Improving land-atmosphere data assimilation coupling

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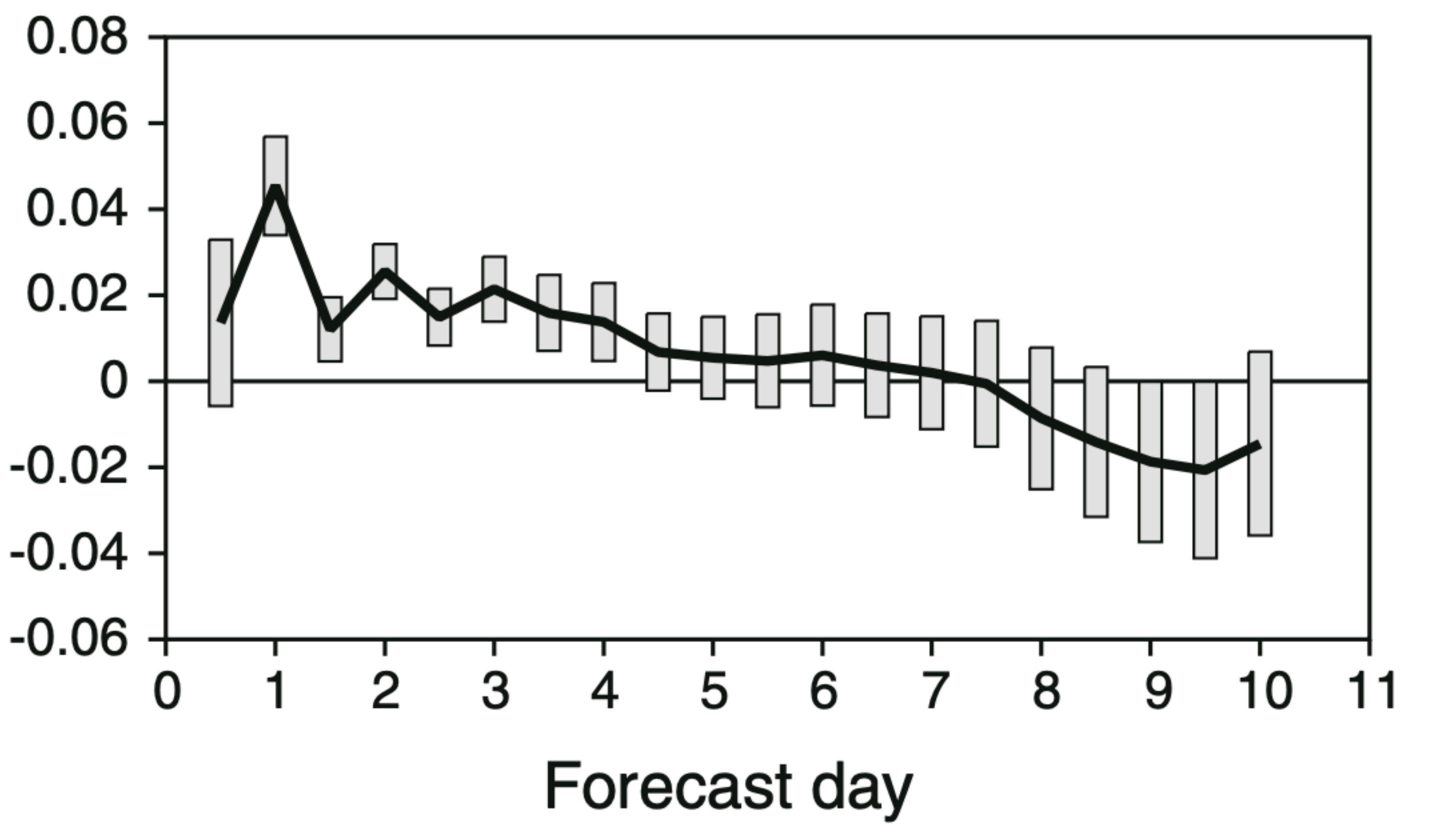
Land DA in NWP Systems

- The first use of land DA within NWP, was introduced at Météo-France in 1985, to update soil moisture and soil temperature from screen-level station observations

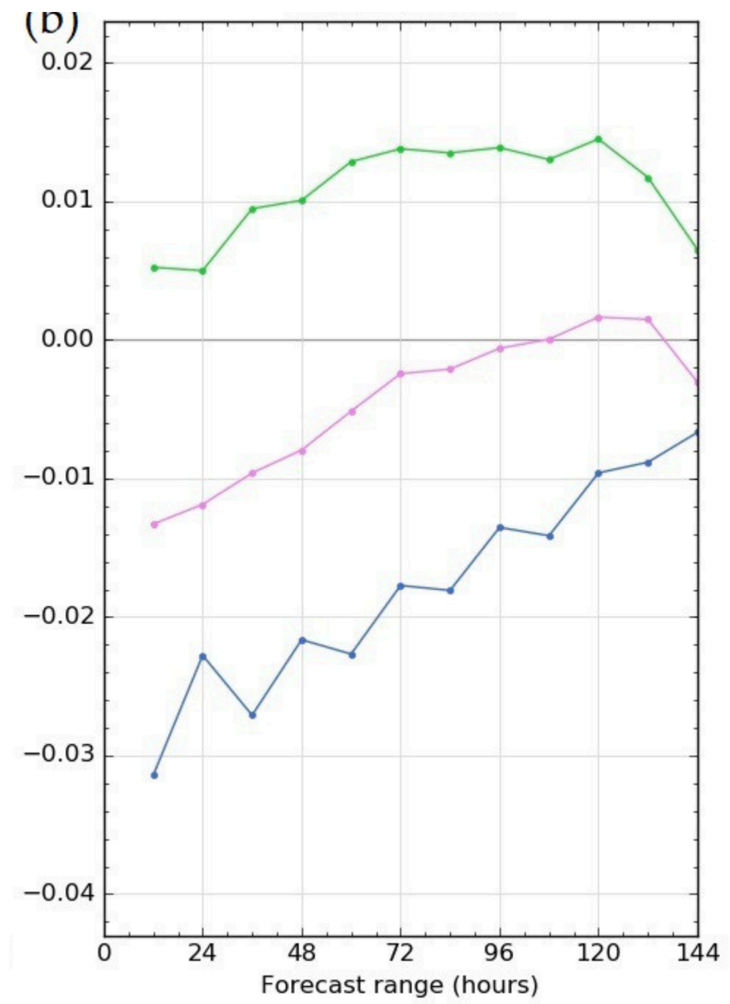
- Today, NWP centers update soil moisture, soil temperature, snow temperature, and snow amount from a selection of observations of screen-level temperature and humidity, satellite soil moisture, satellite snow cover, and station snow depth

- Observed precipitation is also used to force the land surface
  - Better suited to non-NRT systems (reanalyses!)

- Land DA useful for improve initialization of land states, leading to improved atmospheric forecasts; and also for detecting and evaluation model errors



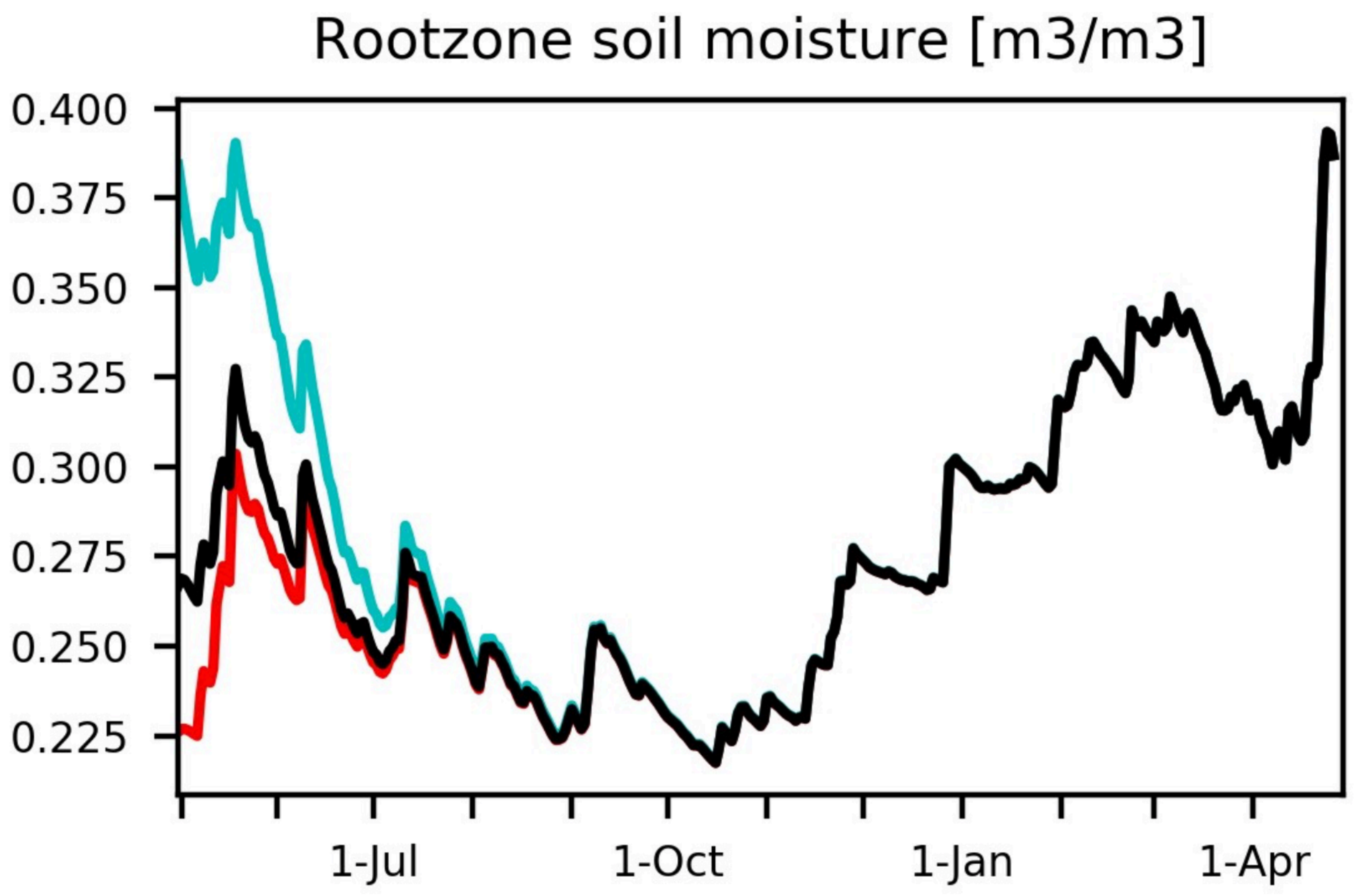
Improvement in normalized root mean square forecast 1000 hPa geopotential error [-] at ECMWF, from updating the snow depth analysis (de Rosnay et al, 2014).



Change in forecast T2m RMSE [K] at UKMO due to the SEKF soil moisture analysis (three different versions shown; Gomez et al, 2020).

Difference Between Land and Atmos. Dynamics

- The land is strongly-forced (dissipative); over time it will converge to a state determined by its forcing
  - No sensitive dependence on initial conditions (not chaotic)
- Land surface models do not simulate horizontal flow between grid cells
  - No horizontal flow of errors
- The land is highly heterogenous
  - Comparison of models and observations is difficult, due to differences in spatial support / difficulty extrapolating
  - Re-gridding can be problematic
- Time scales of land variables can be much longer than the atmosphere



Soil moisture from NASA's Catchment land model. Initialized at three different values, with identical atmospheric forcing.

Land DA in Global Atmospheric Systems

	Land DA in Global NWP systems
ECCC	Soil moisture, soil/surface/snow temperature: OI assimilation of screen-level T, T_d Snow depth: OI of station snow depth
ECMWF	Soil moisture: SEKF assimilation of screen-level T, RH, and satellite soil moisture Soil/snow temperature: 1-D OI of screen-level T Snow depth: OI of station snow depth and satellite soil cover
NASA GMAO	Precipitation replaced with observations prior to entering land surface
NOAA	Soil moisture and soil temperature: Retrospectively corrected with observed precipitation Snow depth: Heuristic correction with gridded snow depth product and satellite soil moisture
UKMO	Soil moisture and soil/snow temperature: Offline SEKF of screen-level T, RH and satellite soil moisture Snow depth: Heuristic correction with satellite snow cover

With input from Stephane Belair, Patricia de Rosnay, Rolf Reichle, and Sam Pullen.

Land DA in Atmospheric Systems

- The land DA update is done separately from the atmospheric DA (weakly coupled), using different methods for different land variables
  - DA methods are simpler than for atmosphere
  - Soil moisture and temperature analysis from screen-level obs: the vertical update of the soil states is decoupled from the horizontal spreading of the observed information

- Above design was initially developed when atmospheric DA was done at relatively coarse resolution
  - Allowed the land DA to be done on the model grid
  - Computationally more affordable
  - Avoided need for model adjoint

- The observations used in the land DA (snow depth, snow cover, screen-level T,q, satellite soil moisture) are not necessarily used in the atmospheric DA. Exceptions are:
  - ECCC assimilates screen-level T, T_d in their 4D-EnVar
  - ECMWF assimilates screen-level RH in their 4D-Var (adding screen-level T in 2024)

With input from Stephane Belair, Patricia de Rosnay, Rolf Reichle, and Sam Pullen.

Land DA in Hydrology

- In contrast to NWP, the hydrology community has traditionally favoured EnKF-type methods
  - More flexible (addition of new obs / updates states), more intuitive specification of model errors, account for errors of the day, more robust to non-linearities

- EnKF-type land DA less common in atmospheric systems
  - ECCC regional NWP system and NASA (LIS/AWFA; GMAO) use EnKF for land DA within coupled system, by running a land-only (offline) ensemble system

- For soil moisture analysis, the hydrology community has focussed on assimilating satellite soil moisture observations (or associated Tb)
  - Assimilation of screen-level observations is effective at improving low-level atmospheric forecasts, but can degrade the soil moisture and temperature states

Moving Towards a Unified Land/Atmosphere DA

- Atmospheric DA now uses ensemble-based methods that are better suited to land DA, and are at/close to model horizontal resolution
- At NOAA:
  - GFS/GDAS uses the GSI Hybrid 4D-EnVar
  - Future JEDI DA system will perform the DA on the model grid

- Opportunity to do the land and atmospheric DA with the same method
  - Enhances sharing of information between components
    - Consistent estimation of background errors -> assimilation of interface observations -> strongly coupled land/atmosphere DA
  - No need to decouple the vertical update from horizontal spreading of observed information
  - Simpler to code / maintain

A new soil moisture/soil temperature analysis for NOAA's global NWP

- NOAA is developing a soil moisture and soil temperature analysis for our global NWP system
  - Initially based on assimilation of screen-level T and RH

- Rest of this presentation:
  - Investigate whether we can expand our atmospheric DA to also perform the land DA update, rather than implementing a separate land DA scheme
  - Use this system to test different options for coupling the land and atmosphere updates from screen-level observations

  - Atmospheric DA uses the GSI Hybrid 4D-EnVar
  - For now, use only EnKF (LETKF) rather than the full hybrid DA to establish best coupling arrangement / use of screen-level observations

Land ensemble spread in NWP systems

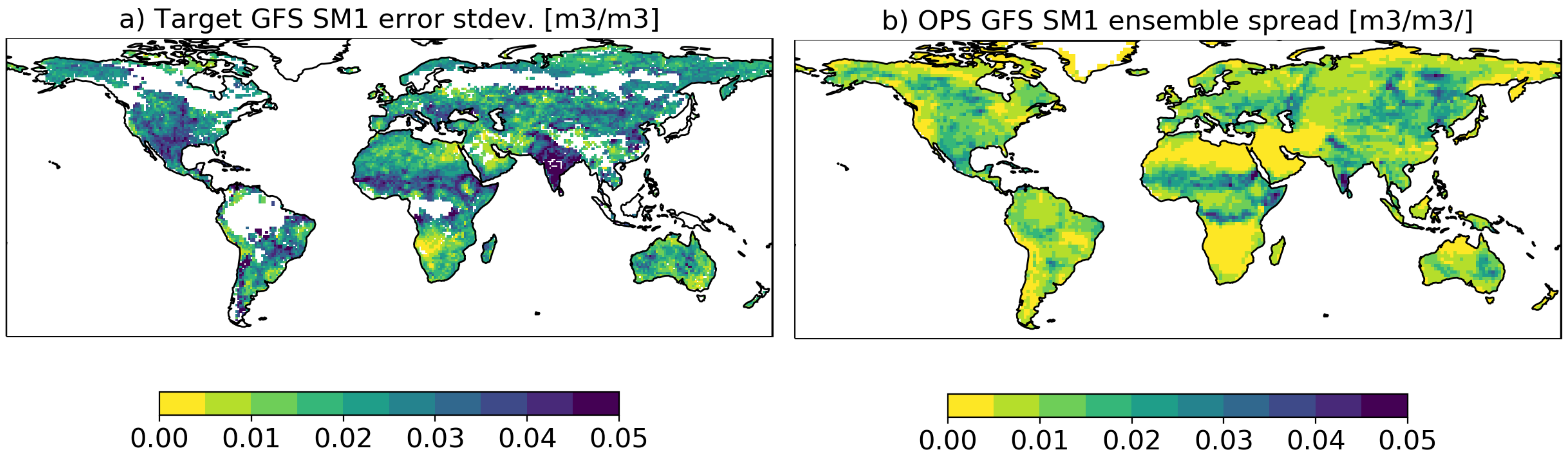
Ensemble Spread

- NWP ensembles are under-dispersed at the land surface
  - Expected, since ensembles are not explicitly perturbed to account for land model uncertainty

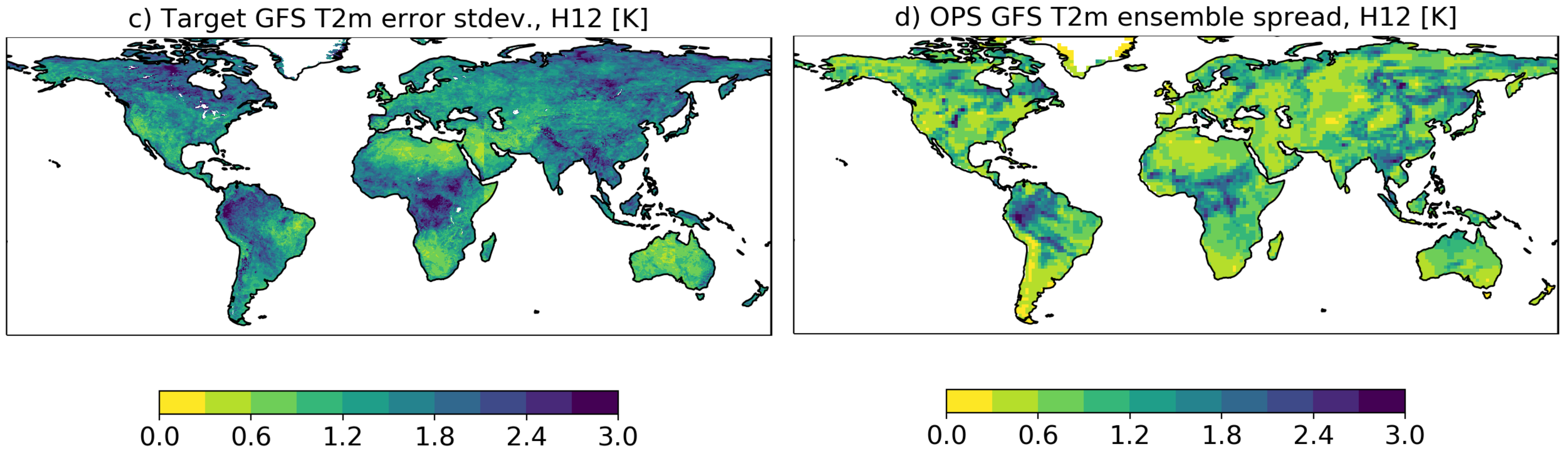
- Previous work: Tested different approaches to adding a scheme to represent forecast uncertainty at/near land in NOAA's NWP ensemble system

- See: Draper, C., 2021, J. Hydromet

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



Boreal summer daytime model $\mathbf{T}_{SL}$ error standard deviation.

