PSL update: Activities related the UFS physics development

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PSL collaborating closely with the UFS community to improve and further develop:

- Grid-resolved and sub-grid cloud physics
  - Effective vs efficient
  - Dynamical-core dependent
  - DA/initialization friendly
- Cloud-radiation interaction
  - Consistent size distribution assumptions, etc.
- Sub-grid turbulence mixing
  - Coherent 3-D mixing vs separate 1-D PBL and H-diffusion
- Air-sea interaction
  - Minimal level of complexity vs full-blown dynamical coupling
- Stochastic physics to account for model uncertainties
- Observational evaluation
  - Problem-targeted data collection vs off-the-shelf available observations

Development activities PSL has been contributing to, in particular

- A generalized, process-level stochastic physics

- Process-Level Assessment of two EDMF PBL Schemes available in the UFS

- A dynamically coherent 3-D subgrid mixing scheme for the UFS applications at gray-zone grid sizes

The Mori-Zwanzig formalism: A general principle for representing subgrid uncertainty

- The model system can generally be expressed in the phase space as the following:

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

- 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

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

(Chorin et al., Optimal prediction and the Mori-Zwanzig representation of irreversible processes, PANS, 2000)

The Mori-Zwanzig formalism (cont'd)

- The following generalized Langevin equation can be obtained by using the Mori-Zwanzig projection operators to map the Liouville equation on to the resolved and sub-grid 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

where ***P*** is the projection to map z onto the resolved variables and ***Q = 1 – P*** is the projection to map z onto the subgrid variables

(Chorin et al., Optimal prediction and the Mori-Zwanzig representation of irreversible processes, PANS, 2000)

The multidimensional Langevin process (MLP)

In the physics literature, stochastic processes described by the generalized Langevin equation are called multi-dimensional Langevin Processes (MLP). 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

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

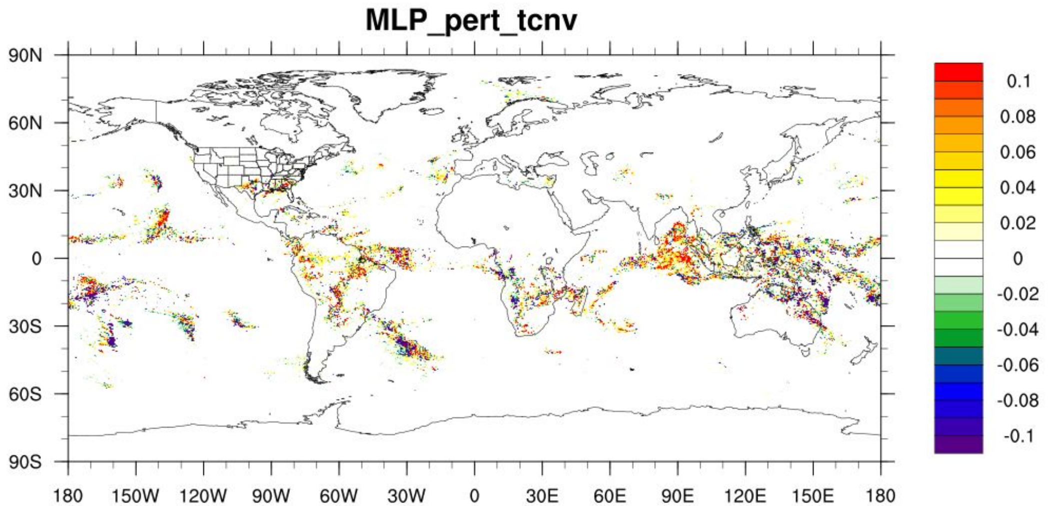
which is a dimensional analogy to the currently widely-used stochastic random pattern generators

