Configuration and Evaluation of a Global Variable-Resolution Model with Various Refinement Approaches

Yihui Zhou[1] (zhouyh@lasg.iap.ac.cn), Yi Zhang[2], Zhuang Liu[3], Jian Li[2], and Rucong Yu[2]

[1]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China;
[2]Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China;
[3]National Supercomputing Center in Wuxi, Jiangsu, China

1. Motivation

High-resolution modeling is generally preferred for accurate simulations of the global weather and climate but demands substantial computational resources. The variable-resolution (VR) modeling approach preserves the benefit of high-resolution modeling for the region of interest at a lower computational cost. The Global-to-Regional Integrated forecast SysTem (GRIST)-Atmosphere framework is tested with idealized dry and moist test cases to examine its performance in an intermediate degree of complexity. The major purpose of this study is twofold:

I. To validate the reasonable behavior of the dynamical model in its VR configuration, and to understand the strength and weakness under various refinement meshes;
II. To provide a guidance of utilizing different VR meshes for real-world modeling in future.

2. Model and mesh generation

2.1 Model

- The model GRIST-A20 uses an unstructured-mesh formulation, which permits the use of Spherical Centroidal Voronoi Tessellation that enables VR modeling.
- The dry dynamical core (dycore) framework is described in Zhang et al. (2019), with an enhanced treatment for vorticity dynamics. The moist atmospheric model is equipped with a general Physics-Dynamics Coupling workflow that has a dycore-tracer-physics splitting function (cf., Zhang et al., 2020).

2.2 Mesh generation

In this study, we use three different ways to construct the original generators.

(i) Icosahedron bisection (Grid-level/Gn);
(ii) Icosahedron bisection with a final-step trisection (GnB3);
(iii) Spherical uniform random (SUR) set of points by the Monte Carlo method.

The VR mesh is constructed through an iterative process based on the density function.

The single-region refinement follows the density function in Ringler et al. (2011):

$$\rho(x_i) = \frac{1}{2(1-\gamma)}\left[\tanh\left(\frac{\beta - \|x_{rc} - x_i\|}{\alpha}\right) + 1\right] + \gamma.$$

Regarding the multi-region refinement, we adapt the formulation for hierarchical refinement:

$$\rho(x_i) = \frac{1}{2(1-\gamma)}\left[\frac{1-\lambda}{1-\gamma}\tanh\left(\frac{\beta_1 - \|x_{rc} - x_i\|}{\alpha_1}\right) + \frac{\lambda-\gamma}{1-\gamma}\tanh\left(\frac{\beta_2 - \|x_{rc} - x_i\|}{\alpha_2}\right) + 1\right] + \gamma.$$

α_1 controls the width of the inner transition zone;
λ represents the inner densifying ratio of the mesh resolution between the finest and finer resolution regions;
β_1 denotes the coverage radius of the finest-resolution region.

The other multi-region refinement is the polycentric refinement, which is the same as the single-region formulation except for adding another refined region with a different refinement center.

