Progress Towards Implementing a State-of-the-Art Land DA in NOAA's Global NWP System (GFS/GDAS)

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Status of Land DA for Global NWP at NOAA

Model State		Assimilated Observations	DA Method
Snow amount (snow depth/SWE)	NOAA	SNODEP snow depth analysis, Satellite snow cover (IMS)	Simple “window” method
	Internationally	Station snow depth, Satellite snow cover (IMS)	EnKF, OI, Cressman
Snow temperature	NOAA	-	-
	Internationally	Screen-level T	OI
Soil moisture	NOAA*	-	-
	Internationally	Screen-level T, q Satellite soil moisture (ASCAT retrieval, SMOS Tb)	Simplified EKF, OI
Soil temperature	NOAA	-	-
	Internationally	Screen-level T	OI

* No soil moisture DA, but is retrospectively corrected for precipitation errors.

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Background / GFSv17

- NOAA's Land DA is being updated as a part of a major upgrade to the GFS/GDAS, GFSv17 system, planned for 2024
- Other related updates in GFSv17 (among many others)
  - Replacing the Noah land surface model with Noah-MP
  - Use of JEDI as the DA platform for all model components
    - JEDI (Joint Effort for Data assimilation Integration) is a unified DA system for Earth system prediction, being developed by the JCSDA and partner organizations

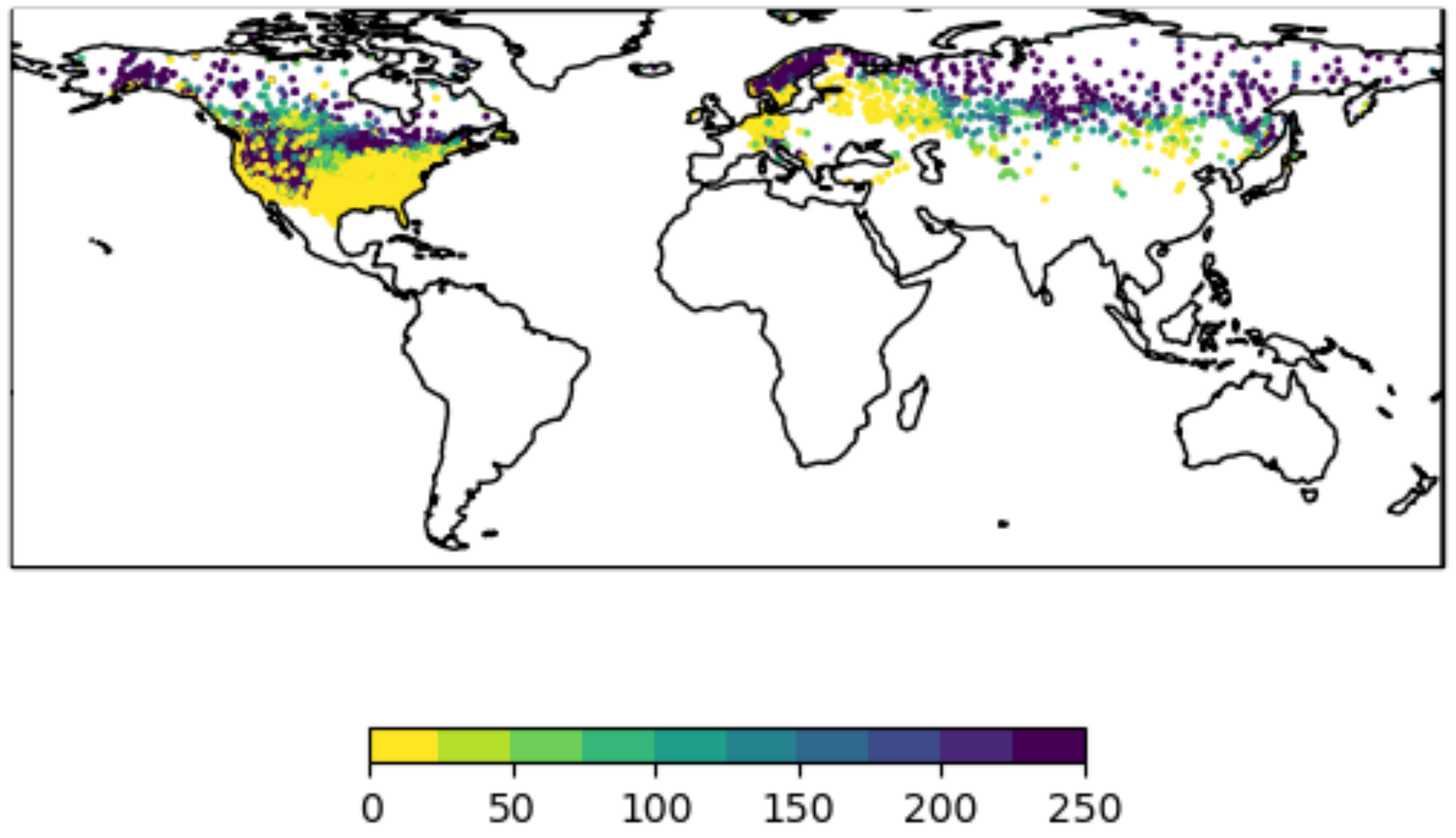
Snow Analysis

New OI-Based Snow Depth Analysis

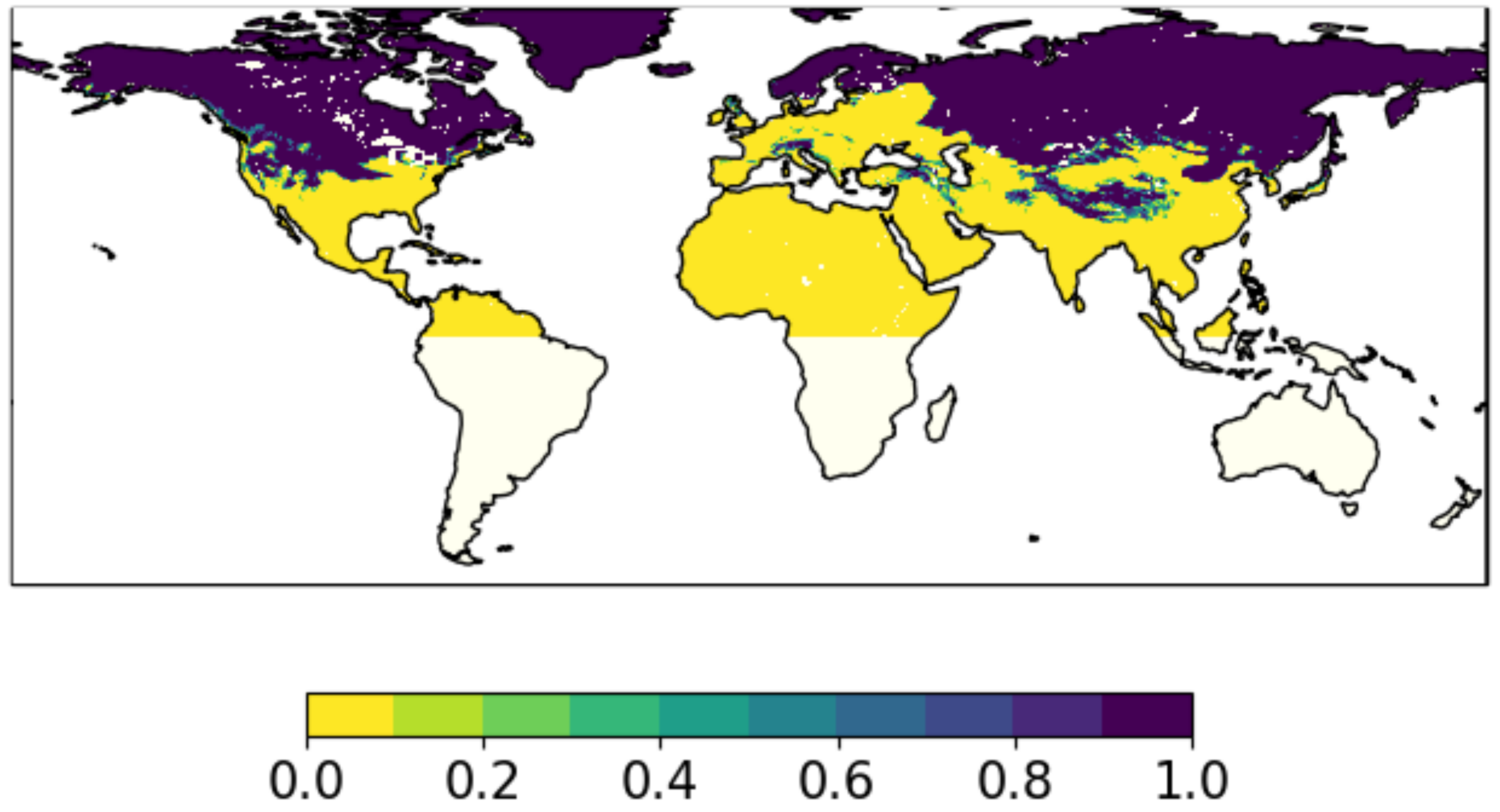
- Developed an Optimal Interpolation (OI) snow depth analysis
  - Assimilates station snow depth and IMS satellite snow cover
  - Based on schemes used elsewhere (ECMWF, EC)

- Snow cover fraction is a model diagnostic, estimated from the snow depth using a snow depletion curve:
  - For each model grid cell, calculate snow cover fraction from (4km) IMS observations
  - Invert the land surface model snow depletion curve to obtain an IMS-derived snow depth from the IMS snow cover fraction
  - Do not assimilate IMS-derived snow depth if background and IMS indicate 100% snow cover

GHCN snow depth [mm], 15 Dec, 2019.



IMS-derived snow cover fraction [-], 15 Dec, 2019.

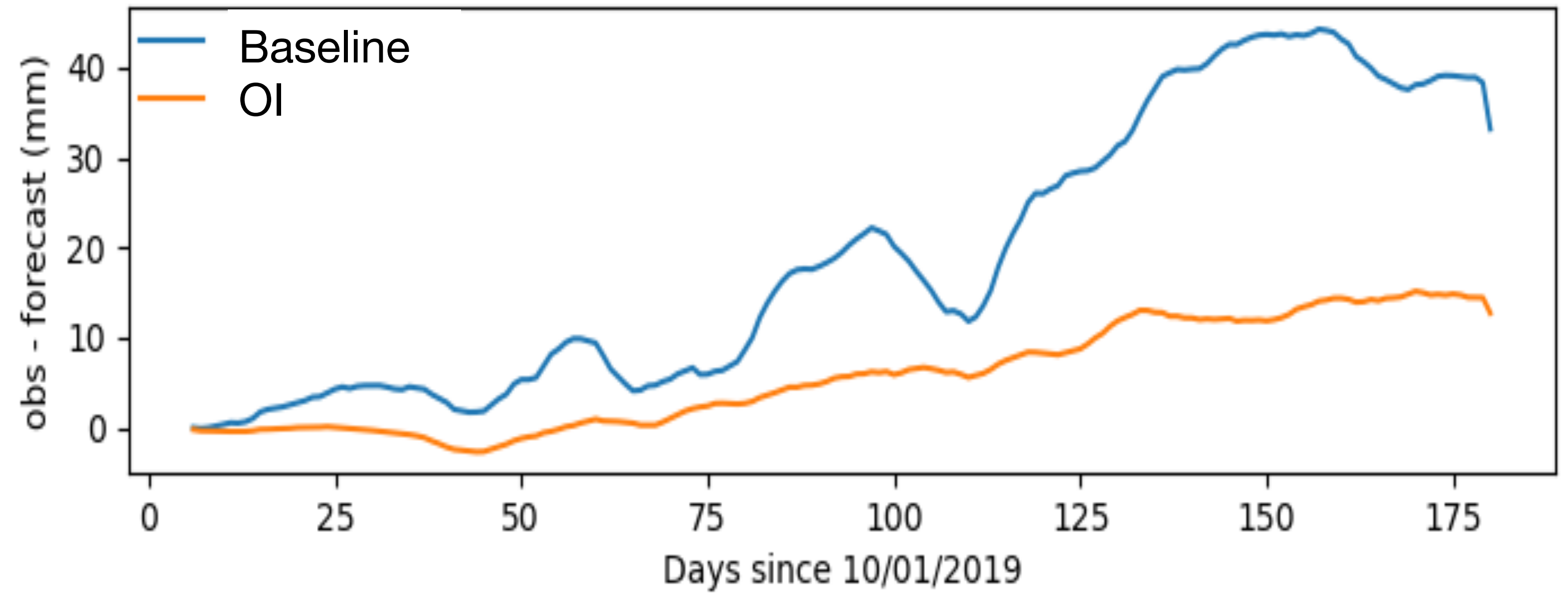


Gichamo and Draper, (sub), WAF.

