Scale Sensitivity of Parameterizations:
Idealized Variable Mesh Spectral Element Simulations

Preliminary report for CAM Development Assessment, December 2014

A. Gettelman, P. Callaghan, Z. Li, P. Lauritzen (NCAR), M. Taylor (SNL)

1. Introduction

Idealized simulations have been conducted to evaluate the performance of the Spectral Element (SE) dynamical core at variable resolution in the Community Atmosphere Model (CAM), and to evaluate different physics packages with variable resolution and the same simulations. This is a test of what is commonly called 'scale aware' parameterizations, but this is truly a horrible term (it implies the parameterization knows the length scale, which most physical parameterizations in GCMs do not). We prefer to state that we are seeking 'scale insensitive' parameterizations.

There has been extensive previous work with CAM-SE. Zarzycki et al (2014a) performed a similar study to this one using CAM-SE in an aquaplanet configuration with a variable mesh grid in the tropics. Results of this study are similar and will be noted below. Zarzycki et al (2014b) explored idealized tropical cyclones on an aquaplanet in the variable resolution CAM-SE, and Zarzycki et al (2014c) used realistic topography and a variable resolution grid over the N. Atlantic to simulate tropical cyclones.

This document contains results for Aquaplanet results for a High Latitude variable resolution mesh with idealized physics (section 2) and full physics (section 3) as well as a refined mesh in the tropics (section 4). A summary is in section 5.

2. Aquaplanet High Latitude Mesh: Baroclinic Wave Tests

Step 1 (which is not the main purpose of this document) was to analyze the dynamics of the spectral element dynamical core using the baroclinic wave test case of Jablonowski and Williamson (2006). A high-resolution region was put from 25-65N on an aquaplanet, and the baroclinic wave test (with idealized) physics was run with uniform high resolution (0.25deg, ne120 in the SE nomenclature), low resolution (1deg, ne30). Figure 1 shows an example of the mesh.

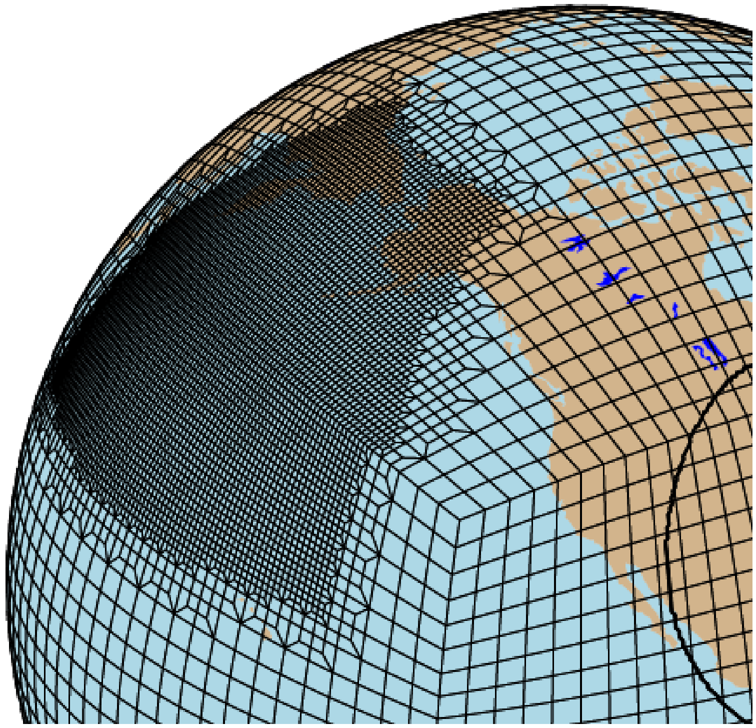

Figure 1: Mid-latitude variable resolution mesh for the Spectral Element (SE) dynamical core.

The main point is that the variable mesh dynamical core seems to properly represent the dynamics in variable resolution, and the dynamics can represent the high-resolution region. Other analyses (not shown) also illustrated that even outside of the high-resolution region in midlatitudes the simulations for variable mesh in the low resolution region look more like the high resolution region. Thus once waves are generated in the high-resolution region, they do propagate as expected into and through the low resolution region.

