Accounting for land model uncertainty in NWP ensemble systems

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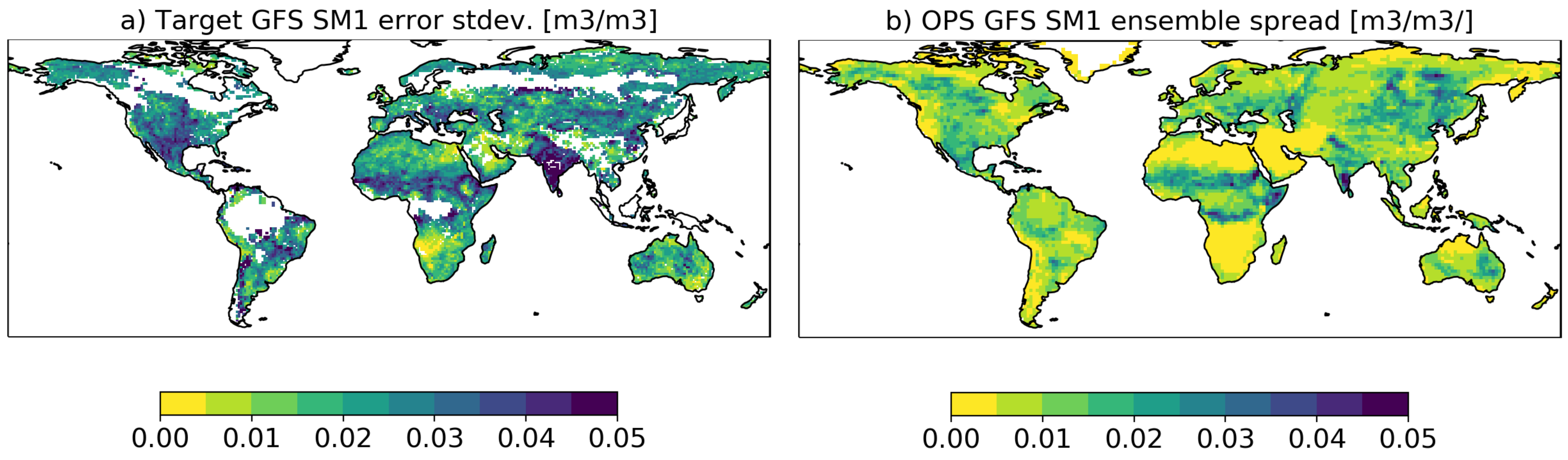
Motivation

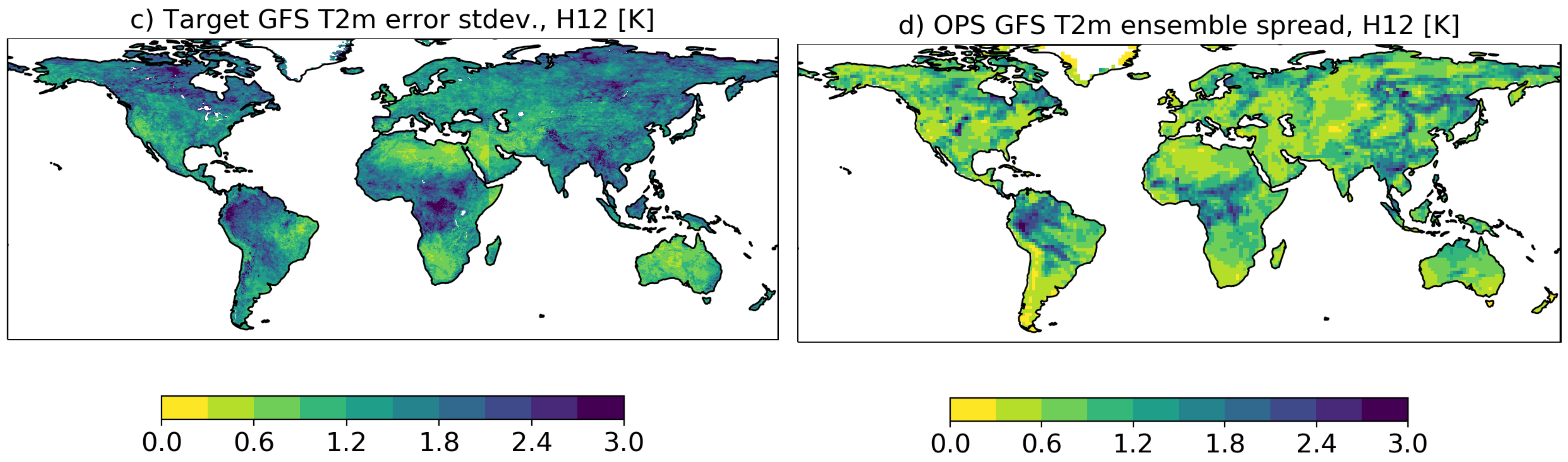
- NWP ensembles underestimate the forecast uncertainty at and near the land surface
  - Ensembles are not explicitly perturbed to account for land model uncertainty
  - Atmospheric forcing is also under-dispersed, but even with better atmospheric spread, still need to account for land model error

- Objective: better represent forecast uncertainty at/near land in NCEP's NWP (GFS) ensemble system
  - Improve ensemble-based model uncertainty estimates (e.g., forecast uncertainty over land)
  - Enable coupled ensemble-based land DA updates in the NWP ensembles

