# The use of multidimensional Langevin processes for stochastic uncertainty quantification in the NOAA Unified Forecast System (UFS)

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# Outline

1. Motivation for stochastic physics development in the UFS

2. Unified framework for simulating process-level uncertainty in subgrid physics parameterizations

3. Preliminary results from testing the unified framework in FV3GEFS

4. Conclusions

# Motivation

It has become a standard at major NWP centers to use stochastic physics to represent uncertainty in the parameterizations of subgrid physical processes. Specifically, stochastic physics is required in the UFS for

(1) mitigating model error in data assimilation,

(2) improving the probabilistic skill of ensemble forecasts, and

(3) developing S2S stochastic prediction methods.

# Available methods for representing model uncertainty in the UFS

- Stochastically Perturbed Physics Tendencies (SPPT) scheme: simulates uncertainty due to sub-grid parameterizations (Palmer et al., 2009)
- Stochastic Kinetic Energy Backscatter Scheme (SKEB): parameterizes a missing and uncertain process (Palmer et al., 2009)
- Stochastically-perturbed boundary-layer humidity (SHUM) scheme: perturbs boundary layer humidity following Tompkins and Berner (2008)
- VC scheme: vorticity confinement based on Sanchez et al (2012)

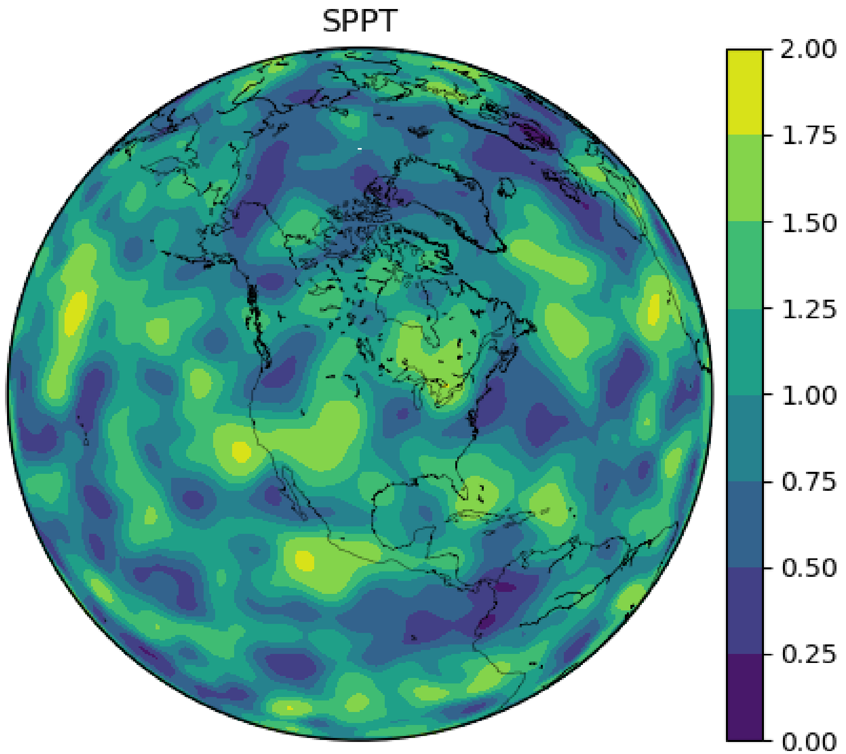
All use stochastic random pattern generators to generate spatially and temporally correlated noise

# Methods for representing model uncertainty in the UFS

An example: the SPPT scheme

$$Total\ Physics\ Tendency = (1 + \hat{e}) \sum_{i=1}^{N} \left(Individual\ Physics\ Tendecy\right)_i$$

$(1 + \hat{e})$




N = 5 in the GEFS:

