NATIONAL WEATHER SERVICE

Future Plans for NCEP Global Data Assimilation

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10th International Symposium on Data Assimilation, Kobe, Japan

Acknowledgements to GFS & UFS Active Developers

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Outline

- GFS overview
- Operational GFSv16-based upgrades
- Development of weakly-coupled GFSv17
- JEDI transition

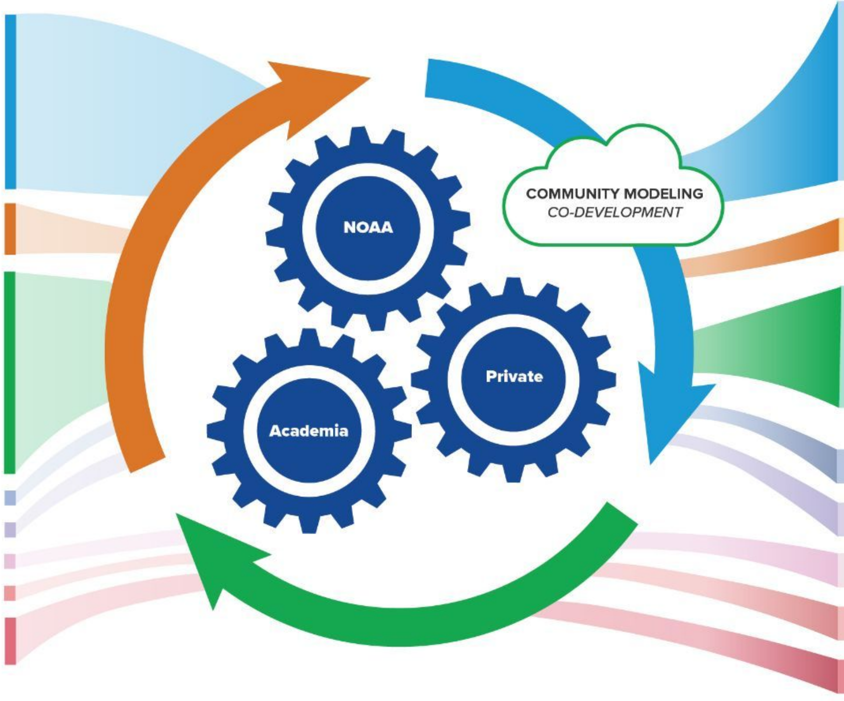
Simplifying NOAA's Operational Forecast Suite

Reducing the 21 Stand-alone Operational Forecast Systems into Eight Applications

21 Independent Stand-alone Systems

- Global Weather, Waves & Global Analysis - GFS/ GDAS
- Global Weather and Wave Ensembles, Aerosols - GEFS
- Short-Range Regional Ensembles - SREF
- Global Ocean & Sea-Ice - RTOFS
- Global Ocean Analysis - GODAS
- Seasonal Climate - CDAS/ CFS
- Regional Hurricane 1 - HWRF
- Regional Hurricane 2 - HMON
- Regional High Resolution CAM 1 - HiRes Window
- Regional High Resolution CAM 2 - NAM nests/ Fire Wx
- Regional High Resolution CAM 3 - RAPv5/ HRRR
- Regional HiRes CAM Ensemble - HREF
- Regional Mesoscale Weather - NAM
- Regional Air Quality - AQM
- Regional Surface Weather Analysis - RTMA/ URMA
- Atmospheric Transport & Dispersion - HySPLIT
- Coastal & Regional Waves - NWPS
- Great Lakes - GLWU
- Regional Hydrology - NWM
- Space Weather 1 - WAM/IPE
- Space Weather 2 - ENLIL

Unified Forecast System (UFS)



UFS Applications

- Medium Range & Subseasonal
- Marine & Cryosphere
- Seasonal
- Hurricane
- Short-Range Regional HiRes CAM & Regional Air Quality
- Air Quality & Dispersion
- Coastal
- Lakes
- Hydrology
- Space Weather

Unified Forecast System

UFS
UNIFIED FORECAST SYSTEM

(UFS; UFSCommunity.org)

- **NOAA wide effort to unify research and operational forecast applications into streamlined code-base**
- **Open-development, documented, community codes**
  - Partners beyond NOAA on many components:
    - Atmos. Dynamical core (FV3) - NASA-GEOS, NCAR
    - Ocean (MOM6) - NCAR, NASA-GEOS
    - Data assimilation (JCSDA) - many partners
    - Common Infrastructure based on MoA with NCAR
- **Public UFS model releases**
  - Medium-Range global operational forecast system (2020)
  - Short-range regional development forecast system (2021)
- **Earth Prediction Innovation Center (EPIC) catalyzes the community strategy by making UFS more accessible and user-friendly**

EPIC
Earth Prediction Innovation Center

Global Forecast System

- Medium-range weather (MRW) UFS application
- Global deterministic model
- Run 4 times a day out to 16 days
    - Hourly output for first 120 hours
    - 3 hourly for days 6-16
- Global Data Assimilation System (GDAS)
    - Catch-up cycle to ingest late-arriving observations
    - 80 ensemble members
- Provides initial and/or boundary conditions for multiple downstream forecast systems including the Global Ensemble Forecast System (GEFS)

Global Data Assimilation System

- **Current major version (v16) operational since March 2021**
    - Most notable change to L127 from L64
    - EnSRF to LETKF for ensemble update
- **Gridpoint Statistical Interpolation (GSI) based hybrid 4D-EnVar system**
    - GSI used for GDAS since 2007
    - ~25 km analysis for ~13km forecast
    - 4D Incremental Analysis Update
- **Numerous types of observations assimilated including:**
    - satellite radiances (using CRTM)
        - numerous platforms/instruments/channels
    - satellite-based ozone and winds
    - radiosondes
    - aircraft-based observations
    - surface station pressure
    - GNSS-RO

Recent Upgrades to the GFS/GDAS

- **GFSv15.1 (June 2019)**
  - Initial implementation of FV3-based GFS
  - Increase analysis increment & ensemble resolution
- **GFSv15.2 (November 2019)**
  - GOES-17 AMVs, KOMPSAT-5 GNSS, METOP-C AMSU-A and MHS
  - NSST Updates
- **GFSv15.2.12 (April 2020)**
  - New Aircraft (TAMDAR, Canadian AMDAR, and LATAM)
- **GFSv15.3 (May 2020)**
  - COSMIC-2

- **GFSv16 (March 2021)**
  - 127 Layers, ~80km model top
  - Modulated-ensemble LETKF & 4DIAU
  - Correlated observation errors, VarQC re-design, Hilbert Curve
  - Metop-C GNSSRO, Geostationary CSR, HDOB
- **GFSv16.1 (May 2021)**
  - Commercial GNSSRO: GeoOptics
- **GFSv16.1.4 (September 2021)**
  - Commercial GNSSRO: Spire
- **GFSv16.3 (November 2022)**
  - Precipitation-affected MW
  - Antenna corrected AMSU-A, ATMS, MHS BT
  - Leo-Geo AMVs, N20 OMPS-TC, Many others…
- **GFSv16.3.9 (September 2023)**
  - Commercial GNSSRO: PlanetIQ, N20 OMPS-NP
- **GFSv16.3.12 (December 2023)**
  - NOAA-21 ATMS/CrIS, GOES-18 ABI, Metop-C ASCAT

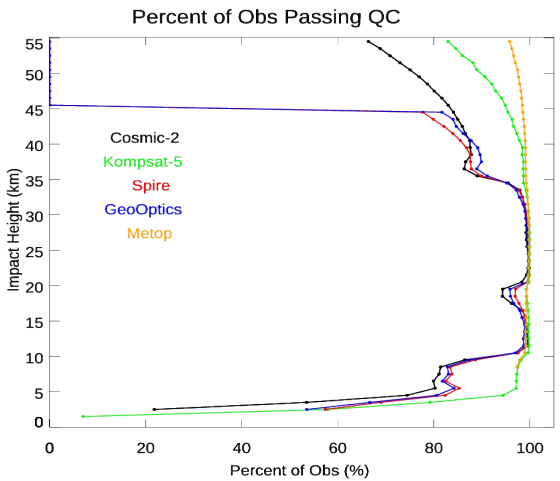
Commercial RO Data

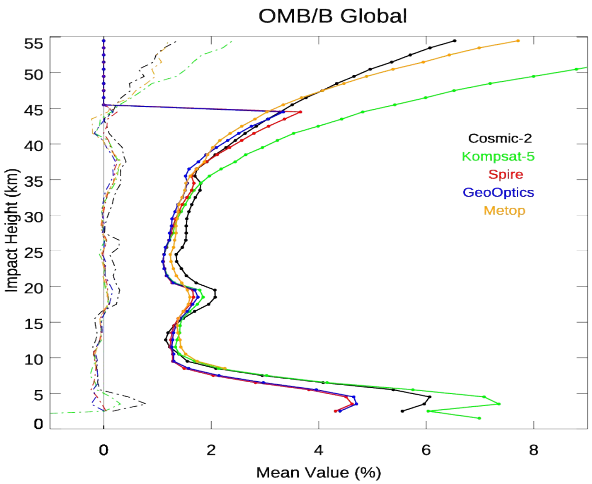
- The Weather Research and Forecasting Innovation Act of 2017: Section 302 authorizes the Commerce Department to enter into agreements for commercial weather data purchases.
- NOAA NESDIS CDP Radio Occultation Data Buy (RODB) contracts:
  - **RODB-1:** 5 delivery orders (DOs) in 2020-2023, Implemented May 2021
    - DO-1: GeoOptics 500 Profiles/day and Spire 500 Profiles/day
    - DO-2: GeoOptics 1,300 Profiles/day
    - DO-3: Spire 3,000 Profiles/day
    - DO-4: GeoOptics 500 Profiles/day and Spire 5,500 Profiles/day
    - DO-5: Spire 3,100 Profiles/day + EUMETSAT Spire 1,600 Profiles/day
  - **RODB-2:** Awarded to Spire and PlanetiQ in 2023 with a 5-year ordering period
    - DO-1T: PlanetiQ 500 Profiles/day and Spire 500 Profiles/day
    - DO-2: PlanetiQ 3,100 Profiles/day
    - DO-3: Spire ~~6,000~~ 3,000 Profiles/day (<1,000 in August 2024) + EUMETSAT Spire 1,600 Profiles/day

Courtesy of Xuanli Li

Commercial RO Assessment

- **DO-4 :** March 2022 – January 2023
- **Data Denial Experiment:** 24 March – 24 April 2022
  - **v16_ctl**: Control run **with** DO-4 data (~500 GeoOptics and ~5,500 Spire)
  - **v16_do4**: Data denial experiment **without** DO-4 data
- **Configuration:** Global parallel experiments GFS v16.1.6, C384 (25 km) resolution



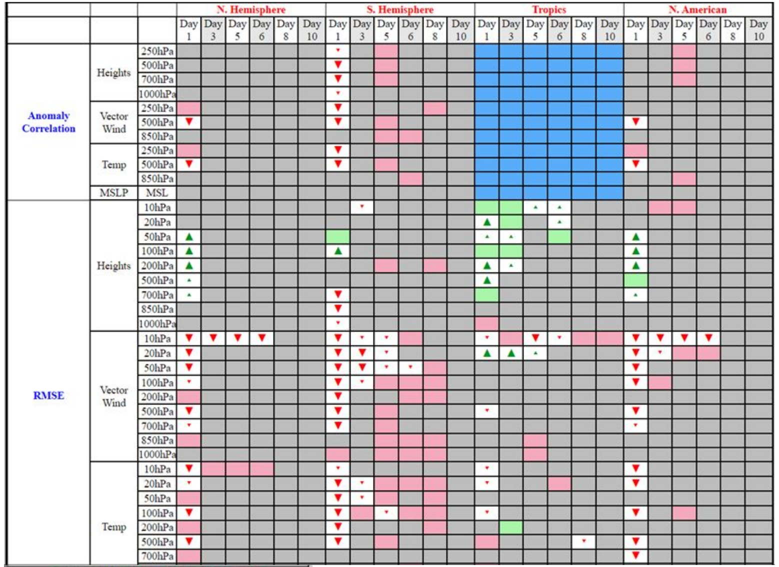


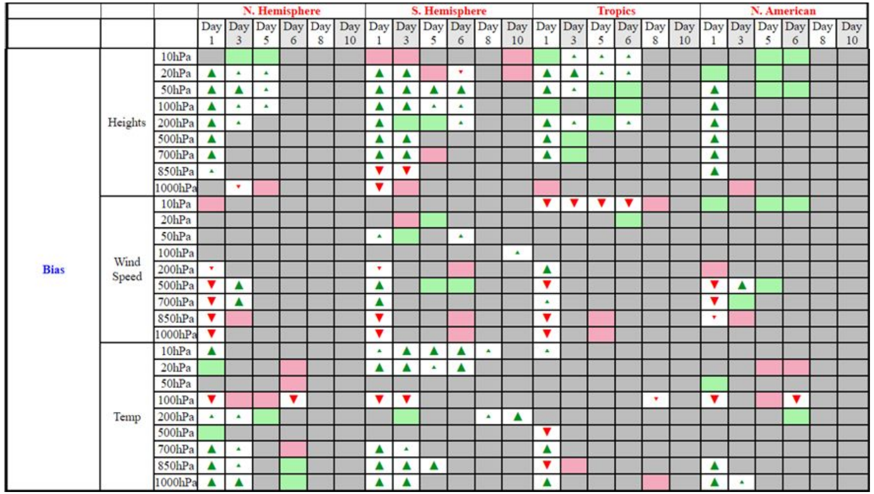
20220324 - 20220424

Data from both Spire and GeoOptics show quality comparable to existing missions

Courtesy of Xuanli Li

Commercial RO Assessment: Fit to ECMWF Analysis





Symbol Legend
▲ V16_DO4 is better than V16_CTL at the 99.9% significance level
▴ V16_DO4 is better than V16_CTL at the 99% significance level
(green) V16_DO4 is better than V16_CTL at the 95% significance level
(gray) No statistically significant difference between V16_DO4 and V16_CTL
(pink) V16_DO4 is worse than V16_CTL at the 95% significance level
▾ V16_DO4 is worse than V16_CTL at the 99% significance level
▼ V16_DO4 is worse than V16_CTL at the 99.9% significance level
(blue) Not statistically relevant
Start Date: 20220324
End Date: 20220424

- **Green: Degradation**
- **Red: Improvement**

Improvement in SH: AC for HGT, wind, and T; RMSE for wind, T, and low level HGT; Bias for low level HGT and WSPD. **Degradation in SH:** bias for HGT and T.

Improvement in NH: AC for mid-level wind and T; RMSE for wind and T; Bias for mid to low level wind. **Degradation in NH:** RMSE for upper level HGT; Bias for HGT and low level T.

Courtesy of Xuanli Li

Planned DA Upgrade to the GFS

Q2FY25

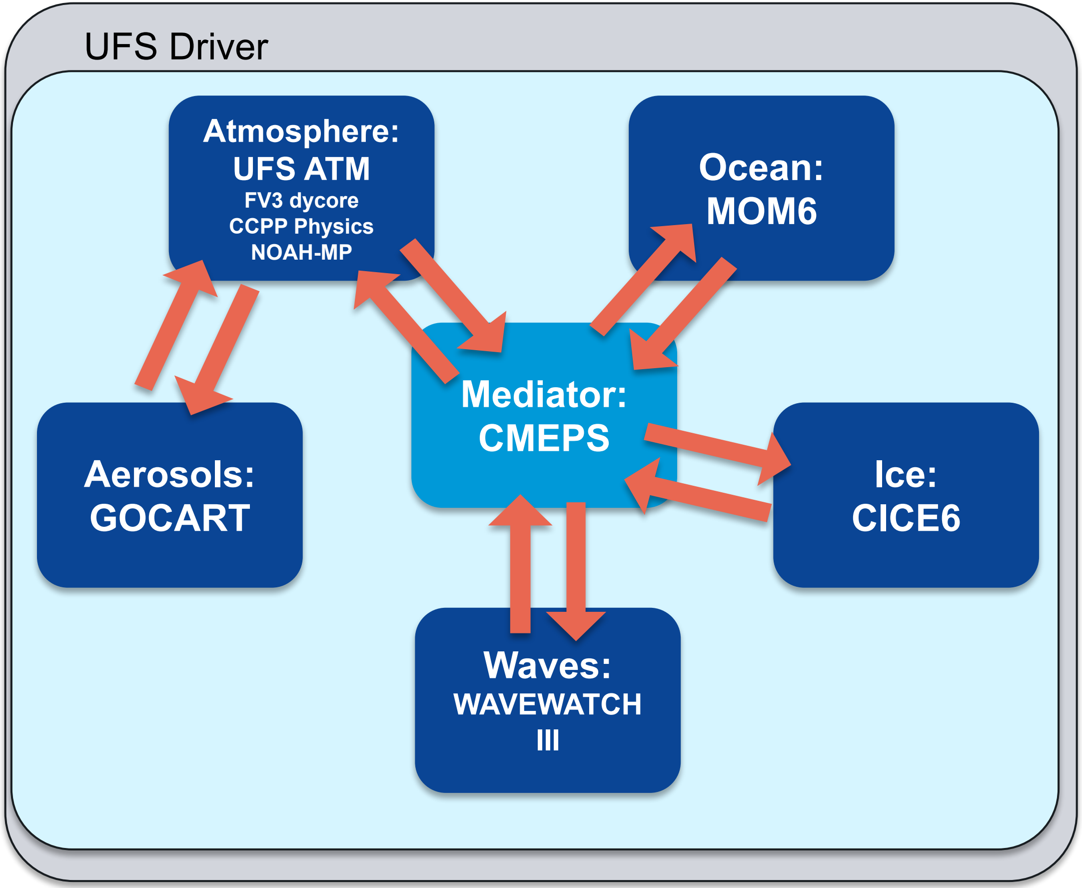
- New Observations
  - Conventional Data - Saildrones
  - Satellite Winds - AMVs from GOES-18, MeteoSat Third Generation - Imaging 1 (MTG-I1)
  - GPSRO - Sentinel-6
  - Radiances - GMI GPM
  - Total Ozone and Ozone Profile - OMPS N21
- Improvements to minimization
  - Use sensible temperature rather than virtual temperature Jacobians for radiance assimilation
  - Down weight channels for IR sensors based on their sensitivity to moisture to improve the convergence characteristics of the minimization

Courtesy of Emily Liu

Weakly Coupled DA: GFSv17

GFSv17 Overview

- Weakly coupled system
  - Atmosphere
  - Ocean
  - Sea ice
  - Land
  - Waves
  - Aerosol (Non-interactive in GDAS deterministic forecast only)
- GFSv17 and GEFSv13 will become more aligned
  - Infrastructure will be as unified as possible
  - Implementation planned for the same day
- New DA components will use JEDI software



Joint Effort for Data assimilation Integration (JEDI)

JEDI is a project within the Joint Center for Satellite Data Assimilation (JCSDA)

JEDI provides a **software infrastructure for data assimilation** that

- is model agnostic
- is generic and portable, from toy models running on laptops to operational Earth system coupled models running in the cloud.
- enables DA on the model native grid
- does not impose one specific DA methodology or algorithm
- provides a framework for rapid uptake of new observations into operations with generic observation handling and modeling
- encourages implementation of model-independent observation operators
- provides a unified Interface for Observation Data Access (IODA)

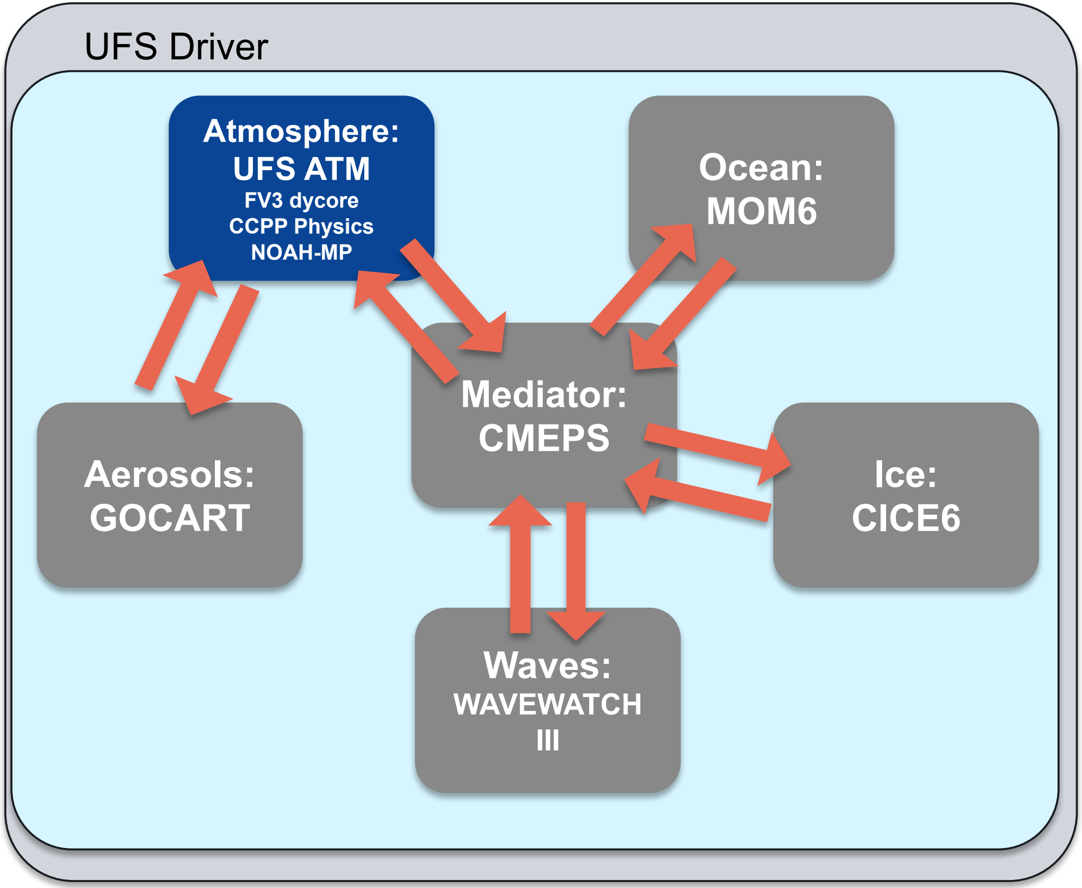
JEDI is intended for **scientific exploration** and **operational forecasting**.

The keys to success are **separation of concerns** and **interfaces**.

Courtesy of Cory Martin

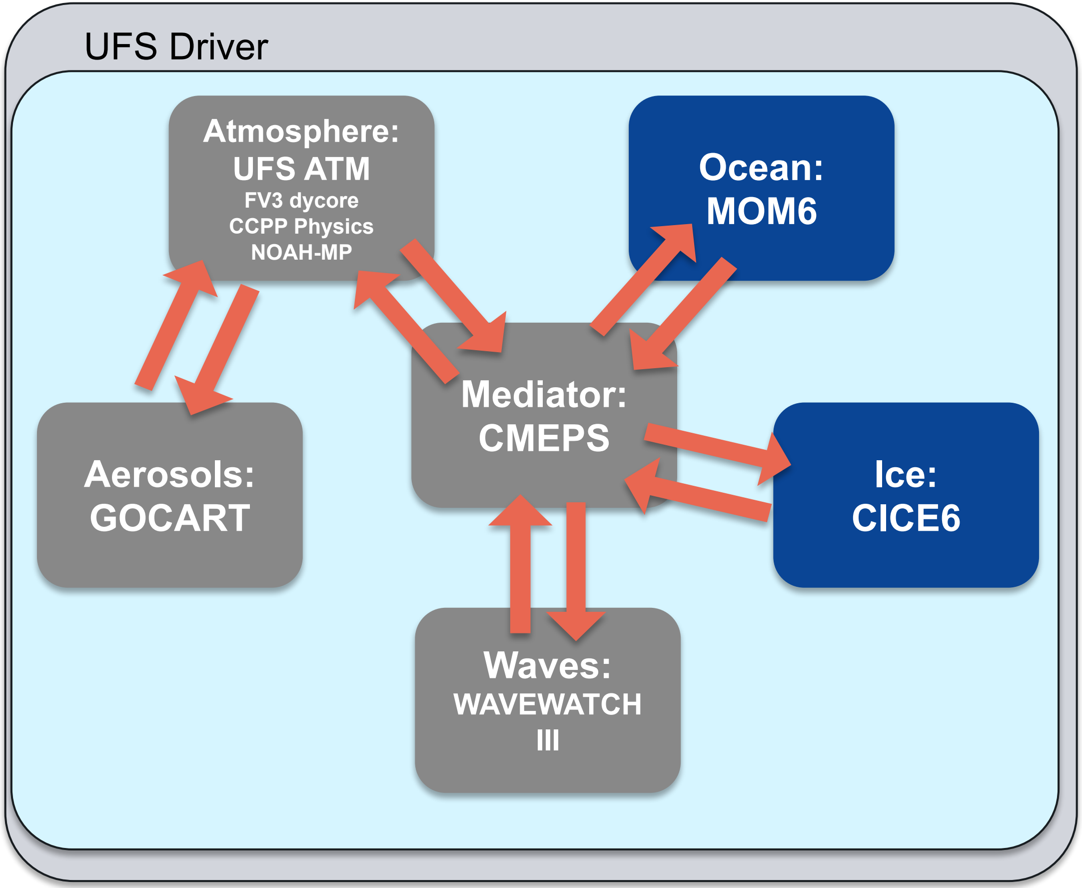
UFS ATM Overview

- Atmosphere
  - Increase in horizontal res for deterministic forecast (C1152)
  - Upgrade to Thompson microphysics
  - **GSI-based hybrid 4DEnVar** deterministic analysis
  - **GSI-based 4D-LETKF** ensemble analysis
  - Additional early cycle ensemble analysis for GEFS initialization (if resources allow)
- Land
  - Upgrade model to Noah-MP
  - **JEDI-based 2DVar** for snow
  - **GSI-based LETKF** for soil, strongly coupled with the atmosphere



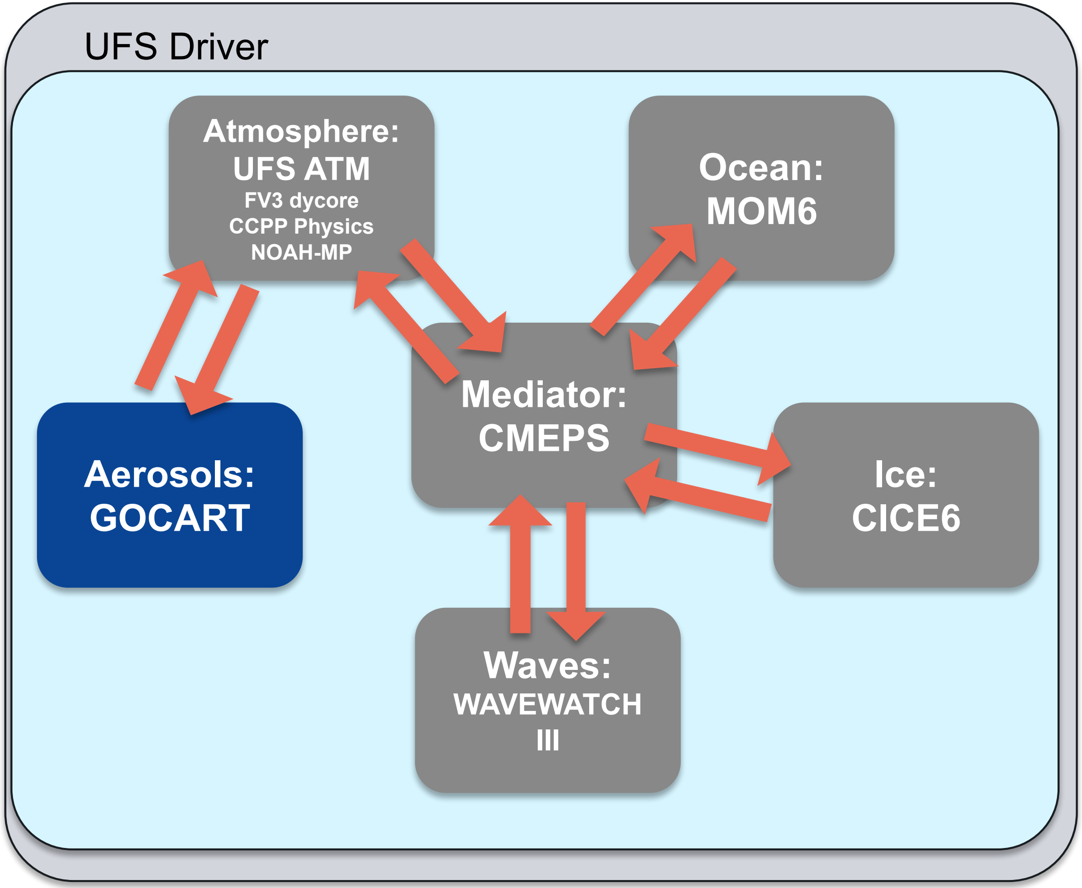
Marine Overview

- Marine
  - Sea-ice Ocean Coupled Analysis (SOCA)
  - Ocean and sea ice are strongly coupled
  - **JEDI-based hybrid 3DEnVar** for deterministic analysis
  - **JEDI-based 3D-LETKF** for ensemble analysis

