Dynamics-physics coupling in the context of the GEM dynamical core with height-based terrain-following vertical coordinate

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1. GEM-H DYNAMICAL CORE

- The operational **GEM-P** dynamical core is based on a log-hydrostatic-pressure-type terrain-following coordinate (TFC) in the vertical.
- The newly developed **GEM-H** core employs a height-based TFC.
- **GEM-H** is expected to be
  - more stable for steep-orography induced instability, and
  - more amenable to optimized 3D iterative solvers.

2. VERTICAL COORDINATE IN GEM-H

- The vertical coordinate in **GEM-H** is defined as

$$z = \zeta + Bz_s$$

  where ζ is the TFC, z is the true height, and z_s is the orography.
- The term B determines the rate of flattening of the orographic imprints on the TFC surfaces with increasing height from the surface.

3. GEM-H FORMULATION

- Derived from elastic Euler equations using an isothermal basic state with temperature T_* and pressure p_* which are connected through the hydrostatic relation, i.e., $\frac{\partial \ln p_*}{\partial z} = -g/(R_d T_*)$.
- Five prognostic equations for five variables: $\mathbf{V} = (u, v, w)$, T, and q [where $q = RT_* \ln(p/p_*)$].
- Vertical coordinate is transformed from (x, y, z) to (X, Y, ζ) coordinate.

4. Temporal Discretization

- General form of an individual equation within the **GEM-H** system:

$$\frac{dF_i}{dt} - G_i = P_i,$$

Advected quantity (F_i)
Physics forcing (P_i)
Dynamics source (G_i)

which is discretized in time using a semi-Lagrangian two-time level Crank-Nicolson scheme as

$$\underbrace{\frac{F_i^A - F_i^D}{\Delta t} - b_i G_i^A - (1-b_i) G_i^D}_{\text{off-centered averaging over trajectories}} = \mathbf{s_c} \overline{P}_i. \qquad [b_i \geq 0.5]$$

Determines dyn-phy copuling ($\mathbf{s_c}$)

A: arrival points at time *t*
D: departure points at *t*-Δ*t*.

5. DYNAMICS-PHYSICS COUPLING

- Depending on the value of the parameter $\mathbf{s_c}$, **GEM** (both **GEM-P** and **GEM-H**) allows two approaches for dynamics-physics coupling: (i) the tendency method, and (ii) the split-adjustment method.
- In the absence of subgrid-scale physics forcings, predictions by the adiabatic and inviscid versions of **GEM-P** and **GEM-H** dynamical cores are found to be equivalent (Husain et al. 2019).

6. TENDENCY METHOD

- Directly incorporates parameterized physics forcing as tendencies in the discretized dynamical equations, i.e. $\mathbf{s_c}$=1.
- Physics forcings are treated explicitly in time, and at each dynamics sub-step it involves solution of equations of the form

$$\frac{F_i^A - F_i^D}{\Delta t} - b_i G_i^A - (1-b_i) G_i^D = P_i^D.$$

- Physics tendency P_i from the previous time step is combined with the RHS terms before determining the combined RHS.
- Predictions from **GEM-P** and **GEM-H** are statistically equivalent .

6. TENDENCY METHOD (*continued*)

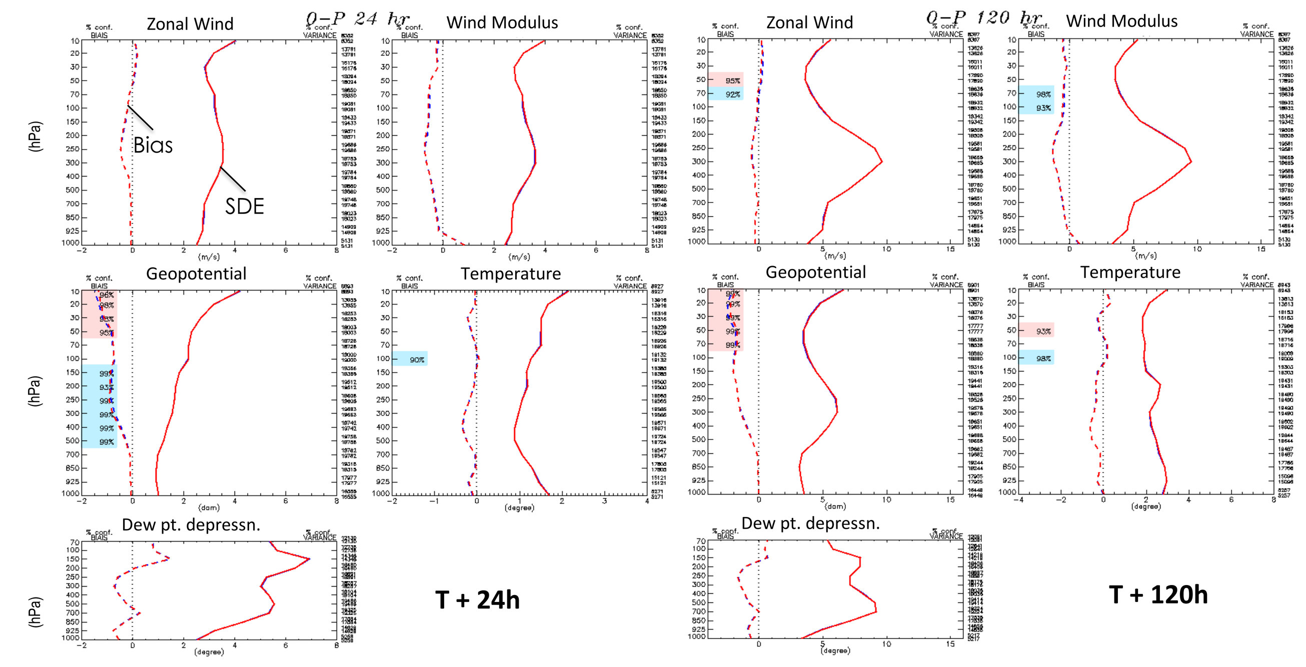

Fig. Upper-air scores for global average of 44 Northern Hemisphere winter cases from 2015 with GEM-P (blue) and GEM-H (refd).