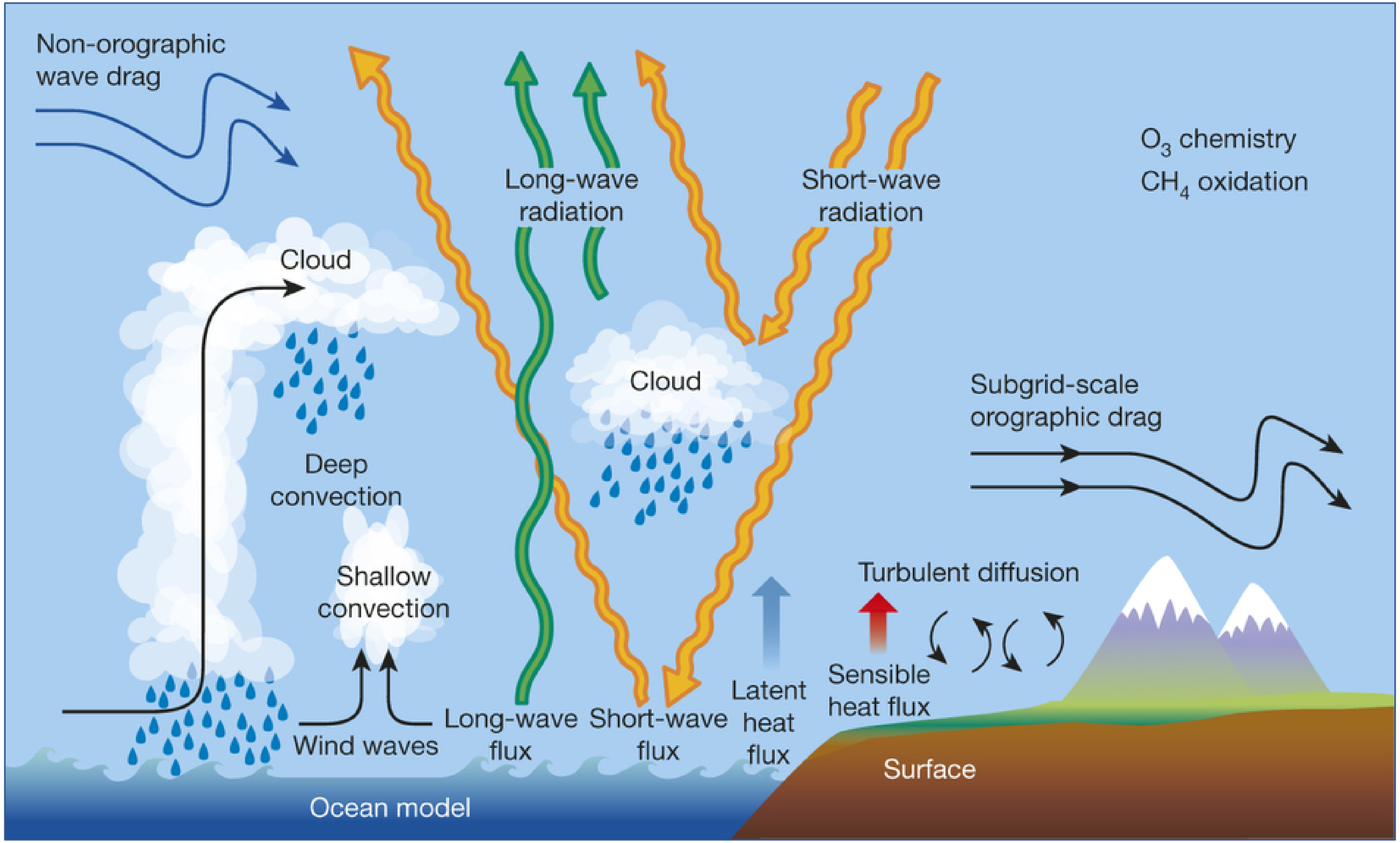
1. Radiation
2. Surface fluxes
3. Turbulent mixing and gravity wave drag
4. Convection
5. Microphysics

Physics tendencies of four variables are randomly perturbed:
U, V, T, q

The random perturbation is invariant vertically but tapered in the boundary layer and stratosphere

(adapted from ECMWF)

# Unified framework for simulating uncertainty in subgrid physics parameterizations




Peter Bauer et al. (2015)

# Seeking a general theoretical framework consistent with the *Correspondence Principle*

A new theory or parameterization should not reject the previous correct theory or parameterization but rather generalize them, so that the old (previous) theory or parameterization becomes a particular case of the new one... While the formulation of the correspondence principle is simple, it is nevertheless a very powerful methodological tool in understanding natural phenomena and developing correct generalizations of the existing theories and parameterizations.

