Accounting for land model uncertainty in NWP ensemble systems: toward ensemble-based coupled land/atmosphere data assimilation

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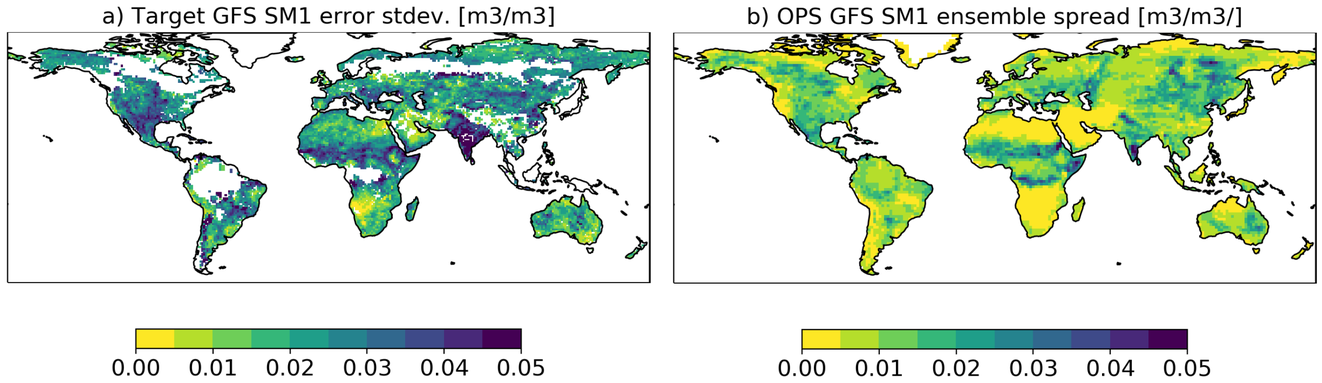
Background

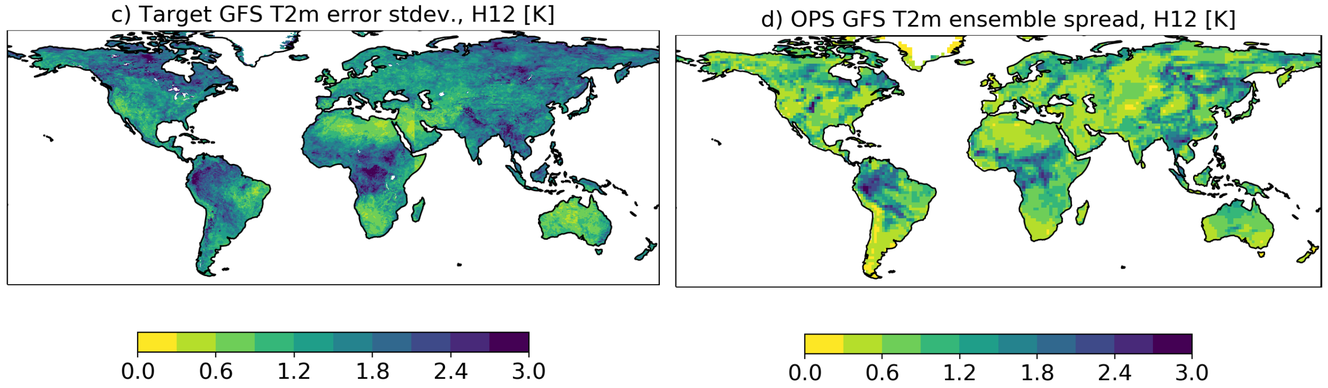
- NWP ensembles are under-dispersed at the land surface
  - Expected, since ensembles are not explicitly perturbed to account for land model uncertainty
  - Atmospheric forcing is also under-dispersed, but even with better atmospheric spread, still need to account for land model error

- Need a scheme to represent forecast uncertainty at/near land in NCEP's NWP (GFS) ensemble system by adding a scheme to account for land model uncertainty

