NOAA

National Weather Service

NCEP FV3GFS Data Assimilation & JEDI Updates

EMC-CWB Joint Workshop, 21 May 2019

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& …. The entire EMC Data Assimilation Team

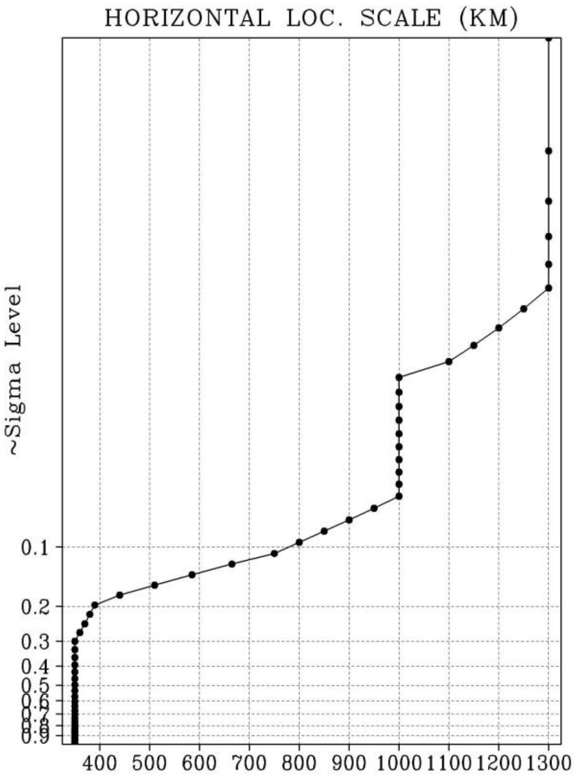
Current Operational GDAS (Hybrid 4DEnVar)

$$J(\mathbf{x}'_c,\mathbf{a}) = b_c \frac{1}{2}(\mathbf{x}'_c)^T \mathbf{B}_c^{-1}(\mathbf{x}'_c) + b_e \frac{1}{2}\mathbf{a}^T \mathbf{L}^{-1}\mathbf{a} + \frac{1}{2}\sum_{k=1}^{K}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}'_k)^T \mathbf{R}_k^{-1}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}')$$

$$\mathbf{z} = \mathbf{B}^{-1}\mathbf{x}'_c \qquad \mathbf{v} = \mathbf{L}^{-1}\mathbf{a}$$

T1534L64 Semi-Lagrangian GFS (GSM)

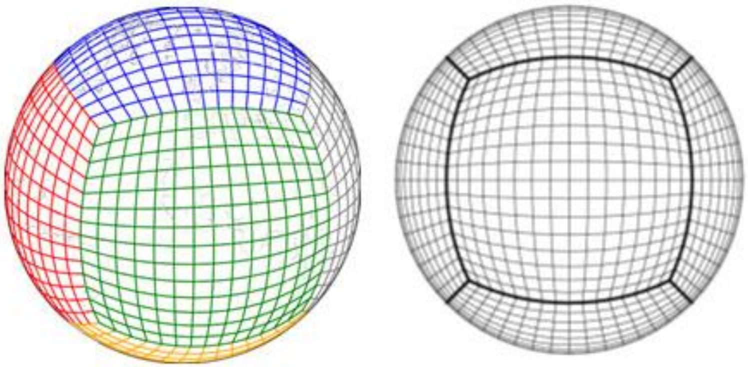
- 80 member ***T574L64*** EnSRF for data assimilation
- Level-dependent localization
- Stochastic physics to represent model uncertainty (SPPT, SKEB, SHUM) – Since January 2015
- Analysis increment at ensemble resolution
- Ensemble perturbations centered about hybrid analysis
  - Ensemble mean state estimate replaced



NGGPS/FV3-GFS (June 2019 Implementation)

NOAA GFDL FV3 selected for dynamic core component of NGGPS

- Using Non-hydrostatic option
- Initial prototyping with (mostly) GFS physics (new: GFDL MP)
- Same vertical levels and model top (~55km)



Courtesy : GFDL

Data Assimilation

– ***Adaptation of current hybrid 4DEnVar scheme (with 80 member EnSRF-updated ensemble)***

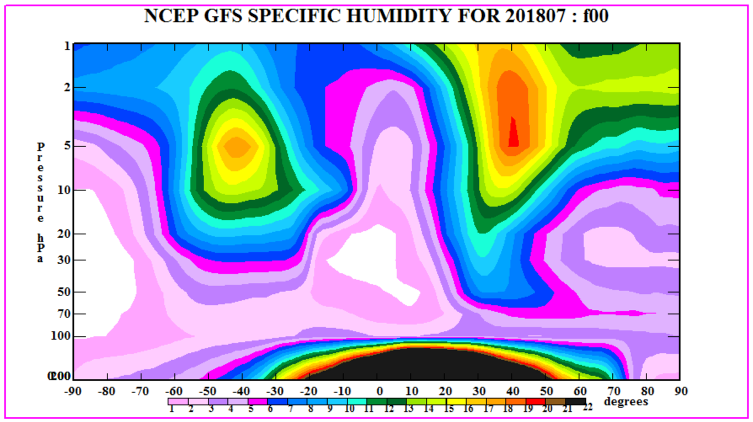
– ***Re-gridding to accommodate current DA infrastructure***

FV3GFS
Key Difference from Current Operations

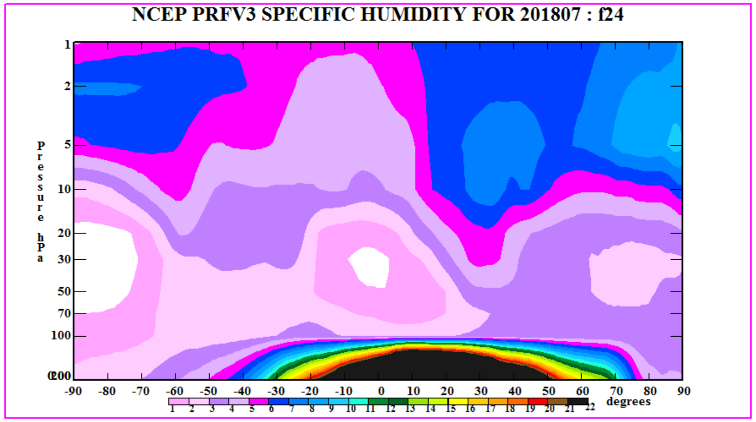
- Ensemble and analysis increment resolution
  - ***While control remains ~13km, ensemble and increment resolution have been increased to ~25 km (currently ~39km)***
- Initialization
  - Current GFS uses digital filter, ***NEMS-FV3GFS not yet using initialization***
    - Both use Tangent Linear Normal Mode Constraint
  - No TC Relocation. Still assimilation single central SLP observation
- Treatment of system error
  - GFS uses SKEB+SPPT+SHUM, ***FV3GFS utilizes SPPT+SHUM only***

FV3GFS
Key Difference from Current Operations

- Modifications to upper levels (largely model, impacts DA)
  - ***Reset stratospheric humidity to HALOE climatology (cold start only at beginning of experiment).***
  - ***New ozone and methane chemistry***

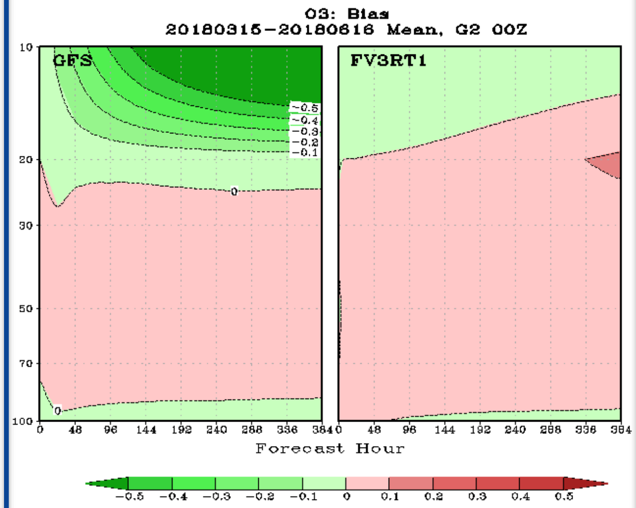


OPS



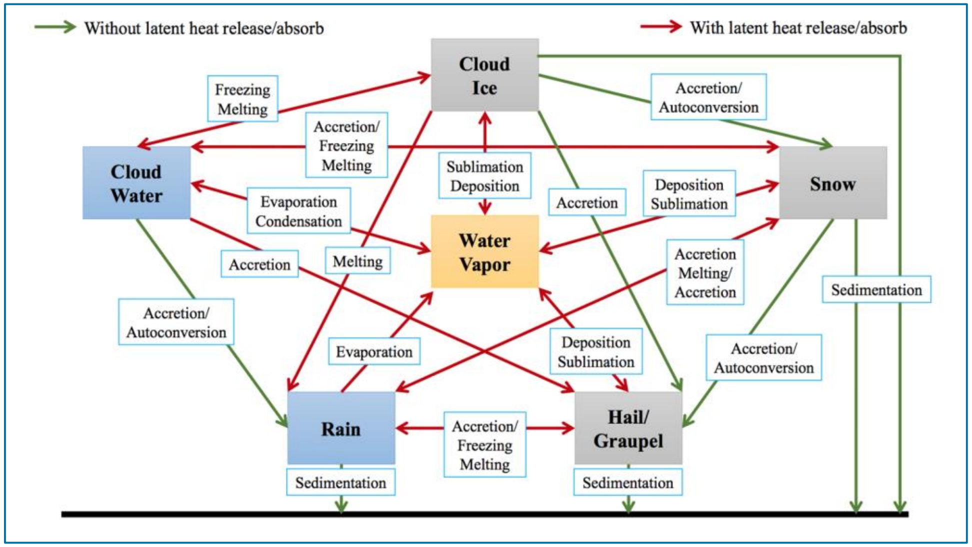
FV3GFS

Global Mean
Ozone Bias



FV3GFS
Key Difference from Current Operations

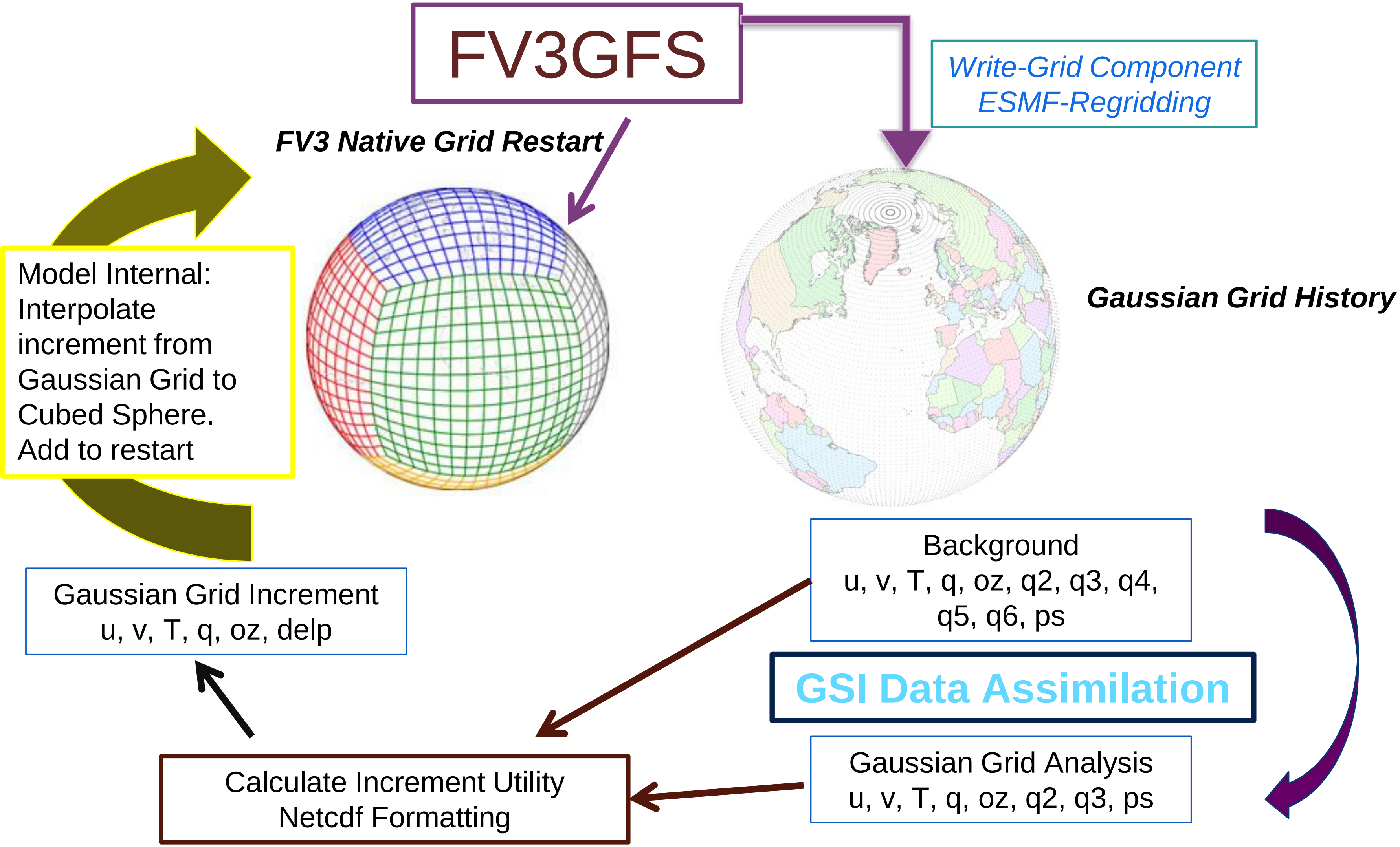
- New microphysics
  - GFS analysis total cloud increment and passes back to model
  - FV3GFS engineered to make this work with new MP scheme (5 species), ***but does not pass cloud increment back to model***



- Observations
  - Operational GFS and to-be operational FV3GFS evolving with new observing system (GOES16 AMVs, NOAA 20 CrIS and ATMS)
  - ***FV3GFS will implement all-sky radiance assimilation for ATMS and additional water vapor channels from IASI***

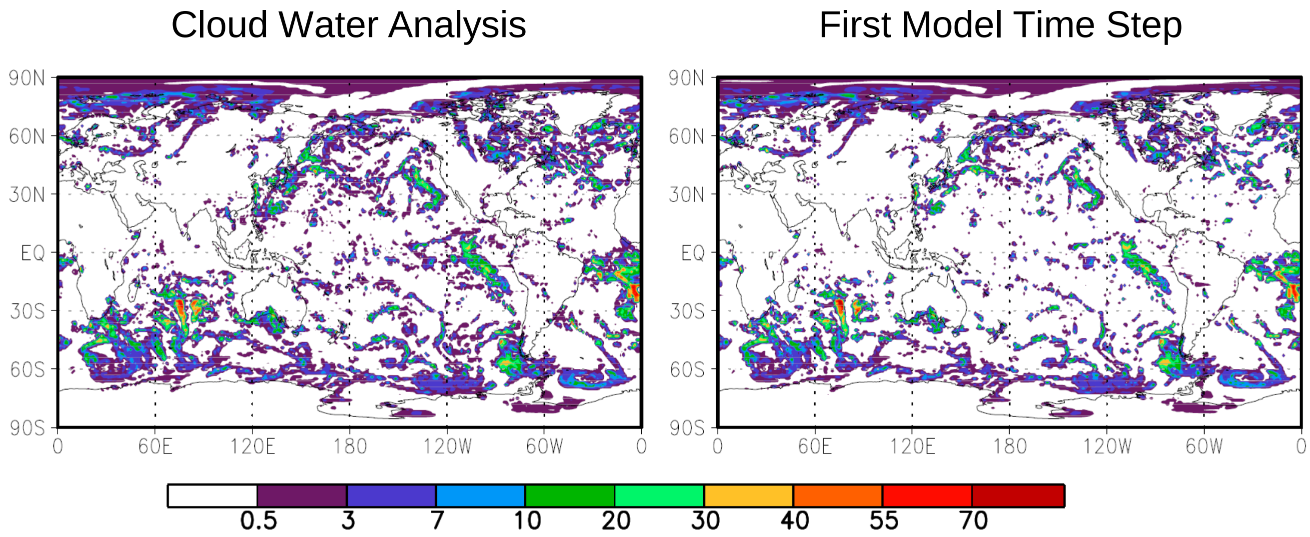
- Inline NSST
  - Background error has been recalibrated

Deterministic Assimilation Cycle



Cloud Analysis

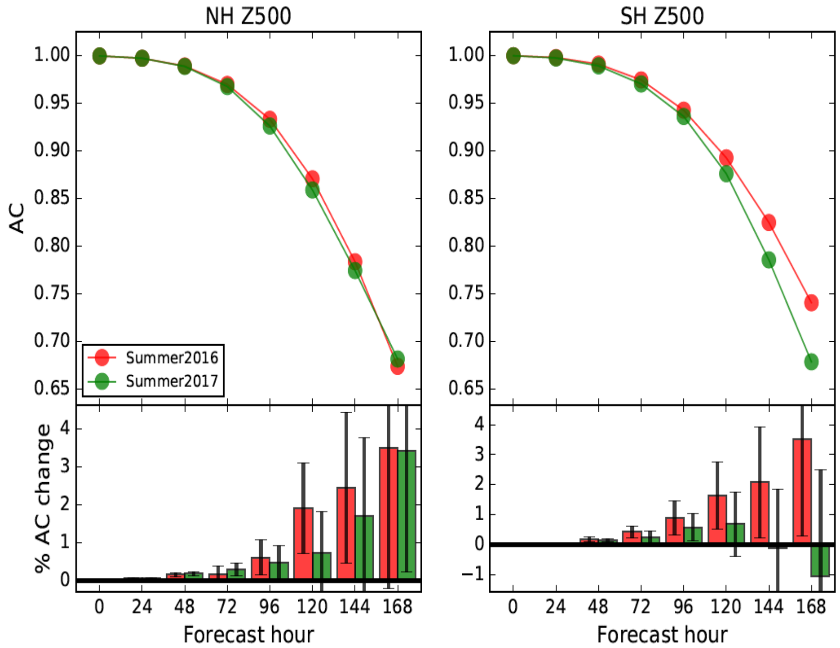
Current operations produces total cloud condensate increment (same as model prognostic variable).