Adapt from "*Thermodynamics, Kinetics, and Microphysics of Clouds*"
*by Khvorostyanov and Curry (2014)*

# How to simulate uncertainty in subgrid physics parameterizations

We have identified that model uncertainty associated with subgrid physics can be expressed as a stochastic perturbation that is the sum of two terms:

$$(\partial \delta \boldsymbol{x} / \partial t)_{subgrid} = [dynamical\ memory] + [stochastic\ perturbation\ of\ subgrid\ process(es)]$$

Bengtsson, L., Bao, J.-W., Pegion, P., Penland, C., Michelson, S., Whitaker., J. 2019: A model framework for stochastic representation of uncertainties associated with physical processes in NOAA's Next Generation Global Prediction System (NGGPS). Mon. Wea. Rev., 147, 893-911.

# Theory for the unified framework: Coarse-graining a model to a reduced resolution

$$\dot{\boldsymbol{x}} = \boldsymbol{M}(\boldsymbol{x}(t)), \qquad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

$$\boldsymbol{x} = \overline{\boldsymbol{x}} + \widetilde{\boldsymbol{x}} = \text{[resolved]} + \text{[unresolved]}$$


1. Kondrashov, D., Chekroun, M. D., and Ghil, M., 2015: Data-driven non-Markovian closure models. Physica D, 297, 33–55.
2. Wouters, J., and Lucarini, V., 2013: Multi-level dynamical systems: Connecting the Ruelle response theory and the Mori-Zwanzig approach. J. Stat. Phys., 151, 850-860.

# Theory for the unified framework: Coarse-graining a model to a reduced resolution

- Rewrite model as the so-called Liouville equation:

$$\frac{\partial \boldsymbol{z}}{\partial t} = \boldsymbol{L}\boldsymbol{z}(\boldsymbol{x}, t), \qquad \boldsymbol{z}(\boldsymbol{x}, 0) = \boldsymbol{a}(\boldsymbol{x})$$

where the Liouville operator is defined as

$$\boldsymbol{L} = \boldsymbol{M} \cdot \nabla$$


1. Ehrendorfer, Predicting the uncertainty of numerical weather forecasts: a review, Meteorol. Zeitschrift. 1997.
2. Chorin et al., Optimal prediction and the Mori-Zwanzig representation of irreversible processes, PANS, 2000.

# Theory for the unified framework: Coarse-graining a model to a reduced resolution

Use the Mori-Zwanzig projection operators to map the Liouville equation onto the resolved and sub-grid variables: **P** is the projection to map ***z*** onto the grid-resolved variables and **Q = I – P** is the projection to map ***z*** onto the subgrid variables

$$\dot{\overline{\boldsymbol{x}}} = \boldsymbol{e}^{t\boldsymbol{L}}\boldsymbol{P}\boldsymbol{L}\overline{\boldsymbol{x}}_0 + \int_0^t \boldsymbol{e}^{(t-s)\boldsymbol{L}}\boldsymbol{P}\boldsymbol{L}\boldsymbol{e}^{s\boldsymbol{Q}\boldsymbol{L}}\boldsymbol{Q}\boldsymbol{L}\overline{\boldsymbol{x}}_0 ds + \boldsymbol{e}^{t\boldsymbol{Q}\boldsymbol{L}}\boldsymbol{Q}\boldsymbol{L}\,\overline{\boldsymbol{x}}_0$$

Resolved dynamics

“memory" term because it is an integration of quantities that are dependent on the model state at earlier times