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



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



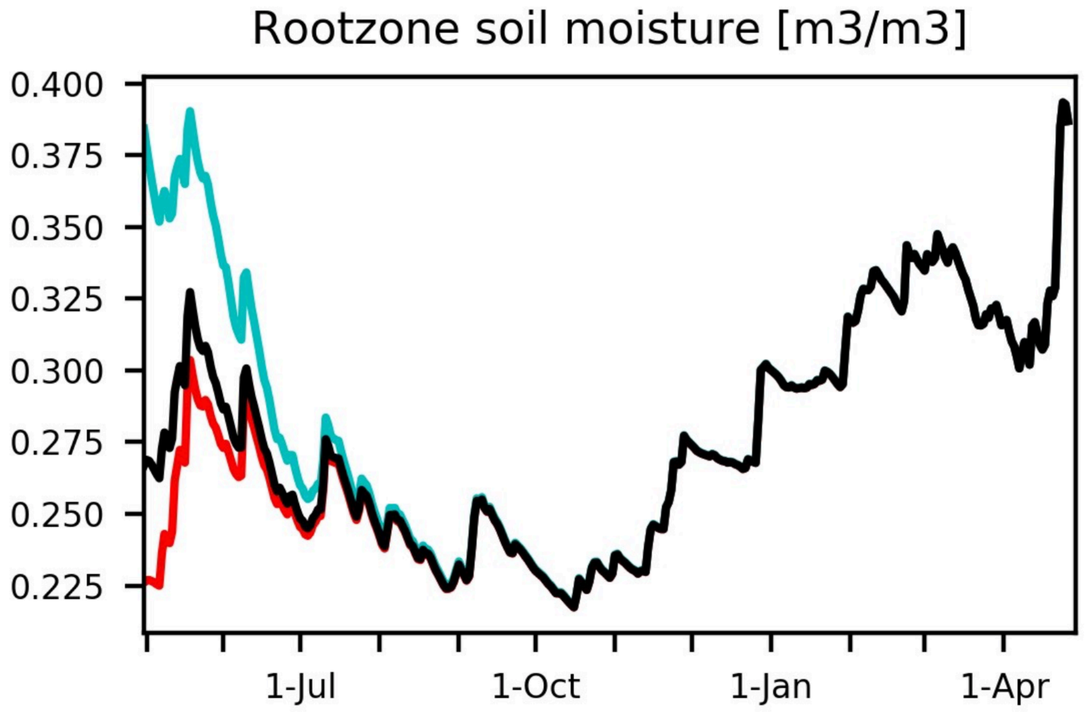
Target estimates, calculated using triple colocation (SM1), and comparison to ERA-5 analysis (T2m)

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
- Land surface models do not simulate horizontal flow between grid cells
  - No horizontal flow of errors
- Little information obtained from perturbing initial conditions

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



Adding Land Model Uncertainty

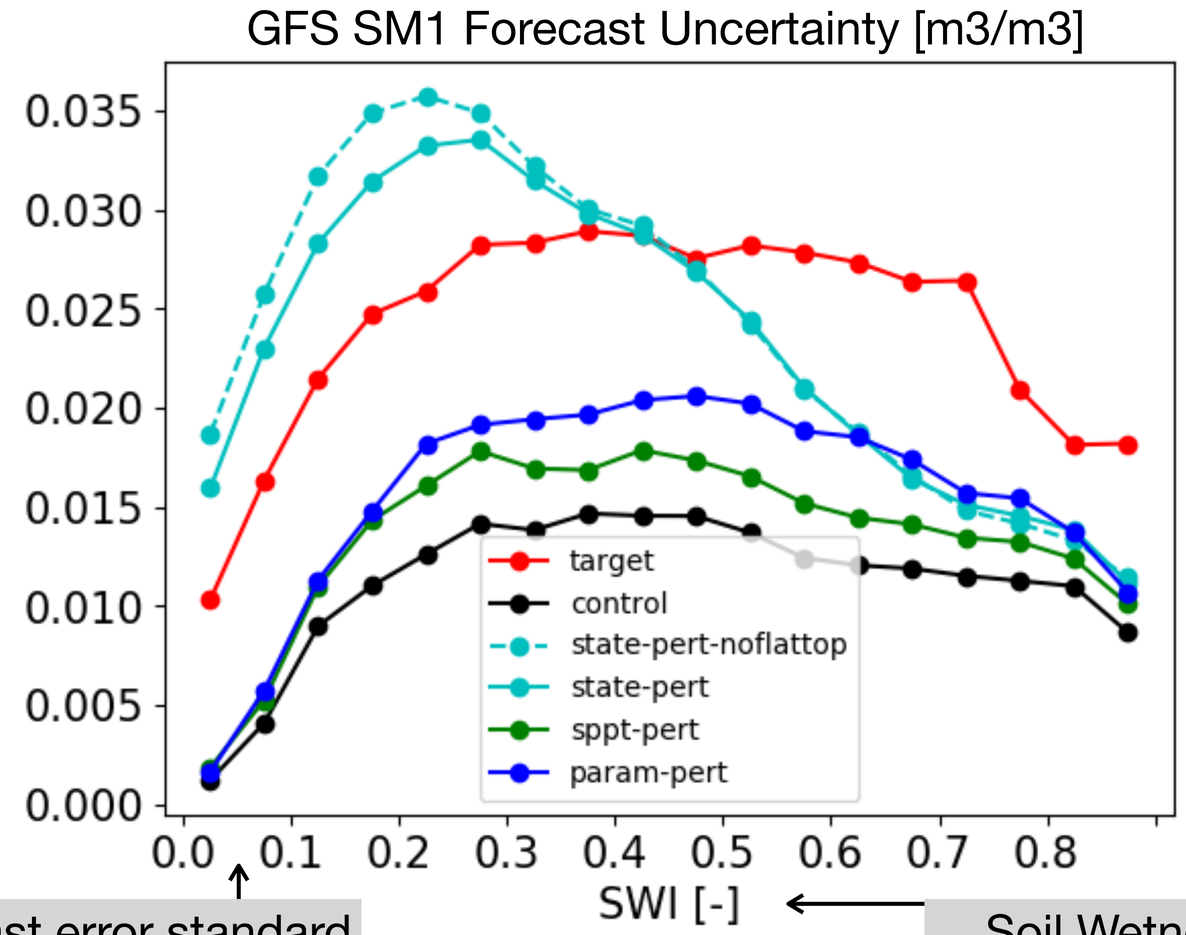
- Test methods drawn from atmospheric and land ensemble DA communities:
  - State-pert: Stochastically perturb the soil moisture content (SMC) and soil temperature content (STC) *at each time step*
    (standard approach used in land-only ensemble data assimilation systems)