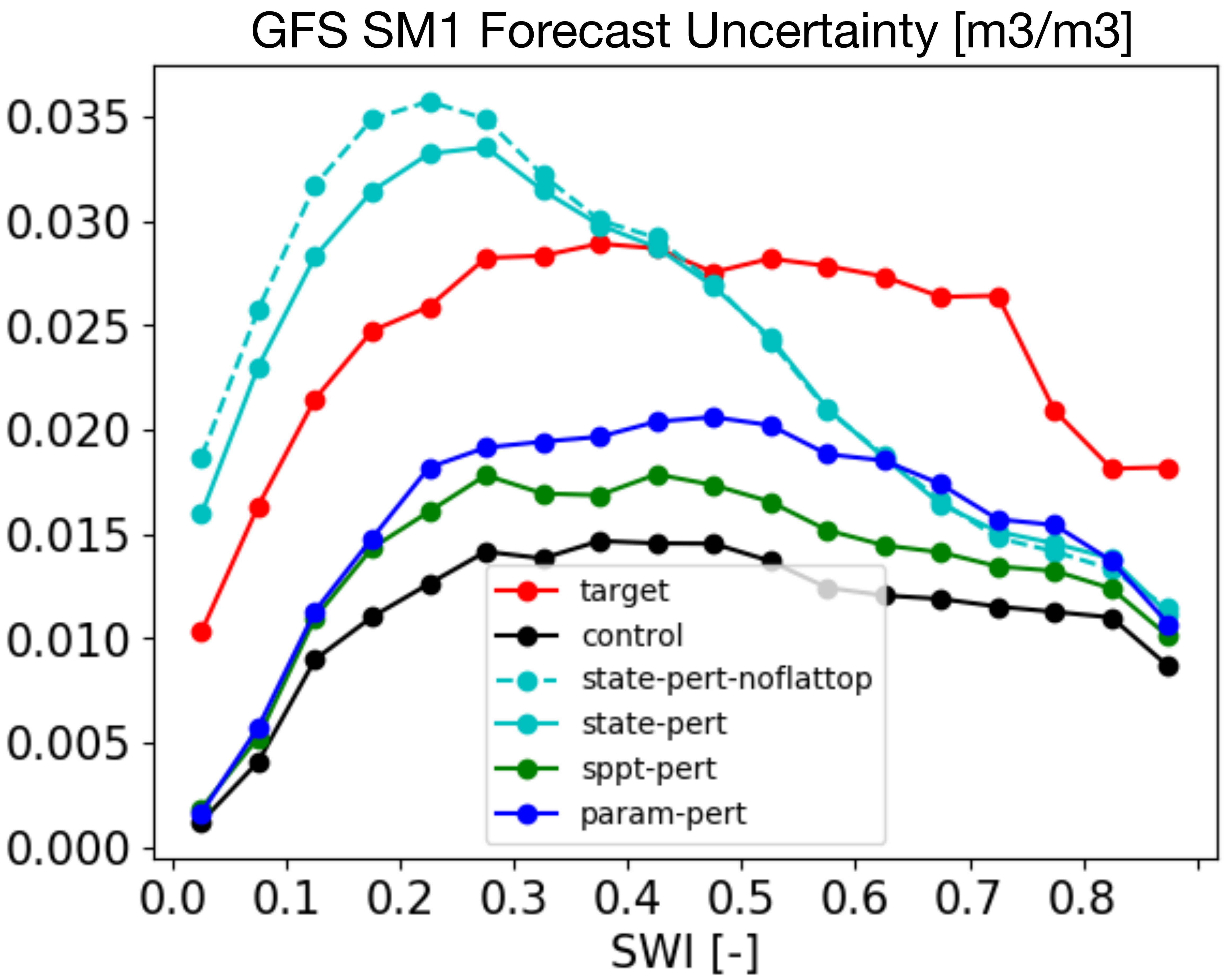


Target estimates, calculated using triple colocation (SM1), and comparison to ERA-5 anal. (T_{SL})

Ensemble standard deviation, from archived operational UFS output

Ensemble Spread

- Recommended method is to perturb key model inputs controlling the land/atmosphere fluxes (e.g. veg. fraction)
  - Generates reasonable spatial patterns in spread
  - Generates ensemble cross-covariances more representative of coupled land/ atmosphere errors
- However, land is highly non-linear; difficult to obtain desired spread without changing ensemble mean (impractical)
- Also: vertical ensembles covariances support updating soil states and atmosphere from screen-level observations



Land/Atmosphere DA experiments

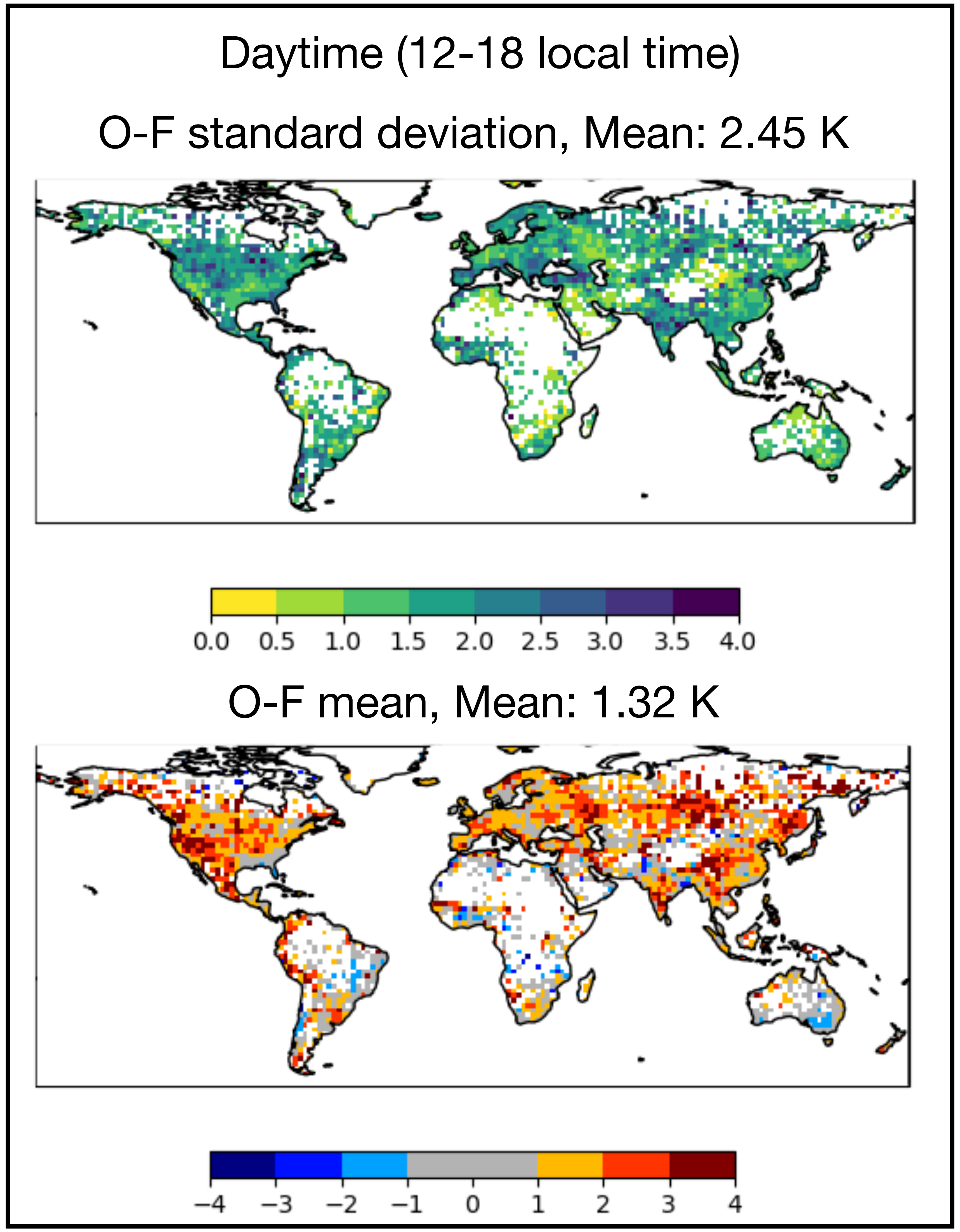
Land/Atmosphere DA Experiments

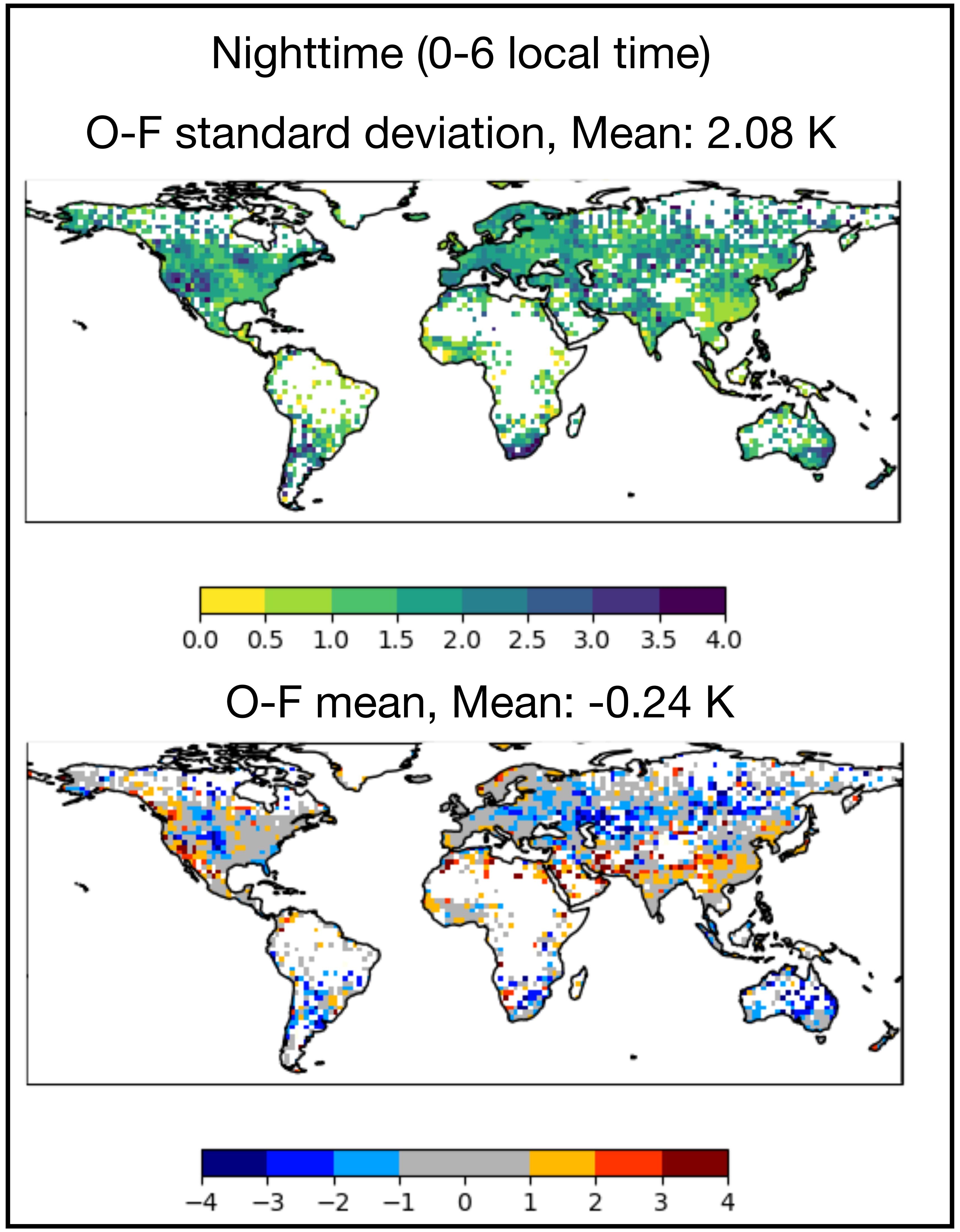
	Update atmosphere*		Update soil moisture+temperature	
	from standard atmos obs	from screen-level obs	from standard atmos obs	from screen-level obs
Control	x			
Screen	x	x		
SfcUpd	x		x	
Screen+SfcUpd	x	x	x	x
SfcUpd-Weak	x			x

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

- DA: GSI EnKF (LETKF)
- Model: GFSv17 (HR1 tag)
  - Includes Noah-MP (new land model being introduced for GFSv17)
  - Land model perturbation scheme not activated (still adapting to Noah-MP)
- Resolution: C192 (50 km), 127 atmos levels & 4 soil levels
- Period: 5-20 June, 2022 (eval last 10 days)
- Evaluation: assess impact on conventional (sondes, station observations) O-F for q, T

Control O-F for Screen-Level Temperature (T_{SL})

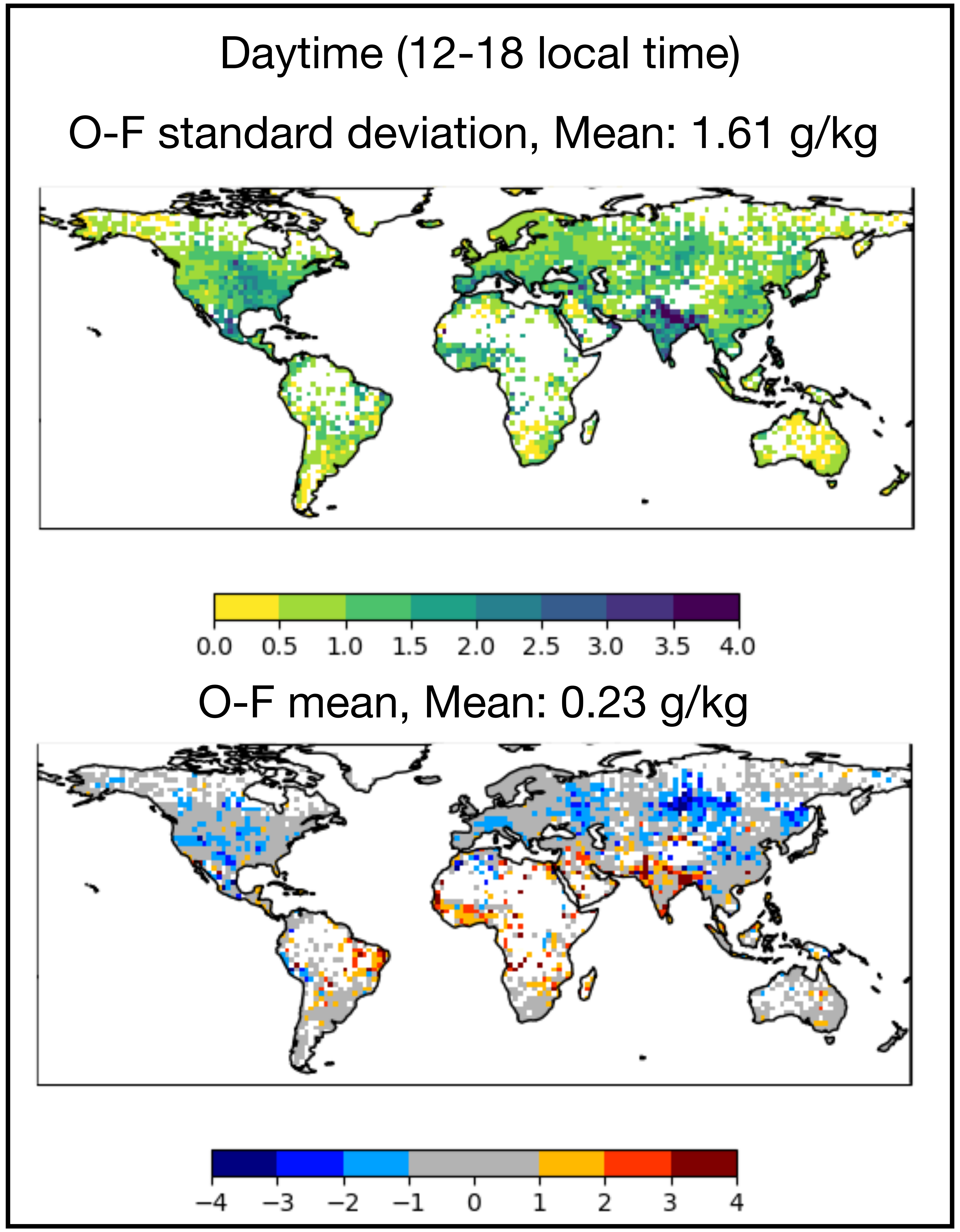


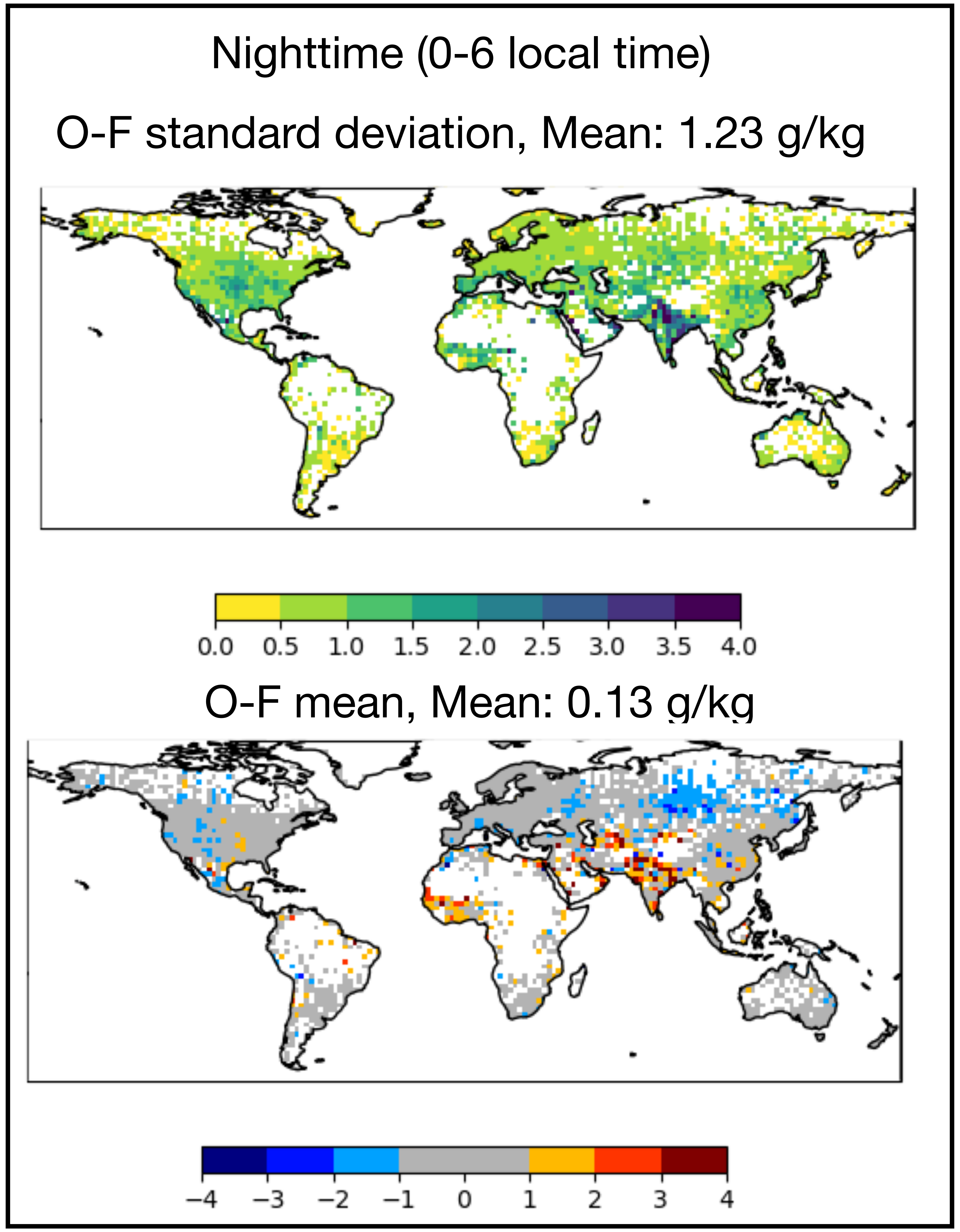


- Substantial day-time cool model bias, lesser night-time warm bias
  - Sondes show similar bias, reduces rapidly away from surface
  - Noah-MP still being tuned; currently testing a potential solution to the diurnal T bias

- The T_{SL} daytime bias will results in sub-optimal DA
  - Vertical T correlations much weaker during the day -> daytime T_{SL} obs expected to have lesser impact

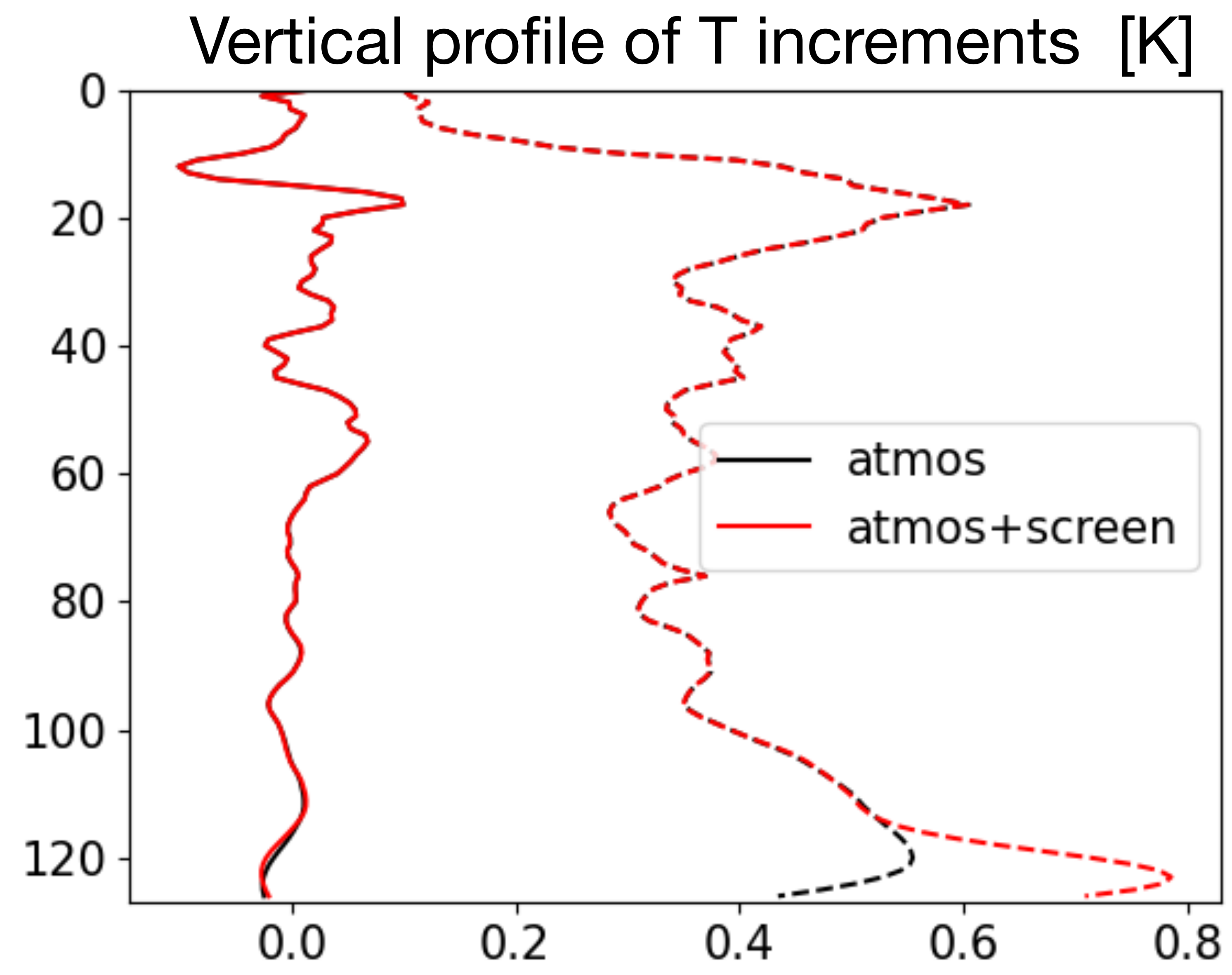
Control O-F for Screen-Level Humidity (q_{SL})