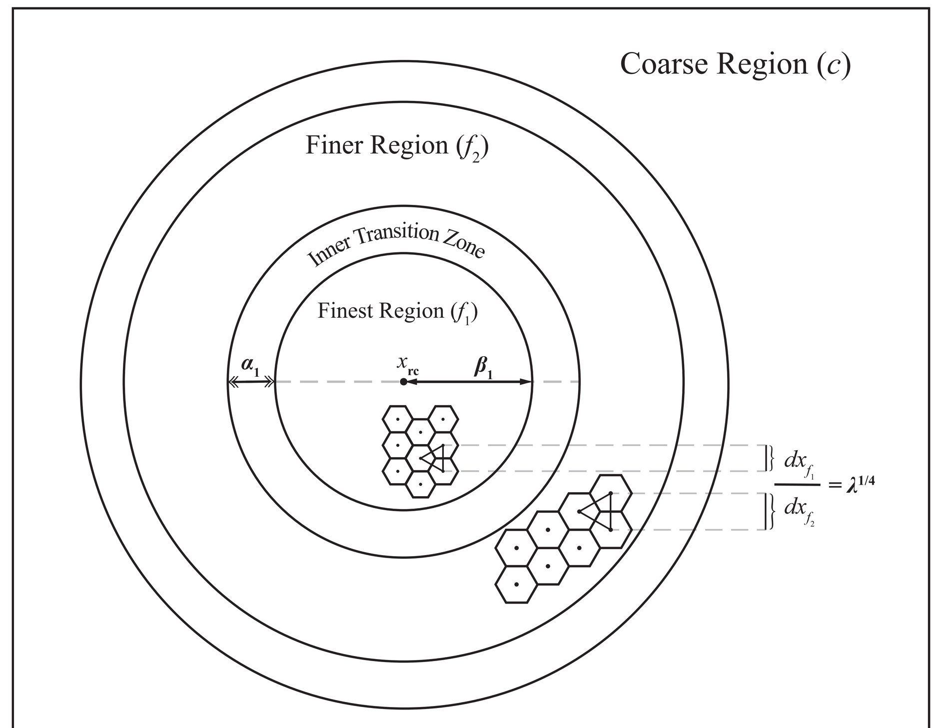


Figure 1. A schematic diagram of the hierarchical refinement mesh, illustrating the function of three parameters of the density function.

3. Dry-atmosphere simulations

3.1 Single-region refinement

We employ both nonhydrostatic and hydrostatic dynamical core for the dry atmospheric simulations. Results of the high-resolution quasi-uniform model are taken as a reference for evaluating the performance of variable-resolution model.

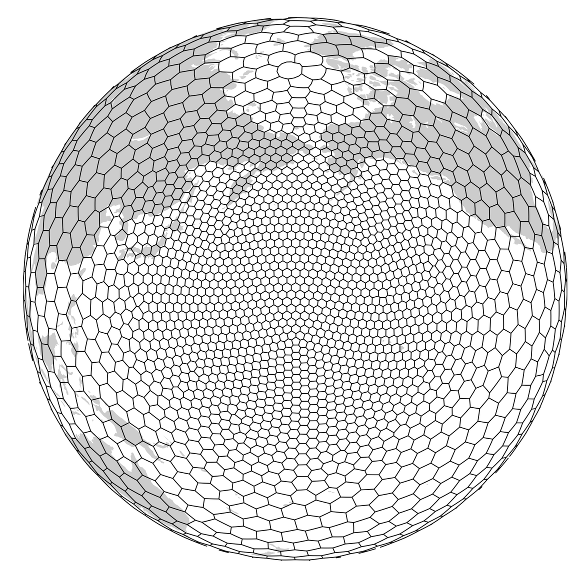


Figure 2. An illustration of the X4 variable-resolution mesh used for the baroclinic wave test with the refinement center x_{rc} at [180°E, 35°N], $\alpha = \pi/20$, and $\beta = \pi/6$. The mesh sizes are scaled up here for a clear vision of each grid cell based on reduced generators.