“noise” term, representing the unresolved dynamics

# Introducing the multidimensional Langevin process (MLP)

In the physics literature, stochastic processes described by the generalized Langevin equation are called multi-dimensional Langevin Processes (MLPs). Two approaches have been pursued to reduce the stochastic simulation of model uncertainty from the generalized Langevin equation to either (1) autoregressive models, AR($q$) or (2) autoregressive moving average models, ARMA($q$, $p$). Thus, the minimal form of the MLP for model uncertainty simulation is the following AR(1) process

$$\delta \boldsymbol{x}(t + \Delta t) = \phi \delta \boldsymbol{x}(t) + \rho \eta(t) \Delta t [d\boldsymbol{x}(t)/dt]_{physics} ,$$

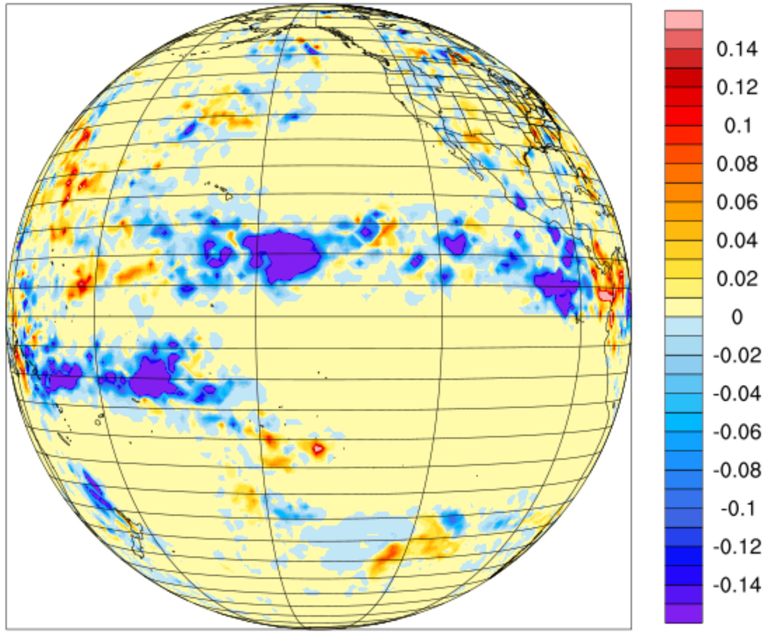
which is a dimensional analogy to the SPPT weight pattern generator

$$\hat{e}(t + \Delta t) = \phi \; \hat{e}(t) + \rho \eta(t)$$

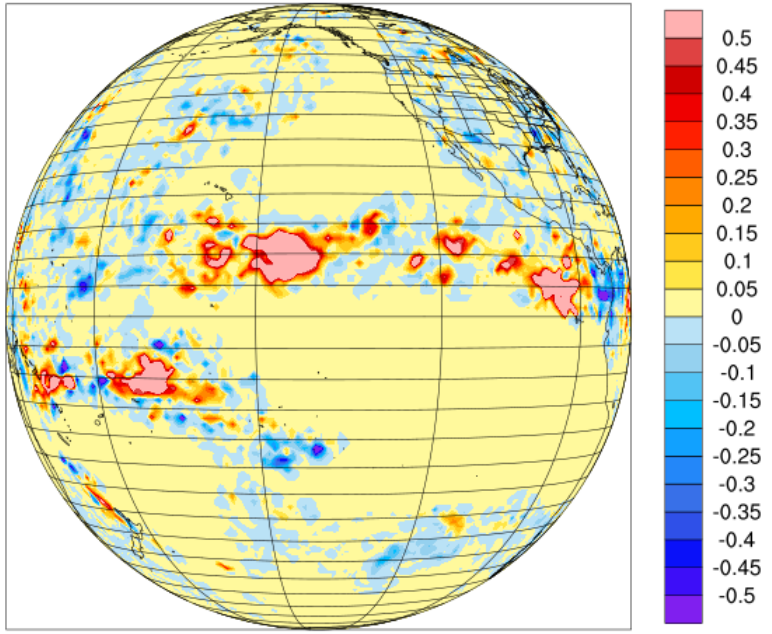

1. Horenko et al., Data-based parameter estimation of generalized multidimensional Langevin processes, *Phys. Rev. E.*, 2007.
2. Shutts, A stochastic convective backscatter scheme for use in ensemble prediction systems, *Q.J.R. Met. Soc.*, 2015.