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



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



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

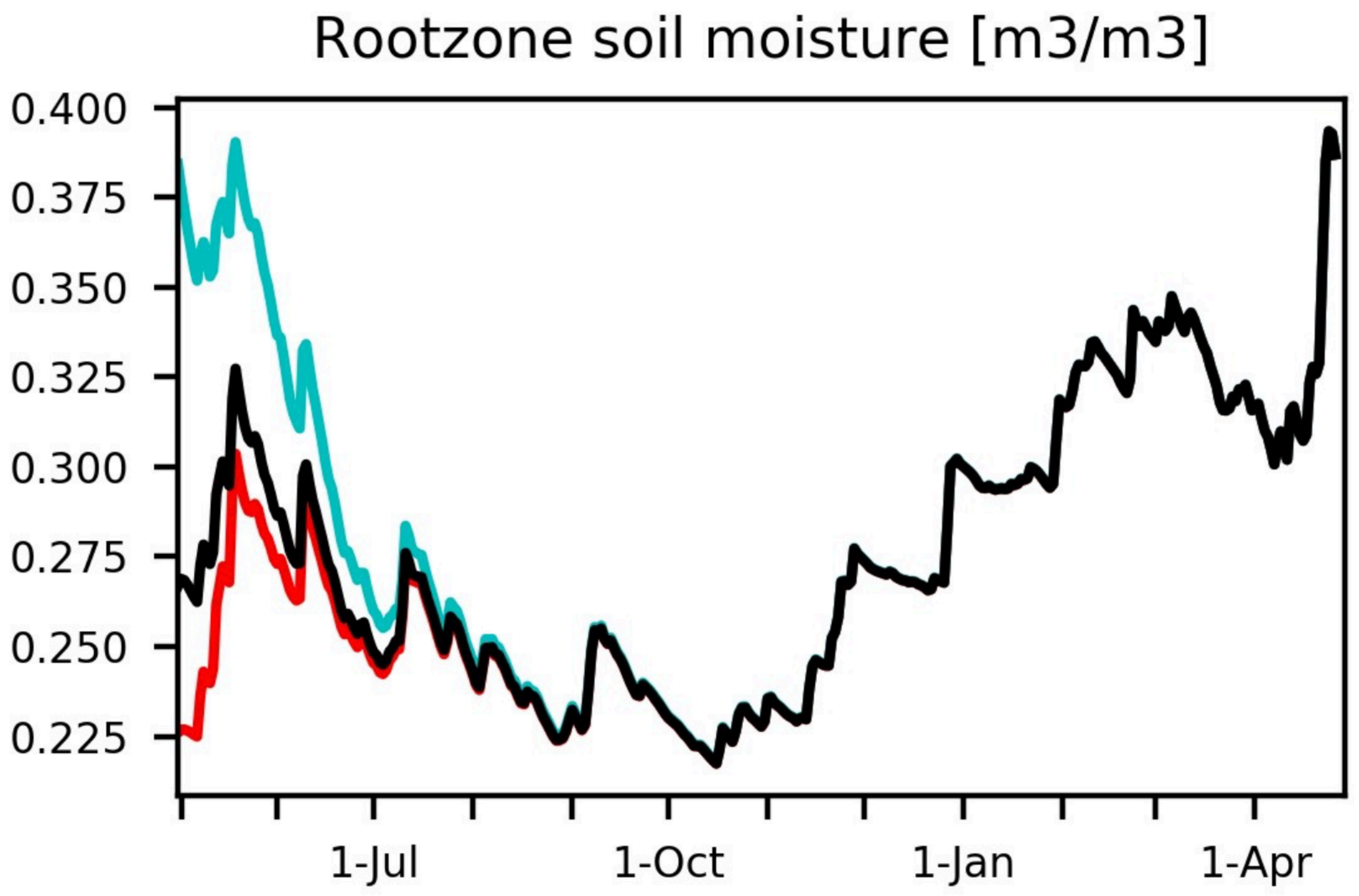
Ensemble standard deviation, from archived operational UFS output

Land Model Physics and Error Propagation

- The land is strongly-forced (dissipative), and over time will converge to a state determined by its forcing
  - Not chaotic, little information gained by perturbing initial conditions

- Land surface models do not simulate horizontal flow between grid cells
  - No horizontal flow of errors

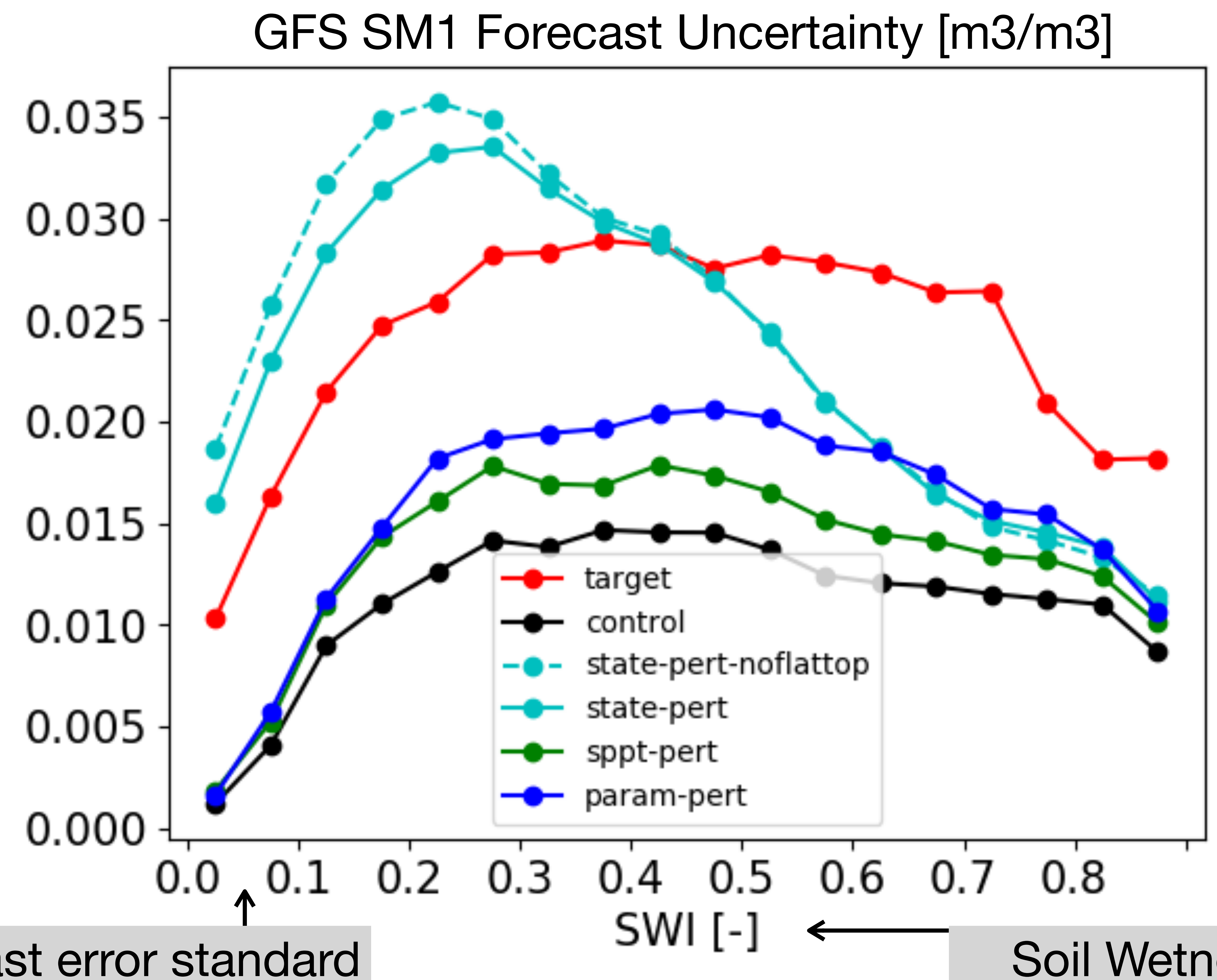
Catchment Root-zone soil moisture simulation, from 3 ICs and identical forcing [m3/m3]