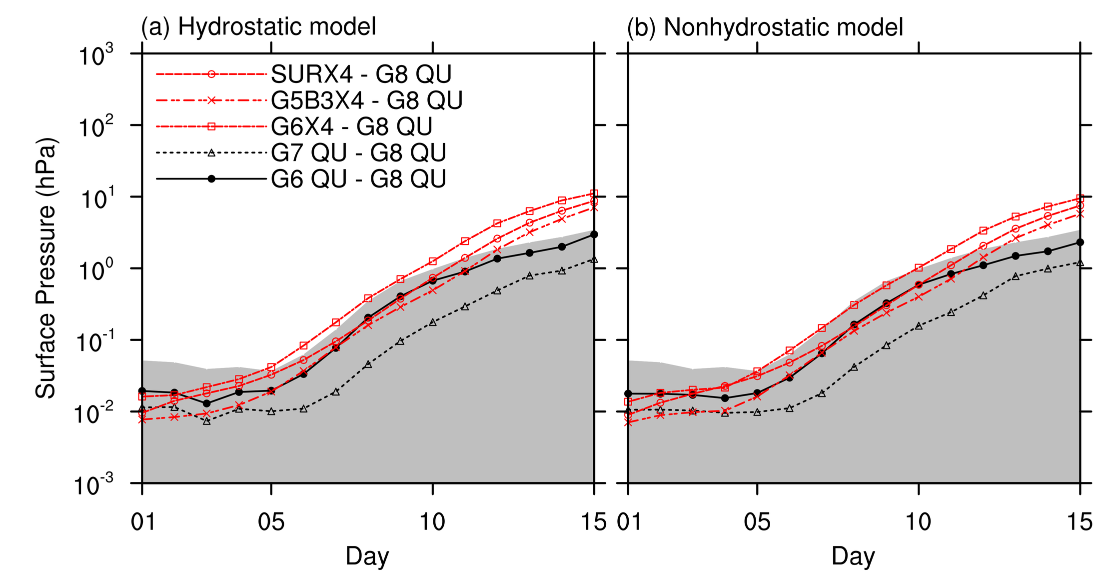
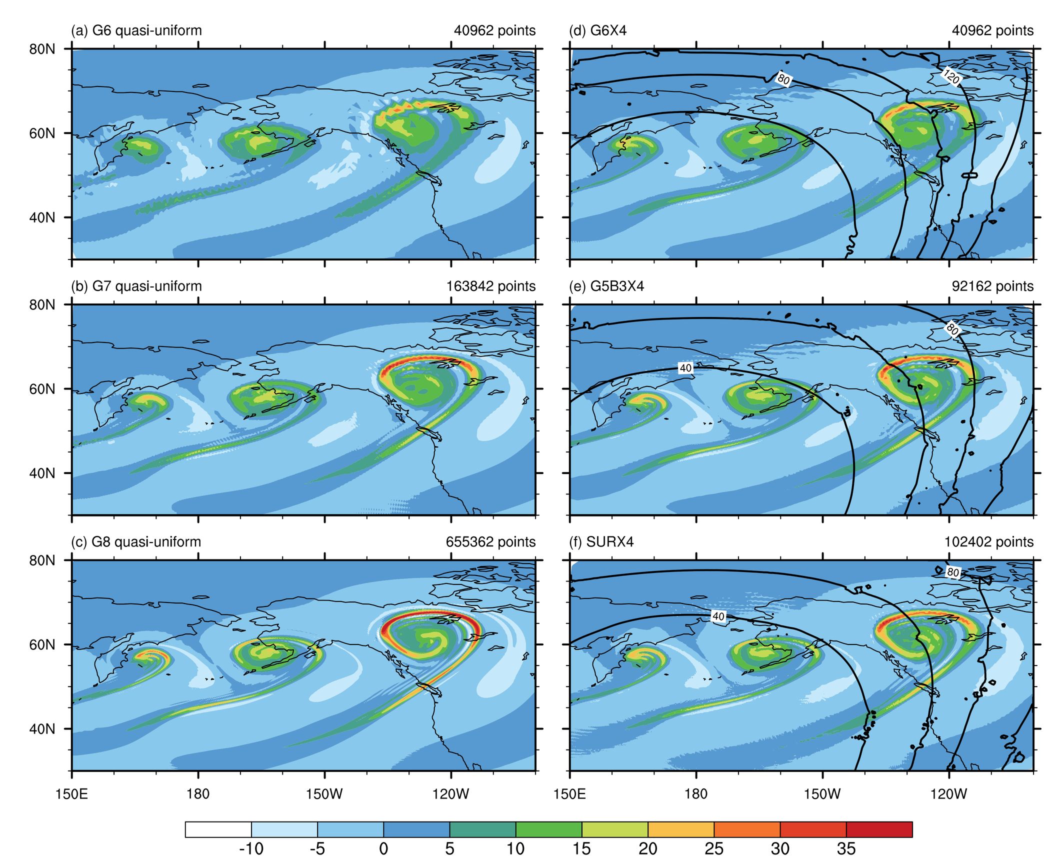


Figure 3. Baroclinic wave test: the l_2 error norms of surface pressure as a function of time for (a) hydrostatic and (b) nonhydrostatic dynamical core. The error of each simulation based on the low-resolution quasi-uniform mesh (black) and the variable-resolution mesh (red) is computed against the high-resolution quasi-uniform G8 mesh.



- The variable-resolution model possesses comparable accuracy compared to the quasi-uniform one.
- In the transition zone, the vorticity is hardly affected by the variation of the mesh resolution.

Figure 4. Baroclinic wave test: relative vorticity (10^{-5} s^{-1}) at the model level near 850 hPa after 10 simulation days simulated by the nonhydrostatic model with (a-c) quasi-uniform and (d-f) variable-resolution meshes. The quasi-uniform meshes include G6 (~120km), G7 (~60km), and G8 (~30km). The contour lines denote the mesh resolutions (km).