# Stochastic perturbations at forecast time 36 h at level 534 mb

$\delta T_{conv}$ →



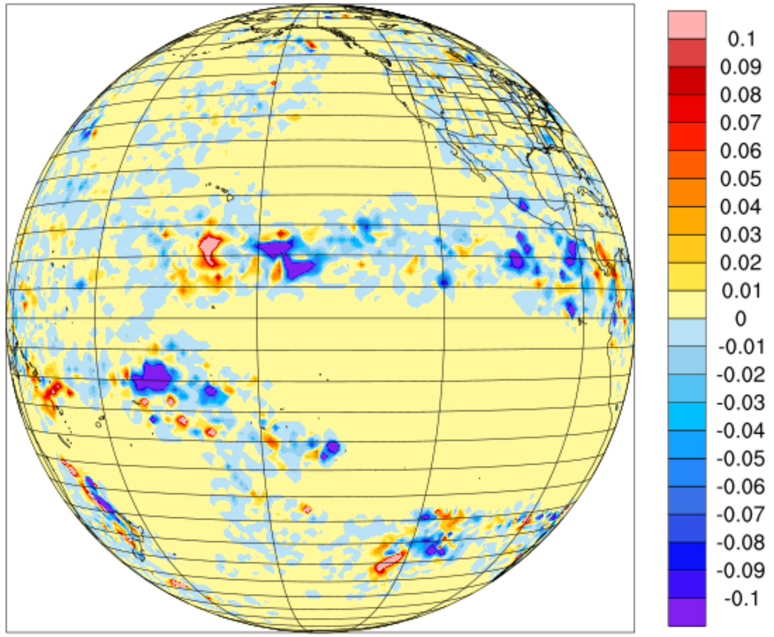

$\delta q_{conv}$ →



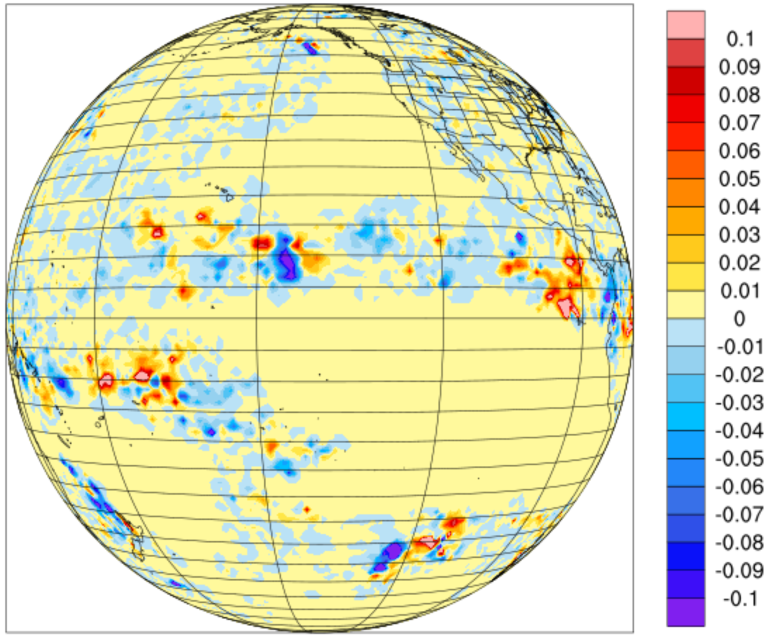

**Initial Time: 00 UTC Aug 1 2014, C192**

# Stochastic perturbations at forecast time 36 h at level 534 mb

$\delta u_{conv}$



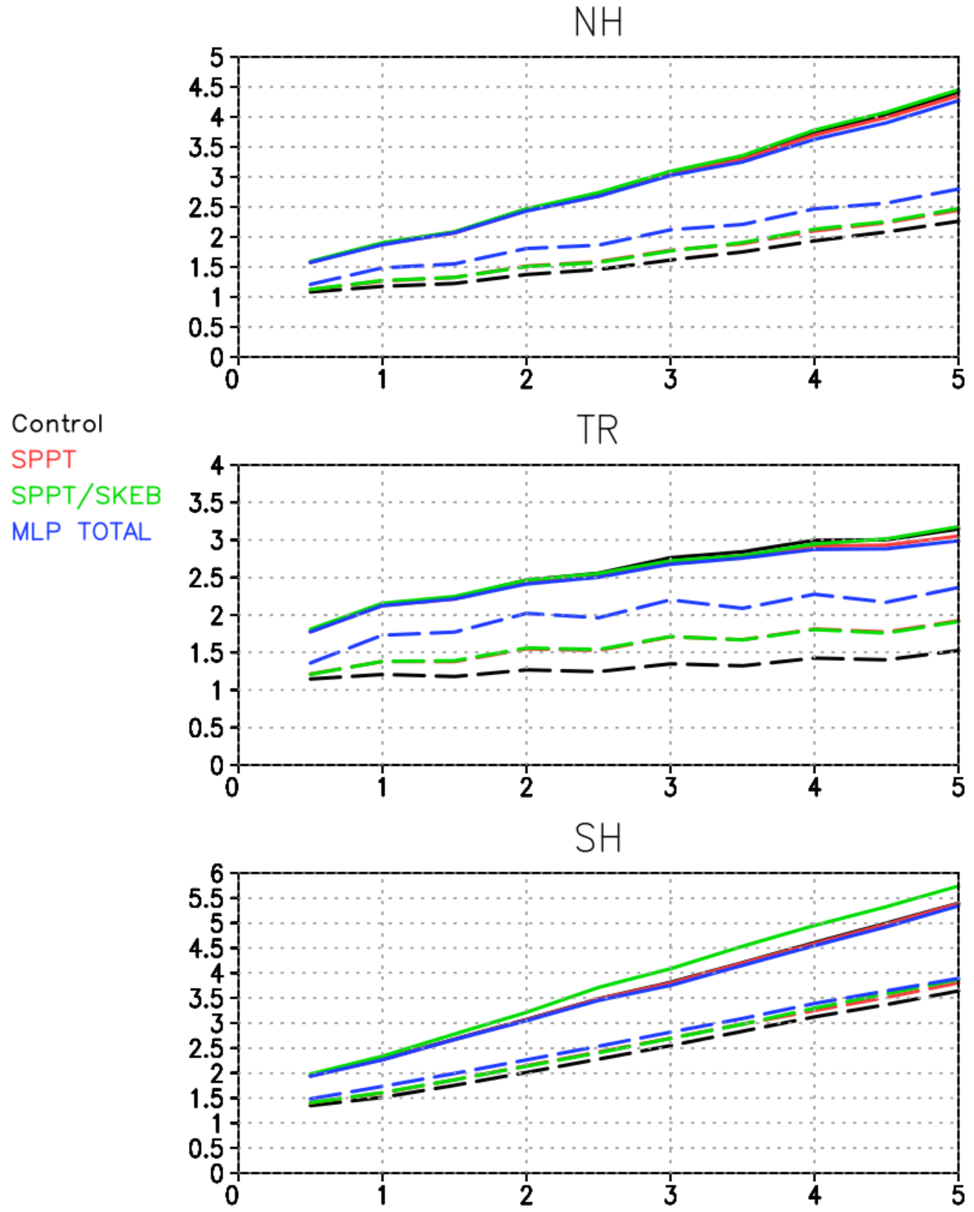

$\delta v_{conv}$