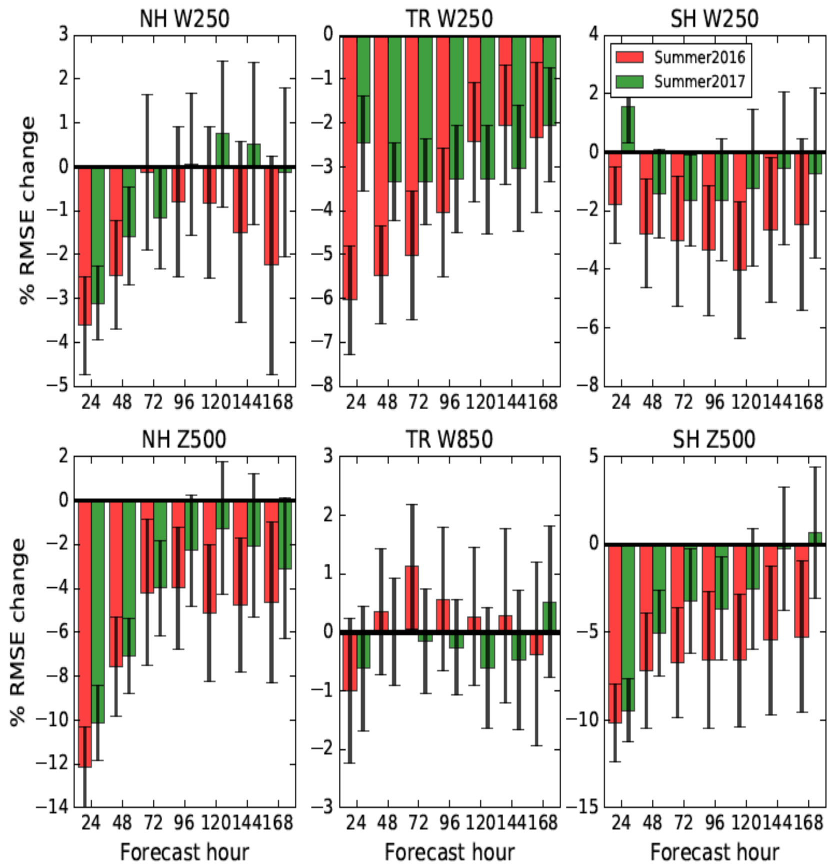
- For FV3GFS, leveraged same control variable:
  - Combine cloud liquid and ice to total cloud (ignore snow, rain, graupel)
  - Compute total cloud increment using current procedure
  - Split into ice and liquid based on temperature
- However, this is inconsistent with new MP. Based on above and further testing (not shown), decided to simply not pass cloud increment back to model (as temporary measure)

Cycled trial verification relative to operations
2016: 6 June-20 July | 2017: 10 June-13 August

500 hPa AC



%RMSE change relative to operational GFS

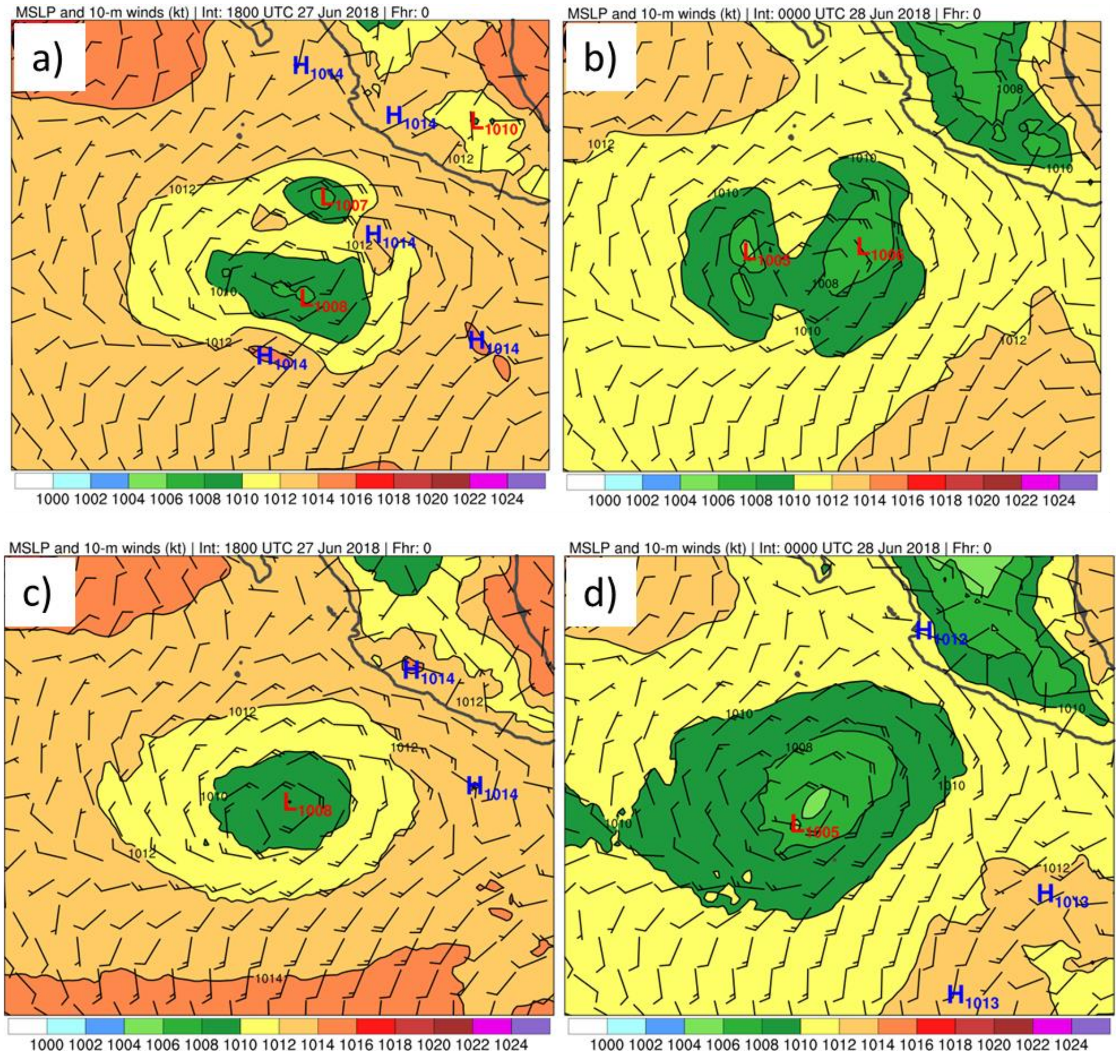


Kleist, D., R. Mahajan, & C. Thomas, 2018: Data Assimilation in the Next Generation Global Prediction System (NGGPS) Era: Initial Implementation of FV3-based Global Forecast System (GFS). JCSDA Quarterly No 61, Fall 2018. Available online at https://www.jcsda.noaa.gov/documents/newsletters/2018_04JCSDAQuarterly.pdf (doi: 10.25923/jw00-r987).

Tropical Cyclone Initialization

GFS

FV3-GFS



1800 UTC
27 June 2018

0000 UTC
28 June 2018

Vortex Relocation + MinSLP Assimilation

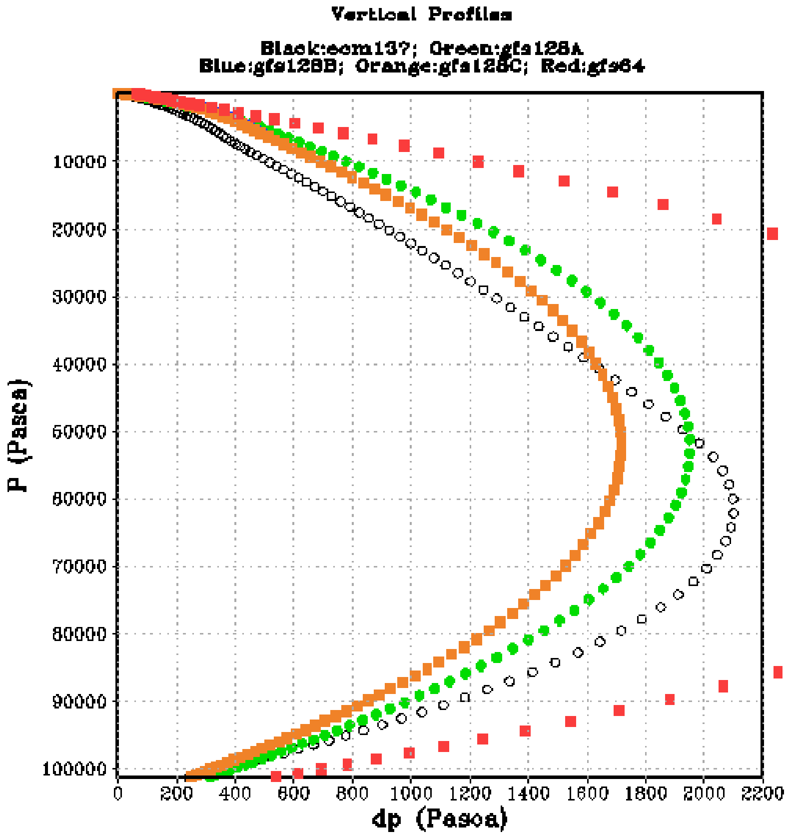
MinSLP Assimilation Only

Other Changes/ Data Upgrades

- NSST
  - Inline SST analysis produced within atmospheric DA
- Observations
  - GOES-17 AMVs
  - OMPS
  - METOP-C AMSU-A and MHS
- Dealing with TAC to BUFR

DA Plans for GFSv16

- Vertical Resolution: **127L with 80km top** (Currently **64L with 50km top**). Adaptation for "advanced physics"
- Ensemble Perturbation Update: LETKF (replace EnSRF), Early Cycle (instead of late, GDAS cycle)
- 4D Incremental Analysis Update
- Inter-channel correlated ob error
- Hydrometeor control variables;
  pass increment to model
- SDL/SDW, Shifting-Lagging (?)
- Global "LDAS"



DA Plans for GFSv16

- Climatological Background Error estimate (bootstrap)
  - With special attention to balance projection coefficients
  - *Initial estimate using NMC methods, cold start forecasts from GEOS-5, Small Sample (~ 50 pairs)*

- Tangent Linear Normal Mode

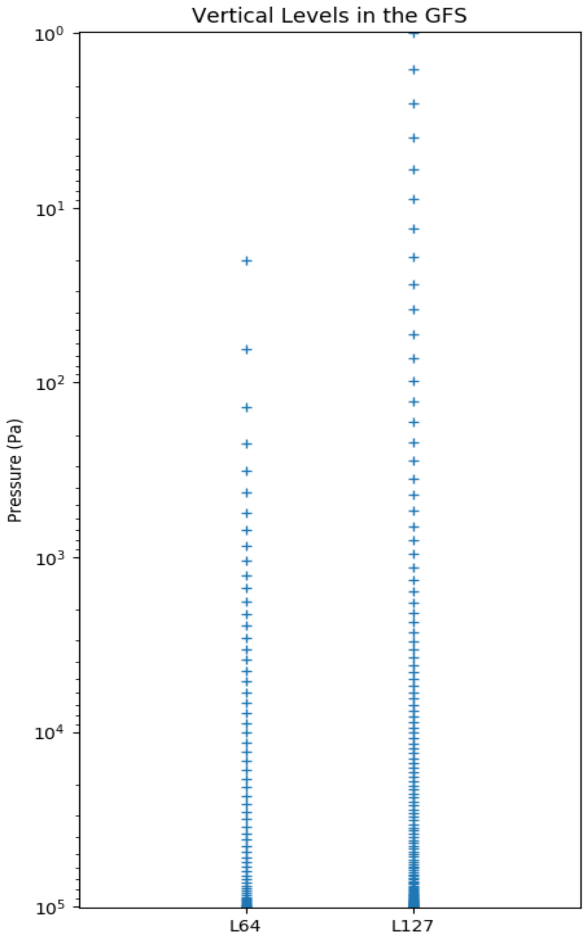
  Constraint

- Hybrid parameters
  - Localization
  - Weights

- Ensemble
  - Stochastic physics parameters
  - Inflation

- Channel selection, Radiative Transfer,

  Bias Correction

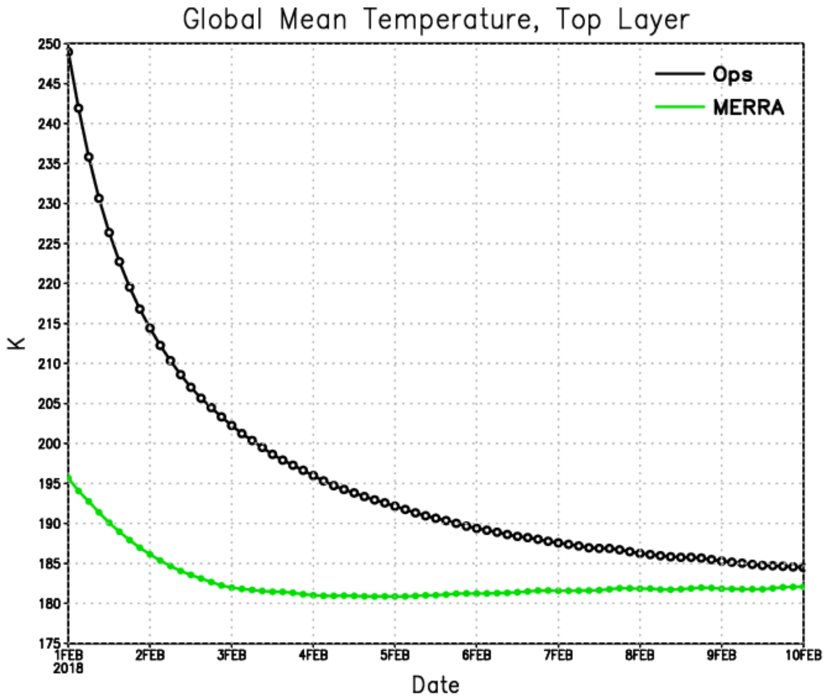


Bootstrap Background Error

The pre-operational FV3GFS uses the same static background error as the spectral model.

NMC method (Parrish and Derber 1992):
Uses a database of lagged forecast pairs at 24 and 48 hours valid at the same time.

GEOS-5/MERRA:
Contains FV3 dynamical core and has a similar model top to the 127-layer configuration. Valery Yudin (CU/CIRES) provided EMC with a program to convert GEOS-5 initial conditions to cubed-sphere tiles.



Bootstrap Background Error

Preliminary lagged pair database

- 24 and 48 hour forecasts
- Initialized from MERRA initial conditions
- January and July 2017
- 00z only
- 60 cases total

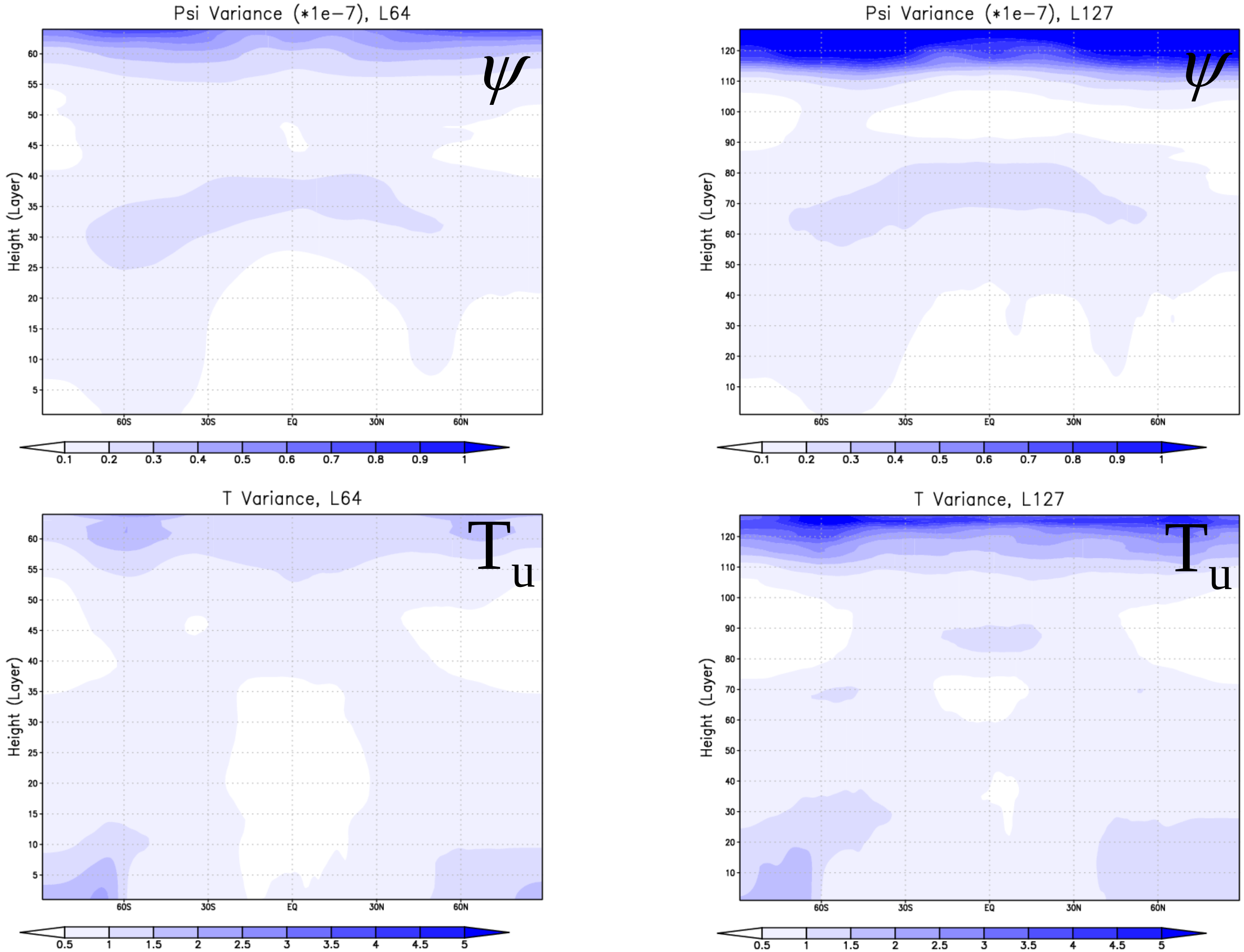
NMC_Bkerror utility

- Utility previously only able to process the older spectral file format.
- Received code from Spire (Razvan Stefanescu) to add the capability of reading NEMS I/O files.