Adding Land Model Uncertainty

- Test methods drawn from atmospheric and land ensemble DA communities:
  - State-pert: Stochastically perturb the SMC and STC *at each time step* (standard approach used in offline land DA platforms, such as LIS GLDAS)
  - 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 experiments:
  - 30 member ensemble at C192, run 30 days from July 10, 2019
  - GFSv16 model, with Noah land model
  - DA cycling, hybrid 3DEnVar DA
  - Assimilating the standard atmospheric obs, using standard atmospheric stochastic physics

Ens. Spread in Soil Moisture Layer 1 (SMC1)



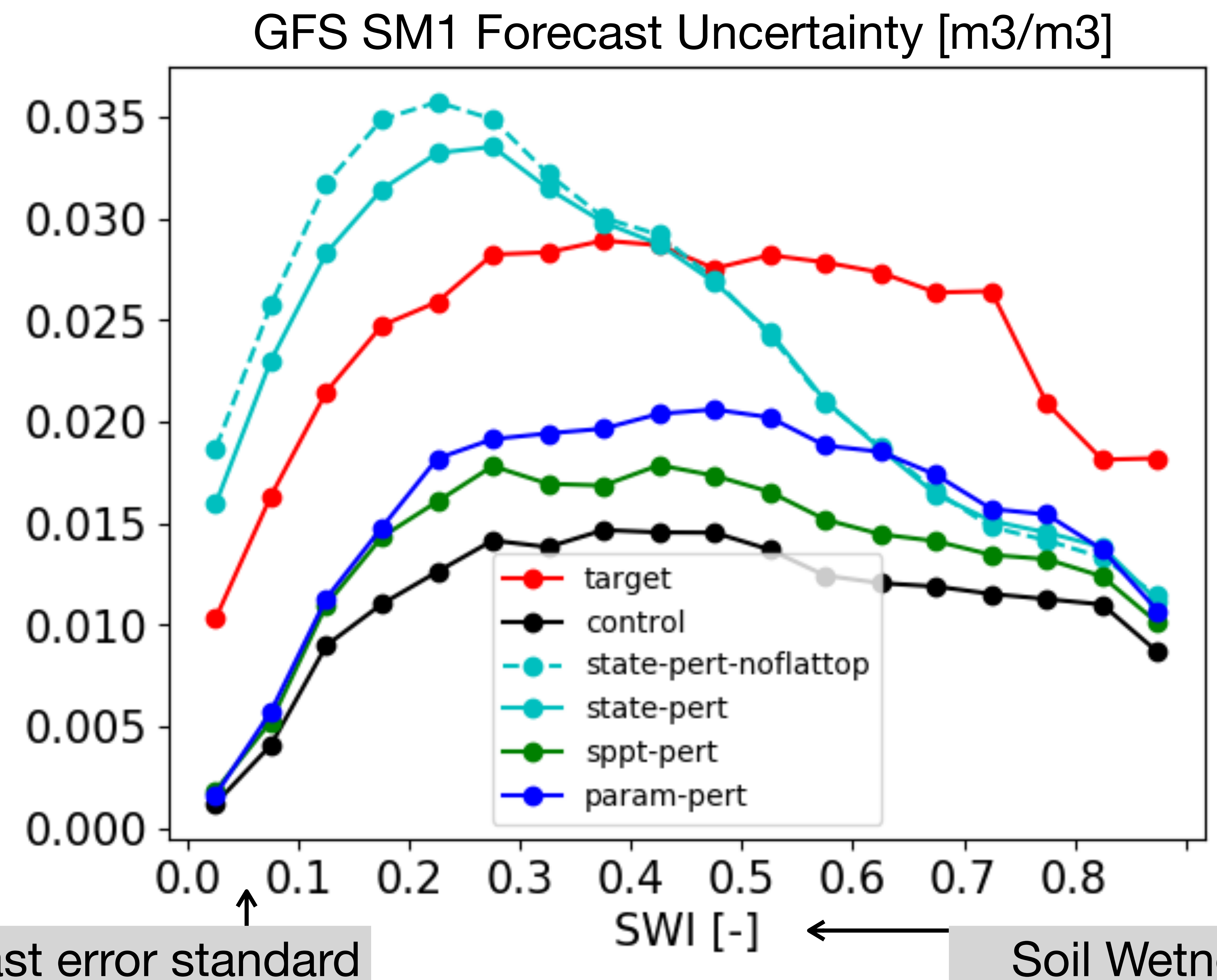
Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from each experiment.

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.

