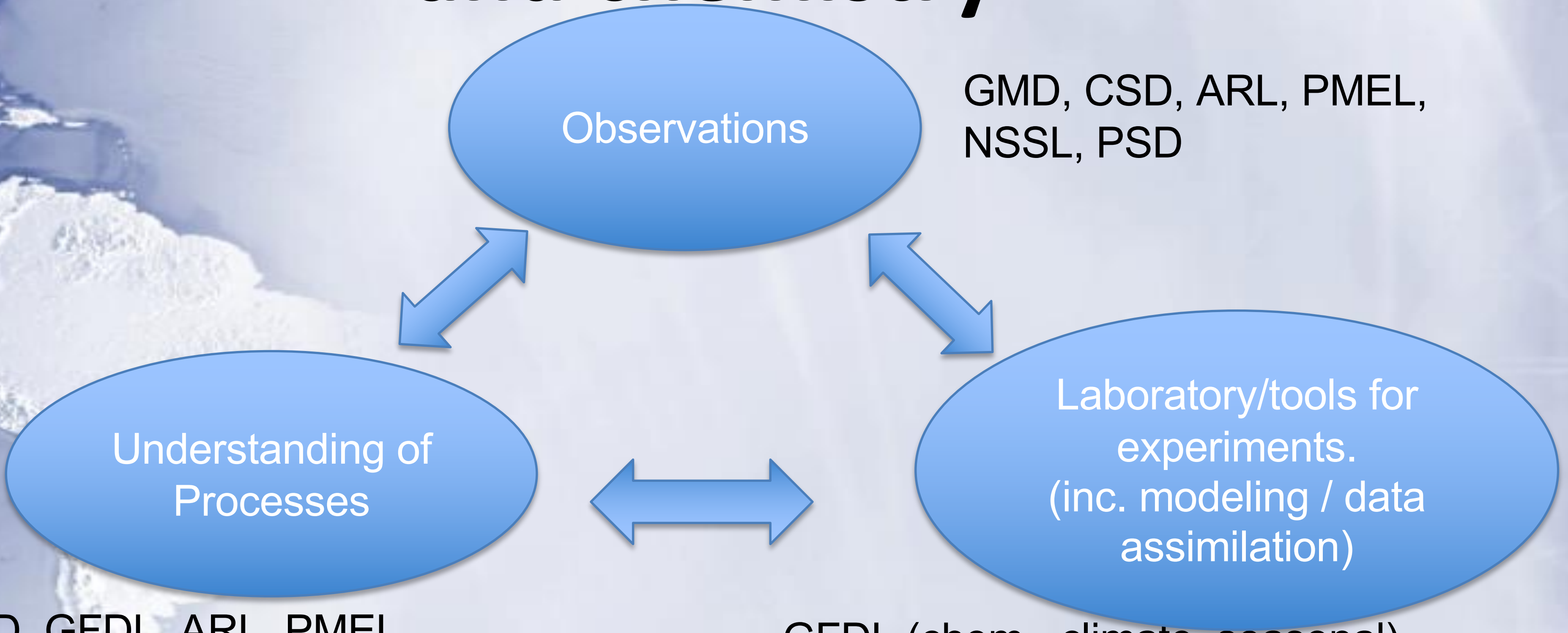
17th JCSDA Technical Review
and Science Workshop
on Satellite Data Assimilation
29-31 May 2019, Washington, DC

NOAA/OAR Overview and Plans on Satellite DA

Stan Benjamin
NOAA / ESRL / GSD
OAR representative for JCSDA Executive Team

Ongoing work contributions From:
ESRL/GSD -- Haidao Lin, Steve Weygandt
Ravan Ahmadov, Mariusz Pagowski
Amanda Back, Guoqing Ge, Ming Hu, Terra Ladwig
NSSL –Thomas Jones,
ESRL/PSD – Jeff Whitaker, Clara Draper,
Phil Pegion, Anna Shlyaeva

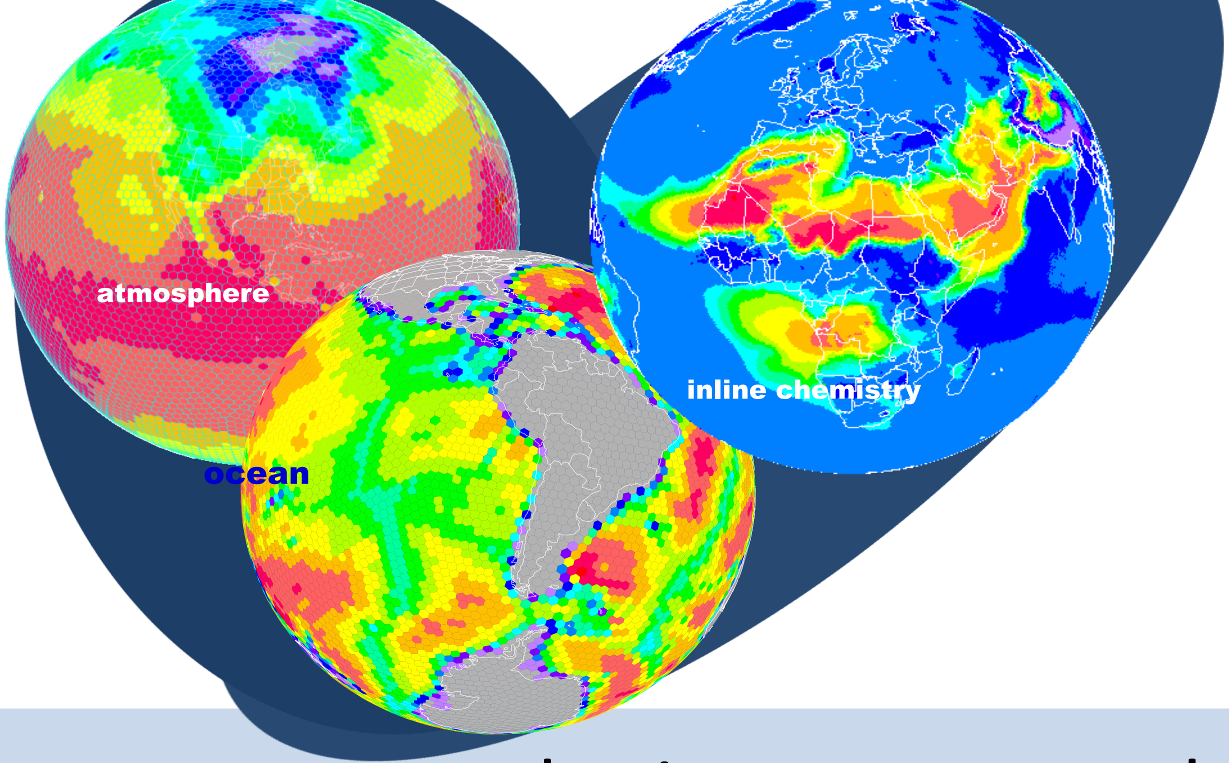
Earth-system science components - OAR contributions to atmospheric composition and chemistry



GMD, CSD, ARL, PMEL, NSSL, PSD

GMD, CSD, GFDL, ARL, PMEL, *PBL – land/ocean* - PSD, GSD, GFDL, ARL)

GFDL (chem - climate, seasonal),
GSD (chem - NWP, subseasonal), PSD, ARL
CSD – actual lab experiments



NOAA Research - Development of Earth-System Models for All Time-Scales

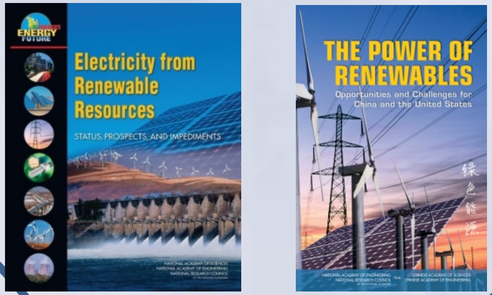
Represent atmospheric processes to land/ocean/lake/hydro models and inline chemistry (/biology)

- for global NWP to seasonal to short-range (<12h) scales
- for improved cloud/precipitation/air-quality forecasts for aviation, energy, transportation, health, and severe weather applications.