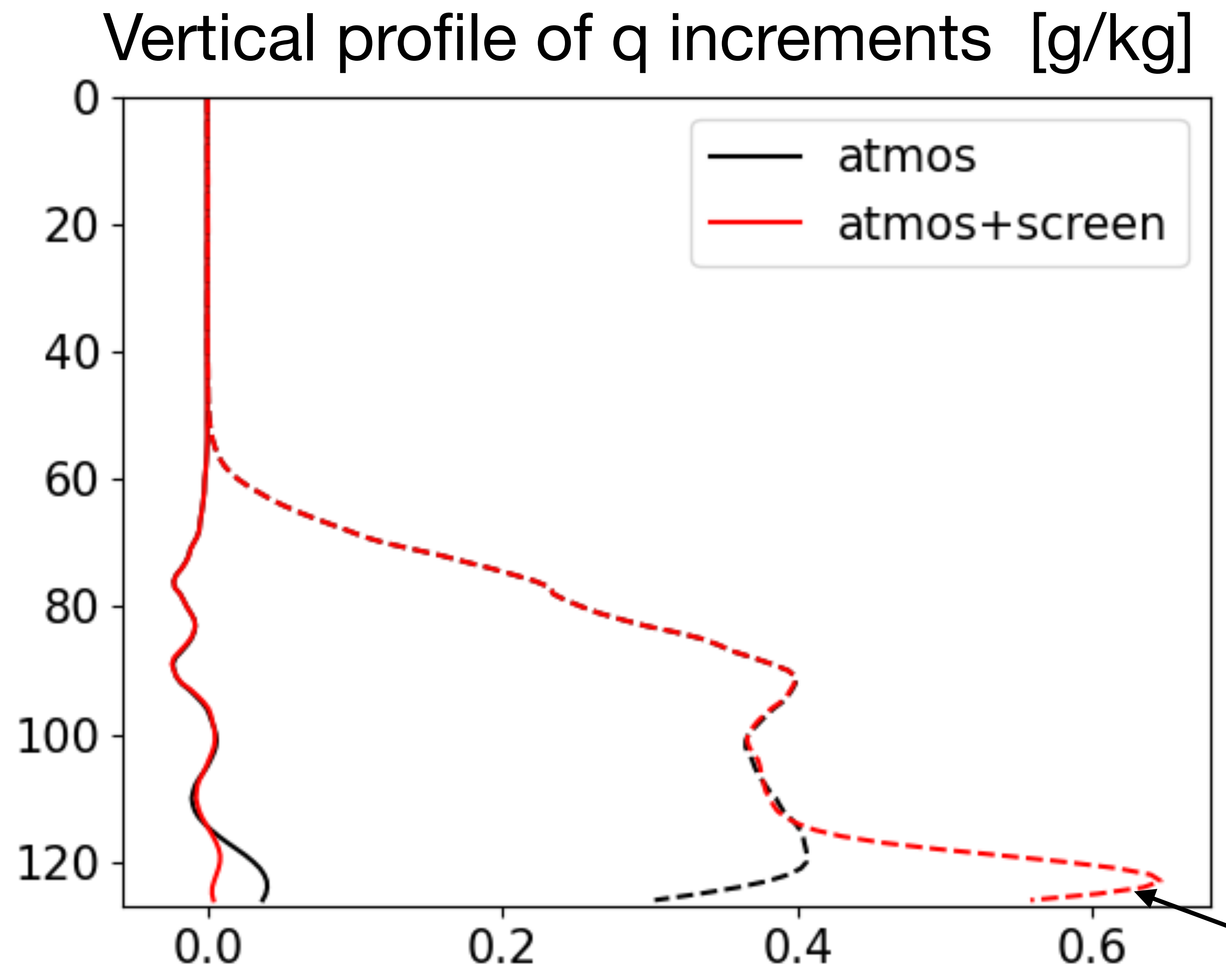




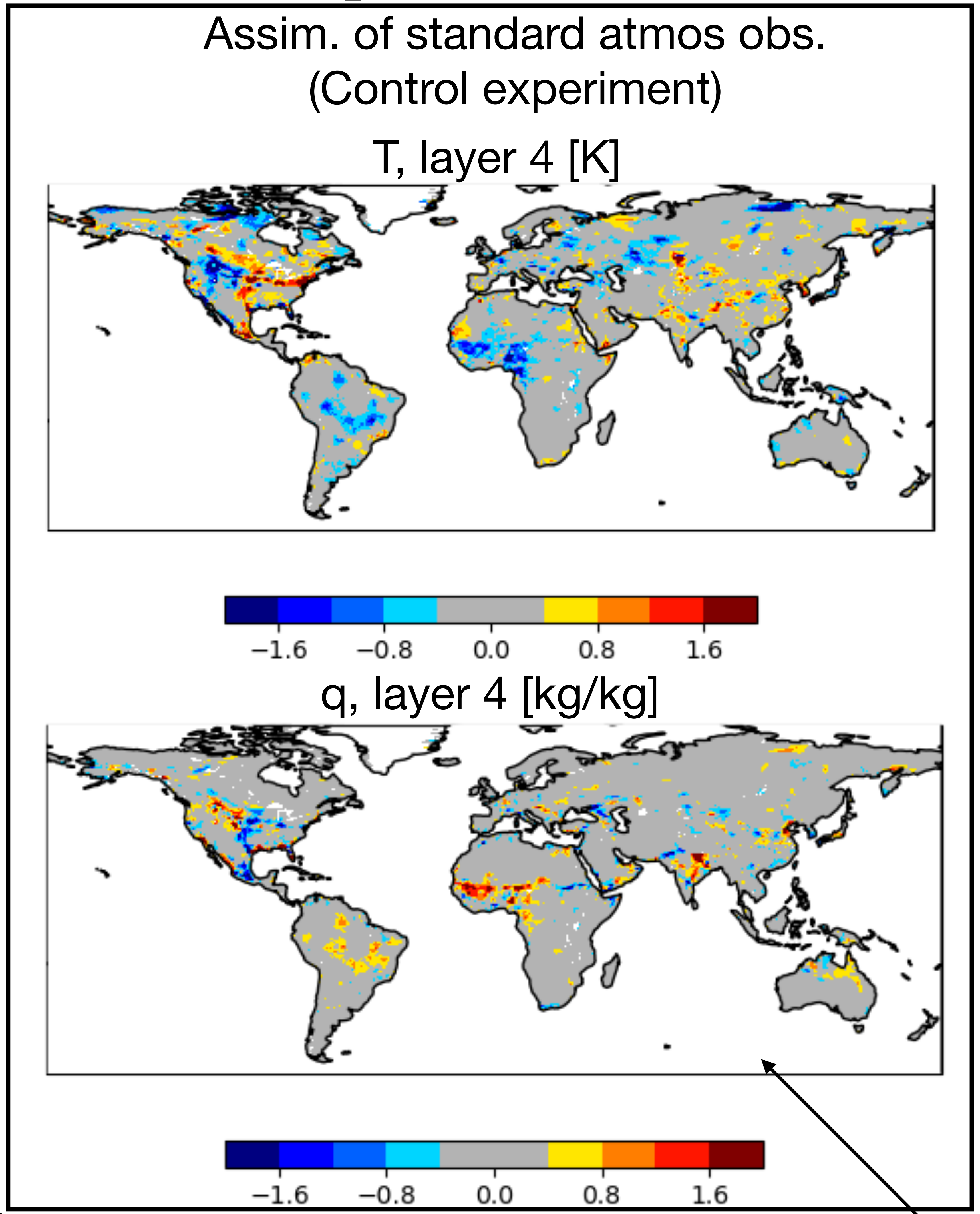
- Small wet bias in some regions, has minimal diurnal cycle

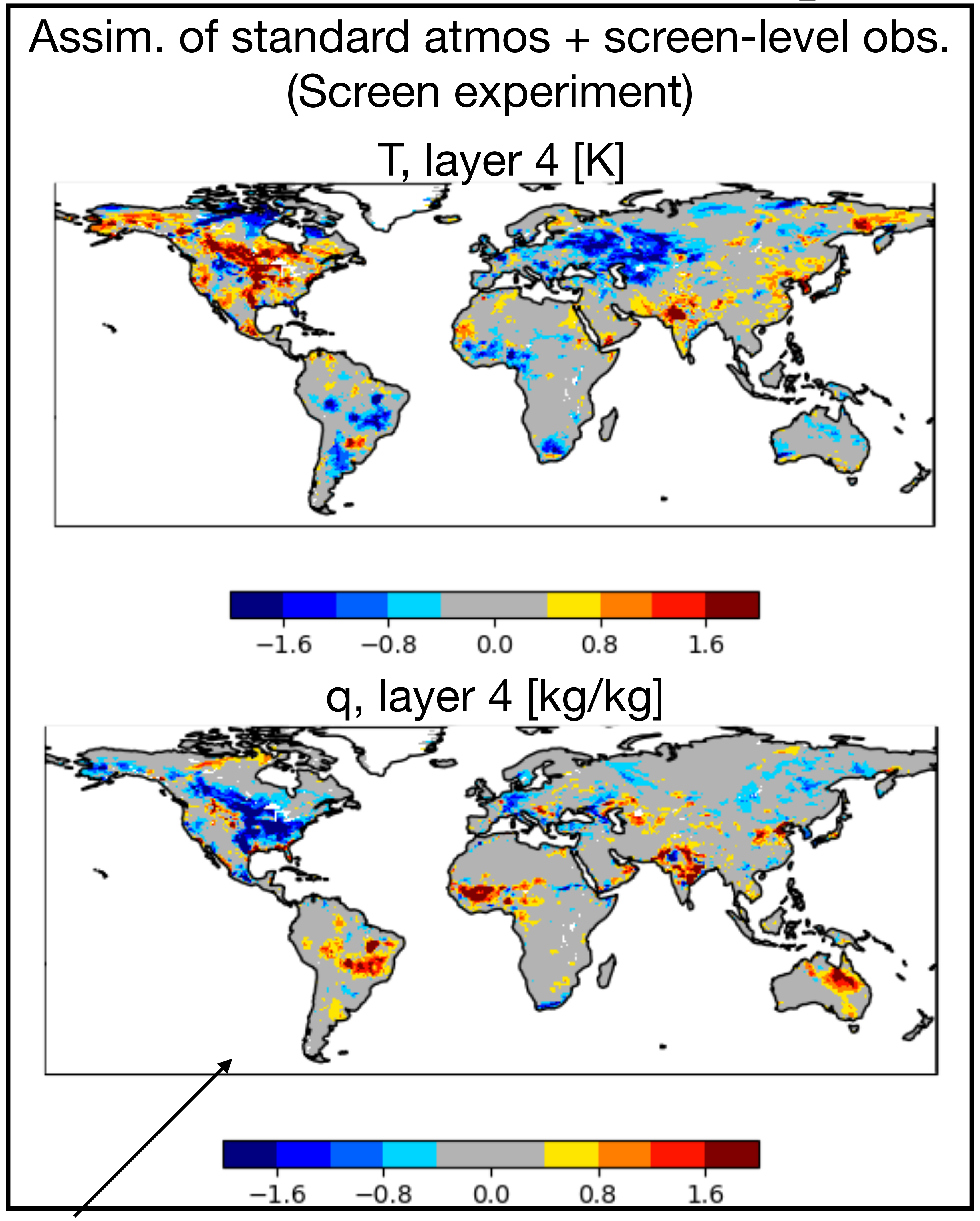
Atmospheric increments - first cycle





Solid - mean increment
Dashed - stdev increment



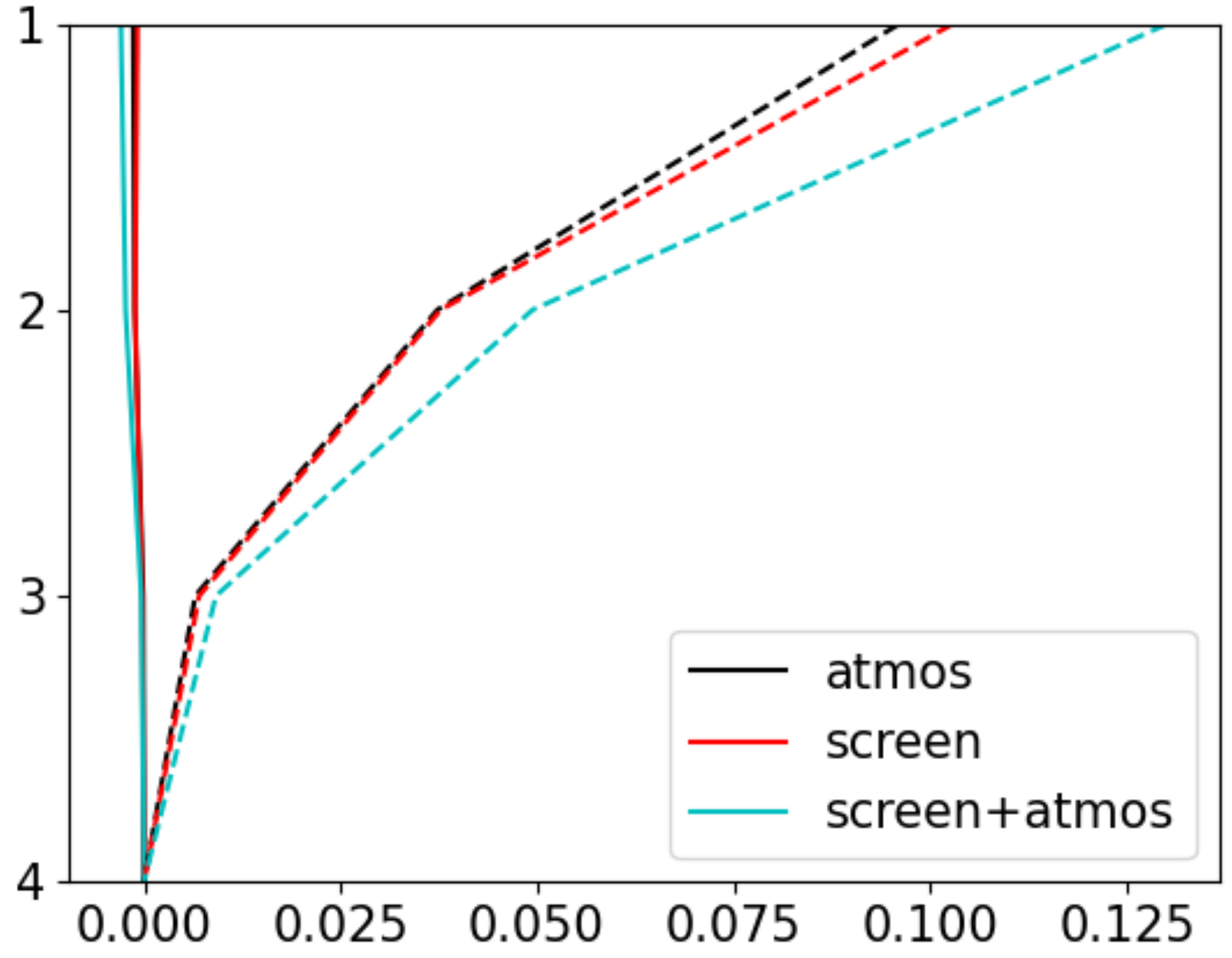


Vertical localization limits increments to 20 layers.

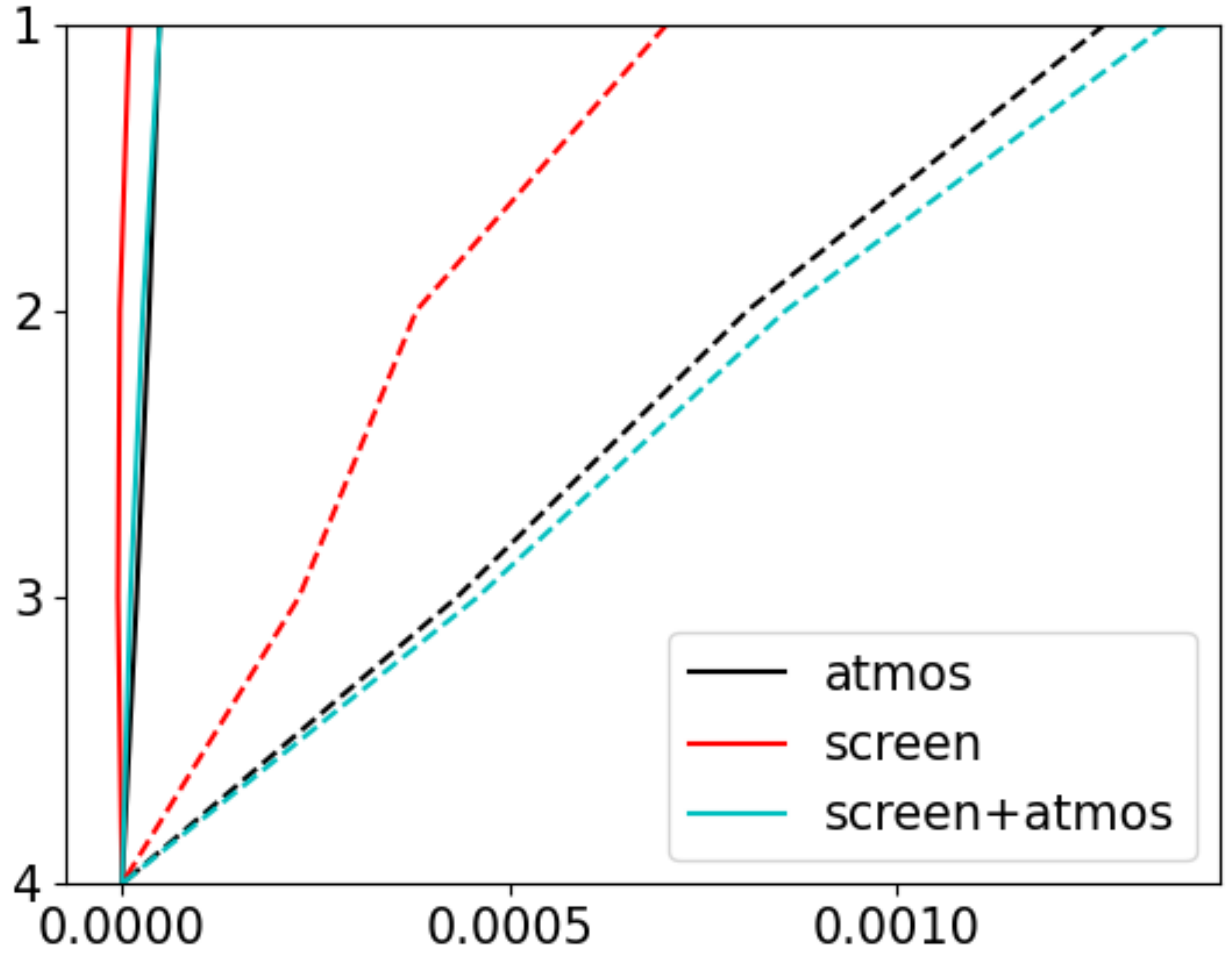
Addition of screen-level observations reinforces pre-existing increments.