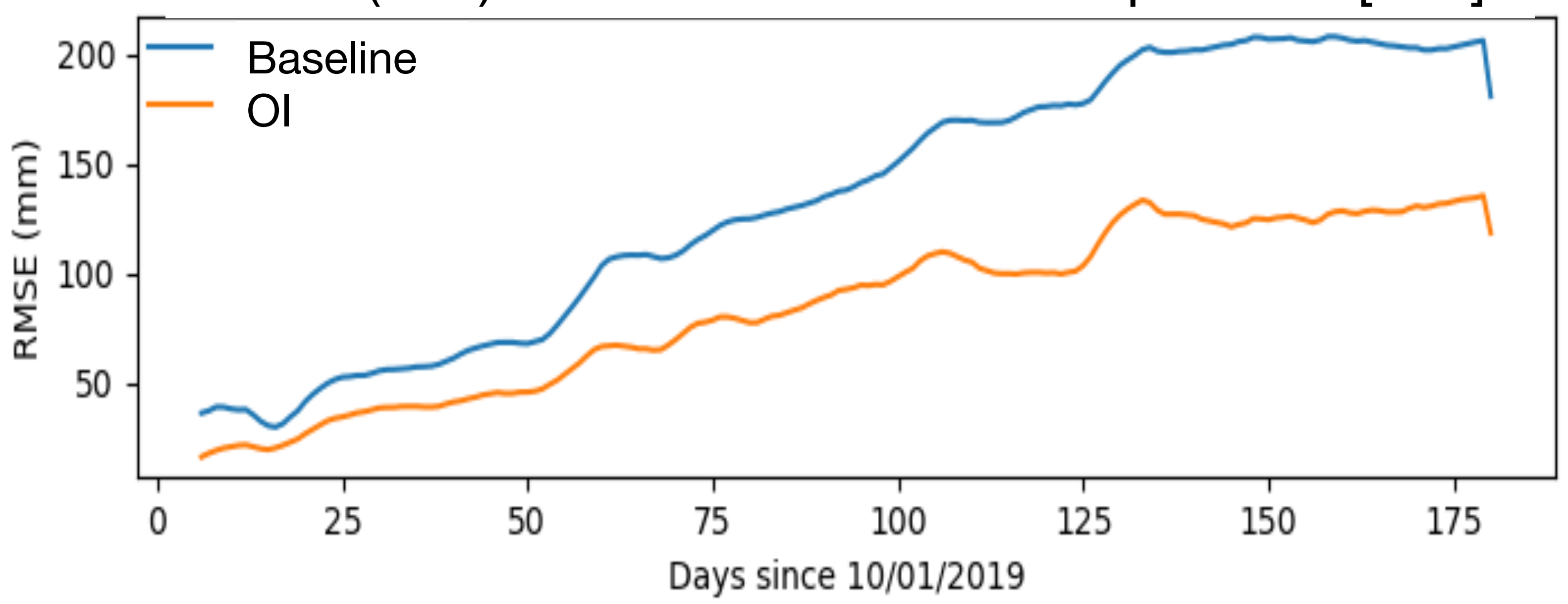
Improvements to GFS from Snow OI

- The OI was evaluated using GFSv15/GDAS (Noah land surface model) at C128 (~1 degree), from October 2019 - April 2020
  - Assimilated GHCN daily snow depth and IMS snow cover once daily
- Compared to the current snow analysis, the snow depth OI:
  - Improved the snow depth background forecast
  - Improved the T2m over snow-affected land (largely due to improved biases)

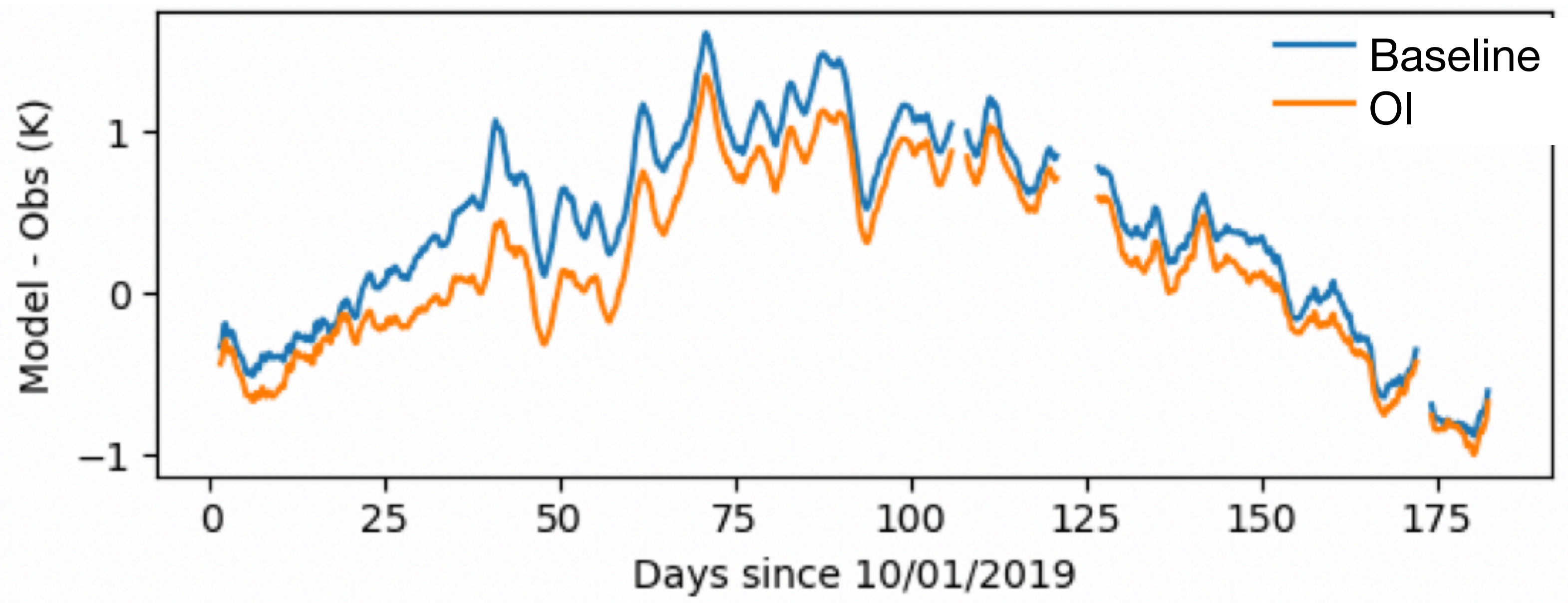
Mean(O-F) for assimilated snow depth obs. [mm]



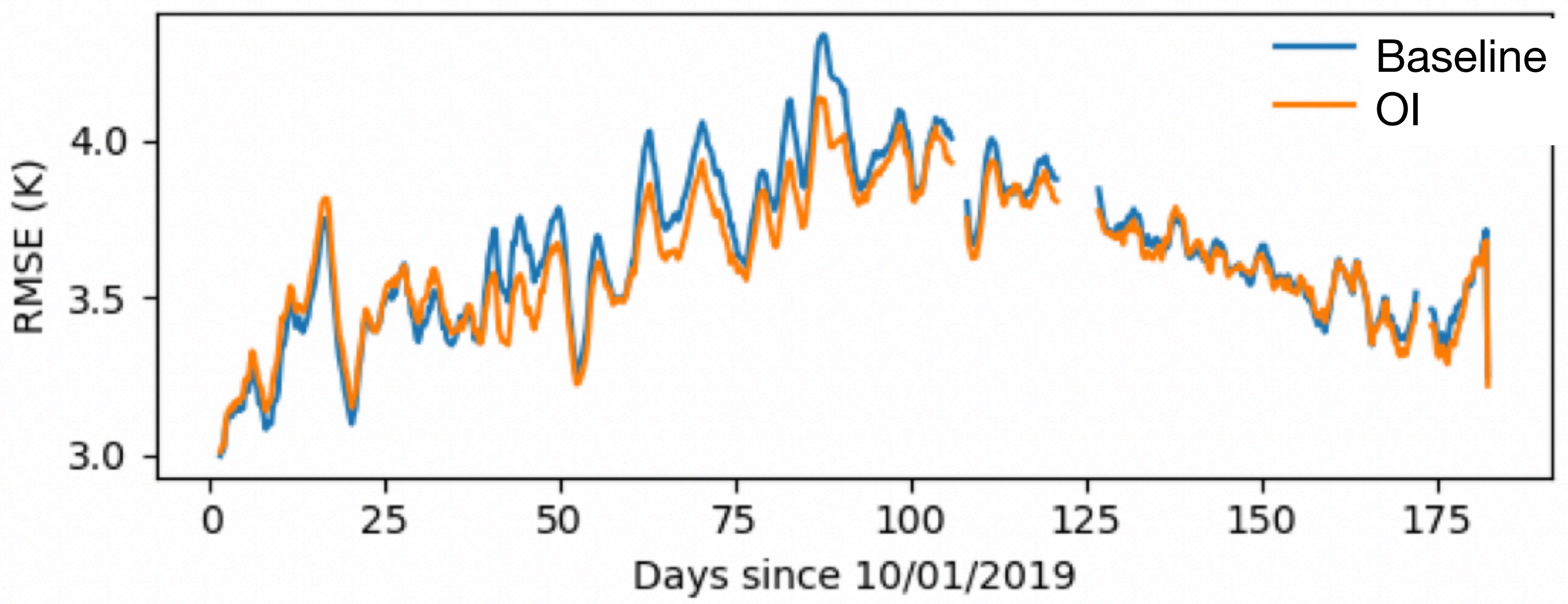
Stdev(O-F) for assimilated snow depth obs. [mm]



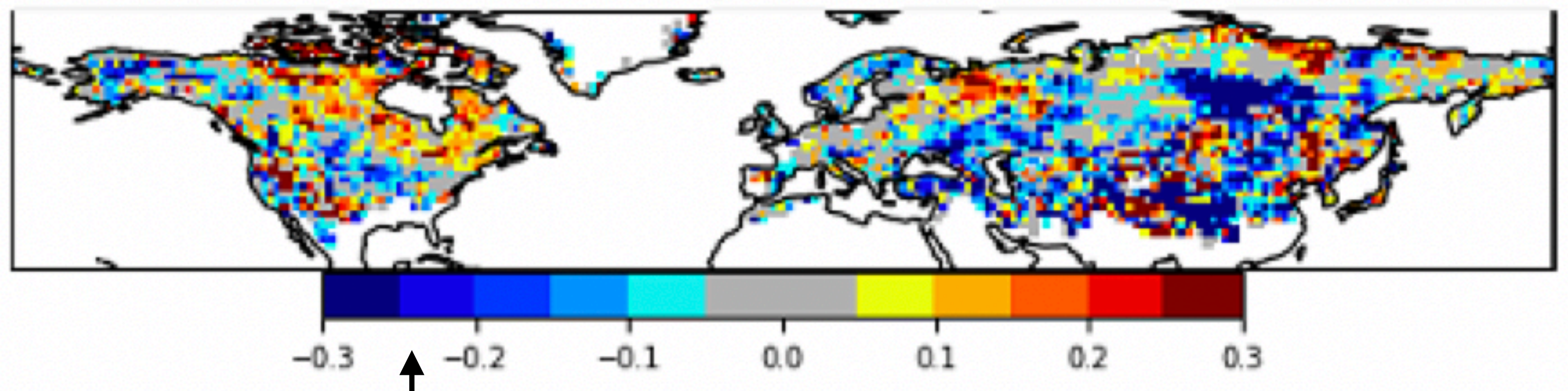
T2m bias over snowy regions [K]



T2m Root Mean Squared Error (RMSE)



T2m: OI RMSE - Baseline RMSE [K]



Blue colors:
OI performs better

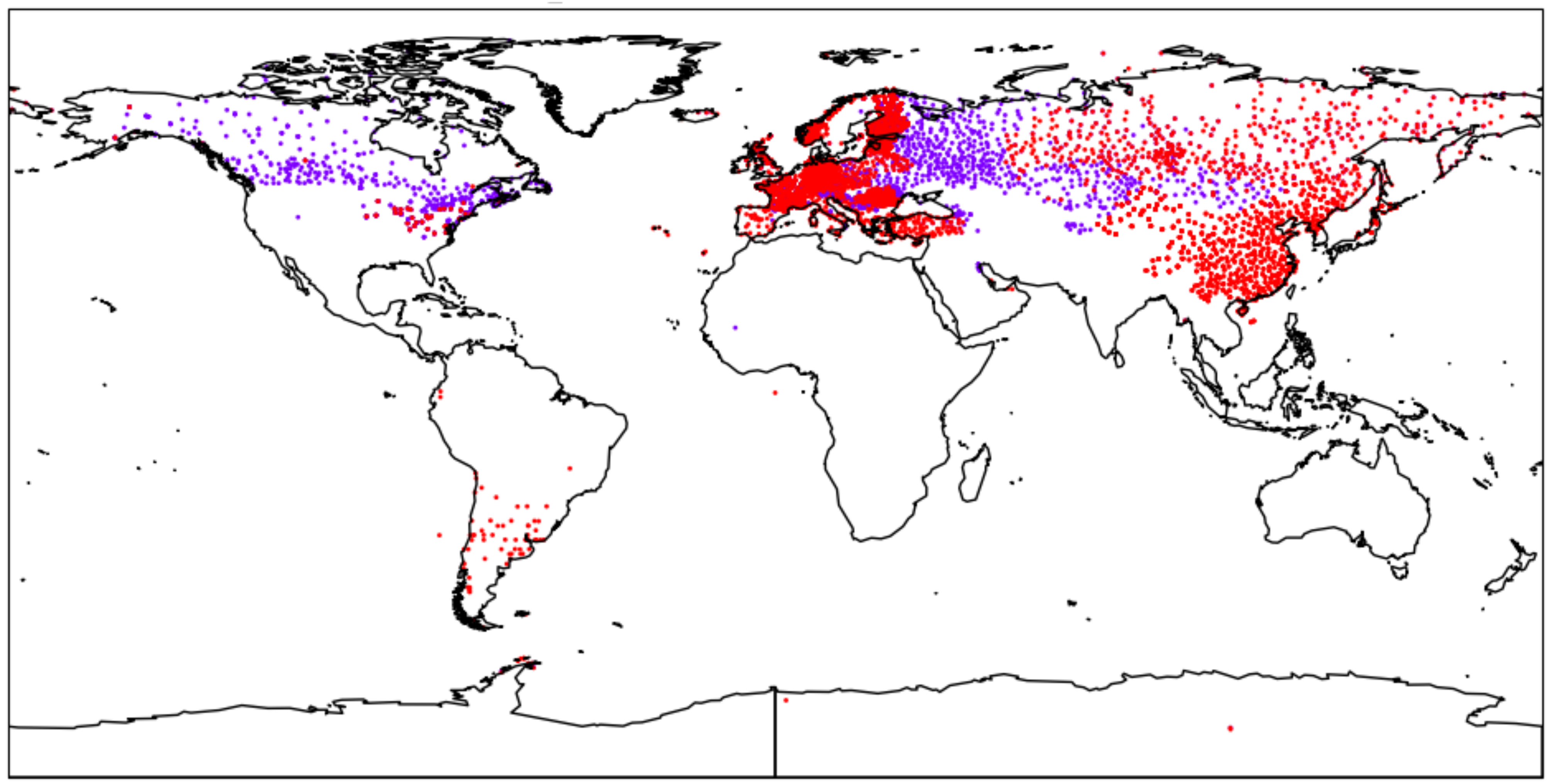
Gichamo and Draper, (sub), WAF.

Transition to GFSv17

- Based on these results, the OI is being transitioned to EMC for operational use

- Requires:
  - Conversion to JEDI
  - Update to Noah-MP land model used in GFSv17
  - For NWP application, replace once daily assimilation of GHCN station snow depth obs with 6-hrly assimilation of station obs from the GTS (Jiarui Dong, EMC/IMSG)

Currently, GTS station snow depth data over the US is limited. NCEP is adding US National Network snow depth data (sched. Spring 2022).