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

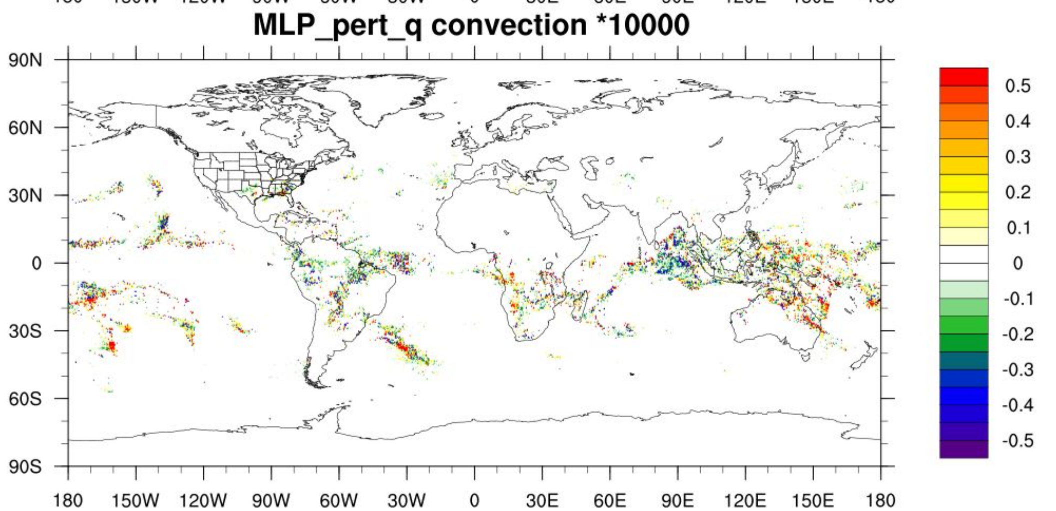
(See, e.g., Shutts, A stochastic convective backscatter scheme for use in ensemble