Land increments - first cycle

Vertical profile of ST incr. [K]



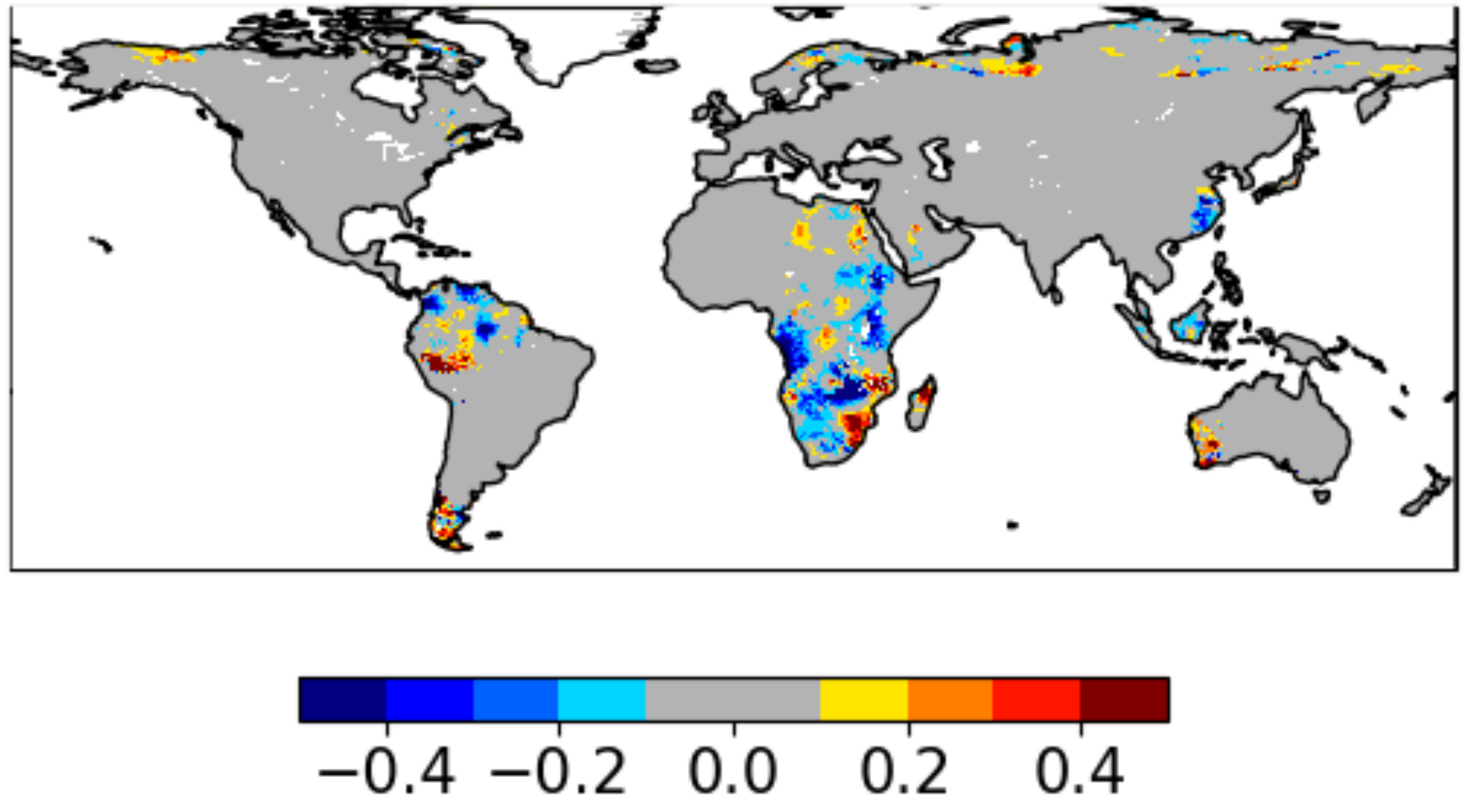
Vertical profile of SM incr. [m3/m3]



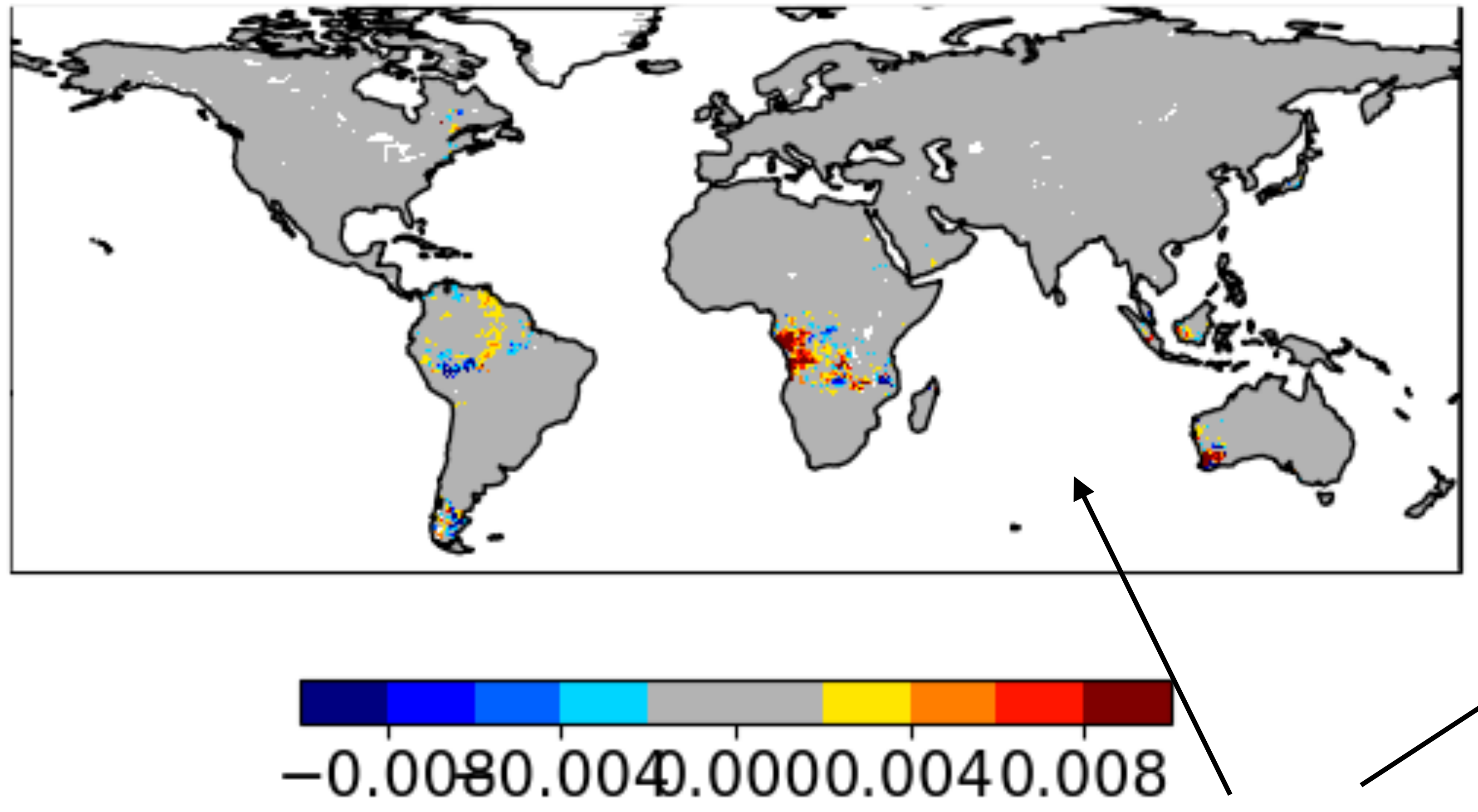
Solid - mean increment
Dashed - stdev increment

Assim. of standard atmos obs.
(SfcUpd experiment)

ST1 [K]

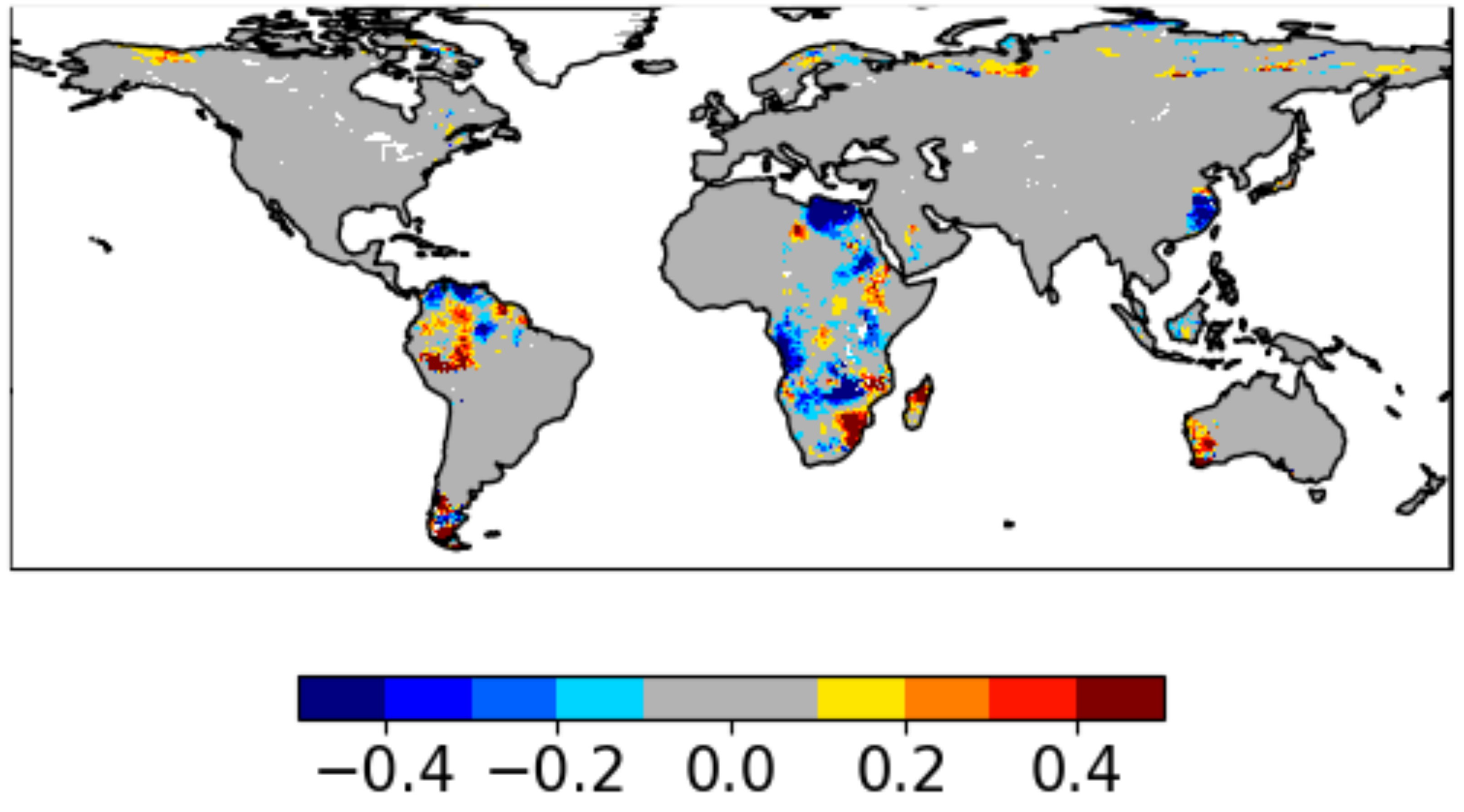


SM1 [m3/m3]

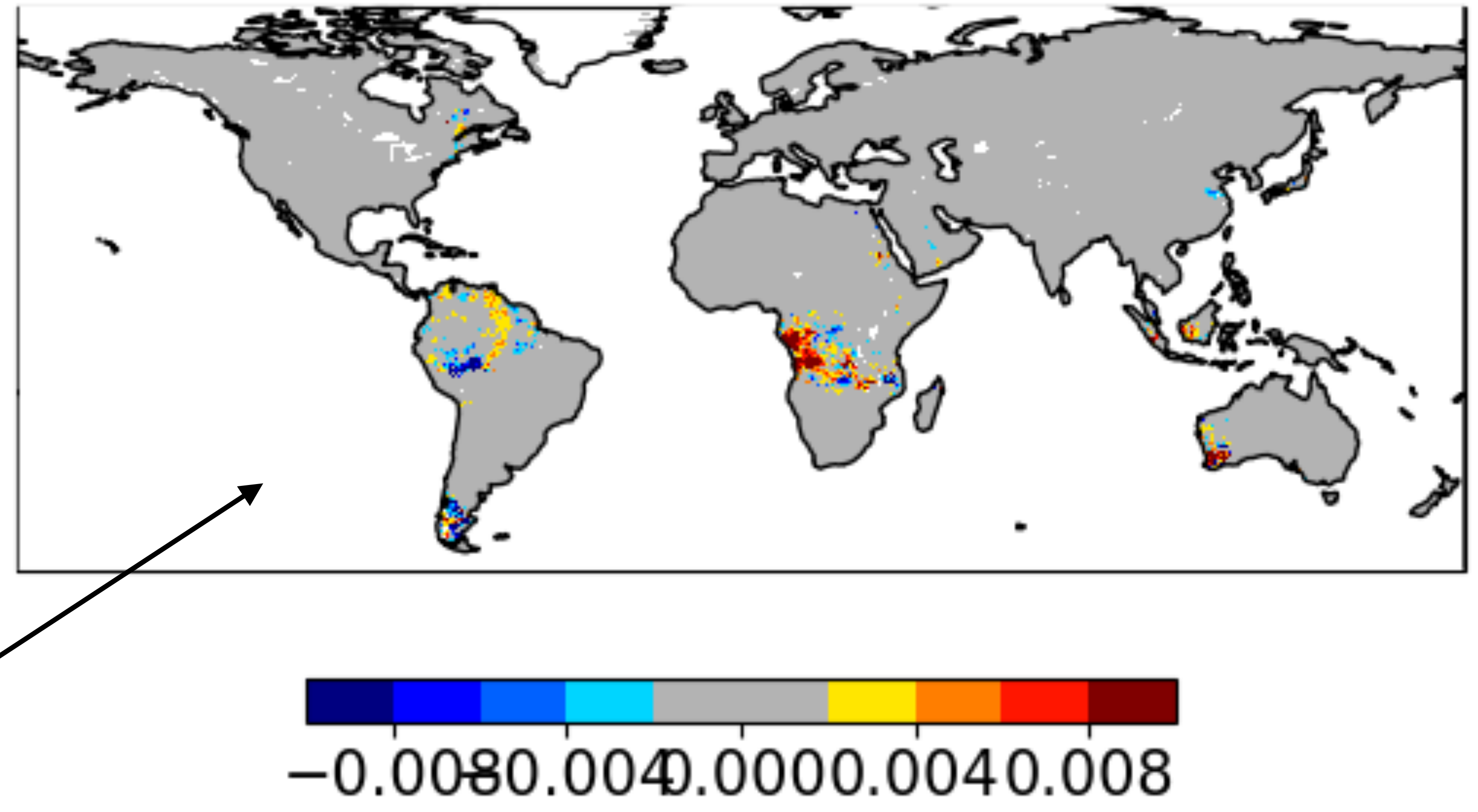


Assim. of standard atmos + screen-level obs.
(Screen+SfcUpd experiment)

ST1 [K]

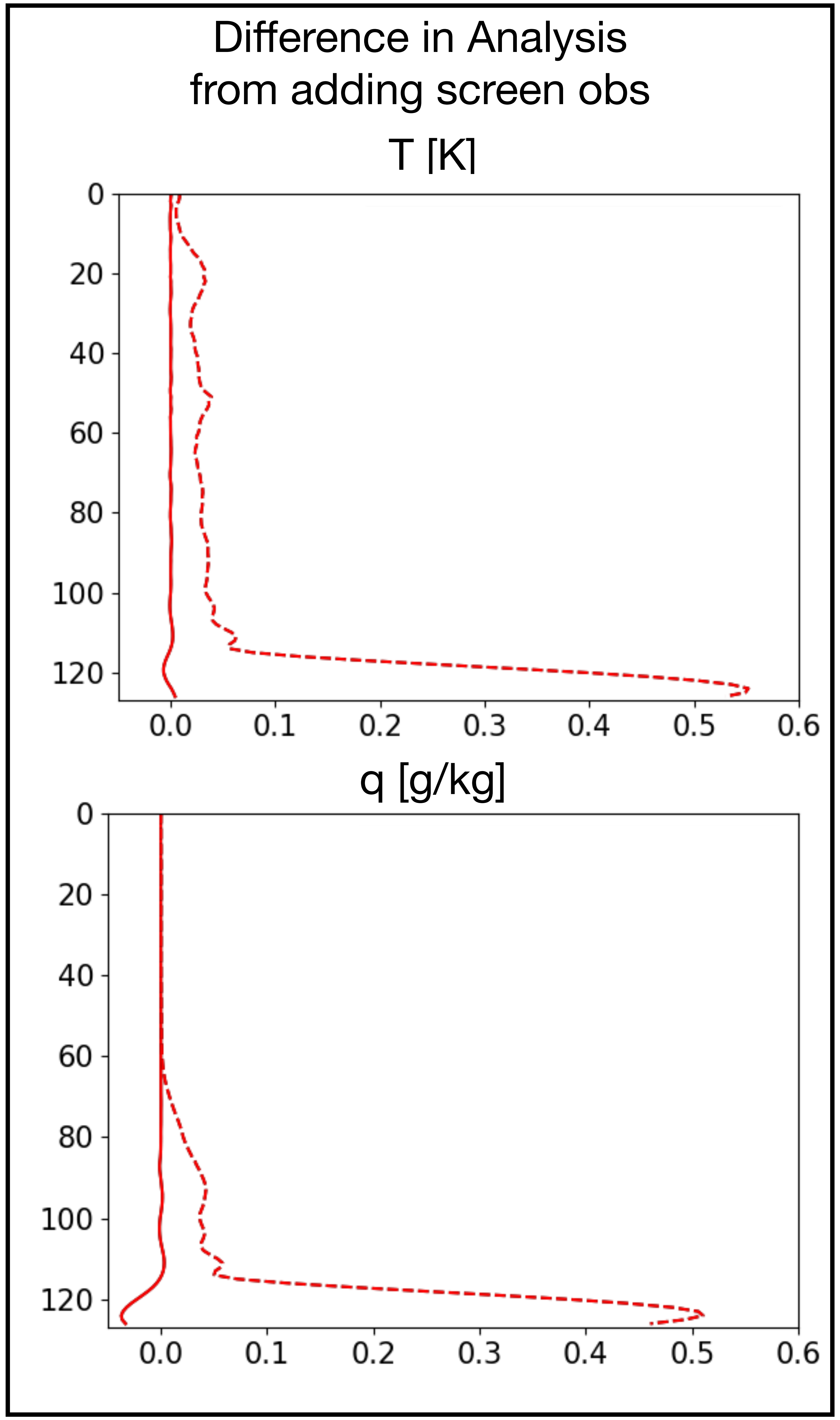


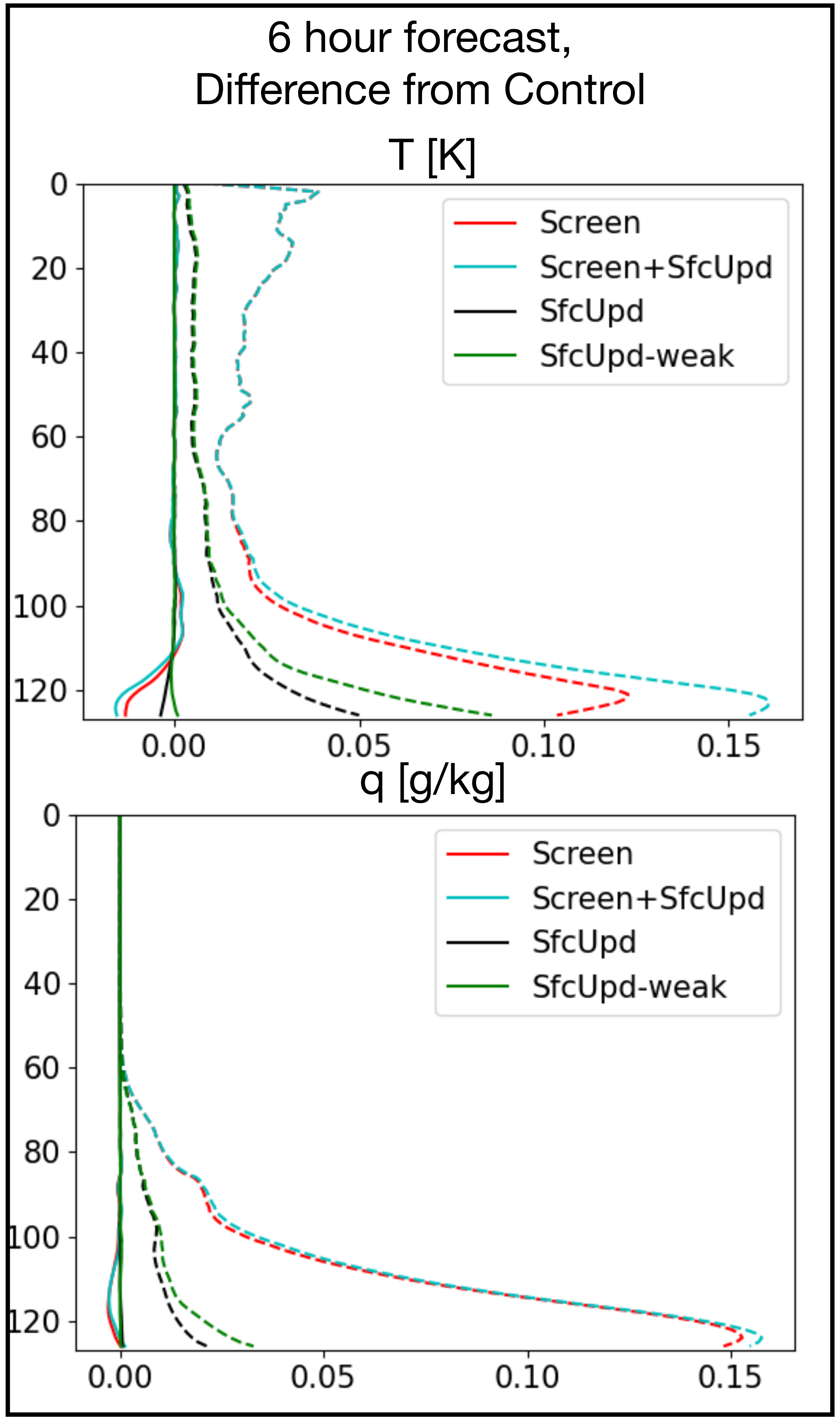
SM1 [m3/m3]



Less consistency between increments from standard and screen obs

Largest increments during the night,
Little similarity with atoms incr.