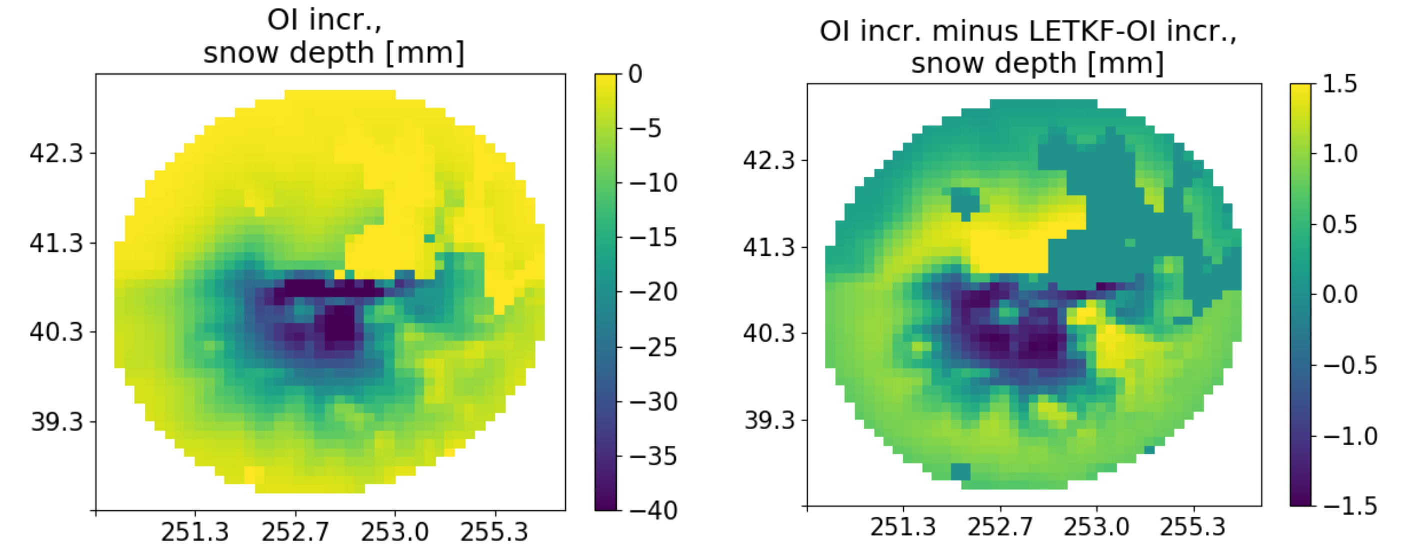


Station Snow depth observations (TAC, SYNOP) from the GTS at NCEP on 1 Feb, 2021. (c/o Jiarui Dong).

Conversion to JEDI

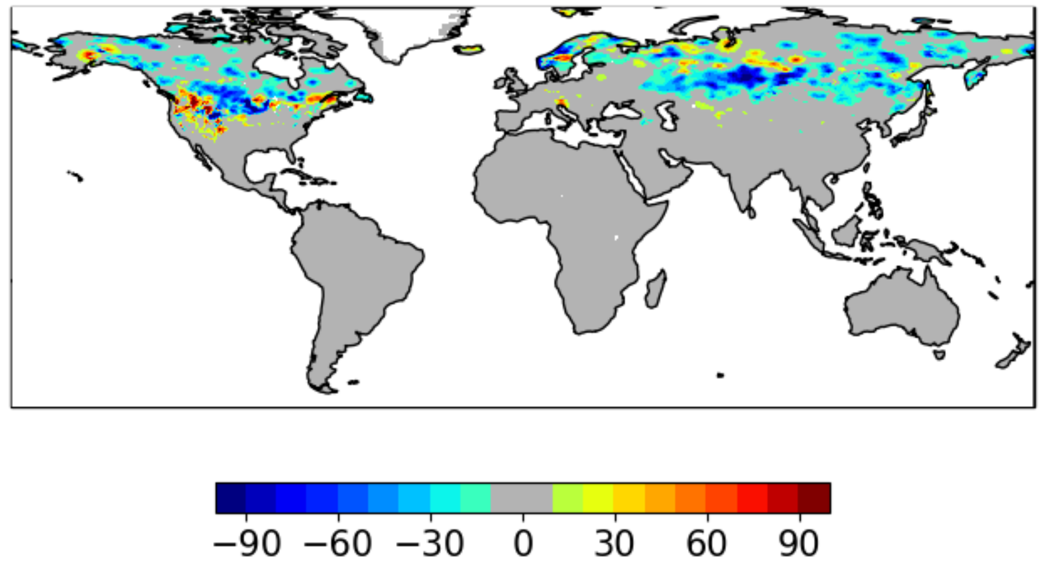
- OI algorithm not yet coded in JEDI, so have approximated OI by using LETKF (LETKF-OI):
  - Use a pseudo-ensemble and localization to approximate the error covariance functions used in the OI (Frolov et al (sub.), QJRMS)
  - Approximation is very good for single observation experiments, but LETKF-OI has smaller increments where multiple observations are assimilated
  - Ideally, will investigate replacing the LETKF-OI with the OI in the future

Single observation experiment: RMSD = 0.8 mm, nRMSD = 8%

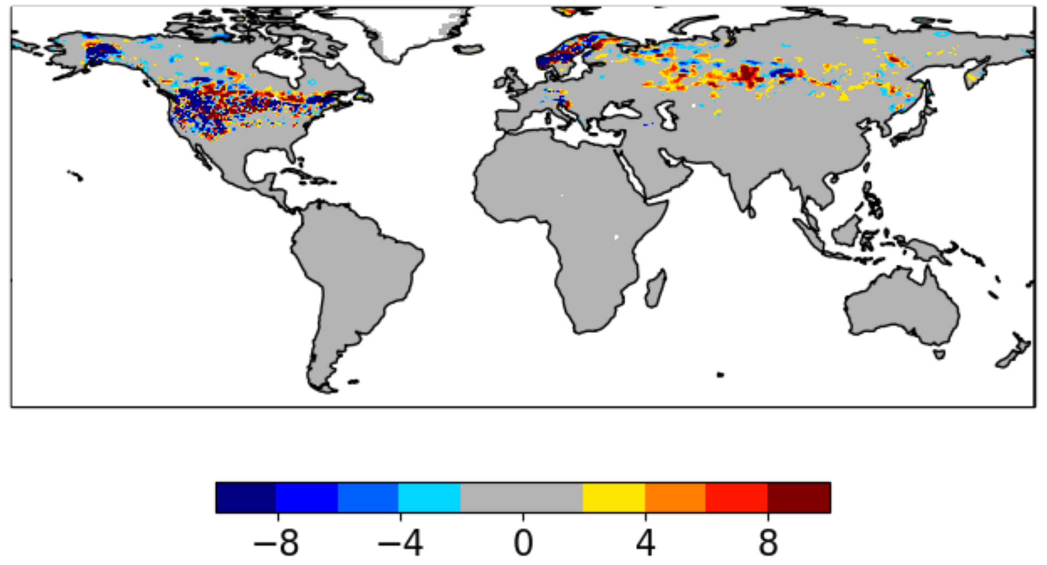


Global assimilation experiment: RMSD = 7 mm, nRMSD = 28%

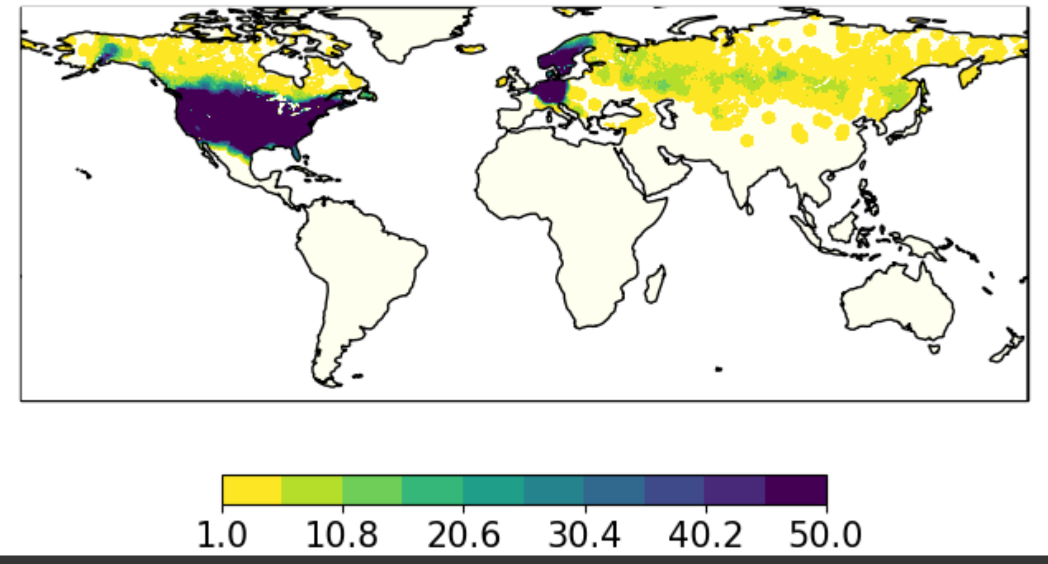
OI increment, snow depth [mm]



OI incr. minus LETKF-OI incr., snow depth [mm]

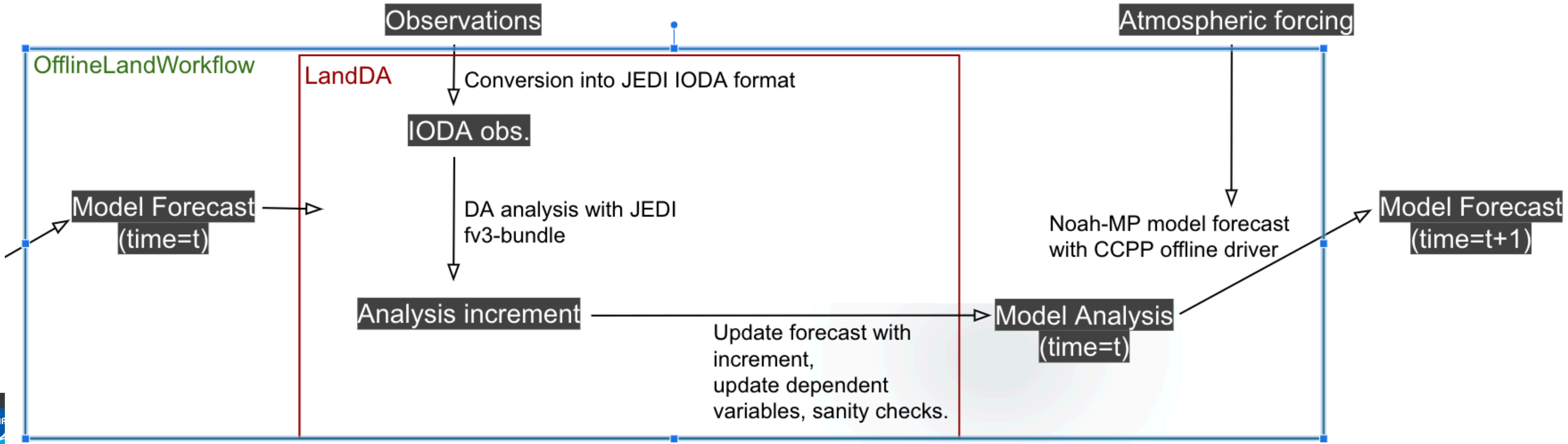


Number of obs assimilated at each grid cell.



Offline JEDI-Based Land DA Workflow

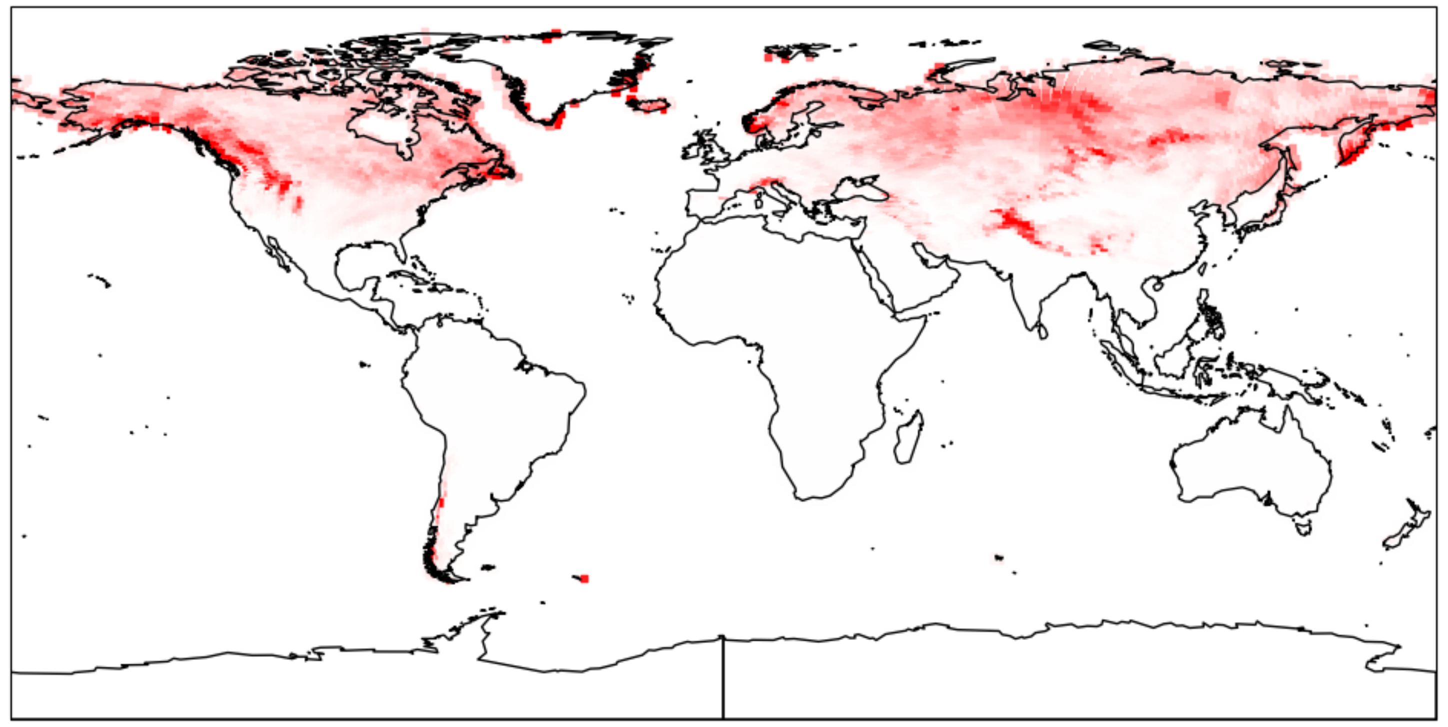
- Built an offline land DA workflow, to perform cycling model forecasts and DA, using same DA and land model code as in coupled GFS (land/atmosphere) DA system
  - Model: UFS (GFS) code via Noah-MP CCPP code base
  - DA: JEDI fv3-jedi bundle for land update (bundle developed for GFS atmos. DA)
- Enables running land DA experiments quickly
  - Useful for development and testing of land model and DA
  - Being made available to research community to speed land research
  - Currently have snow depth LETKF-OI and LETKF, soil moisture LETKF available soon