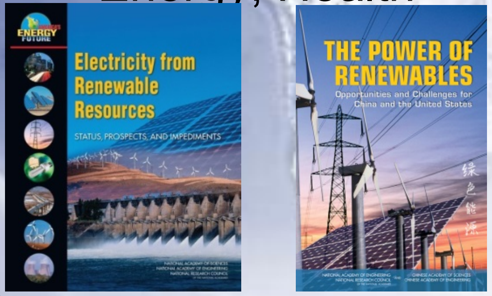
Supporting Society's Decisions

Inform Climate Intervention Decisions

Support Development of Renewable Energy Options



Support Daily Decision-Making on Aviation, Severe Weather, Energy, Health



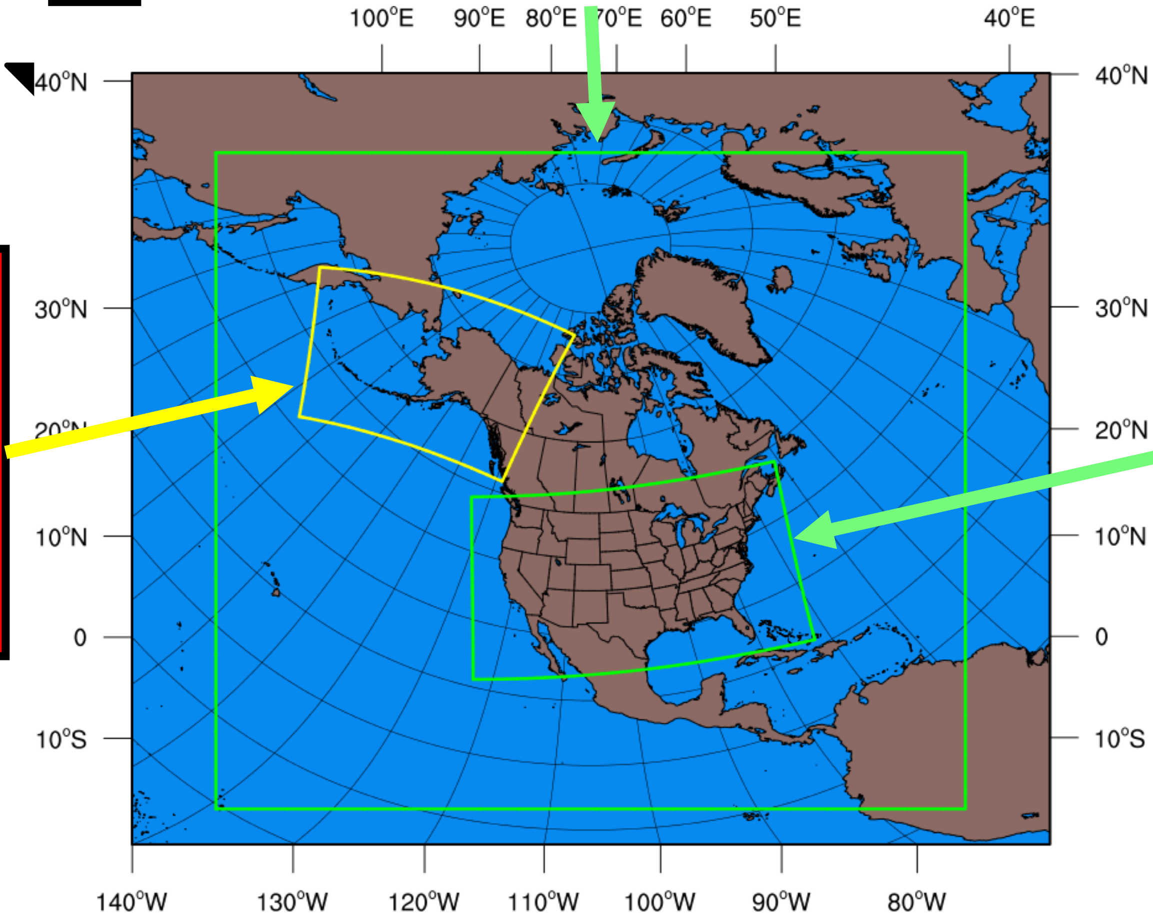
Evaluate Success of Greenhouse Gas and Particulate Emissions Reductions

RAP/HRRR: Hourly-Updating Weather Forecast Suite - July 2018 NOAA/NCEP upgrade

13-km Rapid Refresh (RAPv4) – to 39h (July 2018)

Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh Alaska (HRRR-AK) 36 hr (July 2018)



Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRRv3) – to 36h (July 2018)

- More accurate
- Runs longer (out to 36h)
- Alaska domain added

NOAA
Research
- GSI / DA

2020 RAPv5/HRRRv4 Change Candidates

Data Assimilation	Model	Land-surface / post
Merged with GSI trunk – 2019 ***New Observations for assimilation:*** **GOES-16 radiances,** **new channels for CrIS/ATMS** **TC vitals for trop cyclone location/ strength** **Aircraft/raob moisture obs for p<300 hPa** **VIIRS/MODIS fire radiative power** ***Assimilation Methods:*** **HRRR - 3km ensemble DA (36 mems out to 1h)** **HRRRDAS mean for HRRR IC and BEC**	**WRF-ARWv3.9+ incl. phys changes** ***Physics changes:*** **MYNN PBL update – better sub-grid clouds, improved EDMF mixing** **- remove limit for subgrid qc/qi** **- decrease subgrid qc/qi radii** **RRTMG modifications for subgrid clouds** **Aerosols sources/sinks – fire/smoke, dust - Add smoke with VIIRS FRP** **Improved land-surface/snow model including better 2m T/Td diagnostics** **Latest Grell-Freitas conv (RAP only)** **Lake model for small lakes** **Enhanced gravity-wave drag** ***Numerics changes:*** **Reduced 6th order diffusion inc. hydrometeors** **Removal of mp_tend_lim** **Explicit-Implicit vertical advection**	**Switch to MODIS albedo (higher), replace 1-deg albedo.** **Add zenith-ang albedo adjustment** **15” resolution land-use data** **Fractional sea/lake ice concentration** **FVCOM data for Great Lakes lake temp/ice concentration** **VIIRS/MODIS/GOES fire radiative power**

NOAA Research - GSI / DA

2020 RAPv5/HRRRv4 Change Candidates
Satellite-related

Data Assimilation	Model	Land-surface / post
Merged with GSI trunk – 2019 ***New Observations for assimilation:*** GOES-16 radiances, new full-res channels for CrIS/ATMS TC vitals for trop cyclone location/ strength Aircraft/raob moisture obs for p<300 hPa VIIRS/MODIS fire radiative power ***Assimilation Methods:*** HRRR - 3km ensemble DA (36 mems out to 1h) HRRRDAS mean for HRRR IC and BEC	WRF-ARWv3.9+ incl. phys changes ***Physics changes:*** MYNN PBL update – better sub-grid clouds, improved EDMF mixing - remove limit for subgrid qc/qi - decrease subgrid qc/qi radii RRTMG modifications for subgrid clouds Aerosols sources/sinks – fire/smoke, dust - Add smoke with VIIRS/MODIS FRP Improved land-surface/snow model including better 2m T/Td diagnostics Latest Grell-Freitas conv (RAP only) Lake model for small lakes Enhanced gravity-wave drag ***Numerics changes:*** Reduced 6th order diffusion inc. hydrometeors Removal of mp_tend_lim Explicit-Implicit vertical advection	Switch to MODIS albedo (higher), replace 1-deg albedo. Add zenith-ang albedo adjustment 15” resolution land-use data Fractional sea/lake ice concentration FVCOM data for Great Lakes lake temp/ice concentration VIIRS/MODIS/GOES fire radiative power 2018 – VIIRS greenness veg fraction added to HRRR and RAP

OAR Research efforts

ESRL PSD – global hybrid DA/GSI for NGGPS/FV3
ESRL GSD – Focus on high-frequency assimilation for short-range forecasts of high impact weather

-- Major radiance assimilation upgrade in RAPv5 (in 2020) (add N20 CrIS-FSR, N20 ATMS, GOES-16 ABI water vapor channels, include more direct broadcast data)
-- Use new VIIRS greenness fraction (also in RAPv4)
-- Aerosol DA - VIIRS fire radiative power- HRRR-chem-smoke
-- Cloud analysis: proxy water vapor innovations from GOES, METARs
-- Cloud-top cooling rate assimilation
-- Improved DA of GOES water vapor channels (NSSL)
-- Improved assimilation of cloud water path (NSSL)
-- OSE/OSSE of sat data, especially GPS-RO (AOML/GOSA)
-- Testing impact of AMVs

Candidates of Radiance Updates for RAPv5 (indirectly benefitting HRRRv4)

- Includes new sensors/data
  - ABI infrared data from GOES-16 (3 channels)
  - CrIS-FSR data from S-NPP (72 channels) (and removes CrIS-NSR from S-NPP
    - NSR = normal spectral resolution
    - FSR = full spectral resolution
  - CrIS-FSR data from NOAA-20 (72 channels)
  - ATMS data from NOAA-20 (18 channels)
- Uses direct broadcast (DB) and RARS data from NOAA-20

Haidao Lin
1520 Thursday

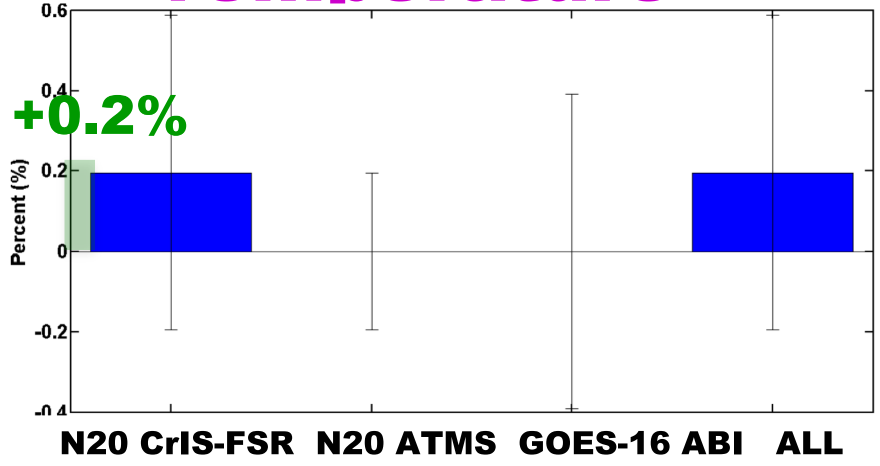
Retrospective Experiments with RAP

- **Control run (CNTL) – (All data in RAPv4)**
  - 1-h cycling run, 7-day retro run (September 09 –15 2018) using RAPv4
  - All data used in operational RAPv4 (conventional + satellite radiance data)
- **Experiment runs**
  - CNTL + NOAA-20 CrIS-FSR (72 channels)
  - CNTL + NOAA-20 ATMS (18 channels)
  - CNTL + GOES-16 ABI (3 channels)
  - CNTL + All above new data sets (planned new radiance data sets for RAPv5)