prediction systems, *Q.J.R. Met. Soc.*, 2015)

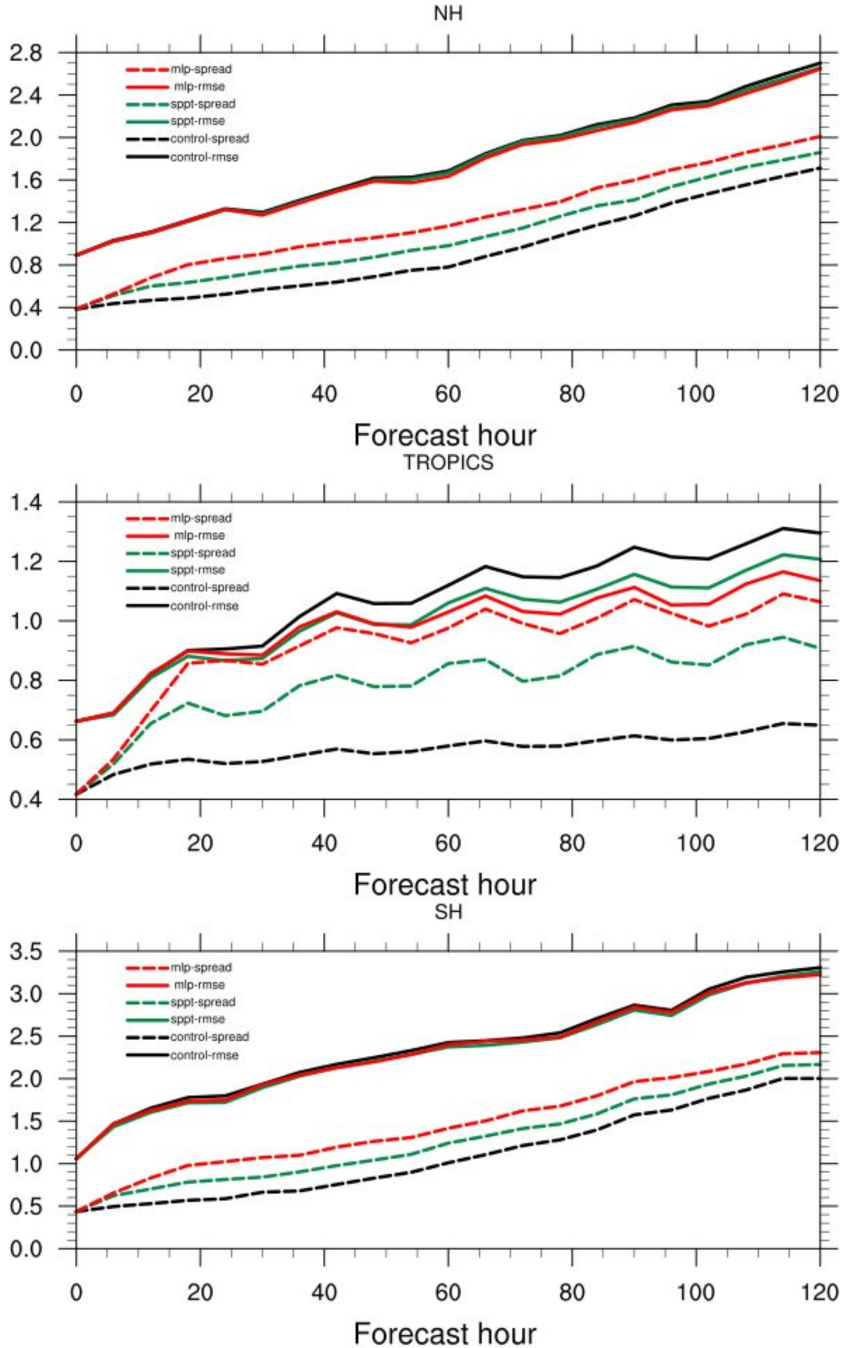
Perturbations of temperature and moisture from the convection scheme at 500 mb at Forecast time 36h