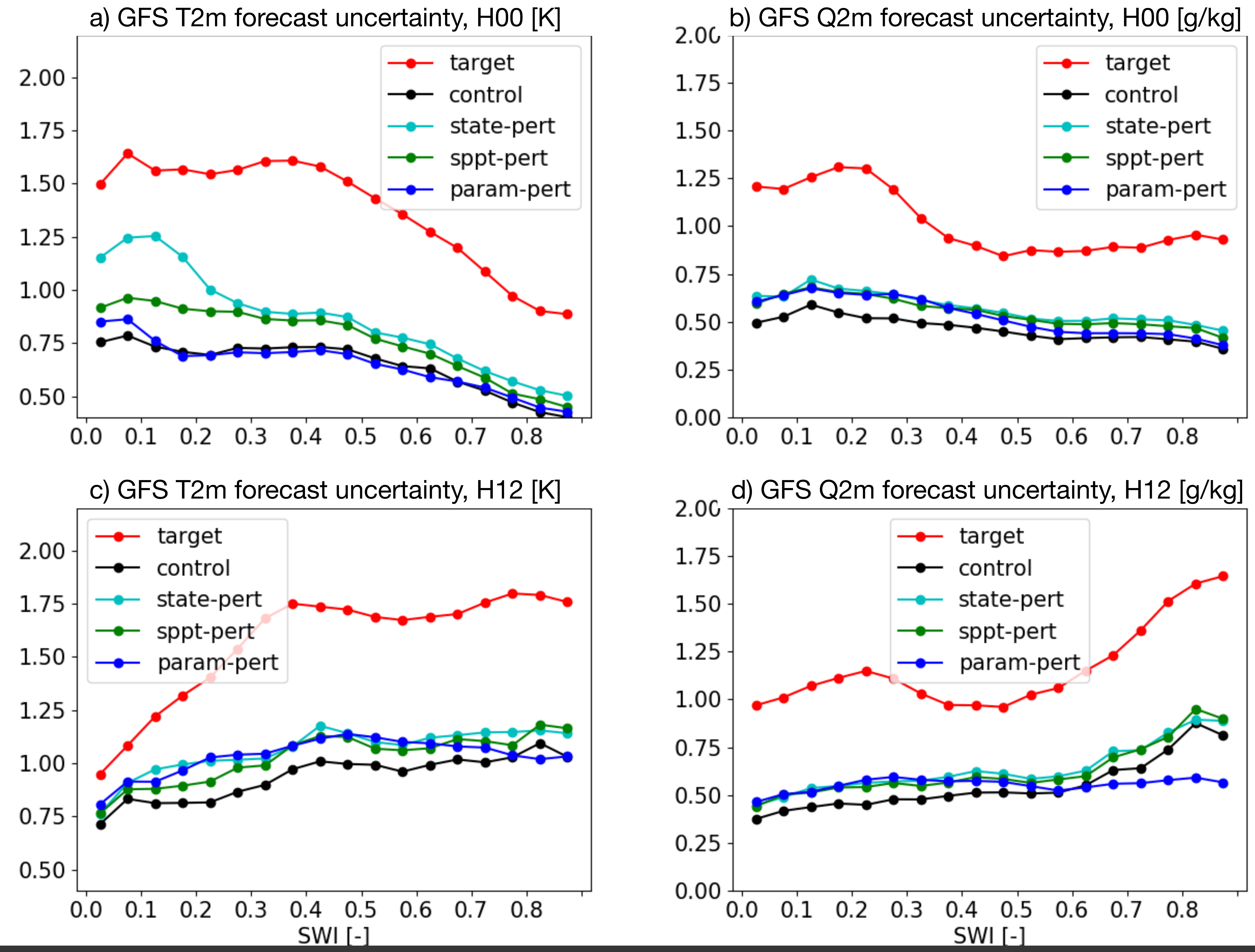
Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from each experiment.