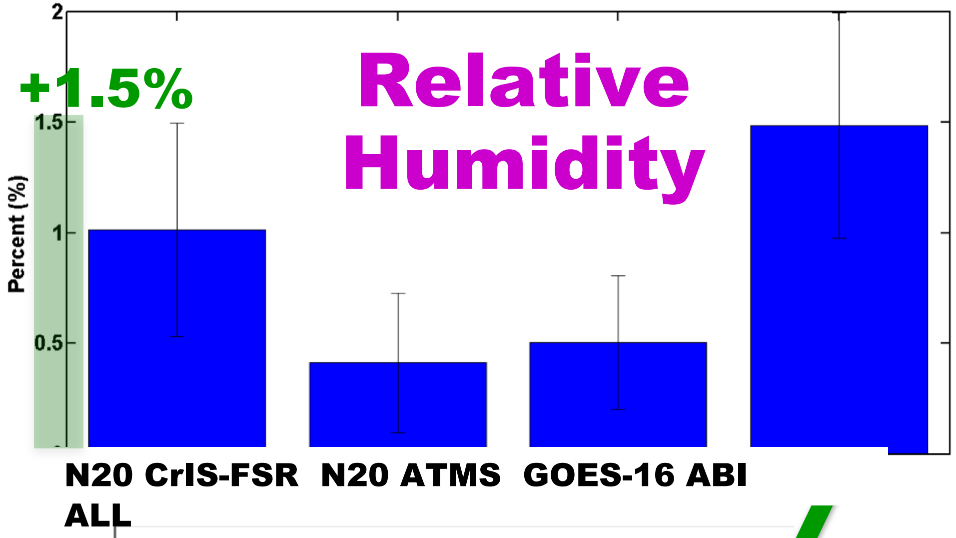
Haidao Lin
1520 Thursday

12-h fcst. Normalized Errors from New Satellite Data Sets

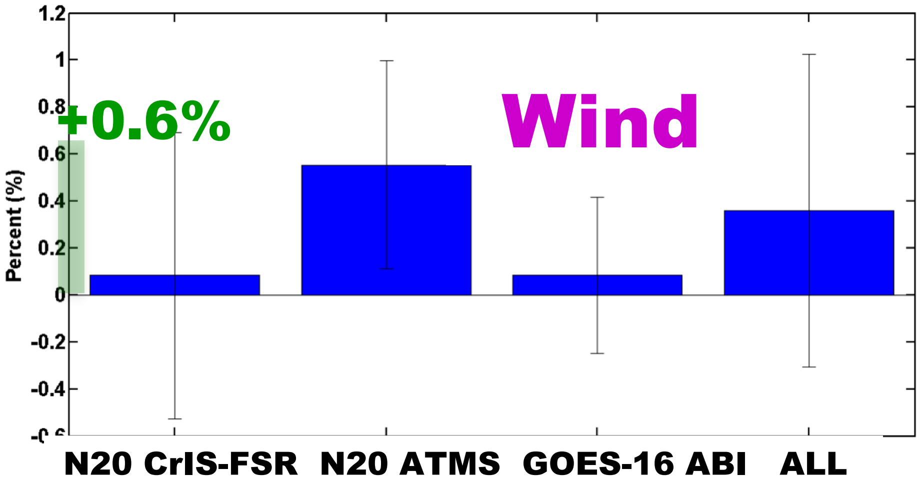
Temperature



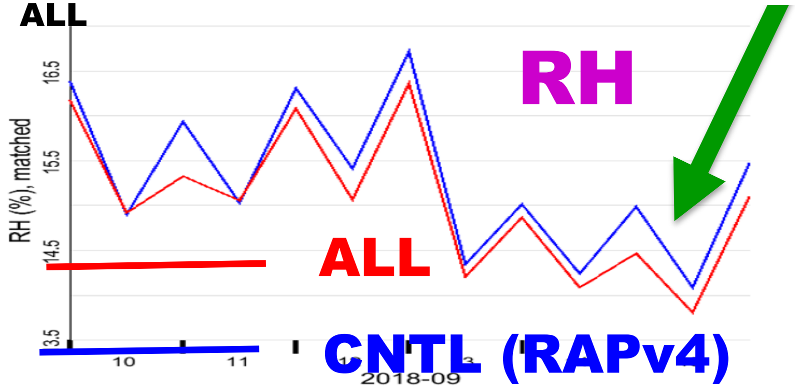
Relative Humidity



Wind



RH



Haidao Lin
1520 Thursday

Radiosonde verification

100-1000 hPa RMS mean

one-week hourly RAP retro run averaged (9-15 Sep 2018)

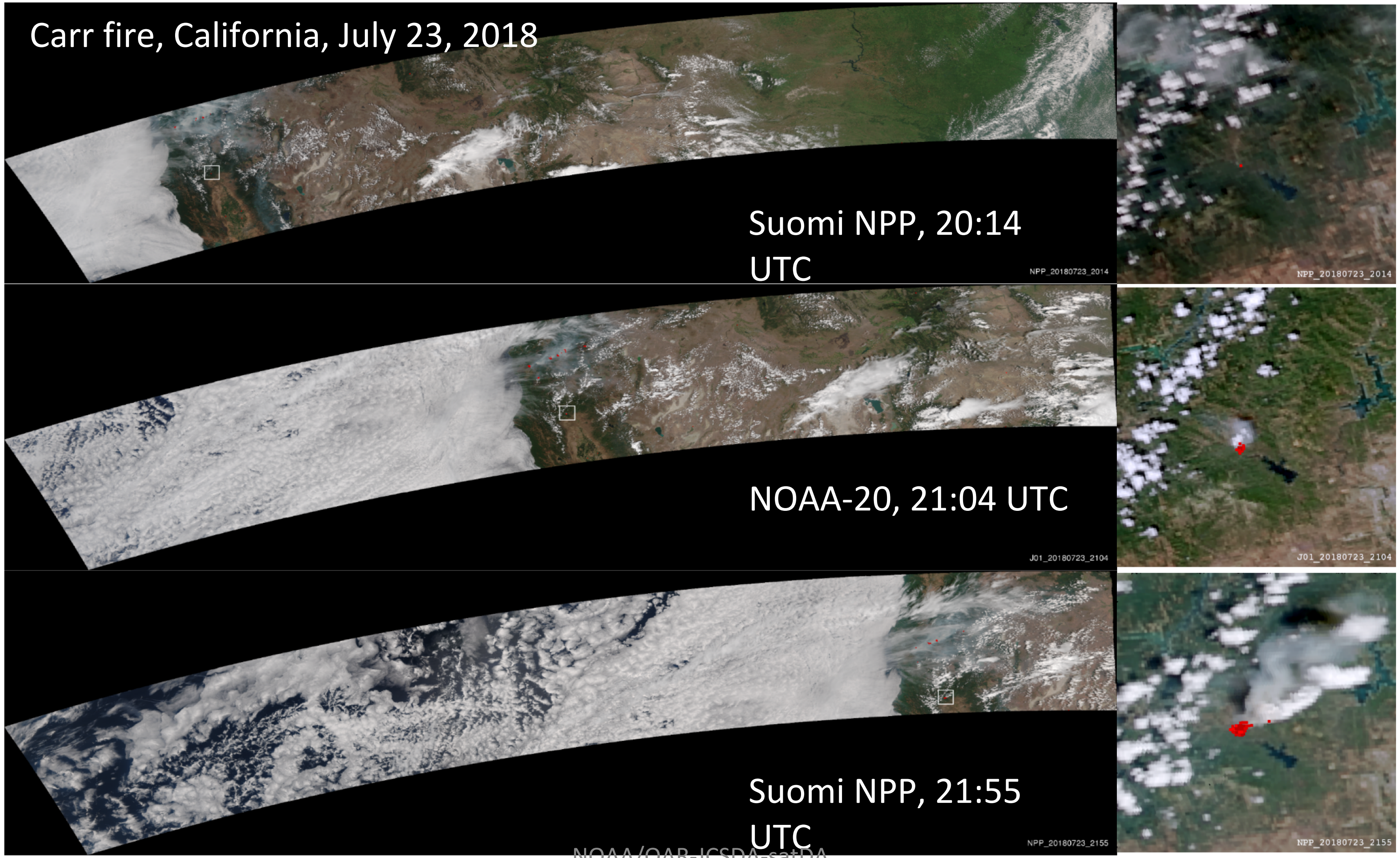
Normalized Errors

$$E_N = \frac{(CNTL - EXPT)}{CNTL}$$

Control run has all operational data in RAPv4

NOAA Research
- VIIRS/MODIS fire radiative power
- Ravan Ahmadov, Eric James

Straka W. (CIMSS)



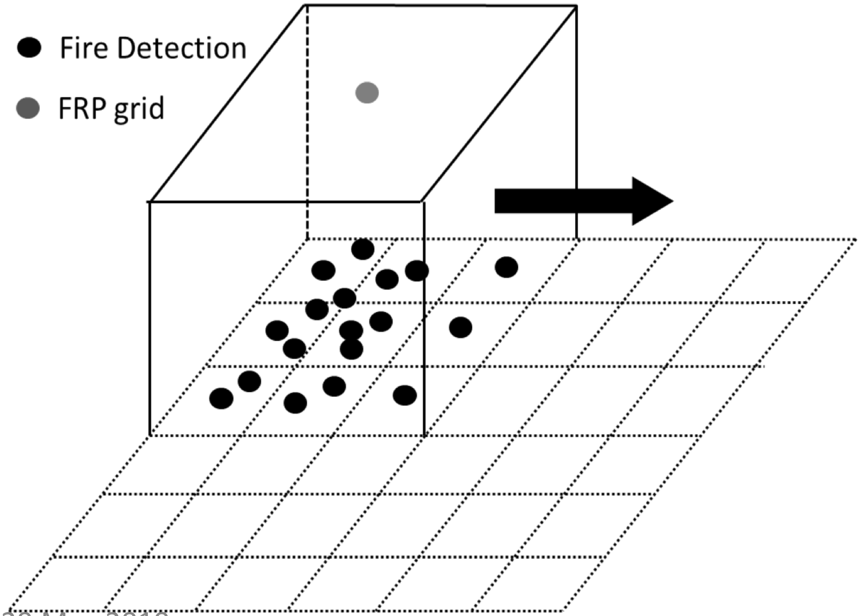
Ingesting real-time VIIRS and MODIS FRP data to the HRRR-Smoke model

The clustering procedure performs a combination of all **fire radiative power** (**FRP**) data from **VIIRS** and **MODIS** according to the model spatial resolution and grid configuration.