Impact retained in subsequent forecast

- Plots show difference in first forecast, from the control experiment, then in subsequent 6 hour forecast
- Impact of increments is not well retained in the subsequent forecast
  - Model error
- Adding updates to the surface states increases impact on T forecasts

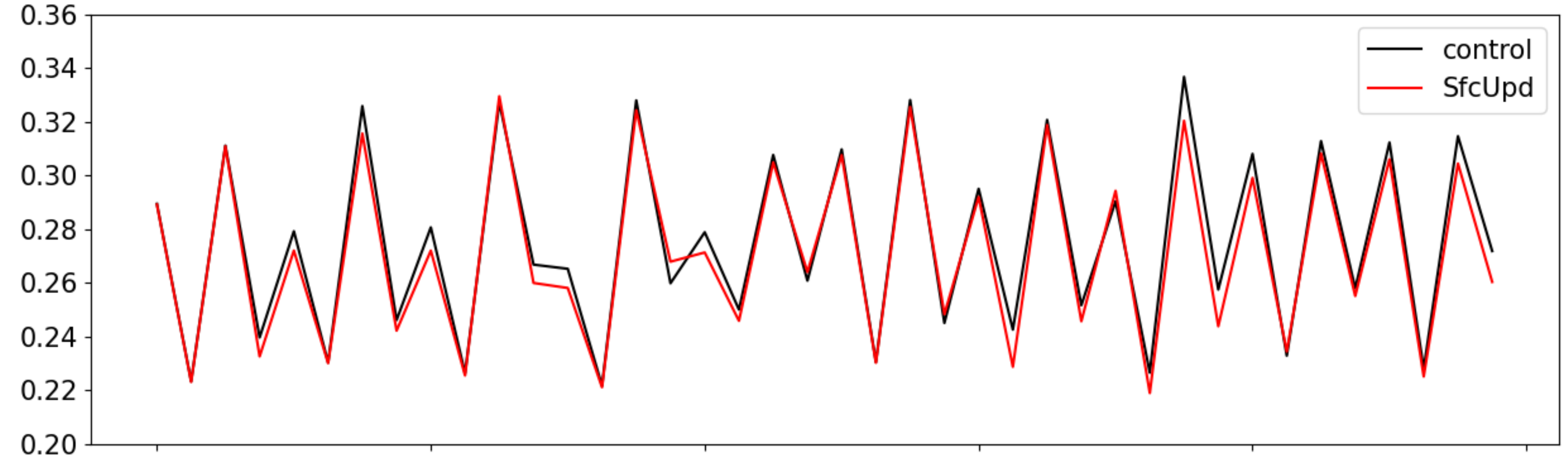
solid lines - means
dashed lines - stdevs

Atmospheric Increment Timeseries

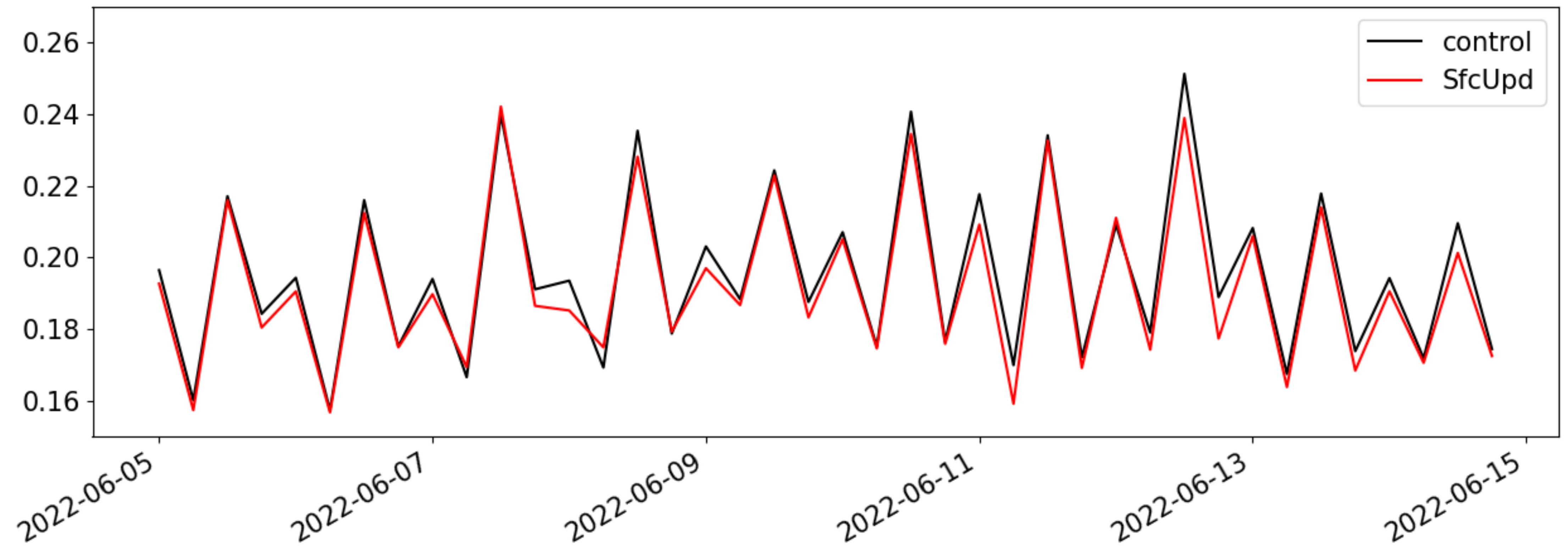
Time-series of sqrt(RMS increments in lowest 20 layers)

Experiments assimilating standard atmos. obs.

Temperature [K]

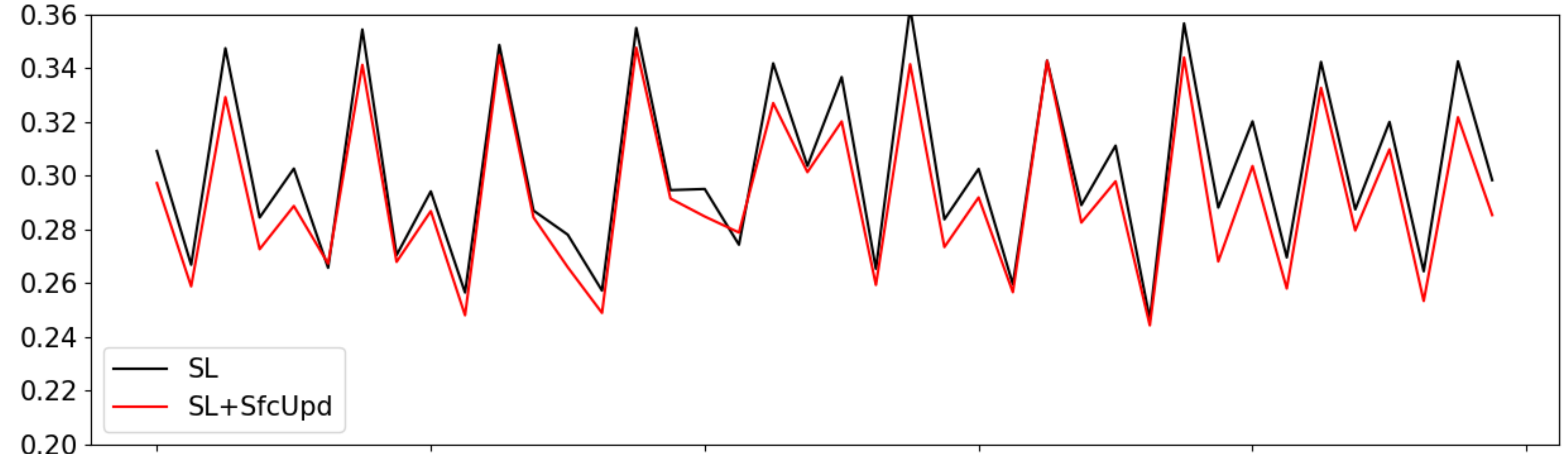


Specific humidity [g/kg]

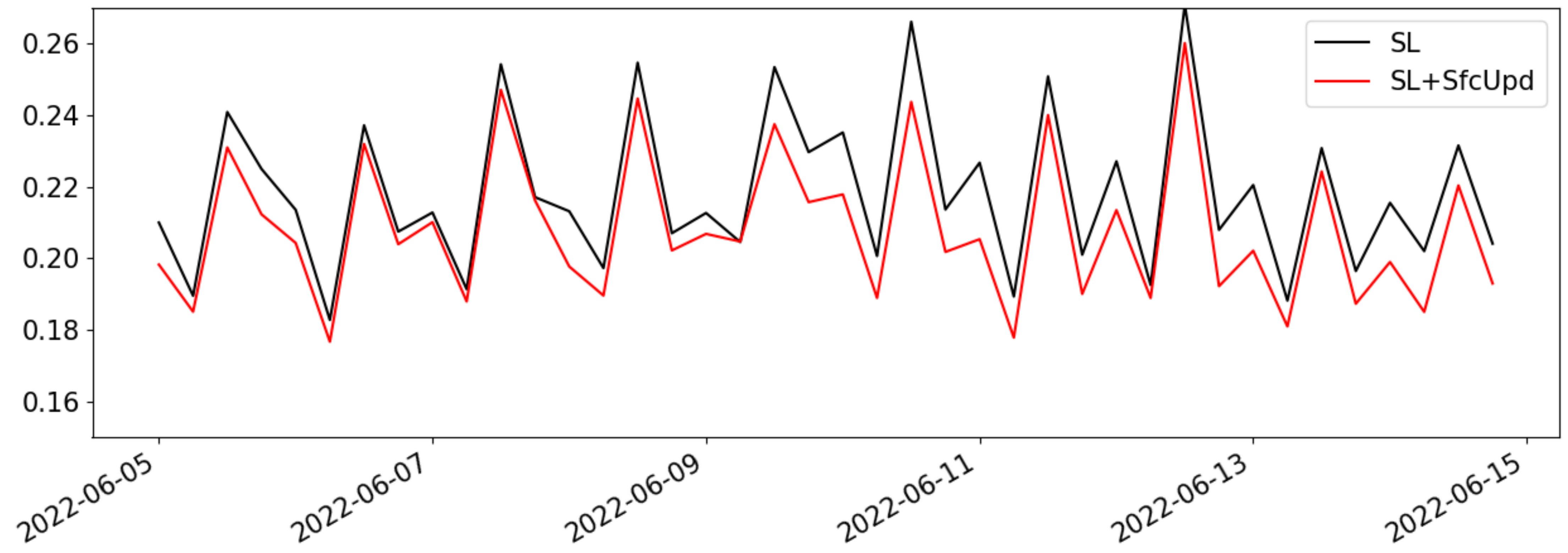


Experiments assimilating standard atmos & screen-level obs

Temperature [K]



Specific humidity [g/kg]



Atmospheric Increment Timeseries

Time-series of sqrt(RMS increments in lowest 20 layers)

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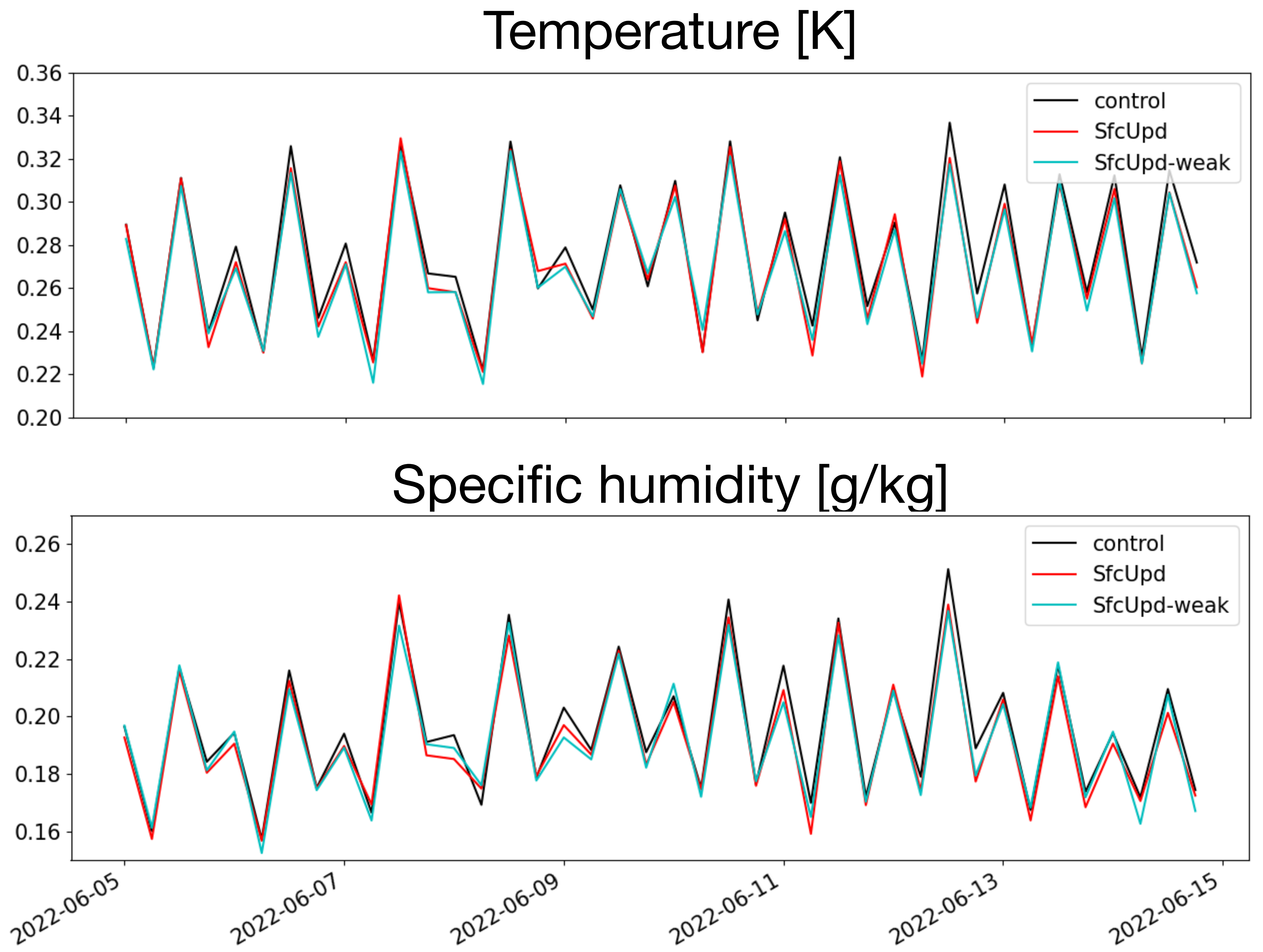
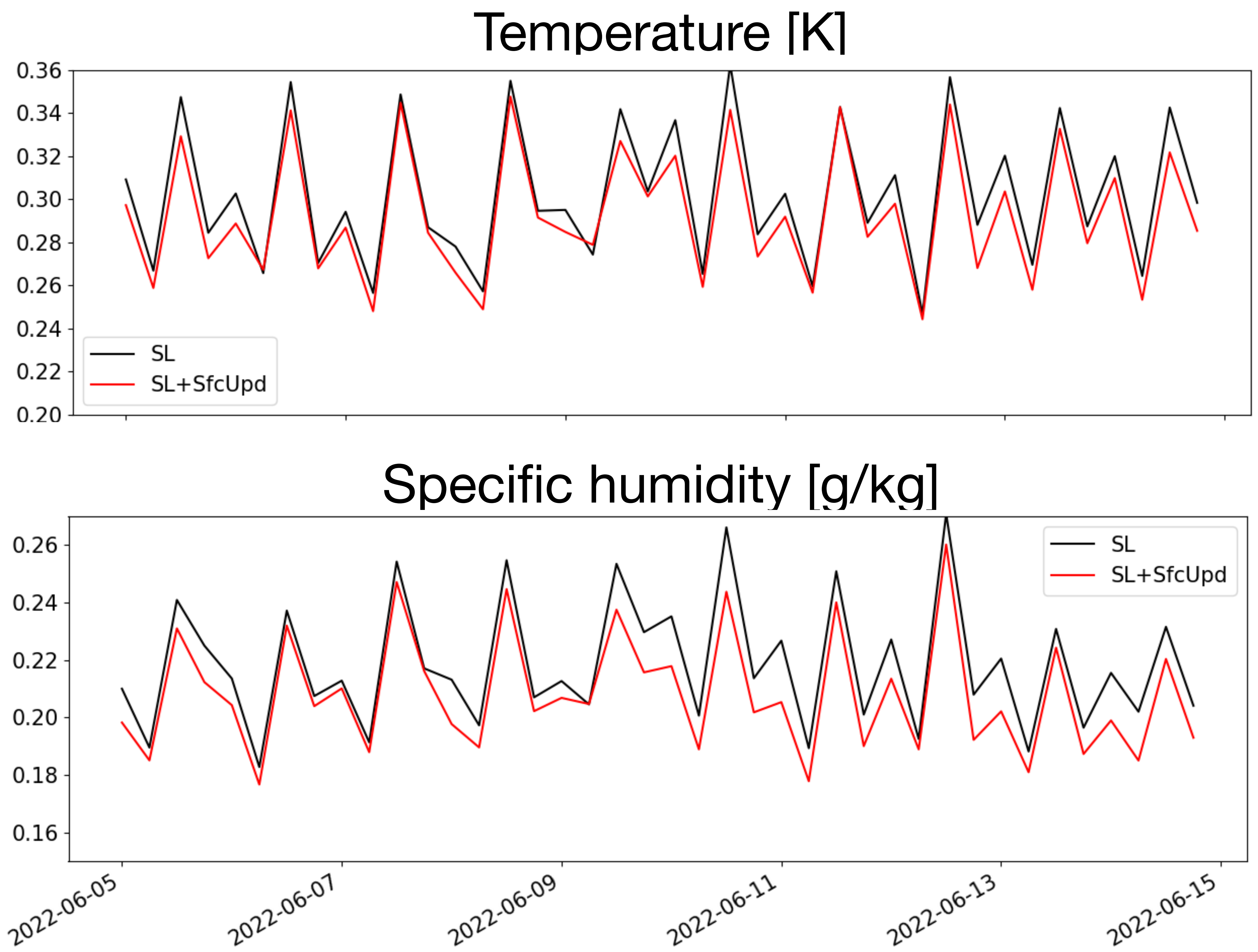
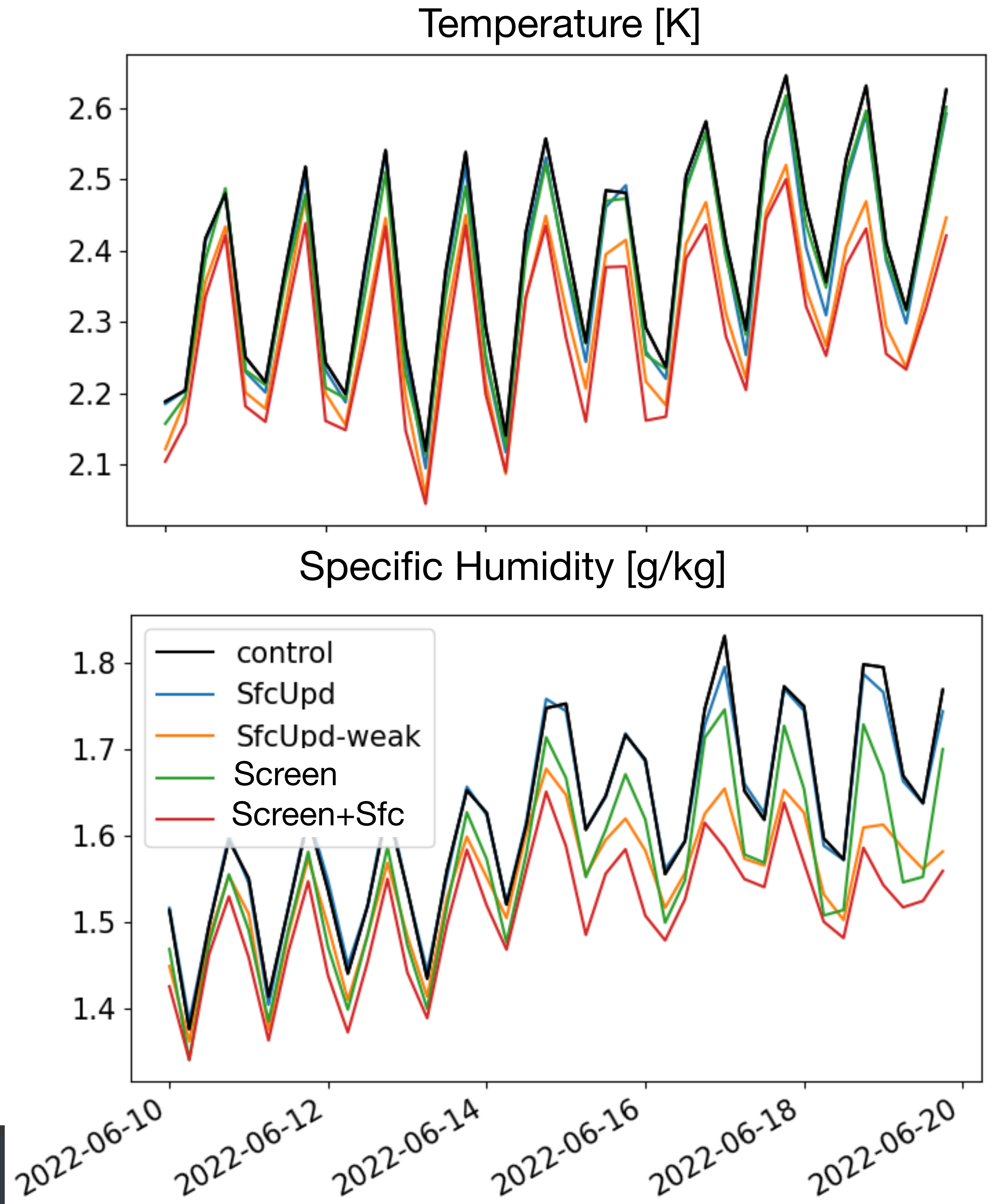