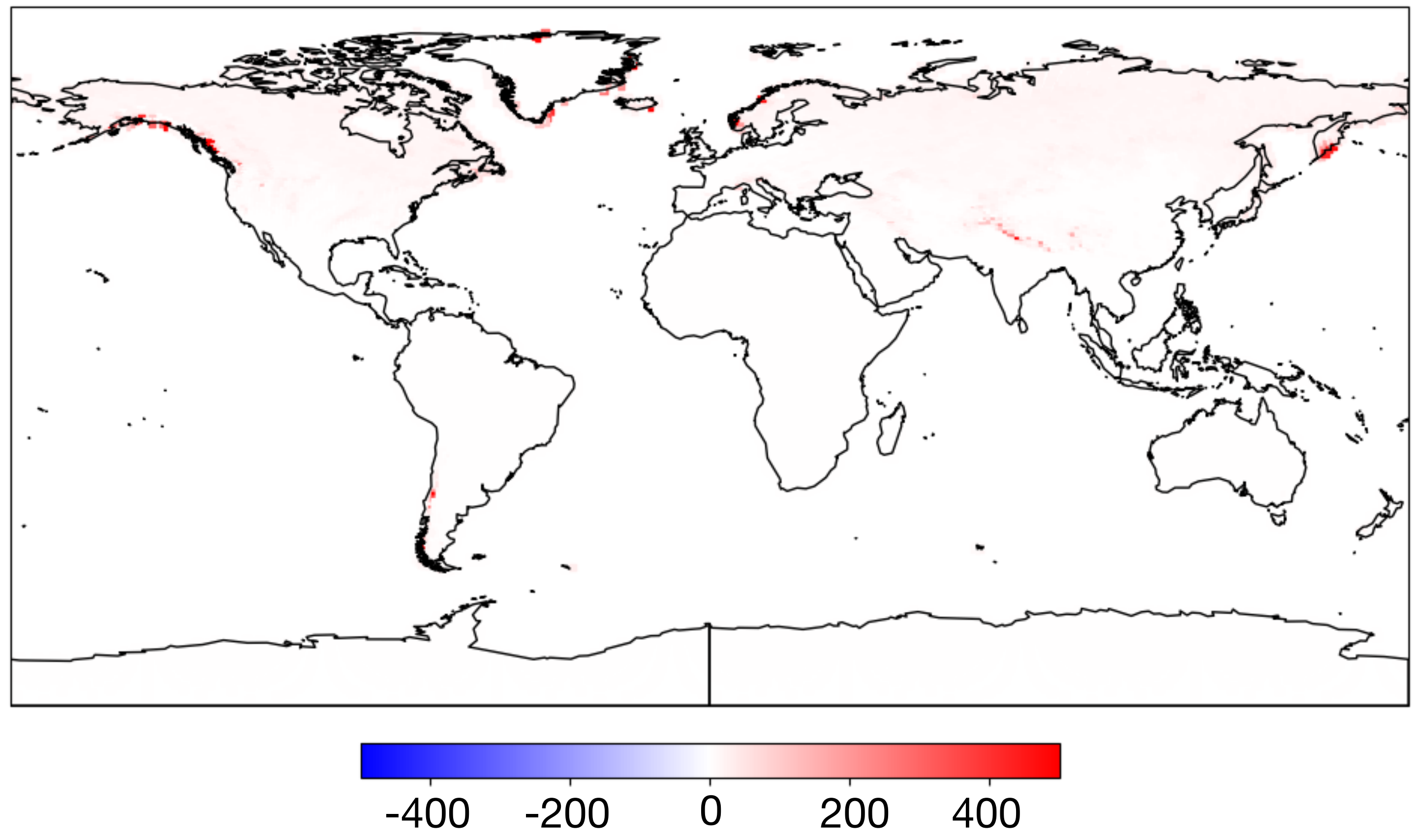
Update to Noah-MP

- Noah had a single snow layer with a single total snow depth, Noah-MP has a multi-layer snow model
  - Relation between snow depth in each layer and total snow depth is not one-to-one
- Partitioning the total snow depth increment according to the fractional snow depth in each layer in the background, then updating SWE in each layer by maintaining layer snow density
- Synthetic twin experiments with offline system show good performance of DA / snow layer partitioning
- Experiments assimilation GHCN snow depth and IMS snow cover observations revealed serious model biases in snow cover fraction over certain land cover types
  - Bias has been traced to parameters used in the Noah-MP snow depletion curve, which are currently being tuned
  - Currently collecting available snow depth observations, and developing methods to identify stations not included in GHCN (and/or GTS)

Snow depth RMSE (open loop), mean: 107.8 mm.



Snow depth RMSE (JEDI LETKF-OI), mean: 19.8 mm



Above: Synthetic twin experiment shows good performance of the LETKF-OI snow depth DA

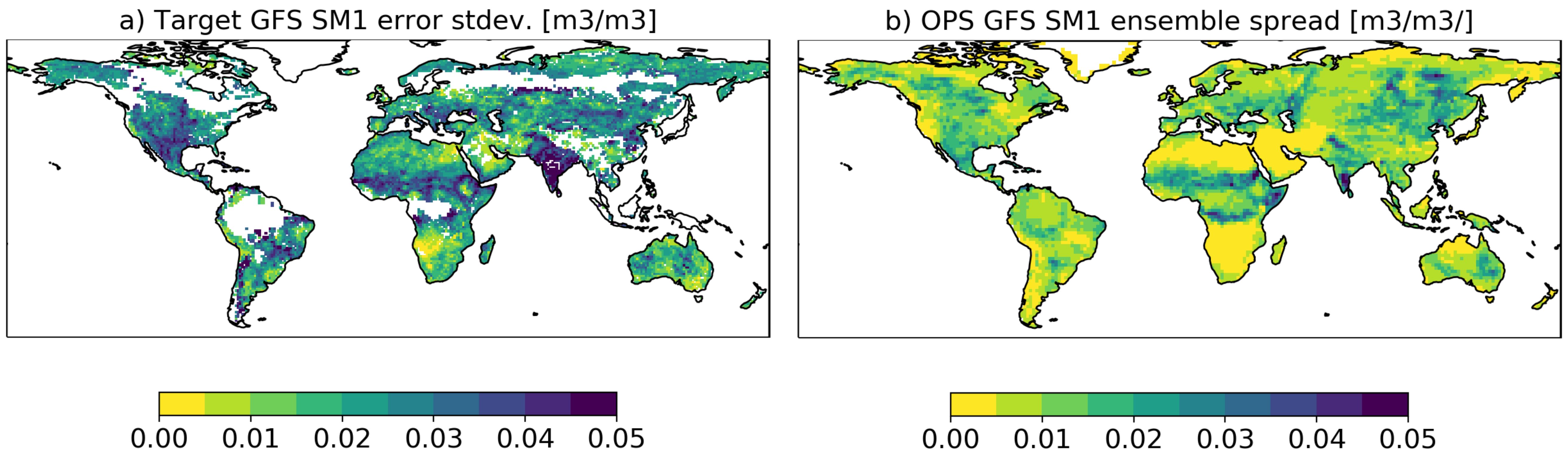
Soil Moisture and Temperature Analysis

Soil Moisture and Temperature DA

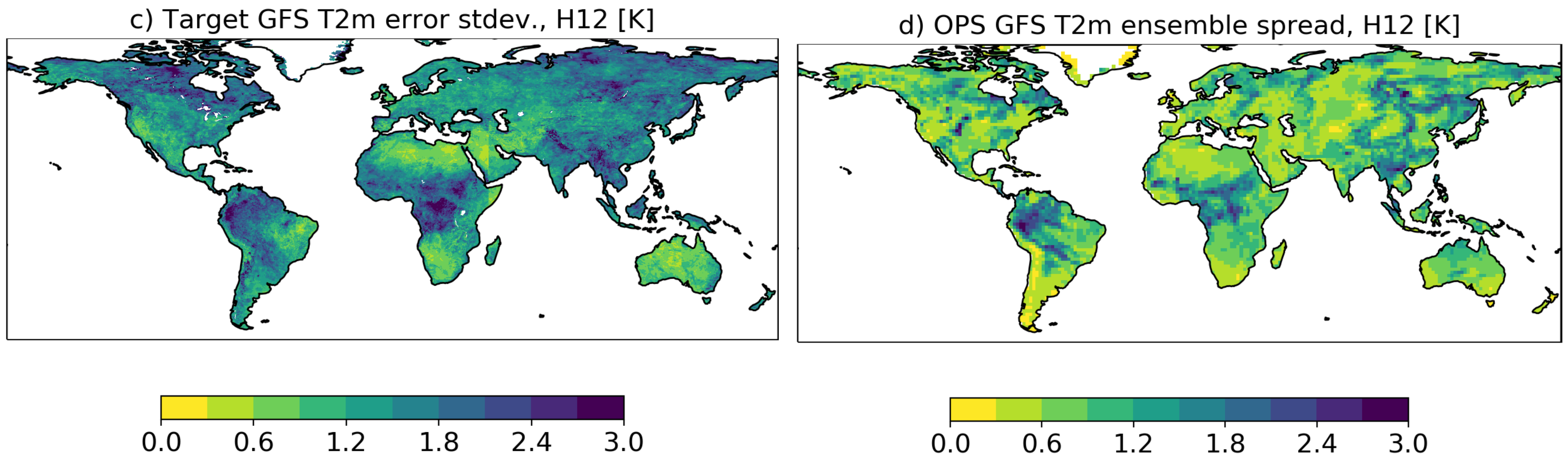
- Developed an EnKF (LETKF) update to soil moisture and soil temperature from T2m and q2m
- The LETKF uses the same code as for the atmospheric update
- The LETKF is applied to the GFS atmospheric ensemble

- NWP ensemble systems (inc. the GFS) are under-dispersed at/near the land surface
  - First step to implementing the LETKF was to enhance GFS land ensemble spread

Boreal summer forecast **soil moisture, layer 1 (SM1)** error standard deviation [m3/m3] with



Boreal summer daytime model **T2m** error standard deviation.

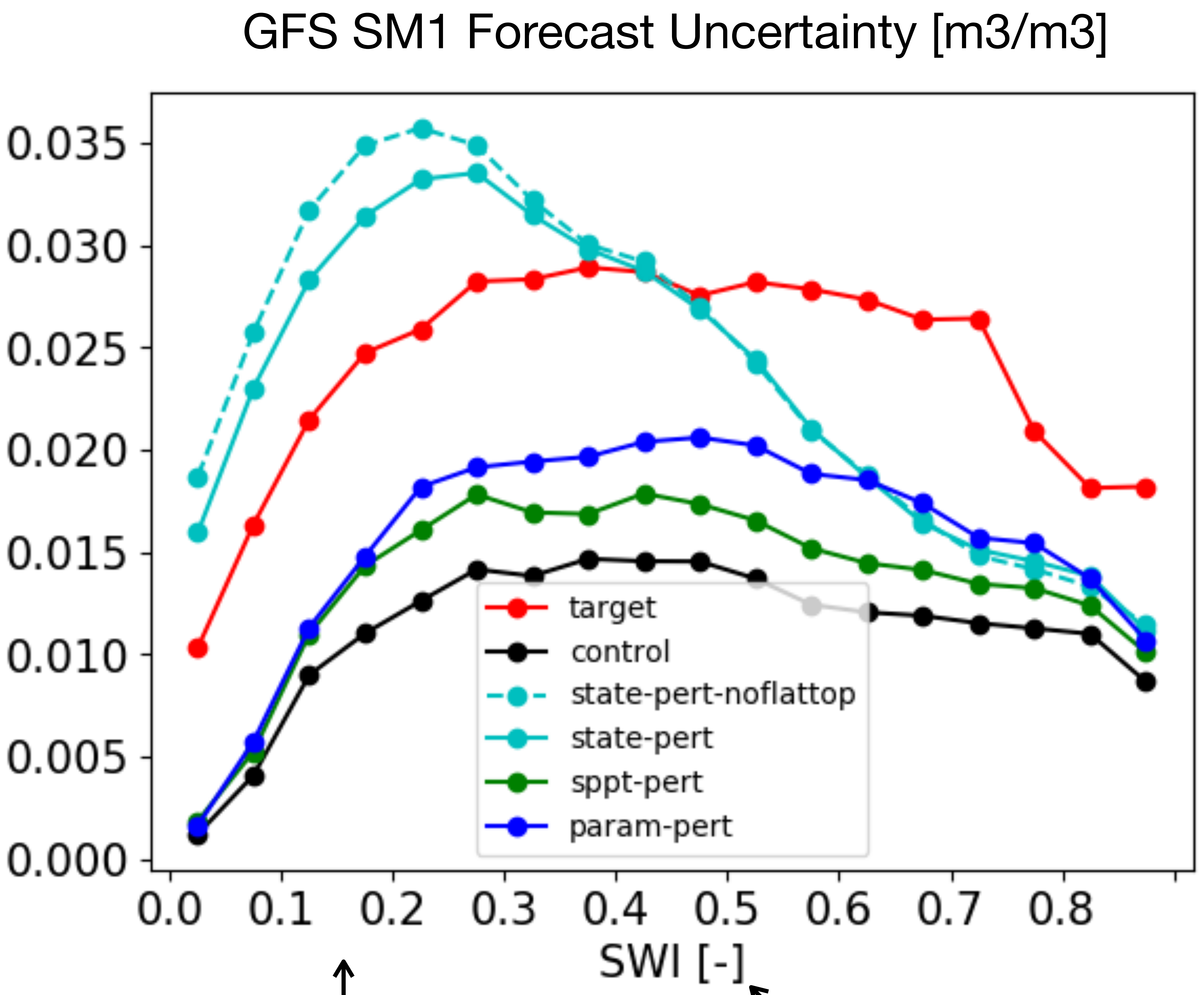


Target estimates, calculated using triple colocation (SM1), and comparison to ERA-5 analysis (T2m)

Ensemble standard deviation, from archived operational UFS output

GFS ensemble spread

- Added method to account for model uncertainty in GFS ensemble by perturbing key model parameters in land/atmosphere fluxes
- Perturbing vegetation fraction (param-pert in figure) creates reasonable spatial patterns in ensemble spread (T2m, q2m, soil moisture)
  - Ensemble is still under-dispersed compared to observation based forecast error estimates
- Also produces ensemble covariances representative of errors in land/atmos fluxes
  - Contrast to perturbing land states, which creates ensembles representative of errors in the land component only