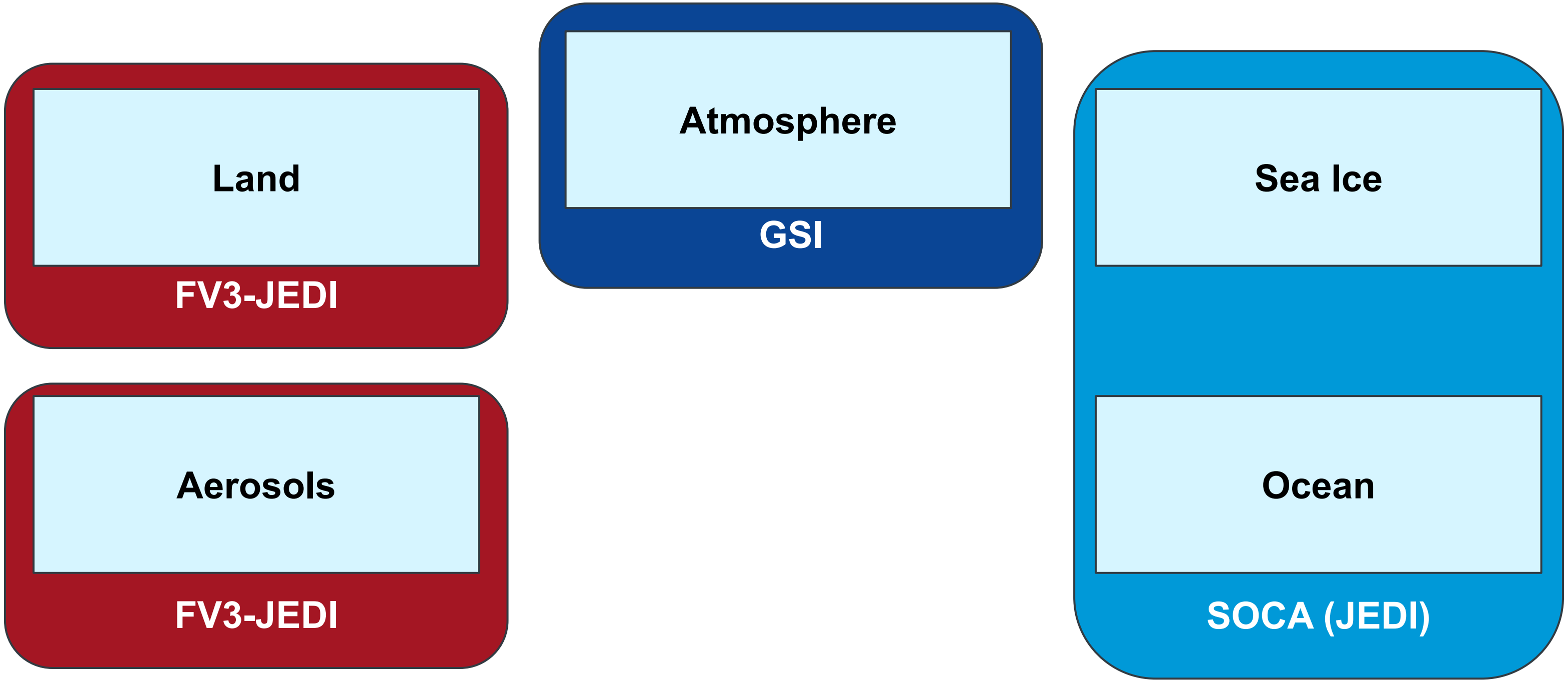


Aerosols Overview

- Aerosols
  - **JEDI-based 3DVar**
  - No ensemble DA component
- Non-interactive aerosols in the deterministic cycling GDAS forecast
- Aerosols included for the GEFS ensemble forecasts
- No aerosols in the deterministic long GFS forecast or GDAS ensemble forecasts



New Coupled Model, New Coupled DA



Currently, GDAS is atmosphere only, with basic offline land surface updates. With GFSv17, weakly coupled (strongly between sea ice and ocean) DA will be introduced for all Earth system components except for waves.

Courtesy of Cory Martin

Atmospheric DA Upgrades for GFSv17

- Scale-Dependent Localization
- All-sky Framework - Update cloud fraction and effective radius calculation based on model upgrade from GFDL to Thompson
- CRTM v3.0 - Improved IR ocean surface emissivity model
- Replace IR cloud detection scheme from MMR to CADS

Scale-Dependent Localization

- GSI-based hybrid EnVar data assimilation has been operational at NCEP for many years
  - GFS/GDAS, NAM, and RAP/HRRR
- Use of scale-dependent localization extension has been proven in the literature and is operational at some NWP centers
  - Includes initial demonstration with prototype GFS/GDAS (collaboration with OU/MAP – Huang et al. 2021, MWR, doi:10.1175/MWR-D-20-0166.1)
- Unified scheme has now been implemented into GSI for use in global and regional applications (*Sho Yokota*)

Scale-Dependent Localization

Courtesy of Sho Yokota

(Buehner and Shlyaeva 2015, *Tellus*; Huang et al. 2021, *MWR*)

$$J(\delta\mathbf{x}_s, \mathbf{a}_1, \dots, \mathbf{a}_K) = \frac{1}{2}\beta_s(\delta\mathbf{x}_s)^T\mathbf{B}^{-1}(\delta\mathbf{x}_s) + \frac{1}{2}\sum_{k=1}^{K}[\beta_e(\mathbf{a}_k)^T\mathbf{A}^{-1}(\mathbf{a}_k)] + \frac{1}{2}(\mathbf{H}\delta\mathbf{x} - \mathbf{d})^T\mathbf{R}^{-1}(\mathbf{H}\delta\mathbf{x} - \mathbf{d}) \quad \left(\frac{1}{\beta_s} + \frac{1}{\beta_e} = 1\right)$$

$\mathbf{B}$: Static background error covariance

$\mathbf{A}$: **Localization**

$\mathbf{R}$: Observation error covariance

$\mathbf{d}$: Innovation

$$\delta\mathbf{x} = \delta\mathbf{x}_s + \sum_{k=1}^{K}(\mathbf{a}_k \circ \mathbf{x}_k^e)$$

$\delta\mathbf{x}$: Analysis increment

$\mathbf{a}_k$: **Control vector**

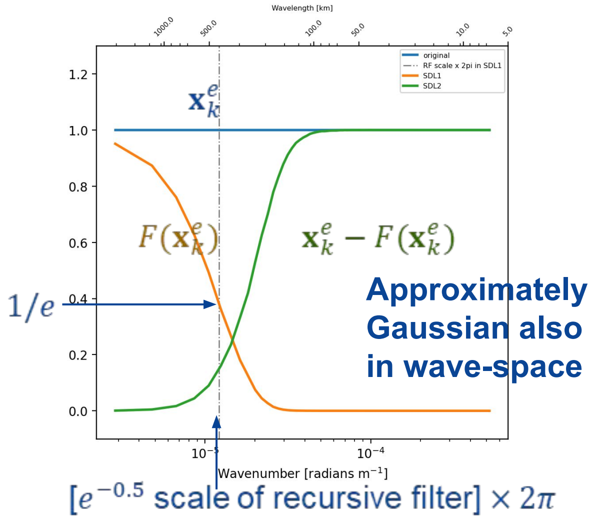
$\mathbf{x}_k^e$: **k-th ensemble perturbations**

In SDL, $\mathbf{A}$, $\mathbf{x}_k^e$, and $\mathbf{a}_k$ are separated to large and small scales as

$$\mathbf{A} \rightarrow \begin{bmatrix} \mathbf{A}_{\text{large}} & \mathbf{A}_{\text{large}}^{1/2}\mathbf{A}_{\text{small}}^{1/2} \\ \mathbf{A}_{\text{small}}^{1/2}\mathbf{A}_{\text{large}}^{1/2} & \mathbf{A}_{\text{small}} \end{bmatrix} \quad \mathbf{x}_k^e \rightarrow \begin{bmatrix} F(\mathbf{x}_k^e) \\ \mathbf{x}_k^e - F(\mathbf{x}_k^e) \end{bmatrix} \quad \mathbf{a}_k \rightarrow \begin{bmatrix} \mathbf{a}_k^{\text{large}} \\ \mathbf{a}_k^{\text{small}} \end{bmatrix}$$

F: **Low-pass filter**

$$\mathbf{a}_k \circ \mathbf{x}_k^e \rightarrow \mathbf{a}_k^{\text{large}} \circ F(\mathbf{x}_k^e) + \mathbf{a}_k^{\text{small}} \circ [\mathbf{x}_k^e - F(\mathbf{x}_k^e)]$$

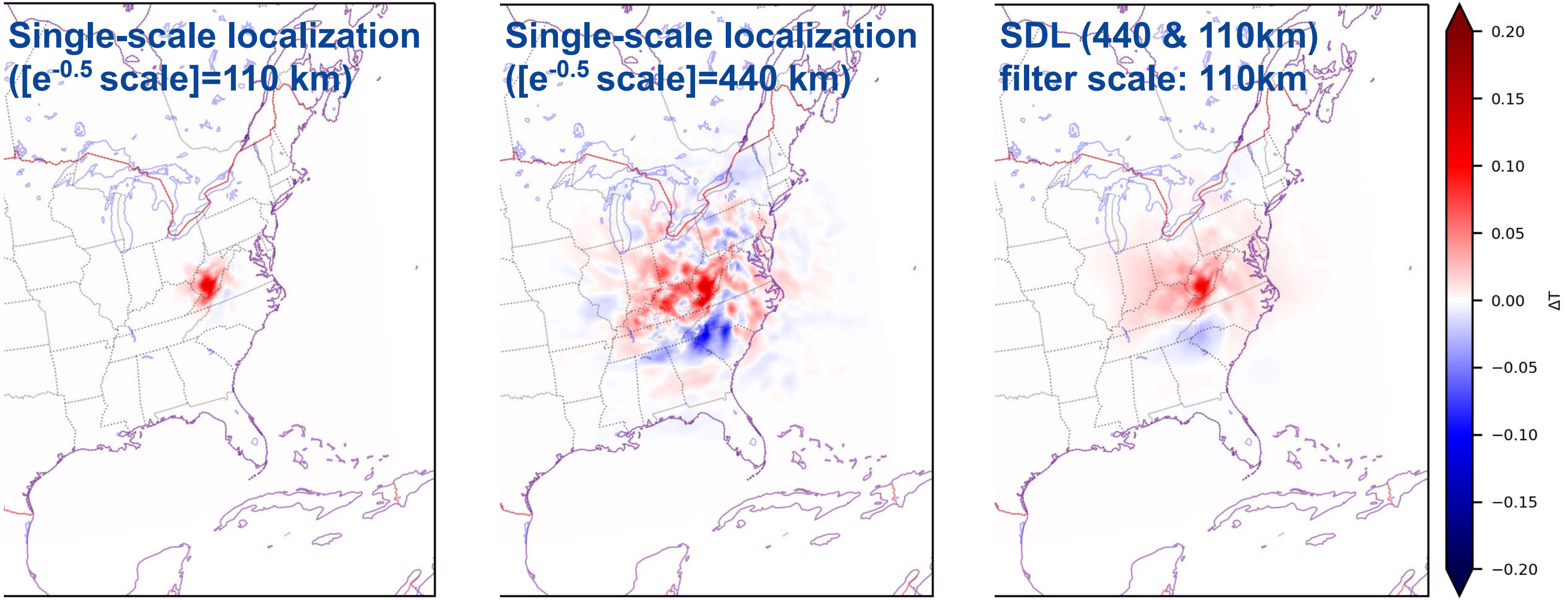


Power spectrum density ratio of ensemble perturbations

Scale-Dependent Localization

Courtesy of Sho Yokota

- Co-developed code by EMC –Ting Lei & Sho Yokota (JMA Visitor) and OU/Map (Xuguang Wang)
- Testing initially performed in **RRFS**



EnVar analysis increment of temperature (K) at 34th vertical level (~500hPa) in assimilation of 500-hPa temperature

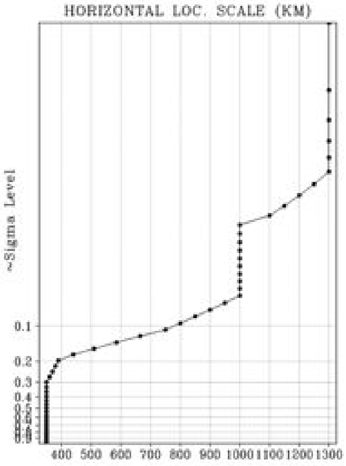
Scale-Dependent Localization: GFS

- Experimental version of GFSv16.1.6
- C384/C192 (half operational resolution), Hybrid 4DEnVar, full operational observation suite
- 16 March-1 May 2023 (verification for April dates)
- All experiments have fixed vertical localization

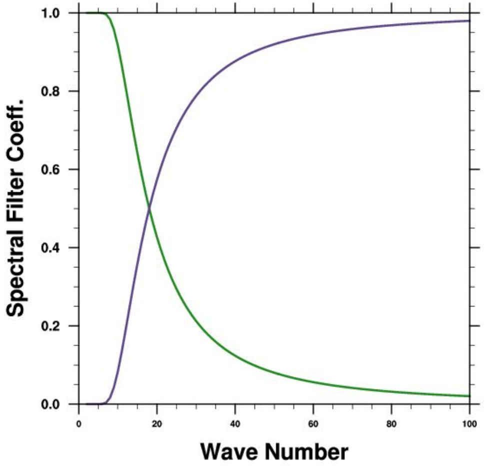
Experiments (*run by Travis Elless*):

- Control, level-dependent horizontal localization
- 2 bands, 1000/300 km localization, scale separation at wave #5
- 2 bands, 1000/300 km localization, scale separation at wave #20 (right)
- 2 bands, 1000/300 km localization, scale separation at wave #16 (Huang et al 2021)
- 3 bands, 1000/300/150 km localization, scale separation at waves #16/50 (Buehner and Shlyaeva 2015)

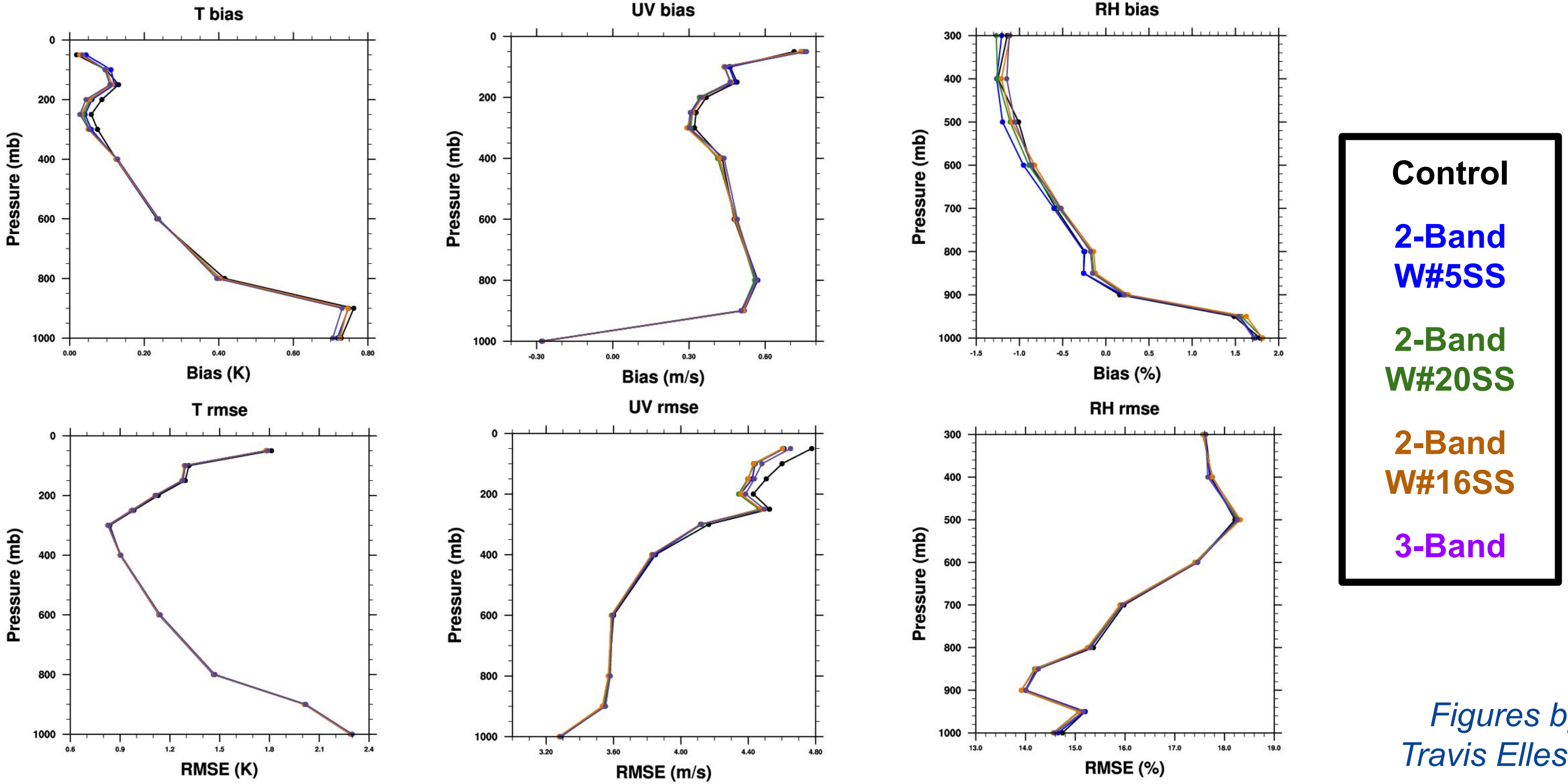
Default:
level dependent
(single scale)
localization



Spectral filter
function



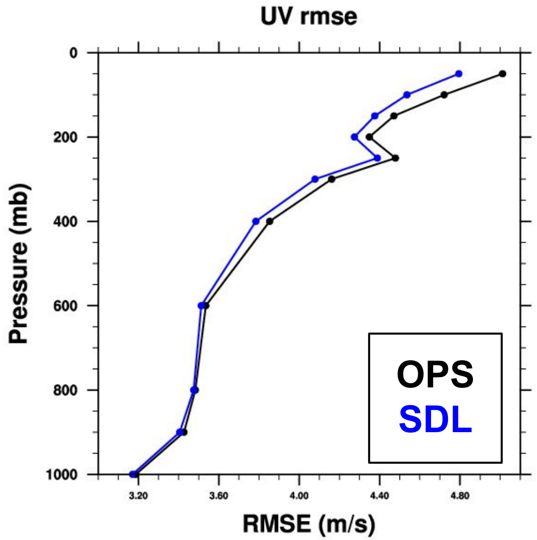
Scale-Dependent Localization: Fits-to-obs (6-hour)

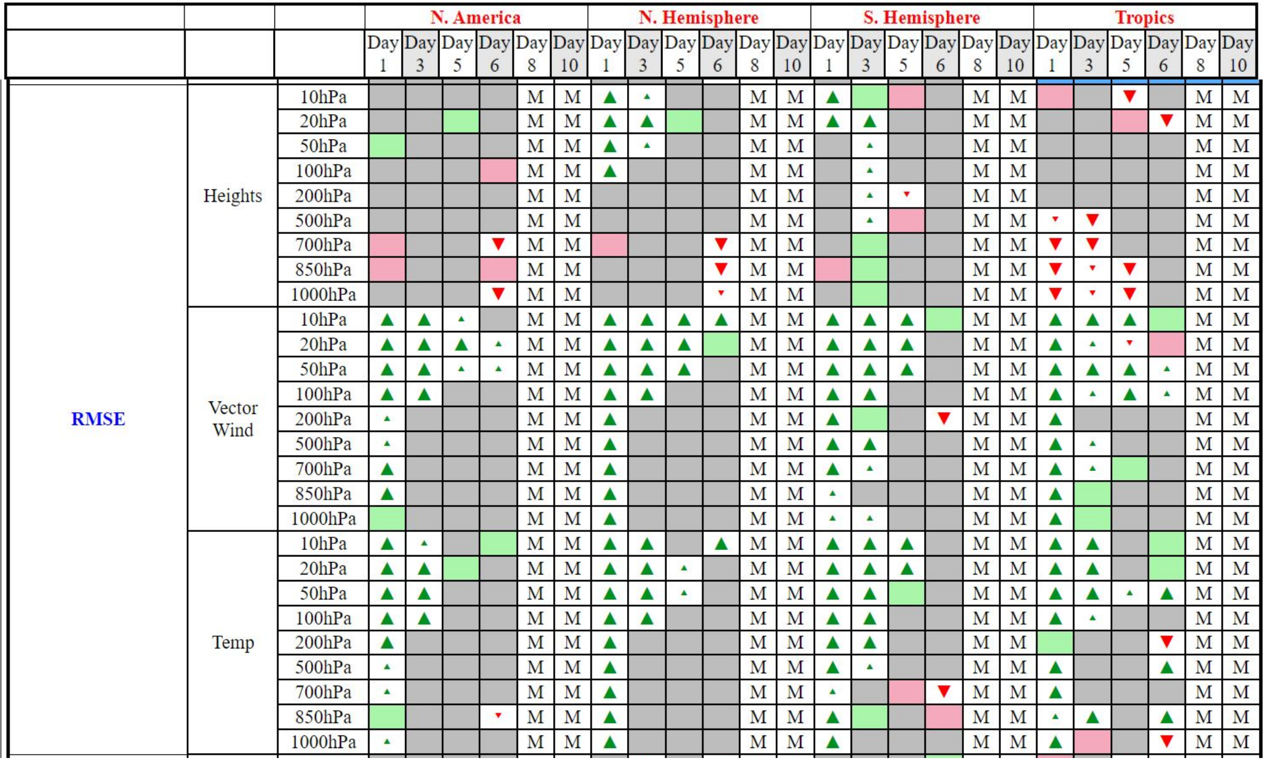


Figures by Travis Elless

SDL: Self-Analysis Scorecard RMSE, Ops Res

Full-resolution results are consistent with the half-resolution experiments.