  - 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)

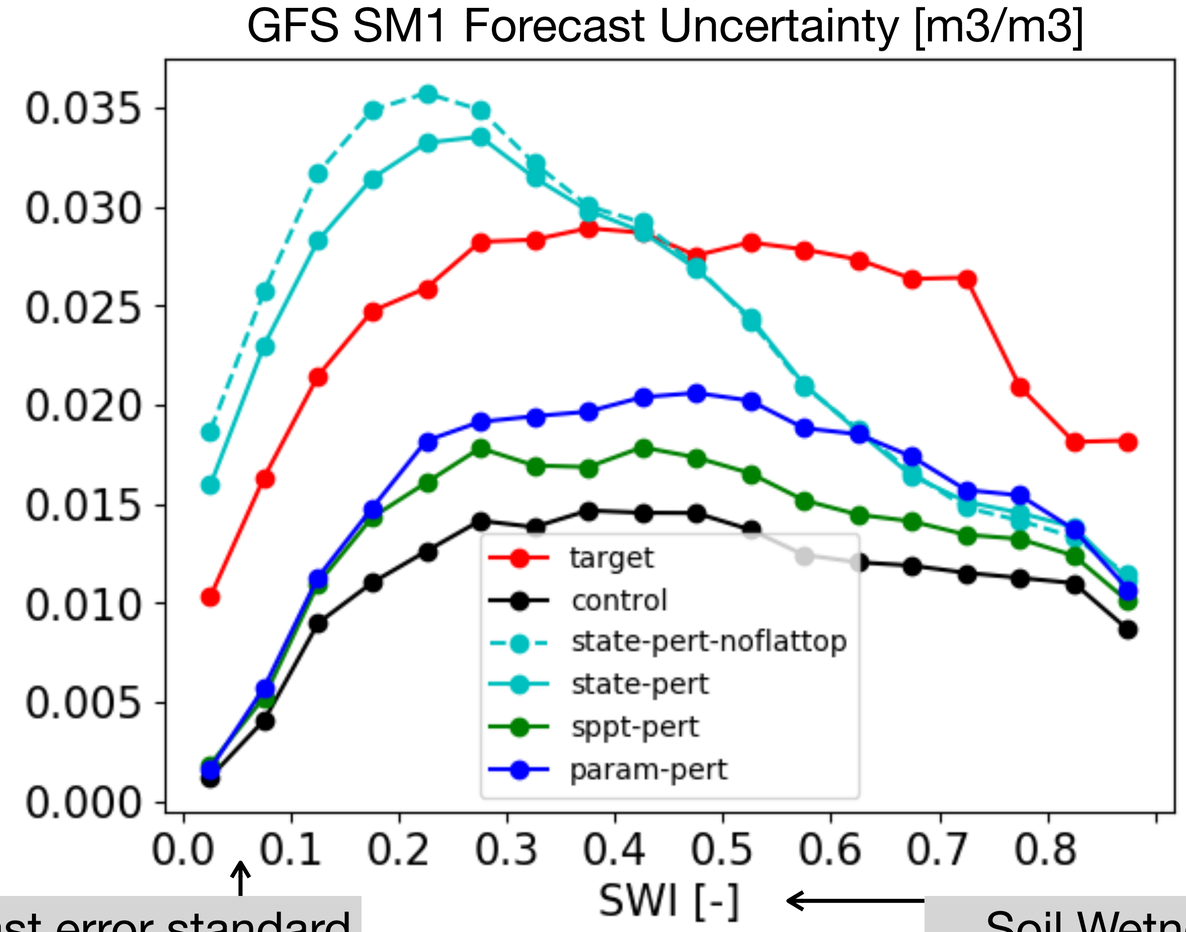


Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from each experiment.