3.2 Multi-region refinement

In the multi-region refinement mode, as a compromise for larger refined regions and less grid points, the model well mimics the baroclinic waves with little grid-scale noise at higher resolutions utilizing higher G-level generators.

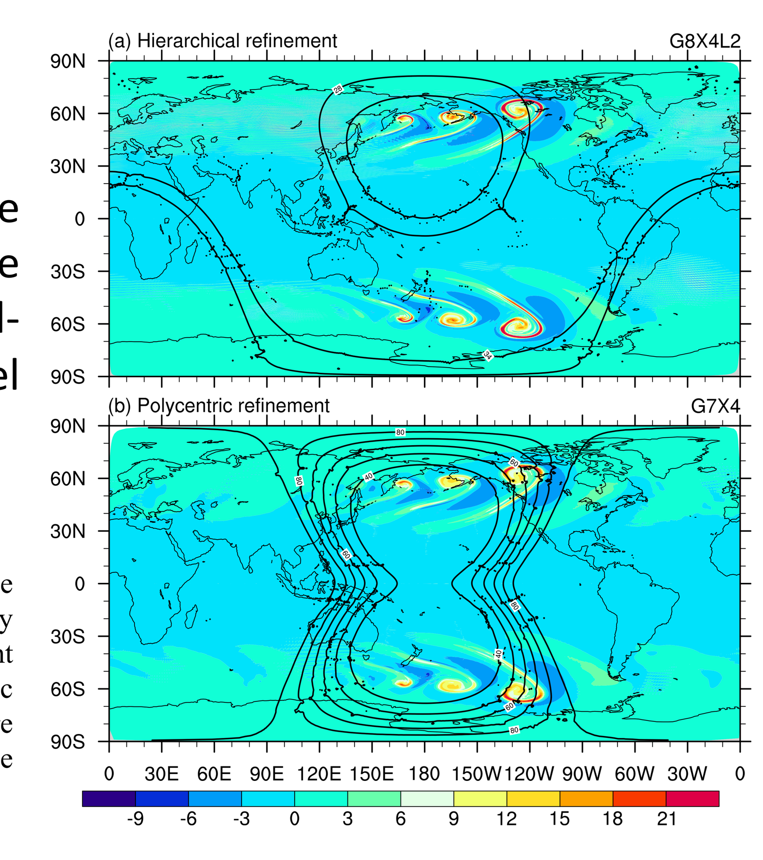


Figure 5. Adding a symmetrical perturbation in the southern hemisphere based on the baroclinic wave test: relative vorticity (10^{-5} s^{-1}) at the model level near 850 hPa at day 10 simulated by the nonhydrostatic model with the two multi-region refinement meshes: (a) the hierarchical refinement mesh G8X4L2 and (b) the polycentric refinement mesh based on G7X4. The values in the southern hemisphere are substituted by their opposite numbers for directly comparison to the vorticities in the northern hemisphere.

4. Moist-atmosphere simulations

In the hierarchical refinement mode, a series of sensitivity tests based on the three refinement parameters validates the maintenance of the tropical cyclone across the transition zone under adverse circumstances. The tropical cyclone rapidly develops regardless of its initial location and the variation in mesh resolution of the inner transition zone.