▲ gsi_sdl768_0 is better than gfs at the 99.9% significance level	▼ gsi_sdl768_0 is worse than gfs at the 99.9% significance level
▴ gsi_sdl768_0 is better than gfs at the 99% significance level	▾ gsi_sdl768_0 is worse than gfs at the 99% significance level
(green) gsi_sdl768_0 is better than gfs at the 95% significance level	(pink) gsi_sdl768_0 is worse than gfs at the 95% significance level
(grey) No statistically significant difference between gsi_sdl768_0 and gfs	(blue) Not statistically relevant

Dates: 20230324-20230404

All-sky Assimilation: Operations

Observation
- Clear, cloudy and precipitation affected radiances are assimilated over the ocean for ATMS AMSU-A

Observation Operator (CRTM)
- Input all 5 hydrometers over ocean
- Cloud optical table -based on GFDL cloud microphysics size distribution and parameters
- At each FOV, calculate cloud fraction and effective radius consist with model assumptions

Analysis Variable (Control Variable)
- Mixing ratio of all five hydrometers are added as part of the control and state variables

Background Error Covariance
- Ensemble-based flow-dependent background covariance are extended to include all five hydrometers.
- Static B for hydrometer is defined as 5% of the background value with reduced correlation length

Observation Error Estimation
- Initial obs error is characterized as a function of averaged cloud amount retrieved from observation and background to ensure Gaussianity
- Enhanced by situation-dependent error inflation

Courtesy of Emily Liu

Bias Correction
- To reduce aliasing forecast model error into observation bias correction, not all samples passed quality control are used in variational bias correction estimation
- Only samples with consistent cloud information from background and observation are used in updating VarBC coefficients
  - At observation location, both background and observation indicate clear or cloudy
  - When both cloudy, the difference in cloud amount must be less than 0.005 kg/m2

Quality Control
- GFS-FV3 model does not model supercooled liquid water cloud during cold air outbreak (CAO) in polar regions. Observations in CAO regions are excluded from assimilation
- Observations affected by highly scattering scenarios from hydrometeors are removed

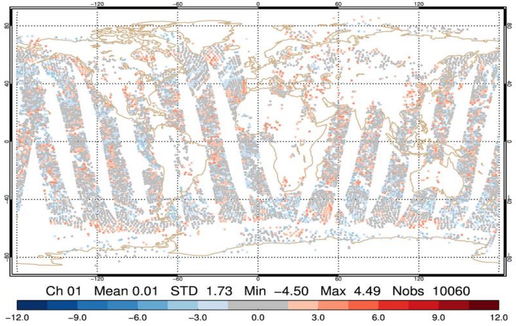
Make consistent use of model physics across components in the DA system

This all-sky framework is a proven concept for MW sensor and it can be extended to all-sky assimilation for IR radiances

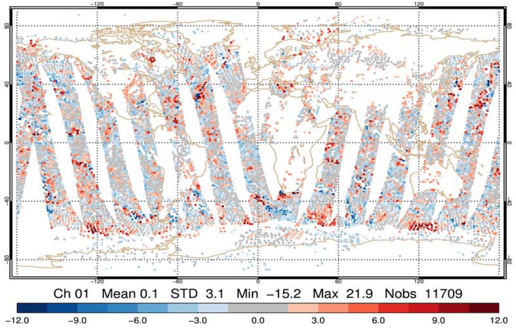
All-sky Assimilation: Initial Implementation

Courtesy of Emily Liu

Clear-sky O-F



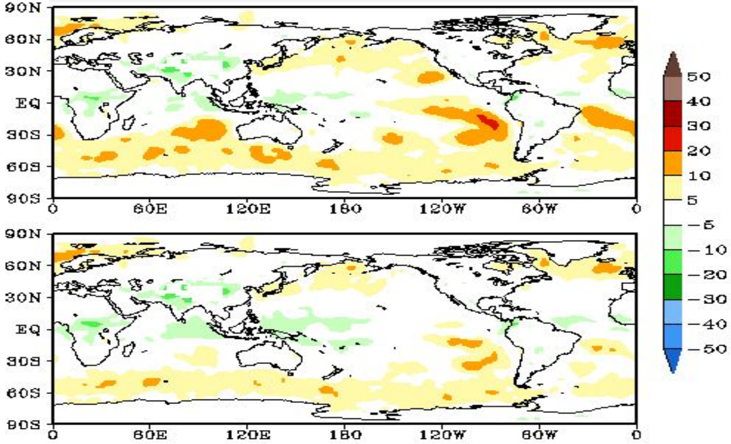
All-sky O-F



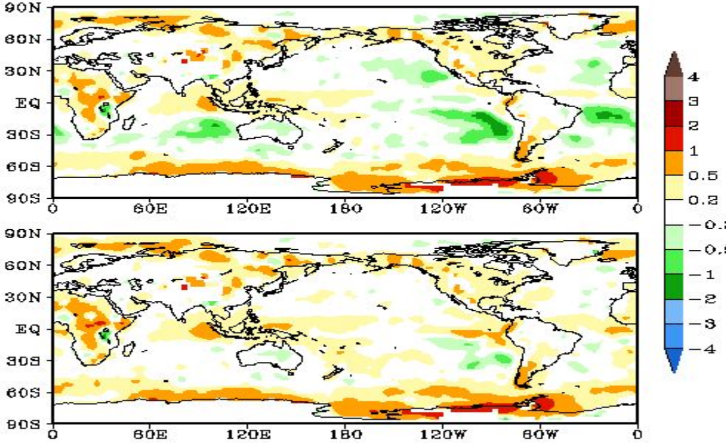
Increase number of obs assimilated

Remove spurious low-level moisture bias (too wet) temperature bias (too cold) caused by clear-sky assimilation

RH Diff @850 hPa



Temp Diff @850 hPa

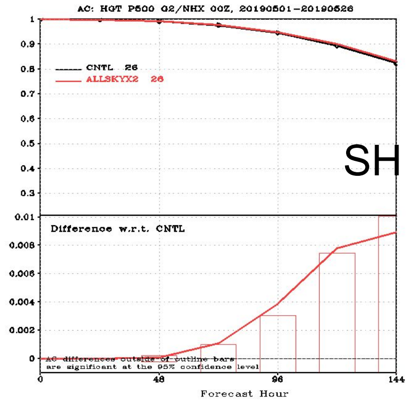


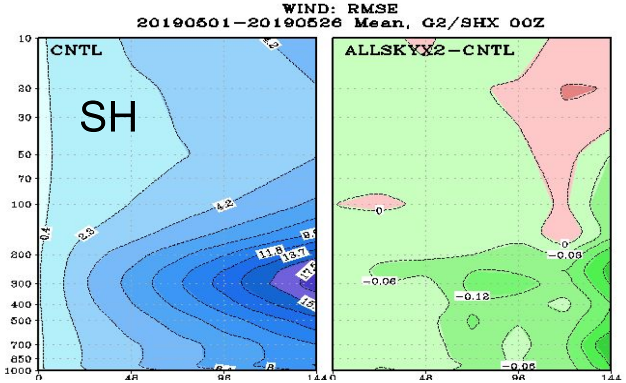
Clear-Sky - ECMWF

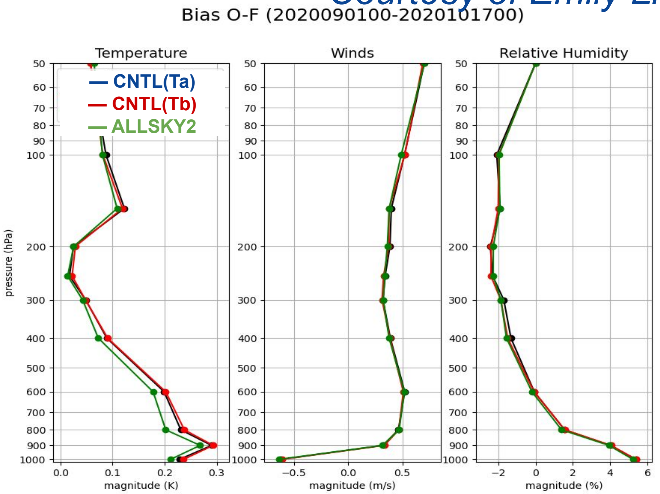
All-Sky - ECMWF

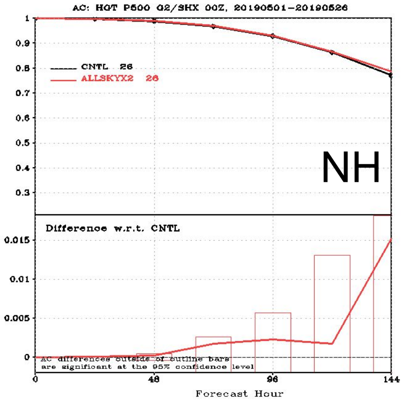
All-sky: Precipitation-Affected Radiances

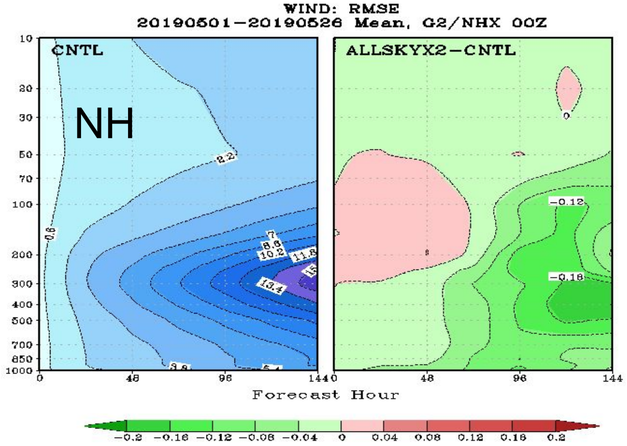
Courtesy of Emily Liu











- Positive impact in SH; Neutral in NH
- Positive impact on winds globally
- Significantly reduce the 6-hour temperature forecast bias in the troposphere

All-sky: GFDL MP vs. Thompson MP in GFS DA

GFDL MP (Goddard-Focused Microphysics):

- **Type**: Single-moment scheme
- **Categories**: Five categories:
  - Cloud water, cloud ice, rain, snow, graupel
- **Based on**: Lin-Lord-Krueger cloud microphysics scheme
- **Characteristics**: Predicts mass of hydrometeors, but does not account for changes in particle concentration.

Thompson MP (Thompson Microphysics):

- **Type**: Double-moment scheme
- **Prediction**: Both mass and number concentration of hydrometeors
  - Cloud ice and rain concentrations are predicted
- **Reference**: (Thompson et al., 2007)
- **Advantages**:
  - Improved representation of cloud microphysics processes

Courtesy of Azadeh Gholoubi

All-sky: Cloud Fraction

GFDL Method: designed for GFDL cloud microphysical scheme using the subgrid variability theory (Le trent and Li, 1991). Cloud fraction occurs only when RH>0.75

Subgrid variability defines an upper bound (qplus) and a lower bound (qminus). Calculation of upper bound and lower bound is based on the linear theory (Lin et al., 1994).

$$\text{CF}=\begin{cases} 1.0, & if\ qsat < qminus \\ \dfrac{\text{qplus} - \text{qsat}}{\text{qplus} - \text{qminus}}, & if\ qminus \le qsat \le qplus \\ 0.0, & if\ qsat > qplus \end{cases}$$

$$CF=min[1.0\ max(CFmin,CF)]$$

Thompson MP: used same relative humidity (RH), saturation mass mixing ratio (qsat), and all five hydrometeors as GFDL method.

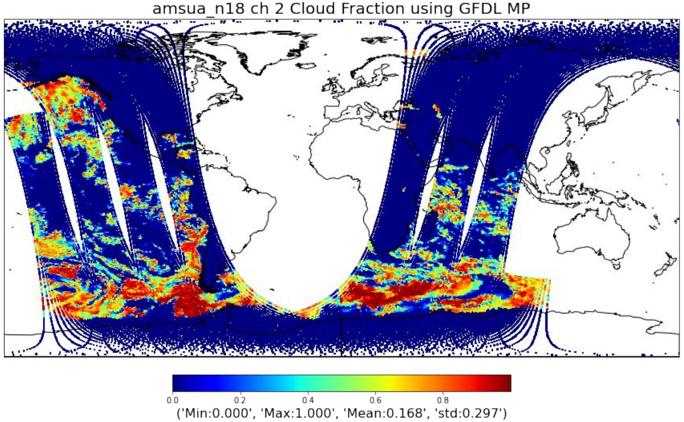
Changes in Thompson MP:

- Smaller threshold for cloud cover calculation
- Cloud cover = 1 when RH >= 1
- Larger cloud cover factor to cloud content to increase cloud cover

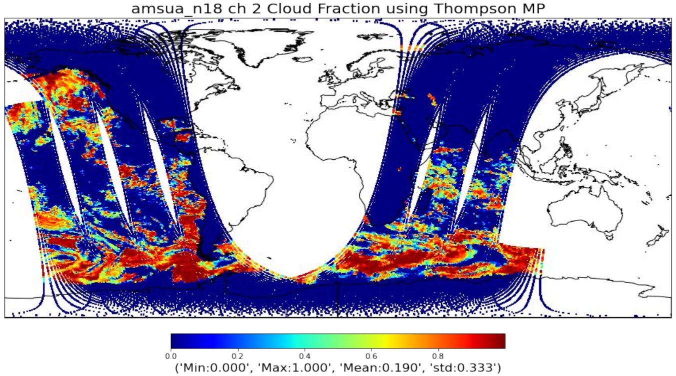
Courtesy of Azadeh Gholoubi

All-sky: GFDL MP vs. Thompson MP in GFS DA

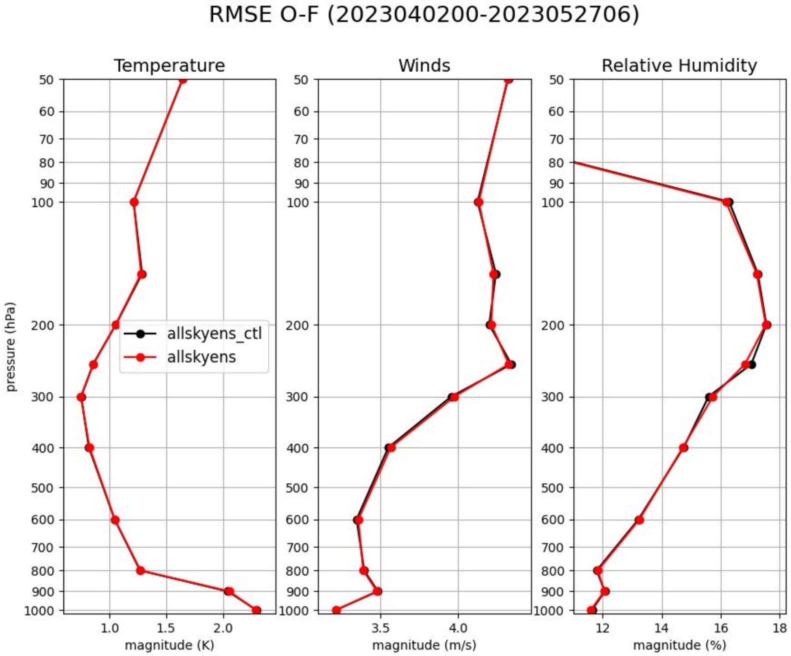
GFDL Method



Xu and Randall (1996)



6-hour fit to conventional obs



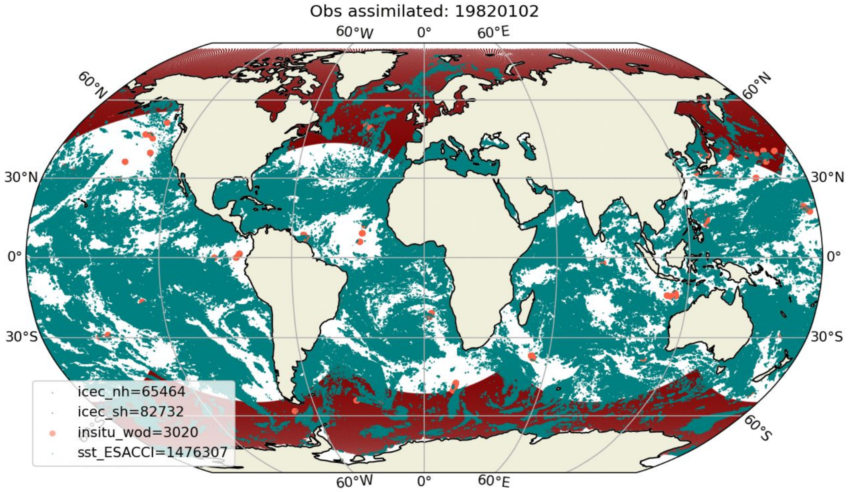
Courtesy of Azadeh Gholoubi

Weakly Coupled DA: Marine

Marine DA: EMC-JCSDA Joint NG-GODAS Interim Reanalysis

- DATM-MOM6-CICE6: ***JEDI-SOCA 3DVar*** framework
- ~40 year ocean reanalysis at one degree, completed Fall 2021
  - Working on real-time extension for CPC monitoring activities
- First demonstration of JEDI viability for future operational applications
- NCEP Office Note (Kim et al., 2022 – https://doi.org/10.25923/26ds-q363)

Obs type	Date
ADT	1993-2020 (NESDIS)
Satellite SST (AVHRR)	1981-200208 (ESACCI L3U), 200208-201811 (NESDIS L3U)
Insitu (T&S)	1979-2020 (WOD)
SSS	SMOS ESA L2 (2010-2020), SMAP RSS/JPL L2 (2015-2020)
Sea ice Conc	NSIDC L3 SSMR, SSMI (1979-200305), EMC L2 (200306-2020 SSMI, SSMIS)



Over 1 Million Observations per day

Courtesy of Guillaume Vernieres

Marine DA: Configuration and Observations

	Target GFSv17 Marine DA system	Current system
Deterministic DA algorithm	**JEDI based** Hybrid Ens. Var. 4D h(x) and 3D background error	**JEDI based** Hybrid Ens. Var. 4D h(x) and 3D background error
Perturbation model	**JEDI based** LETKF	Offline members from an ensemble of coupled UFS forecast
DA window	6 hr window	6 hr window
Initialization	3D IAU for MOM6 direct insertion for CICE	3D IAU for MOM6 direct insertion for CICE
Ensemble size	80	30 offline members

Obs type	Current assimilation
SST retrievals	AVHRR (METOP-A, -B) VIIRS (NOAA-20, S-NPP) ABI (GOES 16-17) AHI (Himawari-8)
Sea ice concentration	AMSR-2 North, South
Altimeters (sea surface height)	CRYOSAT-2 JASON-1, -2, -3 SARAL Sentinel-3A, -3B

Courtesy of Guillaume Vernieres

Marine DA: Background Error

$$\mathbf{B} = \beta_s\, \mathbf{B}_s \cancel{+ \beta_{se}\, \mathbf{B}_{se}}$$

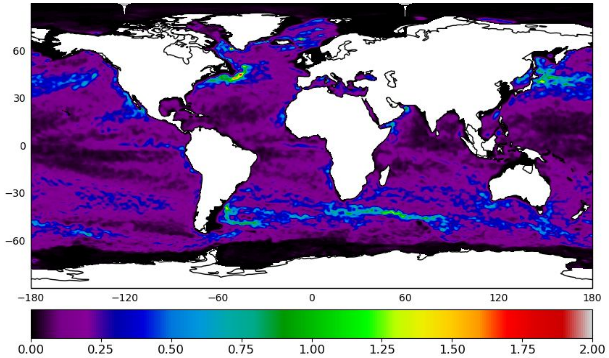
where $\beta_s = 1$ and $\mathbf{B}_s = \mathbf{K}\,\mathbf{D}\,\mathbf{C}_v\,\mathbf{C}_h\,\mathbf{C}_v^T\,\mathbf{D}\,\mathbf{K}^T$

Small Scales

- *Diag $\mathbf{B}_s$ (**D**)*: variance partitioning of the background.
  - *Variance Partitioning:* For each point A, compute stddev of all points surrounding point A and assign to point A.
- *Cross-covariance (**K**):* linearized column physics (steric height balance). Cross correlation for T, S, and ssh
- *Horizontal and Vertical correlations* modeled with an explicit diffusion operator
  - Horizontal decorrelation length scale ($\mathbf{C}_h$) use the Rossby radius of deformation
  - Within the Mixed Layer (ML), the vertical decorrelation length scale ($\mathbf{C}_v$) can be up to 15 layers deep (if the ML is 3 layers deep, $\mathbf{C}_v$ is 3 layers). Below the ML, 5 layers are used $\mathbf{C}_v$

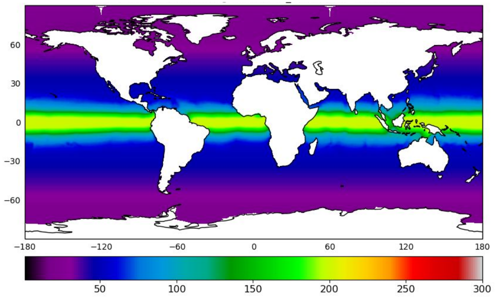
s = static
se = static ens.

Example Bkg Error for SST (D)



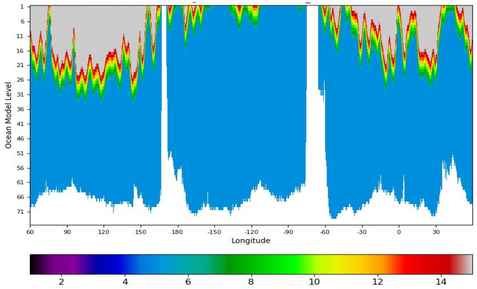
deg-C

Horiz. Length Scales ($\mathbf{C}_h$)



km

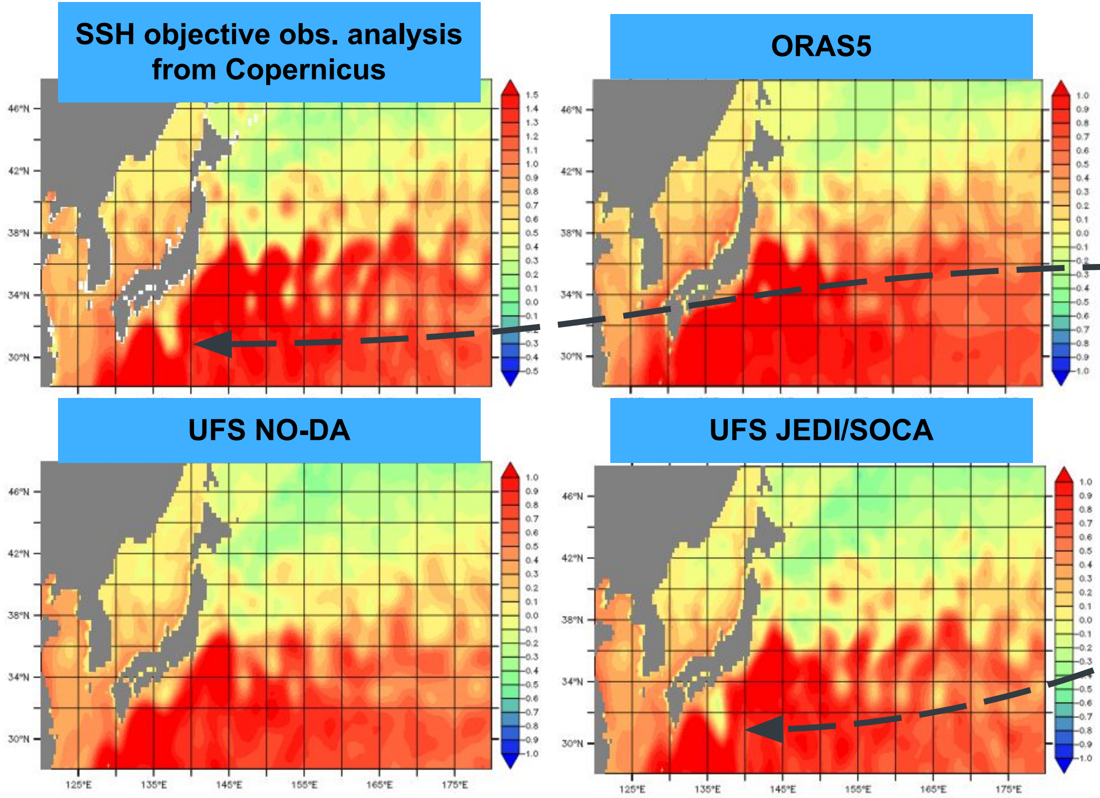
Vert. Length Scales ($\mathbf{C}_v$) at 45°S



Number of layers

Courtesy of Katie Lukens

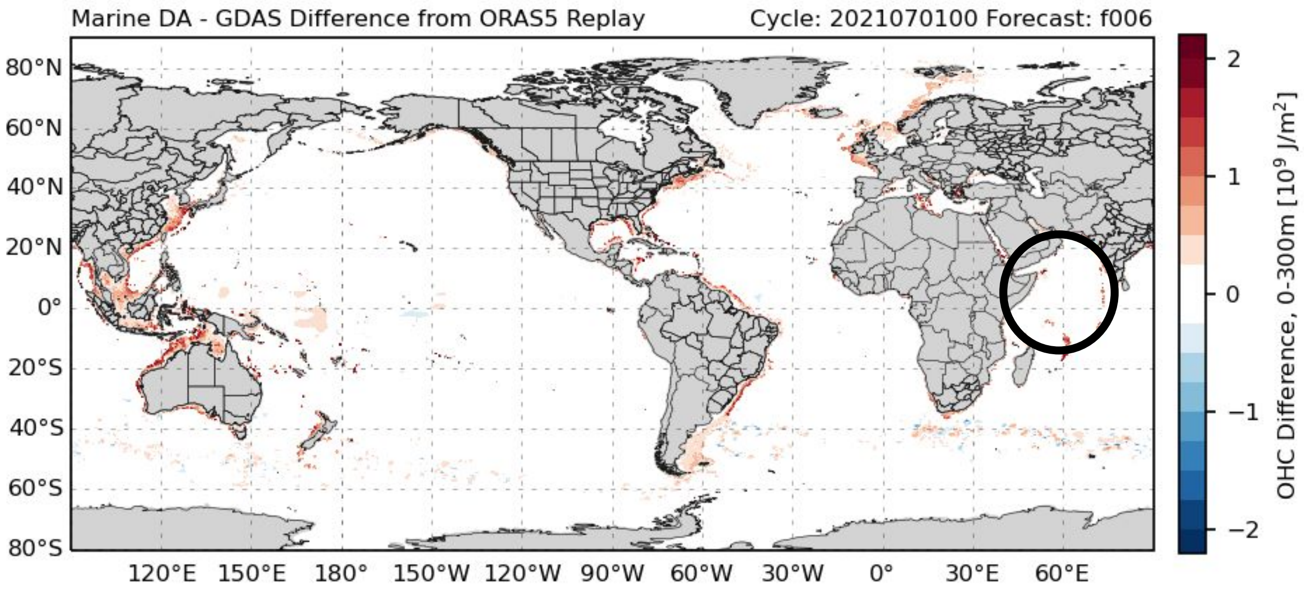
Marine DA: Altimeter Observations



SSH assimilation is critical for the placement of ocean mesoscales and fronts.

Courtesy of Guillaume Vernieres

Marine DA: Upper Ocean Heat Content



Comparison of ocean heat content (OHC) 0-300m from f006 background forecasts in the GFSv17 C02 prototype to the Ocean ReAnalysis System 5 (ORAS5) Replay during the period July 1-11, 2021.

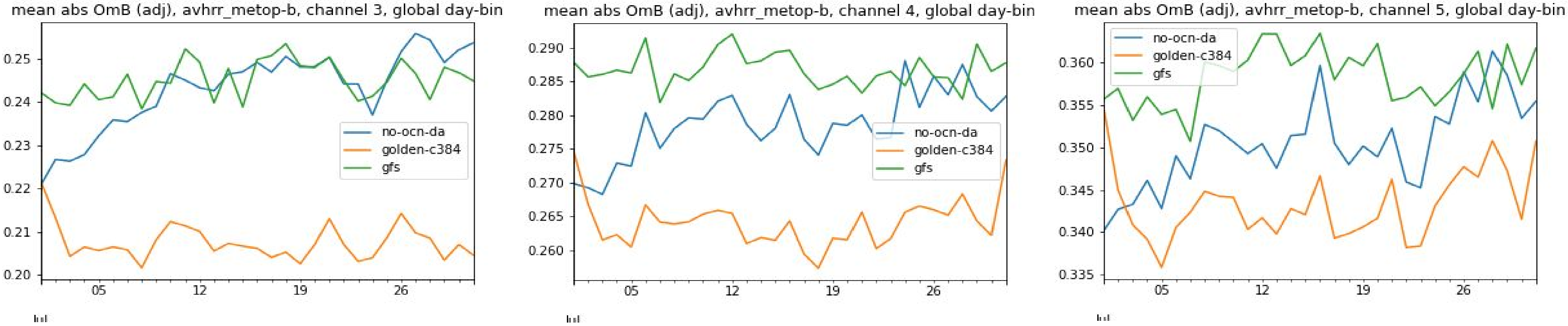
- Differences in OHC increase with time and are largest along the Equator and in areas with strong currents
- Issue with gravity wave propagation is revealed (black circle)
- In situ obs (not yet assimilated) may help reduce the larger differences along the Equator

Courtesy of John Steffen

Marine DA: Radiances

Atmos Observation-Minus-Background (OMB) diagnostics that correspond to SST-sensitive radiance obs are smaller when the ocean provides a better foundation temp. (orange lines), implying that marine DA has a positive impact on the atmospheric side. → **Improvements in marine DA should help further improve the atmosphere.**

Daily Mean OMBs for SST-sensitive Radiances



Coupled C384, ¼ deg Ocean (marine DA off)

GFS (NOAA operations, no ocean model)

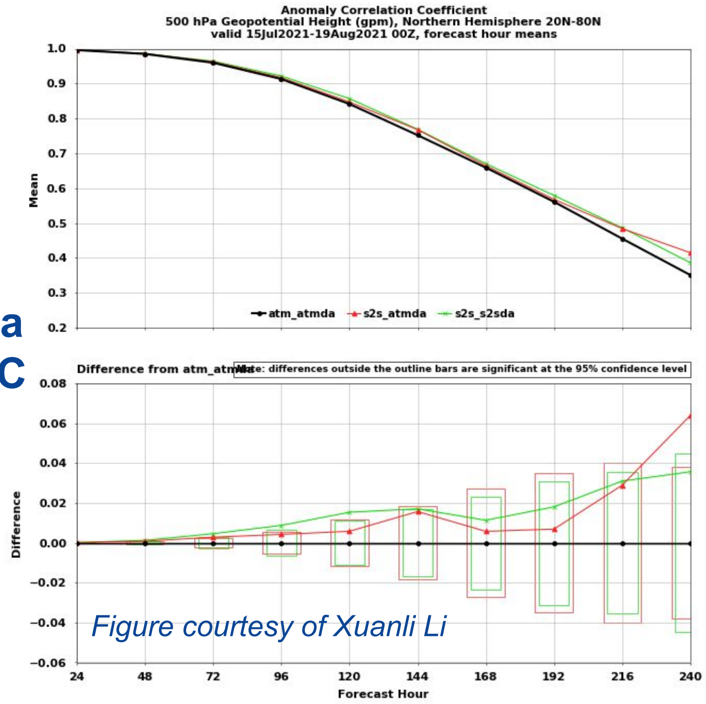
Coupled C384, ¼ deg Ocean (marine DA on)