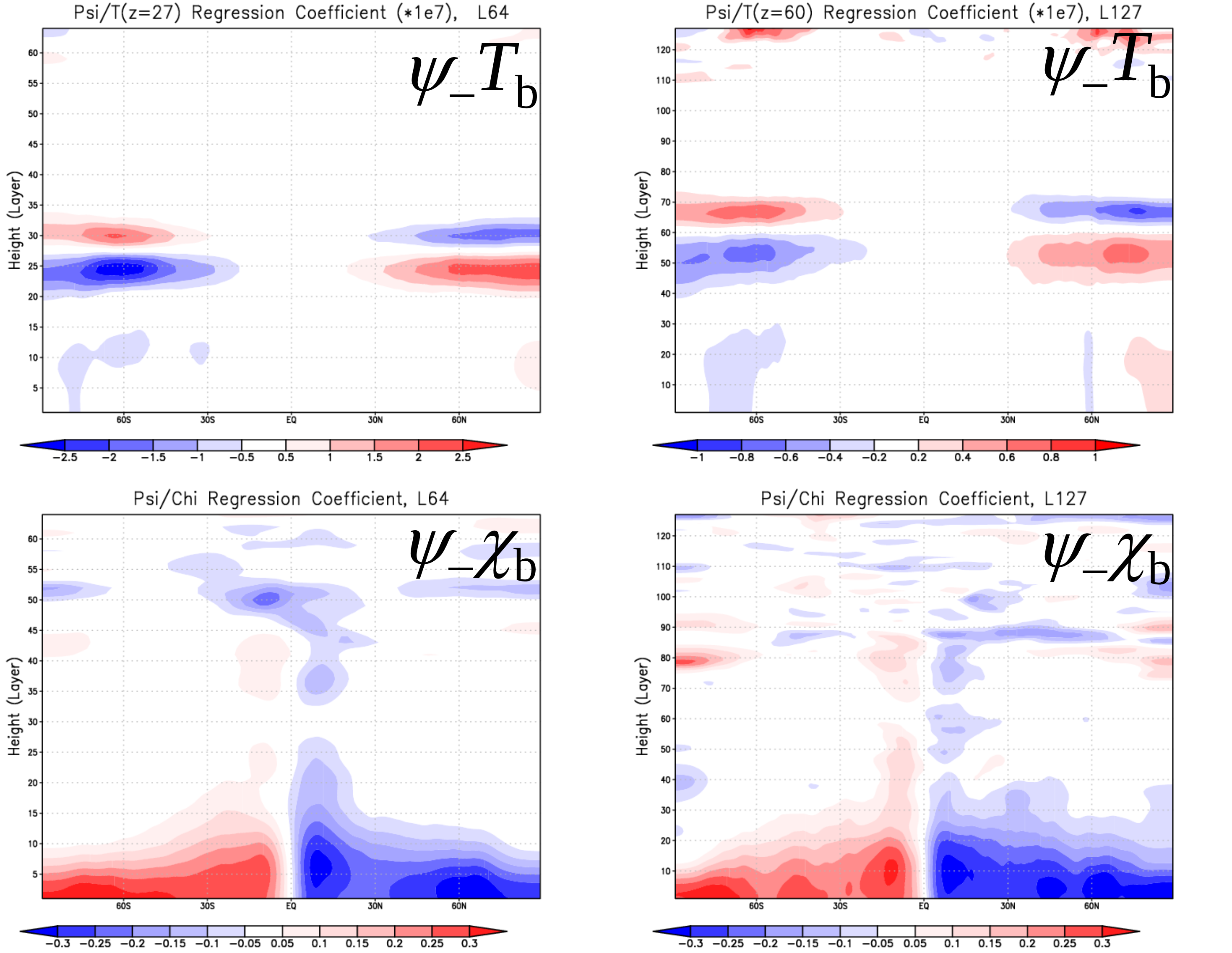
Static background error

- A preliminary static background error was generated.
- After sufficient tuning of the system, a larger lagged pair database will be created and a new static background error will be generated.

Bootstrap Background Error Standard Deviation: *Ops (Left) versus New (right)*



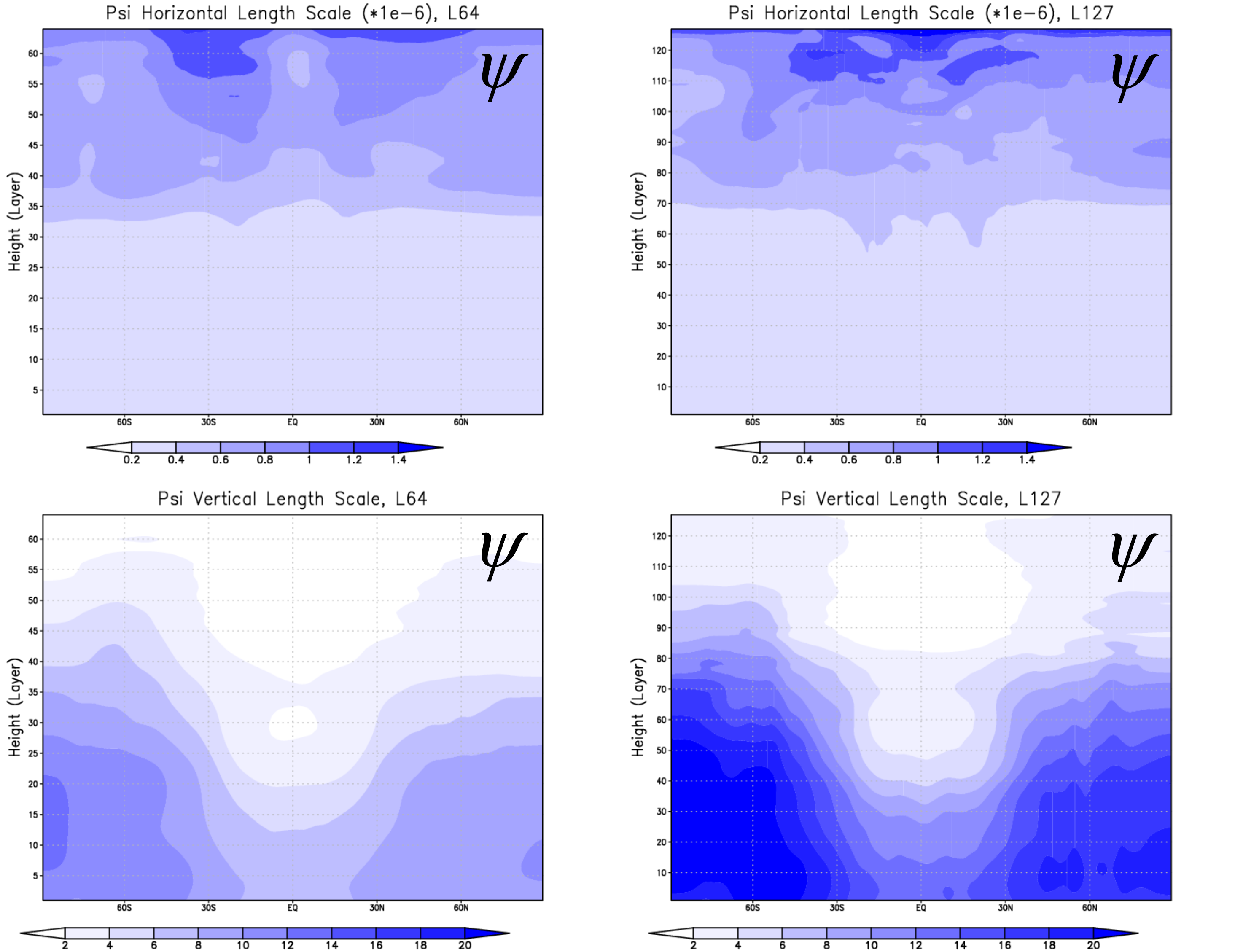
Bootstrap Background Error
Balance Projections: *Ops (Left) versus New (right)*



Bootstrap Background Error Length Scales: *Ops (Left) versus New (right)*

Horizontal (1000s km)

Vertical (# Levels)



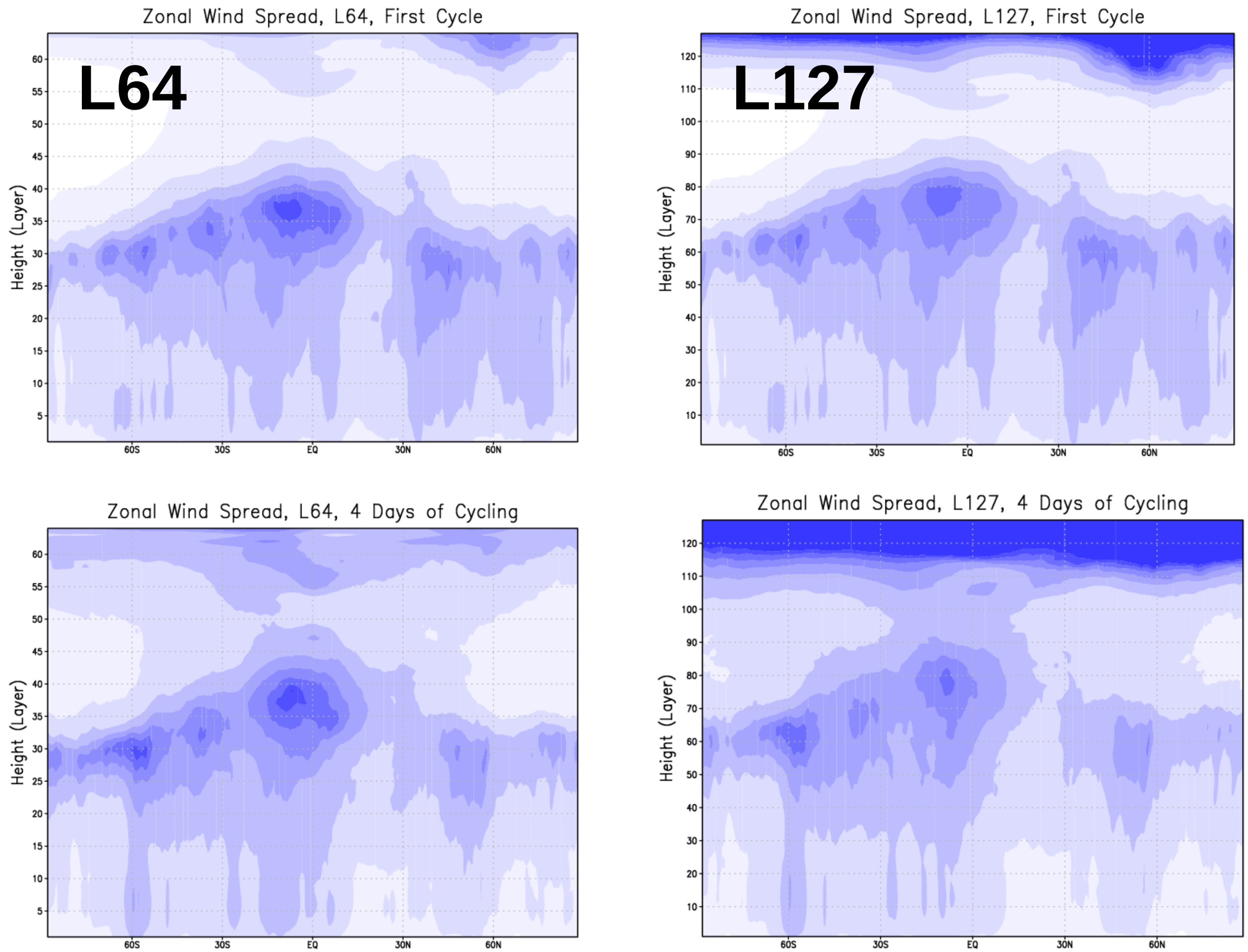
Initial Ensemble Calibration

80 member ensemble

- Little effort on tuning damping and other parameters as part of initial effort
- Run in EnKF-only update mode as well as cycled hybrid EnVar with initial climatological B

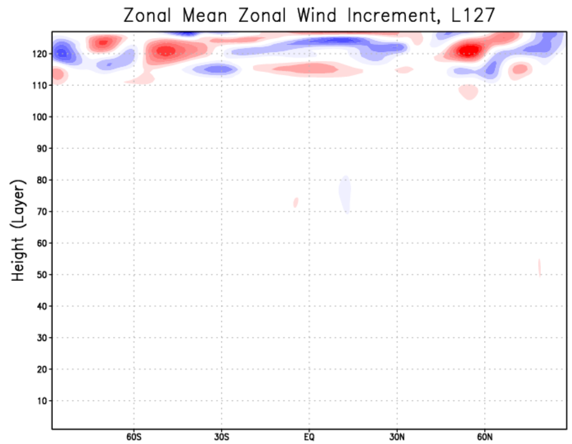
First Cycle

4 Days of Cycling



First Attempts at DA for 127L

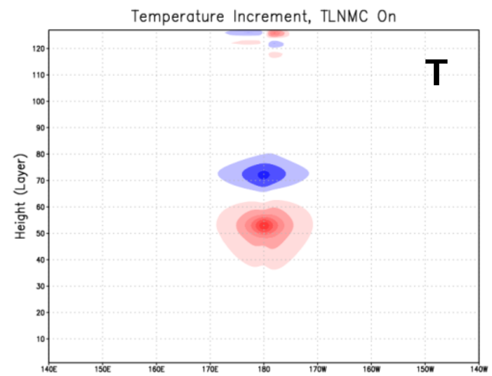
Single Analysis with All Observations

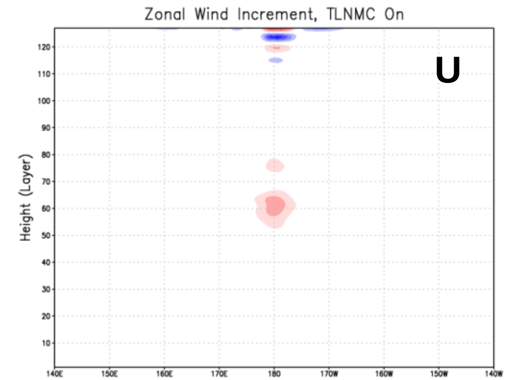


- Increments in the highest layers are dominant
  - Large static error variance
  - Sampling error in regression coefficient
  - Large ensemble spread
  - Tangent linear normal mode constraint
  - Lack of observations