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.

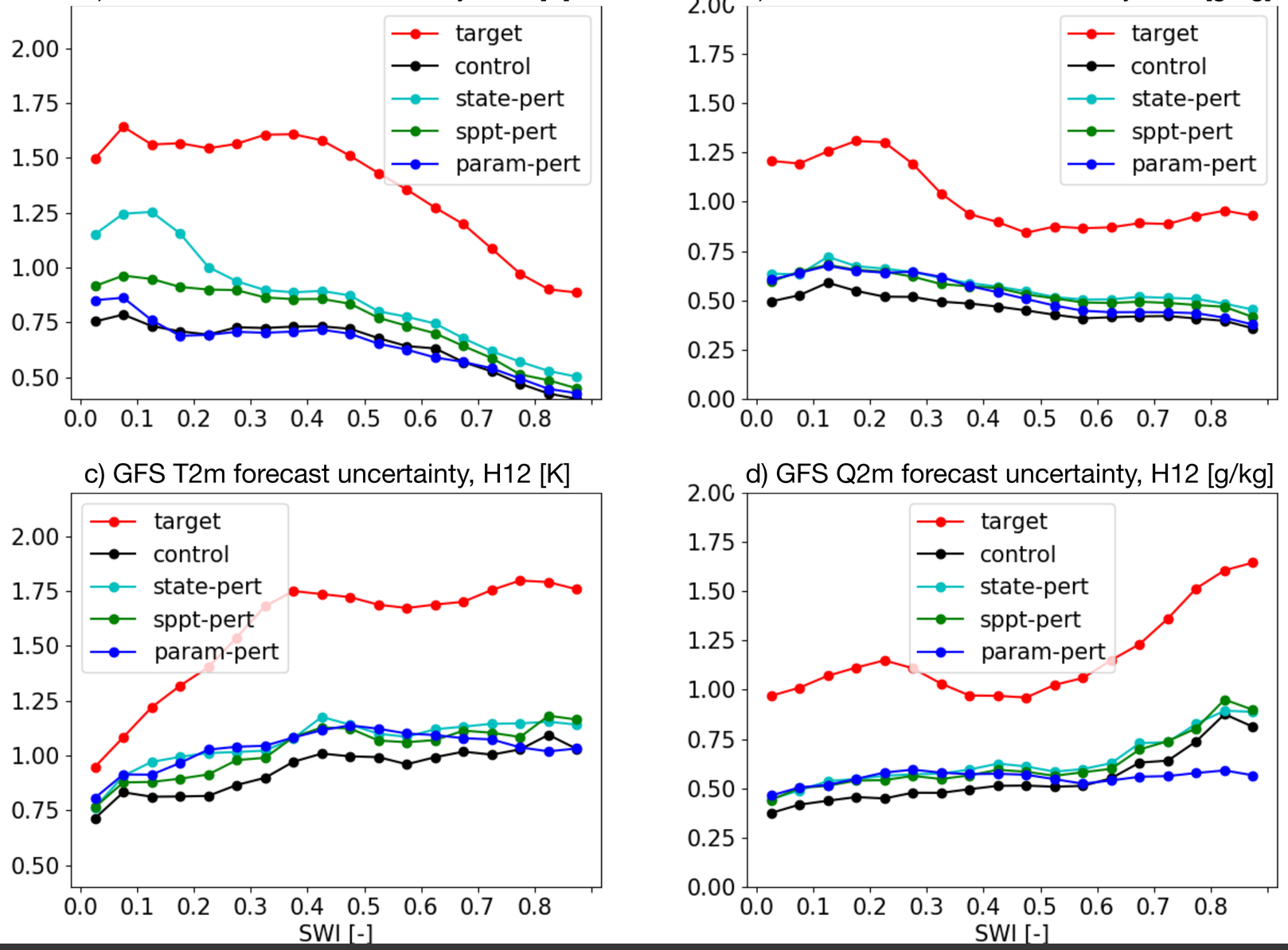
Target (red) is best estimate of forecast error standard deviation (c.f, independent obs). Others are ensemble-based estimates from each experiment.