Courtesy of Andy Eichmann

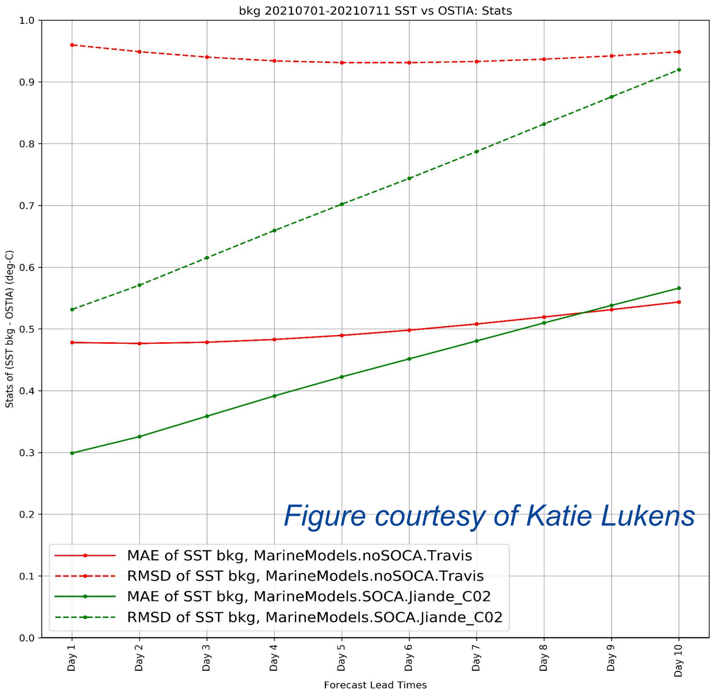
Marine DA: 3DVar Cycling Results

ATM model, ATM DA
S2S model, ATM DA
S2S model, S2S DA

500 hPa NH ACC



Mean stats per lead time for July 1-11, 2021



Valid for 60°S-60°N

SST vs. OSTIA

Weakly coupled DA improves upon the coupled forecast model only

Weakly Coupled DA: Land

Land DA: Background

Courtesy of Clara Draper

- All major national NWP centers use land DA to improve initialization of their land states, leading to improved NWP forecasts
  - Land DA is typically applied to the soil moisture, soil temperature, snow amount, and snow temperature
  - At many global NWP centers, land DA is done as a separate step to atmospheric DA using different algorithms, i.e. weakly coupled DA

- The land DA used in NOAA's global NWP system (GFS/GDAS) is behind international practice
  - Includes only a very simple snow depth analysis
  - (regional system does have a simple soil analysis)

- As a part of a major upgrade to our global NWP system (GFSv17), we are upgrading our land DA system
  - Upgrading the snow depth analysis
  - Introducing our first global soil temperature and soil moisture analysis

Land DA: Soil Moisture and Temperature

- Other centers update soil moisture and soil temperature from observations of screen-level T and q (and in some cases, satellite soil moisture information), using weakly coupled DA
- Instead, we are investigating expanding the atmospheric DA to also do the soil analysis
  - Also, investigating introducing the assimilation of screen-level T and q (into land and/or atmos)
- Initial tests conducted using only the EnKF component of the GSI (for the land and atmosphere) DA
  - Testing the general approach, investigate the best land/atmosphere coupling for the assimilation of screen-level obs, and for updating the soil updates

Courtesy of Clara Draper

Land DA: Soil Analysis Experiments

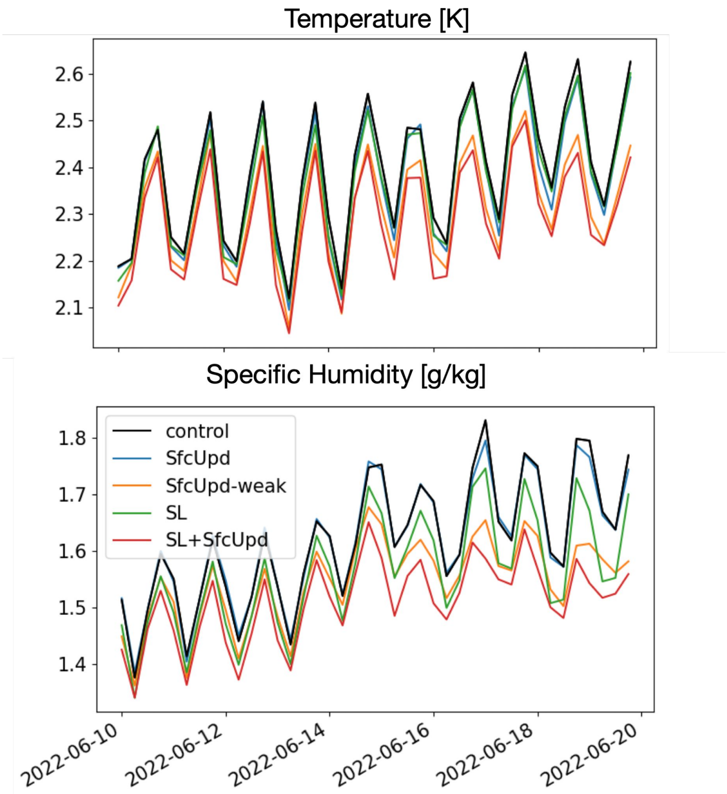
	Update atmosphere*		Update soil moisture+temperature	
	from standard atmos obs	from screen-level obs	from standard atmos obs	from screen-level obs
Control	x			
Screen	x	x		
SfcUpd	x		x	
Screen+SfcUpd	x	x	x	x
SfcUpd-Weak	x			x

* All experiments include bug-fixes/updates to the assimilation of conventional q obs.

- 30 day experiment from June 5, 2022, at 0.5° using GFSv17 HR-1 tag
- Includes a new land model (Noah replaced with Noah-MP)
- Note: Not using the new land parameter-based ensemble perturbation scheme

Draper et al, (in prep)

Soil DA: Comparison to Screen-Level O-F



Mean RMSE

	T [K]	q [g/kg]
Control	2.39	1.62
Screen	2.37	1.56
SfcUpd	2.37	1.61
Screen+SfcUpd	2.28	1.51
SfcUpd - weak*	2.31	1.55

shaded = sig. difference from Control

- All experiments improve the O-F
- Best results from Screen+SfcUpd (3-4% reduction)
- Followed by SfcUpd-weak (screen-level forecasts constrained more by updated surface than atmosphere)

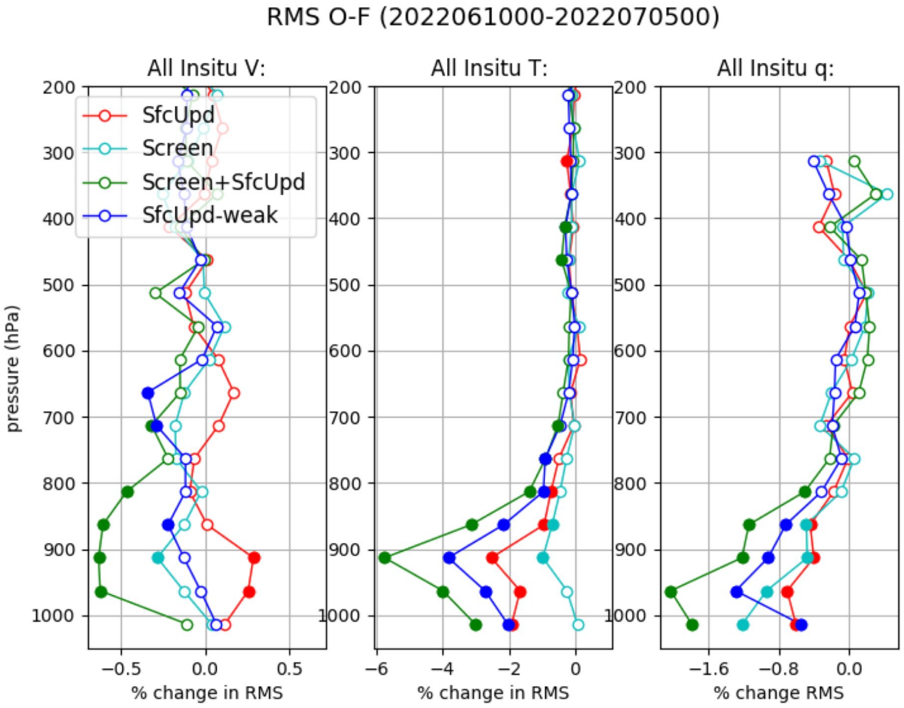
Draper et al, (in prep)

Soil DA: Comparison to conventional obs

Mean RMSE at ~900 hPA

	T [K]	q [g/kg]
Control	1.29	1.67
Screen	1.28	1.66
SfcUpd	1.27	1.65
Screen+SfcUpd	1.24	1.65
SfcUpd - weak*	1.25	1.66

- Best results from Screen+SfcUpd: Small, but consistent improvement (2-5%)
- SfcUpd-weak again next best
- Improvements again are from the surface update (with screen-obs)



Full circle = significant difference from Control

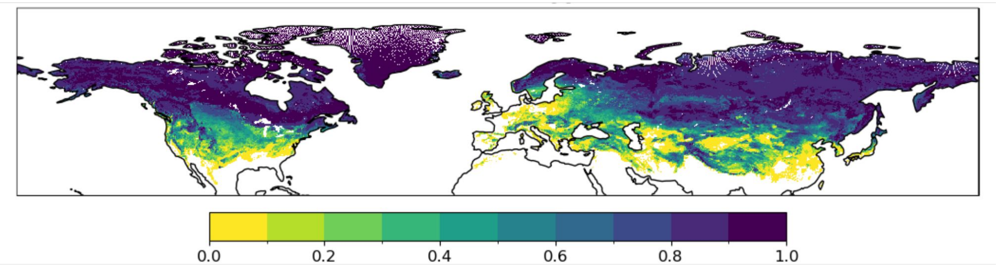
Draper et al, (in prep)

Land DA: Snow

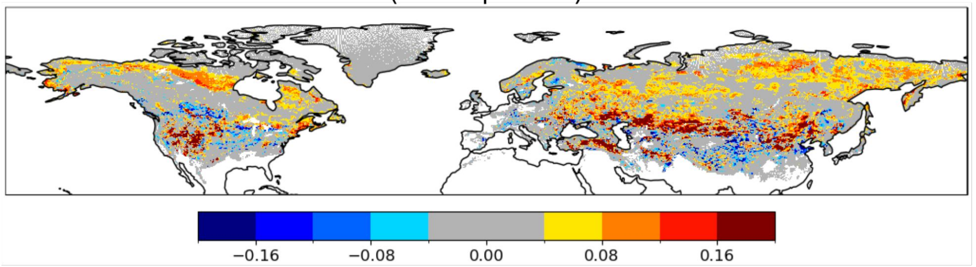
- Upgrading the snow depth analysis to directly assimilate assimilate:
  - Station snow depth from GTS
  - Snow cover from NOAA's Interactive Multisensor Snow and Ice Mapping System (IMS)
- Assimilation done with a 2DVar
  - based on the Optimal Interpolation (OI) DA algorithm used elsewhere (Brasnett,1999; ECCC, ECMWF)
  - Coded in JEDI
- Plots shows snowpack evaluation for one year experiment at ~13 km, using land-only model forced by ERA-5

Courtesy of Clara Draper

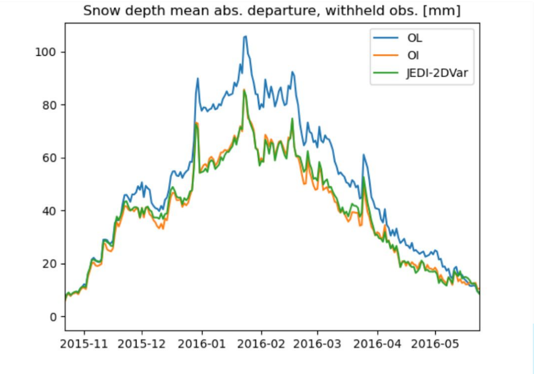
Threat score against IMS snow cover, no snow assimilation



Improvement in threat-score, from assimilation of IMS and GHCN (not independent!)



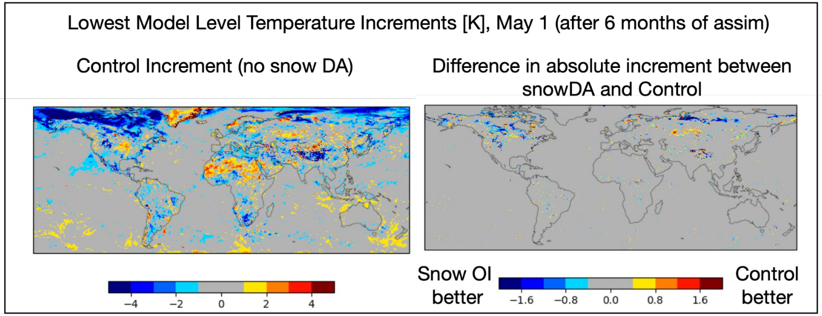
Mean Absolute Error in Snow Depth [mm] From assimilation of GHCN station snow depth ops (evaluated against withheld obs)



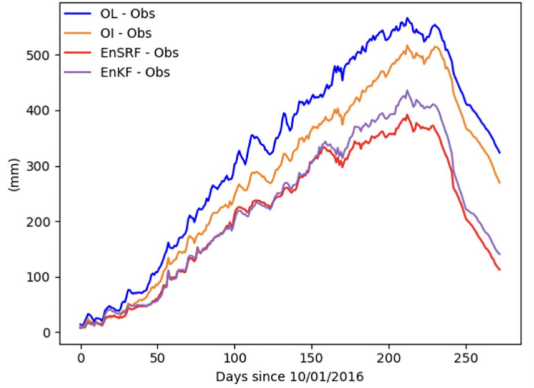
Snow DA: Next Steps

Courtesy of Clara Draper

- Currently working towards forecast impact experiments in the atmospheric system
- An earlier version was implemented in PSL's reanalysis replay, showing small improvements in the low-level temperatures
- Longer term: move towards same approach as for soil states, and implement a Hybrid snow depth DA
- Early work shows EnKF outperforms OI/2DVar, due to better capturing very large model errors over deep snow
  - But cannot assimilate snow cover where there is no snow in model (ensemble spread equals 0)
  - Hybrid will resolve this issue (combine advantages of Var and ensemble Bs)



RMS(O-F) snow depth [mm]
Plot from T. Gichamo.



Weakly Coupled DA: Aerosols

Aerosol DA: Overview

Currently one of the few, if not only, operational centers to not have aerosol DA initializing their aerosol prediction system

- **6-hourly cycles 4x a day with early and late cycles**
  - Early cycle to initialize the GEFS long forecasts (one deterministic aerosol analysis provided from the cycling DA system)
  - Late cycle to initialize the high resolution GDAS forecast (without radiative feedback)
- **Analysis resolution C192L127 (~0.5 deg); background resolution C1152L127 (~9km)**
- **3DVar FGAT with 3-hourly backgrounds**
- **VIIRS EPS 550nm AOD from S-NPP, N20, N21**

Courtesy of Cory Martin

Aerosol DA: Quality Control and Error Assignment

- **Basic QC of the VIIRS AOD product include:**
  - Rejecting ‘low quality’ obs as defined by NESDIS
  - Inflating errors when obs differ significantly from the forecast
  - Fixing the valid ob range from 0 to 4.9 AOD
  - Only using observations between 60N-60S
- **Exploring the use of Variational Bias Correction**
  - Biases between platforms that can be corrected with changes in coefficients every analysis cycle
  - Normally, this uses an independent anchor but ECMWF/CAMS has used NOAA-20 to anchor other VIIRS obs

Courtesy of Cory Martin

Aerosol DA: Error Covariance Estimation and Tuning

Because we are running a 3DVar analysis, the background error covariance matrix is essential to the performance of the system.

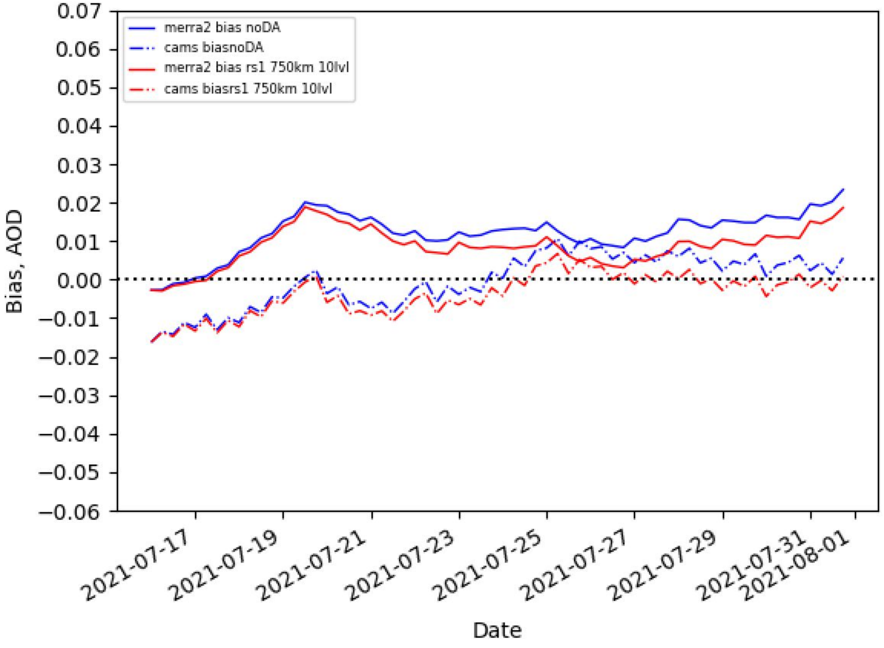
Multiple methods for computing B have been explored:

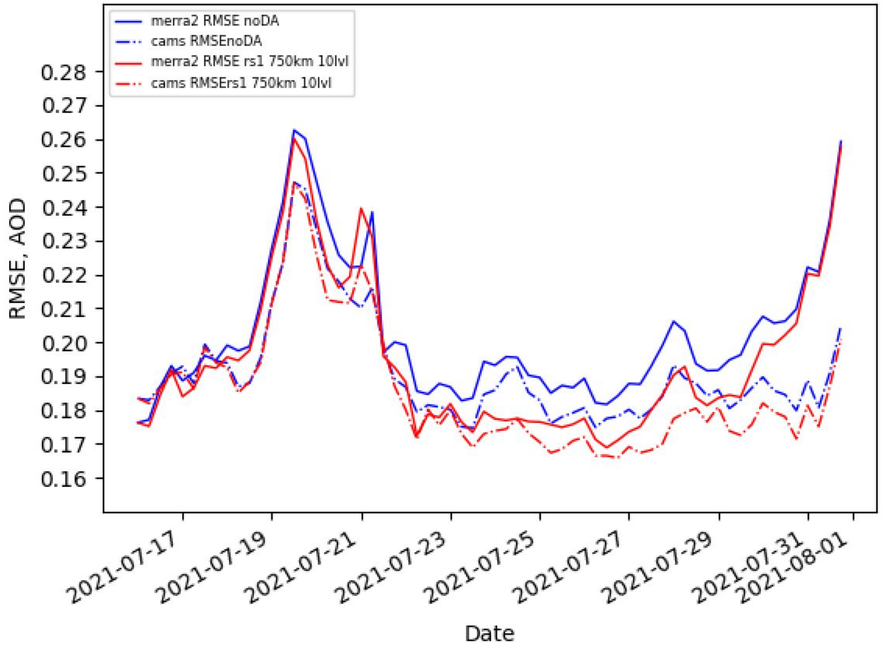
- **“NMC Method” (lagged forecast pairs)**
- **“BUMP” estimates from an offline ensemble**
- **Time varying covariance**
  - Uses background from each cycle to compute variance from neighboring gridpoints

Our plan is a hybrid of the 2nd and 3rd approaches

Courtesy of Cory Martin

Aerosol DA: Comparison to MERRA2/CAMS





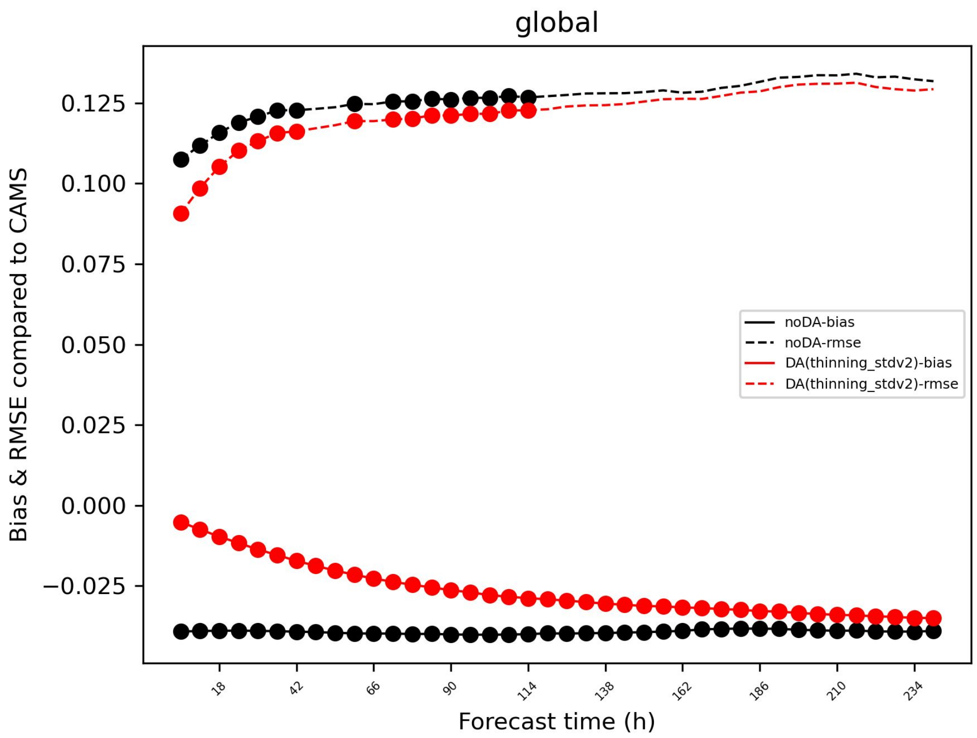
DA is improving the forecast, but still more tuning is needed.

Courtesy of Andy Tangborn

Aerosol DA: Impact on AOD Forecasts

Student T-test suggests that (somewhat limited sample size) VIIRS AOD assimilation can have a significant impact on the model's forecast of AOD.

"Significant" reduction of RMSE out to ~5 days and mean bias reduction out to 10+ days are possible.



Courtesy of Yaping Wang

Transition to JEDI

Joint Effort for Data assimilation Integration (JEDI)

JEDI is a project within the Joint Center for Satellite Data Assimilation (JCSDA)

JEDI provides a **software infrastructure for data assimilation** that

- is model agnostic
- is generic and portable, from toy models running on laptops to operational Earth system coupled models running in the cloud.
- enables DA on the model native grid
- does not impose one specific DA methodology or algorithm
- provides a framework for rapid uptake of new observations into operations with generic observation handling and modeling
- encourages implementation of model-independent observation operators
- provides a unified Interface for Observation Data Access (IODA)

JEDI is intended for **scientific exploration** and **operational forecasting**.

The keys to success are **separation of concerns** and **interfaces**.

Courtesy of Cory Martin

JEDI Transition

Notional schedule for UFS-applications is not (and may not perfectly align with) transition of JEDI infrastructure. This necessitates an incremental, multi-tiered approach:

1. Observation Processing Reengineering – Replace legacy “obsproc” software with JEDI-based tools (IODA + UFO)
2. From GSI to JEDI, starting with GFS/GDAS
   a. UFO development and acceptance
   b. Validation of ensemble and variational solvers
   c. Completely replace GSI-based solvers with JEDI (starting with hybrid 4DEnVar as is currently operational)
3. From GSI to JEDI for other atmospheric applications (RRFS, HAFS, and RTMA, all of which will leverage GSI in initial operational capabilities)
4. New capabilities for non-atmospheric components directly in JEDI

Courtesy of Cory Martin

JEDI Transition: Evaluation and Prototyping

Evaluation

- Forward Operators and Quality Control Procedures
- Ensemble and Variational Analyses
- Scalability, Reproducibility, Timing
- Full System Validation and Verification

Prototyping

- Libraries and Software Infrastructure
- Integration into Existing Workflow
- “Plumbing” Tests and Prototypes
- Operational-like Configurations

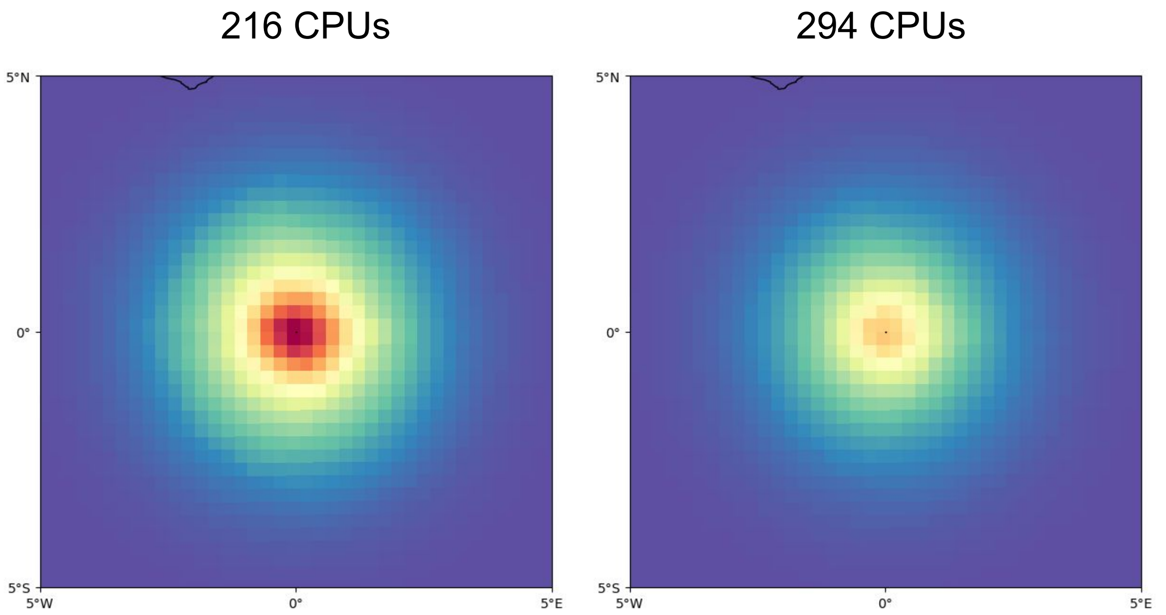
Courtesy of Cory Martin

JEDI Transition: Solver

GSI background error added to JEDI by NASA GMAO

Early testing included some single ob sensitivity tests, which resulted in differences with different PE counts