δT_{conv}



δq_{conv}





Solid=RMSE
Dashed=Spread

850 mb Temperature RMSE and Spread averaged over 9 cases initialized at 0000 UTC on: January 1, 2017, January 15, 2017, April 1 2017, April 15 2017, July 1, 2017, July 15 2017, October 1, 2017, October 15, 2017 and November 1 2017. Top panel is averaged over the Northern Hemisphere, the middle panel is averaged over the tropics and the lower panel is averaged over the Southern Hemisphere.

Single-Column Model (SCM) Experiments

A LASSO case (Gustafson et al. 2020) included in the CCPP-SCM release is used for the SCM experiments. LES simulations were used to derive the initial sounding and the forcing.

- Initialized: 18 May 2016 at sunrise of local time
- Site: ARM's Southern Great Plains site near Lamont, OK
- Convective ABL development with formation of shallow clouds

Comparison of two PBL Parameterizations: the GFSv15 **Hybrid-EDMF** and the GFSv16 **TKE-EDMF** Schemes

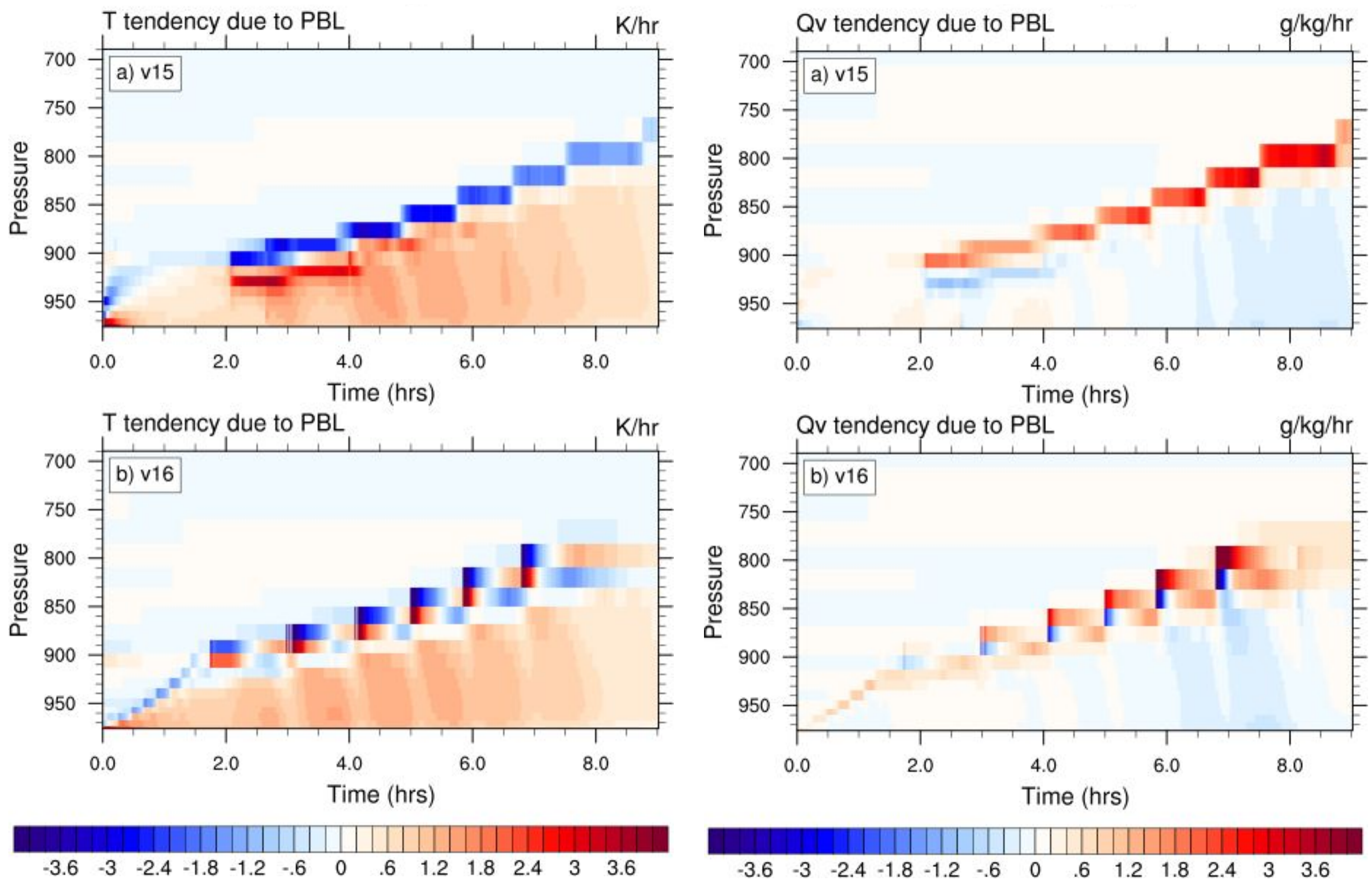
Tendencies due to ABL Processes

Hybrid-EDMF (v15, top) vs TKE-EDMF (v16, bottom)