Experiments assimilating standard atmos & screen-level obs



Screen-level sqrt(RMS 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

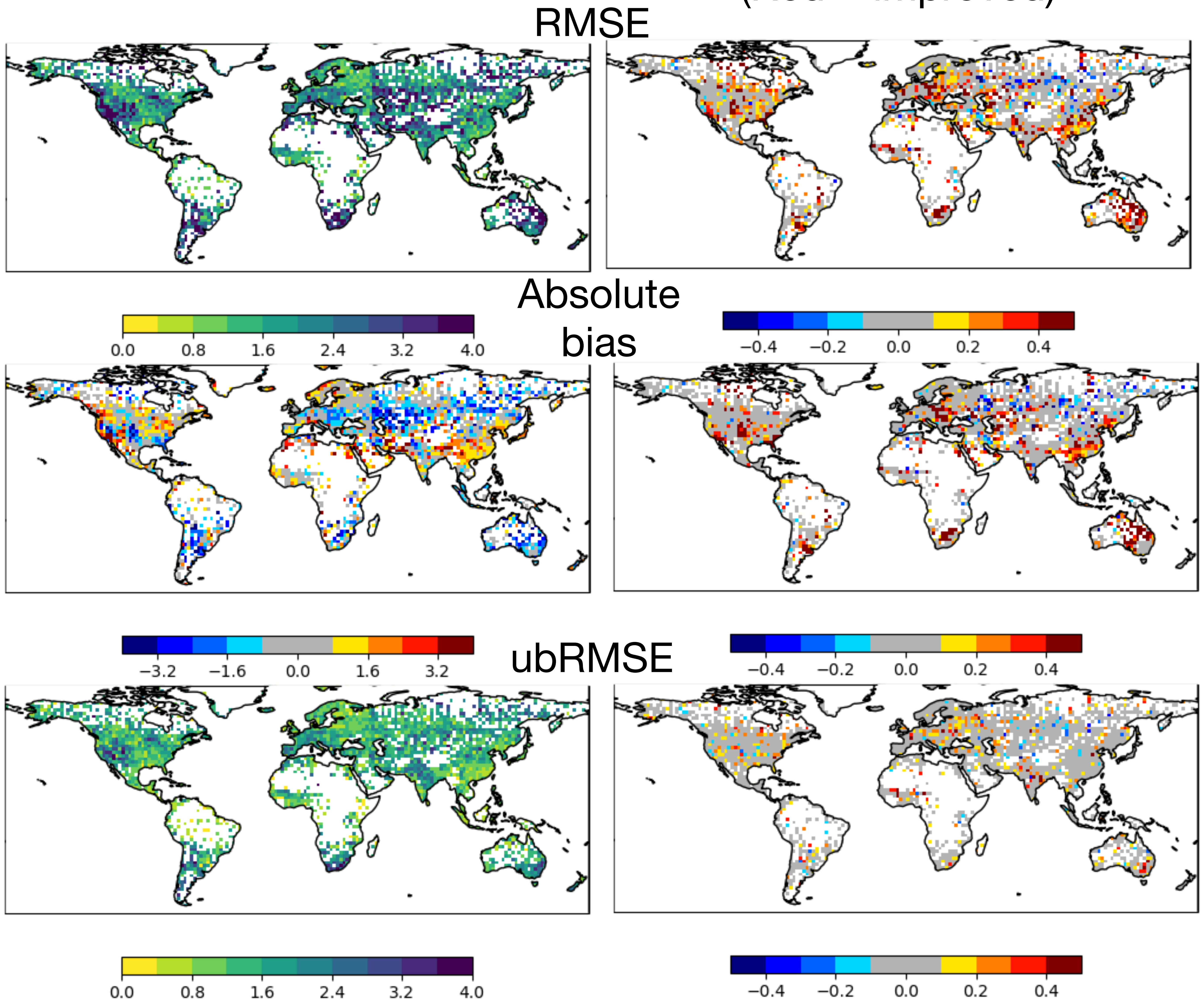
shaded = sig. difference from Control

- 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)

Diurnal Screen-Level O-F statistics Screen-SfcUpd experiment

Control T_{SL} O-F statistics [K] nighttime

Improvement from Control [K]
Significant diffs plotted only
(Red = improved)



RMSE

T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	1.75	1.64	Night	1.02	0.95
Day	2.05	1.95	Day	1.29	1.22

Bias (absolute)

T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	-0.21 (1.25)	-0.22 (1.17)	Night	0.14 (0.72)	0.17 (0.65)
Day	1.38 (1.64)	1.31 (1.54)	Day	0.24 (1.00)	0.27 (0.93)

ubRMSE

T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	1.03	0.98	Night	0.62	0.58
Day	1.02	1.00	Day	0.68	0.66

shaded = sig. difference from Control

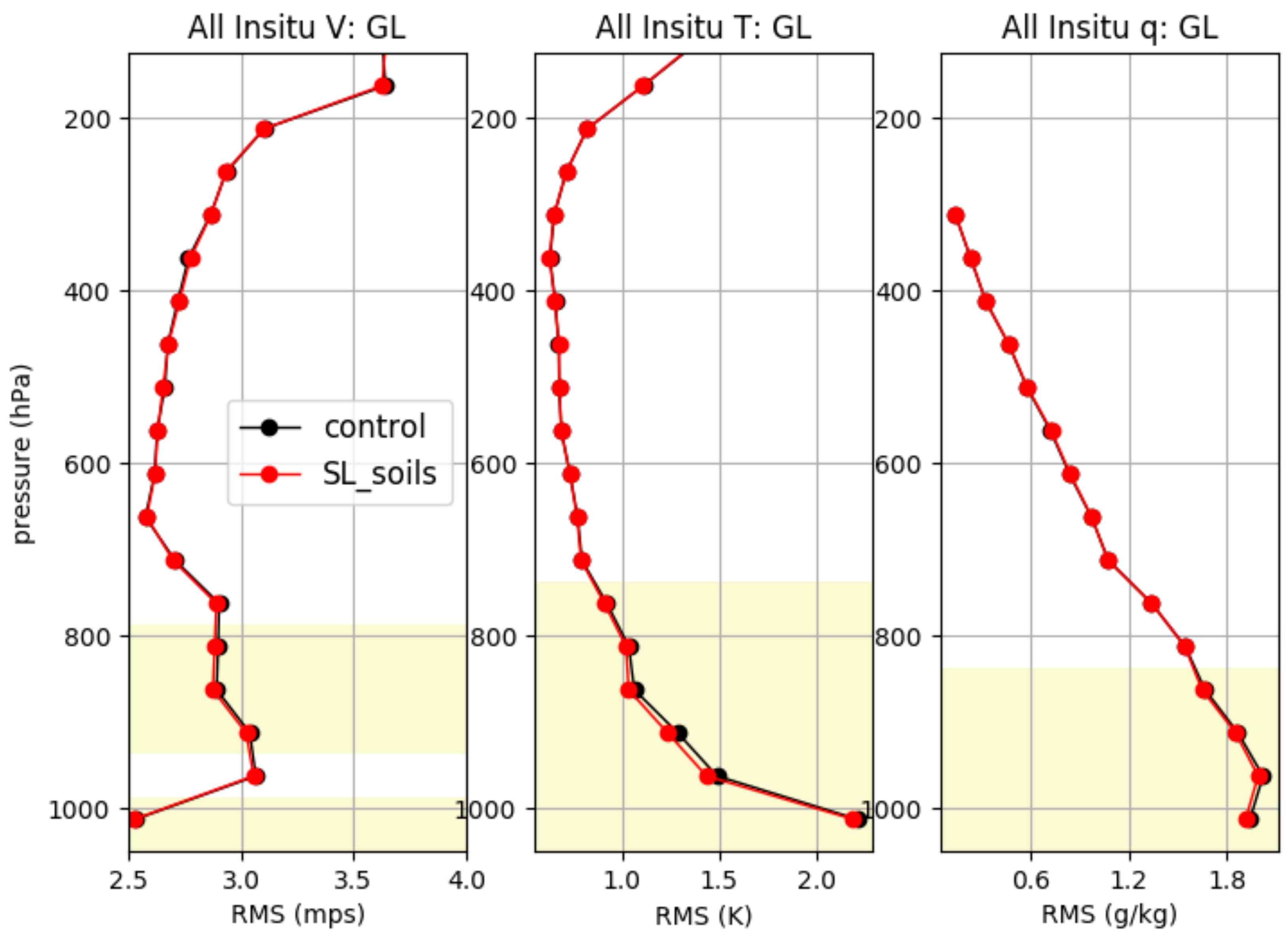
Upper air conventional sqrt(RMS O-F)

Mean RMSE at ~900 hPA

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

- Screen+SfcUpd: Small, but consistent improvement (1-3%)

Screen+SfcUpd Experiment



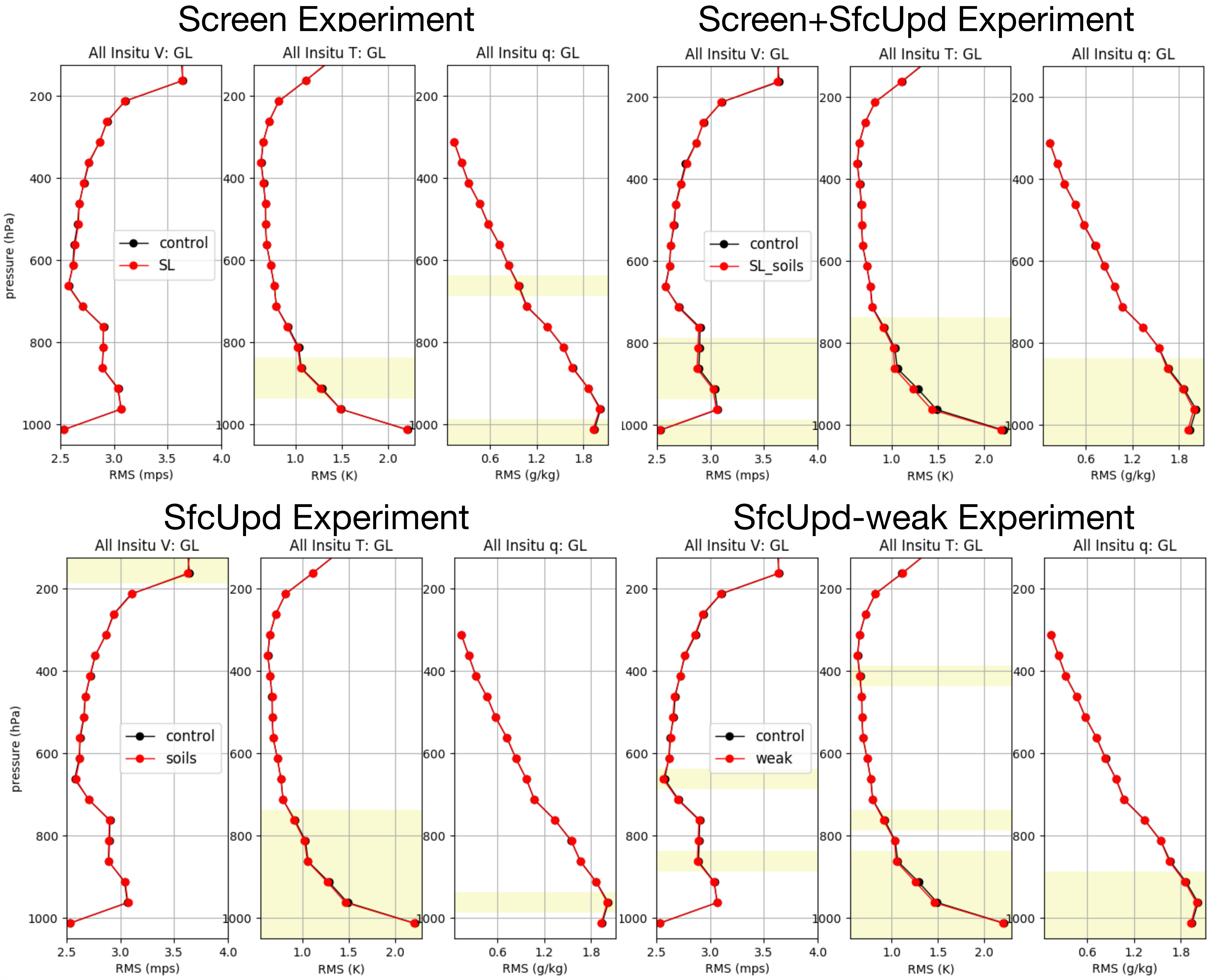
shaded = significant difference from Control

Upper air conventional sqrt(RMS O-F)

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

- Screen+SfcUpd: Small, but consistent improvement (1-3%)
- Coming from the surface update (with screen-obs)

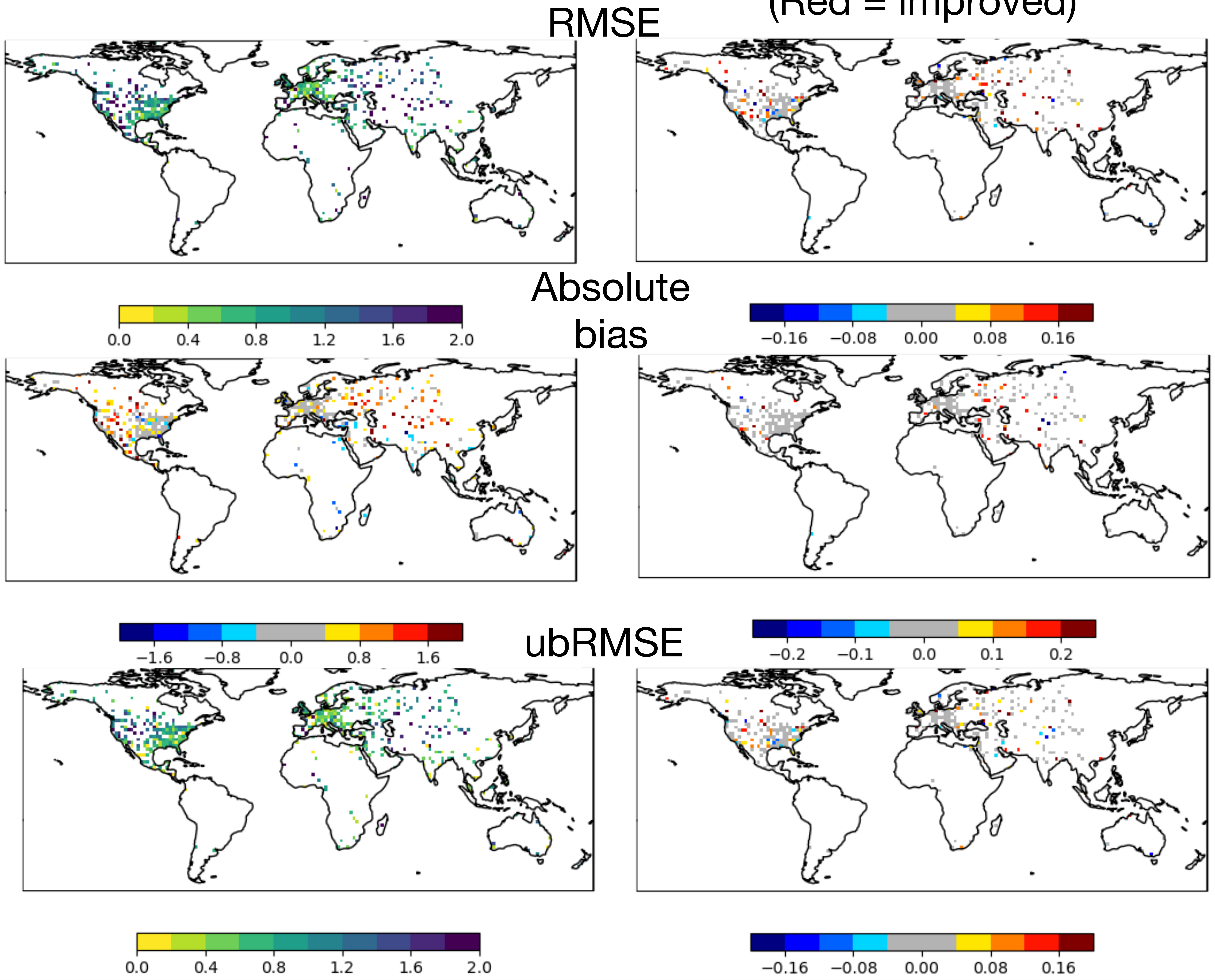


shaded = significant difference from Control

Diurnal Sonde (1100-800 hPA) O-F statistics Screen-SfcUpd experiment

Control Sonde T O-F [K] nighttime

Improvement from Control [K] Significant diffs plotted only (Red = improved)



RMSE

T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	0.97	0.94	Night	1.08	1.05
Day	1.11	1.06	Day	1.10	1.08

Bias (absolute)

T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	0.37 (0.64)	0.35 (0.61)	Night	0.09 (0.59)	0.13 (0.71)
Day	0.49 (0.79)	0.44 (0.74)	Day	0.12 (0.57)	0.16 (0.69)

ubRMSE

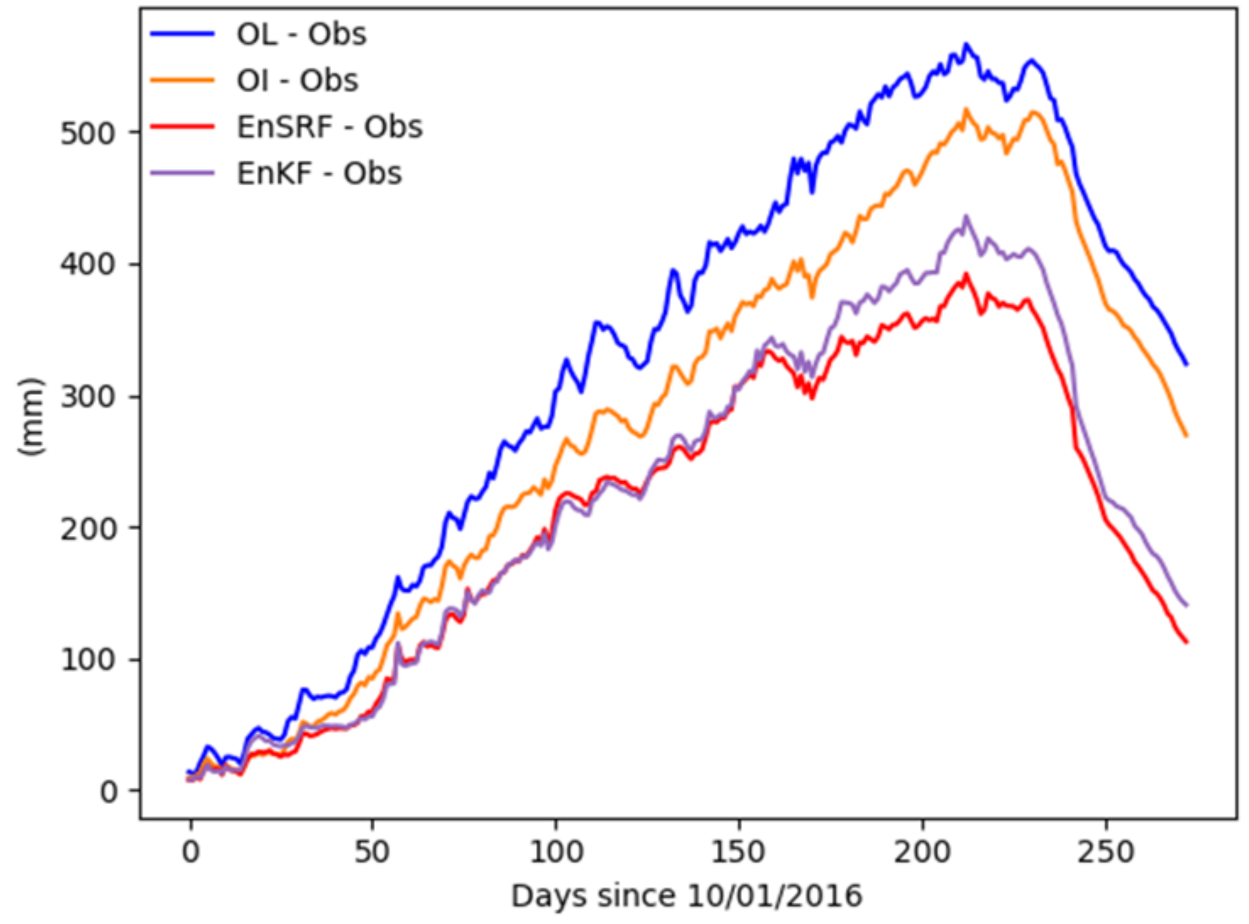
T [K]	Control	Screen-SfcUpd	q [g/kg]	Control	Screen-SfcUpd
Night	0.59	0.58	Night	0.78	0.76
Day	0.62	0.61	Day	0.71	0.70

shaded = sig. difference from Control

EnKF snow depth assimilation

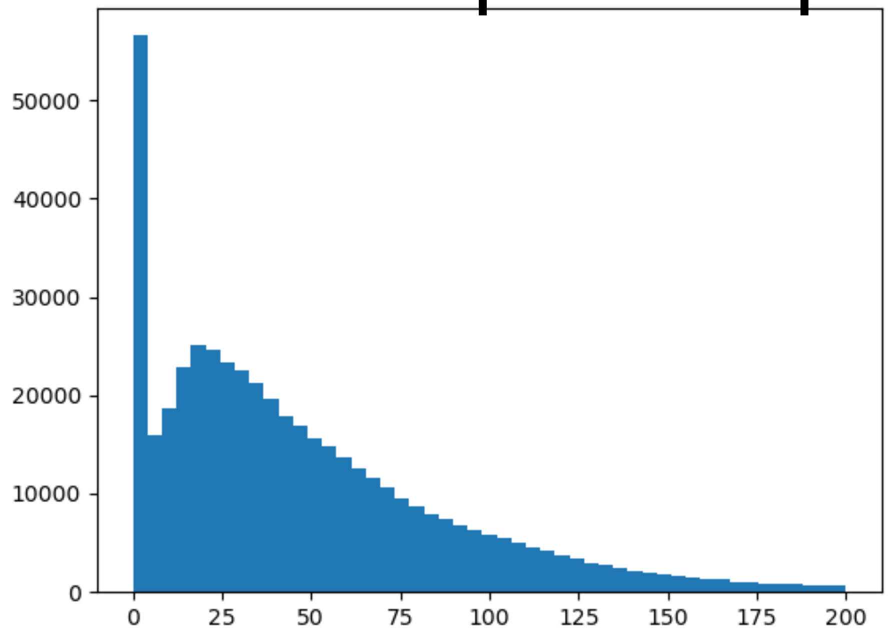
- NOAA is replacing our current snow depth assimilation with an OI-based scheme
- Offline (land-only) experiments show can get better performance, in terms of snow depth O-F, from EnKF than OI
- Also working towards unifying the snow depth DA with the atmos DA
  - Obtaining sufficient spread in the NWP ensemble may be difficult