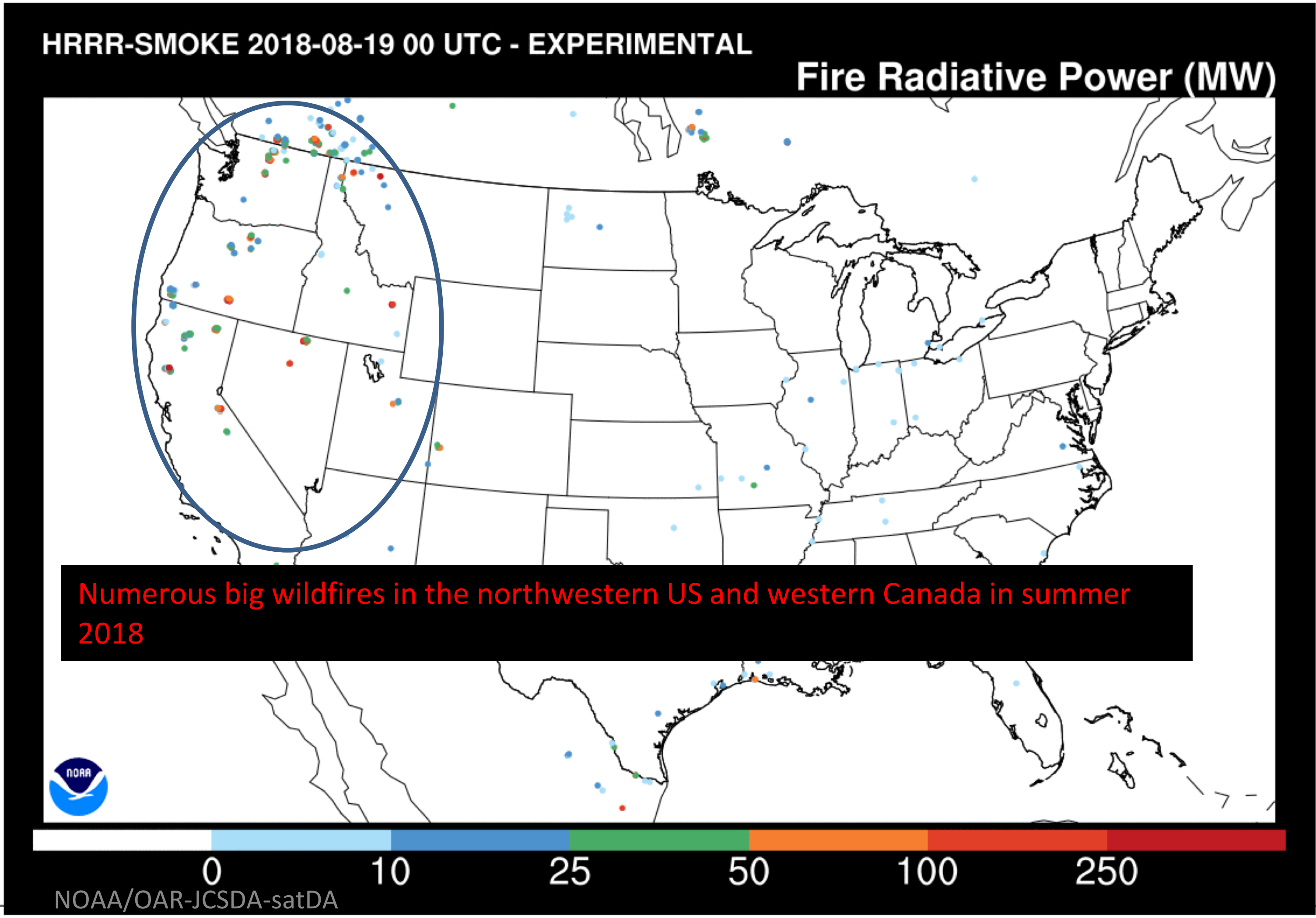
Biomass burning emissions are estimated as follows:

FRE= FRP x time (fire duration)

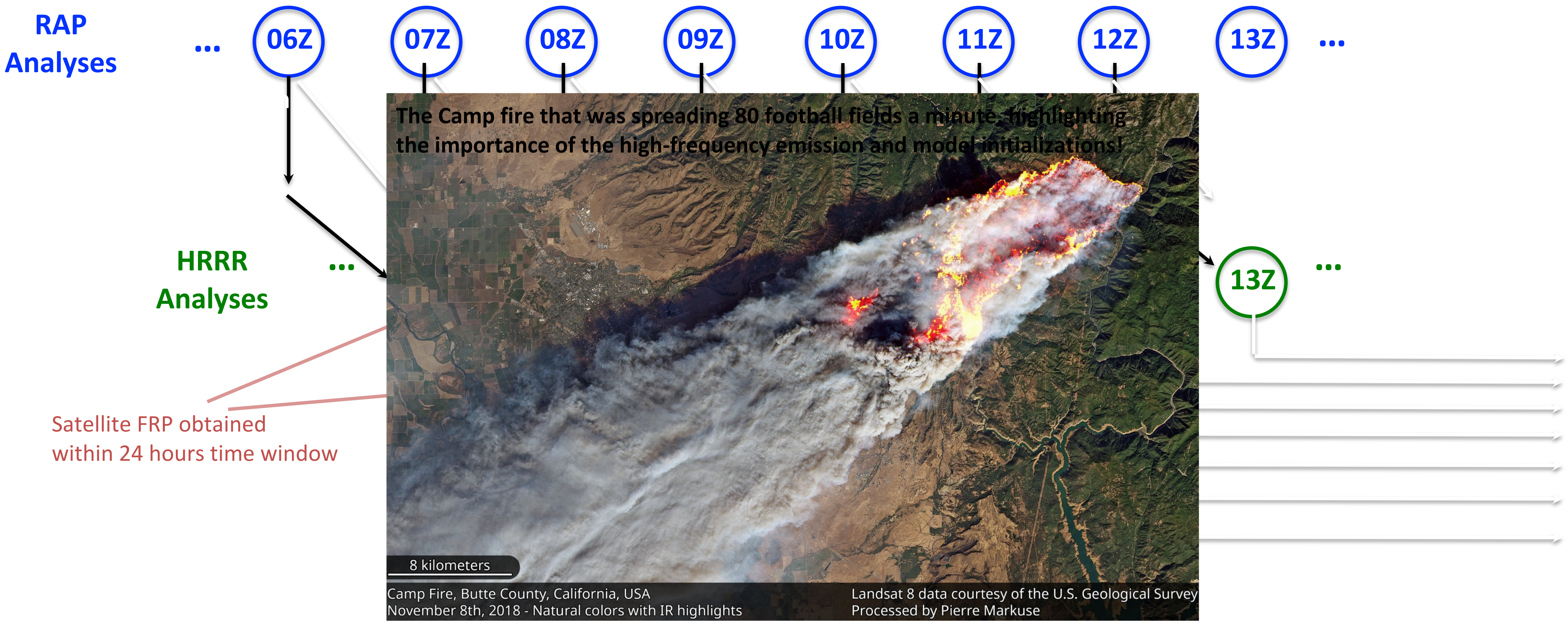
$$M^{[\epsilon]} = FRE_{grid_{(lon,lat)}} \cdot \gamma . EF^{[\epsilon]}$$



Averaged satellite FRP data (24 hours) mapped over 3x3km HRRR CONUS grid pixels for August 19, 2018



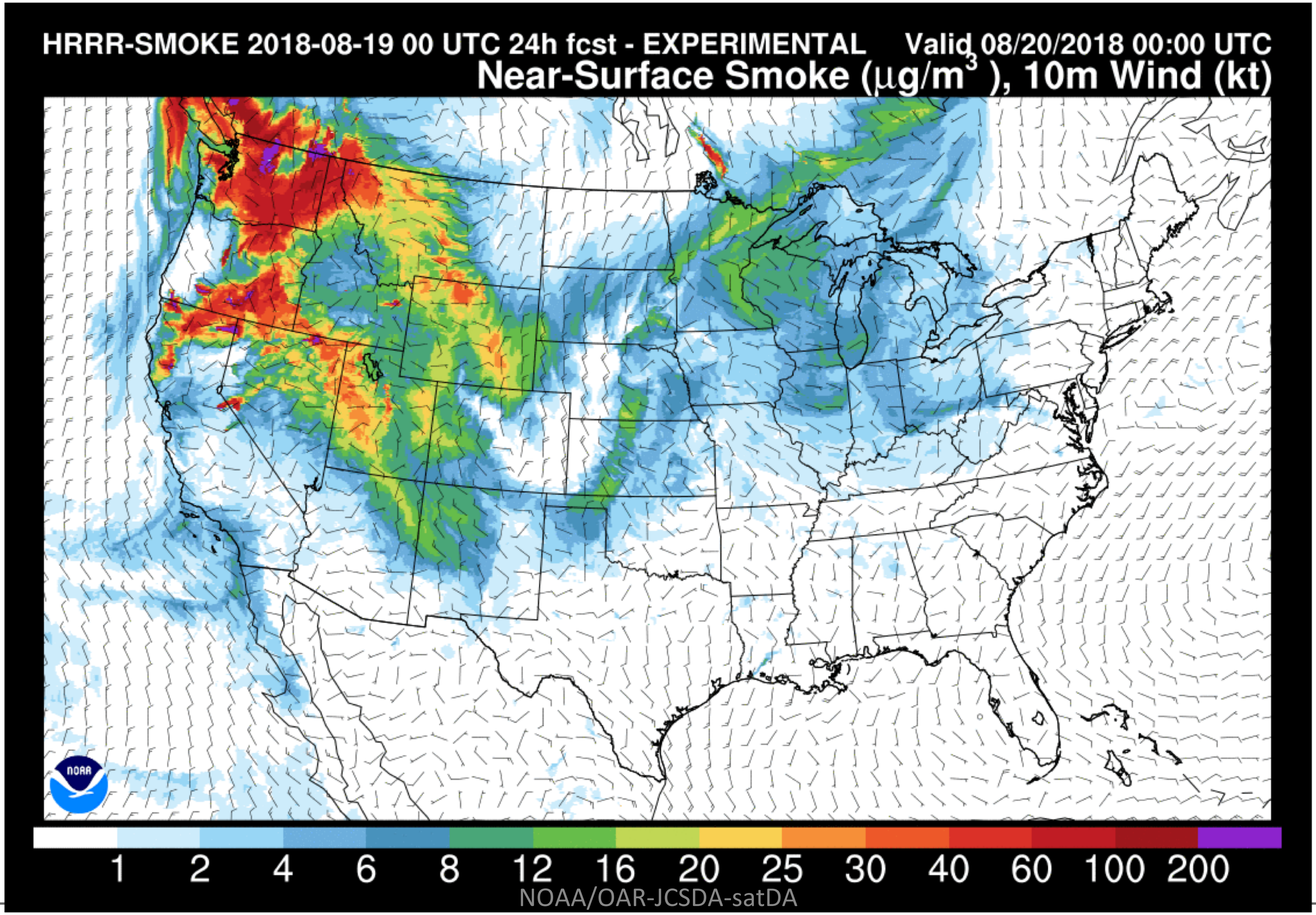
Hourly cycle of HRRR: 1-h spin-up for each forecast
New weather and smoke forecasts are produced 24 times a day



- Starting in March 2018 smoke emissions are simulated every hour for input to HRRR-Smoke. Simulated 3D smoke fields are cycled between the consecutive HRRR-Smoke forecasts.