7. SPLIT-ADJUSTMENT METHOD

- Dynamics step does not account for physics forcing, i.e., $\mathbf{s_c}$=0 (inviscid and adiabatic dyanmics solution).
- General form of discretized equations in the absence of physics:

$$\frac{F_i^{A*} - F_i^D}{\Delta t} - b_i G_i^{A*} - (1-b_i) G_i^D = 0$$

  where F_i^{A*} is the interim solution of the dynamics sub-step.
- Parameterized physics forcings are applied as grid-point adjustments as

$$(\delta F)_{phys} = F_i^A - F_i^{A*} = \Delta t P_i.$$

- The operational **GEM**-based NWP systems use the split method.
- With the operational **GEM-P**, only $(\delta u)_{phys}$, $(\delta v)_{phys}$ and $(\delta T_v)_{phys}$ adjustments are made in the split mode.
- In **GEM-H**, $\left(\frac{d \ln T_v}{dt}\right)_{phys}$ is added to the continuity equation in the tendency mode, making it a hybrid approach (Husain et al. 2019).
- Predictions from **GEM-P** and **GEM-H** are equivalent (not shown).

8. SPLIT vs TENDENCY METHOD

- The split method is found to be more noisy (Husain et al. 2019).
- Other researchers have in the past pointed out potential limitations of the split approach (Caya et al. 1998, Staniforth et al. 2002).
- However, the current implementation of the physics parameterizations in GEM leads to better forecast skills with the split method (for both **GEM-P** and **GEM-H**).

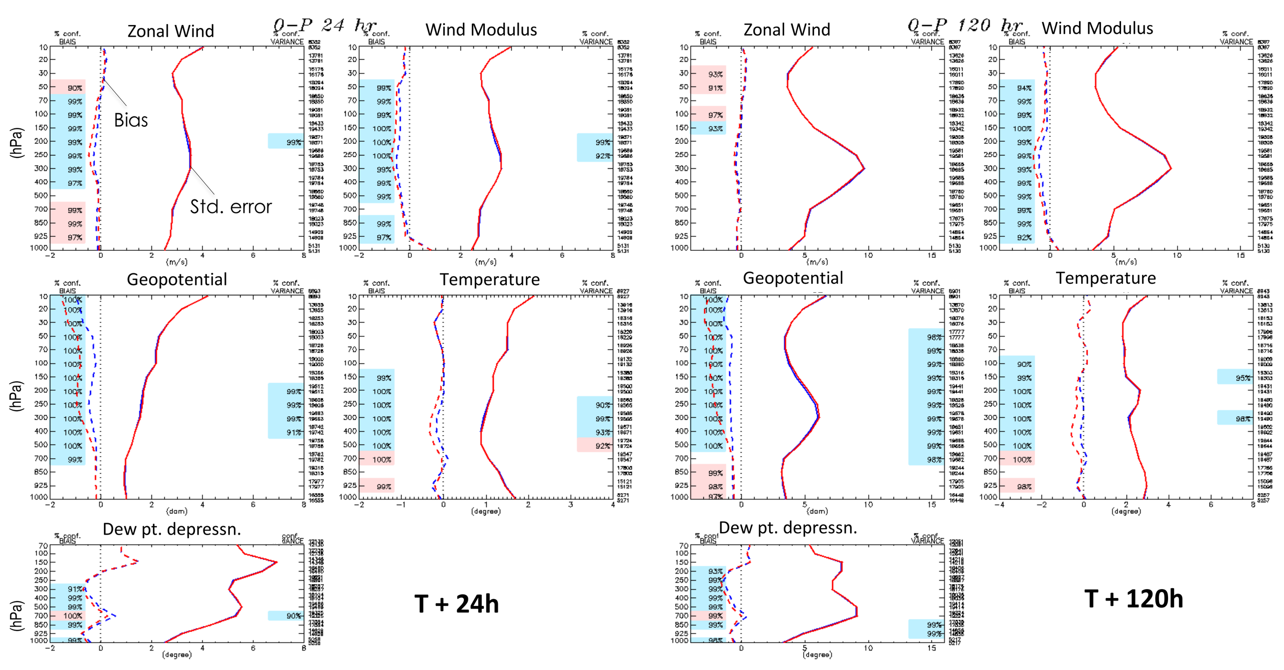

Fig. Upper-air scores for global average of 44 Northern Hemisphere winter cases from 2015. with split (blue) and tendency (red) methods with GEM-H.

9. FUTURE WORK

The objective is to devise an optimal dynamics-physics coupling strategy that will be theoretically more consistent while producing better or equivalent forecast skills when compared to the split method.

References

Caya, A., R. Laprise, and P. Zwack (1998): Consequences of using the splitting method for implementing physical forcings in a semi-implicit semi-Lagrangian model. Mon. Wea. Rev., 126: 1707-1713.

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Staniforth, A., N. Wood, and J. Côté (2002): Analysis of the numerics of physics-dynamics coupling. Q. J. R. Meteorol. Soc., 128: 2779-2799.

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