Increment | 0,0 | Air T at 1000 hPa

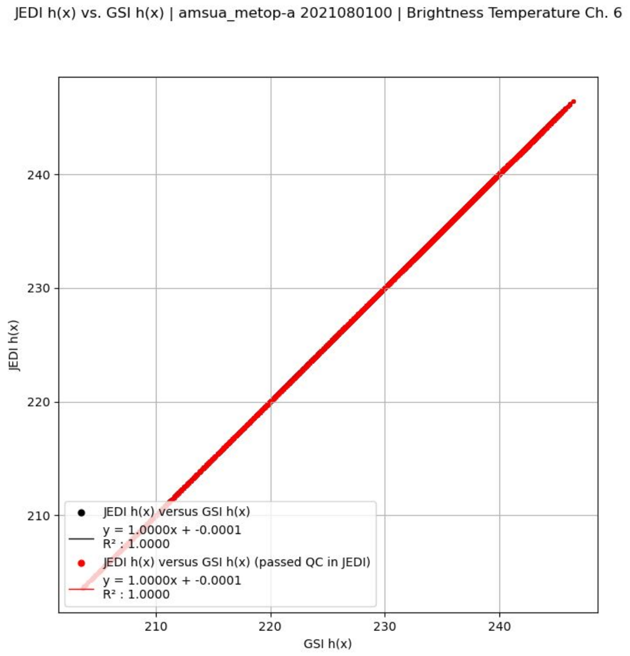


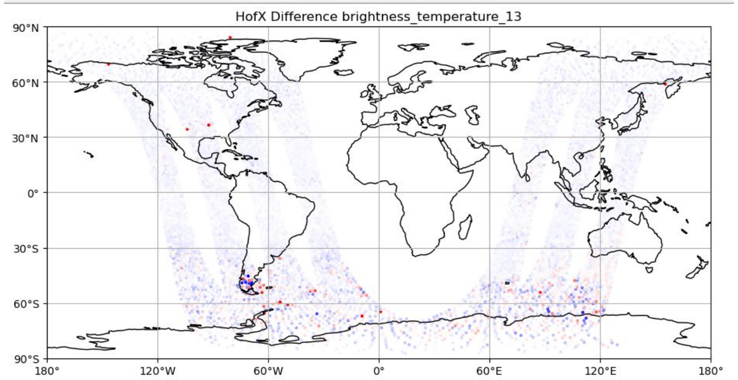
Figures courtesy of Alex Swan, Mississippi State University

JEDI Transition: Forward Operators

Most validation work to date has focused on the UFO

- Model simulated observations (H(x))
- Quality Control
- Error Assignment





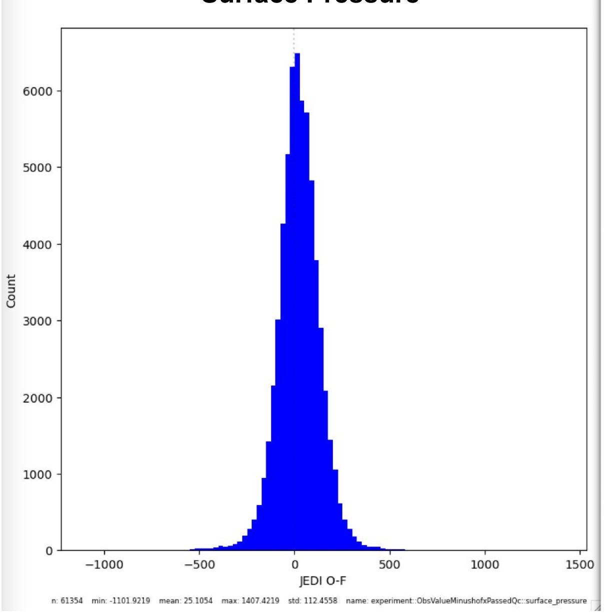
For the same model fields, do we get the same simulated observations? Yes!
<- Interpolation leads to some differences though

Courtesy of Cory Martin

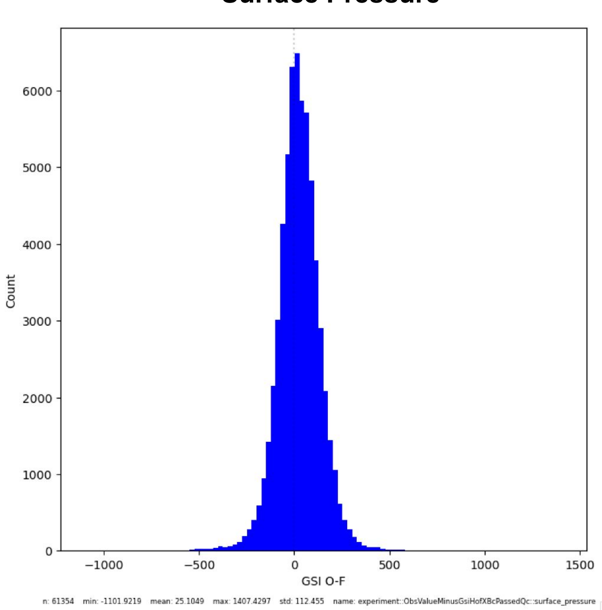
JEDI Transition: QC and Obs Errors

After translating all of these QC procedures from Fortran code to YAML, we need to verify that things are working as intended **for every observation type.**

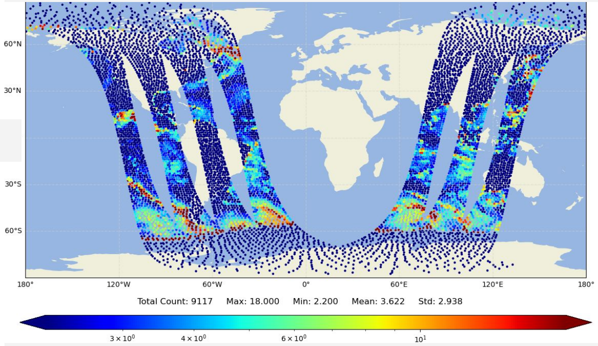
JEDI O-F passing JEDI QC | sfc Surface Pressure



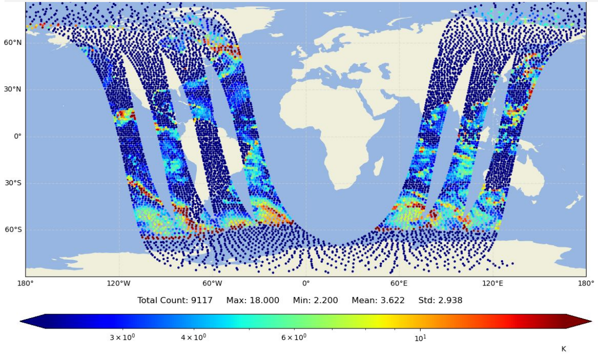
GSI O-F passing GSI QC | sfc Surface Pressure



GSI Initial Obs Error AMSU-A N19 Ch 2



UFO Initial Obs Error AMSU-A N19 Ch 2



Courtesy of Cory Martin

Summary

- Development by NCEP/EMC and colleagues at PSL/GSL/JCSDA/others continues towards a weakly coupled GFS cycling system with an implementation target of early 2026.
- While the atmospheric DA will continue to use GSI software for the near future, DA for the new components (ocean/ice/snow/aerosol) will be JEDI-based.
- GSI-based atmospheric DA upgrades for GFSv17 include all sky advancements and scale-dependent localization.
- The transition of the atmospheric DA to JEDI is occurring in parallel with the weakly coupled system development.

Questions

Contact:

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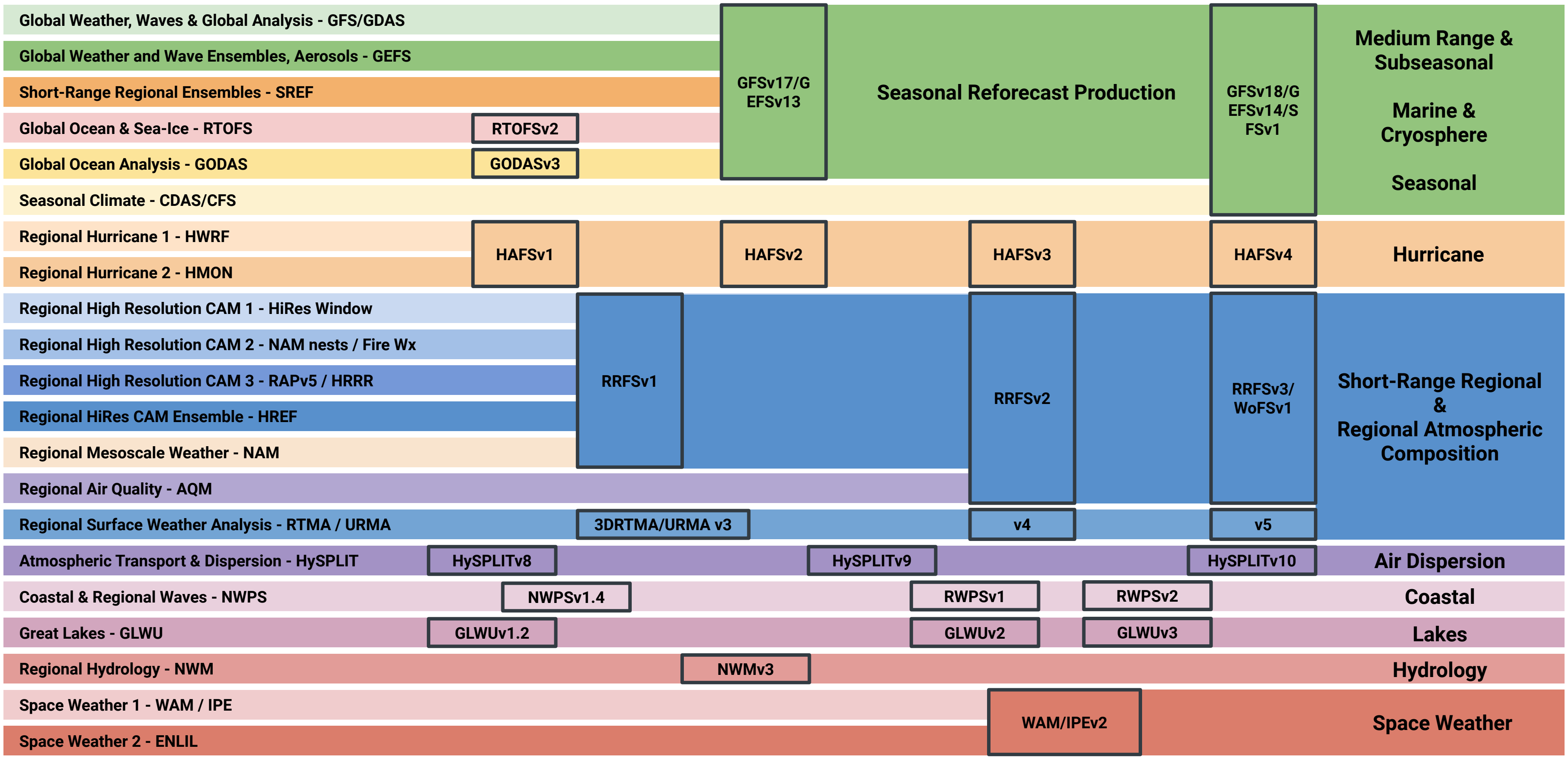
NOAA/NWS/NCEP/EMC
catherine.thomas@noaa.gov

Backup Slides

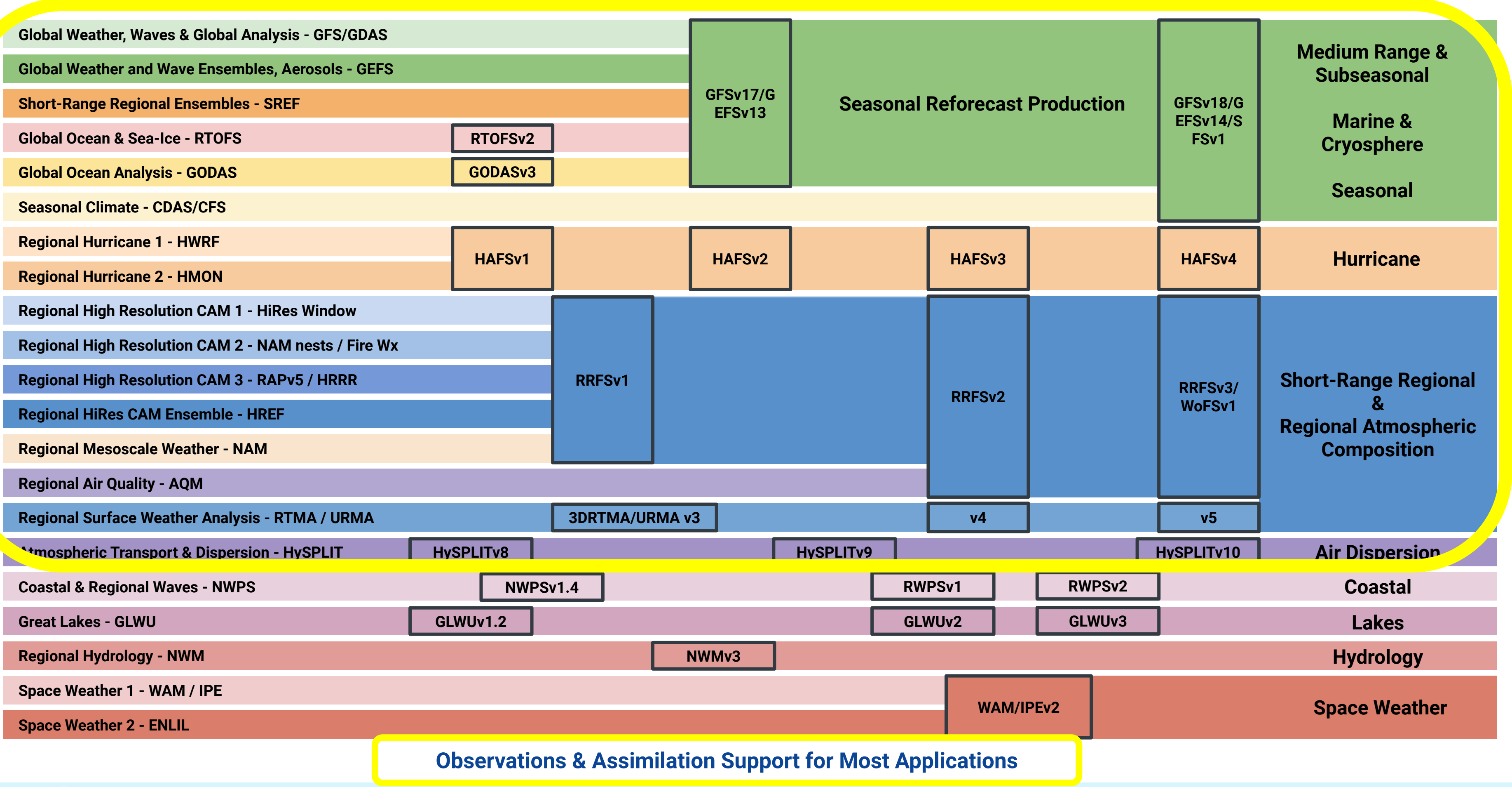
Historical Overview of NCEP Global Data Assimilation

<table>
<tr><th>Year</th><th>1991</th><th>1995</th><th>1998</th><th>2007</th><th>2012</th><th>2014</th><th>2015</th><th>2016</th><th>2017 - 2018</th><th>2019 - 2020</th><th>2021</th><th>2022</th></tr>
<tr><td>Analysis</td><td colspan="3">Spectral Statistical Interpolation</td><td colspan="9">Gridpoint Statistical Interpolation (GSI)</td></tr>
<tr><td rowspan="2">Algorithm</td><td colspan="4">3DVar</td><td colspan="3">Hybrid, 3DEnVar
T574/T254 L64
EnSRF, 80 ensembles</td><td colspan="2">Hybrid, 4DEnVar
T574/T574 (39 km) L64
EnSRF, 80 ensembles</td><td>Hybrid, 4DEnVar
T766/T766 (25 km) L64
EnSRF, 80 ensembles</td><td colspan="2">Hybrid, 4DEnVar
T766/T766 (25 km) L127
LETKF, 80 ensembles</td></tr>
<tr><td colspan="8"></td><td colspan="4">Near Sea Surface Temperature (NSST) Analysis - 3DVar for foundation temperature since 2017</td></tr>
<tr><td>Balance</td><td colspan="3"></td><td colspan="9">Tangent-linear Normal Model Constraint (TLNMC)</td></tr>
<tr><td>Satellite Data</td><td>NESDIS Retrievals</td><td colspan="6">● Direct Radiance Assimilation
● Clear-sky Radiance Assimilation</td><td colspan="4">● Direct Radiance Assimilation
● Correlated obs error for Hyperspectral IR sensors (2021)
● All-sky Framework for MW sensors
○ All-sky Assimilation for AMSU-A (2016) and ATMS (2019)
○ Non-precipitating cloud affected radiances are assimilated
○ Cloudy scenes are assumed to be overcast</td><td>● Direct Radiance Assimilation
● Correlated obs error for Hyperspectral IR
● All-sky Framework for ATMS/AMSU-A
○ Precipitation-affected data assimilated
○ Fractional cloud coverage accounted for
○ Consistent use of cloud microphysics assumptions between model and DA</td></tr>
<tr><td>Obs Operator</td><td></td><td colspan="2">Community Radiative Transfer Model (CRTM)</td><td colspan="4">CRTM Scattering Solver
Advanced Doubling & Adding Method (ADA)</td><td colspan="5">CRTM with Scattering Solver (ADA) + Simulation under Fractional Cloud Coverage (2017)
● Cloud Overlap (Total Cloud Cover)
● Two-column Radiance Calculation</td></tr>
<tr><td>Bias Correction</td><td colspan="2">Offline</td><td colspan="3">Two-step Bias correction
● VarBC for air-mass predictors
● Time-moving average of O-F for scan angle predictors</td><td colspan="7">Variational Bias Correction (VarBC) for all predictors</td></tr>
<tr><td rowspan="2">Forecast</td><td colspan="2">Spectral Model
Sigma Eulerian
T126
L18 (1991)
L28 (1993)</td><td colspan="5">Spectral Model
Hybrid Semi-Lagrangian (2007)
Zhao-Carr Microphysics(cloud water and ice)
T170 (105km) L42 (1998)
T574 (23km) L64 (2010)</td><td colspan="2">Spectral Model
Hybrid Semi-Lagrangian
Zhao-Carr Microphysics
T1534 (13km)
L64, Model Top 55km</td><td>FV3 Dynamic Core
GFDL Microphysics
5 Hydrometers
T1534 (13km)
L64, Model Top 55km</td><td colspan="2">FV3 Dynamic Core
GFDL Microphysics
5 Hydrometers
T1534 (13km)
L127, Model Top 80km</td></tr>
<tr><td colspan="6"></td><td colspan="6">Stochastic Physics Parameterization for Ensembles since 2015: SPPT (tendency), SHUM (moisture), and SKEB (winds)</td></tr>
<tr><td>Initialization</td><td colspan="3"></td><td colspan="6">Digital Filter Initialization (DFI)</td><td>No DFI</td><td colspan="2">4D Incremental Analysis Update (IAU)</td></tr>
</table>

16 years of development under the GSI code base



Global Weather, Waves & Global Analysis - GFS/GDAS
Global Weather and Wave Ensembles, Aerosols - GEFS
Short-Range Regional Ensembles - SREF
Global Ocean & Sea-Ice - RTOFS
Global Ocean Analysis - GODAS
Seasonal Climate - CDAS/CFS
Regional Hurricane 1 - HWRF
Regional Hurricane 2 - HMON
Regional High Resolution CAM 1 - HiRes Window
Regional High Resolution CAM 2 - NAM nests / Fire Wx
Regional High Resolution CAM 3 - RAPv5 / HRRR
Regional HiRes CAM Ensemble - HREF
Regional Mesoscale Weather - NAM
Regional Air Quality - AQM
Regional Surface Weather Analysis - RTMA / URMA
Atmospheric Transport & Dispersion - HySPLIT
Coastal & Regional Waves - NWPS
Great Lakes - GLWU
Regional Hydrology - NWM
Space Weather 1 - WAM / IPE
Space Weather 2 - ENLIL
RTOFSv2
GODASv3
GFSv17/G EFSv13
Seasonal Reforecast Production
GFSv18/G EFSv14/S FSv1
Medium Range & Subseasonal
Marine & Cryosphere
Seasonal
HAFSv1
HAFSv2
HAFSv3
HAFSv4
Hurricane
RRFSv1
RRFSv2
RRFSv3/ WoFSv1
Short-Range Regional & Regional Atmospheric Composition
3DRTMA/URMA v3
v4
v5
HySPLITv8
HySPLITv9
HySPLITv10
Air Dispersion
NWPSv1.4
RWPSv1
RWPSv2
Coastal
GLWUv1.2
GLWUv2
GLWUv3
Lakes
NWMv3
Hydrology
WAM/IPEv2
Space Weather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Regional Air Quality - AQM
RRFSv1
RRFSv2
RRFSv3/WoFSv1
Short-Range Regional & Regional Atmospheric Composition
Regional Surface Weather Analysis - RTMA / URMA
3DRTMA/URMA v3
v4
v5
Atmospheric Transport & Dispersion - HySPLIT
HySPLITv8
HySPLITv9
HySPLITv10
Air Dispersion
Coastal & Regional Waves - NWPS
NWPSv1.4
RWPSv1
RWPSv2
Coastal
Great Lakes - GLWU
GLWUv1.2
GLWUv2
GLWUv3
Lakes
Regional Hydrology - NWM
NWMv3
Hydrology
Space Weather 1 - WAM / IPE
Space Weather 2 - ENLIL
WAM/IPEv2
Space Weather
Observations & Assimilation Support for Most Applications

Commercial Weather Data Pilot

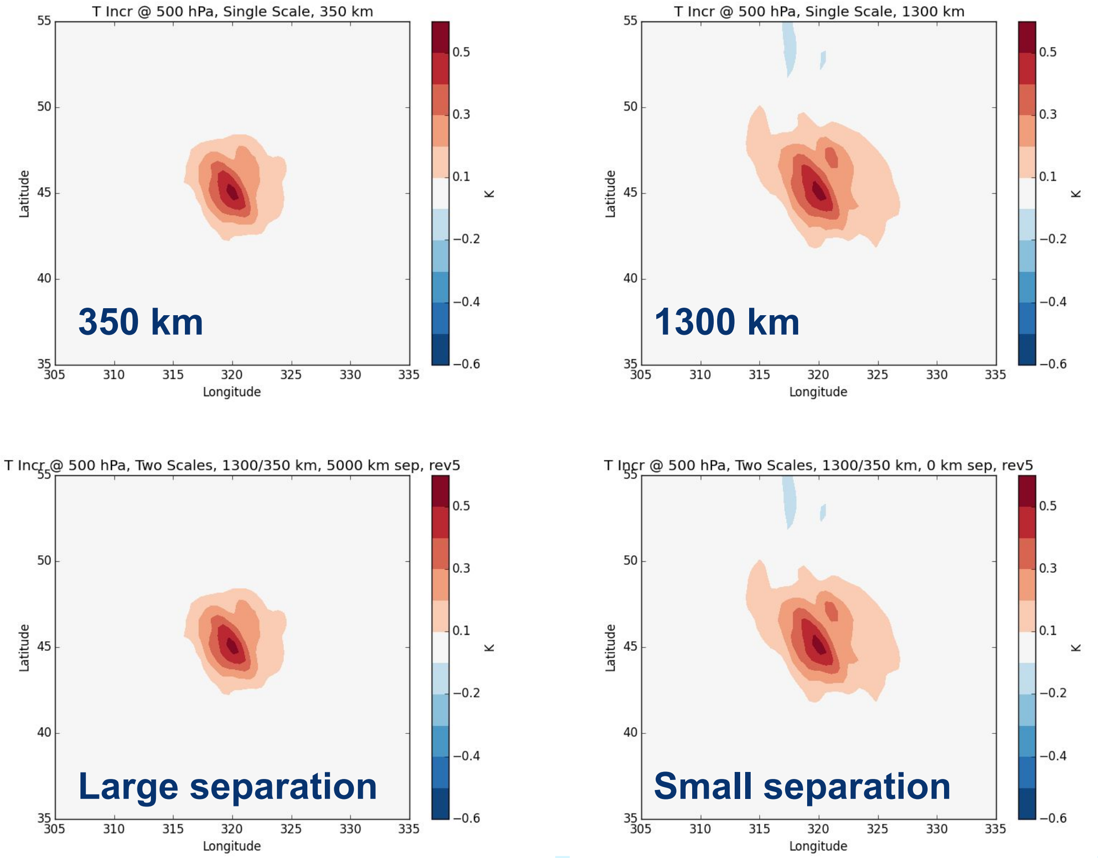
- In 2017, Taiwan and the U.S. decided not to proceed with the high-inclination polar orbit component of COSMIC-2
- Commercial Weather Data Pilot (CWDP) program: To assess the potential viability of commercial weather data in NOAA's weather modeling and forecasting
- CWDP Round 1 in 2016-2017:
  - Bring radio occultation data from commercial companies to NOAA
  - Awarded to GeoOptics, Inc. and Spire Global, Inc.
  - Focus: Provide space-based GNSS RO data, to demonstrate data quality and potential value to NOAA's weather forecasts and warnings.
- CWDP Round 2 in 2018:
  - Awarded to GeoOptics, Inc., Spire Global, Inc., and Space Sciences and Engineering LLC
  - Results: Commercial sector capable of providing RO data supporting NOAA's operational products and services.
- CDP Radio Occultation Data Buy (RODB) contracts:
  - RODB-1: Awarded to GeoOptics, Inc., and Spire Global with a series of delivery orders (DOs) in 2020-2023
  - RODB-2: Awarded to Spire Global and PlanetiQ in 2023 with a 5-year ordering period

Scale-Dependent Localization: GFS

- Single temperature observation tests for GFS were performed.
- **Two-scale tests using varying scale separation reproduced the single scale tests.**
- Variable- and time-dependent localization are available as well.