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		

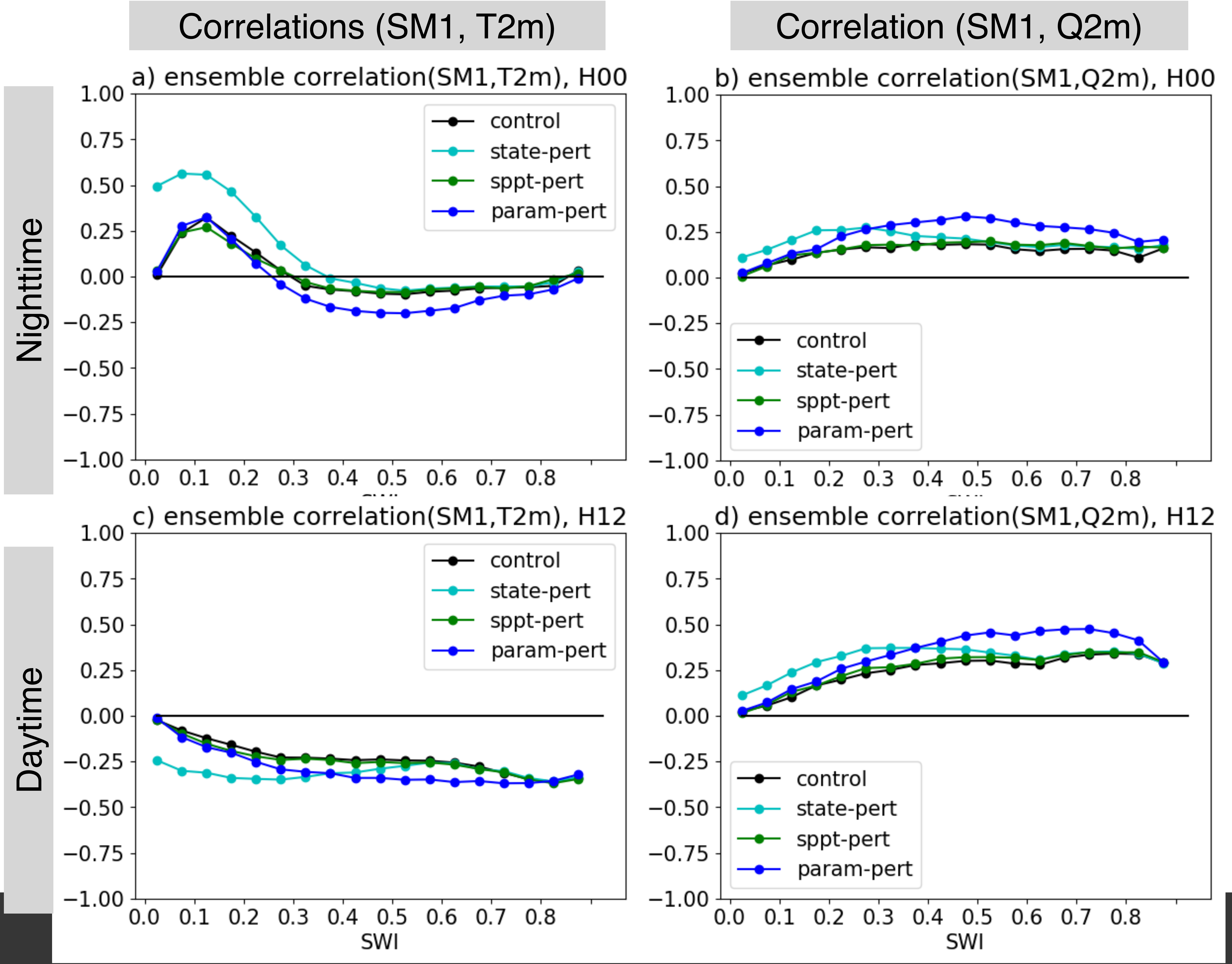


Results binned into 6 hour local time windows

Target estimates calculated by comparison to ERA-5 analysis.

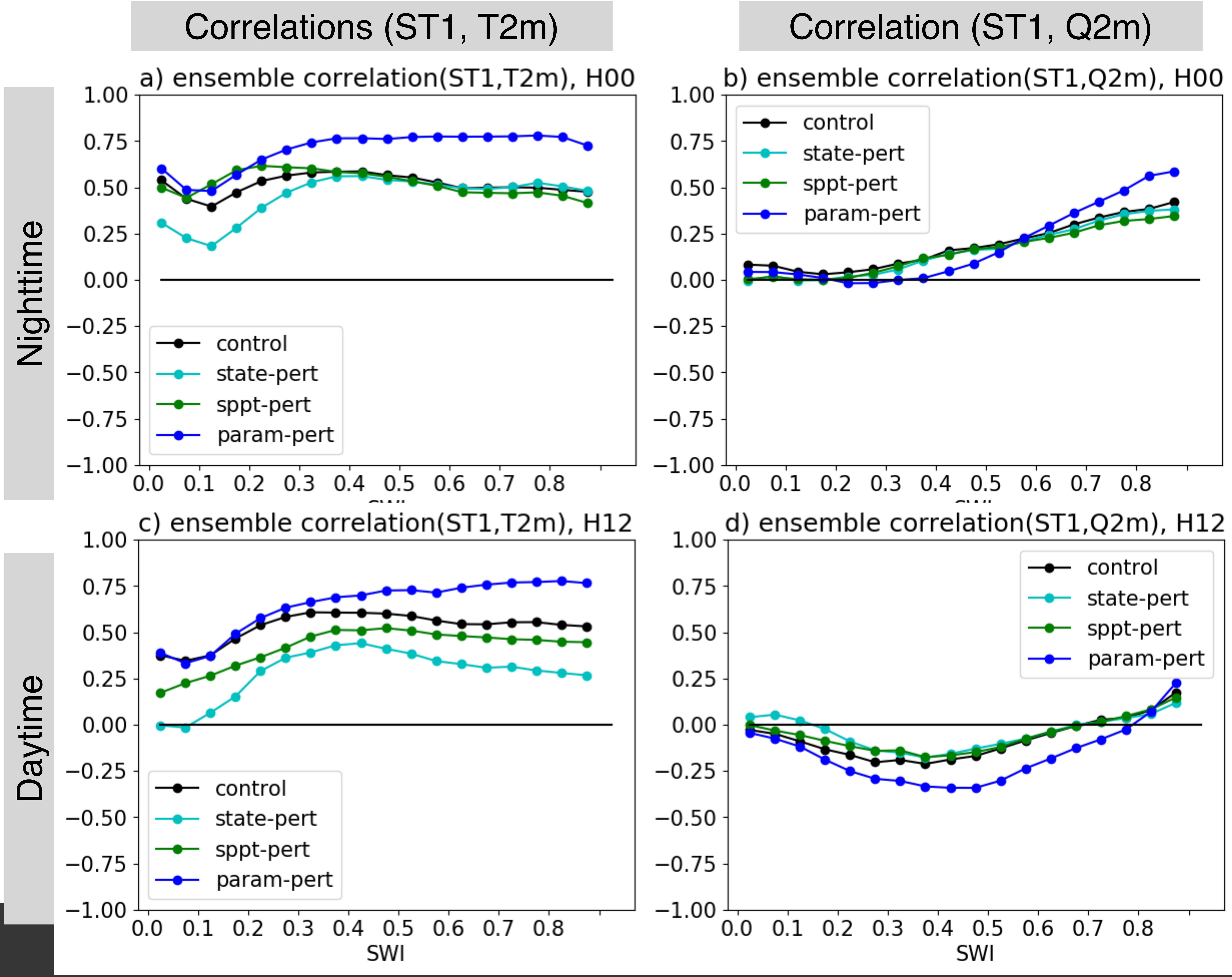
Ensemble land/atmosphere correlations, soil moisture layer 1 (SM1)