Snow depth sqrt(RMS O-F) [mm] from different DA methods

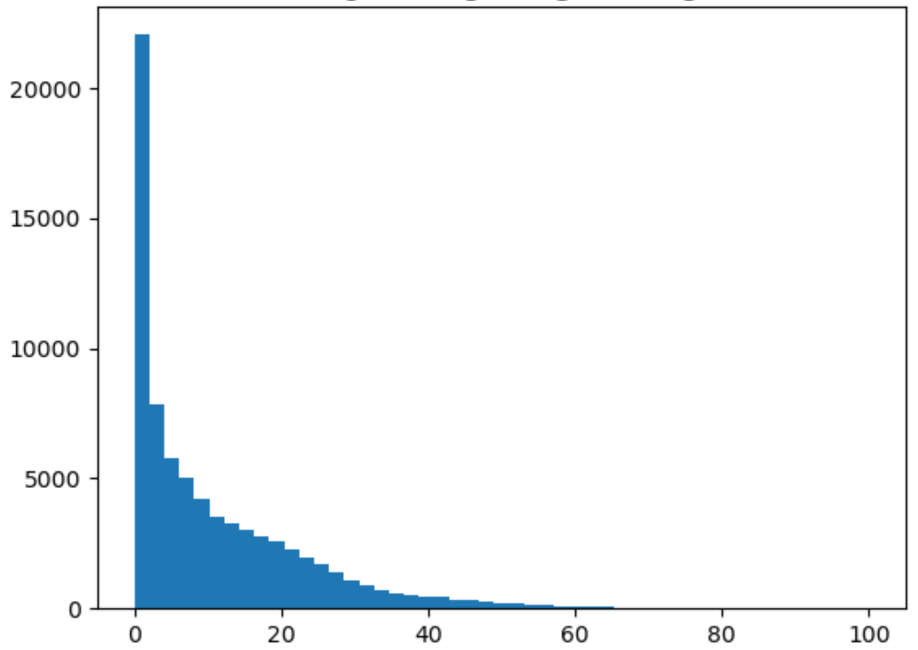


Ensemble stdev snow depth [mm]

Offline open-loop



GFS OPS



With Tseganeh Gichamo

Conclusions (1/2)

- Now that atmospheric DA uses ensemble-based methods, there is opportunity to better unify land and atmospheric DA to enhance sharing of information between the two components

- Tested different coupling options for assimilating screen-level obs and updating soil states (moisture, temperature)
  - Clear benefit to assimilating the screen-level obs, with more benefit from assimilation into land than atmosphere
  - Also benefit to updating the land states (even without the screen-level obs)
  - Greatest benefit from assimilating screen-level obs into both atmos and land using a single coupled update (reminder: not really assimilating land obs here; screen-level obs are interface obs)
    - Using this approach to develop the new soils analysis at NOAA
    - Weakly coupled experiment (assimilate screen-level observations into surface only) nearly as good

- Next steps:
  - Check DA benefit holds with latest model version (reduced diurnal T bias)
  - Add land perturbation scheme GSI Hybrid 4D-EnVar
  - …

Conclusions (2/2)

- …
  - Test using full 4D-EnVar, rather than pure EnKF, for atmospheric update (and ultimately, the soil update too)
    - Hybrid may be more appropriate to land model problem: allows a climatological aspect to B; possibility to compensate for under-dispersed ensembles
    - Hybrid methods starting to be used up by the land DA community (e.g., Tristan Quaife's group at Uni. Reading)
  - Longer term: Test use the coupled DA (or other data-based methods) to update model parameters: land model biases are more problematic for NWP than (random) initial condition errors

- Out-standing questions:
  - Do these results hold if assimilating true land obs (satellite soil moisture, snow depth, etc)?
  - Here, control experiment has no soil update. How would this approach (using the "atmospheric" EnKF) compare to one of the established land DA methods?
    - Recall: the land is very different to the atmosphere; compromises/assumptions made during DA also differ

Thanks for Listening

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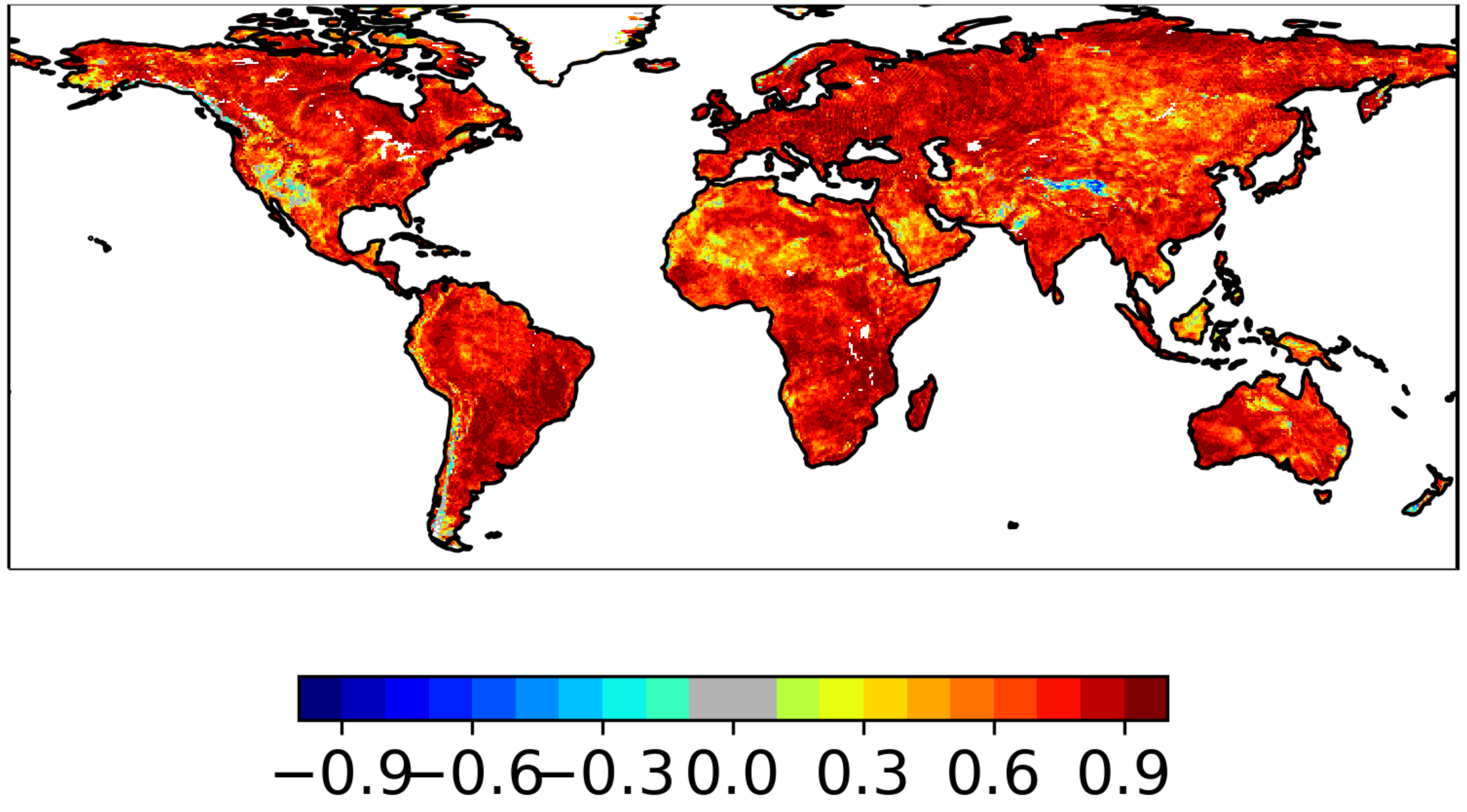
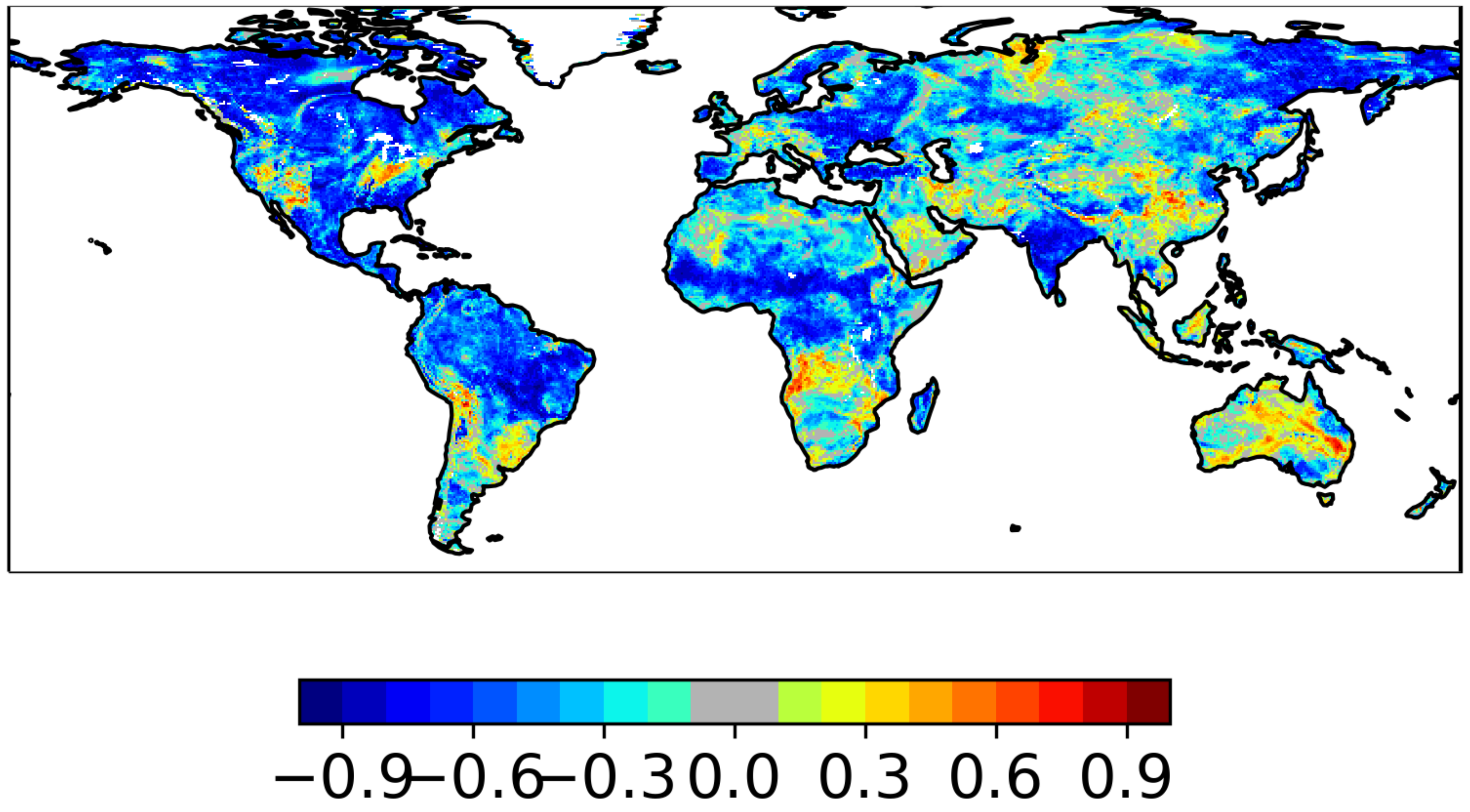
Vertical correlations for updating soil states

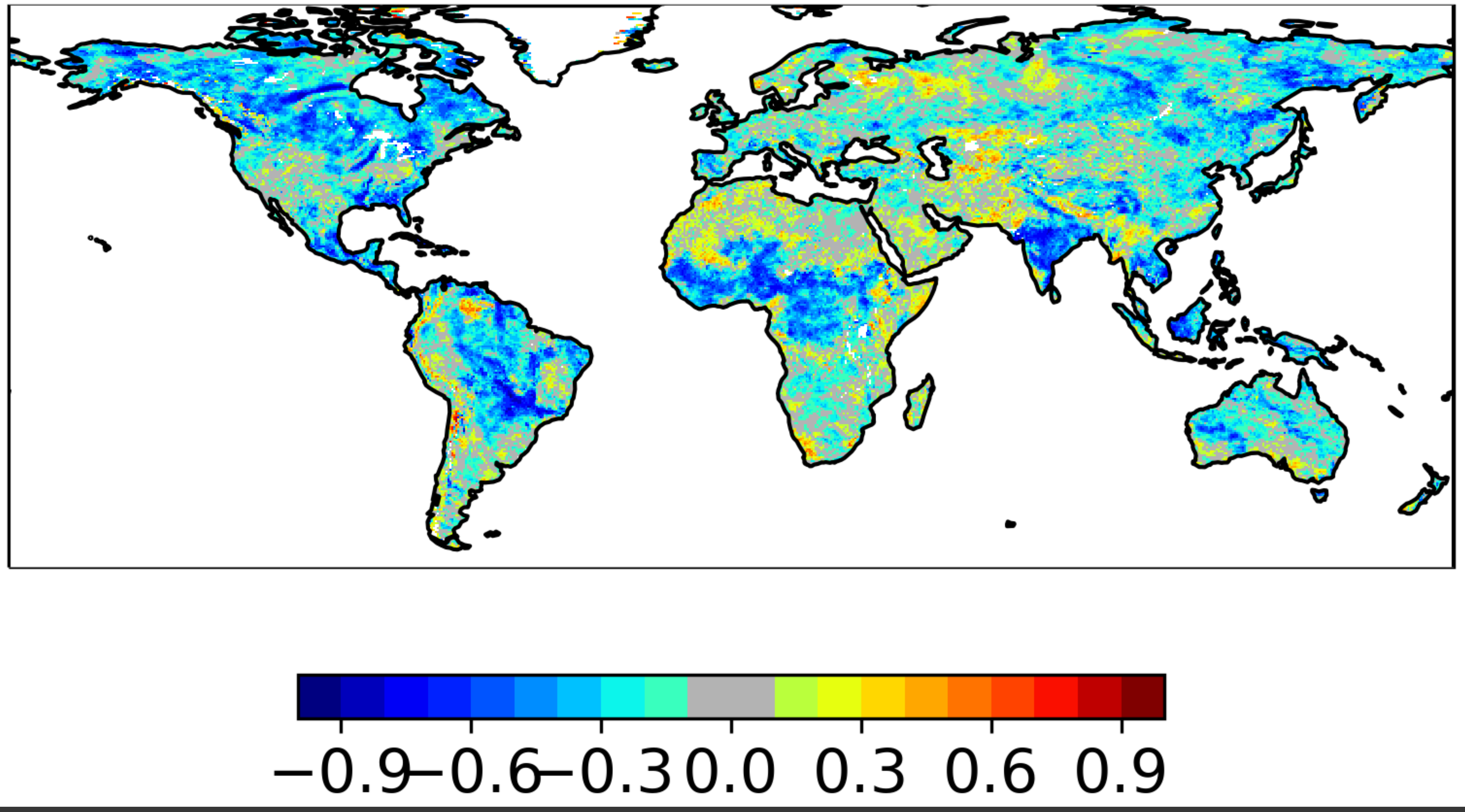
Ensemble correlation (T_{SL}, ST1)



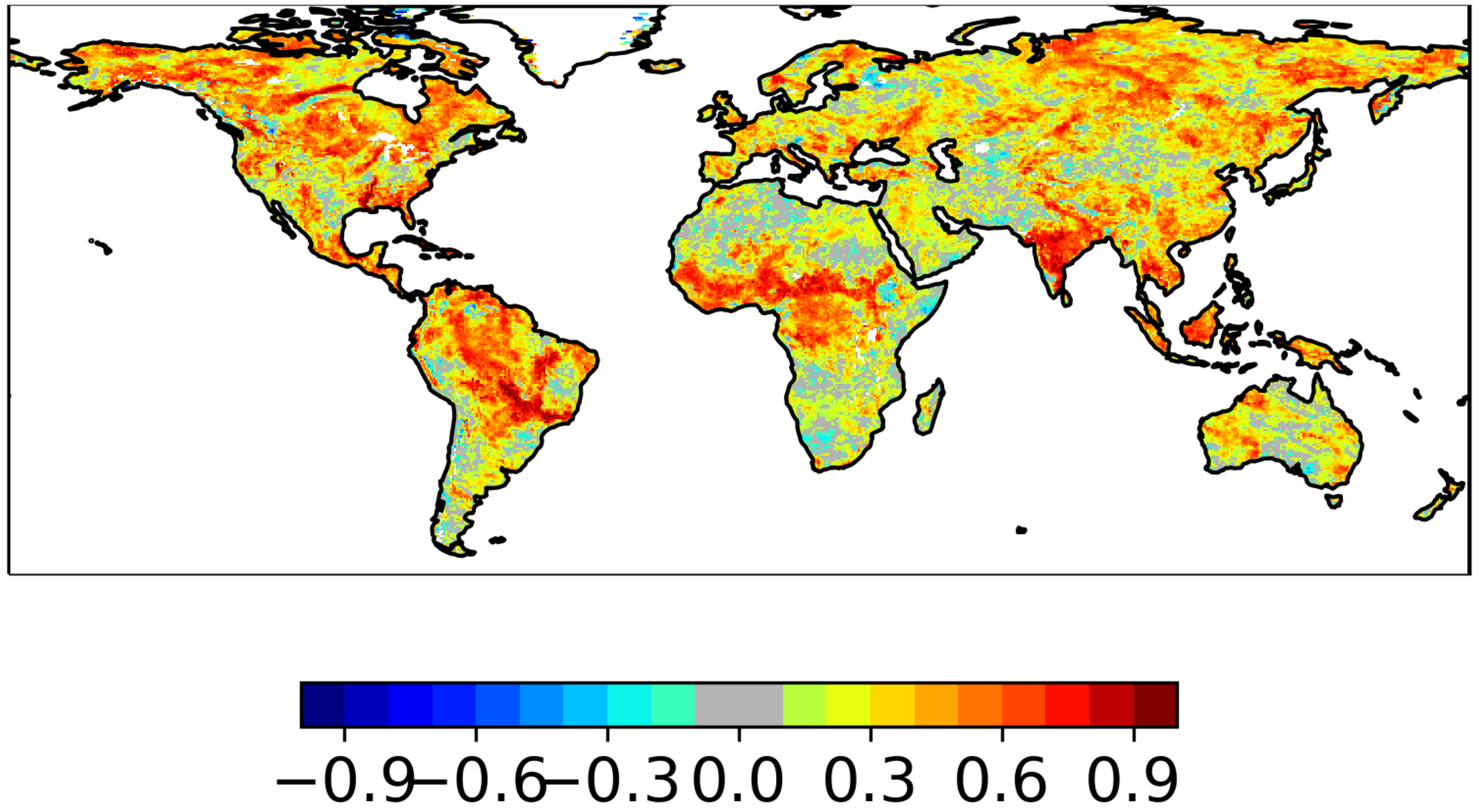
Ensemble correlation (RH_{SL}, ST1)



Ensemble correlation (T_{SL}, SM1)

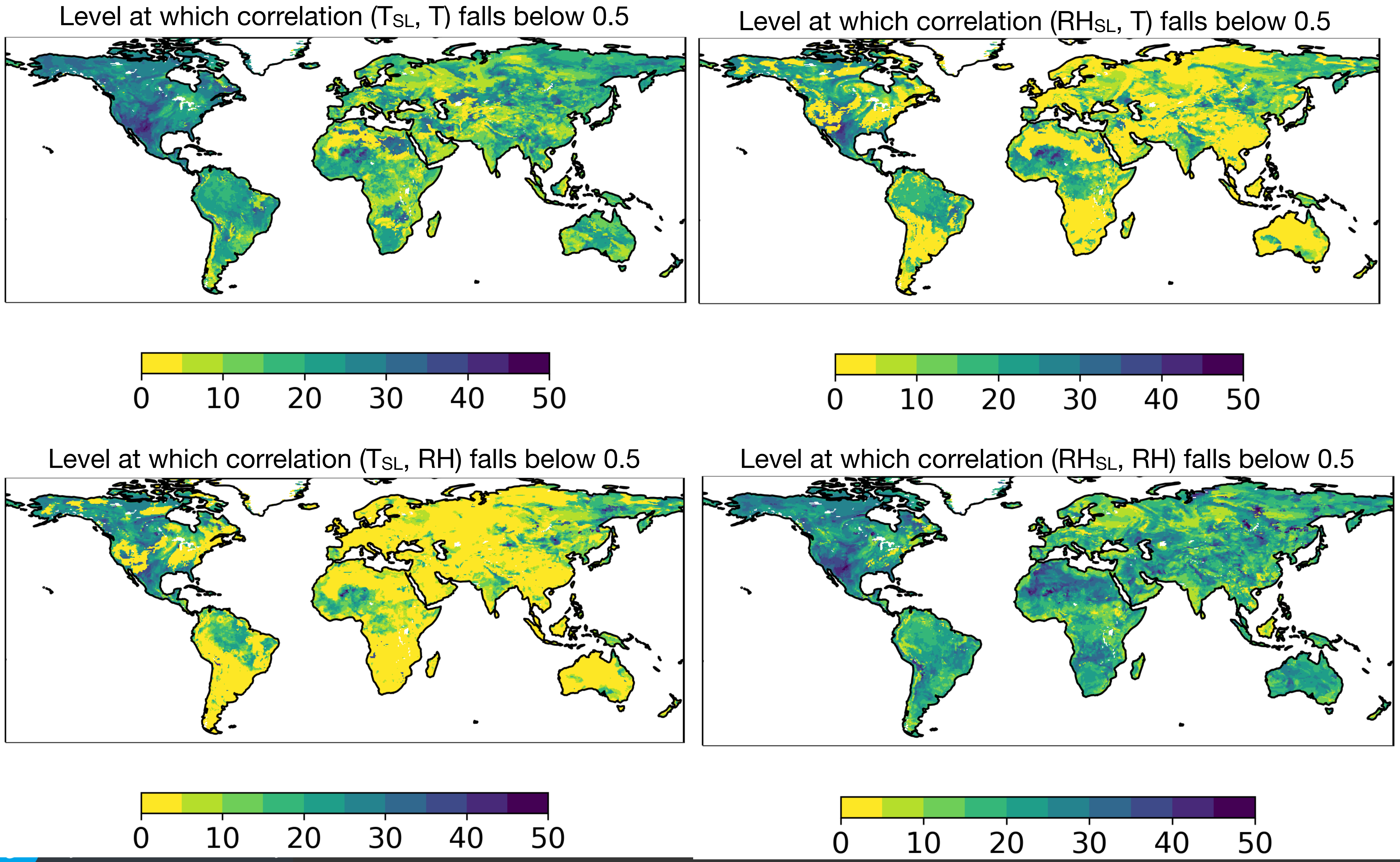


Ensemble correlation (RH_{SL}, SM1)



- Soil temperature: strong correlation with T_{SL}, often with RH_{SL}
- Soil moisture: correlations strong in some regions; smaller / noisy in other regions
- Note: GSI humidity observations and control state are RH (q correlations near surface much less homogenous)