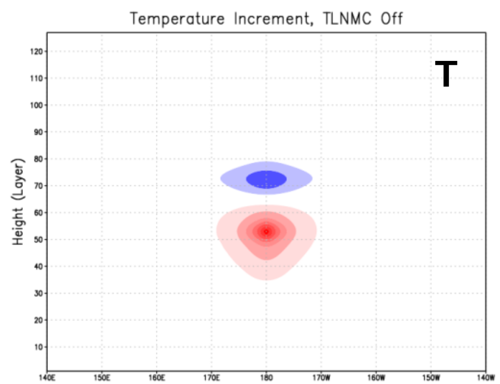
Single T Observation Impact Test

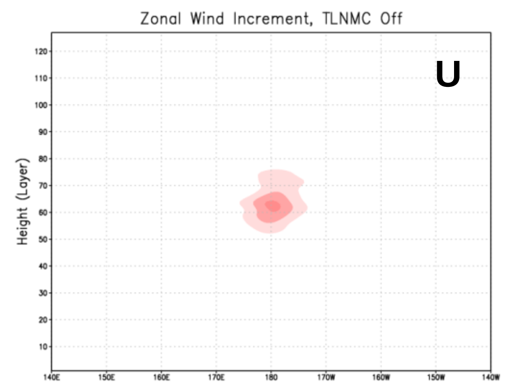
TLNMC On





TLNMC Off

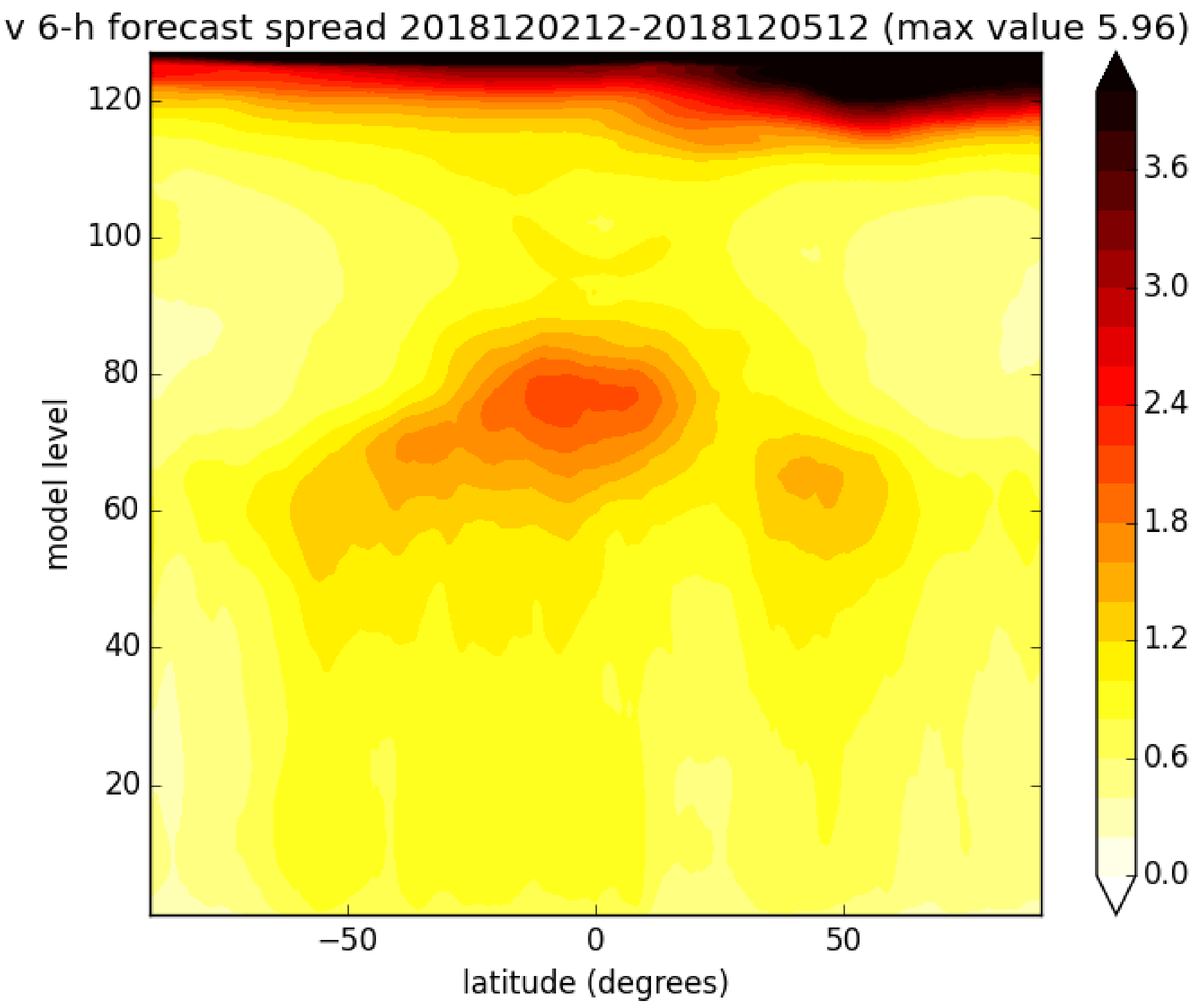




Large Spread in Ensemble at Model Top

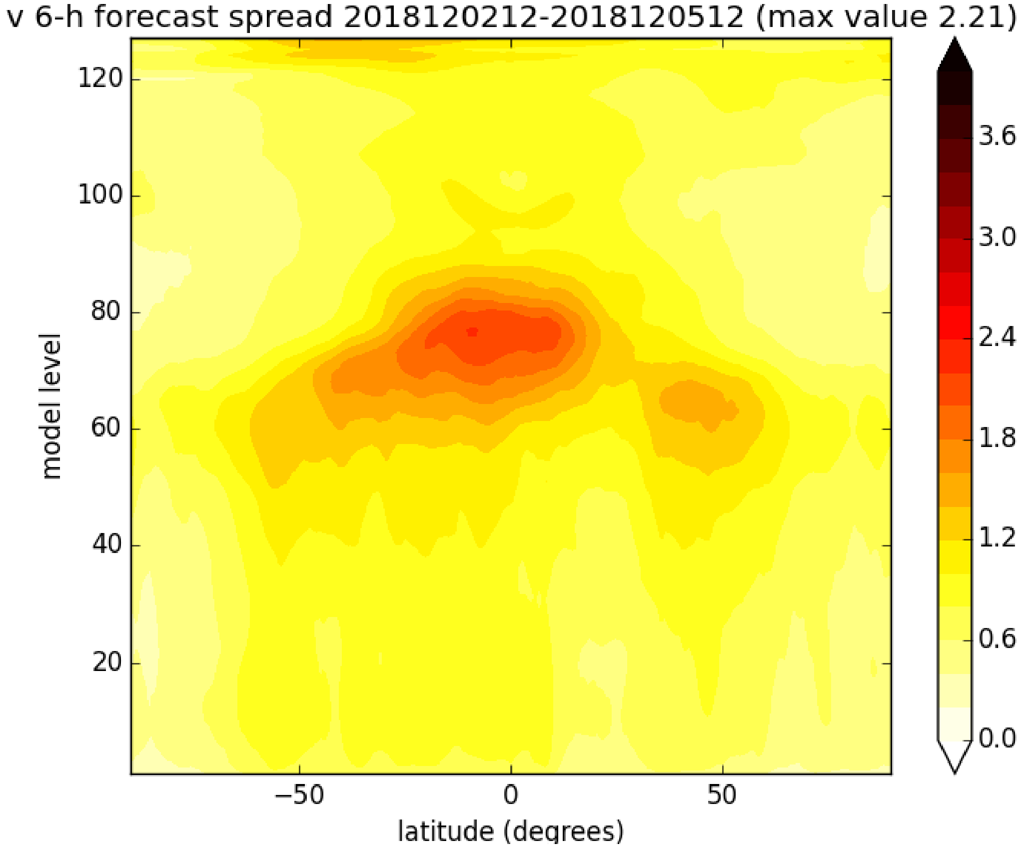
Ensemble spread (v) for 6-h forecast

turning off stochastic physics has no effect

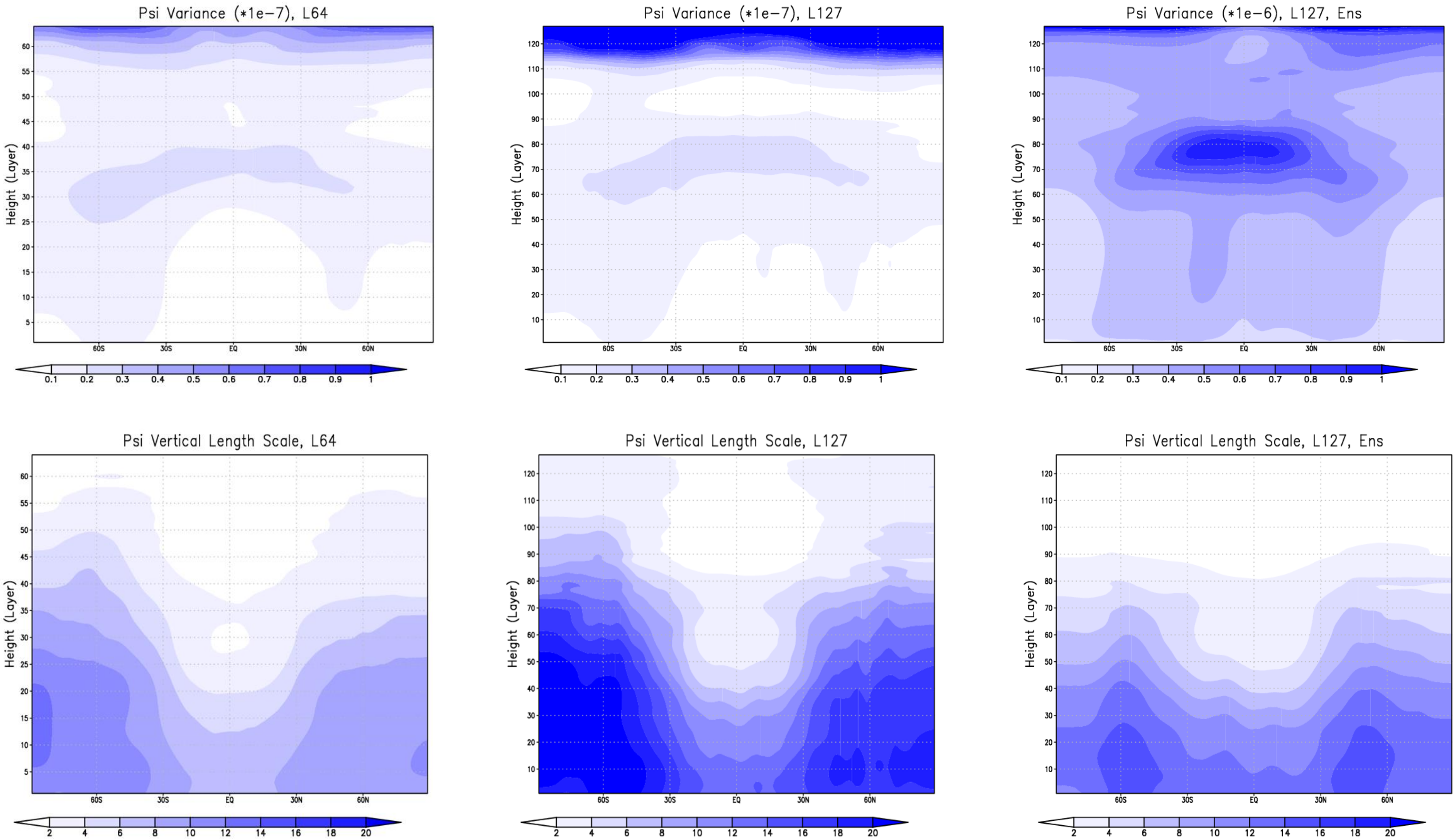


Enhanced Upper Level Damping

- Turned off dycore rayleigh damping.
- Increased divergence damping at top two levels (any further increase causes model to blow up).
- Old GSM rayleigh damping activated at 7.5 hPa – increases ral_ts per day every scale height



Re-compute climatological B from ensembles
One month sample, 80-member EnKF, “NMC Code”



What Next?

Model Damping

- To control model stability and ensemble spread, have tested and proposed changes to Rayleigh and divergence damping near model top
- Need to explore within context of updated, unified gravity wave drag

New Background Error

- Ensemble-based climatological B much more realistic but requires calibration
  Based on 06-h perturbations, not 24/48-h lagged forecast pairs

Tangent Linear Normal Mode Constraint

- As seen in tests, large projection to upper layers, exacerbated by large variances
- Look at adding more vertical modes? Engineer to reduce projection to upper layers?
- IAU sufficient replacement?

Efficiency

- More levels adds cost & GSI is reaching scalability limit. Exploring options to speed up DA update (minimization algorithm, TLNMC options, iteration count)

What Next?

LETKF / IAU / Early Cycle

- Infrastructure is already in place to run IAU (3D/4D)
- To enable 4DIAU for the ensemble, LETKF is more efficient for prescribing 4D analysis increment
- For technical reasons, this will also include some tuning (data selection, etc.); so will incorporate as part of plan to update ensemble as part of "early cycle"

Cloud increments

- Currently not passing hydrometeor updates back to model. This will be re-visited within context of IAU

Model error representation

- SKEBS is available and candidate for re-inclusion

Extract more from ensemble

- Shifting, lagging, and scale-dependent weighting/localization have all been tested with varying levels of maturity. While candidates, these are not high priority.

Observations

- New observations (ADM-Aeolus, etc.), all-sky improvements, inter-channel correlated observation errors

Status of radiance data assimilation in the FV3GFS

Microwave:

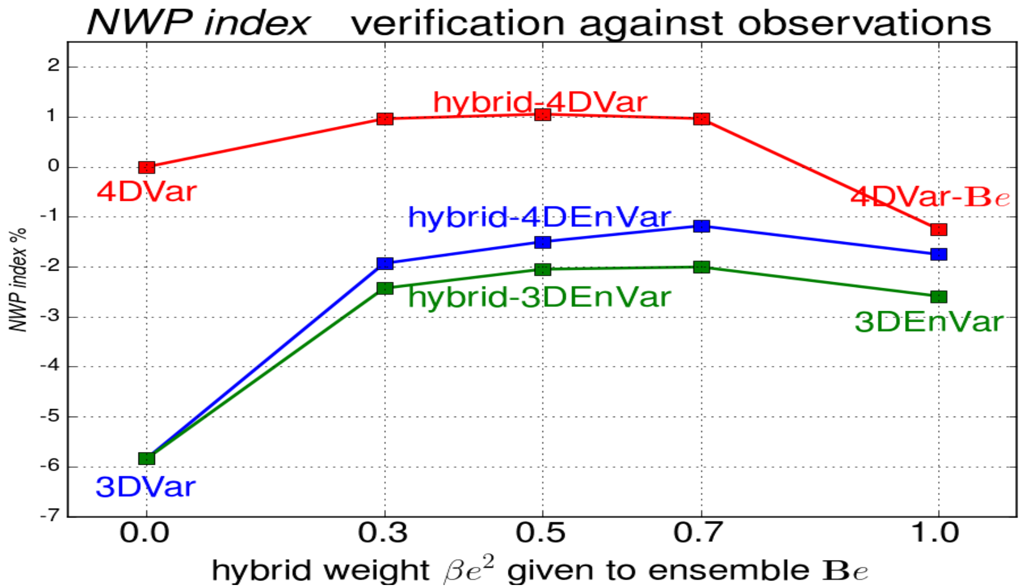
- AMSU-A: NOAA-15, 18, 19, MetOp-A, MetOp-B, Aqua
- ATMS: NPP, NOAA-20
- MHS: NOAA-18, 19, MetOp-A, MetOp-B
- SSMIS: DSMP-F17
- SAPHIRE: Megha-Tropique

Infrared:

- AIRS: Aqua
- GOES-15 Sounder
- IASI: MetOp-A, MetOp-B
- CrIS: NPP, NOAA-20
- SEVIRI: MeteoSat-8, 11
- AVHRR: MetOp-A, NOAA-18

- ❑ Both clear-sky and cloudy radiances from AMSU-A and ATMS over ocean FOVs are assimilated in the **all-sky** approach (Zhu et al. 2016; Zhu et al. 2019)
- ❑ Only clear-sky radiances are assimilated from other sensors
- ❑ Himawari AHI, GPM GMI under development & testing

Hybrid 4DEnVar versus 4DVar



For UMKO System, Courtesy D. Barker & A. Lorenc (see Lorenc et al. 2017)

- Hybrid 4DEnVar ~2-3% worse than hybrid 4DVar.
- But much cheaper…….

DA Plans for Global NWP

Given results from UKMO, **draft test plan for inter-comparison between Hybrid 4DEnVar and Hybrid 4DVar (with FV3 TL/AD)**

- Continue to invest in improvements to 4DEnVar as it is operational system (time evolving full rank B, time evolving localization)
- Forward thinking, HPC considerations
- Consider implication of choices on coupled data assimilation
- Is TL/AD available for coupled model, etc.
- Further exploitation of information from ensembles
- Scale dependent hybrids (weights, localization), shifting/lagging, multi-resolution
- Can we close the gap between Hybrid 4DEnVar and Hybrid 4DVar?
- ***Choice of algorithms may be application dependent***!