- 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

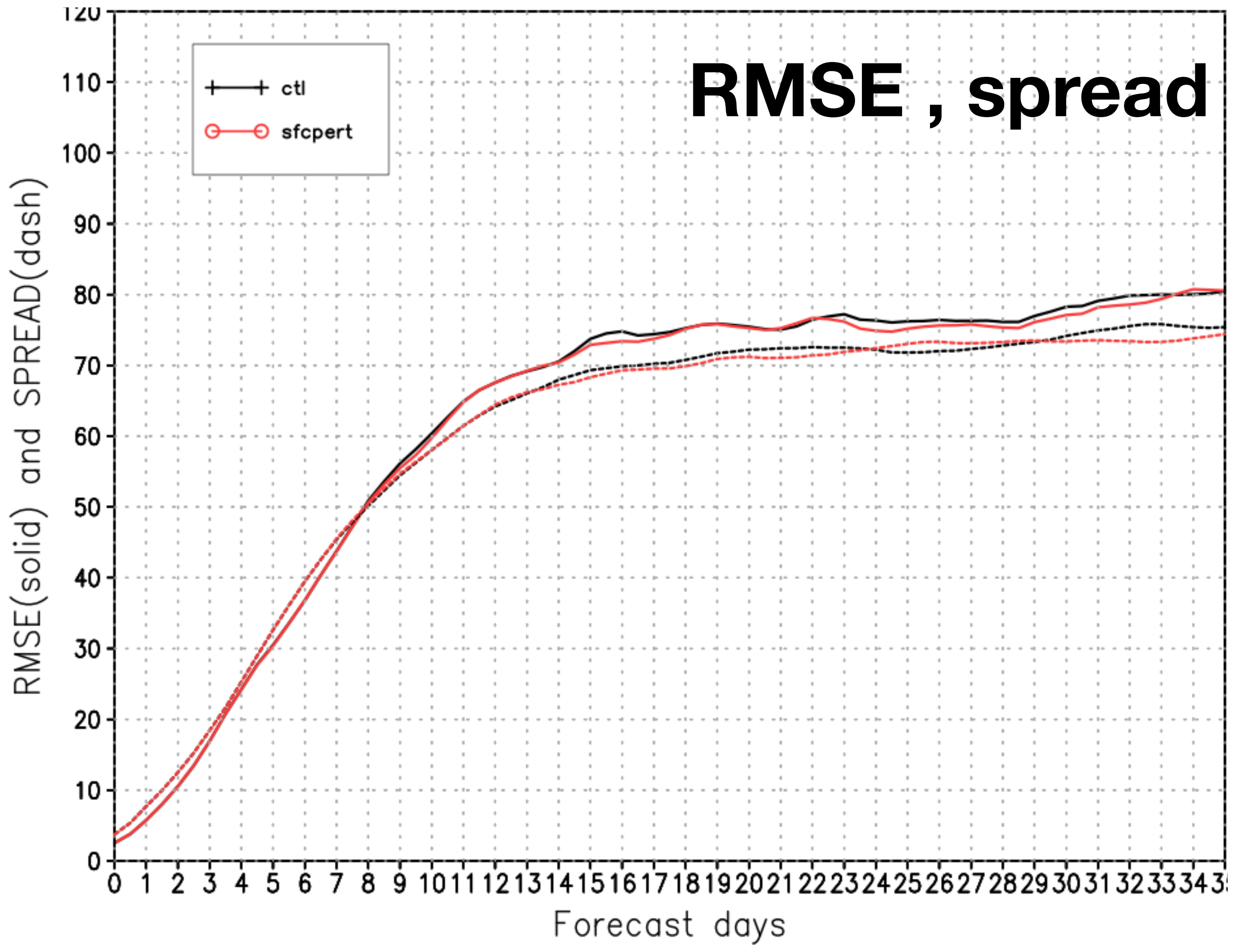


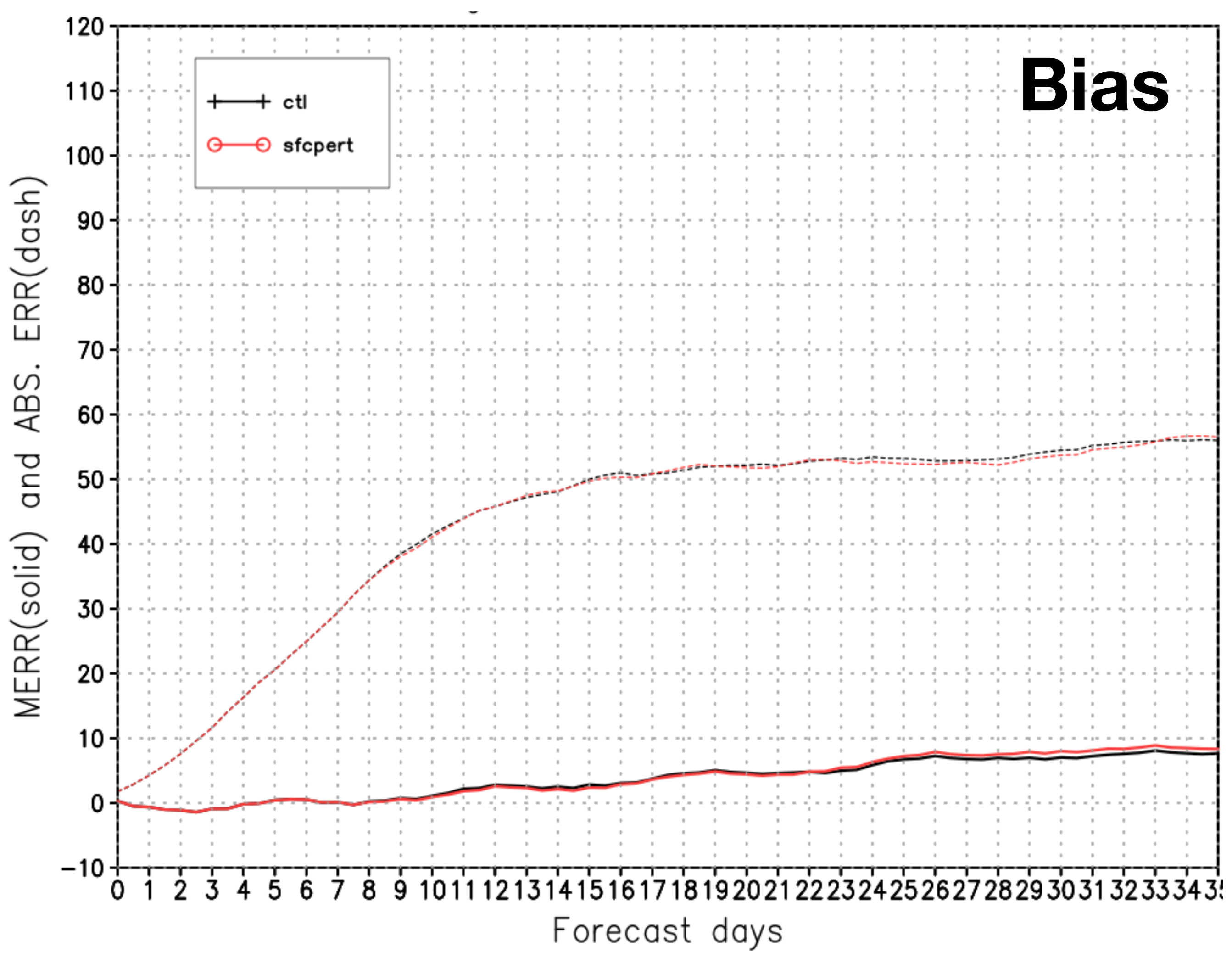
Ensemble land/atmosphere correlations, soil temperature layer 1 (ST1)