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	a) GFS T2m forecast uncertainty, H00 [K]	b) GFS Q2m forecast uncertainty, H00 [g/kg]
Daytime	c) GFS T2m forecast uncertainty, H12 [K]	d) GFS Q2m forecast uncertainty, H12 [g/kg]

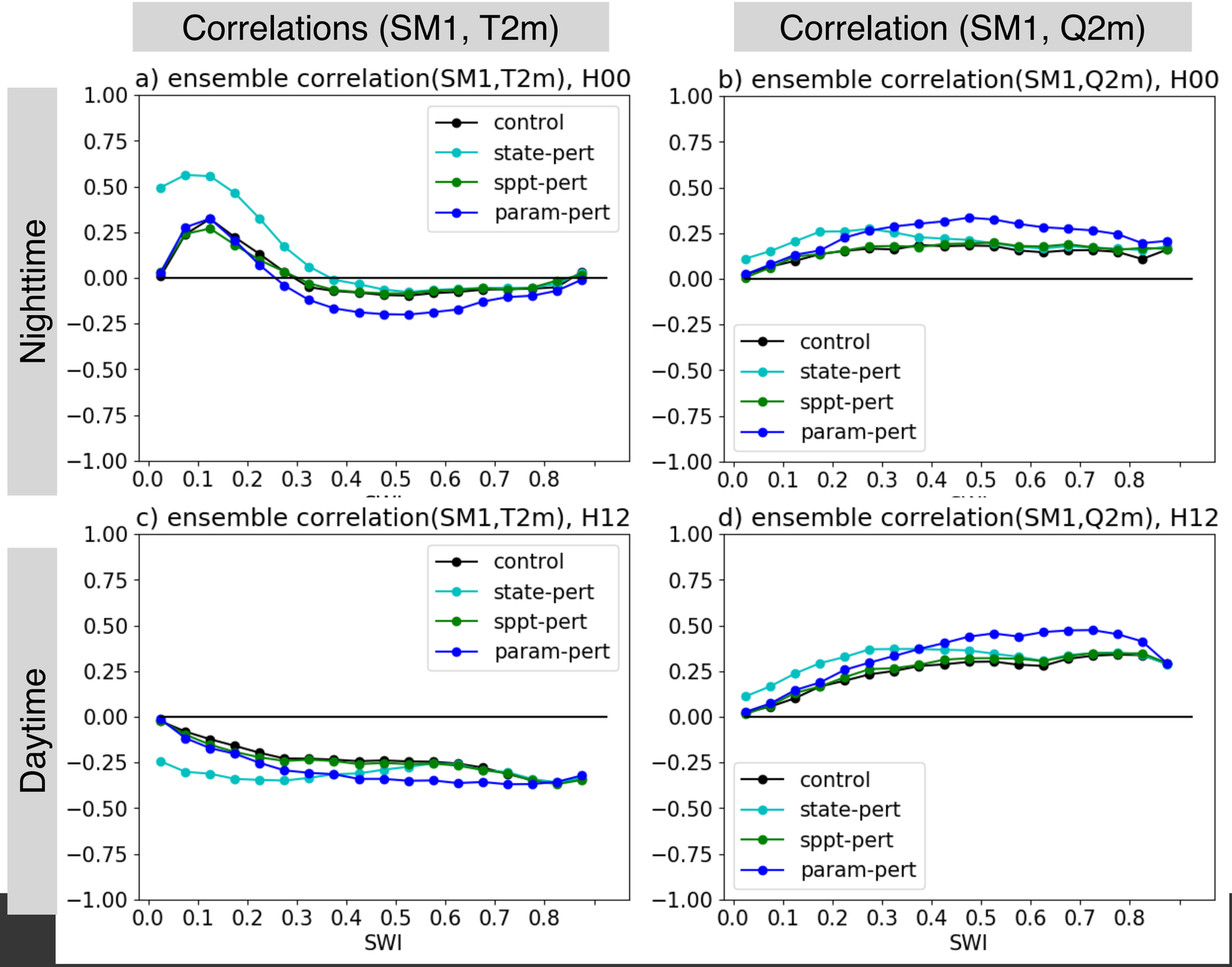


Results binned into 6 hour local time windows

Target estimates calculated by comparison to ERA-5 analysis.