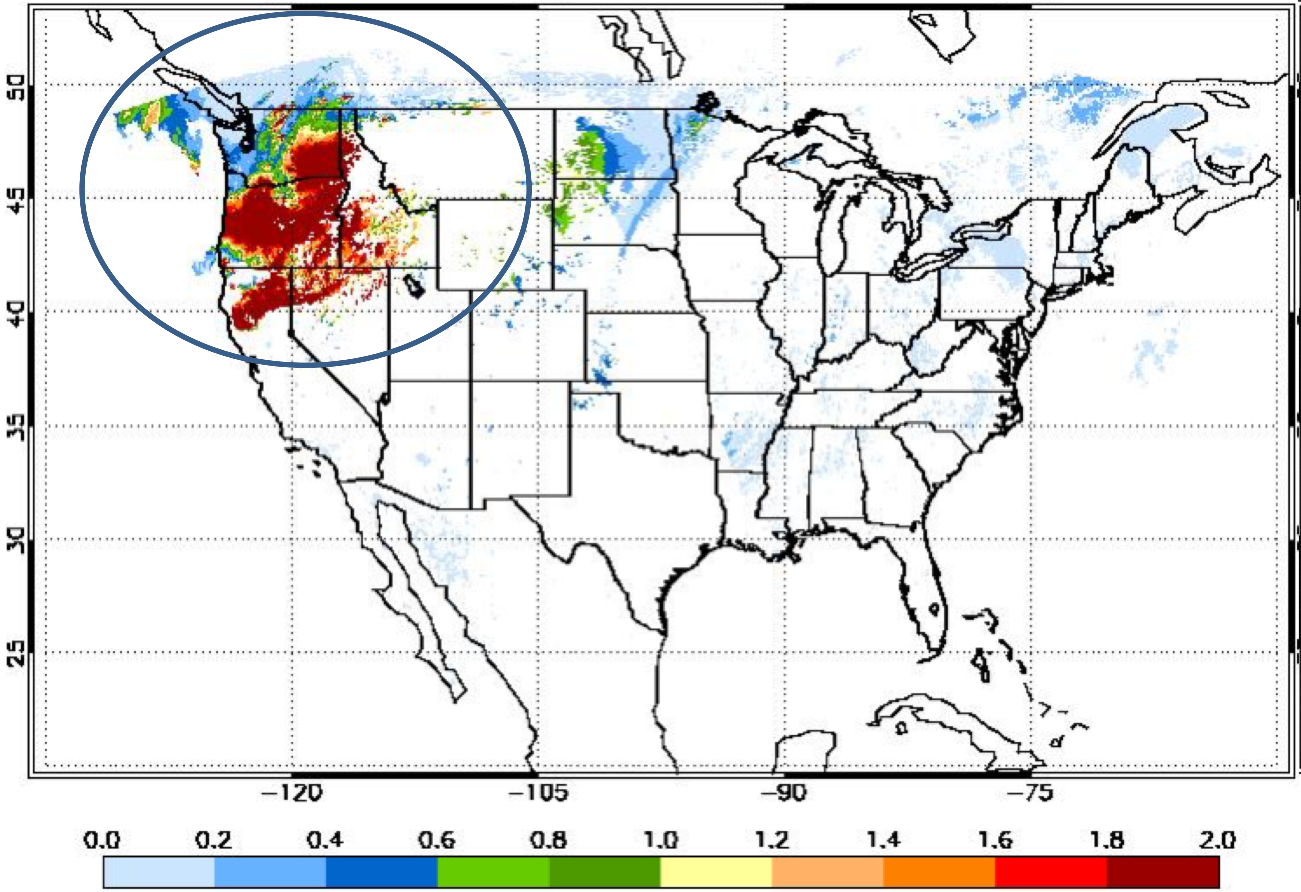
Near-surface smoke forecast for August 19, 2018 (rapidrefresh.noaa.gov/hrrr/HRRRsmoke/)

This plot shows simulated fine particulate matter (PM2.5 or fire smoke) concentrations and wind at the first model level (~8m above ground). This is the forecast of the near-surface fire smoke for August 19, 6pm EDT over the CONUS. This forecast is based on the model simulation of 24 hours from the model initialization time, which is 6pm EDT, August 18, 2018.

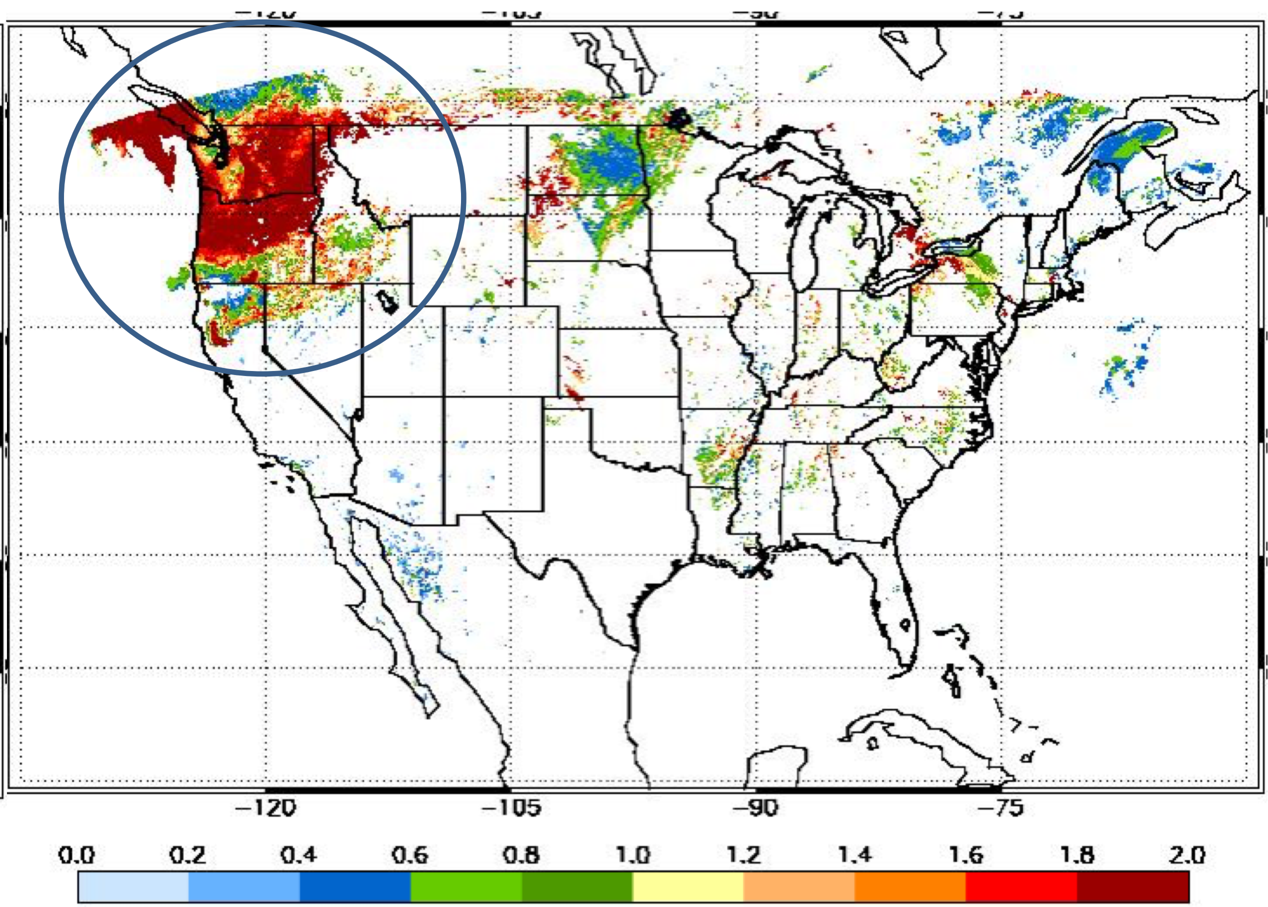


Forecast verification using the VIIRS AOD data, 20 August 2018

HRRR-Smoke AOD



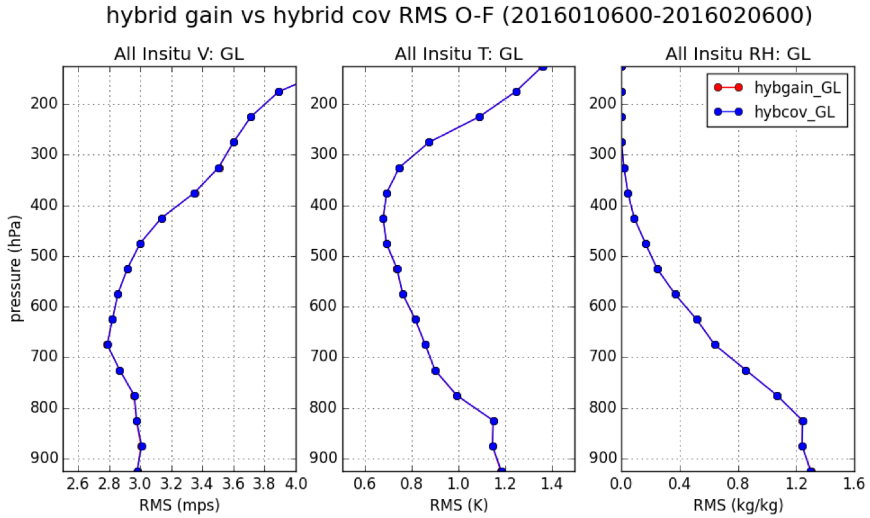
VIIRS satellite AOD x smoke mask



HRRR/RAP-Smoke does NOT assimilate any AOD data (yet).
The model does NOT simulate the aerosol composition, aging and hygroscopicity.
The model does NOT include anthropogenic aerosols and dust.

NOAA/ESRL / PSD

Jeff Whitaker, Phil Pegion, Tom Hamill,
Clara Draper, Anna Shlyaeva



1) added 4D-IAU capability and linearized H for EnKF to EMC rocoto-based workflow. (Anna, Clara, Jeff)

2) tested hybrid-gain 3DVar/EnKF approach as a alternative to hybrid 4DEnVar (a ppt slide and plot attached- bottom line is that they perform identically). (Jeff)

3) work underway with EMC to prepare for L127 upgrade (new static **B** based on EnKF ensemble, tuning stochastic physics and sponge layer) (Jeff)

4) improvements in representation of land-surface uncertainty in EnKF ensemble in preparation for coupled atmos/land update (Clara, Phil)

5) FV3GFS GEFS reanalysis for GEFS v12 from 2000-19 to be completed by end of FY19 (C384 control, C128 ensemble, hybrid 4DEnVar with 80-mem ensemble) (Tom, me, Anna)

Hybrid Gain vs Hybrid Covariance DA for FV3GFS

- Hybrid Covariance DA (a.k.a. hybrid 4DEnVar)
  - $\alpha \mathbf{B}^{3DVar} + \beta \mathbf{B}^{EnKF}$ (α = 0.125, β = 0.875 in current system).
  - Single solution obtained iteratively with separate terms in cost function.
- Hybrid Gain DA
  - $\mathbf{x}^a - \mathbf{x}^b = \mathbf{\Delta x} = \alpha \mathbf{\Delta x}^{3DVar} + \beta \mathbf{\Delta x}^{EnKF}$ (equivalent to blending Kalman gains, Penny 2014 Appendix B)
  - Compute 3DVar and EnKF increments separately, blend them and add to background.
  - Why bother?
    - Faster, since $\mathbf{\Delta x}^{3DVar}$ is faster to compute than hybrid 4DEnVar increment.
    - Unlike hybrid 4DEnVar, uses EnKF to update mean (not just perturbations). Useful for testing improvements to EnKF solver.