Single Scale

Two Scales 350/1300 km



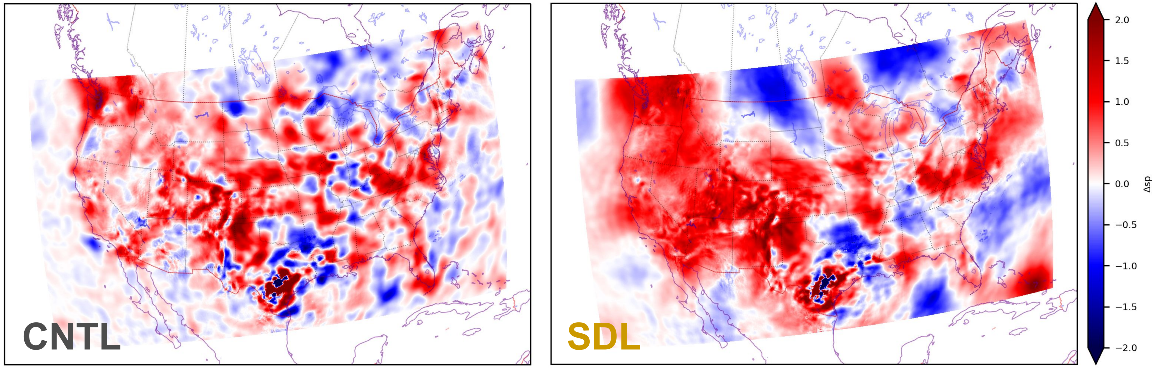
Scale-Dependent Localization *(Sho Yokota)*

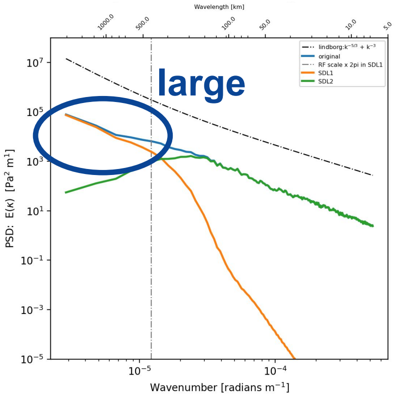
Spatial scale depends on the power spectra of ensemble perturbations

→ Smoother increment of surface pressure → Smaller imbalance

Power spectrum density of ens perts (mem #1) of ps and lowest-level T in each scale of SDL

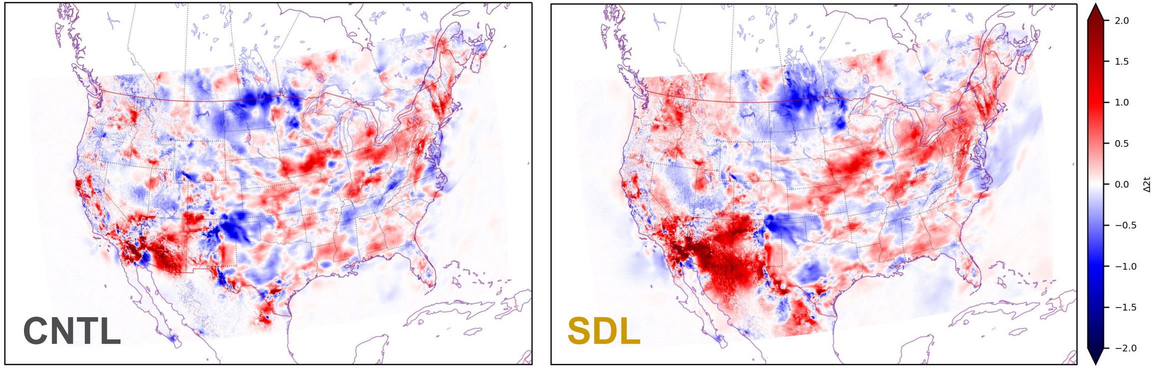
surface pressure (hPa)

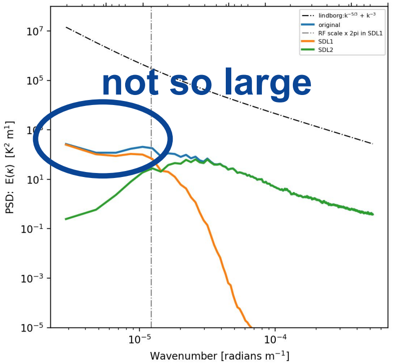




surface temperature (K)

EnVar analysis increment at 04z on 05/11





Results: Self-Analysis Scorecard and Day-5 ACC

2-Band W#16SS

Anomaly Correlation Coefficient

			N. America						N. Hemisphere						S. Hemisphere					
			Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10
2-Band W#16SS Anomaly Correlation Coefficient	Heights	250hPa					M	M					M	M					M	M
		500hPa					M	M	▾				M	M					M	M
		700hPa	▾				M	M	▼				M	M	▼				M	M
		1000hPa					M	M					M	M					M	M
	Vector Wind	250hPa	▴				M	M	▲				M	M	▲				M	M
		500hPa					M	M	▲				M	M	▲				M	M
		850hPa	▴				M	M	▲				M	M					M	M
	Temp	250hPa	▲				M	M	▲				M	M	▲				M	M
		500hPa	▴				M	M	▲				M	M					M	M
		850hPa	▴				M	M	▲				M	M	▴				M	M
	MSLP	MSL					M	M					M	M					M	M

3-Band

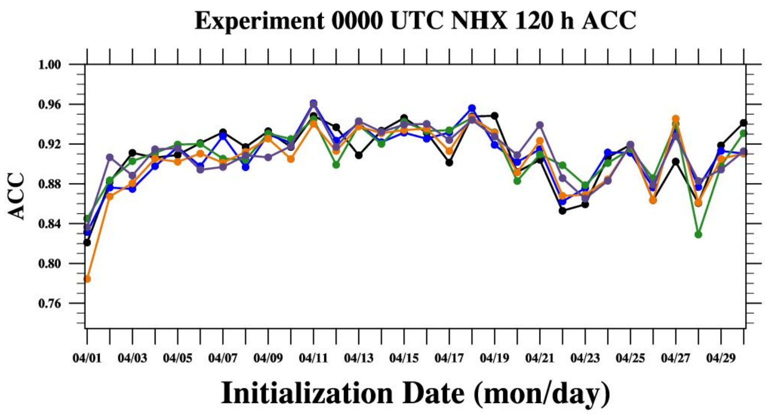
Anomaly Correlation Coefficient

			N. America						N. Hemisphere						S. Hemisphere					
			Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10
3-Band Anomaly Correlation Coefficient	Heights	250hPa					M	M					M	M	▾				M	M
		500hPa					M	M					M	M	▼				M	M
		700hPa					M	M	▼				M	M	▼				M	M
		1000hPa					M	M					M	M					M	M
	Vector Wind	250hPa	▲				M	M	▲				M	M	▲				M	M
		500hPa	▲				M	M	▲				M	M	▲				M	M
		850hPa	▲				M	M	▲	▴			M	M	▲				M	M
	Temp	250hPa	▲				M	M	▲	▲			M	M	▲				M	M
		500hPa	▲				M	M	▲				M	M	▲				M	M
		850hPa	▲				M	M	▲	▲			M	M	▲				M	M
	MSLP	MSL					M	M					M	M					M	M

Scorecard Symbol Legend

▲	sdl_exp_3band_1000_300_150 is better than control_MarApr_2023 at the 99.9% significance level	▼	sdl_exp_3band_1000_300_150 is worse than control_MarApr_2023 at the 99.9% significance level
▴	sdl_exp_3band_1000_300_150 is better than control_MarApr_2023 at the 99% significance level	▾	sdl_exp_3band_1000_300_150 is worse than control_MarApr_2023 at the 99% significance level
	sdl_exp_3band_1000_300_150 is better than control_MarApr_2023 at the 95% significance level		sdl_exp_3band_1000_300_150 is worse than control_MarApr_2023 at the 95% significance level
	No statistically significant difference between sdl_exp_3band_1000_300_150 and control_MarApr_2023		Not statistically relevant

Dates: 20230401-20230430



Control: 0.909

2-Band W#5SS: 0.909

2-Band W#20SS: 0.910

2-Band W#16SS: 0.904

3-Band: 0.910

Results: Self-Analysis Scorecard ACC, Ops Res

			N. America						N. Hemisphere						S. Hemisphere					
			Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10	Day 1	Day 3	Day 5	Day 6	Day 8	Day 10
Anomaly Correlation Coefficient	Heights	250hPa					M	M					M	M		▴			M	M
		500hPa					M	M					M	M		▴			M	M
		700hPa				▼	M	M				▼	M	M					M	M
		1000hPa					M	M				▼	M	M		▴			M	M
	Vector Wind	250hPa					M	M	▲				M	M	▲				M	M
		500hPa	▴				M	M	▲				M	M	▲	▴			M	M
		850hPa	▲				M	M	▲				M	M	▴				M	M
	Temp	250hPa	▲				M	M	▲				M	M	▲	▲			M	M
		500hPa	▴				M	M	▲				M	M	▲	▴			M	M
		850hPa					M	M	▲				M	M	▲				M	M
	MSLP	MSL					M	M				▼	M	M		▴			M	M

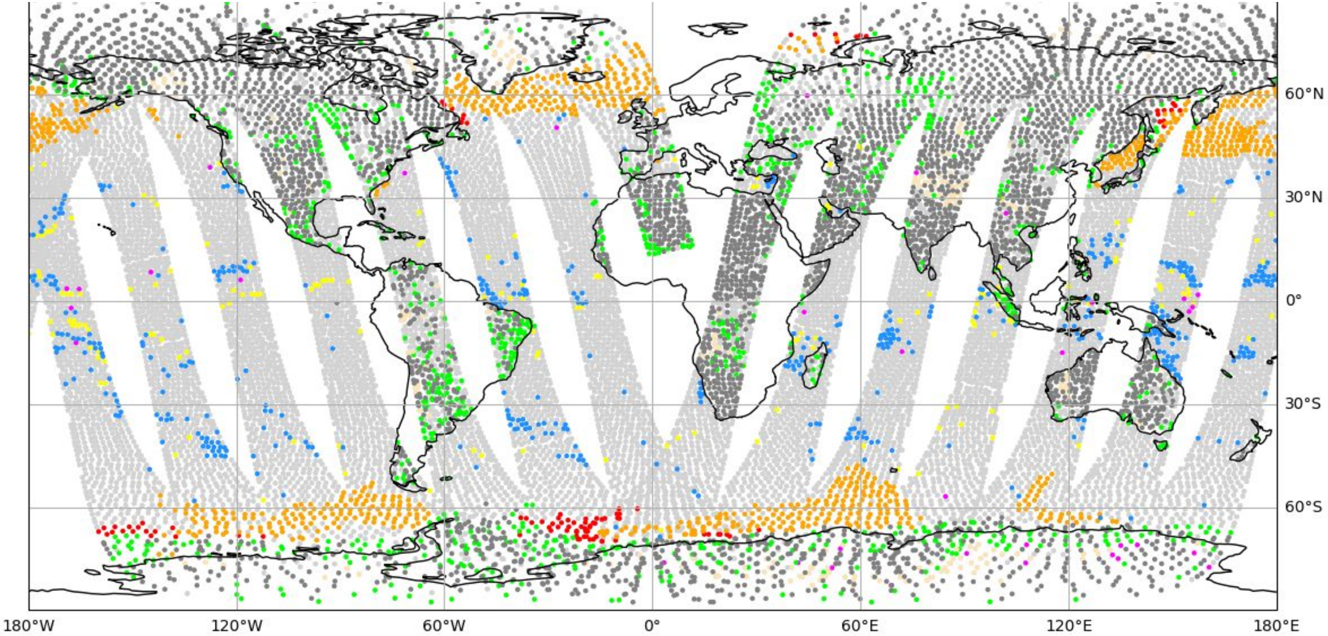
Plans for All-sky Radiance Assimilation *(Emily Liu)*

<table>
<tr><th></th><th>GFS.V16.3.0 (November 2022)</th><th>GFS.V17</th></tr>
<tr><td rowspan="2">OBS
AMSU-A
ATMS</td><td colspan="2">Antenna-corrected temperature (SDR)</td></tr>
<tr><td colspan="2">Include precipitation-affected data over ocean (true all-sky)</td></tr>
<tr><td rowspan="3">Obs Operator

(CRTM)</td><td>CRTM-2.4.0
● Cloud optical table based on GFDL model PSD
● Bug fix for surface emissivity Jacobian under scattering conditions</td><td>CRTM-2.4.1
● Cloud optical table based on Thompson model particle size distribution
○ table characterized by effective radius
○ table characterized by hydrometeor mixing ratio</td></tr>
<tr><td colspan="2">● All hydrometeors and fractional coverage are considered in simulated BT
● Fractional coverage is considered by cloud averaged overlap assumption
● Two-column BT calculation</td></tr>
<tr><td colspan="2">Absorption/emission and multiple scattering by precipitating particles</td></tr>
<tr><td rowspan="5">Analysis</td><td>● Update GSI-Model interface to read in precipitating hydrometeors</td><td>● Update GSI-Model interface to read in extra prognostic variables from Thompson Physics (number concentration for cloud ice and Rain)</td></tr>
<tr><td colspan="2">● Data thinning - no preference
● Hydrometeor control variables: ql, qi, qr, qs, and qg
● General precipitation screening removed, only filter out highly scattering scenarios</td></tr>
<tr><td>● Additional QC: cold air outbreak check</td><td>Re-examine CAO check</td></tr>
<tr><td>● At each observation footprint (performed at each outer loop)
● Calculate the GFDL cloud fraction profile
● Calculate the GFDL effective radius for each hydrometeor</td><td>● At each observation footprint (performed at each outer loop)
● Calculate GFDL cloud fraction profile (check update)
● Calculate effective radius for each hydrometeor based on Thompson physics</td></tr>
<tr><td colspan="2">● Symmetric observation error model - error is a function of averaged cloud amount predicted from observation and background
● Variational bias correction - use data samples contain consistent cloud information in the observation and background</td></tr>
<tr><td>Bkg Error</td><td colspan="2">● Flow dependent through ensembles or all hydrometers
● Static: 5% of the background hydrometeor</td></tr>
<tr><td>Obs Error</td><td>● Symmetric observation error model - error predictor is the average of cloud amount from background and observation)</td><td>● Symmetric observation error model - recalculate due to change in the forecast model including cloud physics</td></tr>
<tr><td>Initialization</td><td colspan="2">4D Increment Analysis Update (IAU) without increments from hydrometeors</td></tr>
</table>

Quality Control for Radiances Affected by Surface and Hydrometers

The light grey indicates the data passed QC and assimilated. Observations with larger innovations, greater sensitivity to surface emissivity, inconsistent quality control for similar channels, and invalid retrieved cloud liquid water are not assimilated. In addition, observations under situations where either the forecast model (e.g. cold air outbreak) or the observation operator (e.g. extreme scattering by precipitation hydrometeors) performs poorly are also excluded from assimilation. The QC procedures indicated by various colors are summarized below:



- Innovation check (observation-calculation difference > threshold)
- Inter-channel consistency check for tropospheric channels
- Cloud liquid water retrieval check
- Surface emissivity sensitivity check (remove it too sensitive)
- Cold air outbreak (CAO - situation where model consistently fails to predict super-cooled water)
- 54 GHz precipitation check (over land only)
- 52 GHz thick cloud check (over land only)
- 53 GHz scattering check (observation operator is less accurate)

For input data after thinning: ~65% assimilated globally; ~90% over ocean assimilated

Replace IR Cloud Detection from MMR to CADS

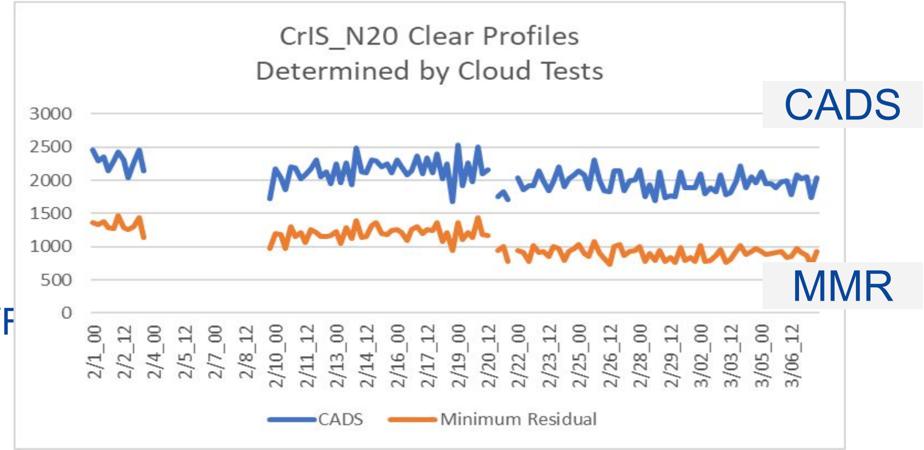
Minimum Residual cloud detection (MMR - Ops)

- Was designed for legacy instruments (HIRS, GOES-Sounder)
- Works consistently for AIRS and IASI
- Has a bias correction drift and reduction in observations for CrIS

Cloud and Aerosol Detection Software (CADS)

- Currently used for AIRS, IASI, and CrIS at ECMWF
- Is expected to work for future hyperspectral instruments (MTG-IRS, IASI-NG, etc.)
- Has capabilities to detect aerosols and trace gases if appropriate channels are available.
- Have not observed a bias correction drift and observations counts are consistent with IASI (need to test with longer time period)

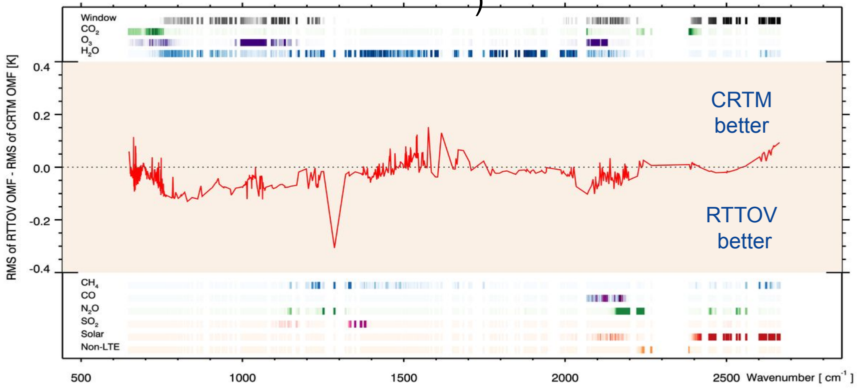
Clear FOV Counts for 962.51cm^{-1}



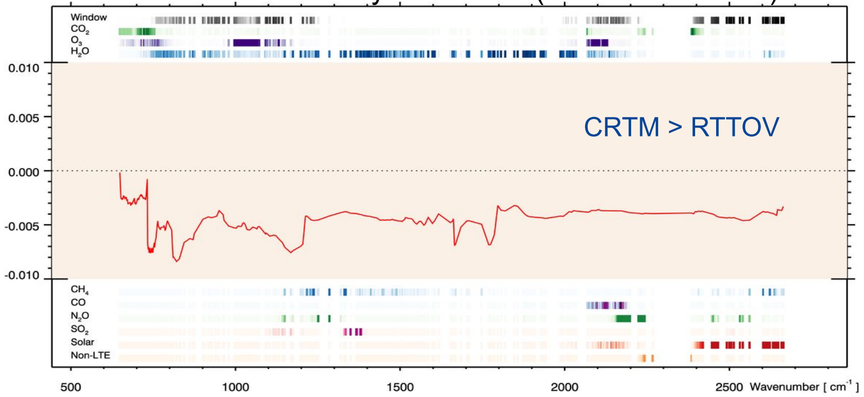
- Minimum Residual tends to be more conservative
- CADS tends to be more consistent with the VIIRS cloud mask

Ocean Surface Emissivity is Biased in Ops

RMS (OMF_{RTTOV}) - RMS (OMF_{CRTM})

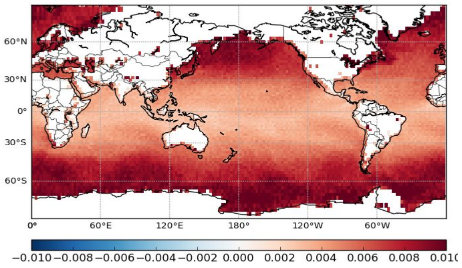


Surface Emissivity Difference (RTTOV - CRTM)

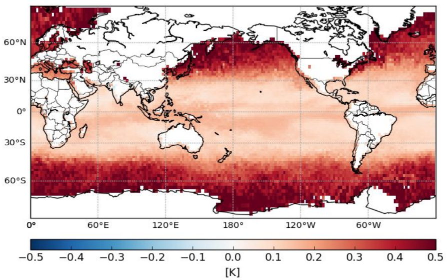


- Comparison between observation and simulated observation from CRTM and RTTOV indicates that RTTOV is consistently better than CRTM for window channels
- There is a latitudinal biases in CRTM which consistently estimates higher emissivity values than RTTOV due to lack of SST dependency in the regression model
- CRTM v.3 has the improved ocean emissivity model which accounts for the SST dependency – under testing in GFS

CRTM – RTTOV @ 801 Wavenumber cm^{-1}



Surface Emissivity



Brightness Temperature

Snow Representation

GFDL MP:

- **Assumption**: Snow has a spherical shape with constant bulk density
- **Mass-Diameter Relation**:
  - Power law: $m(D)=(\pi/6)\rho_s D^3$
  - Reference: (Lin et al., 1983)
- **Snow Size Distribution**:
  - Exponential shape
  - Distribution determined by size alone

Thompson MP:

- **Assumption**: Snow has a nonspherical shape (Fractal-like aggregated crystals) with bulk density that **varies inversely with diameter**
- **Mass-Diameter Relation**:
  - $m(D)=0.069D^2$
  - Reference: (Cox, 1988)
- **Snow Size Distribution**:
  - Depends on **ice water content** and **temperature**
  - Represented as a combination of **exponential** and **gamma** distributions
  - Reference: (Field et al., 2005)

3-parameter Gamma Distribution Function

$$n(D) = N_o\, D^{\mu}\, e^{-\lambda D}$$

GFDL Scheme (single-moment):

- N_o ,y-Intercept parameter is fixed
- μ , shape parameter is set to zero thus reverting to exponential distribution (Marshall-Palmer)
- λ, slope of distribution can be calculated from hydrometeor mixing ratio
- Mixing ratio q_x is prognostic

$$\lambda = \left(\frac{a\, N_{ox}\, \Gamma(\mu + b + 1)}{\rho_a q_x} \right)^{\frac{1}{\mu+b+1}}$$

Thompson Scheme (double-moment cloud ice and rain):

- N_{0x}, the intercept can be calculated from N_{tx} as:

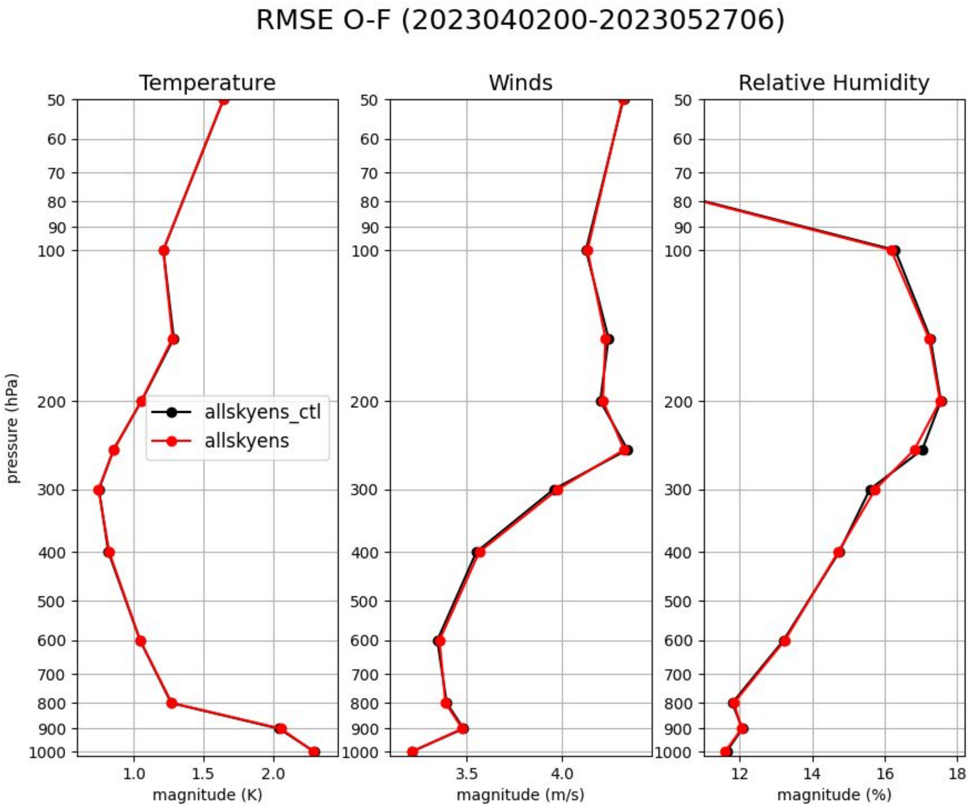
$$N_{ox} = \frac{N_{tx}\, \lambda^{\mu+1}}{\Gamma(\mu+1)}$$

- μ , is set to zero for exponential distribution (Marshall-Palmer) or prescribed (variable for cloud water)
- λ, the slope can be calculated from N_{tx} and q_x as:
- Both mixing ratio q_x and total number concentration N_{tx} are prognostic

$$\lambda = \left(\frac{a\, N_{tx}\, \Gamma(\mu + b + 1)}{\Gamma(\mu+1)\, \rho_a q_x} \right)^{\frac{1}{b}}$$

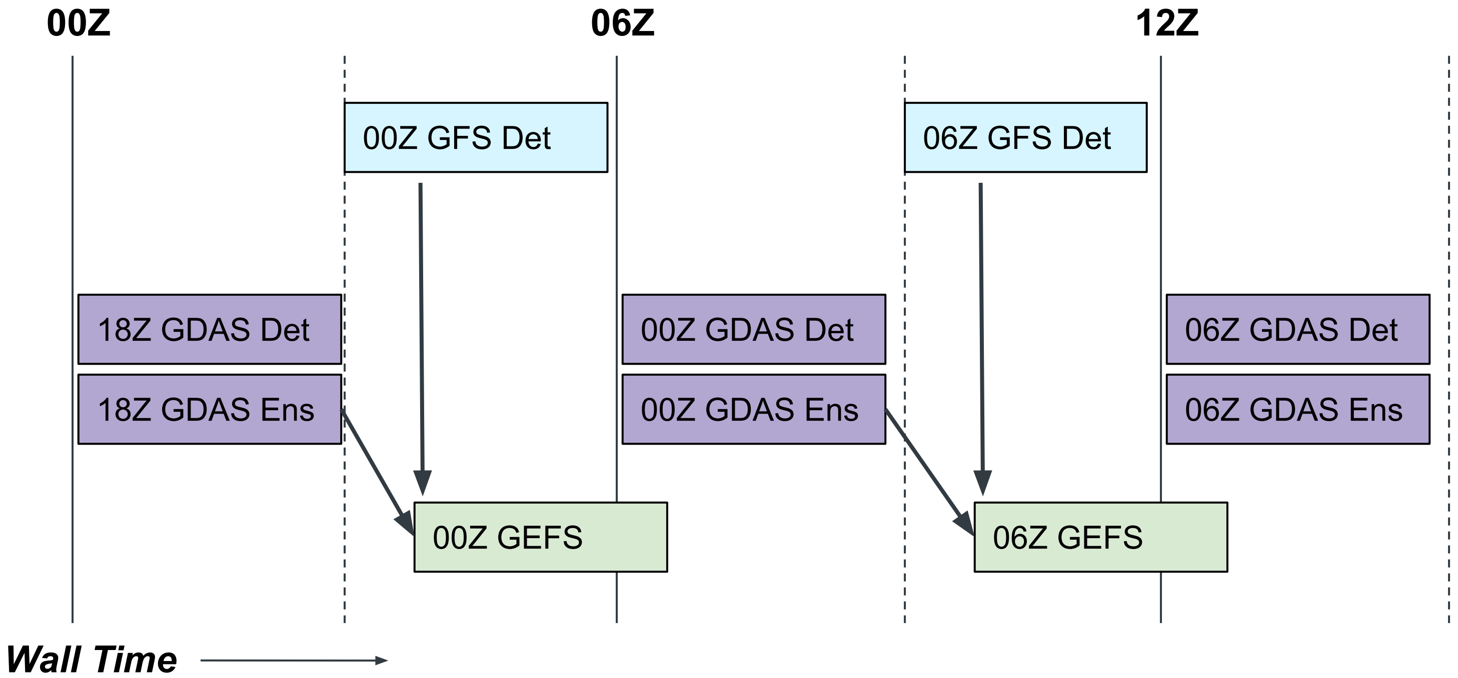
N_{tx} : total number of particles in the distribution

- **allskyens_ctrl** : **GFDL-MP** in GSI
- **allskyens : Thompson-MP** in GSI



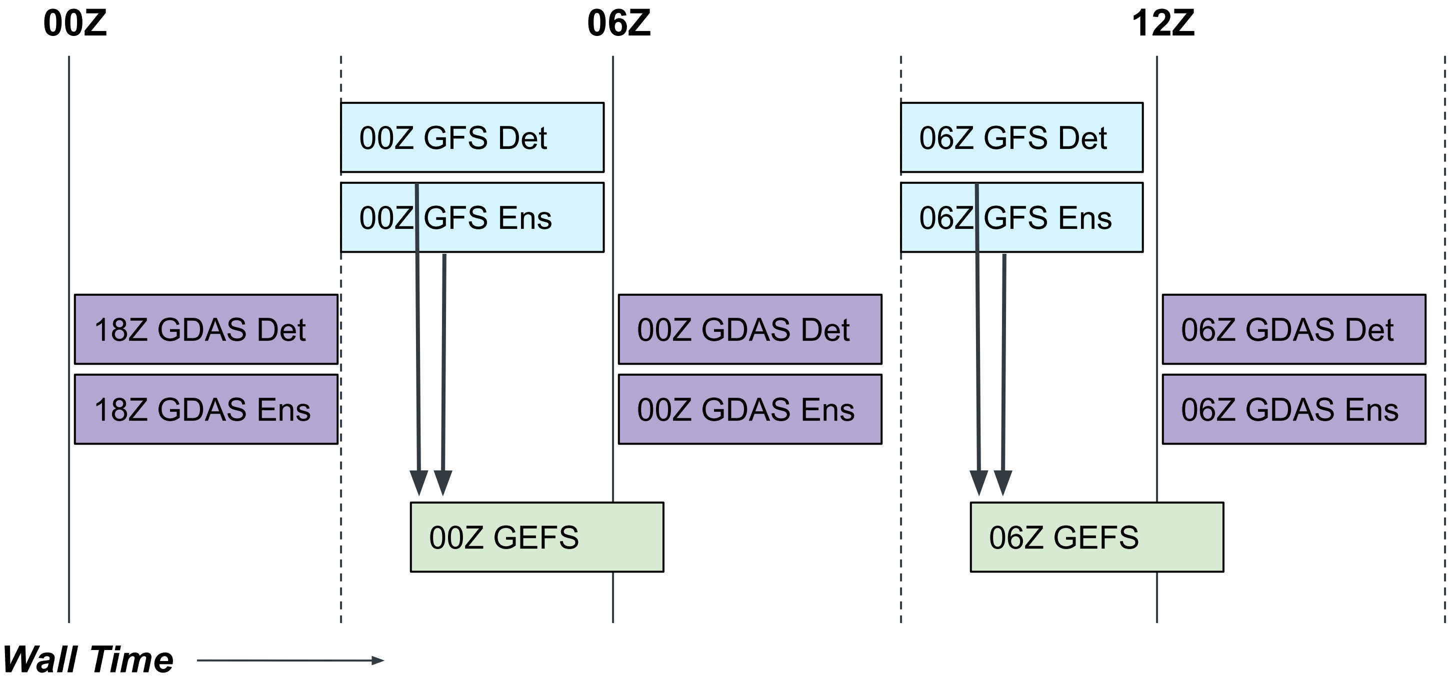
Early Cycle EnKF: Operations

- In operations, the GEFS initializes using the 6 hour forecast from the previous cycle's GDAS ensemble.