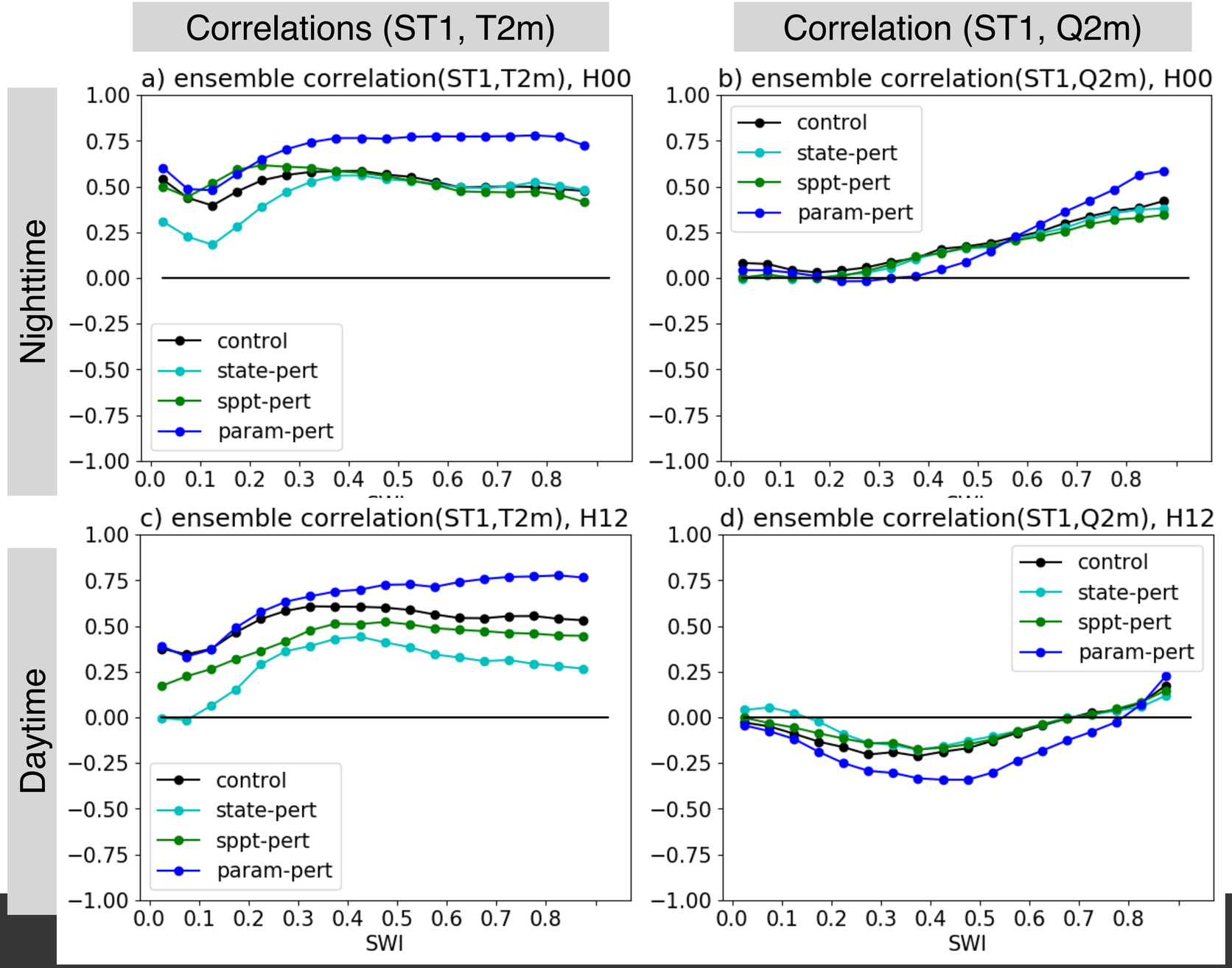
Ensemble land/atmosphere correlations, soil moisture layer 1 (SM1)

- 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)

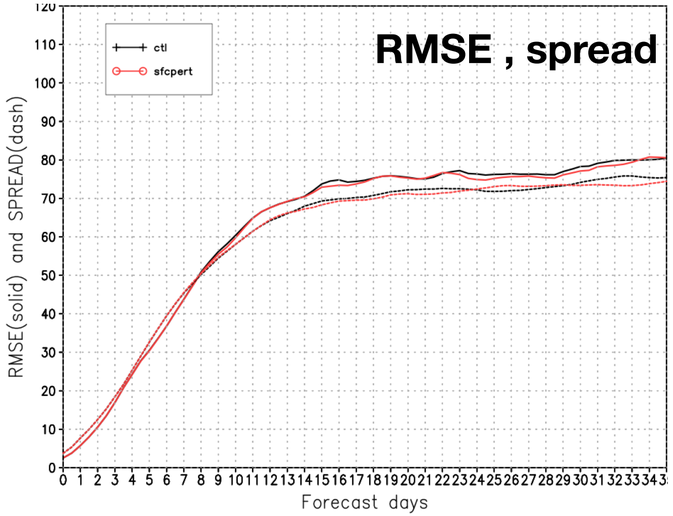
- State-pert weakens the ST1, T2m correlations (atmosphere is driving the land/ atmosphere coupling)
- Param-pert experiment again generally strengthens the correlations