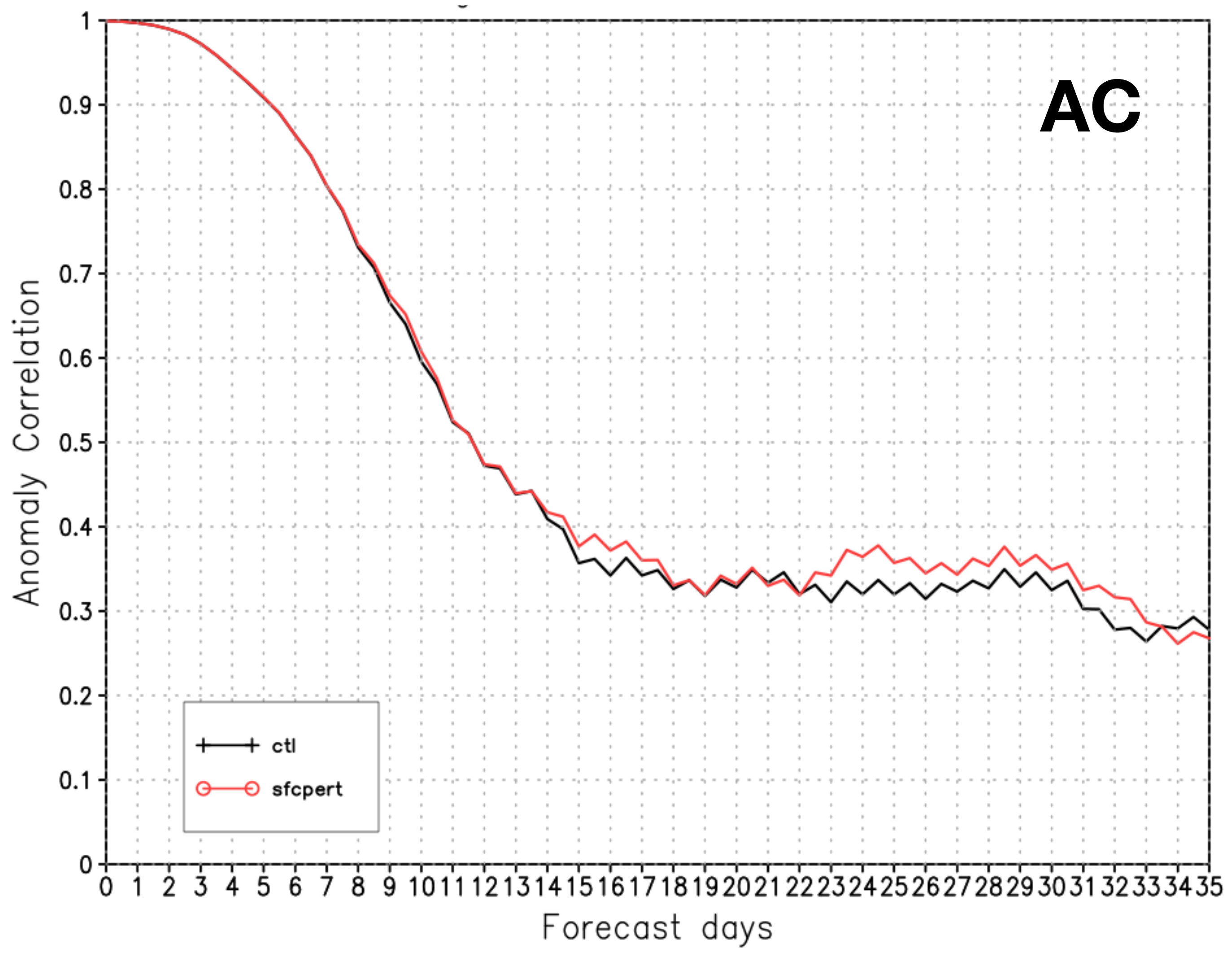
- State-pert weakens the ST1, T2m correlations (atmosphere is driving the land/atmosphere coupling)
- Param-pert experiment again generally strengthens the correlations



Forecast Experiments at EMC







NH
500 hPA height

- Based on these experiments, colleagues at EMC tested perturbing vegetation fraction, roughness length, and albedo in longer forecast experiments (16 cases over a Boreal summer)
  - Limited impact on atmospheric spread and RMSE metrics (expected)
  - The land perturbations enhances pre-existing warm bias over Sahara (traced to roughness length perturbation)

C/o - Bing Fu, Hong Guan, Yuejian Zhu

Summary and Conclusions (1)

- NCEP's GFS (and other) NWP ensemble system is under-dispersed at and near the land surface
  - Need to explicitly account for land model uncertainty when generating the ensembles
  - Land and atmosphere have very different dynamics, and different error growth behavior, cannot simply extend atmospheric methods

- For coupled data assimilation, cross-component correlations are very important
  - Perturbation methods targeting only one component will overestimate (underestimate) forecast error correlations where that (the other) component is driving the coupling

Summary and Conclusions (2)

- For NCEP's GFSv16 NWP system, best results obtained by perturbing model parameters important to land/atmosphere fluxes
  - For land/atmosphere data assimilation, this directly targets fluxes between the components, creating error cross-covariances representative of errors in those fluxes
  - For applications interested in forecast uncertainty, generates more realistic spatial patterns in uncertainty than other methods
  - Work presented today was with Noah land model, working on implementing a similar scheme for Noah-MP (code is in place, but struggling to create perturbations that don't induce excessive spread in soil temperature)