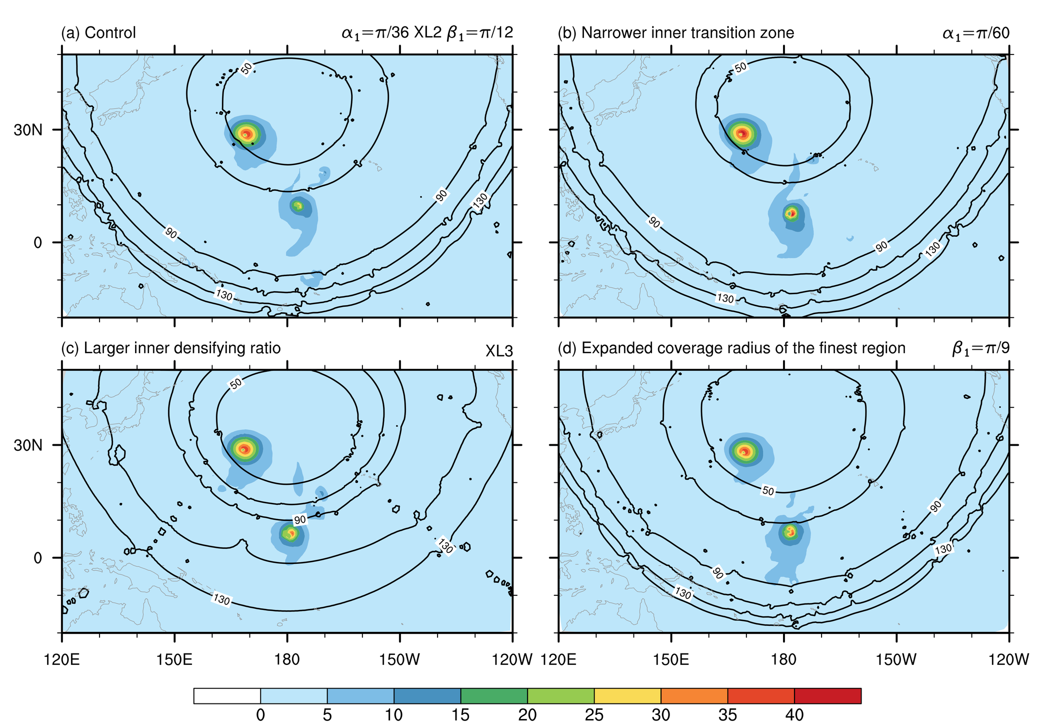


Figure 6. Idealized tropical cyclone test case: the horizontal wind speed (m/s) at 850 hPa after 10 simulation days based on hierarchical refinement meshes with (a) the control, (b) reduced α_1 and (c) higher λ for more rapid changes in the mesh resolution of the transition zone, and (d) larger β_1 to make the transition zone affect the tropical cyclone in an earlier stage. The tropical cyclone is initialized at [180°E, 10°N] in the finer region, near the transition zone between the finest and finer regions. The contour lines denote the mesh resolutions (km).

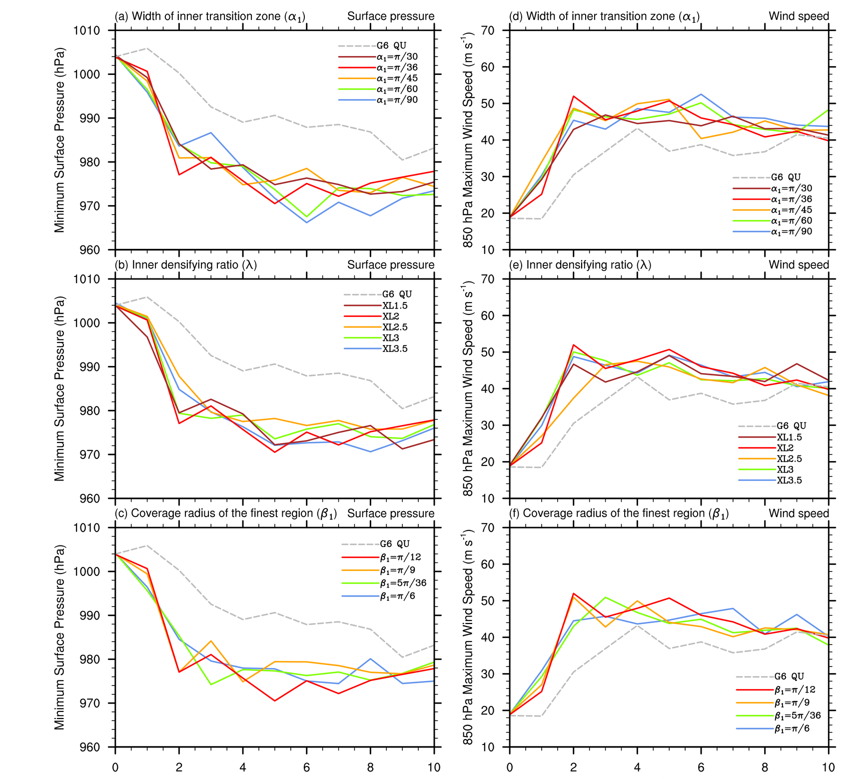
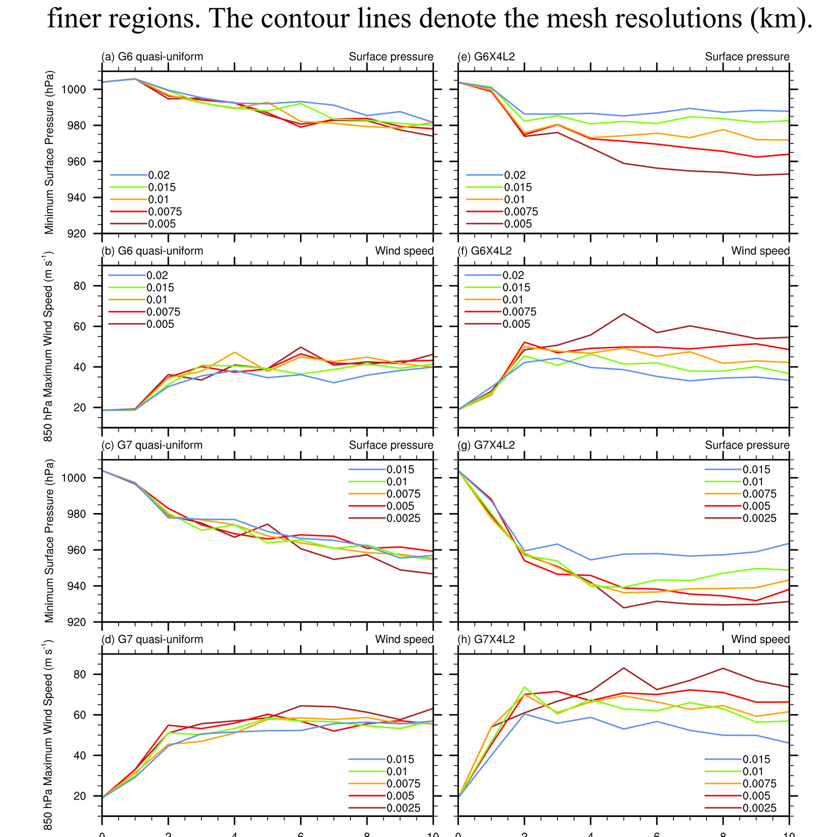