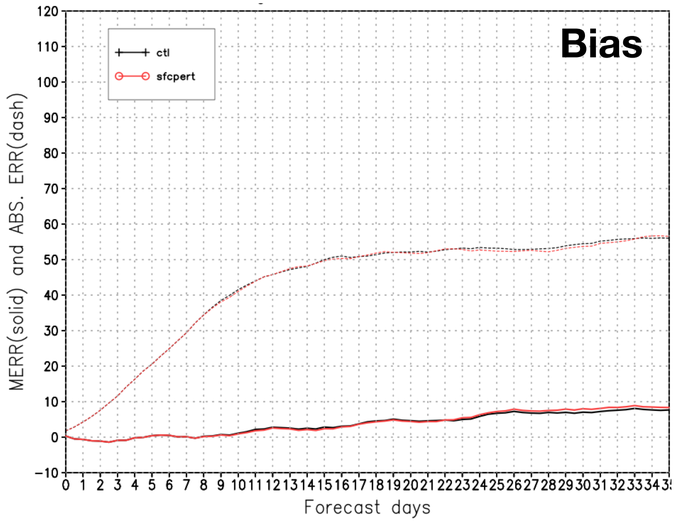


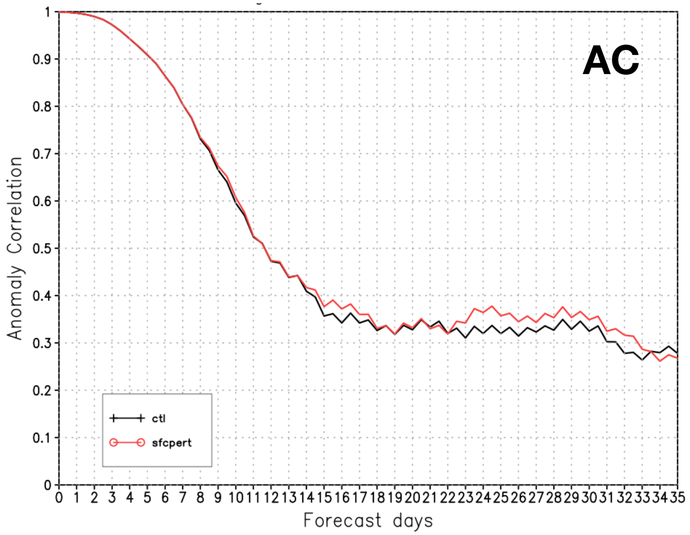
Summary of Experiment Results

- Adding (uniformly distributed) perturbations to the soil moisture states gives ensemble spread representative of the local soil moisture persistence
  - For soil moisture results in spatial patterns not representative of expected forecast errors
- SPPT for soil moisture is inherently limited in the amount of spread that can be added
- Perturbing model parameters (vegetation fraction) gives reasonable spatial patterns in resulting ensemble spread
  - Will also lead to ensemble land/atmosphere covariances representative of errors in the land/atmosphere coupling
  - In these experiments, the ensemble is still under-dispersed

Forecast Experiments at EMC







NH
500 hPA height

- Forecast experiments (16 cases over a Boreal summer), with perturbed vegetation fraction, roughness length, and albedo
  - Limited impact on spread and RMSE
  - Also enhances pre-existing warm bias over Sahara

C/o - Bing Fu, Hong Guan, Yuejian Zhu (NOAA NCEP)

Conclusions

- Land dynamics differ from atmospheric dynamics, need to design perturbation schemes that account for this

- Recommended method to account for land model error in ensembles is to perturb key parameters controlling the land/atmosphere fluxes
  - Generates reasonable spatial patterns in ensemble spread
  - Generates ensemble cross-covariances more representative of errors in land/atmosphere coupling
  - Now using in ensemble data assimilation experiments

- Land is highly non-linear, adding land perturbations will likely change the ensemble mean behavior
  - Land is difficult to observe, typically tune land models to optimize atmospheric forecasts; will likely need to retune after adding a land perturbation scheme

Conclusions

- Some thoughts on ensemble-based land data assimilation:
  - Land is not chaotic, has no horizontal flow; ensemble response to applied ICS perturbations (errors) depends on pattern of applied perturbations (errors) and how the model persists these perturbations (errors). Latter depends on local conditions, can be reasonably estimated from climatology.
  - Do we even need ensemble-based data assimilation?
    Yes! Need errors of the day to include atmospheric errors of the day (precip!).
    Atmospheric events like precip can dramatically shift the land/atmosphere coupling.