- However (!), land model physics are highly non-linear; introduction of a land perturbation scheme will almost certainly change the ensemble mean land states
  - Difficult to evaluate mean land states (soil moisture!), and land/atmosphere models are instead tuned to give best atmospheric results from the model's mean state
  - Changes to the mean require re-tuning the ensemble, may not be feasible
  - May need to limit spread induced in land surface to avoid impractical changes in ensemble mean

Thanks for Listening

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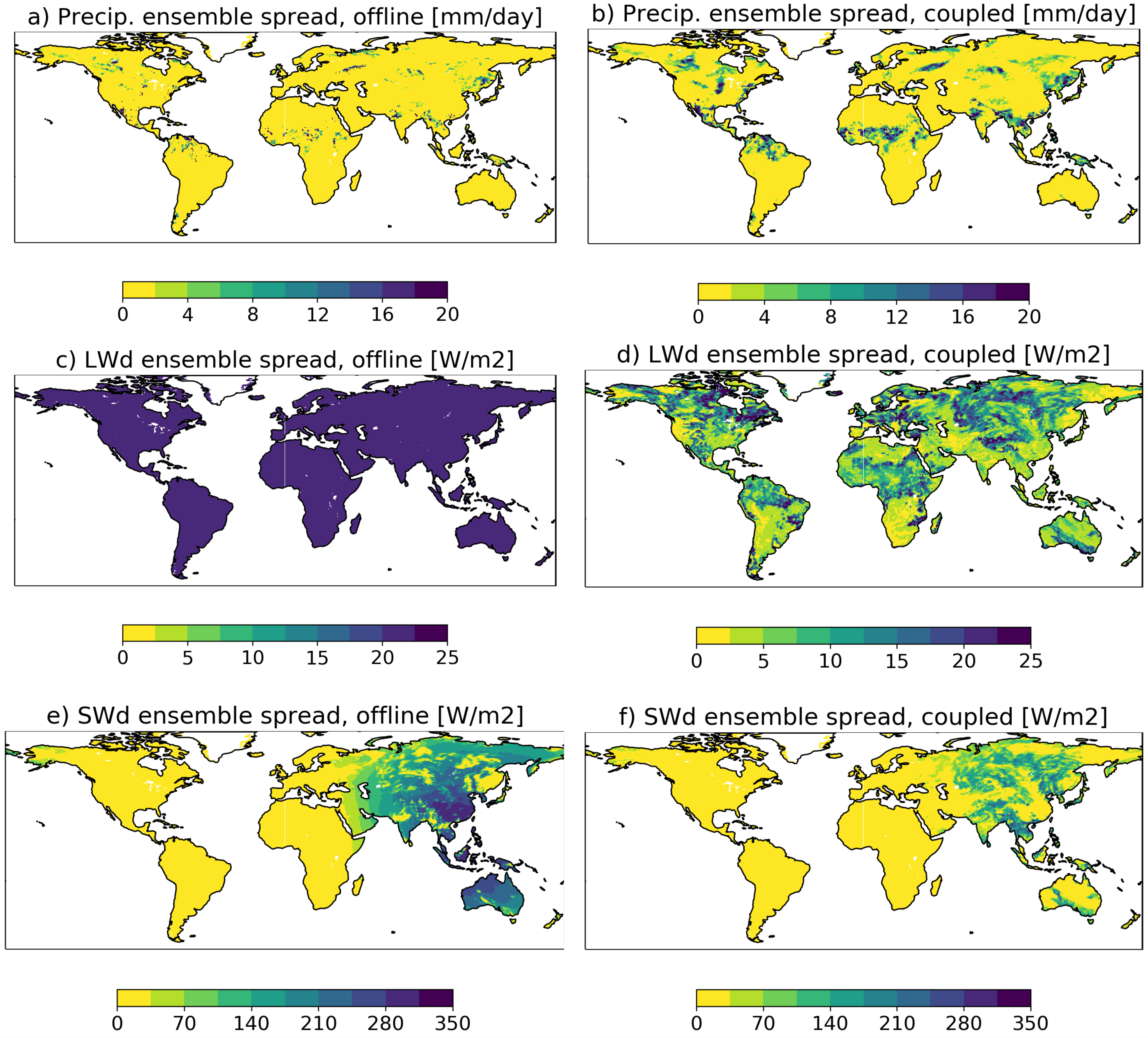
Full details:

Draper, C., 2021: Accounting for Land Model Uncertainty in Numerical Weather Prediction Ensemble Systems: Toward Ensemble-Based Coupled Land–Atmosphere Data Assimilation. J. Hydrometeor., 22, 2089–2104, https://doi.org/10.1175/JHM-D-21-0016.1.

Atmospheric Forcing Uncertainty

Typical Offline Ensemble Spread | Operational GFS Ensemble Spread



- Left: example uncertainty estimates as used in a typical offline land DA system (perturb a single atmospheric realization using perts. drawn from best estimate of the error distribution)
- Right: example uncertainty estimates from the GFS ensemble (estimates from ensemble of GFS forecasts)
- Atmospheric forcing spread in GFS likely under-estimates forecast error in radiation
- Full GFS ensemble produces more realistic spatial error structure

Summary and Conclusions (2)

- Offline (land-only) ensemble-based DA systems, recommendations:
  - Replace current method of regularly perturbing model states, as creates unrealistic spatial patterns
  - Use atmospheric ensemble forcing, in place of perturbing a single atmospheric realization
    … or for atmospheric systems, do the DA within the atmospheric ensemble

- Coupled data assimilation, recommendations:
  - Use ensemble perturbation approaches that directly target fluxes between the components, to create error cross-covariances representative of errors in those fluxes
  - Perturbation methods targeting only one component will overestimate (underestimate) forecast error correlations where that (the other) component is driving the coupling

- NCEP's GFS NWP system:
  - Applying the parameter perturbation approach (expanded to perturb veg. fraction, roughness height, and albedos)
  - Developing EnKF DA of 2m variables to update model soil moisture and temperature
    (for now, focus on soil temperature only, due to soil moisture / T2m model error)
  - Looking into impact on ensemble mean and skill (EMC colleagues)