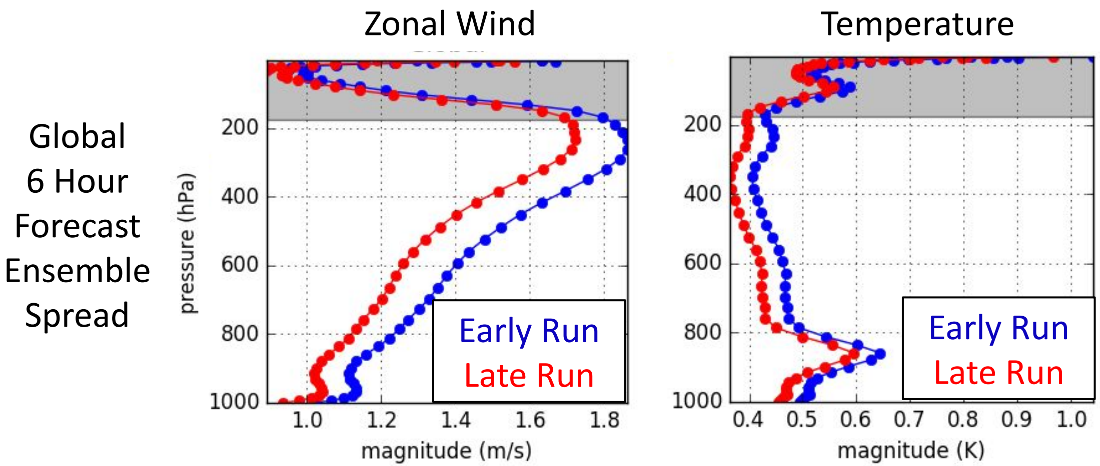
Early Cycle EnKF: GFSv17

- Running the EnKF update in the early cycle will **allow the GEFS to initialize using an ensemble analysis from the same cycle**, providing a greater connection between the GFS and GEFS.



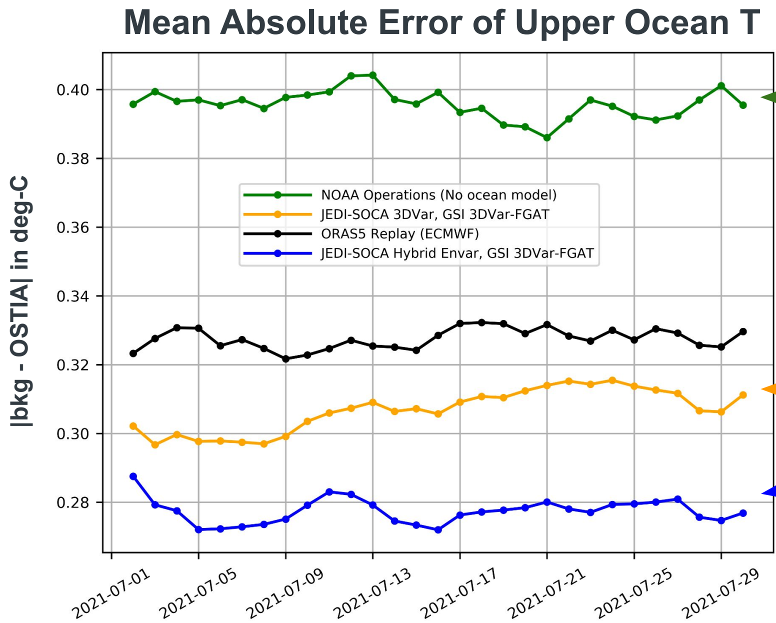
Early Cycle EnKF

- In operations, the GEFS initializes using the 6 hour forecast from the previous cycle's GDAS ensemble.
- Running the EnKF update in the early cycle will **allow the GEFS to initialize using an ensemble analysis from the same cycle**, providing a greater connection between the GFS and GEFS.
- The early cycle has fewer observations available → increased ensemble spread
- A late cycle EnKF would still be run as it is now in operations.
- The size of the ensemble for the early cycle EnKF will likely be the same size as the GEFS ensemble (dependent on available resources).



Marine DA

Motivation: Upper ocean temperature plays a critical role in the coupling of atmospheric and oceanic processes in NWP. Foundation temperature from NOAA operations exhibits larger differences with OSTIA (i.e., "truth") than what is produced by retrievals from AVHRR and others (based on results for July 2021).



Foundation temperature from NOAA operations

- Operations does not utilize an ocean model.

Foundation Temperature: Ocean temperature at the depth at which it is free, or nearly free, of any diurnal variability

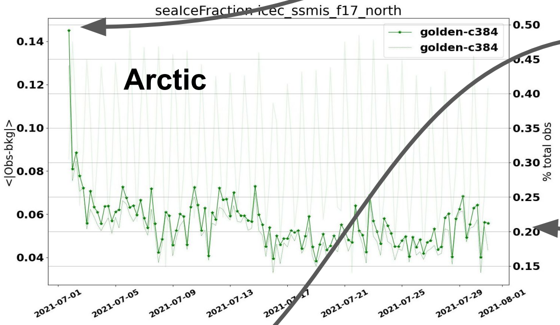
Foundation temperature constrained with SST retrievals using JEDI-SOCA

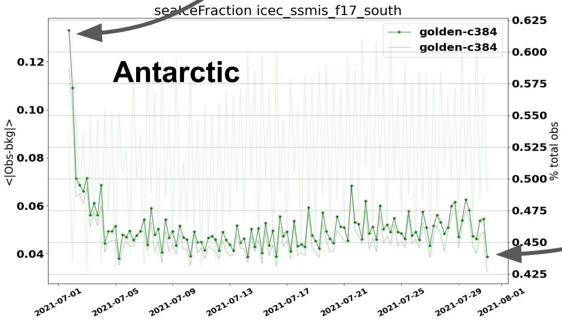
- Static SST regression coefficients are constructed by matching the retrievals to quality controlled in situ (drifter) obs (30-50 cm depth) via nearest neighbor method. (Ignatov et al., 2016; doi: 10.3390/rs8040315)

Objective: To improve the initialization and coupled UFS forecast as related to upper ocean temperature

Marine DA: Sea-ice

Seaice concentration OMB statistics



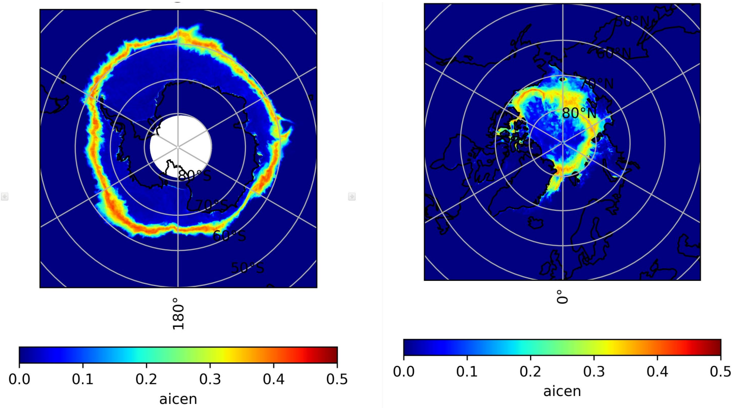


Started from a benchmark SOCA based short reanalysis (~6 months)

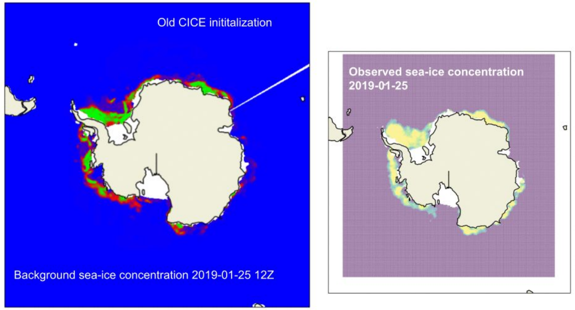
Significant error reduction in the WCDA system

Recent updates:

- Background error



- CICE6 initialization



Cycling Prototypes

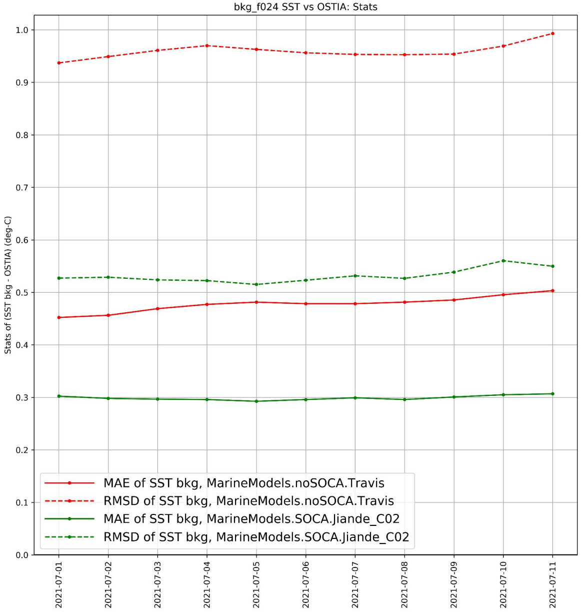
- Purpose
  - Accelerate testing of cycling in GFSv17
  - Building up to a real time parallel
  - Observe the long term evolution of states (land, ocean, etc)
- Configuration
  - 3DVar: C384 atmosphere, 0.25 degree ocean/ice
  - 10 day forecast at 00z only
  - Cycling as long as possible (~year)
  - Initial set
    - ATM model, ATM DA
    - S2S model, ATM DA
    - S2S model, ATM DA, SOCA

Special thanks to Travis Elless and Jiande Wang for running the initial set.

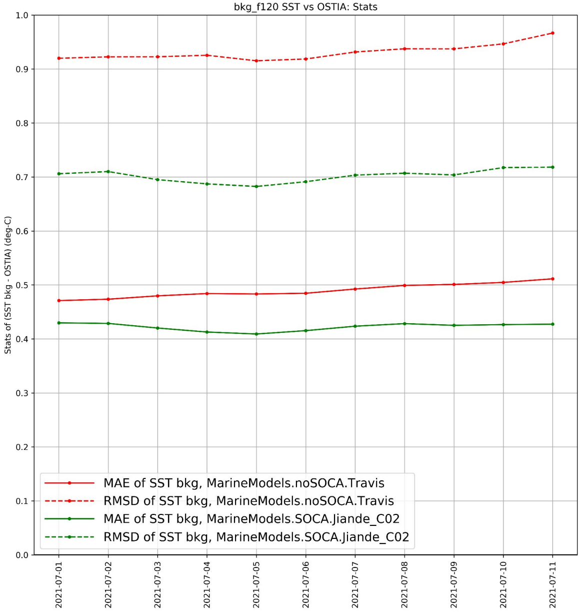
Results: SST Forecast Verification

Forecasts - OSTIA: Error Stats vs Time

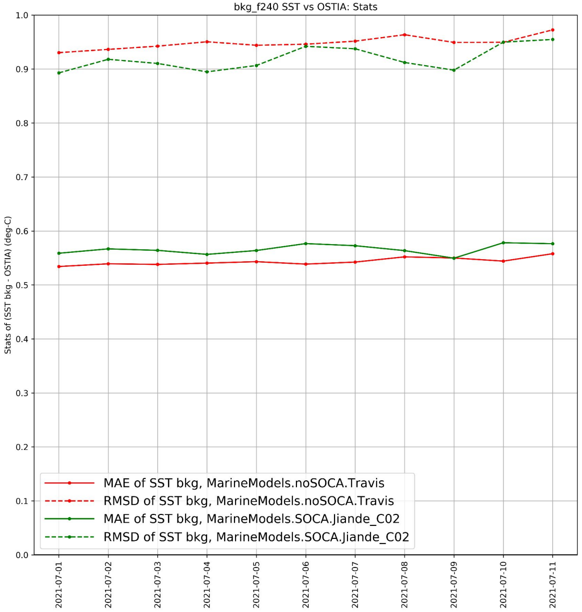
f024 (Day 1)



f120 (Day 5)



f240 (Day 10)



Valid for 60°S-60°N

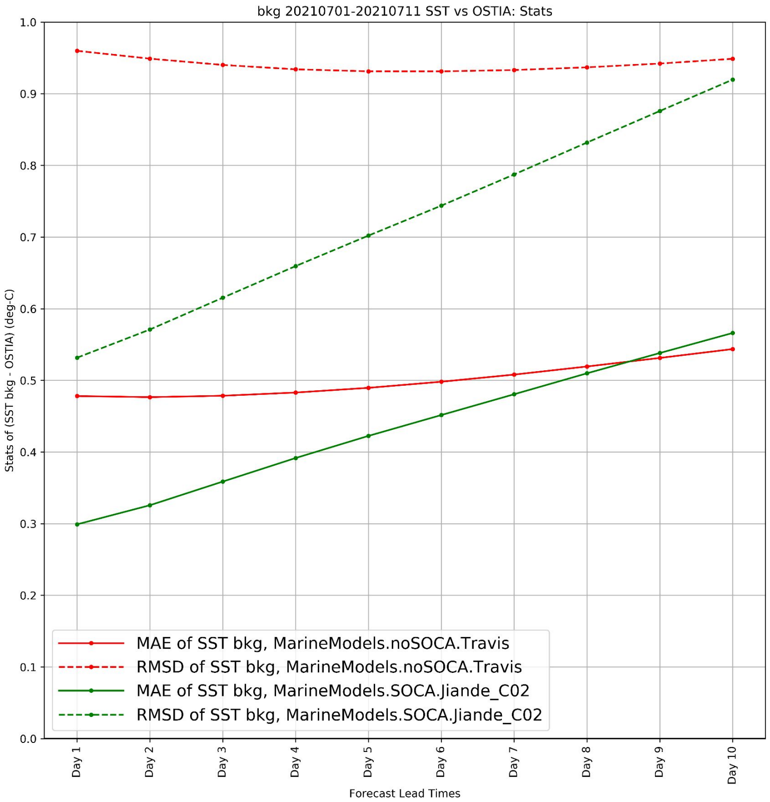
- Errors for run with S2S DA (**green lines**) are generally stable over time and are smaller than those for the run without S2S DA (**red lines**)
- Note that RMSD for run without S2S DA (**red dashed lines**) does not vary much between forecast lead times

Results: SST Forecast Verification

Forecasts - OSTIA: Error Stats vs Forecast Lead Time

- Errors for run with S2S DA (**green lines**) increase with forecast lead time (as expected) and are generally smaller than those without S2S DA (**red lines**)
- Unexpectedly, RMSD for run without S2S DA (**red dashed line**) decreases from Day 1 to Day 5

Mean stats per lead time for July 1-11, 2021



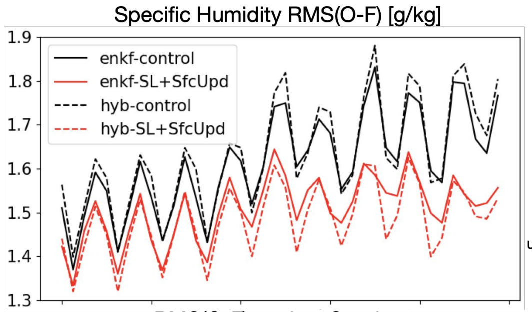
Valid for 60°S-60°N

Unifying the atmospheric and land DA

- At other global NWP centers, land DA is done as a separate step to atmospheric DA
  - Uses much simpler DA methods (OI, empirical coefficients, Simplified Extended Kalman Filter), and uses different DA methods for different land variables
  - Land and atmospheric DA are then necessarily weakly coupled
  - Done separately for historical reasons
- Rather than implement a separate method for the land DA, NOAA is pursuing expanding the atmospheric DA to also do the land DA
  - Introduces possibility of (more) strongly coupled land/atmosphere DA, sharing of code / h(x), etc
  - Upgrades the land DA methods to the more advanced (ensemble-based) methods that are favoured by the hydrology community

Soil Analysis: Next Steps

- Based on above experiments, implementing strongly coupled land/atmosphere update with addition of screen-level obs
- Need to update soil analysis to use the GSI Hybrid 4DEnVar
  - Hybrid or Var updates not well established for soil moisture and soil temperature analysis
  - Hybrid methods starting to be used in land community, and and may be more appropriate than pure EnKF for the land problem
- For GFSv17 using an intermediate solution, of applying the ensemble-mean EnKF soil increment to the control member in place of the Hybrid/Var soil update (atmos update is full Hybrid)
- Relative improvements from adding the screen-level obs and the soil analysis are enhanced when using the Hybrid method, compared to initial EnKF experiments
- Currently working towards forecast impact tests of above system

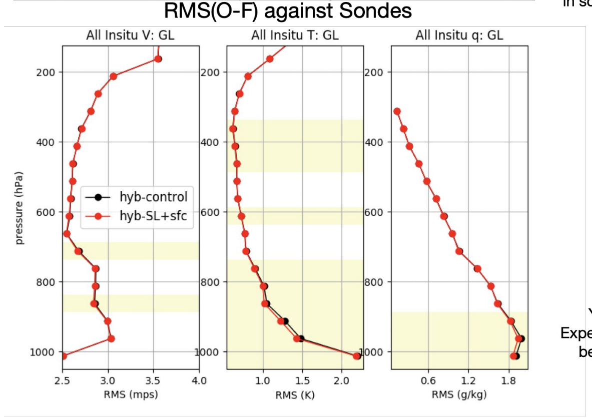


Control (black line)
Standard atmos only DA

Solid: EnKF
Dashed: Hybrid

SL+SfcUpd (red line)
Strongly coupled soil/atmos updates, plus screen-level obs

similar improvements
in screen-level T



Yellow shading:
Experiment significantly better than control

Thinning vs Superobbing

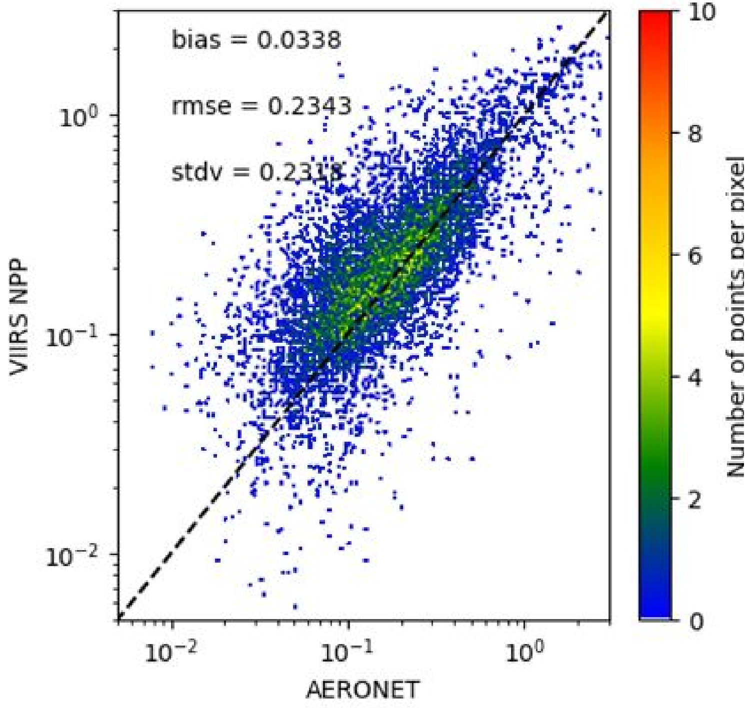
VIIRS observations are ~750m, far too dense to assimilate all.

- DA generally assumes observations are independent and not correlated, which isn't the case here.
- Two main ways to handle this:
  - Thinning - select only every n-th observation, either randomly, or with some sort of space/time structure
  - superobbing - averaging/binning several observations into one new observation
- Aiming to have ~one observation per model grid point

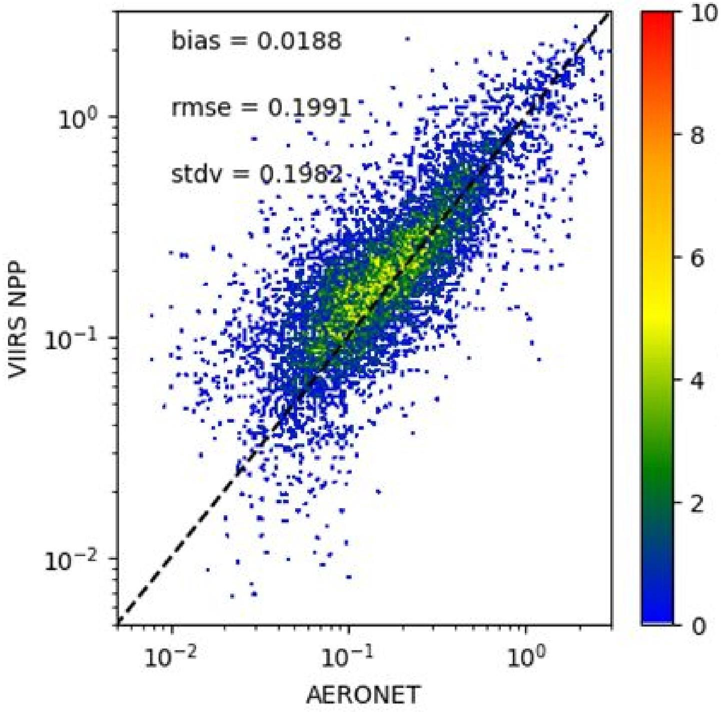
Yaping Wang

Thinning vs Superobbing

Thinned

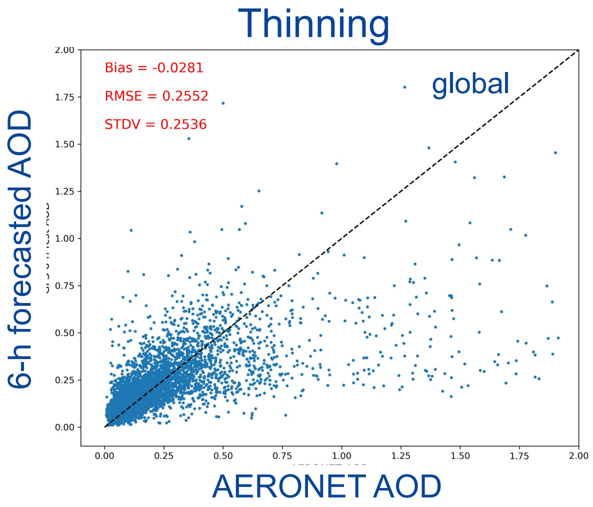


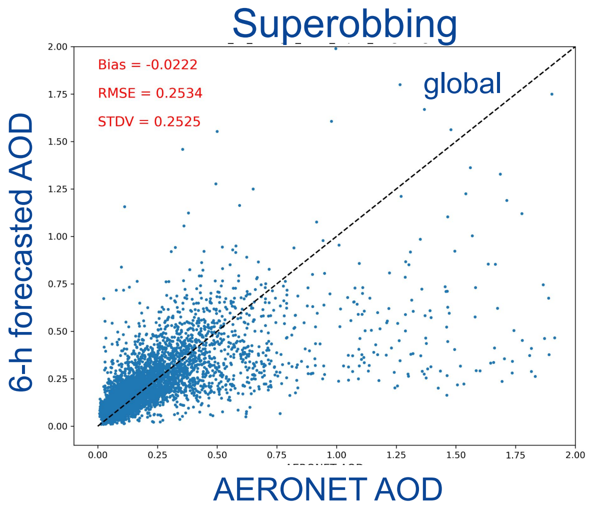
Superobbed



Yaping Wang

GOCART 6-h forecast verified against AERONET AOD
(01 Aug 2021 - 14 Aug 2021)





On global scale, superobbing reduces the mean bias, RMSE and STDV, compared to thinning.

	North America		Europe		South America		Africa		East Asia	
	Thin	Superob	Thin	Superob	Thin	Superob	Thin	Superob	Thin	Superob
BIAS	-0.0735	**-0.0669**	**0.0172**	0.0199	-0.0099	**-0.0043**	-0.0158	**-0.009**	**0.0027**	0.0085
RMSE	0.3644	**0.3631**	0.0904	**0.0882**	**0.1128**	0.1225	0.1275	**0.1216**	0.1867	**0.1767**

Yaping Wang

Variational Bias Correction

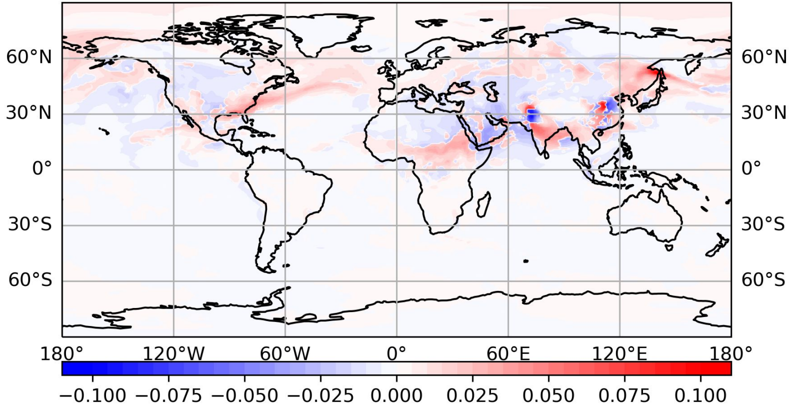
Exploring multiple bias predictors:

Difference of absolute error against CAMS

(VarBC (**sulfate**) - CTRL)

Positive: VarBC has smaller error

Negative: CTRL has smaller error



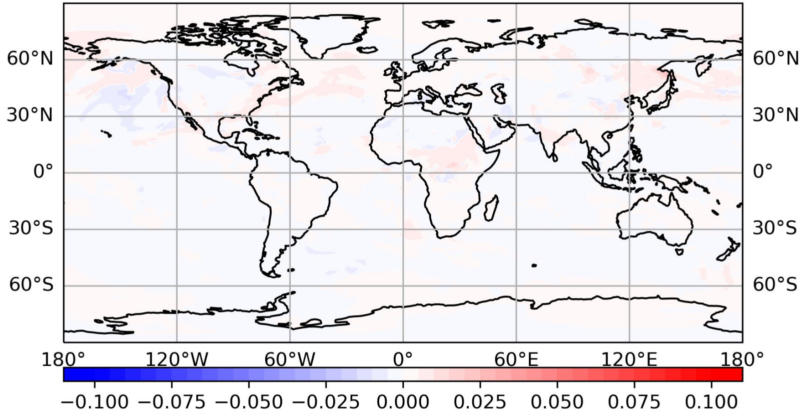
VarBc reduces the error over east Asia, central Africa, Europe and east North America.