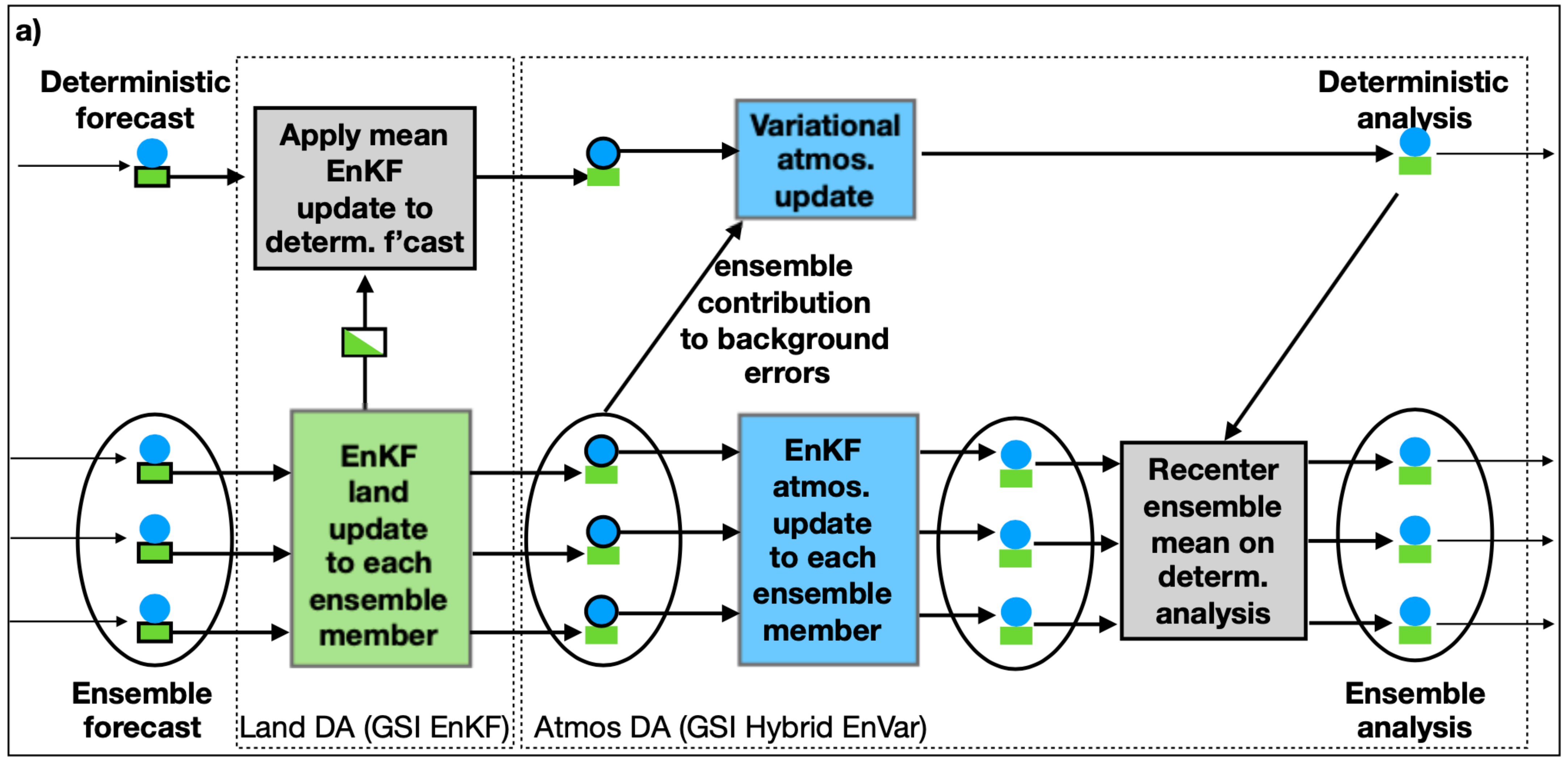
Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from different experiment.

Soil Wetness Index

Draper, J Hydromet, 2021

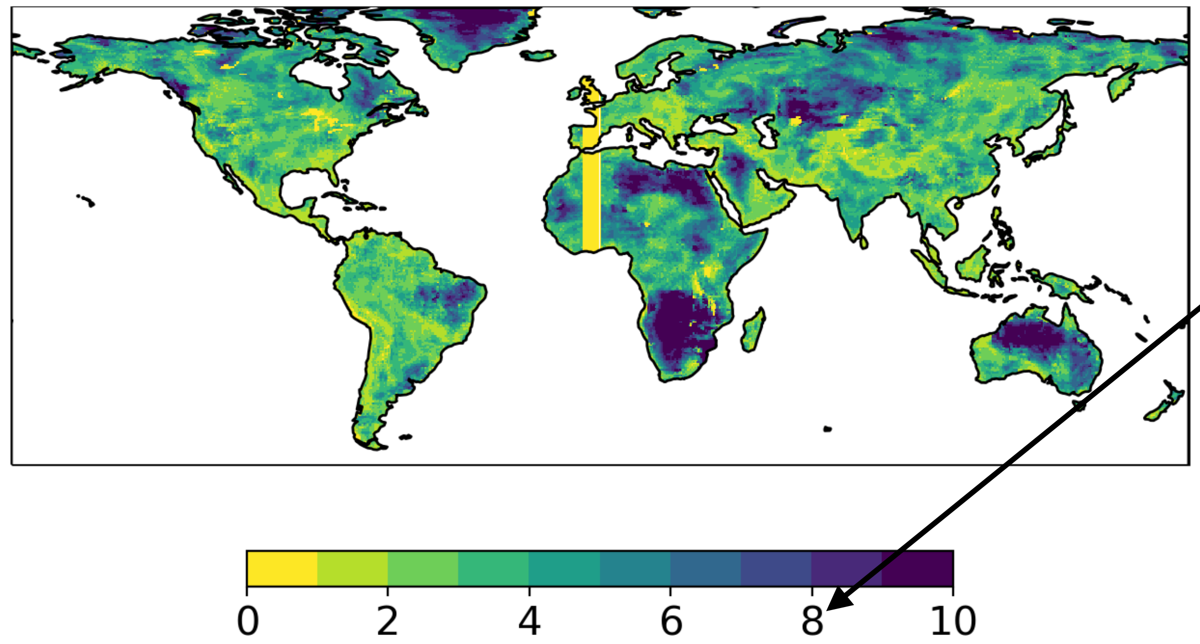
GFS EnKF of T2m to update Soil Temperatures

- Conducted one month experiment from 20200701418, at C192 (~0.5 degree), using GFSv16 model (Noah LSM), standard atmos stochastic physics plus perturbed vegetation fraction
  - Control: LETKF of standard suite of atmospheric observations
  - 2mDA: Control + LETKF assimilation of T2m to update soil temperature in top 3 layers
  - GFSv16 soil moisture / T2m relationship known to be incorrect, using temperatures only for initial development



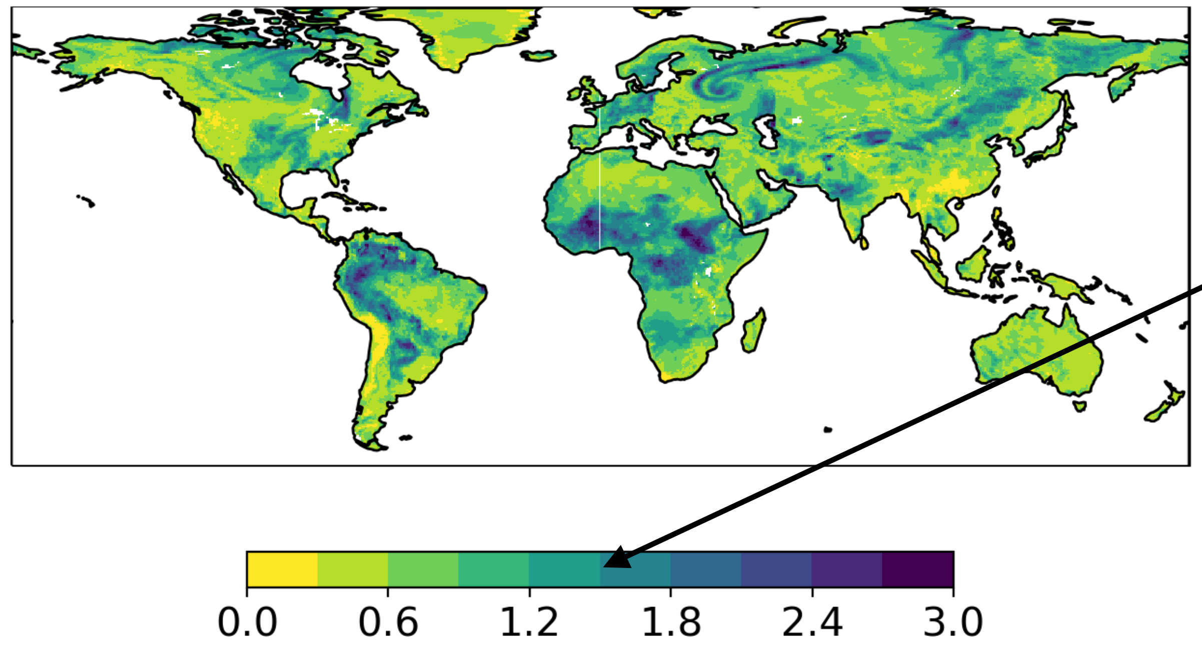
Example T2m Increments / Ensemble Spread

Ensemble T2m decorrelation length [in 0.5 degree grid cells]



ECMWF OI e-folding scale is 420 km
(~8 0.5 degree grid cells)
LETKF G-C localization cutoff is 1100 km,
similar to e-fold. of 420 km

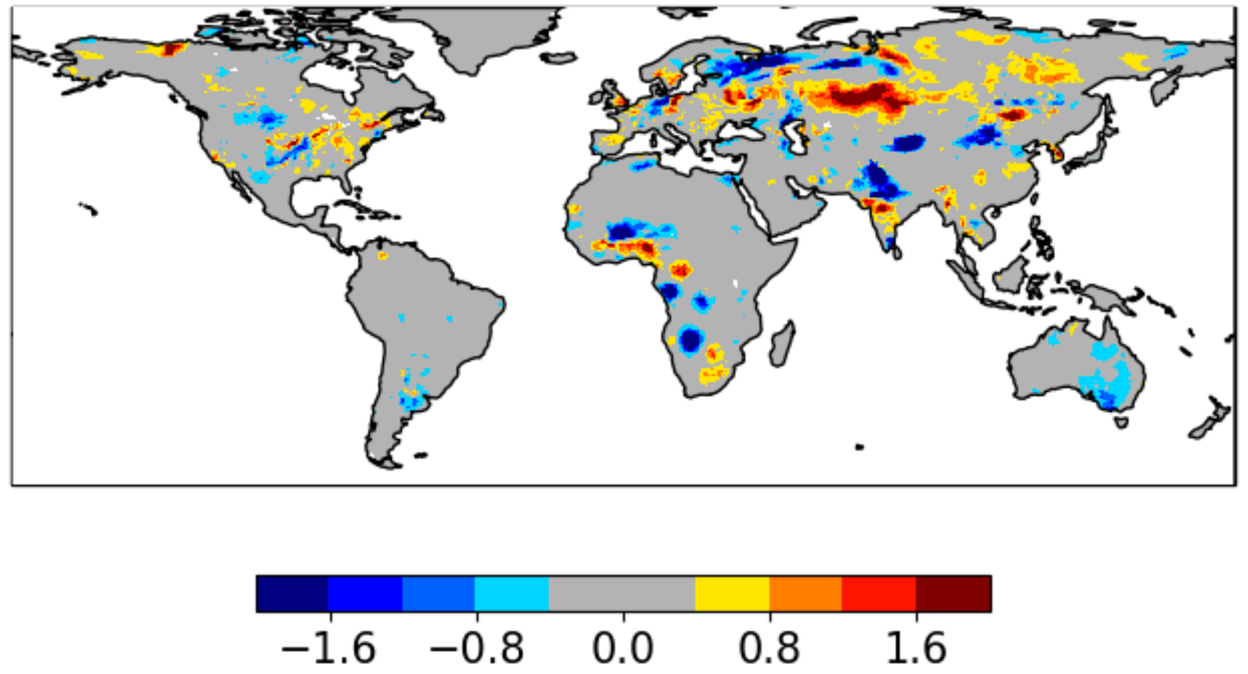
Ensemble standard deviation in T2m [K]



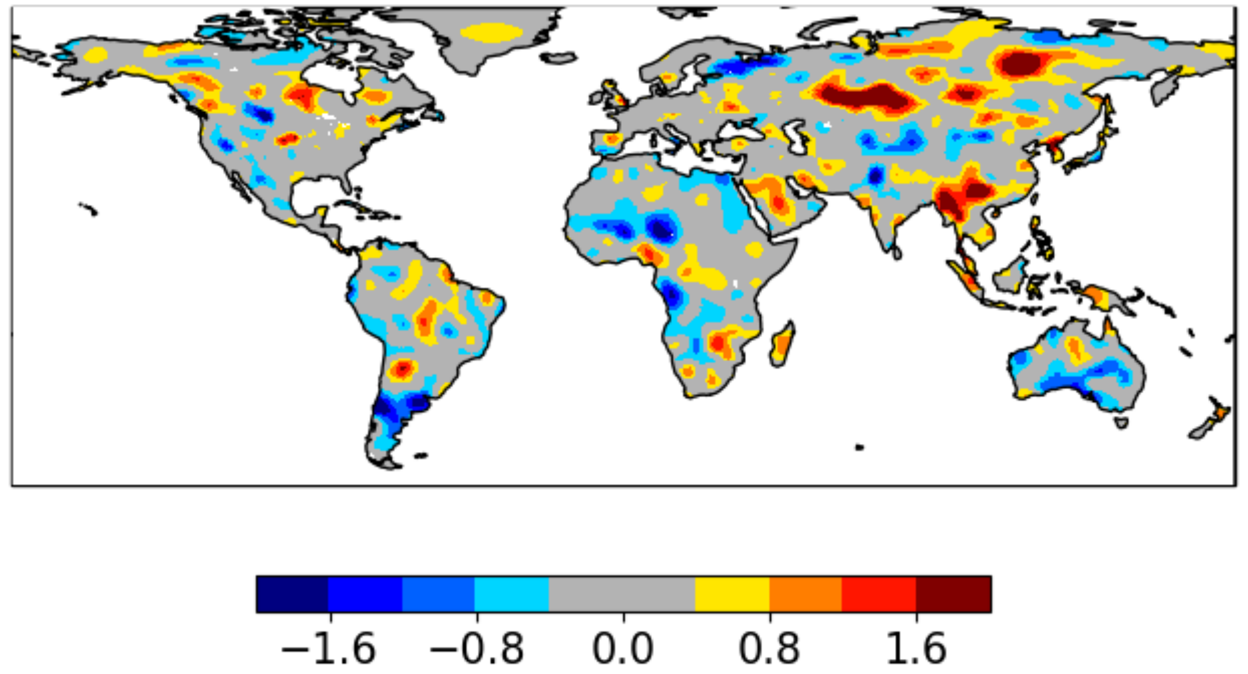
ECMWF OI
background error is 1.5 K

- Compared to ECMWF's OI T2m DA, the LETKF generally has smaller background error and shorter lengths scales
- Results in slightly smaller increments, and more fine-scale spatial detail
- Note: T2m is a diagnostic, any increments applied are not retained by the model

GSI (EnKF) T2m LETKF increment [K]