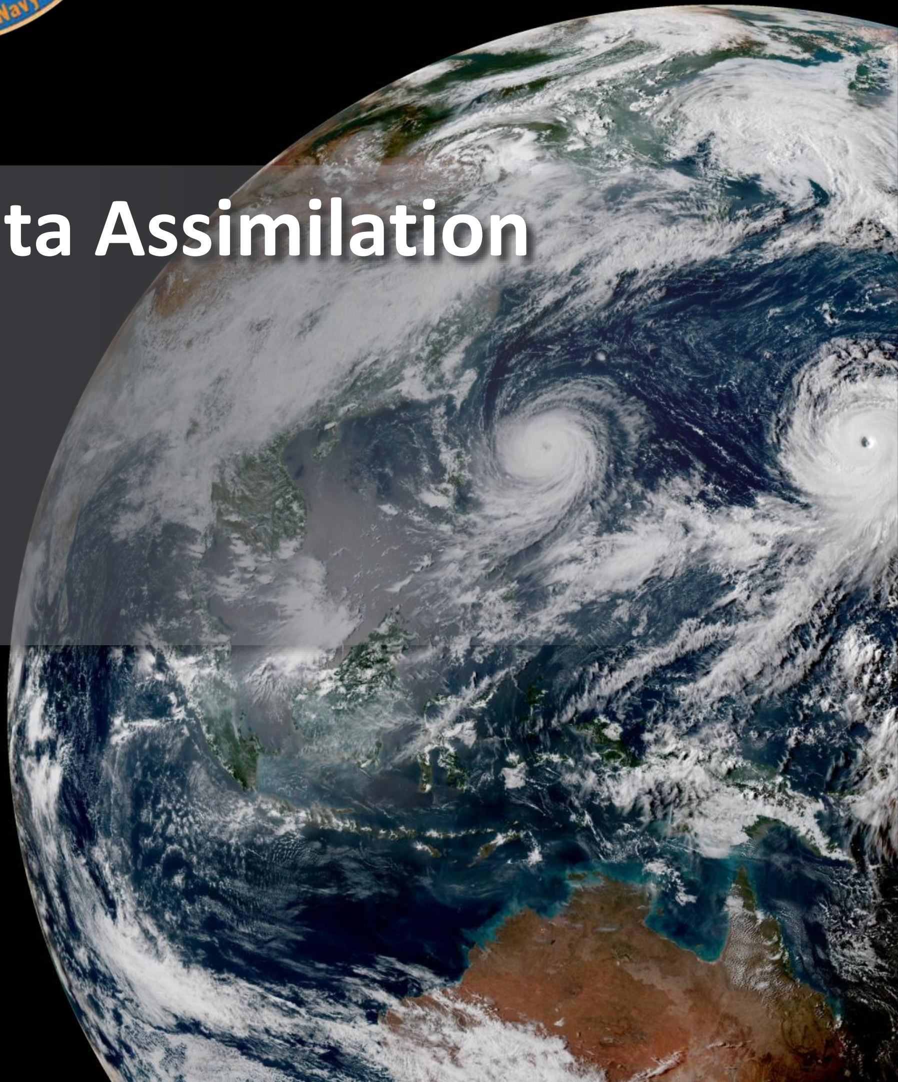
Supplemental-funded global hourly updating system

- Recent proposal for "Continuous DA" from ECMWF as alternative?
- Additional/alternate cadence strategies

Better/more monitoring, online tools

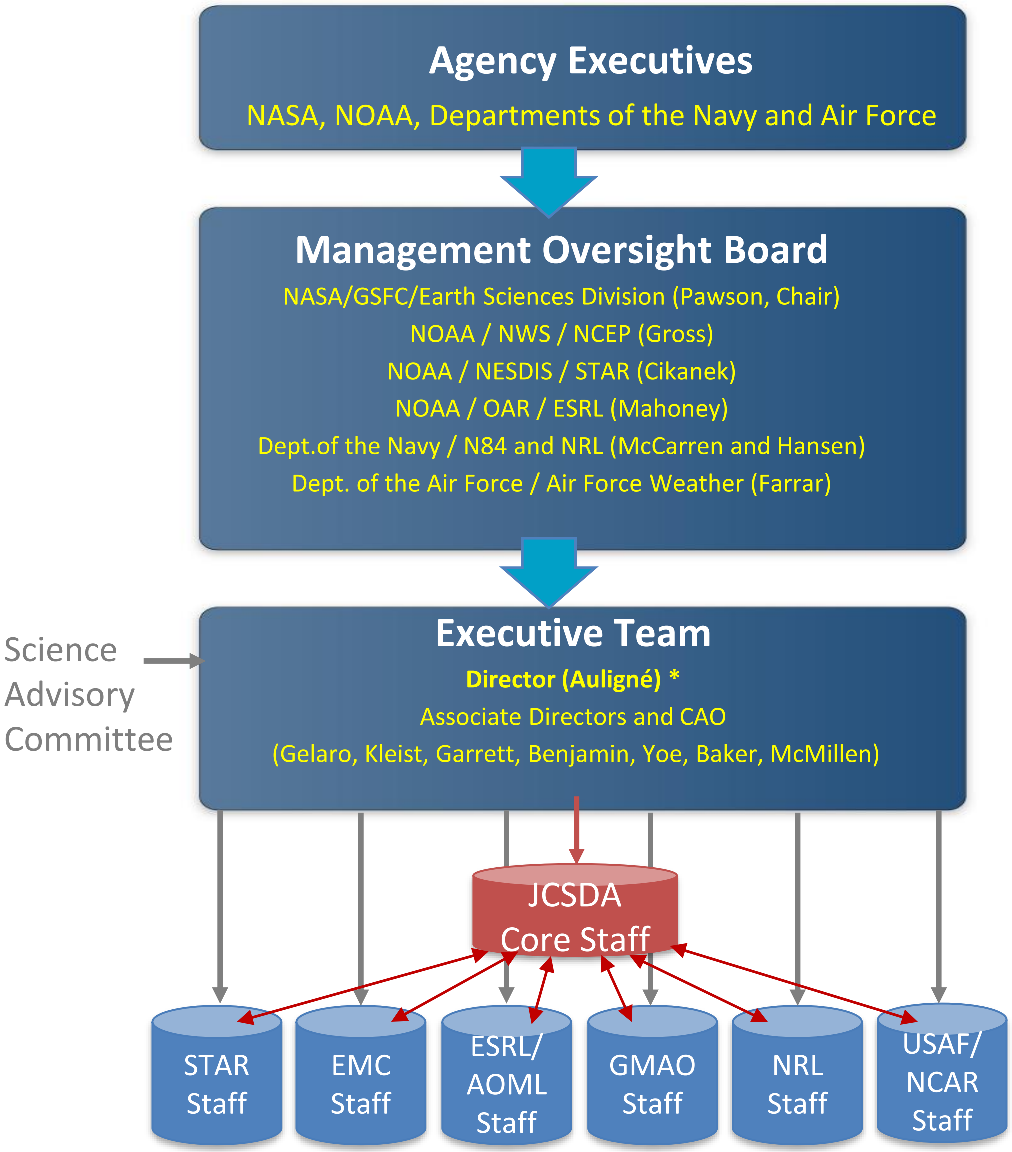
- Includes EFSOI, PQC testing, etc.

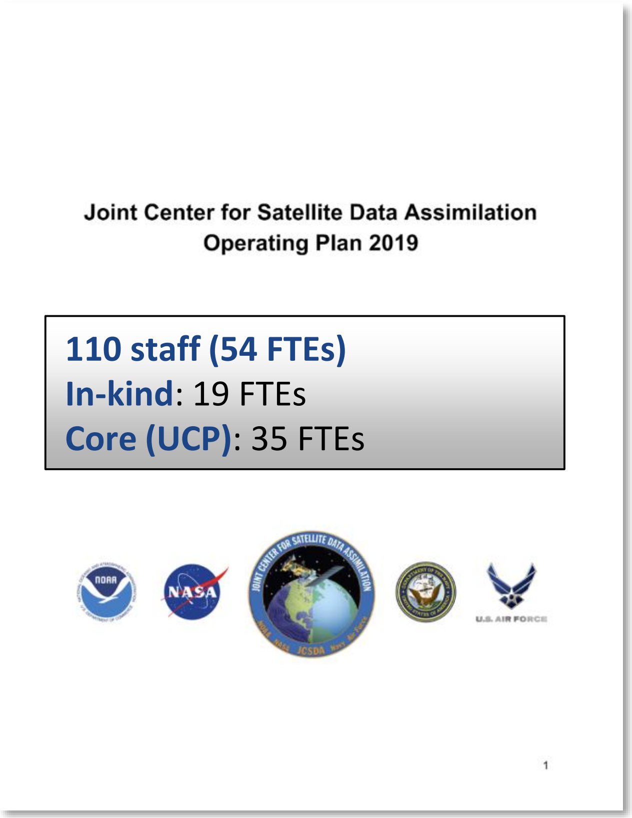
Joint Center for Satellite Data Assimilation



Slides Courtesy
Tom Auligné, JCSDA Director

JCSDA Concept of Operations





Joint Center for Satellite Data Assimilation
Operating Plan 2019

110 staff (54 FTEs)
In-kind: 19 FTEs
Core (UCP): 35 FTEs

U.S. AIR FORCE

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Priority Milestones for 2019

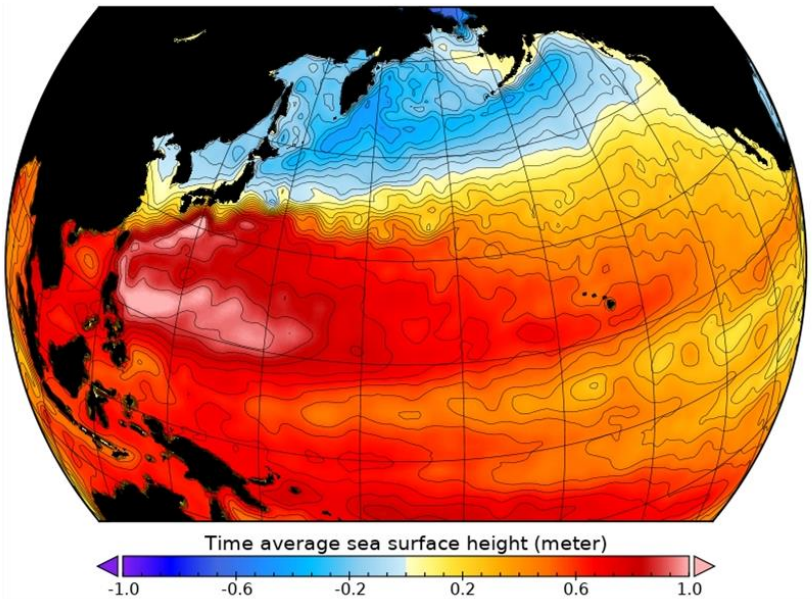
CRTM
- Version 3.0 beta release, and community package for coefficients generation

NIO
- Transition all operational obs. operators to UFO, additional all-sky/all-surface radiances

IOS
- Evaluation of commercial weather data pilot. Observation impact real-time diagnostics

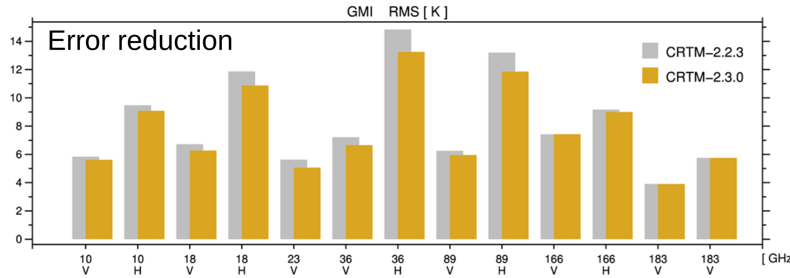
SOCA
- Cycling assimilation for MOM6-CICE5

JEDI
- UFO release toward use in NOAA EnKF
- Realistic atmospheric data assimilation
  MPAS, GEOS, FV3GFS, WRF, LFric, NEPTUNE
- Prepare coupled Earth system DA
  atmosphere, ocean, waves, land, aerosols, cryos.



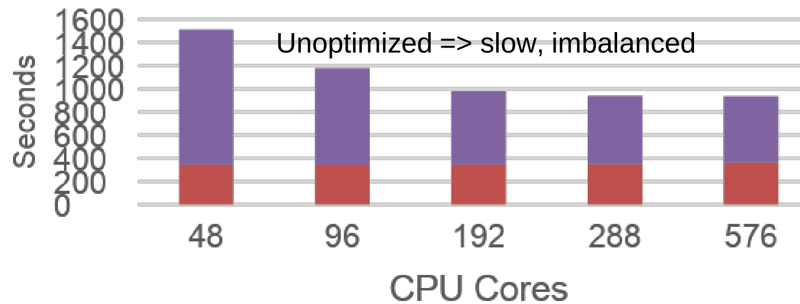
Community Radiative Transfer Model (CRTM)

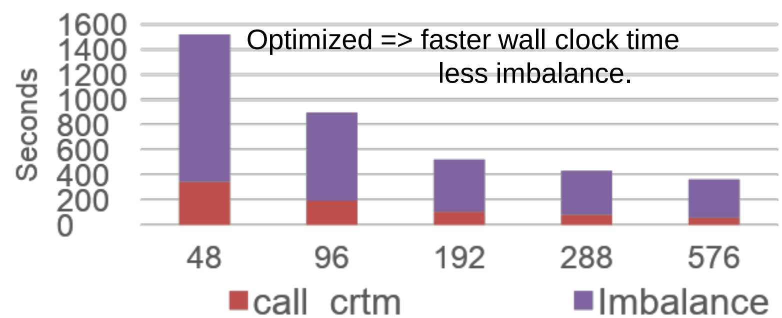
(1) Significantly **improved solar/infrared simulation accuracy**



(1) Implementation of cloud fraction capability and **improved physical consistency**, enabling **accurate cloudy radiance simulations** and assimilation capabilities in cloud and precipitation impacted regions

(1) Computational acceleration: improved the speed up to 8x



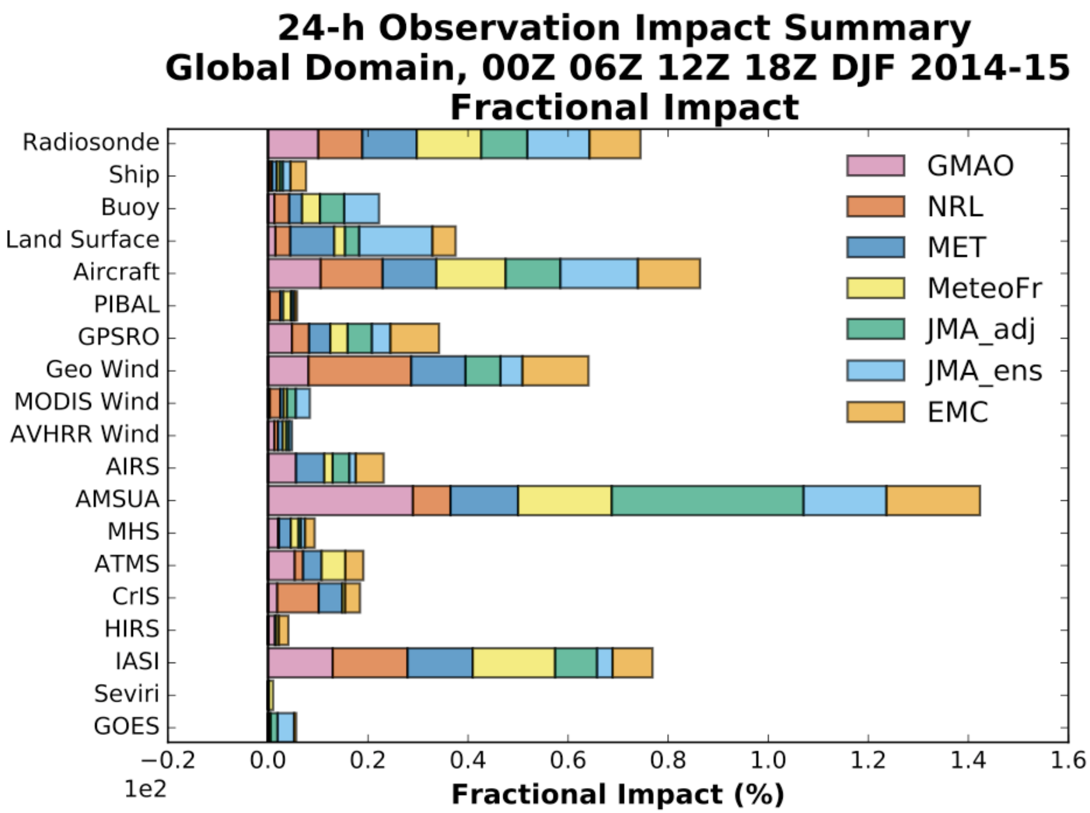


(1) The CRTM team has built a **strong path to operations across multiple agencies** through expansion of operational radiative transfer products and rapid/responsive support

(1) Visibility: Over 1,000 articles citing the CRTM since 2004, 260+ since 2016

(1) 200+ sensors supported. Recently: EON_MW, Sentinel-3A, Meteosat-11 SEVIRI, GOES 16/17 ABI, Metop-C AVHRR3/IASI, GPM-GMI, SMAP, SMOS, TEMPEST-D, COMS MI, Himawari-8/9 AHI, N19 MHS/AVHRR/HIRS/AMSUA, NPP/JPSS1 CrIS/ATMS/VIIRS, COWVR, TROPICS

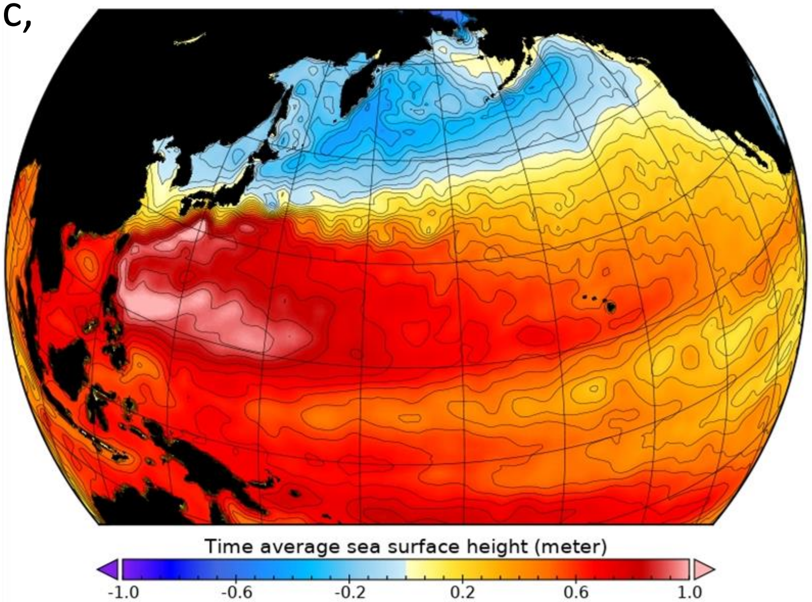
Impact of Observing Systems (IOS)



- **Commercial satellite data evaluation (CWDP)** phase I: evaluation and report submitted
- GNSSRO evaluation and **monitoring package** released.
- Forecast Sensitivity – Observation Impact (FSOI) **inter-comparison** experiment
- Running **real-time FSOI** with GFS operations
- Developed tools for on-demand **data mining and visualization** on the Cloud (AWS).
- Prototype new observation bias correction based on **machine learning**