UFS Convection-Allowing Model - Background

The goals and work plan for this project are aligned precisely with the Unified Forecast System (UFS) Strategic Implementation Plan (SIP) Convection Allowing Model (CAM) annex.

Color codes in the three elements of the work plan below correspond to those in Annex 7: Convection-Allowing Models.

CAM timeline FY19-21

	FY19				FY20				FY21			
Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

RAPv5/HRRRv4 (FY18 Q4 – FY19 Q3)
- Assimilation of radar, satellite, and other high-resolution obs using storm-scale ensemble DA
- Improvements to model physics

Deliverables: RAPv5/HRRRv4 (FY19 Q2 – FY20 Q2)
- Deliver RAPv5/HRRRv4 to NCO
- Assistance for EMC/NCO in parallel
- Evaluation of RAPv5/HRRRv4 using community assessment (MEG and testbeds)
- EBD: RAPv5/HRRRv4 operational?

HRRRv4 Development & Handoff (FY21)

Meso/CAM Transition to FV3 (FY18 Q4 – FY20 Q2)
- SAR tests/infrastructure/CCPP physics
- FV3-RAP replacement for RAP/NAM/SREF
- HREF: Replacing NMMB members
- Tests of ensemble DA using SAR-FV3

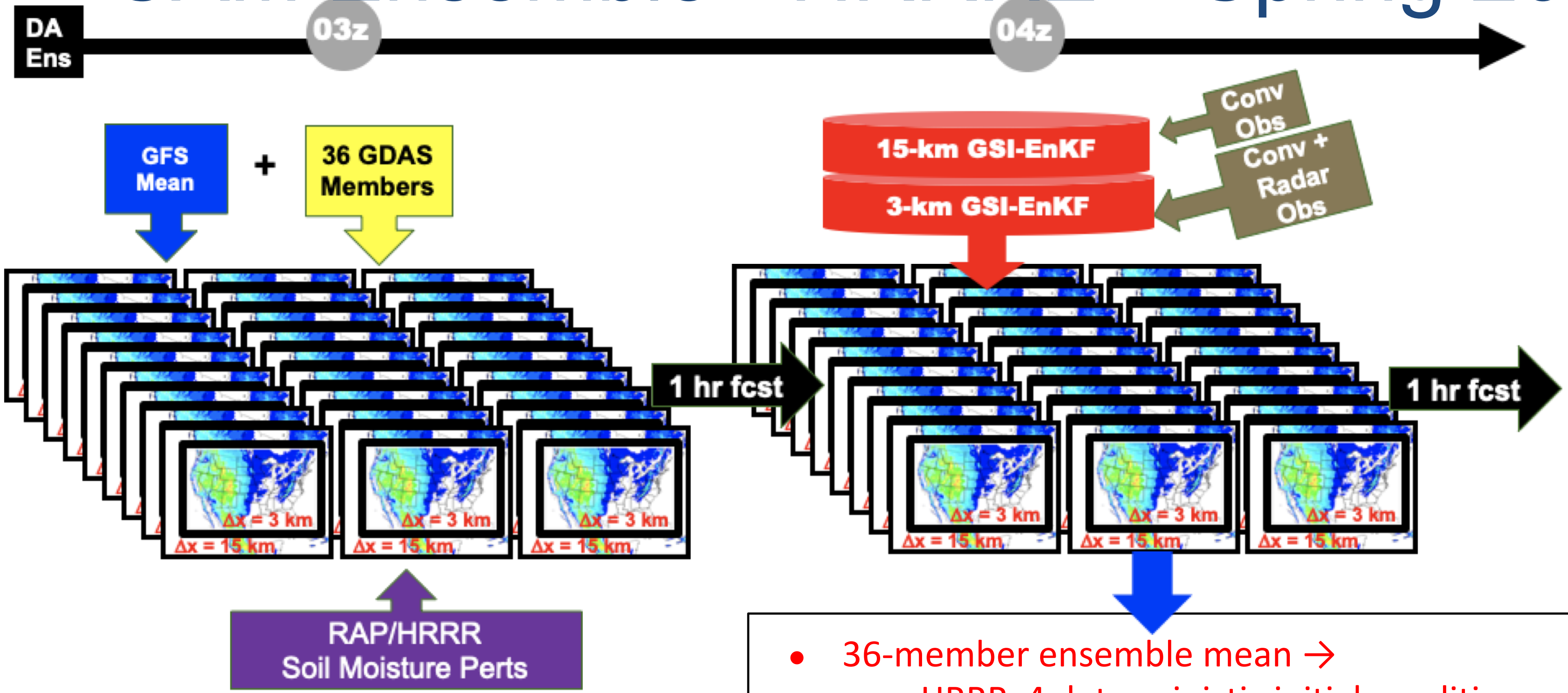
SAR-FV3 Development/Testing for Meso/CAM (FY21)

Milestones for Meso/CAM Transition (FY19 Q3 – FY20 Q4)
- Complete CCPP port of HRRR physics
- Complete development of FV3 RAP
- Evaluation of deterministic FV3 MESO & CAM to current RAP and HREF members using community assessment (MEG and testbeds)
- EBD: HREF member(s) replacement by SAR?
- EBD: RAP/NAM replacement by SAR?

RRFS Development (FY18 Q4 – FY19 Q3)

FV3 CAM ensemble with DA (FY20 Q3 – FY21 Q4)
- Demonstration of ensemble analysis and forecast system using SAR FV3 and JEDI
- Demonstration of experimental WoF system using SAR FV3 and JEDI
- Development of stochastic physics for single core
- Community assessment (MEG and testbeds)

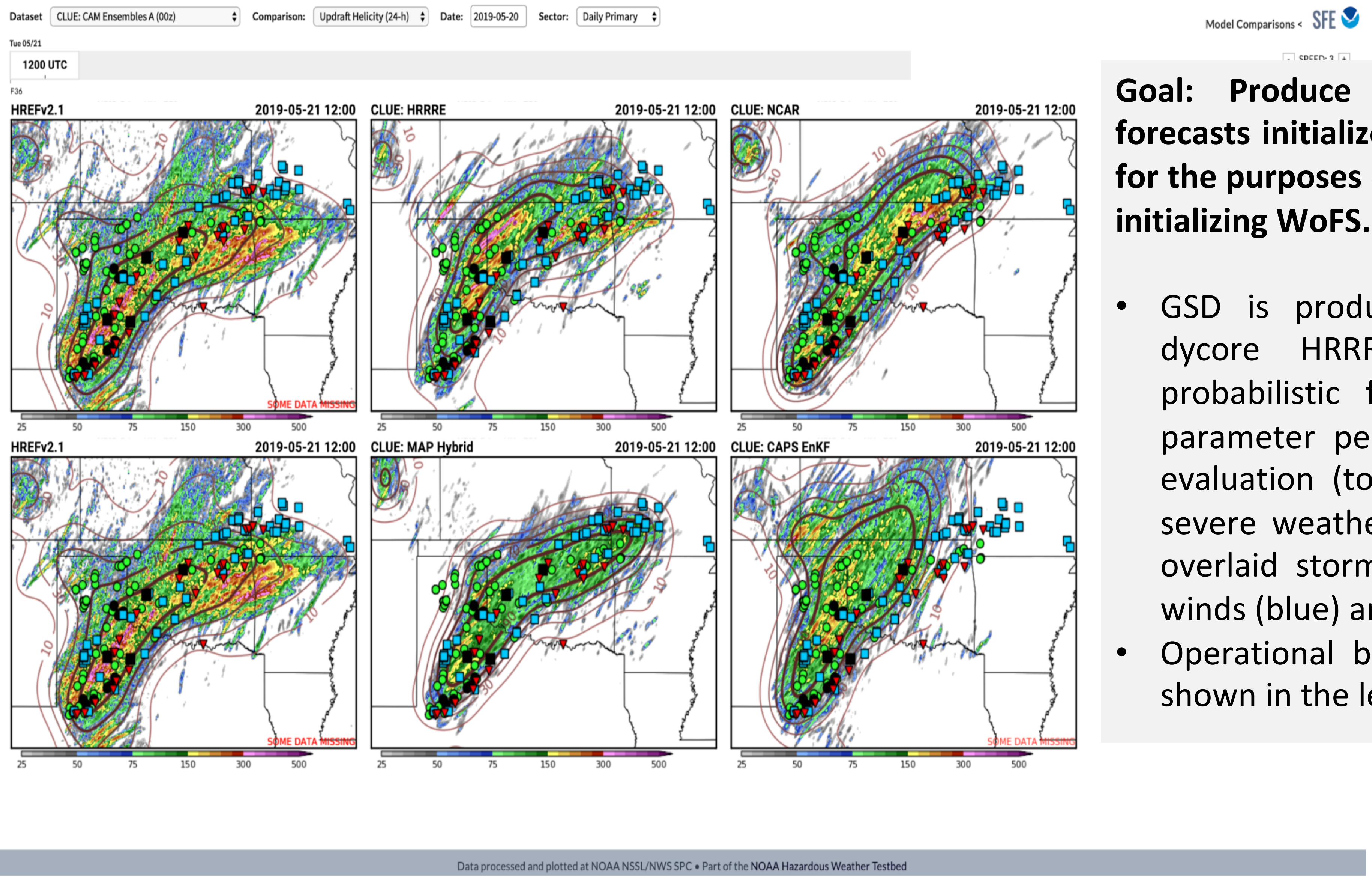
CAM Ensemble - HRRRE – Spring 2019



- 36-member ensemble mean →
  HRRRv4 deterministic initial condition
- 36-member background error covariance →
  HRRRv4 deterministic hybrid analysis
- 9-member HRRRE ensemble forecast (0-36hrs) →
  Single-model CAM ensemble (w/SPP physics)
- 9-member HRRRE lateral boundaries for WoFS
- 36-member HRRRE initial condition for WoFS

HRRR = 3km High-Res Rapid Refresh
WoFS = Warn-On Forecast System

CAM Ensemble - HRRRE – Spring 2019



Goal: Produce real-time, 9-member ensemble forecasts initialized from HRRRDAS during testbeds, for the purposes of getting community feedback and initializing WoFS.