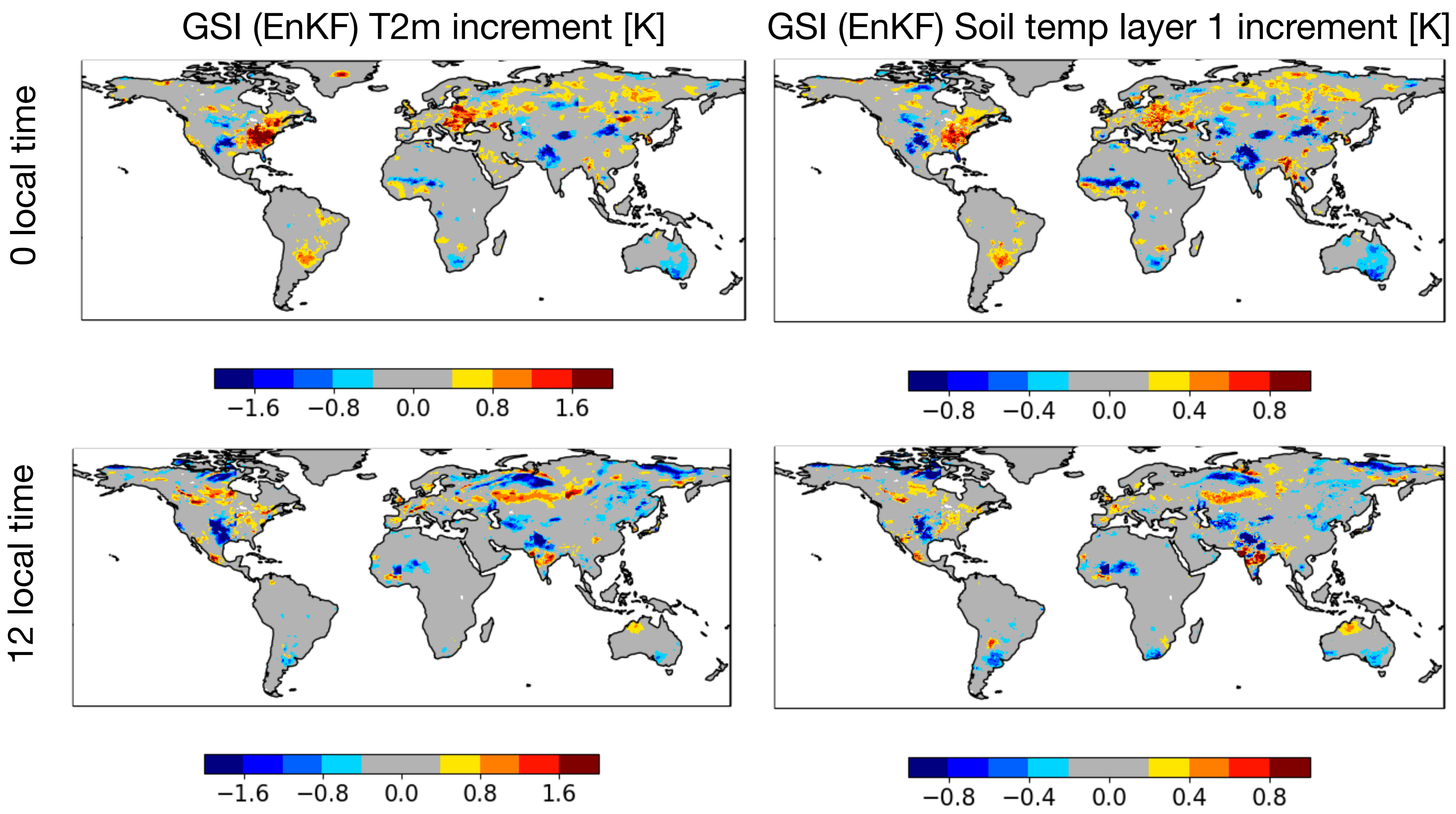


ECMWF OI T2m increment [K]



Plots are for 15 UTC,
202007015

Example Soil Temperature Increments



Note different color scales

- As expected, soil temperature increments have very similar spatial pattern to T2m increments
- Soil temperature increment in layer 1 less than half T2m increment
  - Mean ratios: 0.47 night, 0.38 day
- Soil temperature increments rapidly reduce with depth

Plots are for 202007015, and have been binned into night and day time windows

T2m O-F statistics after one month

- After one month of assimilation, there is very little difference between the CONTROL and 2mDA T2m O-F (and other stats.)
- The difference between the soil temperature in layer 1 is small (similar magnitude to individual increments)
- Conclusion: DA method appears reasonable, but model response to increments may be suspect
  - Now moving towards experiments with Noah-MP

CONTROL T2m O-F stats [K] in local time windows, 20200815

	0	**6**	**12**	**18**
Mean	0.059	-0.311	-0.392	0.397
Stdev	2.09	2.08	2.05	2.08

2mDA T2m O-F stats [K] in local time windows, 20200815

	0	**6**	**12**	**18**
Mean	0.056	-0.308	-0.397	-0.401
Stdev	2.10	2.09	2.06	2.09

Summary / Next Steps

- Making good progress towards updating the snow DA:
  - Implemented an Optimal Interpolation method in JEDI, which is a significant improvement on the current method, and is being prepared for operations
  - Early experiments revealed serious Noah-MP snow cover fraction biases, these are currently being tuned
  - Main outstanding task for implementation is to update to GTS snow depth observations (all experiments to date with GHCN, not available in real time)
  - Also investigating whether EnKF can outperform the OI (Tseganeh Gichamo)

Summary / Next Steps

- Soil moisture and temperature DA is still in early stages
  - Developed an LETKF-based approach, applied directly to atmospheric ensemble
  - Required enhancing the land ensemble spread in the GFS ensemble, achieved by adding a scheme to perturb land model parameters in the ensemble
  - Initial experiments with the Noah model show that the LETKF increments and ensemble characteristics appear reasonable
  - Assimilation of T2m observations to update soil temperature had very little impact on subsequent T2m forecast skill
  - Noah-MP now available in GFS, currently working on repeating the above experiments with Noah-MP and adding in q2m observations and SMC updating

- Developed an offline land DA system for use in development, evaluation, and for community research
  - Available to community on GitHub (email: clara.draper@noaa.gov)

Thanks for listening!

contact: clara.draper@noaa.gov

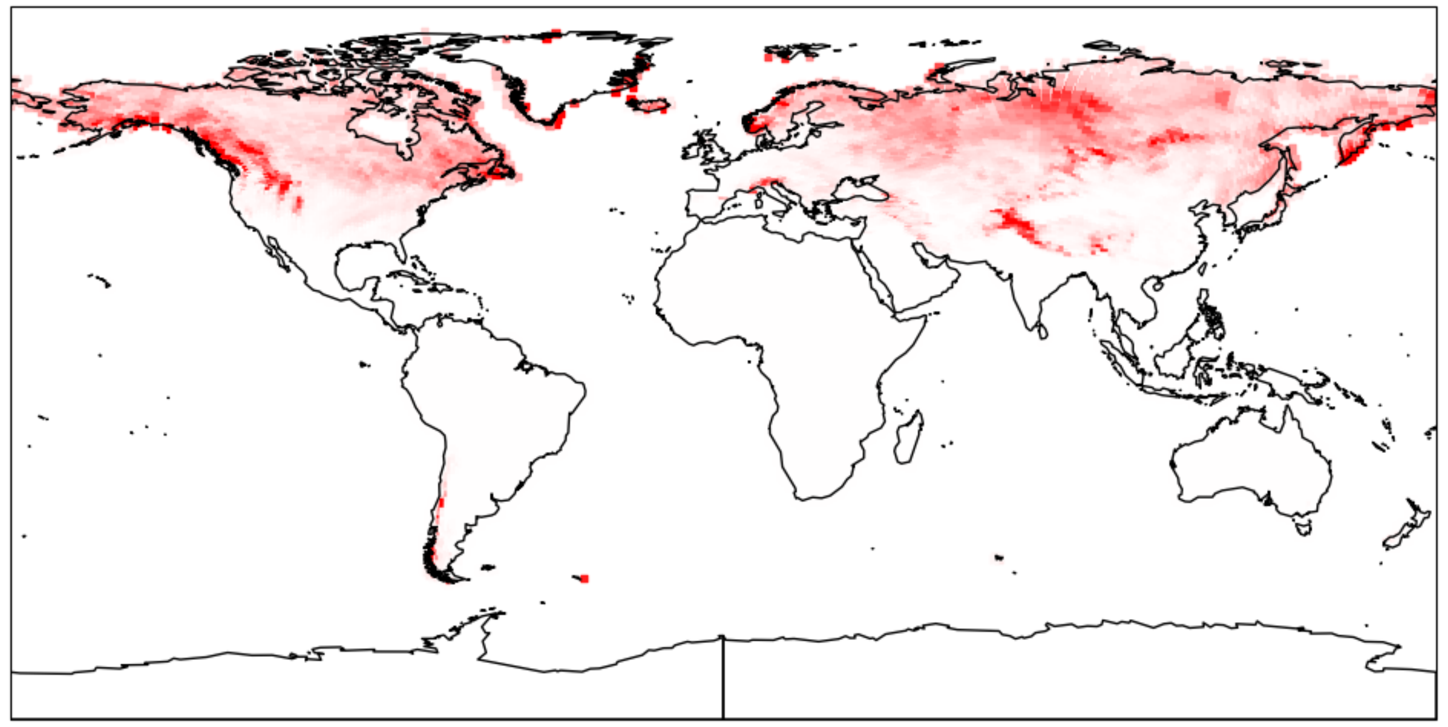
Offline Cycling Noah-MP model and JEDI DA system

- Offline land DA / model workflow for Noah-MP
  - Uses same JEDI (fv3-jedi) DA code as for GFS land and atmosphere updates, same Noah-MP code as in GFS
  - Snow layer disaggregation scheme from previous slide

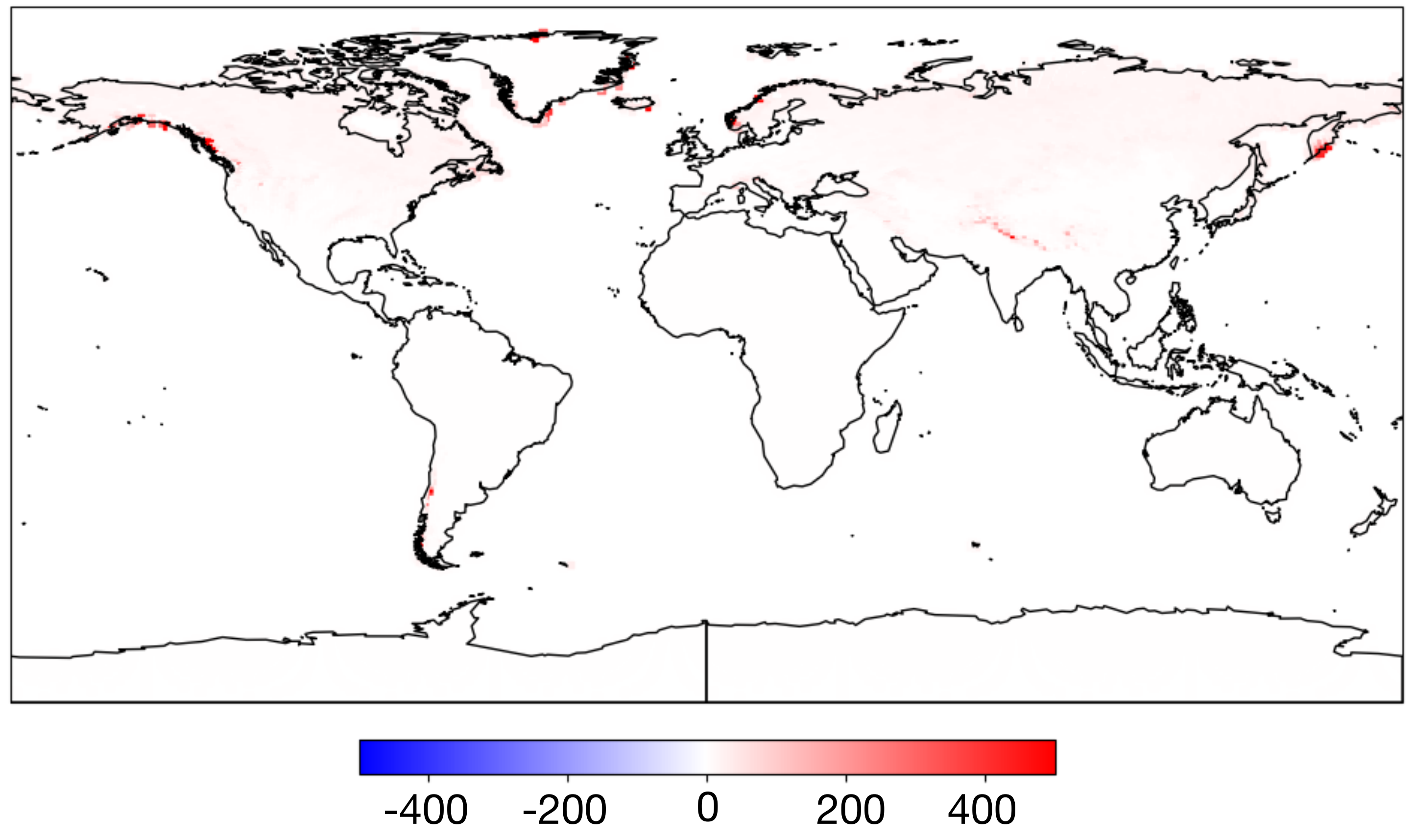
- Test JEDI LETKF-OI in synthetic experiment
  - One year experiment
    - Created truth using GSWP3 forcing
    - Created synthetic snow depth observations by perturbing truth with Gaussian errors
    - Assimilated synthetic observations into the model forced with GDAS
    - Evaluate DA output against truth
  - Results indicate good performance of the snow depth DA (also in SWE, fluxes, and snow temperature)

- Currently running experiments assimilating GHCN snow depth and IMS snow cover, for evaluation against independent observations

Snow depth RMSE (open loop), mean: 107.8 mm.