Vertical correlations for updating atmospheric states



- Correlations between screen-level at lowest model level generally high and homogenous
- Plots shows model level at each magnitude reduces below 0.5
- Strongest vertical profile is during night

Accounting for land model error in NWP ensembles

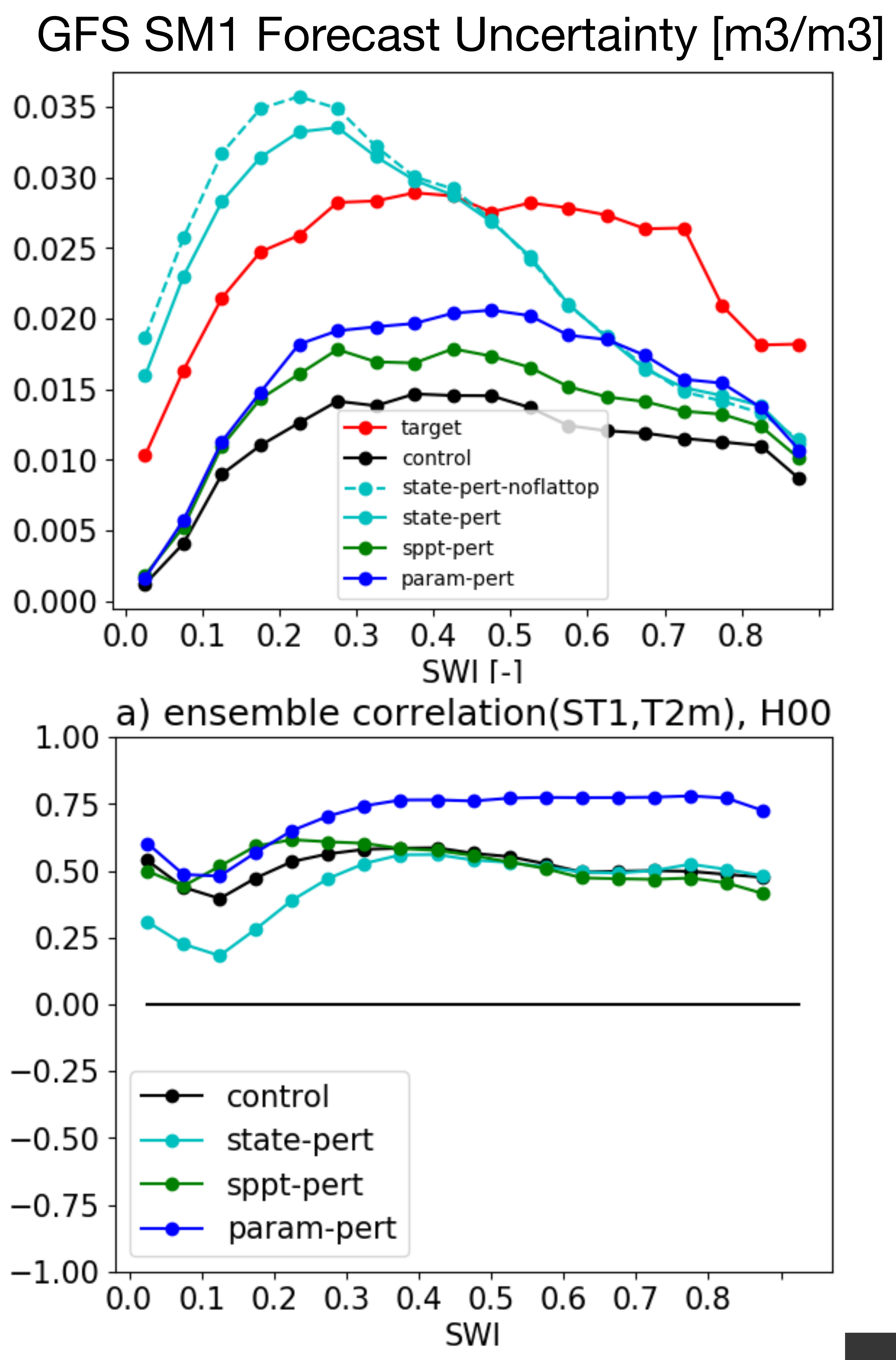
- No information gained on model error growth / instability by adding perturbations to the soil moisture states
  - Resulting ensemble spread function of state perturbations added and local model persistence

- SPPT not well suited to soil moisture

- In a coupled data assimilation system applying perturbations to one component only will gives ensembles with higher cross-component covariances where that component is driving the coupling, and lower covariances where the other component is driving the coupling

- Recommended method to account for land model error in NWP ensembles is to perturb key parameters controlling the land/atmosphere fluxes (in these experiments, vegetation fraction)
  - Generates reasonable spatial patterns in ensemble spread
  - Generates ensemble cross-covariances more representative of errors in land/atmosphere coupled model

- Caveat: Land is highly non-linear; difficult to obtain sufficient spread to represent forecast uncertainty without inducing large changes in ensemble mean (impractical)



Adding Land Model Uncertainty

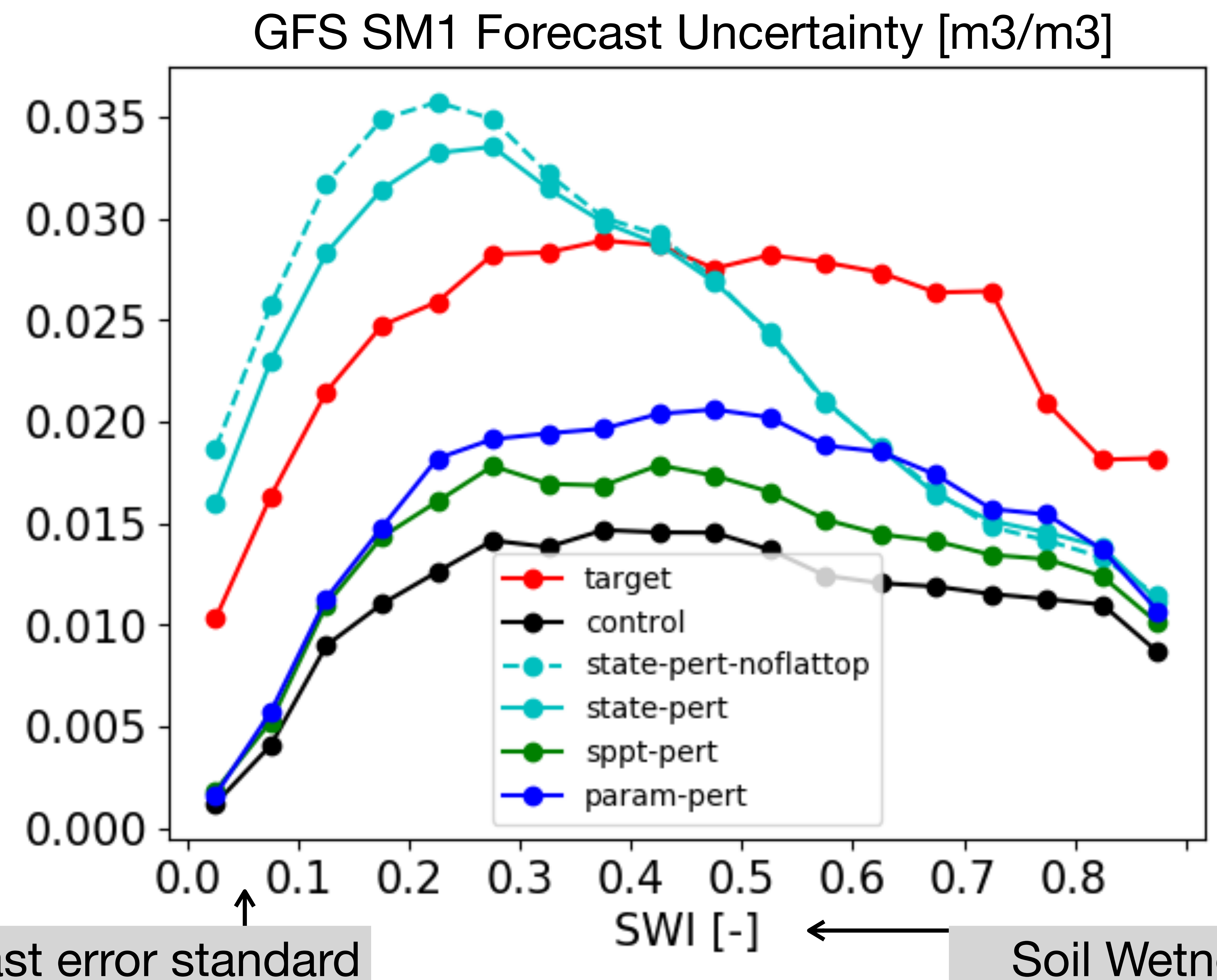
- Test methods drawn from atmospheric and land ensemble DA communities:
  - State-pert: Stochastically perturb the soil moisture content (SMC) and soil temperature content (STC) *at each time step*
    (standard approach used in land-only ensemble data assimilation systems)

  - SPPT-pert: Apply stochastically perturbed physics tendencies (SPPT) scheme to SMC and STC
    Motivation: use model physics to provide relationship between SM and ST deltas

  - Param-Pert: Stochastically perturb key model parameters controlling the land /atmosphere fluxes (here: vegetation fraction)
    Motivation: physically consistent perturbations in the land and atmosphere

- Tested each in a suite of data assimilation experiments:
  - 30 member ensemble at ~0.5 degrees (C192), run 30 days from July 10, 2019
  - Atmospheric data assimilation is cycled every 6 hours, using hybrid 3DEnVar DA
  - Assimilating the standard atmospheric obs, using standard atmospheric stochastic physics

Ens. Spread in Soil Moisture Layer 1 (SMC1)



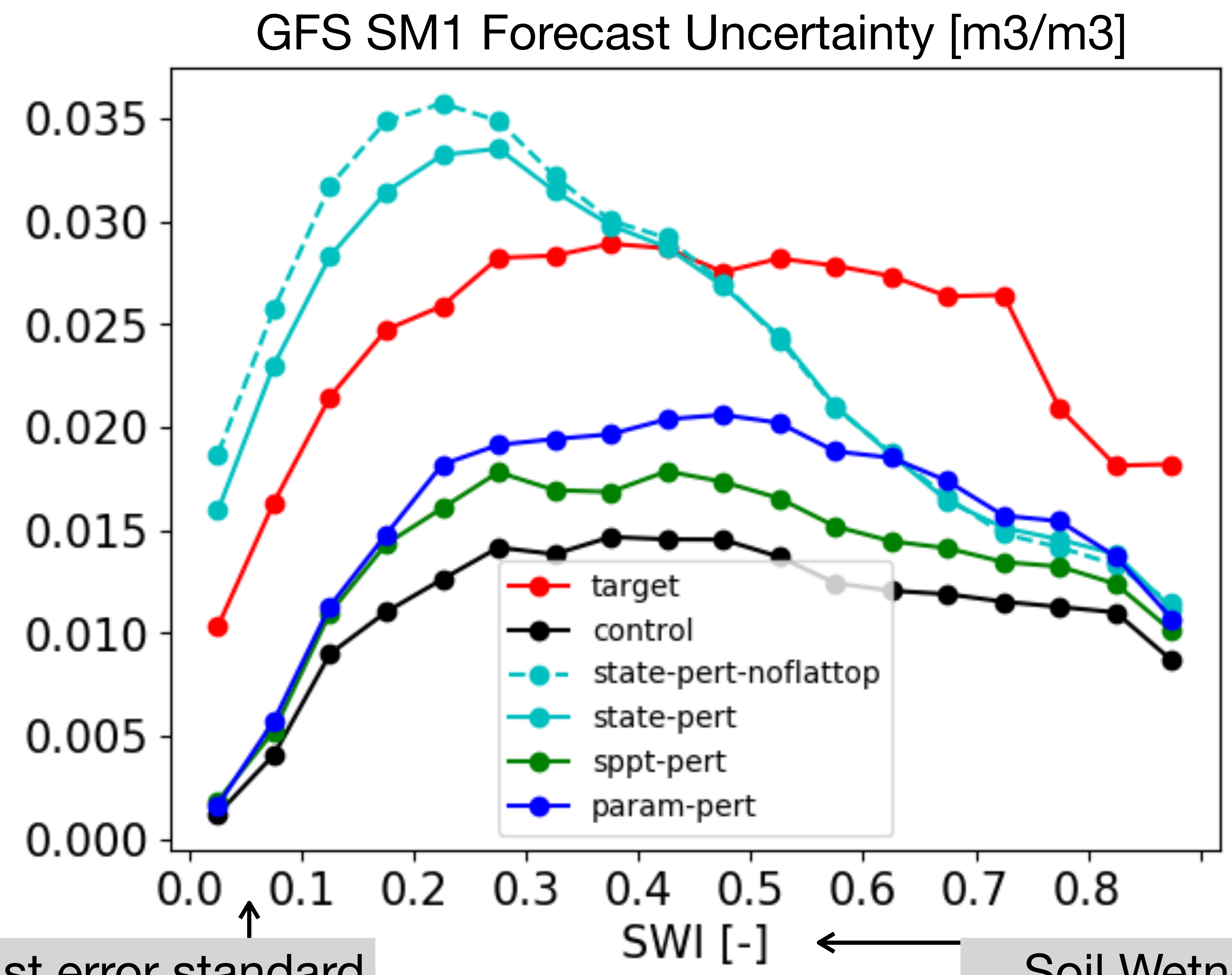
Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from each experiment.

Soil Wetness Index = Soil moisture, scaled between dry (0) and wet (1) limits.

Ens. Spread in Soil Moisture Layer 1 (SMC1)

- State-pert induces too much spread in dry regions. Due to soil moisture memory being longer in dry conditions.

- SPPT-pert can induce only a small amount of spread. Inherent limitation of the method.



- Param-pert looks reasonable. Spread could be inflated by perturbing additional variables.

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

Soil Wetness Index = Soil moisture, scaled between dry (0) and wet (1) limits.

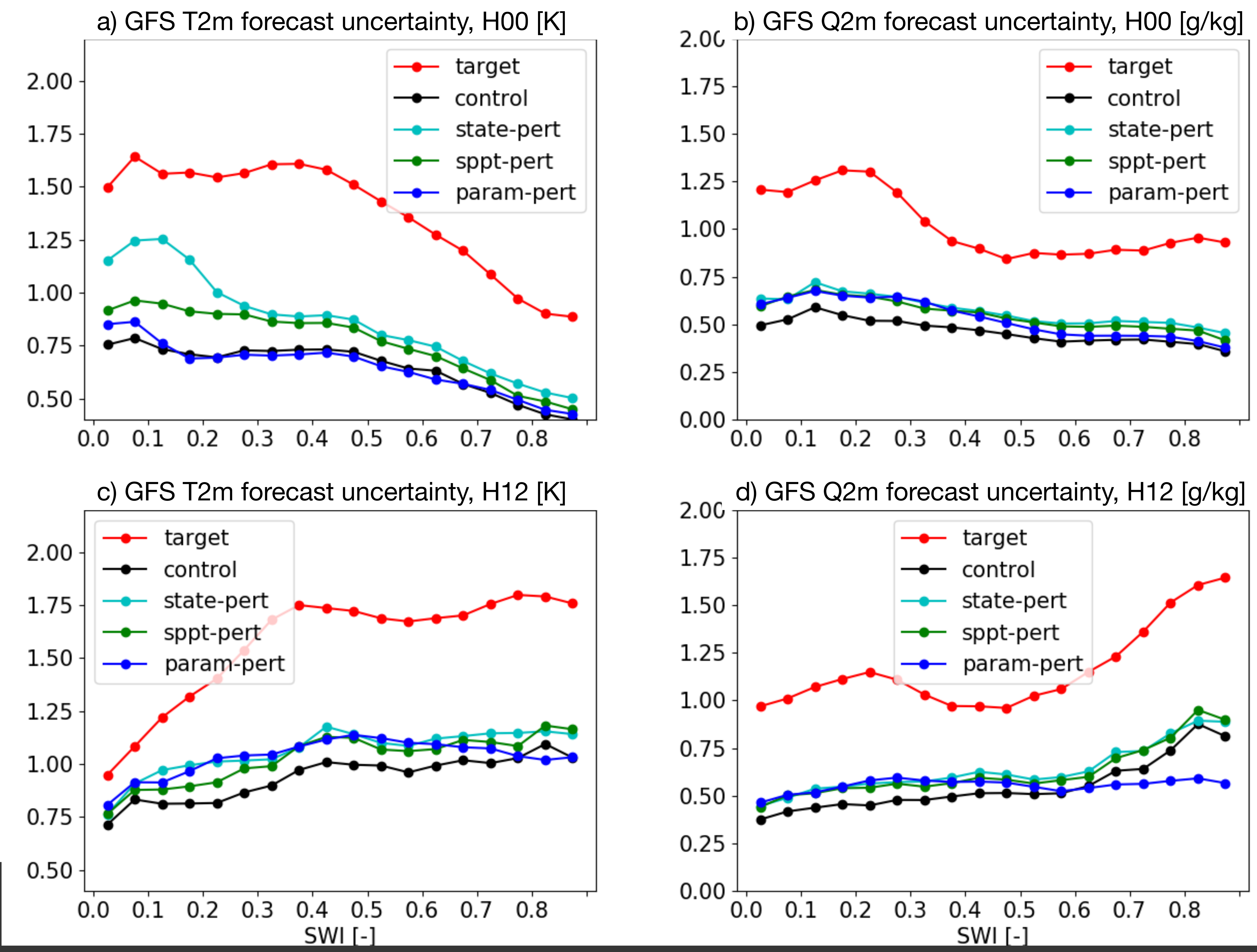
Ens. Spread in 2m Temperature and Specific Humidity

Induced spread is generally limited in all experiments

2m Temperature	2m Specific Humidity

Nighttime

Daytime

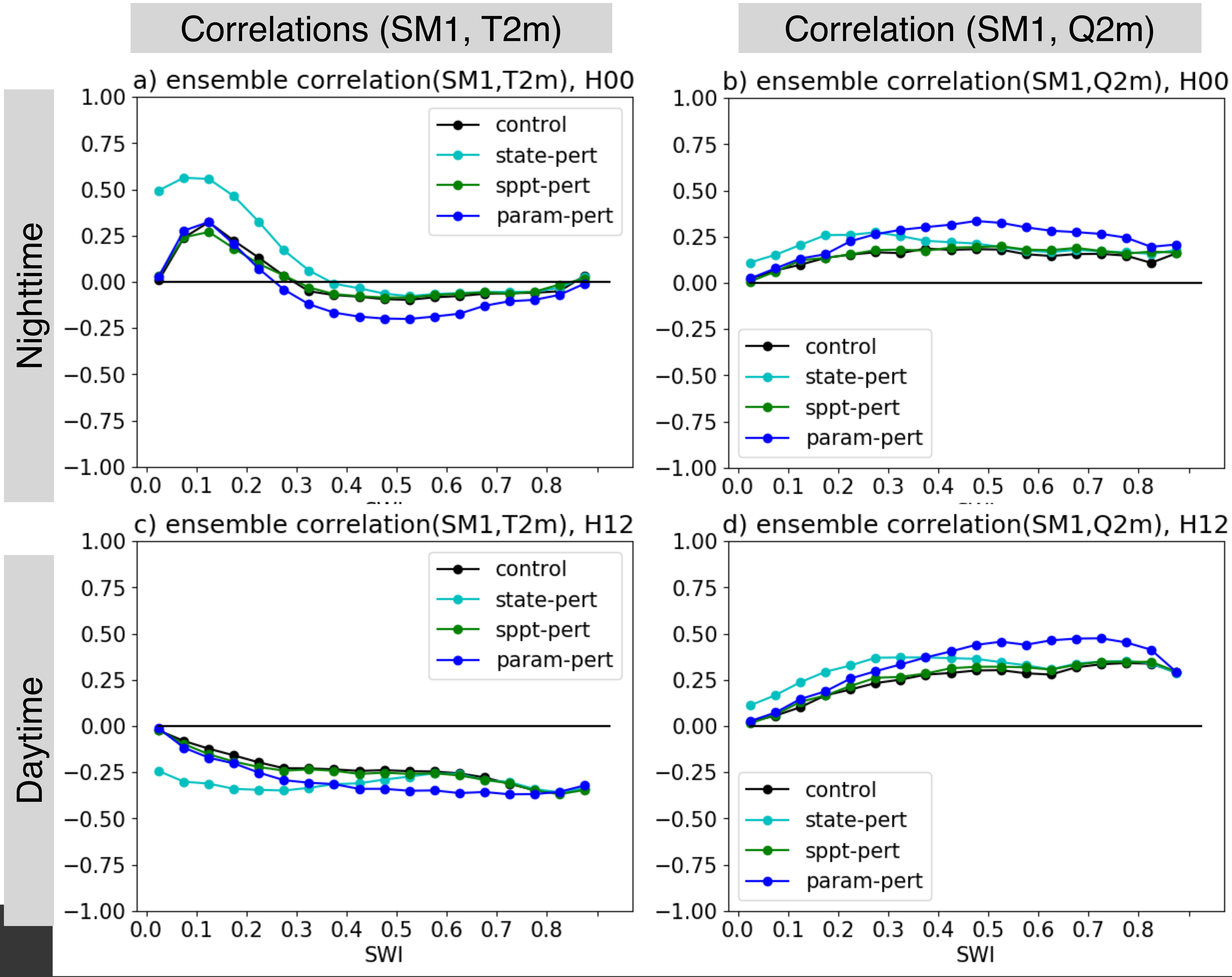


Results binned into 6 hour local time windows

Target estimates calculated by comparison to ERA-5 analysis.

Ensemble land/atmosphere correlations, soil moisture layer 1 (SM1)

- All experiments have incorrect positive SM1, T2m correlation in dry areas at night (problem in the model)
- State-pert strengthens correlations under dry conditions (when soil moisture drives land/atmosphere coupling)
- Param-pert experiment generally strengthens the correlations



Ensemble land/atmosphere correlations, soil temperature layer 1 (ST1)

- State-pert weakens the ST1, T2m correlations (atmosphere is driving the land/atmosphere coupling)
- Param-pert experiment again generally strengthens the correlations