- GSD is producing real-time 9-member single-dycore HRRR ensemble (HRRRE) 0-36 hr probabilistic forecasts using stochastic physics parameter perturbations as shown in the HWT evaluation (top-middle panel) for a high-impact severe weather period on 20-21 May 2019 with overlaid storm-reports of tornadoes (red), high-winds (blue) and hail (green).
- Operational baseline CAM ensemble (HREFv2.1) shown in the left column.

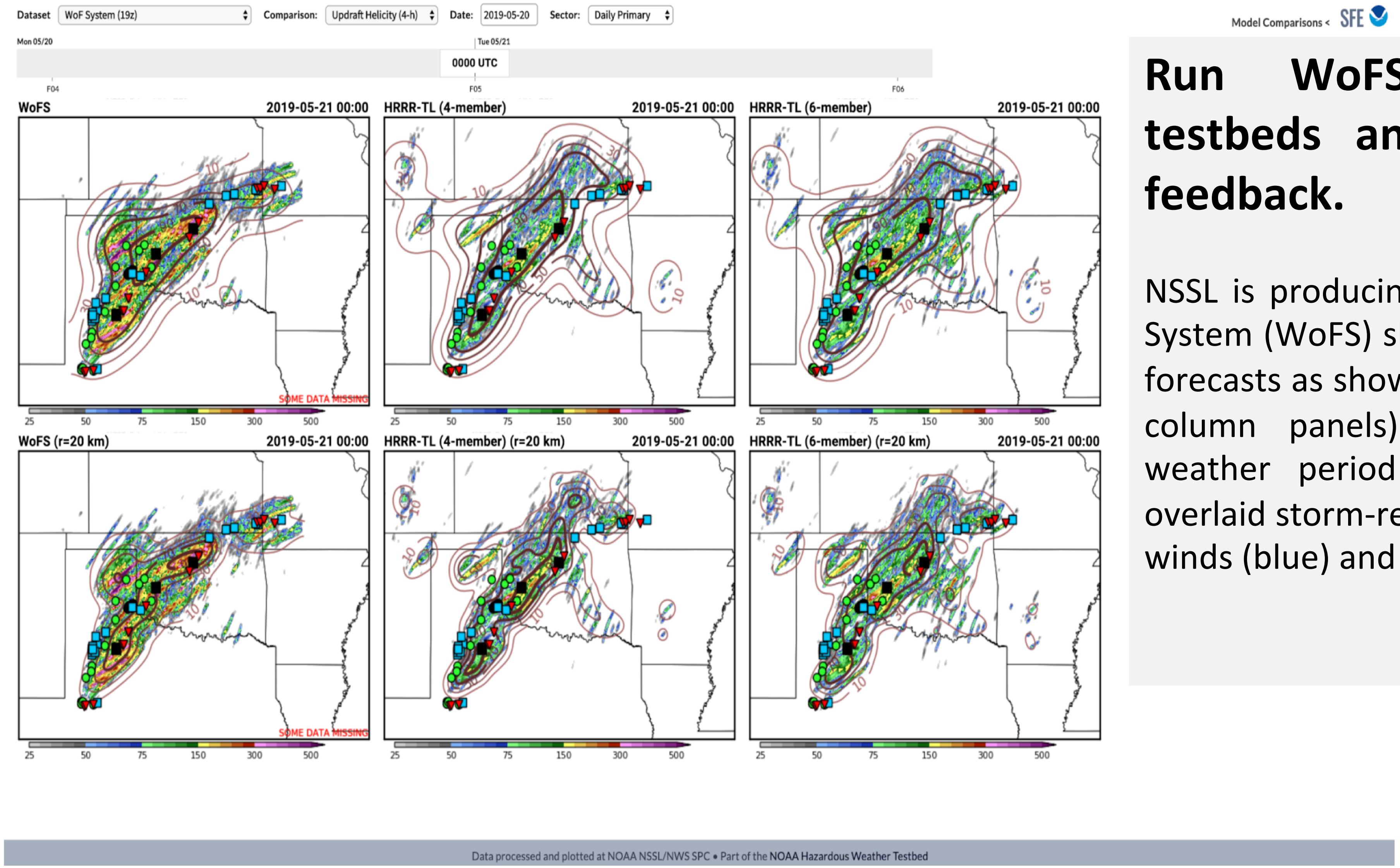
Warn-on Forecast (WoF) Satellite Data Assimilation

NOAA Research - GSI / DA

Thomas Jones - NSSL

- **Warn-on-Forecast System:** https://wof.nssl.noaa.gov/
  - Convection-permitting ensemble data assimilation system with a horizontal resolution of 3 km and cycled at 15 minute intervals with ensemble 0-3 hour forecasts initiated at 30 min intervals
  - Assimilates conventional observations, radar reflectivity & radial velocity, GOES-16 satellite data
- **Satellite Data:**
  - **Cloud water path (CWP):** CWP retrievals have been assimilated into WoFS since 2015 with GOES-16 replacing GOES-13 in 2018
    - Consistent improvement in reflectivity and updraft helicity forecasts by improving CI and cloud analyses
  - **Atmos Motion Vectors (AMVs)**: High-res GOES-16 AMV retrievals currently assimilated in 2019
    - Retrospective experiments indicate modest forecast improvements near boundaries
    - Very strict QC currently being used, but initial tests relaxing these thresholds have generally given positive results. Will change over this summer
  - **Clear-sky water vapor radiances**: 6.2 um water vapor channel assimilated in real-time during summer 2018 experiment
    - No negative impacts seen, but positive impacts were also small
    - Retrospective testing of 6.2 and 7.3 um channels is underway and recent modifications to the system have improved the results. Changes will be implemented this summer
  - **All-sky water vapor radiances:**
    - Initial testing being performed, but early results are not positive
    - Some improvement seen in CI forecasts, but a high cloud bias develops afterward leading to model instability after a few hours of assimilation. (No CWP in these tests)

Warn-on Forecast demo - Spring 2019



Model Comparisons < SFE

Run WoFS (NEWS-e) during testbeds and obtain community feedback.

NSSL is producing real-time Warn-On-Forecast System (WoFS) short-term (0-6 hr) probabilistic forecasts as shown in the HWT evaluation (left-column panels) for a high-impact severe weather period on 20-21 May 2019 with overlaid storm-reports of tornadoes (red), high-winds (blue) and hail (green).

Lightning detection into HRRR

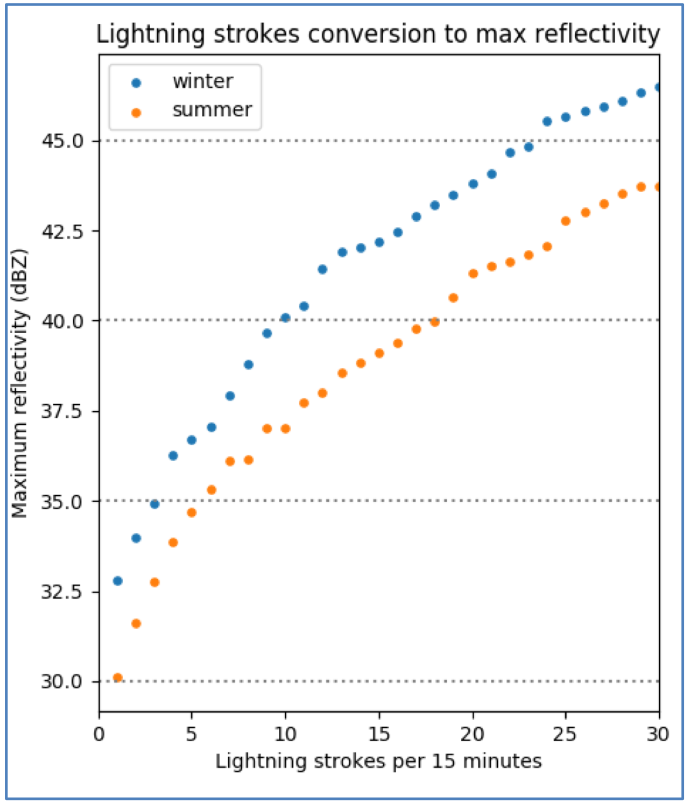
HRRR/RAP currently assimilates cloud-to-ground lightning strokes from Vaisala's GLD360 and NLDN ground-based networks

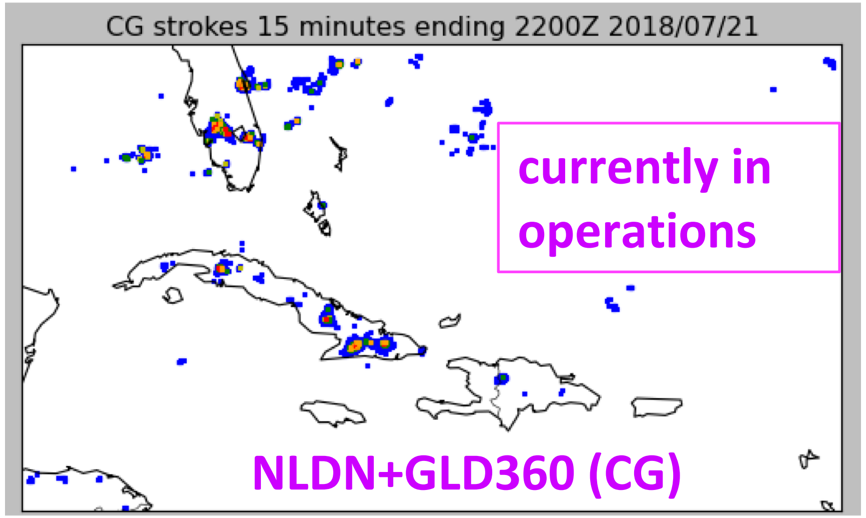
Via empirical model, strokes converted to season-dependent reflectivity profile