Snow depth RMSE (JEDI LETKF-OI), mean: 19.8 mm



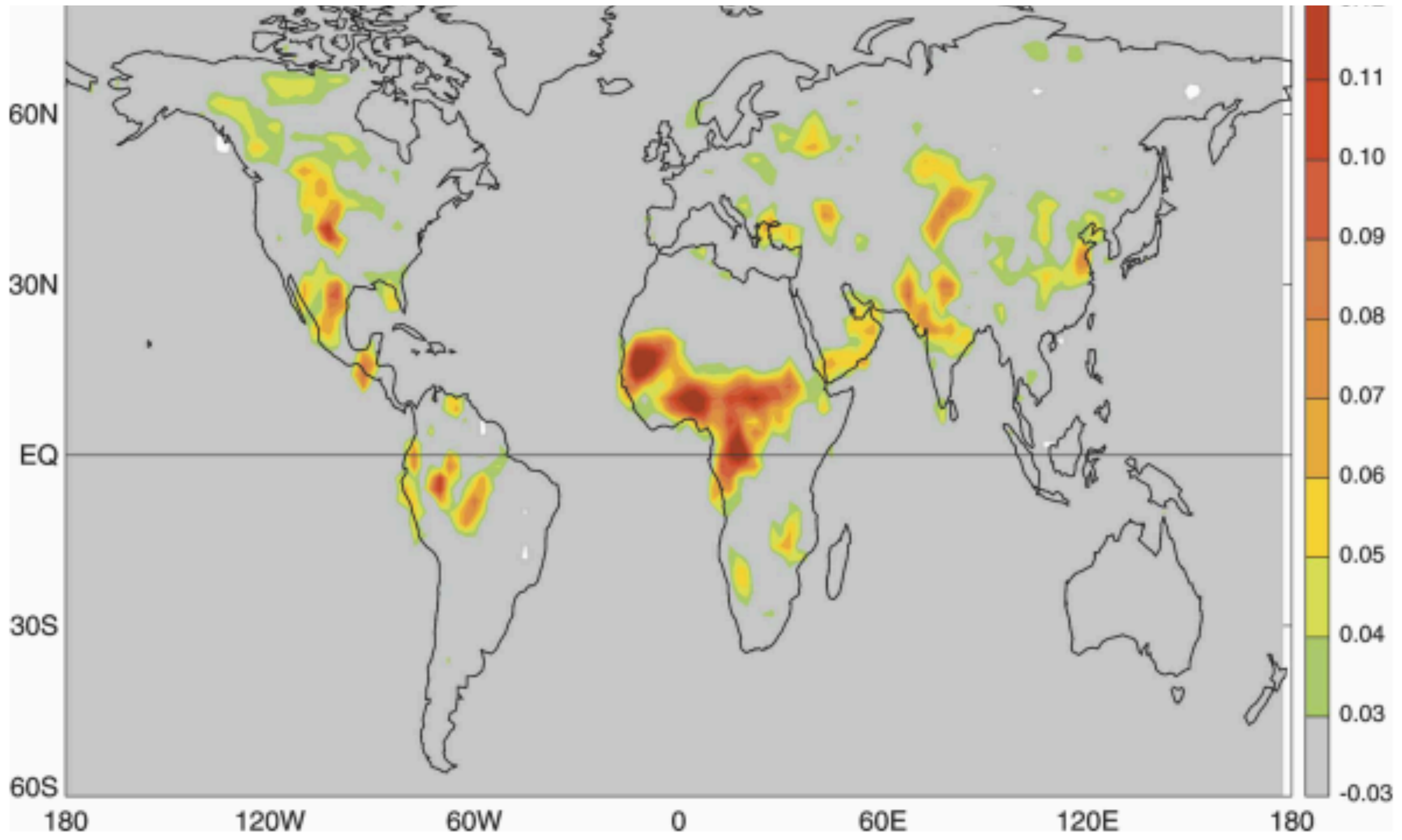
Figures: A. Gholoubi

Design of the Land DA System

- Required features:
  - Ability to develop and evaluate the land DA in offline (land only) mode (rather than using full GFS)
  - Use same DA code and same model code in the offline DA system as in the coupled (land/atmosphere) DA system
  - Ability to extend to more strongly coupled DA (use same code base for both land and atmosphere DA updates)

- For the land DA use the fv3-jedi JEDI bundle (used for GFS atmospheric DA)
  - Using same DA code as for atmospheric update
  - Can leverage off (larger) fv3-jedi effort

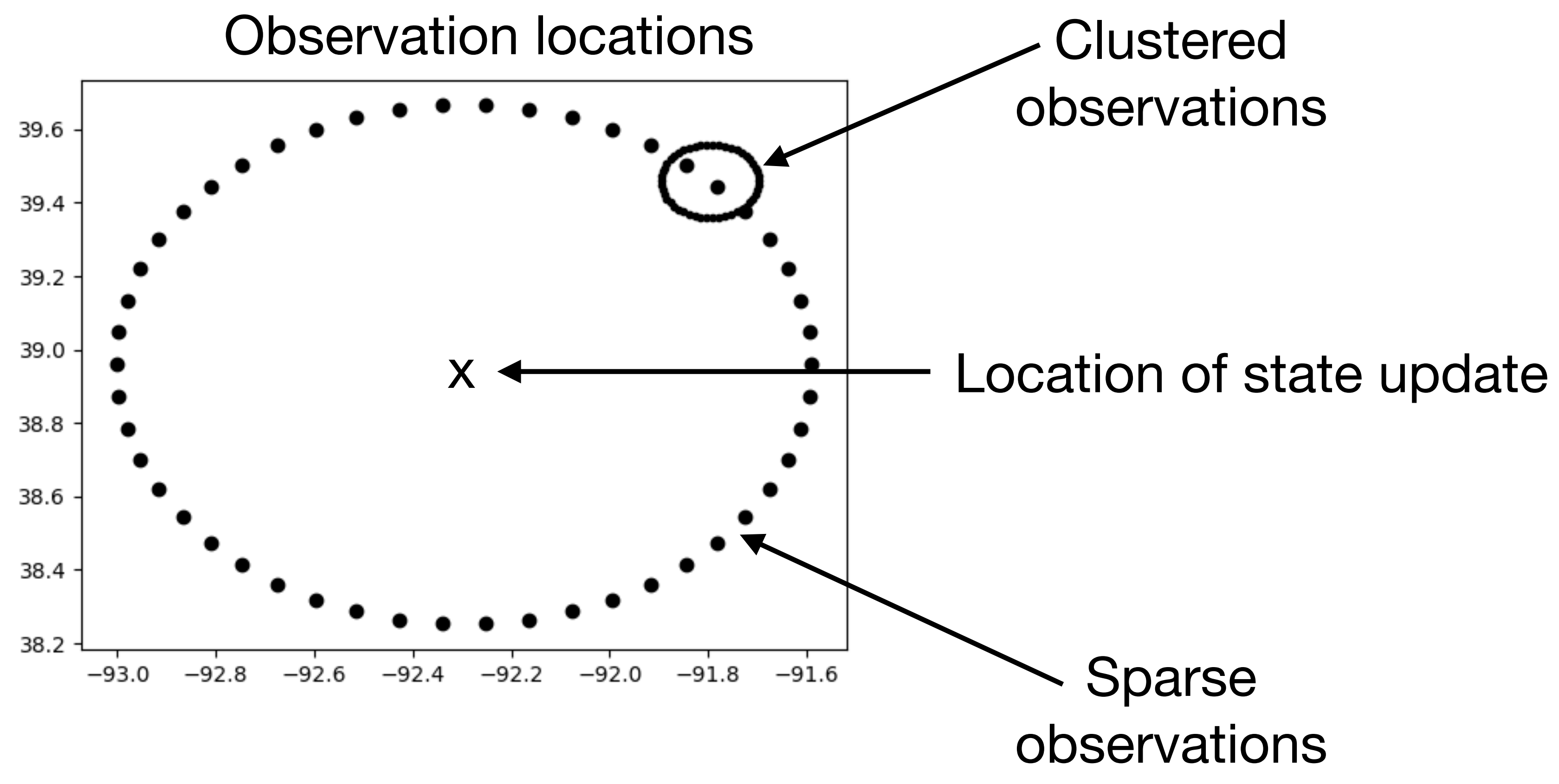
- Build an off-line workflow to perform cycling model forecasts and DA with the DA performed on the GFS model grid (FV3 tile space)

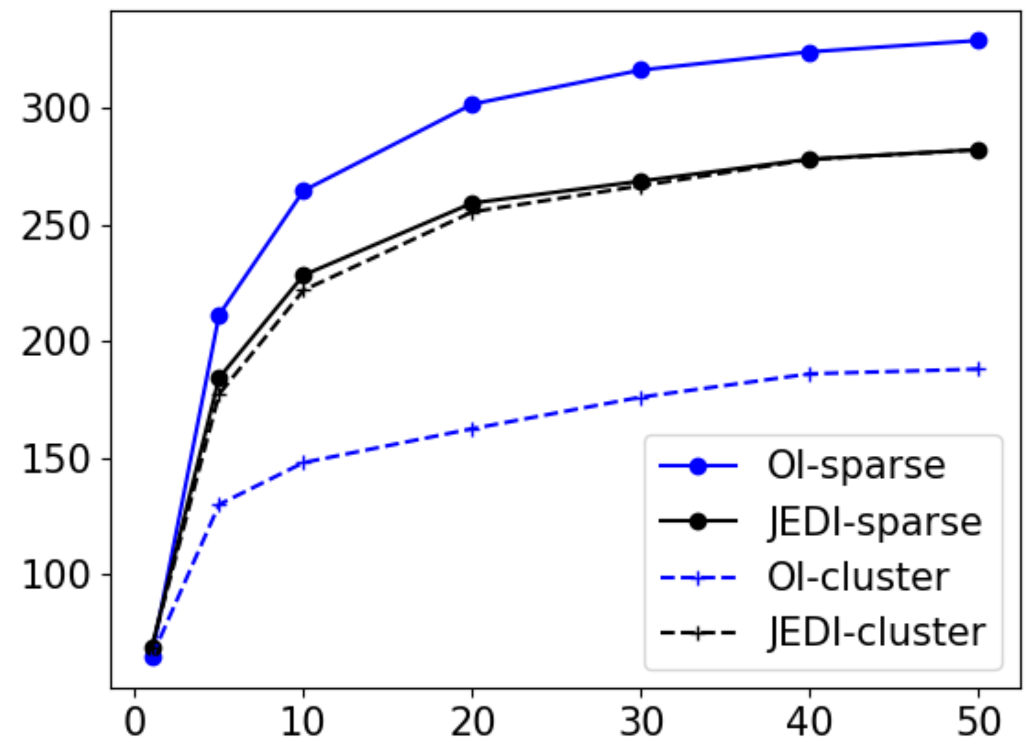


Koster et al (2006): regions of strong soil moisture/precipitation coupling
(i.e., land initial conditions affect forecast skill)

Accounting for distance between obs

- LETKF-OI has no off-diagonal localization, pseudo ensemble has same perturbations everywhere (H(x) ensemble perturbations perfectly correlated)
  - Results in generally smaller increment than the OI when have multiple observations
  - But depends on distance between obs, the increment may be larger than the OI if the obs are tightly clustered





Snow depth [mm] increment at X, from:
1. Assimilation of sparse observations
2. Assimilation of clustered observations
(Same O-F at all points)

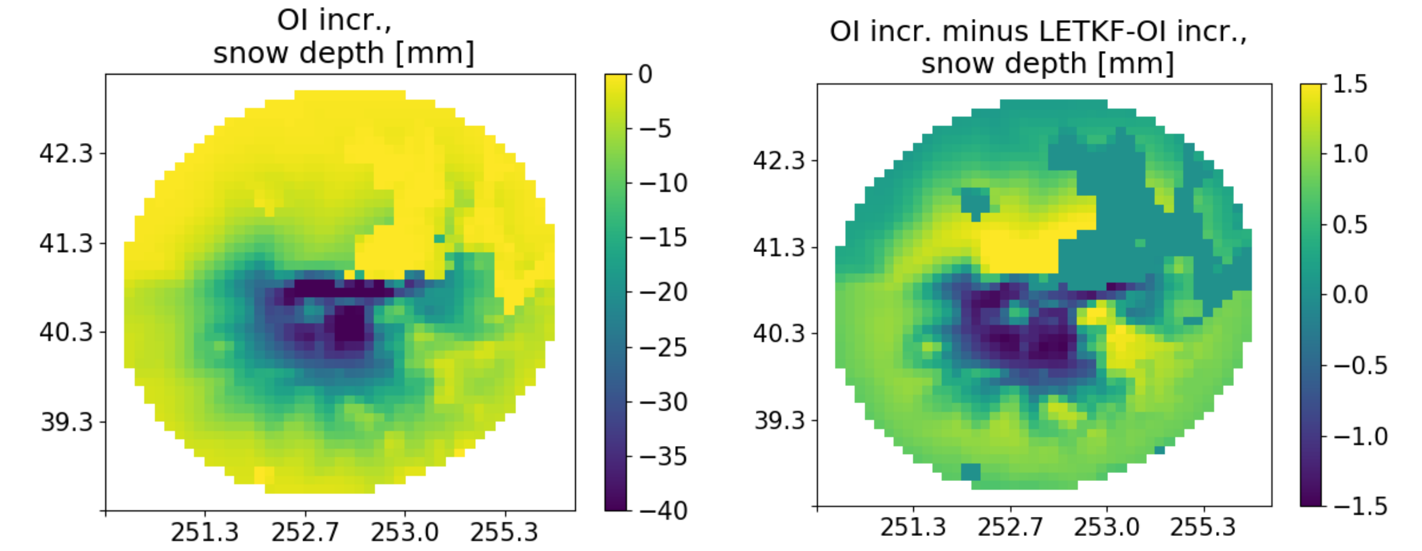
OI v (JEDI) LETKF-OI

- Single observation experiment
  - Agreement is very good

- Global experiment
  - LETKF-OI generally has smaller increments where multiple observations are assimilated
  - The difference in substantial (nRMSD ~ 30%), and ability of OI to differentiate where observations are close together is likely more accurate

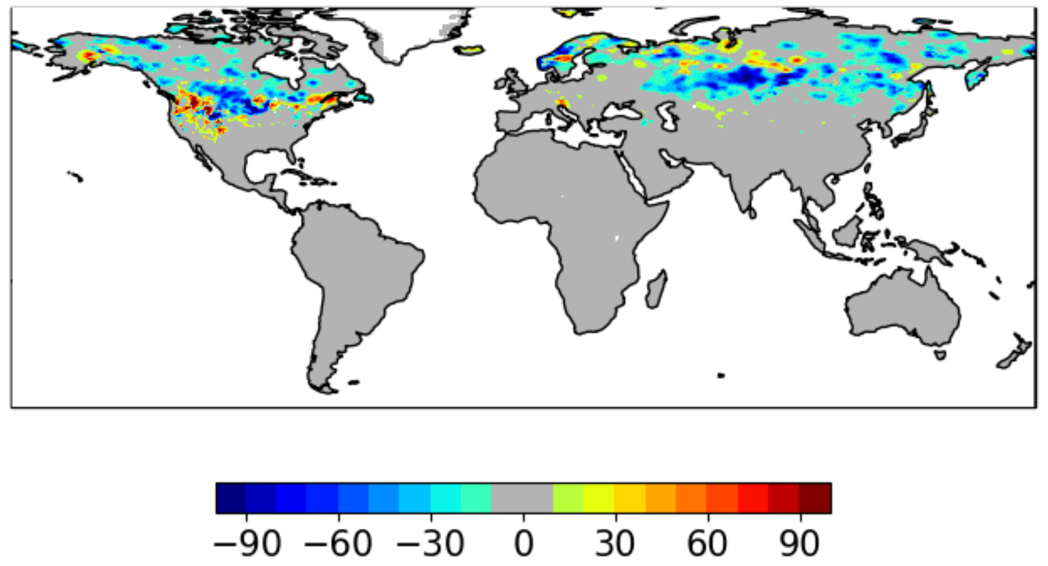
- Solution:
  - Introduce off-diagonal inflation for R
  - Introduce localization of B through ensemble tapering
  - Code the OI!