- In a coupled data assimilation system (land/atmosphere) relying on perturbations in one component (ie., land) will lead to an ensemble with higher cross-component covariances where that component is driving the coupling, and lower covariances where the other component is driving the coupling
  - This will have consequences for the data assimilation increments
  - Better to perturb the cross component fluxes

Thanks for Listening

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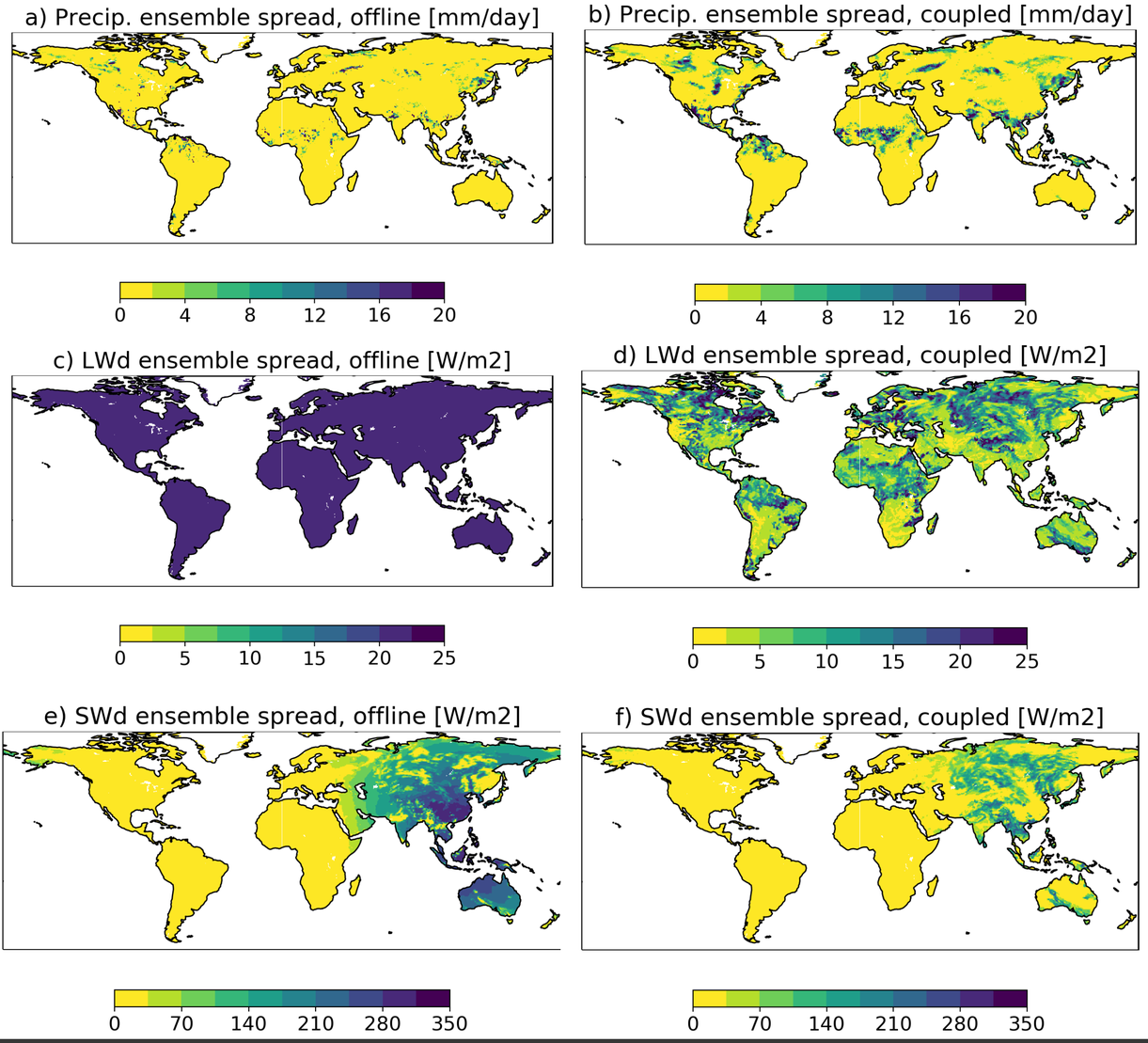
More info: Draper (2021), J. Hydromet, doi:JHM-D-21-0016.1

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