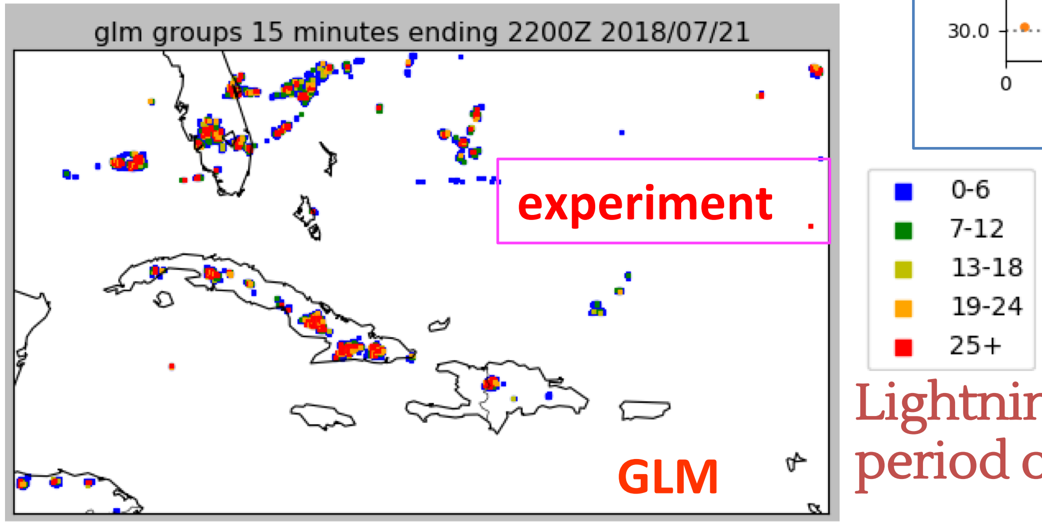
Max of co-located lightning-derived reflectivity and MRMS reflectivity taken for conversion to LH

Groups are GLM (GOES satellite) equivalent of strokes, include in-cloud

In the Caribbean, expect (and find) greater density of GLM due to both IC inclusion and better coverage away from land

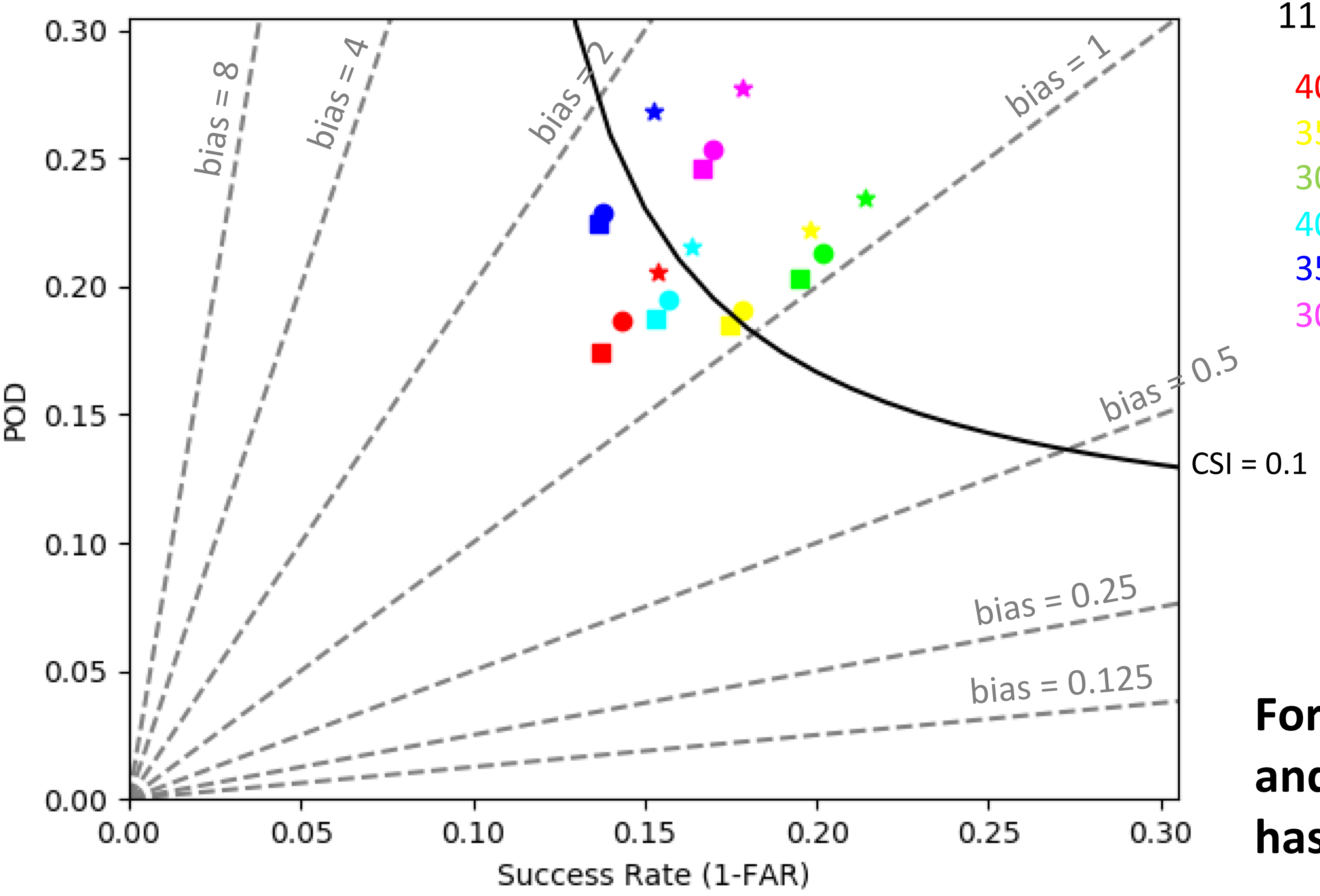






Lightning obs density in 15-min period on HRRR-CAR grid

Verification of 1-hour forecasts (11-day test)



11 runs averaged skill

40 dBZ CREF vs Brightness Temp

35 dBZ CREF vs Brightness Temp

30 dBZ CREF vs Brightness Temp

40 dBZ CREF vs GLM groups

35 dBZ CREF vs GLM groups

30 dBZ CREF vs GLM groups

GLM assim ★

CG assim ●

No lightning ■

For each verification data type and threshold, GLM ingest run has highest skill

OAR Research Plans

Continue focus of high-resolution, high-frequency assimilation for high impact weather, with emphasis on combining satellite data with radar data.   Current applications – regional domain but applicable to global high-frequency assimilation also.

Continued work on aerosol assimilation, tropical assimilation, and satellite data impact assessments (OSEs and OSSEs).

Assignment of resources toward JEDI – UFO testing, computer science optimization expertise

JCSDA effort to more fully integrate our research efforts and make sure they are well-coordinated with R2O efforts within NOAA

Upcoming talks -

- Thu   1520 – Haidao Lin – 2020 RAP sat rad DA including GOES-ABI, ATMS, S-NPP variation

NOAA/OAR: Areas of expertise and mission relative to DA

- **Global ensemble assimilation** (PSD - Whitaker, Pegion, Shlyaeva)
- **JEDI, software design for NWP and DA** (GSD - Govett and team, Hu)
- **Cloud/radar assimilation** (GSD - Dowell, Ge, Hu, Ladwig, H. Wang
  NSSL – Gao, Wicker, X. Wang (OU))
  - Examples: HRRRE 3km hourly/15km ensemble DA, WoF ens DA,
    Ens / Var cloud analysis, Global cloud analysis work
- **Lightning (Geostationary Lightning Mapper** – GLM, add to NLDN) – GSD - Hu, Back, Ge
- **Hurricane-specific DA** (AOML – Sipple, Aksoy)
- **Surface/soil assimilation** (PSD – Draper, GSD - Hu, Benjamin, Smirnova)
- **Aerosol DA** (GSD – Pagowski)
- **Nowcasting – 3d RTMA** (GSD - Hu, Ge, Alexander, Benj, Weyg; NSSL – Gao, MRMS group)
- **Radio occultation assimilation** (AOML - Cucurull)
- **Satellite product assimilation** (NSSL - Jones, GSD – Back, Weygandt)
- **Satellite radiance assimilation** (GSD – Lin, Weygandt)
- **OSE** (GSD - James, Benjamin), **OSSE (**AOML - Cucurull)
- **Ocean/climate -** GFDL

Straka W. (CIMSS)

Physical definition of power:

$$Power = A\varepsilon\sigma T^4$$

A = area
T = blackbody temp
ε = emissivity
σ = Stefan-Boltzmann const

For a mixed pixel of fire and non-fire:

$$FRP_{def} = A_{sample}\varepsilon\sigma\sum_{k=1}^{n} p_k T_k^4$$

Approximation using radiances:

$$FRP_{MIR} = \frac{A_{sample}\sigma}{a}(L_{MIR} - L_{B,MIR})$$

L_{MIR} 4 µm observed radiance

$L_{B,MIR}$ 4 µm calculated background radiance

A_{sample} Area of pixel

a A constant (function of instrument SR

p_k Instantaneous proportion of pixel on fire

$$Mass\ consumed \propto F$$

Uncertainties associated with sat Fire Radiative Power data:

- Sensitivity to cloudiness and dense smoke
- It is a snapshot of the fire intensity, it does not provide continuous information on the evolution of a fire.
- Fires typically occupy a small fraction of the satellite pixel area. So it is hard to estimate the instantaneous fire size.
- Sensitivity to the scan angle, background radiance estimates etc.

Rapid Refresh (v4) / HRRR: Obs - Conventional

Hourly Observation Type	Variables Observed	Obs Count / Hour
Rawinsonde	Temperature, Humidity, Wind, Pressure	120 (most @00z/12z)
Profiler – 915 MHz	Wind, Virtual Temperature	20-30
Radar – VAD	Wind	125
Radar	**Radial Velocity**	**125 radars**
Radar reflectivity – CONUS	3-d refl →Rain, Snow, Graupel	1,500,000
Lightning	**(proxy reflectivity)**	**NLDN**
Aircraft (AMDAR, TAMDAR)	Wind, Temperature	2,000 -26,000
Aircraft – WVSS, TAMDAR	Humidity	100 - 3500
Surface/METAR	Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather	2800 - 3200
Surface/Mesonet	**Temperature, Moisture, Wind**	**~20/10/5K (~10K monitored)**
Buoys/ships	Wind, Pressure	200 – 400 (every 3h)
GOES AMVs	Wind	2000 - 4000
AMSU/HIRS/MHS/ATMS/CrIS **(RARS)**	Radiances	1K-10K
GOES	**Radiances**	**large**
GOES cloud-top press/temp	Cloud Top Height	100,000
GPS – Precipitable water	Humidity	350-400
WindSat Scatterometer	Winds	2,000 – 10,000