TEMPERATURE | **SPECIFIC HUMIDITY**

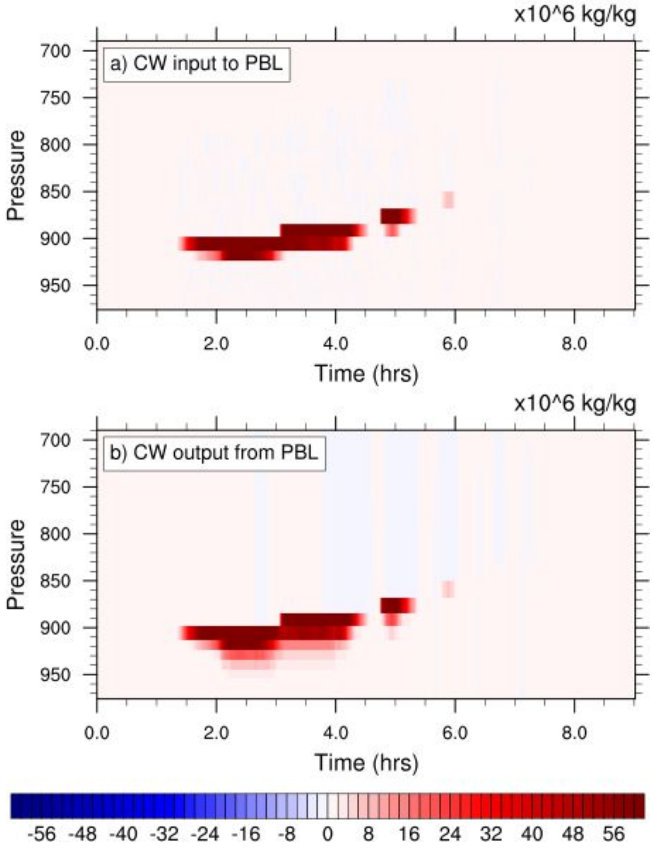
Hybrid-EDMF

TKE-EDMF

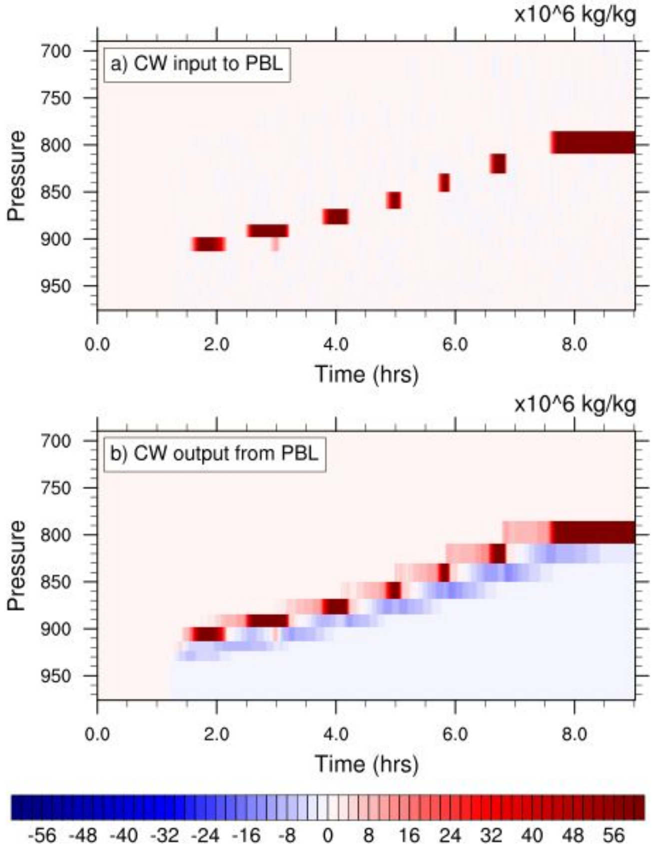


Cloud Water in the ABL:
ABL input (top) vs output (bottom)

V15 Control



V16 Control



Summary of our findings from the SCM experiments

- Sensitivity experiments using a single-column model show that the TKE-EDMF scheme mixes more strongly than the Hybrid-EDMF scheme for the LASSO/MSDA case. In particular, the nonlocal mixing is more dominant in the TKE-EDMF scheme than in the Hybrid-EDMF scheme, indicating an intrinsic uncertainty in the partitioning of the local and nonlocal mixing.

- **The unphysical realization of cloud water redistribution due to the mass flux mixing in the TKE-EDMF scheme is the root cause for the unphysical structure of the thermal state tendencies and the artifact of negative cloud water near the top of a simulated convective ABL.**

- The two PBL schemes in NOAA's GFS, i.e., the Hybrid-EDMF (v15) and TKE-EDMF (v16) schemes, solve the diffusion equation to yield temperature tendency assuming that (T/θ) is constant, an approximation to the governing equation of enthalpy diffusion.

A joint JTTI project (FIU, AOML, EMC and PSL) to develop a scale-adaptive 3D TKE mixing scheme in the HAFS

Purpose: Treat subgrid mixing in a coherent three-dimensional fashion by relaxing the conventional assumption of scale and formulation separation between the horizontal and vertical subgrid mixing

Approach: Blend vertical diffusivities from the LES and PBL parameterizations in the three-dimensional TKE equation

Objective: Enables a coherent 3-D subgrid mixing to work adaptively between the mesoscale NWP to LES grid-spacing limits