**Initial Time: 00 UTC Aug 1 2014, C192**

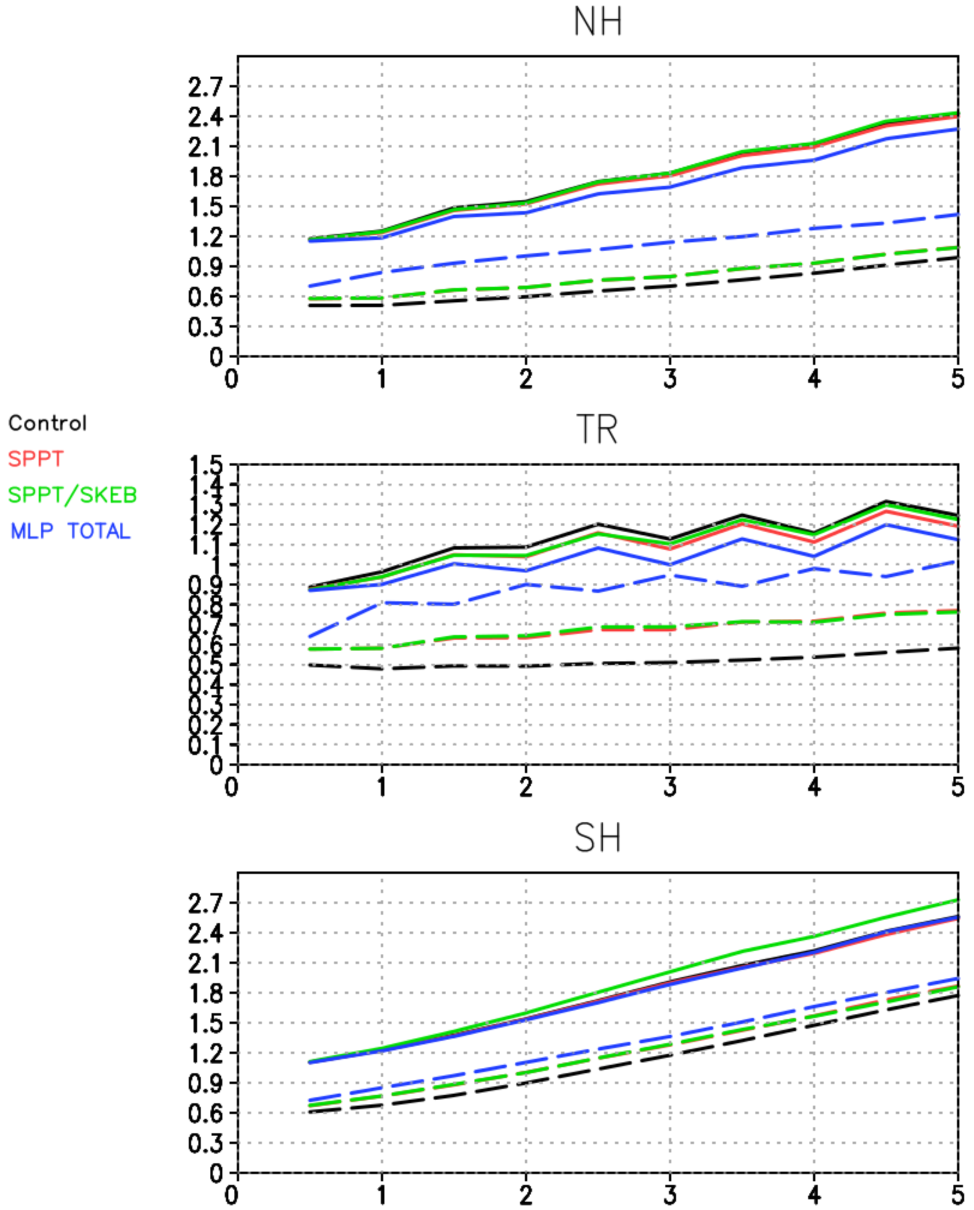
# 5-day forecasts, 850 mb U-component of wind RMSE and Spread
# Initial Times: 00 UTC Aug. 1-5 2014, C192

**Solid=RMSE**
**Dashed=Spread**



# 5-day forecasts, 850 mb Temperature RMSE and Spread
# Initial Times: 00 UTC Aug. 1-5 2014, C192

**Solid=RMSE**
**Dashed=Spread**



# Conclusions

- We are accelerating the stochastic physics development in the UFS using a unified theoretical framework to account for uncertainty in subgrid physics.
- The unified theoretical framework is based on the application of multi-dimensional Langevin Processes (MLPs).
- An MLP can be used for simulating model uncertainty in any subgrid transport process, including turbulent fluxes.
- Preliminary testing in NOAA’s UFS shows promise in increasing ensemble spread while reducing RMSE.