Single observation experiment: RMSD = 0.8 mm, nRMSD = 8%

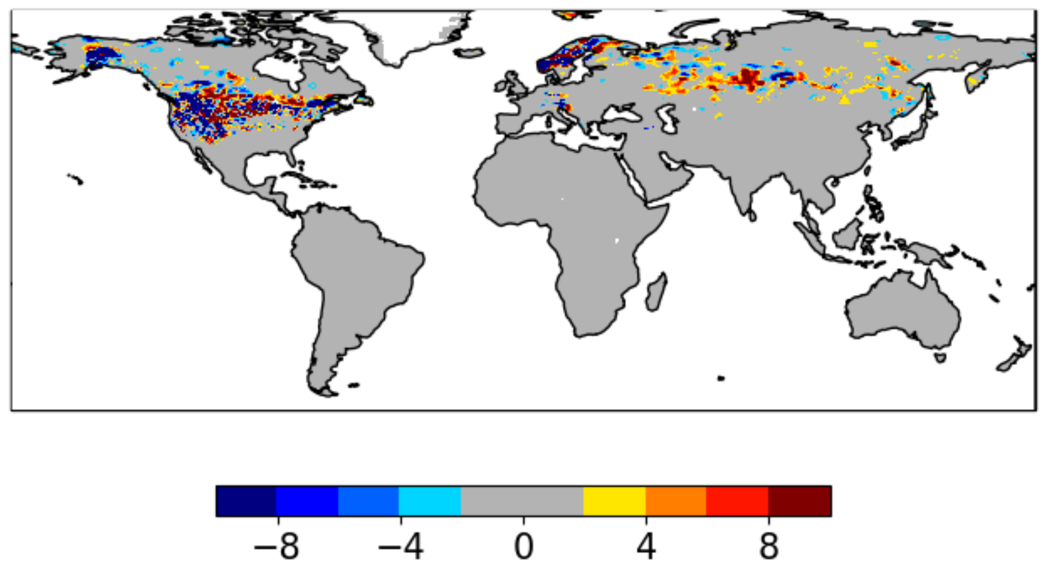


Global assimilation experiment: RMSD = 7 mm, nRMSD = 28%

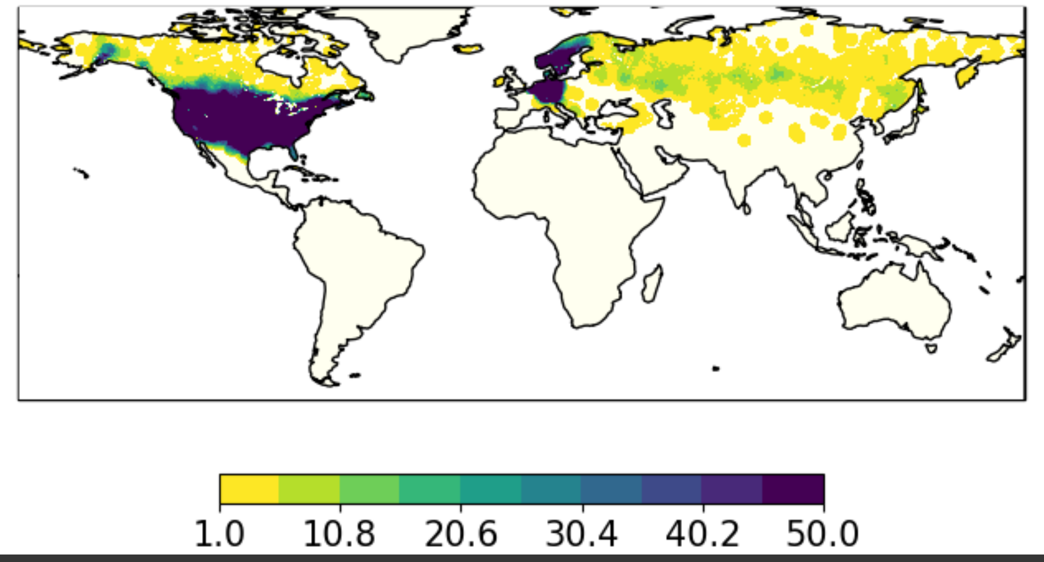
OI increment, snow depth [mm]



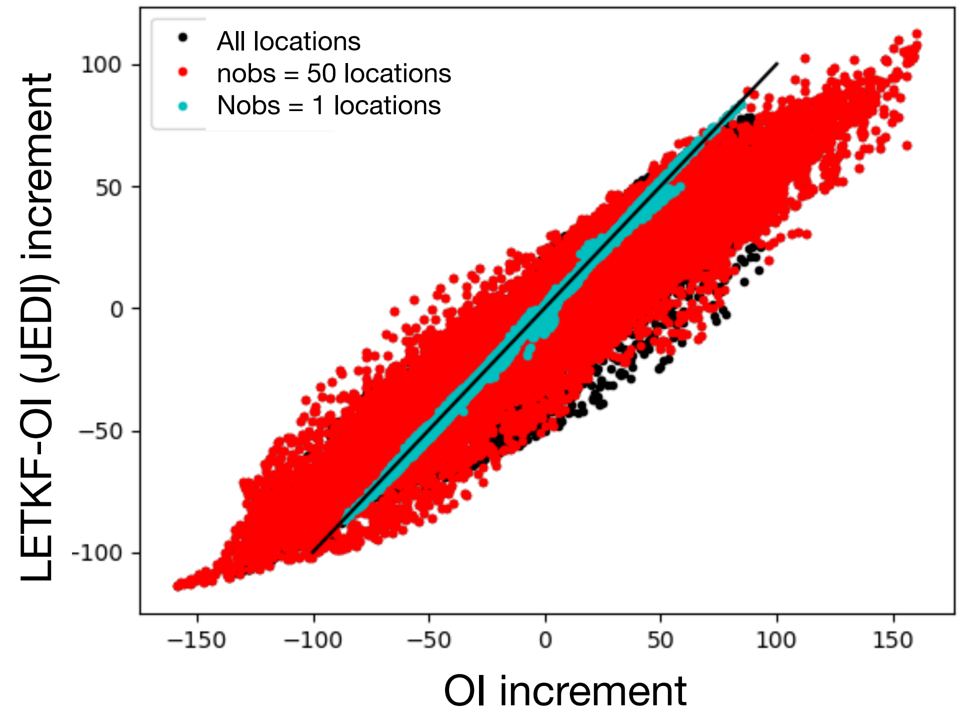
OI incr. minus LETKF-OI incr., snow depth [mm]



Number of obs assimilated at each grid cell.



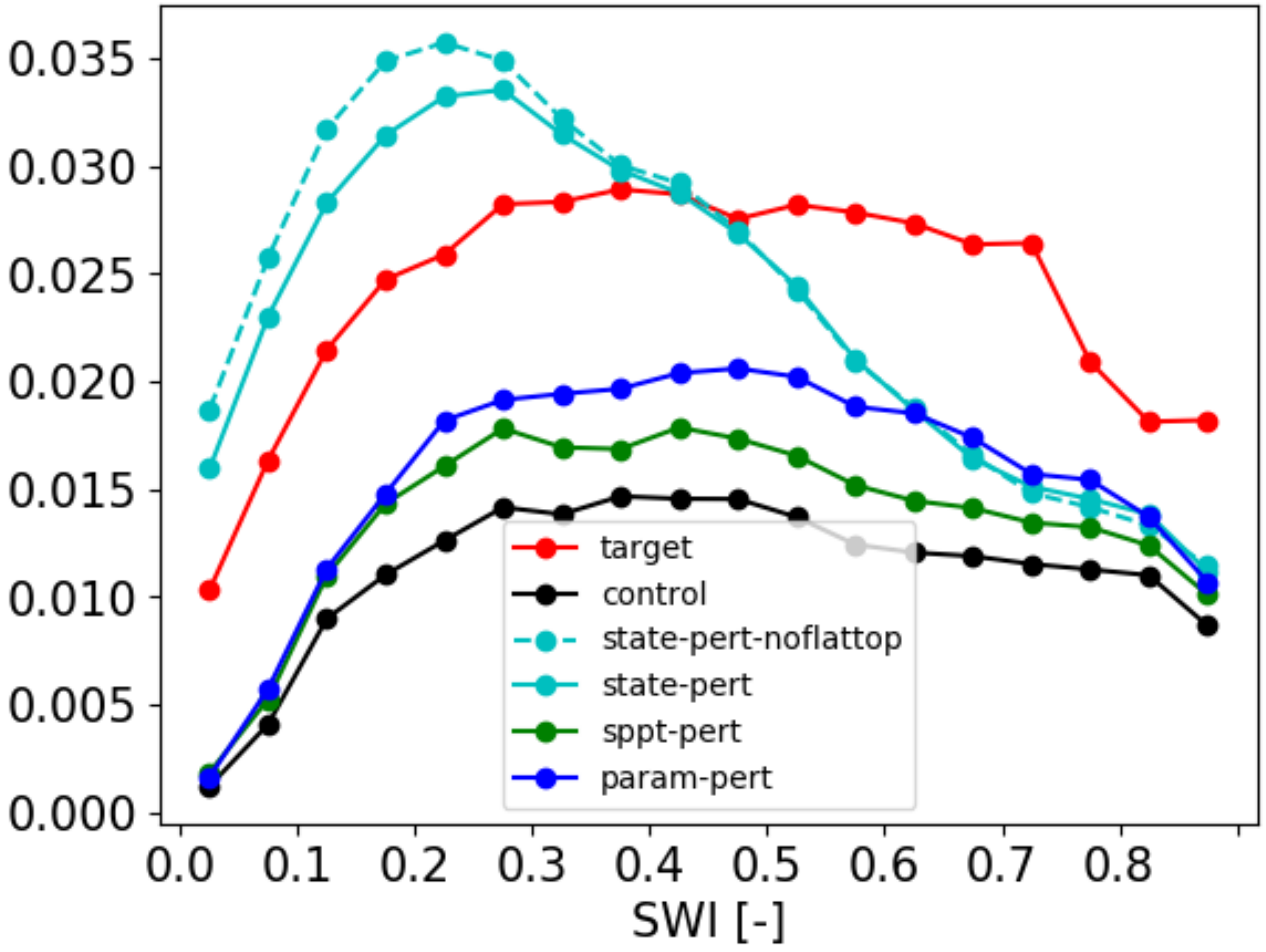
OI v. LETKF-OI increments



LETKF-OI Increments are smaller than the OI where there are multiple obs (red points)

GFS ensemble spread

- Tested several methods to add ensemble perturbations to account for land model uncertainty
  - Perturbing the soil moisture and temperature at each time step created unrealistic spatial patterns in the soil moisture ensemble spread
  - Applying SPPT to the soil states inherently limited in the amount of soil moisture spread that can be induced
  - Perturbing key model parameters in land/atmosphere fluxes created reasonable spatial patterns in ensemble spread



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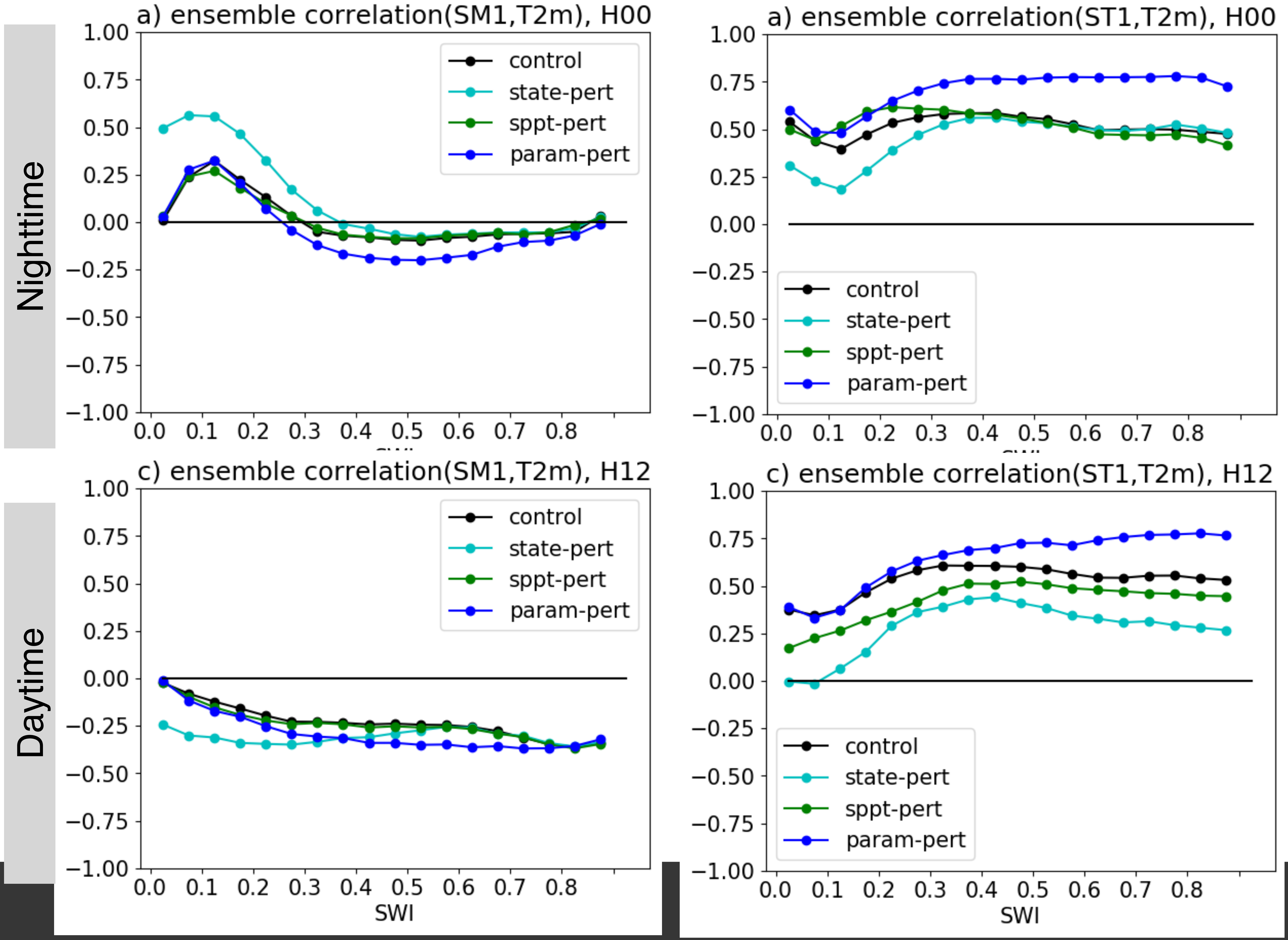
Ensemble land/atmosphere correlations, T2m

Adding perturbations to the soil states (state-pert, sppt-pert):

- Strengthens soil moisture correlations under dry conditions (soil moisture drives land/atmosphere coupling)
- Weakens the soil temperature correlations (atmosphere is driving the land/atmosphere coupling)

Adding perturbations to the parameters (param-pert) generally the strengthens correlations

Correlations (SM1, T2m) | Correlations (ST1, T2m)



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Ensemble land/atmosphere correlations, T2m

Adding perturbations to the soil states (state-pert, sppt-pert):

- Strengthens soil moisture correlations under dry conditions (soil moisture drives land/atmosphere coupling)
- Weakens the soil temperature correlations (atmosphere is driving the land/atmosphere coupling)

Adding perturbations to the parameters (param-pert) generally the strengthens correlations

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