Figure 7. Idealized tropical cyclone test case: temporal evolution of minimum surface pressure and maximum 850-hPa horizontal wind speed based on the quasi-uniform G6 and hierarchical refinement meshes with (a, d) α_1, (b, e) λ, and (c, f) β_1 changed in the sensitivity tests. The three mesh parameters denote the width of the inner transition zone, the inner densifying ratio, and the coverage radius of the finest-resolution region, respectively.



- The intensity of the tropical cyclone increases as the Smagorinsky horizontal diffusion coefficient becomes smaller.
- The variable-resolution model exhibits higher sensitivity to the diffusion coefficient than the quasi-uniform model.

Figure 8. Temporal evolution of minimum surface pressure and maximum 850-hPa horizontal wind speed based on the quasi-uniform meshes (left column) and hierarchical refinement meshes (right column) with decreasing Smagorinsky horizontal diffusion coefficients marked by colors.

5. Conclusions

- Despite the increased global error, the variable-resolution model can reproduce a comparable result in the refined regions with the fine-resolution quasi-uniform model.
- Providing a more flexible formulation adapted by the density function, the model stability is testified within the multi-region refinement approaches under higher-resolution conditions.
- The variable-resolution model shows a higher sensitivity to the diffusion coefficient, highlighting the importance of parameter tuning and proper model configurations.

Key References

Ringler, T. D., Jacobsen, D., Gunzburger, M., Ju, L., Duda, M., and Skamarock, W.: Exploring a Multiresolution Modeling Approach within the Shallow-Water Equations, Mon. Wea. Rev., 139, 3348-3368, 2011.
Zarzycki, C. M., Jablonowski, C., and Taylor, M. A.: Using Variable-Resolution Meshes to Model Tropical Cyclones in the Community Atmosphere Model, Mon. Wea. Rev., 142, 1221-1239, 2014.
Zhang, Y., Li, J., Yu, R., Liu, Z., Zhou, Y., Li, X., and Huang, X.: A Multiscale Dynamical Model in a Dry-mass Coordinate for Weather and Climate Modeling: Moist Dynamics and its Coupling to Physics, Mon. Wea. Rev., accepted, 2020.