Sea-ice/Ocean Coupled Assimilation (SOCA)

- IODA/UFO:
  - Fairly complete set of marine UFO (ocean and sea-ice)
  - Conventional observations from FNMOC (Argo, CTD, XBT, moorings, gliders, …)
  - NESDIS sea surface height (Jason 2-3, SARAL, Cryosat-2, Sentinel-3a)
- Model encapsulation
  - MOM6 model advance: Thermodynamic,
  - dynamics (barotropic/baroclinic)
- Surface sensitive radiance
  - OSE (AMSU-A)
  - GMI/SMAP UFO prototype
- 3DVAR and multivariate Static B (ocean and sea-ice)
- High-resolution (¼ degree MOM6)
- Cycling



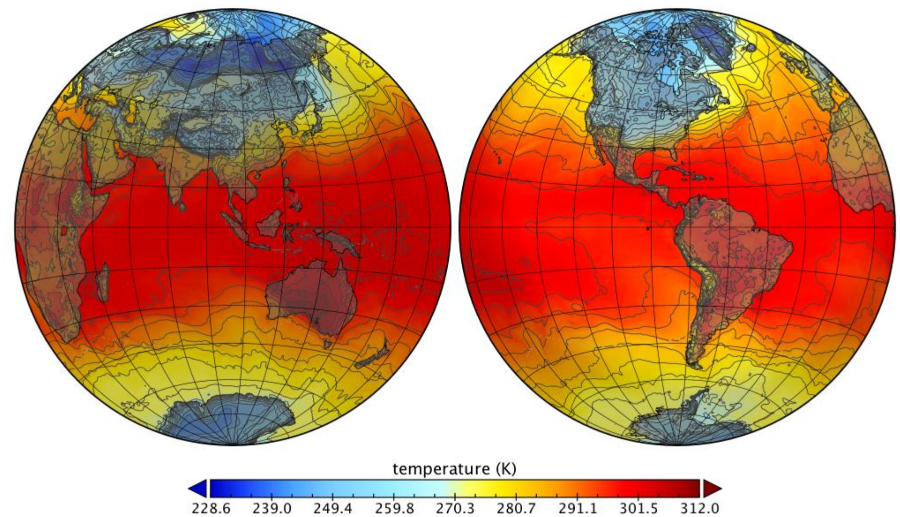
30-day cycling assimilation of satellite SST (NESDIS/ACSPO AVHRR L2P) and altimetry (Jason-2, Jason-3, Sentinel-3a, Cryosat-2, SARAL) with MOM6 1 degree model, 24-hour window. Kuroshio large meander correctly placed

Joint Effort for Data assimilation Integration (JEDI)

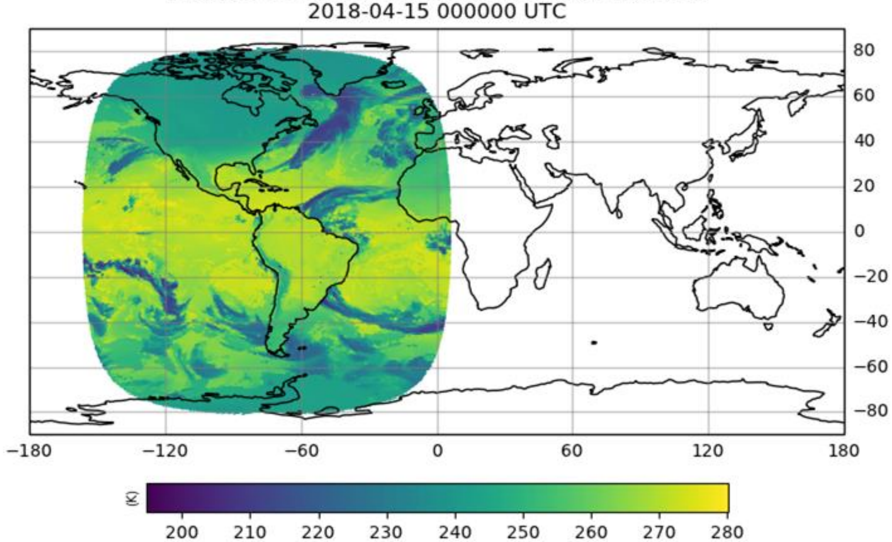
Much more than a concept:

4DVar running with FV3GFS/GEOS
3DVar (and 4DEnVar) with MPAS (cycling)
3DVar (and 4DEnVar) with LFRic
3DRPCG with MOM6-CICE5

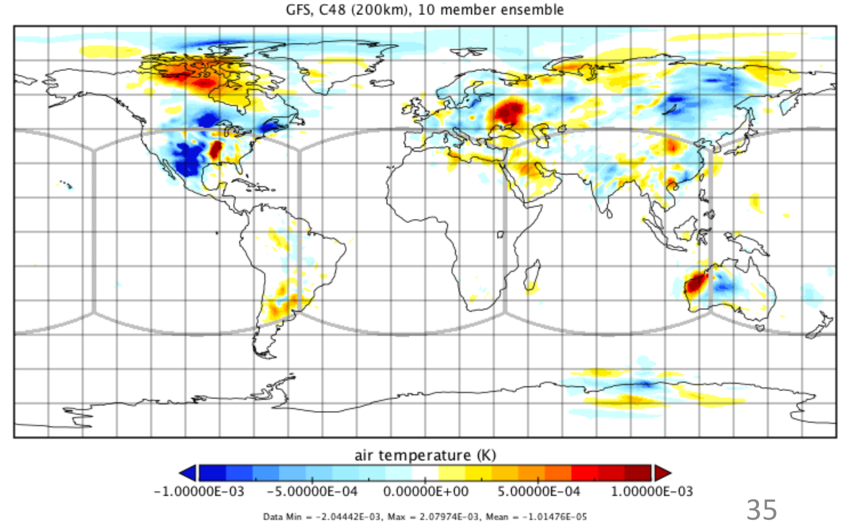
temperature



Model simulated brightness temperature.
ADVANCED BASELINE IMAGER (GOES-R) channel 1
2018-04-15 000000 UTC



Analysis increment | hybrid 3DVar FGAT
GFS, C48 (200km), 10 member ensemble



Model Interfaces Status

	State	3D H(x)	M(x)	4D H(x)	3D-Var	TL/AD	4D-Var
FV3-GFS (NOAA)	✓	✓	✓	✓	✓	✓ (dry)	
FV3-GEOS (NASA)	✓	✓	✓	✓	✓	✓	✓
MPAS (NCAR)	✓	✓	✓	✓	✓	N/A	
WRF (NOAA/NCAR)	✓	✓	✓		✓		
LFRic (UKMO)	✓	✓	✓	✓	✓		
NAVGEM (NRL)	✓						
NEPTUNE (NRL)	✓	✓					
CICE5 (JCSDA/NOAA)	✓	✓			✓	N/A	
MOM6 (JCSDA/NOAA)	✓	✓	✓	✓	✓	N/A	

Observation Interfaces Objectives

- Share observation operators between JCSDA partners and reduce duplication of work

- Faster use of new observing platforms

  Satellite missions expensive + short lifetime. Include instruments science teams

- A shared Interface for Observation Data Access (IODA)

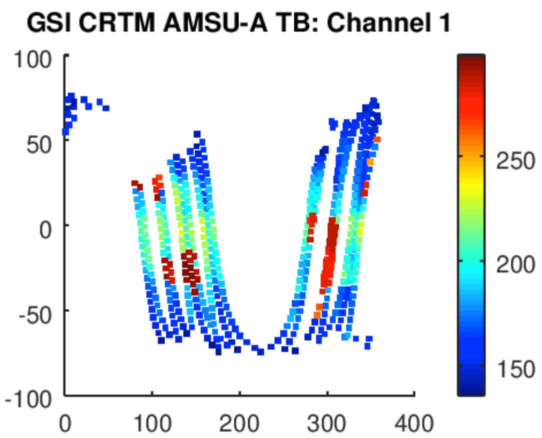
  For sharing data, operators and diagnostic tools

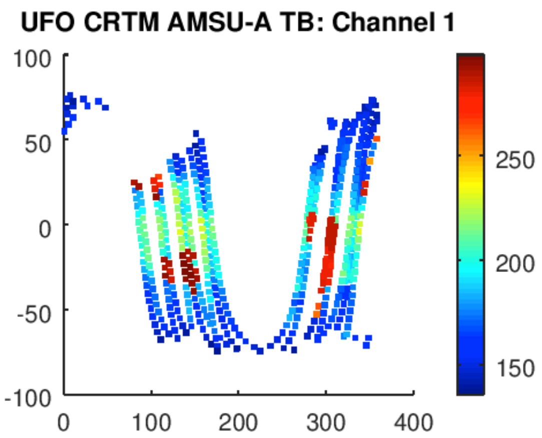
- Unified Forward Operator (UFO)

  Build a community *app-store* for observation operators

Unified Forward Operator (UFO)

Instrument Type	Nonlinear	Linear (tangent)	Adjoint
Radiosonde	✓	✓	✓
Aircraft	✓	✓	✓
AMVs	✓	✓	✓
Aerosol Optical Depth	✓	✓	✓
Satellite Radiances	✓	✓	✓
GNSSRO Refractivity & BA	✓	✓	✓





JEDI: High-level Status

JEDI is for **scientific exploration** and **operational forecasting**... and exchanges between them.

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

- Is model agnostic
- Does not impose one specific DA methodology or algorithm
- Encourages implementation of model-independent observation operators
- Provides a unified Interface for Observation Data Access (IODA)

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

JEDI Transition for Global NWP

(1) JEDI-UFO for EnKF (Sept. 2019)
Replace use of GFS for computation of O-F for EnKF only

(2) JEDI-EnKF Solver (Sept. 2020)
Replace GSI-based EnKF with JEDI-EnKF

(3) JEDI-UFO connected to GSI Solver (Sept. 2021)
Connect JEDI observer to current solver using diag/netcdf files

(4) JEDI-Solver / Full scale replacement of GSI (Sept. 2022)
Full-scale replacement of GSI

Questions/Discussion

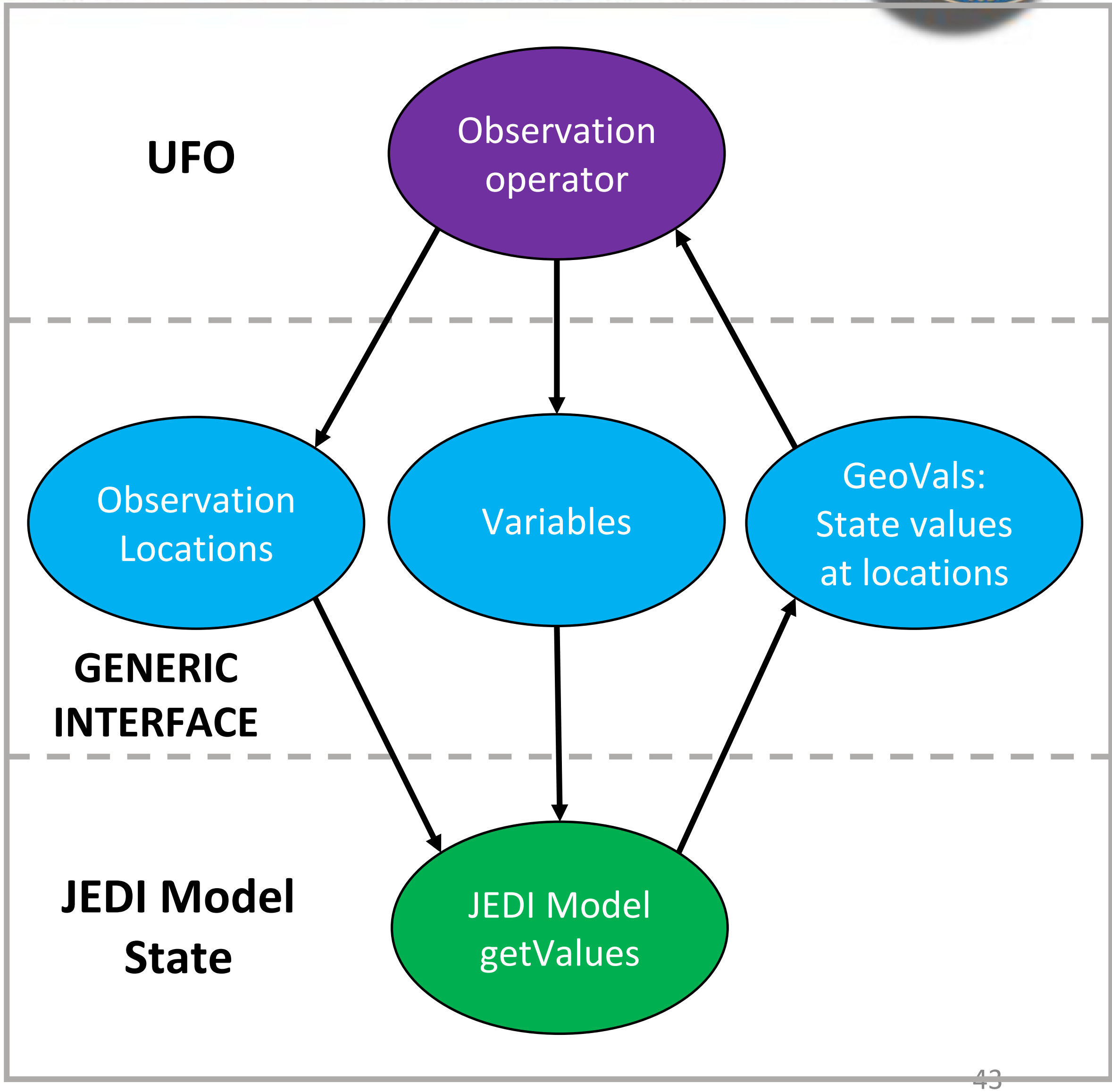
JEDI-FV3GFS interface

Unified Forward Operator (UFO)

The Unified Forward Operator (UFO) is **game-changer for future developments**

- introduces standard interfaces between the model and observation worlds. Interpolation from model native grids to observation locations
- calls abstract “observation filters” before and after the actual operator (e.g. Gross error check, background check, blacklisting)
- observation operators are independent of the model and can easily be shared, exchanged, compared

The ‘App Store’ of model-agnostic observation operators

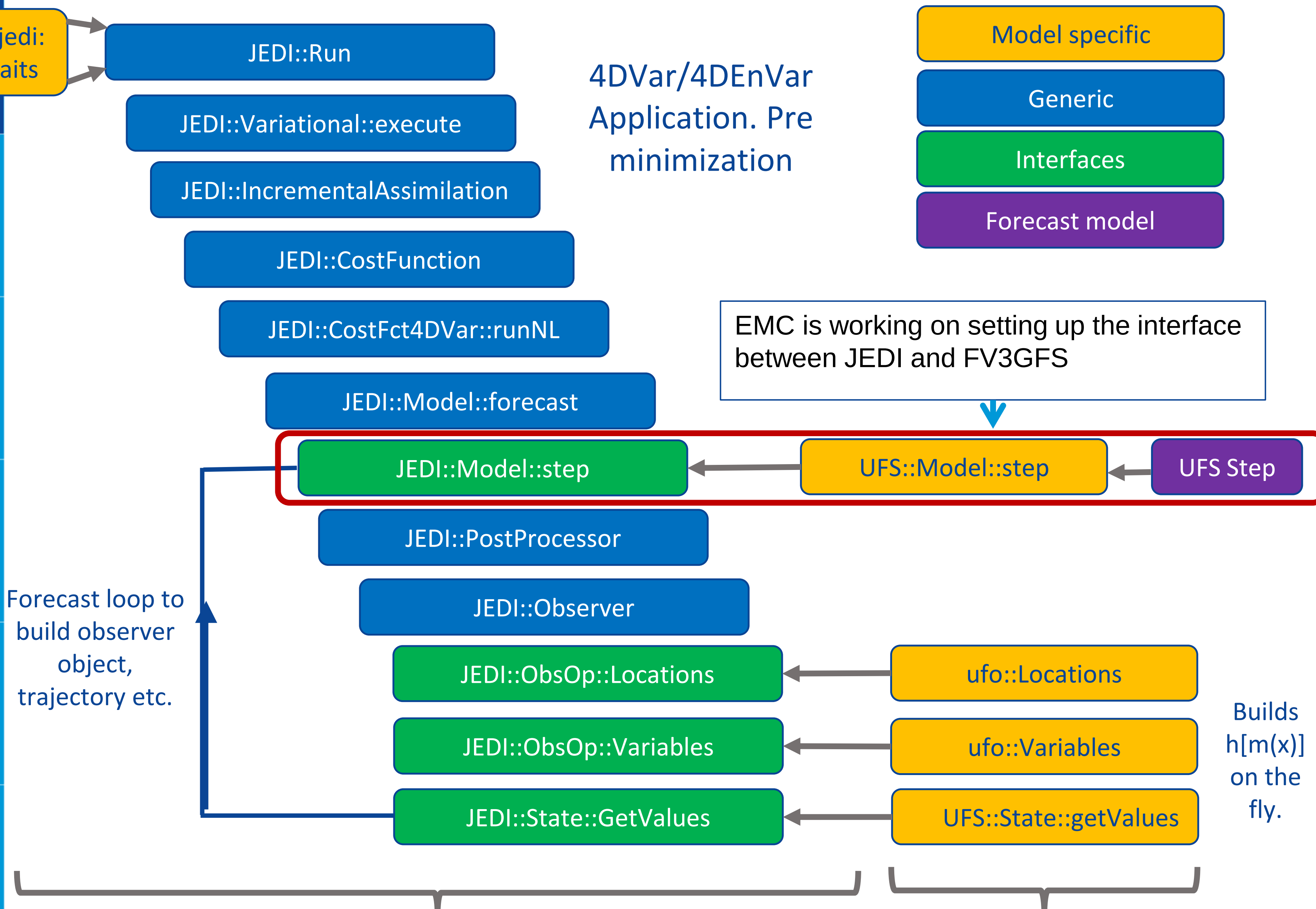


The UFS System Architecture WG DA Focus Team

Jeff Whitaker (NOAA/OAR)
Dan Holdaway (NASA/JCSDA)
Rahul Mahajan (NASA/JCSDA)
Jun Wang (NOAA/EMC)
Gerhard Theurich (NRL/NESII)

Task: Identify potential technical issues for connecting UFS and JEDI, develop a prototype interface, provide direction for future collaboration between JEDI and UFS developers.