Difference of absolute error against CAMS

(VarBC (**Constant**) - CTRL)

Positive: VarBC has smaller error

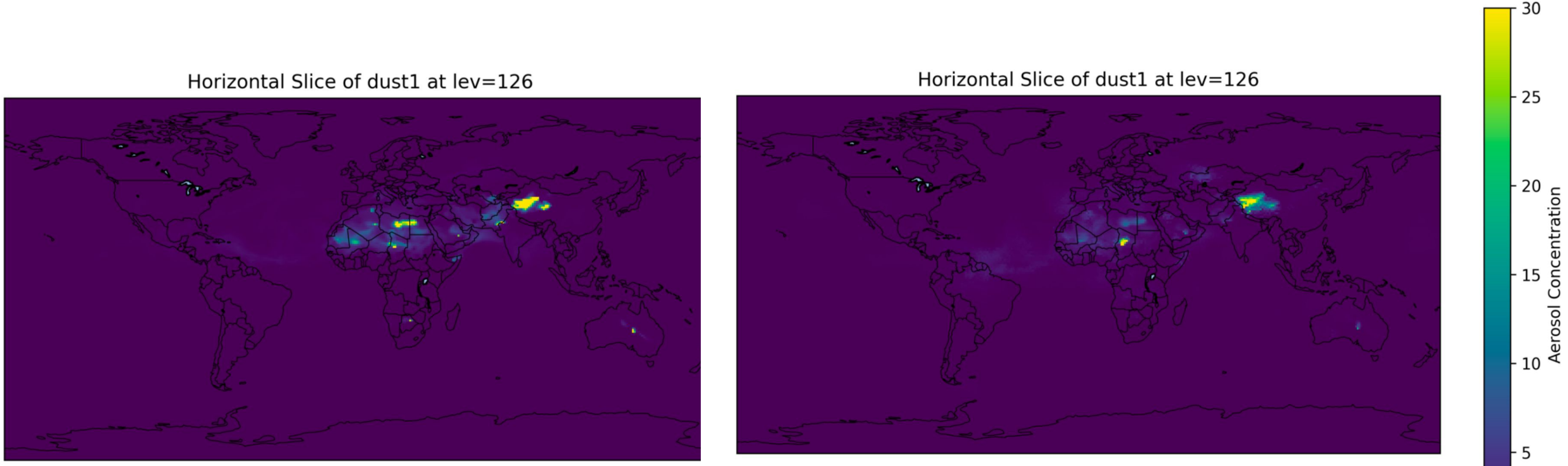
Negative: CTRL has smaller error



Not much impact

Yaping Wang

Local Variance as a Function of Background



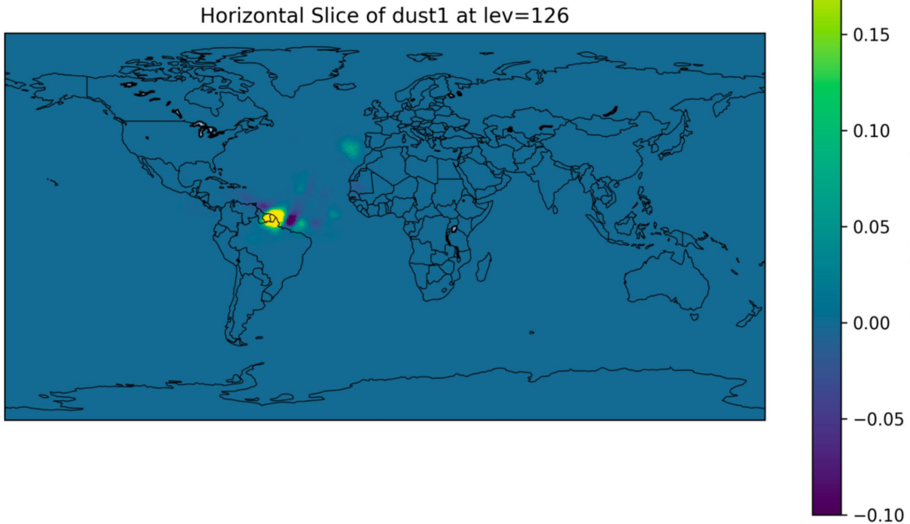
Near-surface forecast dust in the smallest size bin

Near-surface dust variance in the smallest size bin

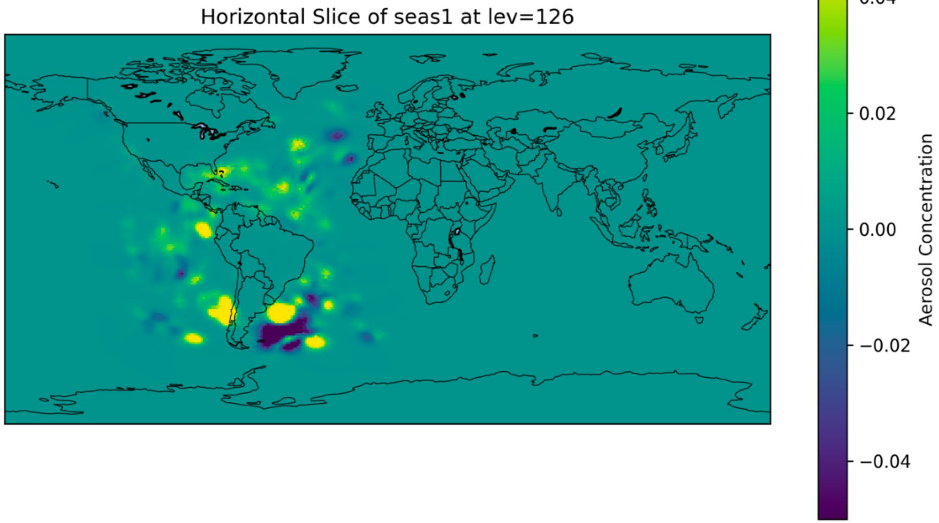
Andy Tangborn

Aerosol Analysis Increments

Surface Dust



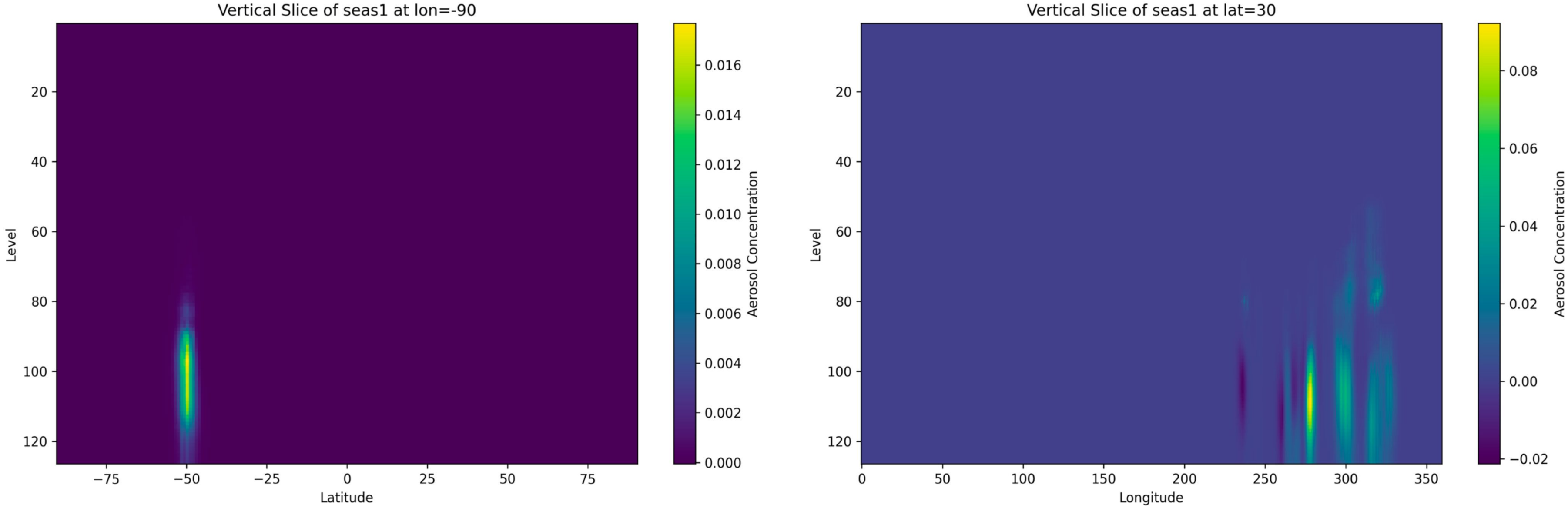
Surface Sea Salt



Aerosol assimilation is tricky. One 2D observation for 15 3D tracers.

Andy Tangborn

Aerosol Analysis Increments



Aerosol assimilation is tricky. One 2D observation for 15 3D tracers.

Andy Tangborn

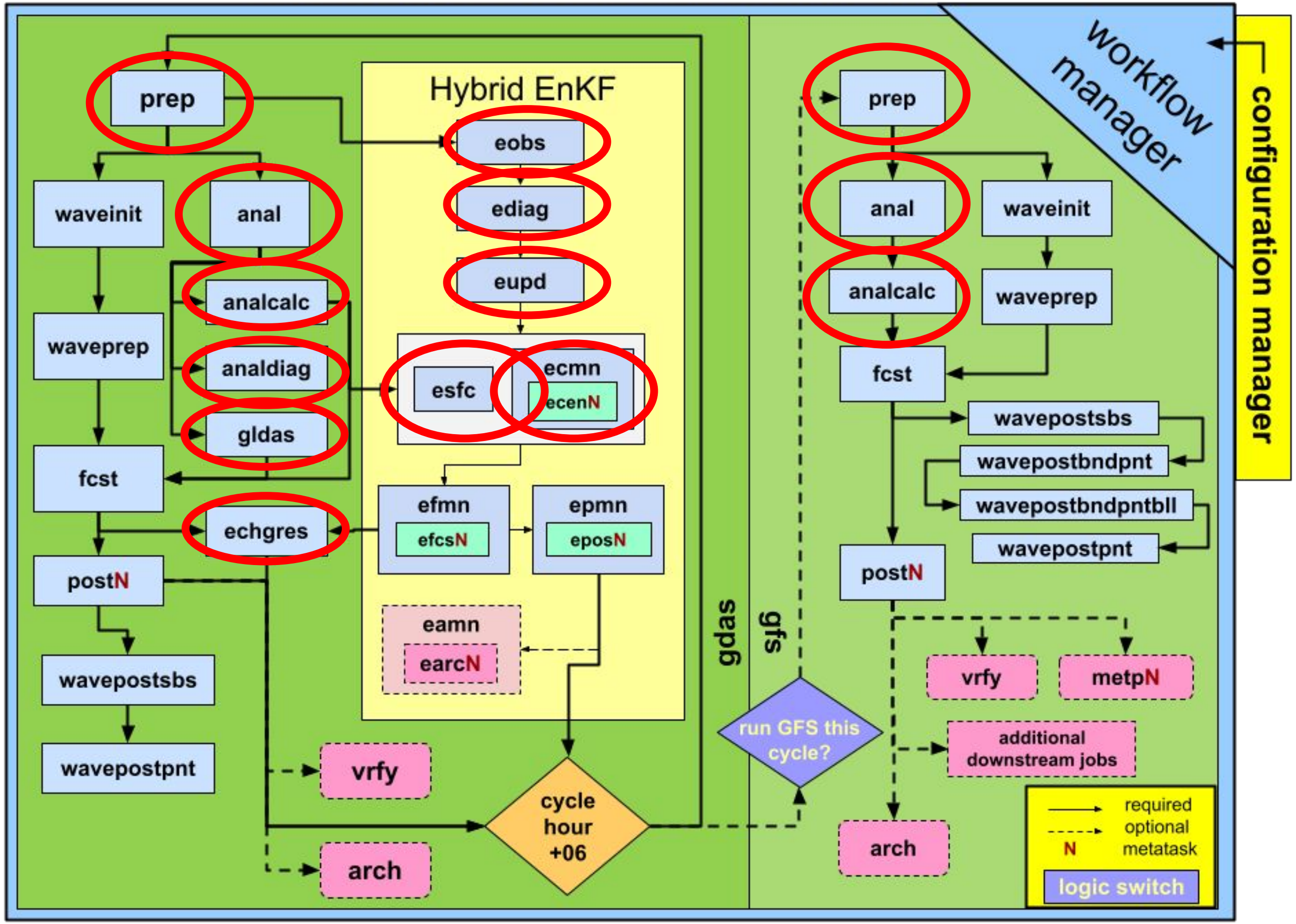
Translation of Quality Control Procedures

```fortran
! QC for clear condition
     else   ! <lcw4crtm>
        qc4emiss=.false.
        if(factch6 >= one .or. latms_surfaceqc)then
           efactmc=zero
           vfactmc=zero
           errf(1:ich544)=zero
           varinv(1:ich544)=zero
           do i=1,ich544
              if(id_qc(i) == igood_qc)id_qc(i)=ifail_factch6_qc
           end do
           if(id_qc(ich890) == igood_qc)id_qc(ich890)=ifail_factch6_qc
           errf(ich890) = zero
           varinv(ich890) = zero
           if (latms) then
              do i=17,22   !  AMSU-B/MHS like channels
                 if(id_qc(i) == igood_qc)id_qc(i)=ifail_factch6_qc
                 errf(i) = zero
                 varinv(i) = zero
              enddo
           endif
!       QC3 in statsrad
           if(.not. mixed.and. luse)aivals(10,is) = aivals(10,is) + one
```

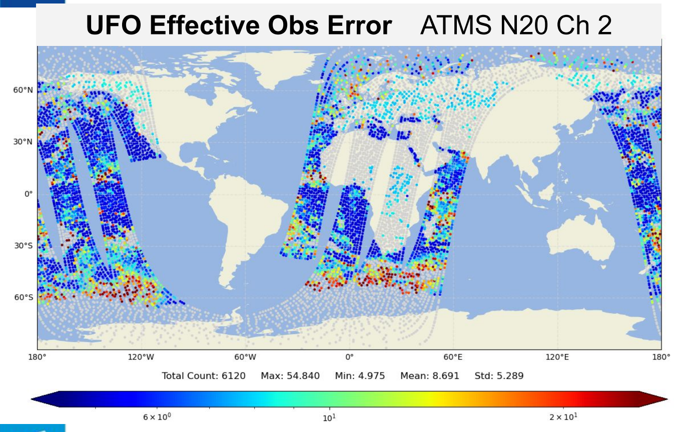
```yaml
# Step 3: CLW Retrieval Check (background_based)
- filter: Bounds Check
  filter variables:
  - name: brightnessTemperature
    channels: 1-6, 15
  test variables:
  - name: DerivedMetaData/CLWRetFromBkg
  maxvalue: 999.0
  actions:
    - name: set
      flag: CLWRetrievalReject
    - name: reject

# Step 4: Window channel sanity check
- filter: Bounds Check
  filter variables:
  - name: brightnessTemperature
    channels: 1-6, 15
  test variables:
  - name: DerivedMetaData/Innovation
    channels: 1, 2 4-6, 15
  maxvalue: 200.0
  minvalue: -200.0
  flag all filter variables if any test variable is out of bounds: true
```

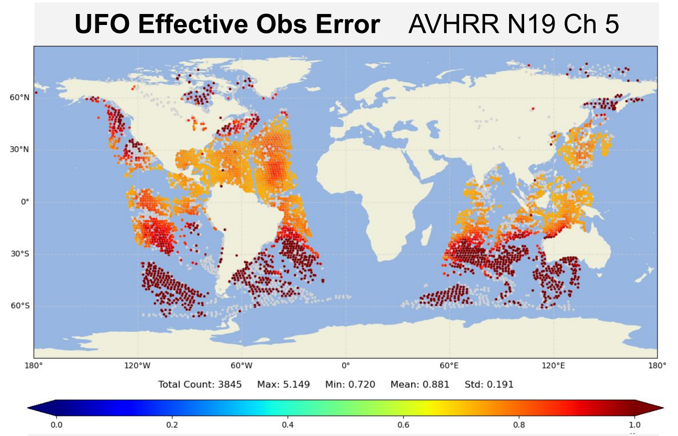
Compiled Fortran Code → YAML Configuration Using Generic Tools

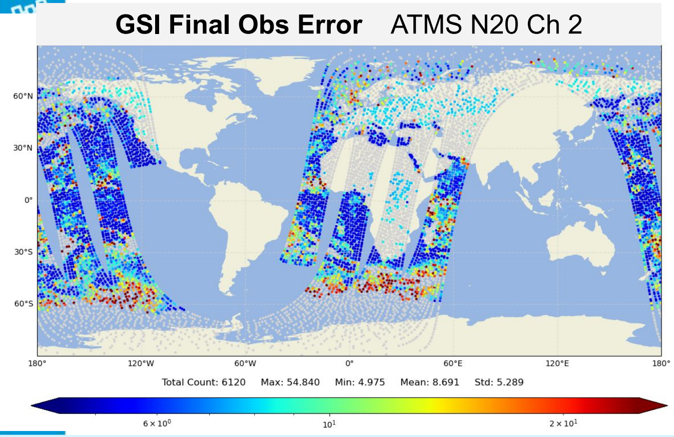
Global Model Parallel Sequencing - v16

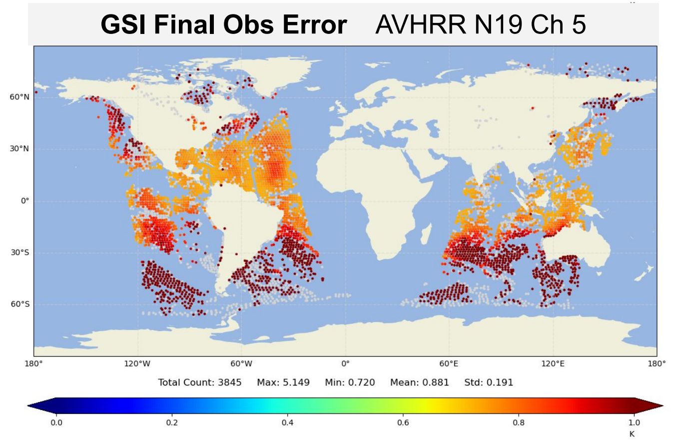


JEDI Transition: QC and Error Assignment









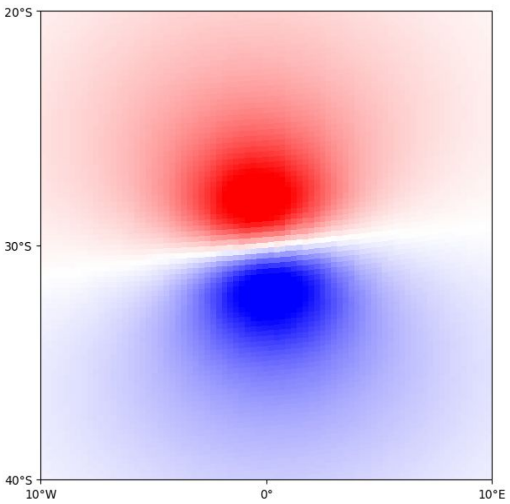
After translating all of these QC procedures from Fortran code to YAML, we need to verify that things are working as intended

JEDI Transition: Solver

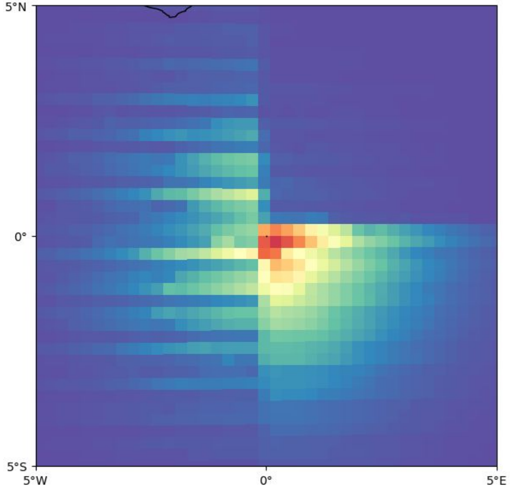
GSI background error added to JEDI by NASA GMAO

Our summer intern ran some single ob sensitivity tests, found differences with different PE counts, and is still under investigation

Increment | -30,0 | U Wind at 1000 hPa



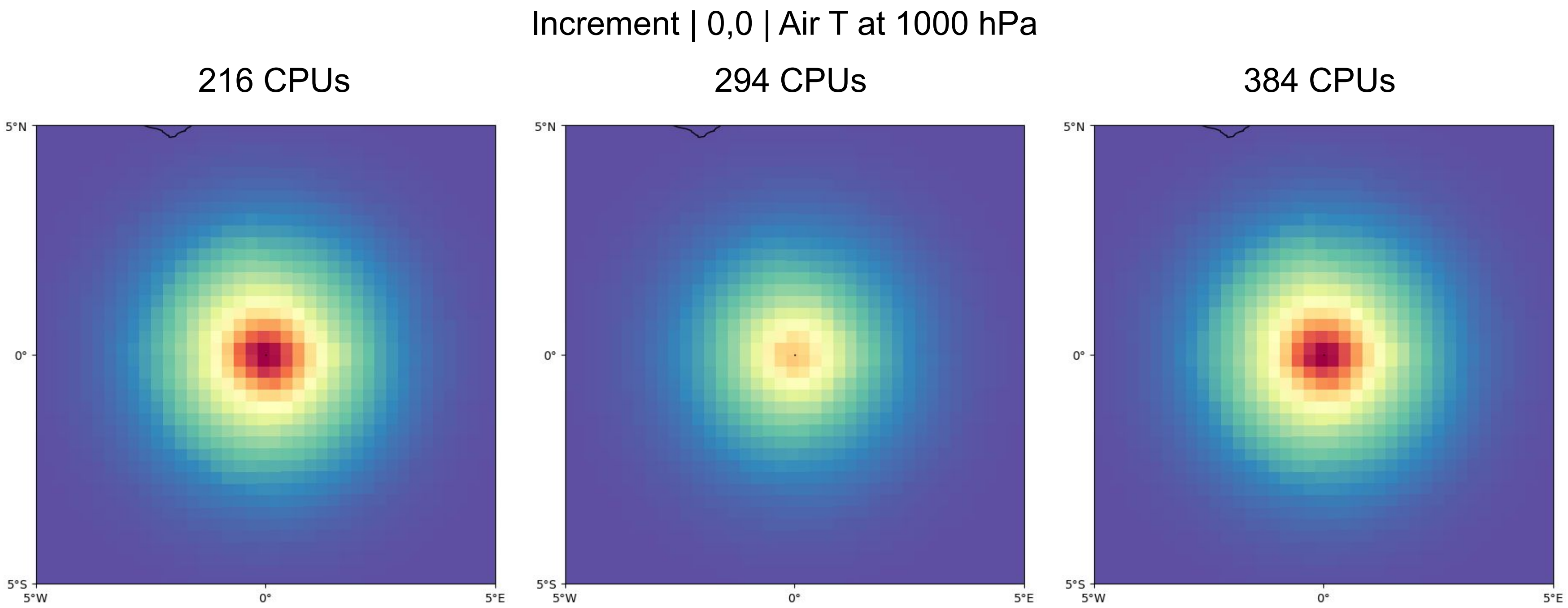
Wind increment from temperature observation looks physically reasonable.



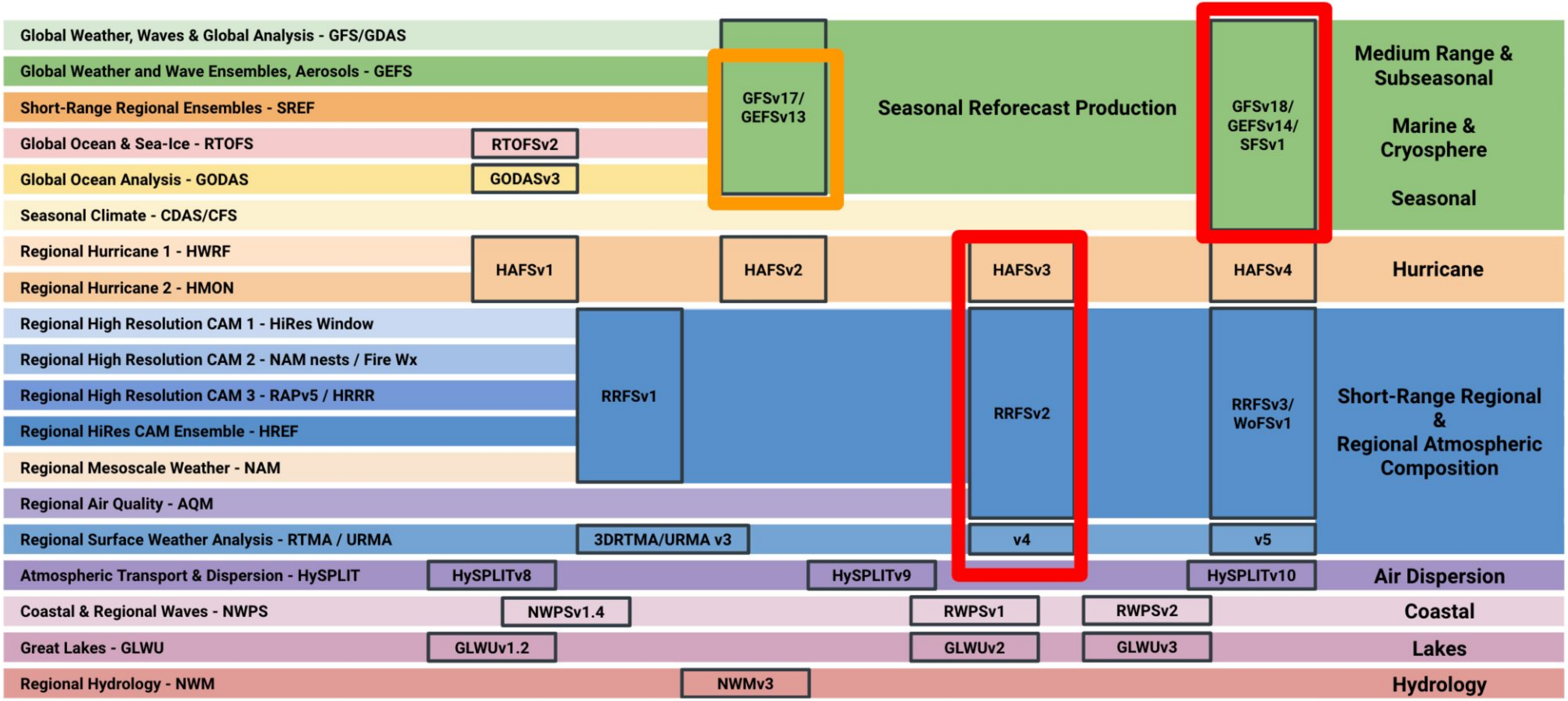
This increment is definitely not correct!

Figures courtesy Alex Swan, Mississippi State University

JEDI Transition: Solver



Figures courtesy Alex Swan, Mississippi State University



Notional JEDI Transition Schedule

Full Transition
Non-Atm Components