Work has been done:
A workable solution was found to interface JEDI with a NUOPC-based FV3GFS model through the NUOPC driver
Required a few additions to the NUOPC API.
JEDI-FV3GFS exchange fields are added in the import and export states in FV3GFS.
JEDI ‘cap’ that drives NUOPC driver can be generic.



Generic C++ code, not aware of the grid structure or model type.

Implementation, C++ or Fortran

Overview of FV3GFS low-skill case project

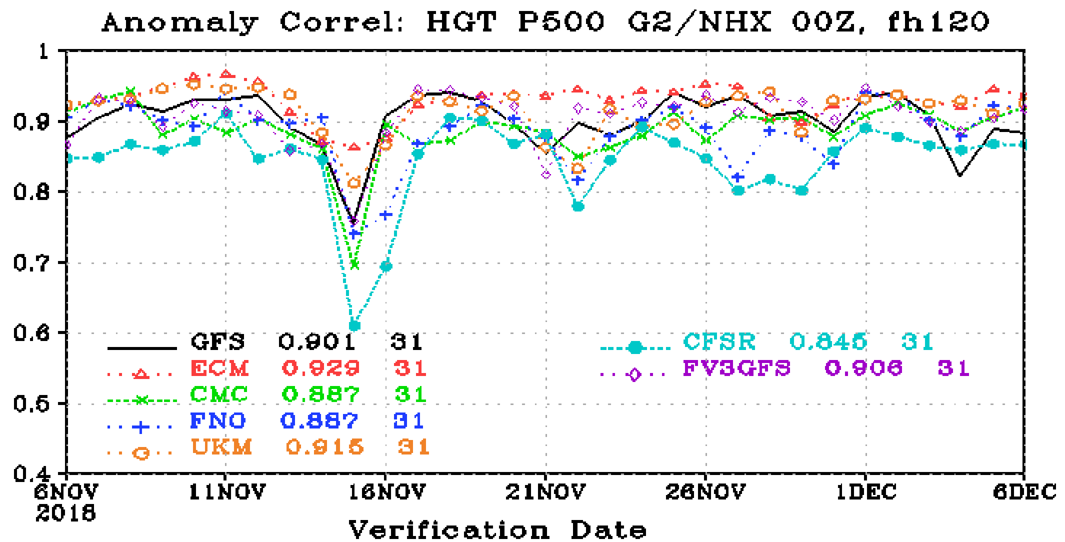
Motivation

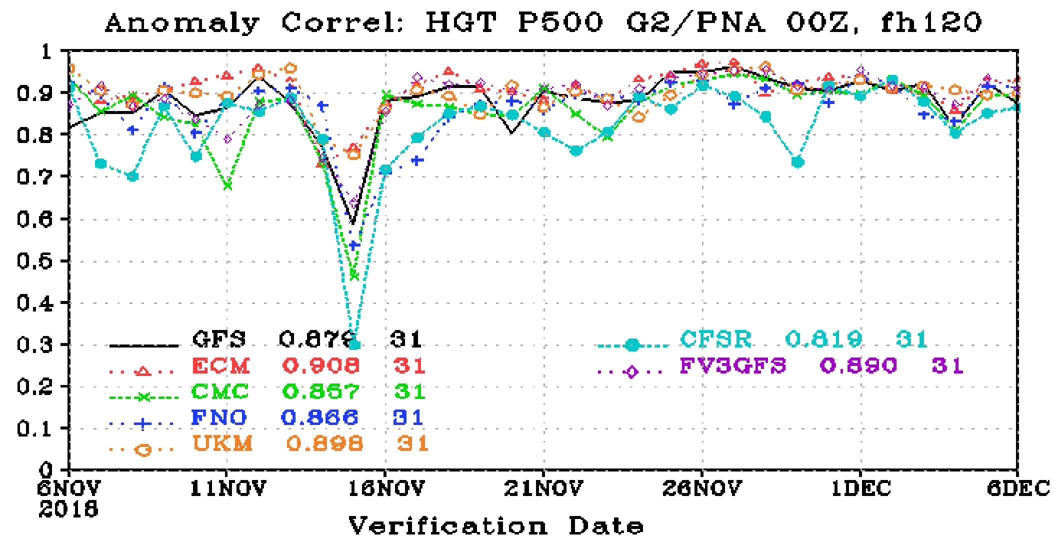
- All forecast models still occasionally have periods where 5-day forecast skill is significantly reduced on hemispheric and/or regional scales

- Previous studies have evaluated low skill events over Europe in ECMWF forecasts (e.g., Rodwell et al. 2013) and identified regions/processes likely responsible for producing poor forecasts

- What regions/processes/features are associated with poor hemispheric forecasts in the FV3GFS? Poor regional forecasts?

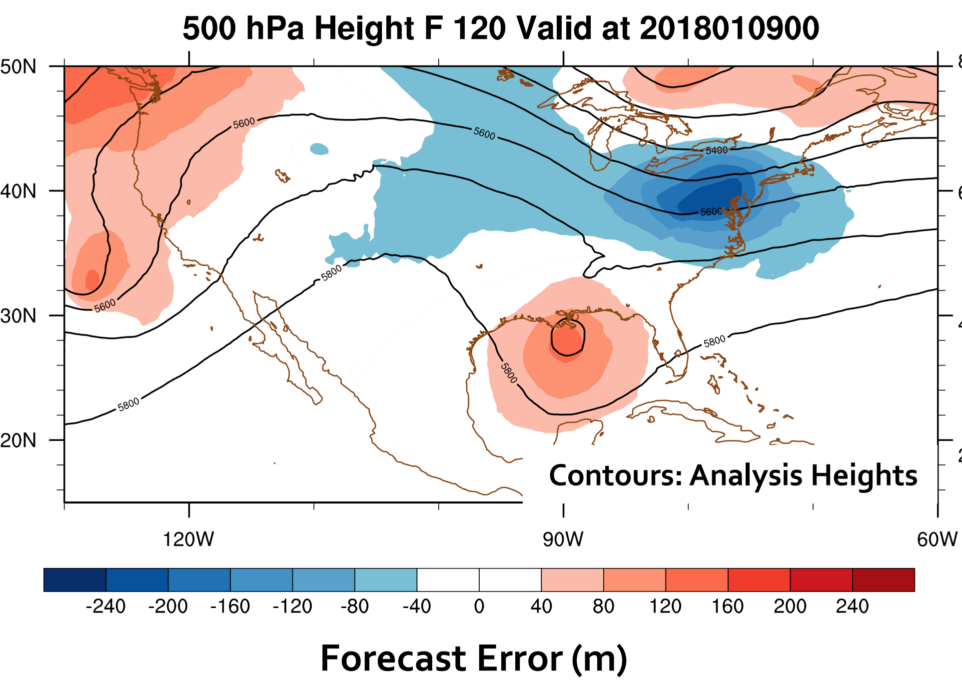
- For the poor hemispheric cases identified in recent FV3GFS, individual forecasts are analyzed to identify common features between events

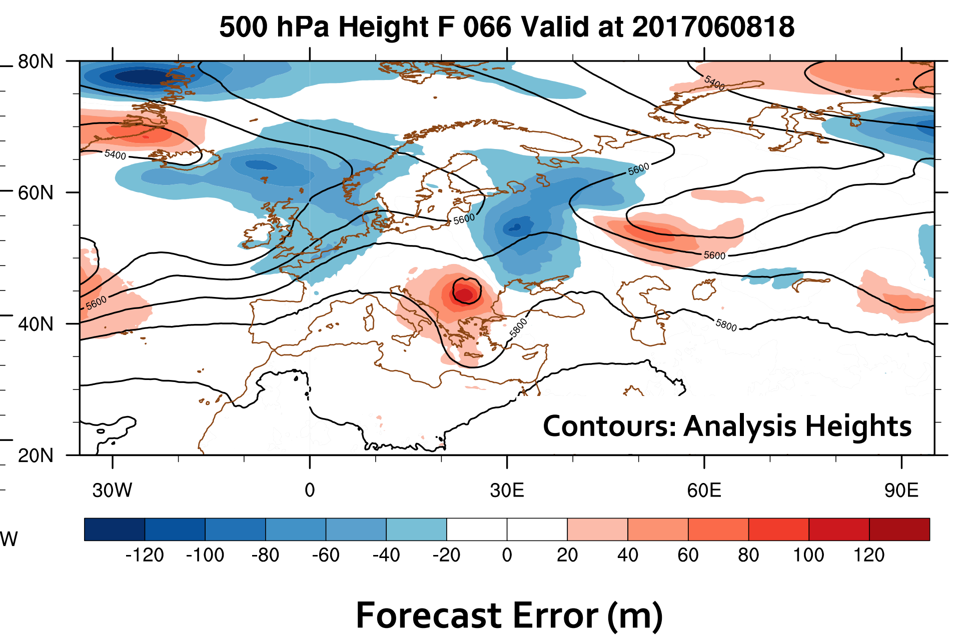




Common Factors Across Poor Hemispheric Cases

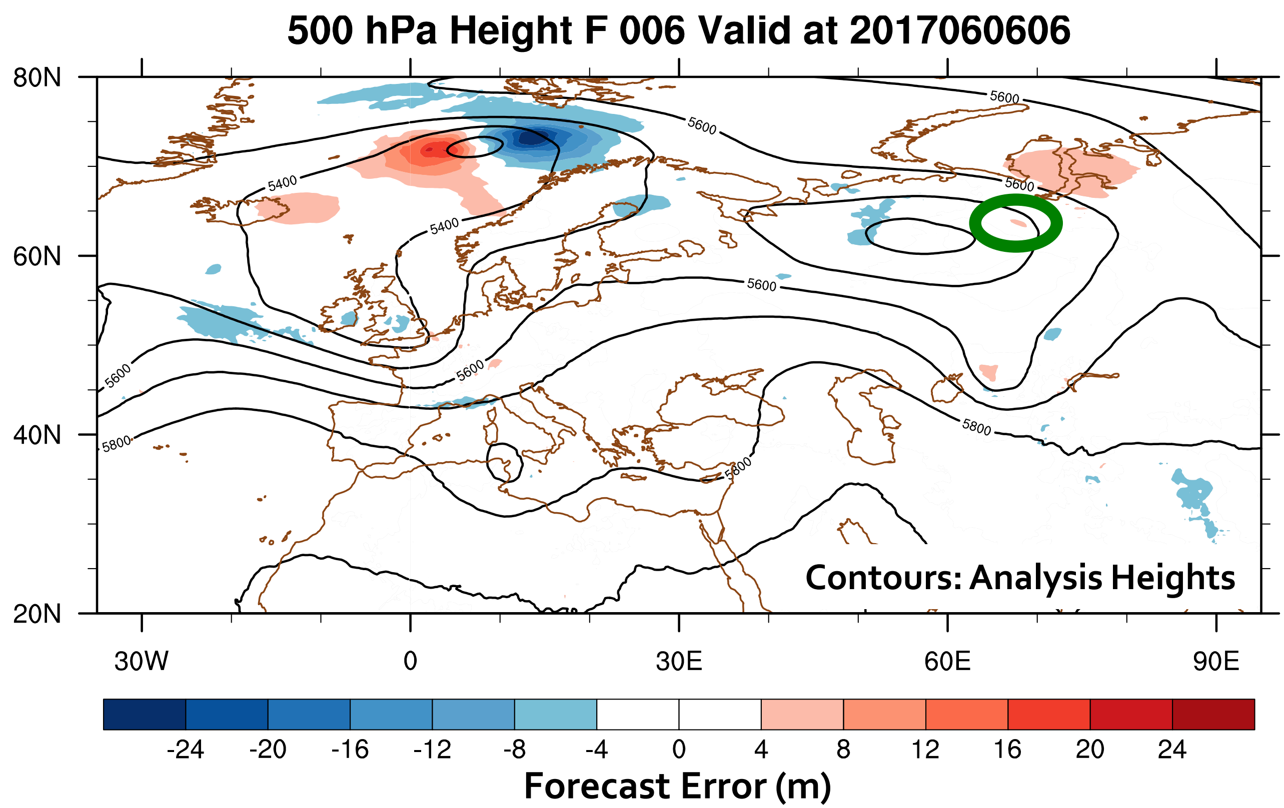
- Several cases have difficulty correctly capturing cutoff cyclone events
  - The forecast will either have the feature rejoin the flow too quickly or not develop the cutoff at all





Common Factors Across Poor Hemispheric Cases

- Several cases are also associated with mid-latitude/sub-polar cyclones that eventually open up into the flow incorrectly
- Errors tend to circulate around cyclone and allow the feature to join the flow at the wrong place



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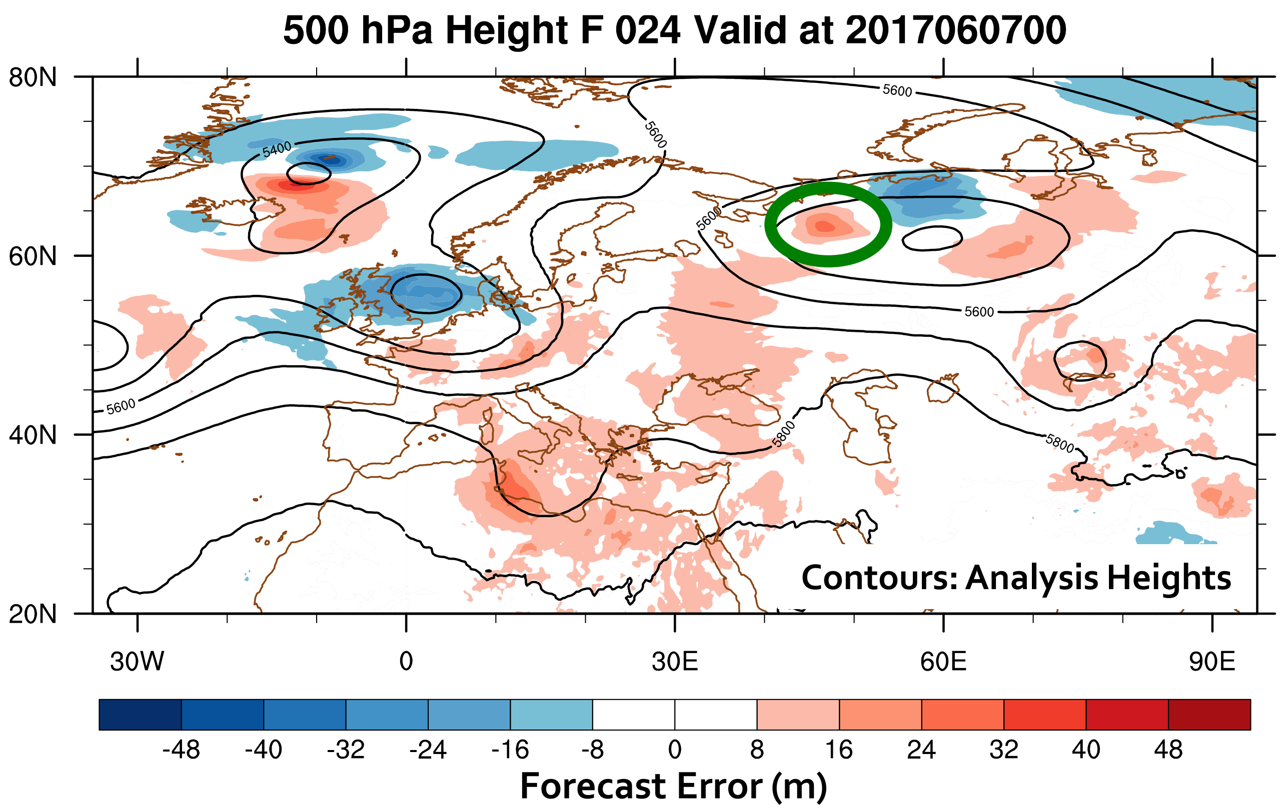

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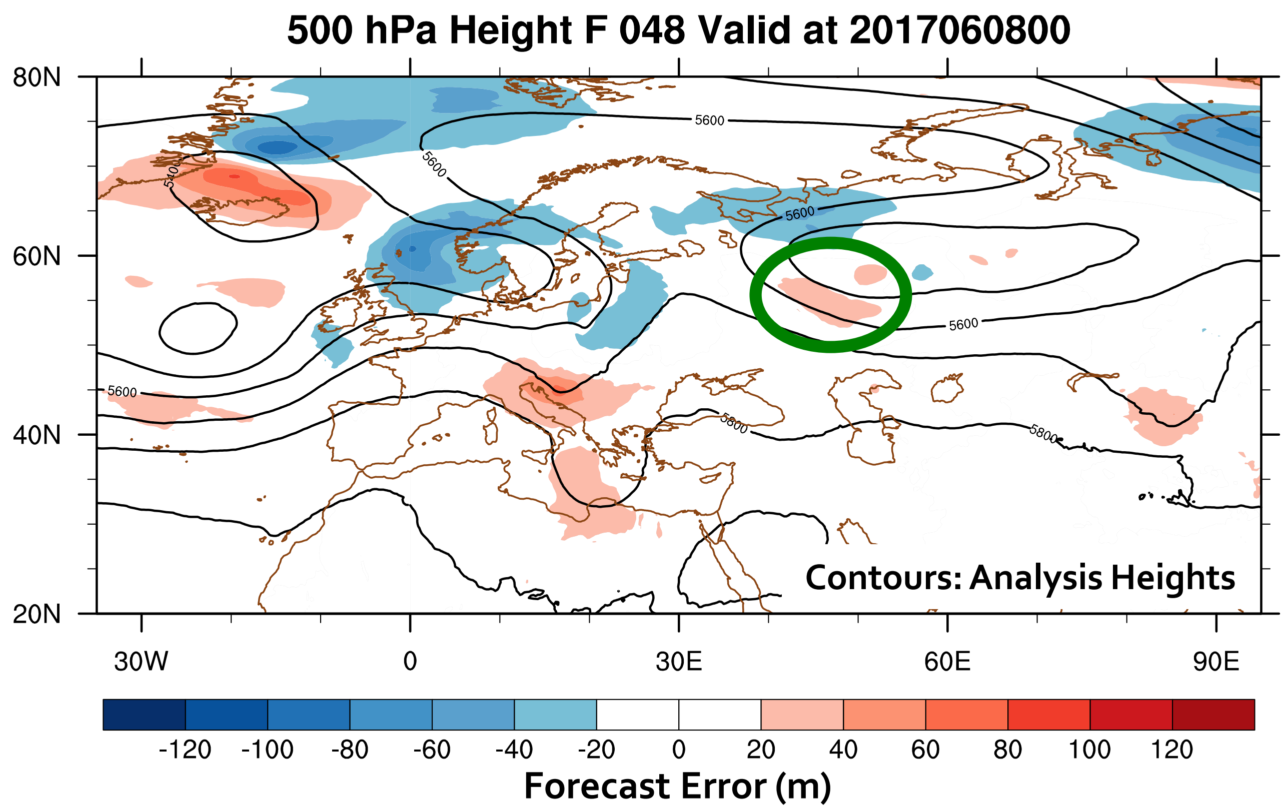

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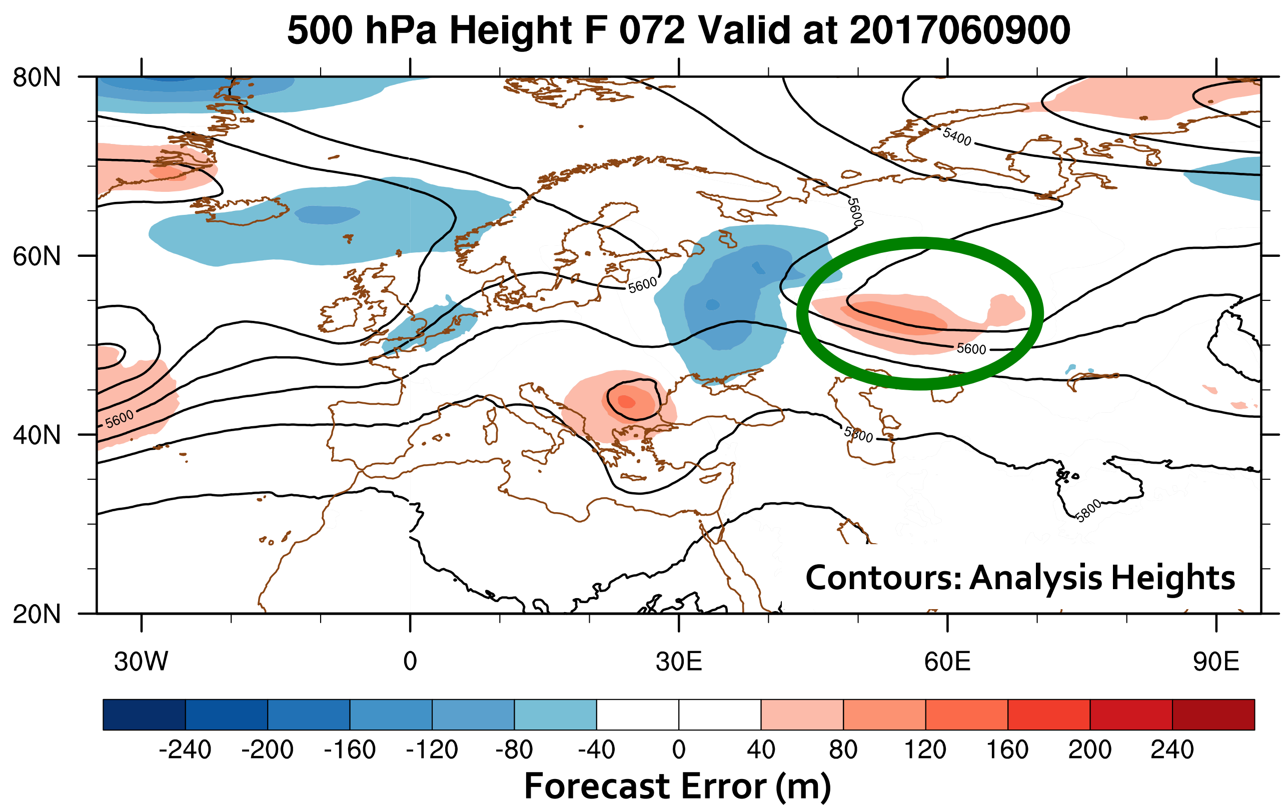

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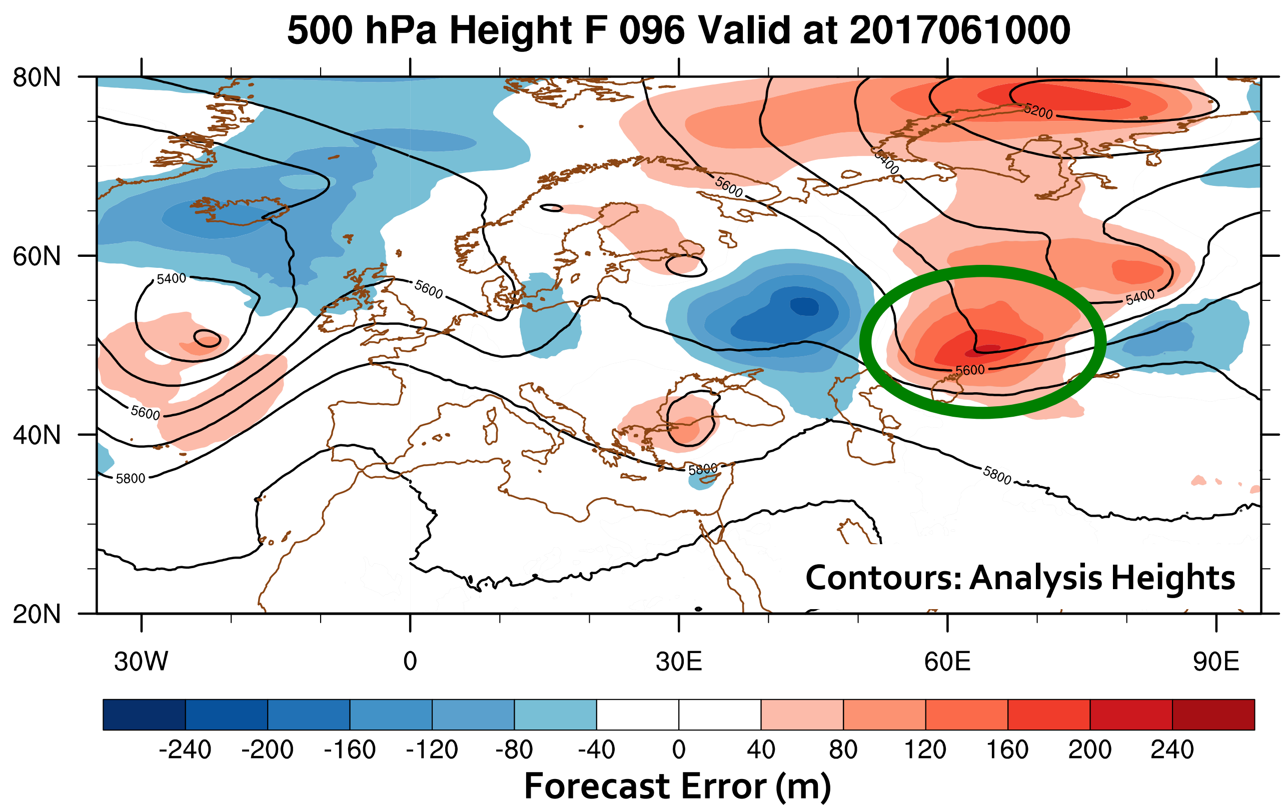
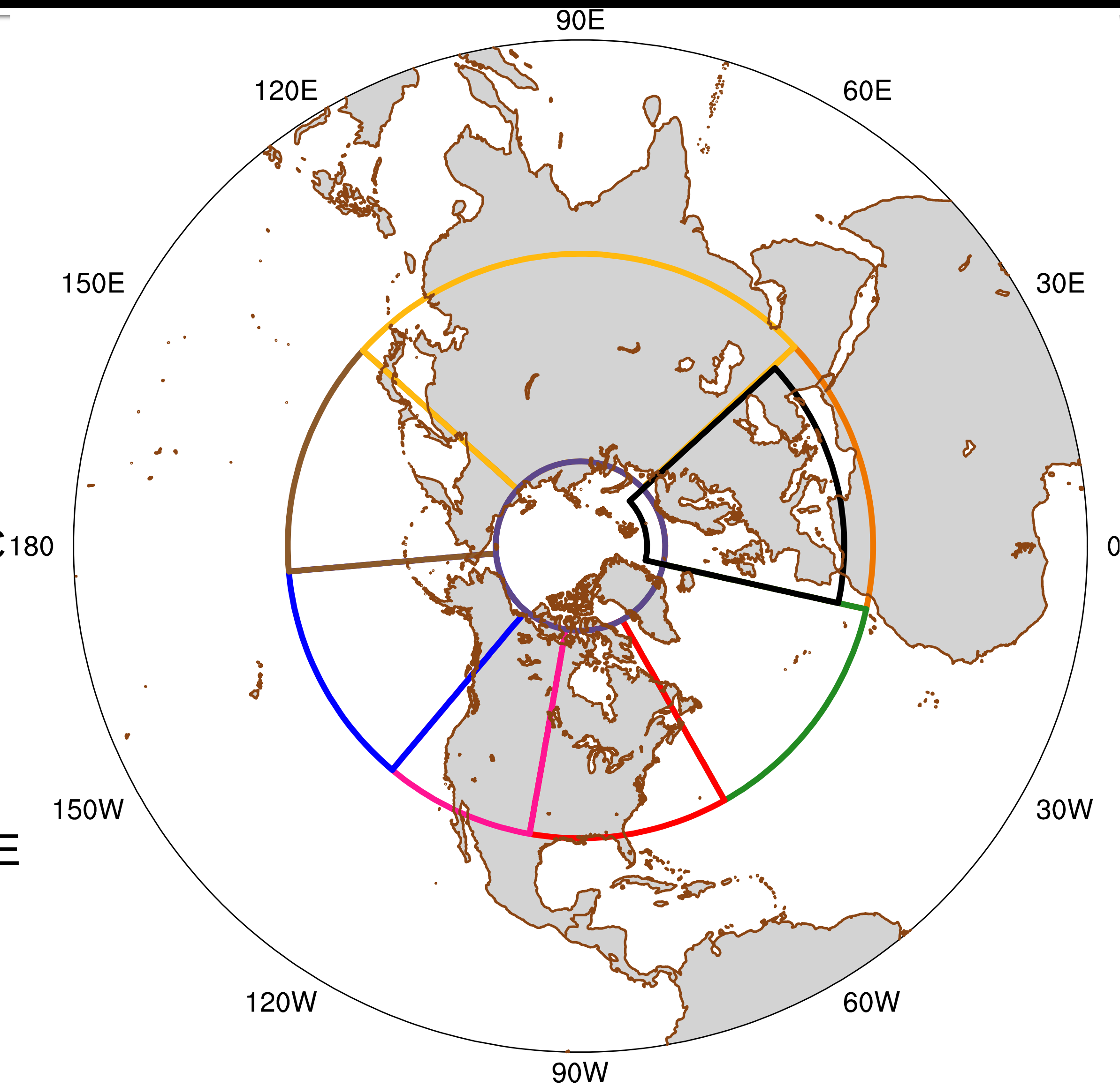


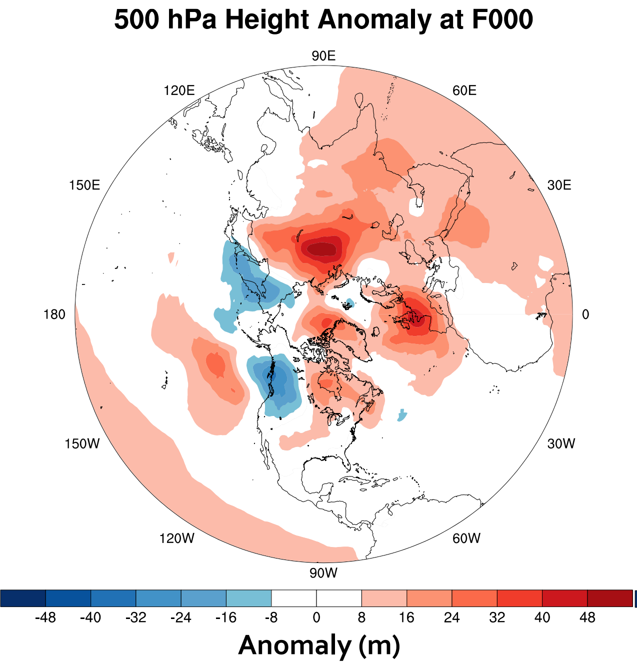
Poor Regional Forecast Details

- Follow a similar methodology to Rodwell et al. (2013)
- Utilize FV3GFS forecast initialized from reanalysis datasets
  - ~15 years worth of forecasts
- Calculate sector 5-day ACC and RMSE values for different regions across the NH
  - Bust forecast identification: ACC values ≤ 0.5 and RMSE ≥ 60 m
- Composite across all identified low-skill cases

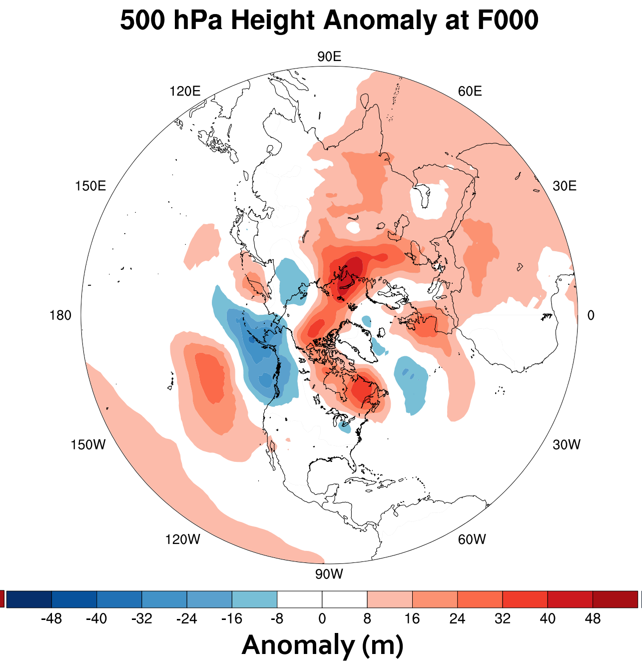


Regional Composite Anomaly at F000

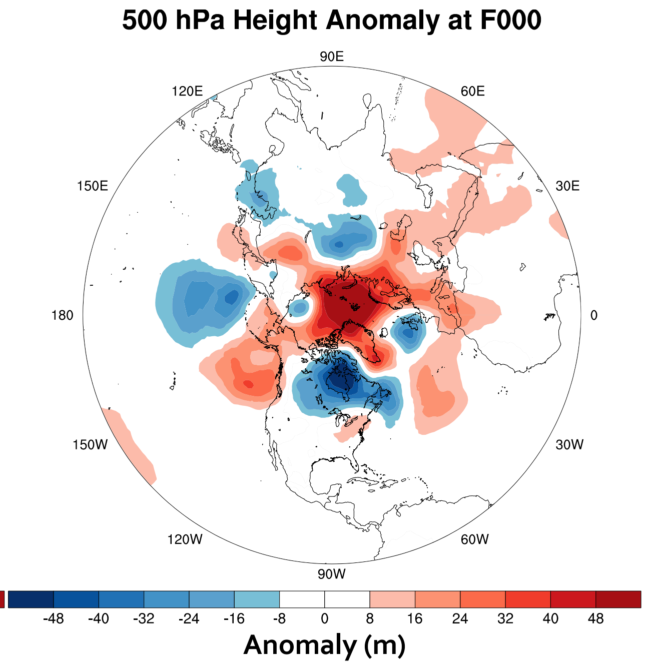
Western US



Eastern US



Europe



- Both USA and Europe sectors highlight a pattern anomaly in the East Pacific suggesting this area could be key in causing low skill forecasts

Future Directions

- Assess how the composite pattern evolves overtime to identify processes likely aiding in the creation of forecast errors for each region

- Compare with other current modeling systems to identify which processes could be model specific issues and which ones are a larger predictability issue

- Evaluate low skill events using new FV3-based GEFS forecasts to determine better highlight initial condition error regions and subsequent processes lead to loss of skill and uncertainty in the forecast