3. Aquaplanet High Latitude Mesh: Full Physics

This gives us some confidence in the configuration and in the dynamical core. The next step was to run the aquaplanet model with full physics. This was done for the mid-latitude refinement case again. Three different physics packages were used: CAM4, CAM5 and CAM-CLUBB. The CAM-CLUBB configuration is the older MG1 version. Note that all three configurations use the same basic deep convective scheme (Zhang and Macfarlane, 1995, hereafter ZM), with a slightly different closure (Neale et al, 2008). ZM is the same basically in all three configurations. But the shallow convective scheme is different in all three: Hack (1994) for CAM4, Park and Bretherton (2009) for CAM5 and CLUBB (Bogenschutz et al 2010) for CAM-CLUBB. Also note that CLUBB combines the macrophysics, boundary layer and shallow convection into one scheme that drives stratiform microphysics.

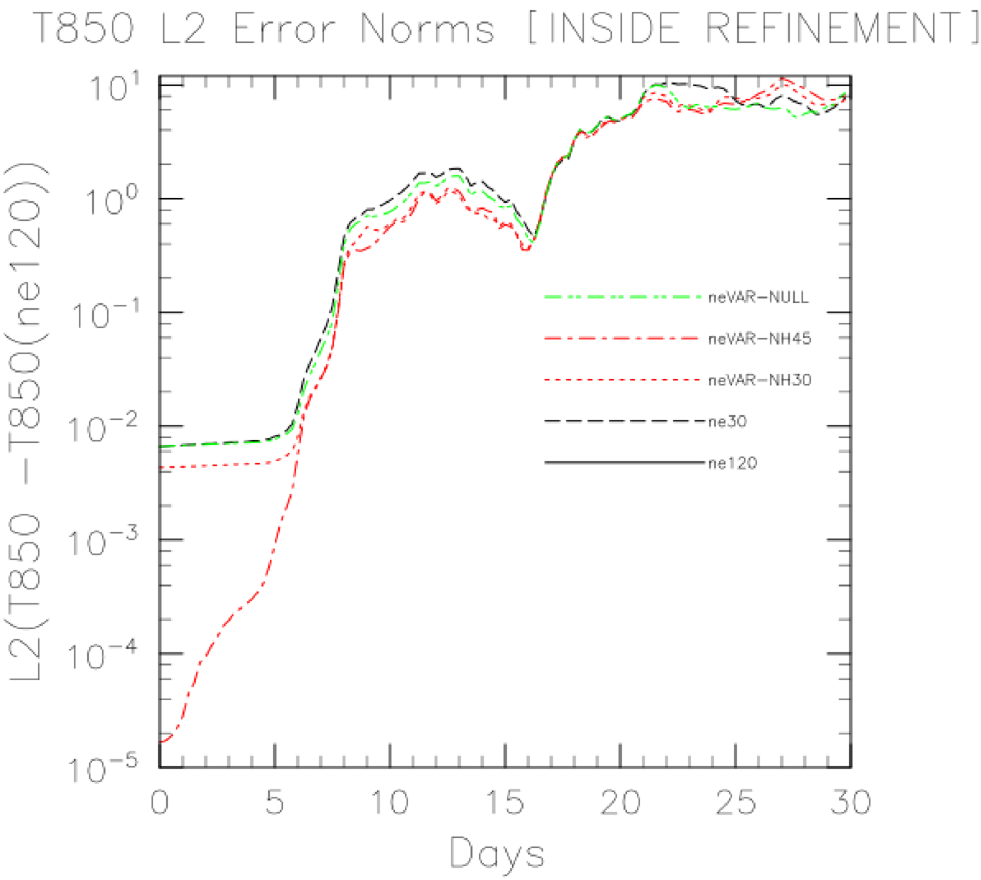

Figure 2: 850hPa temperature field L2 error norms following Jablonowski and Williamson (2006) inside a region of mid-latitude mesh refinement. L2 error norms show the difference from a reference, in this case uniform 0.25deg (ne120) resolution for variable mesh (neVAR-NH45: red dot dash), variable mesh with uniform ne30 settings for hyperviscosity (neVAR-NH30: red dotted), uniform low resolution (ne30: black dash) and uniform low with variable resolution settings (neVAR-NULL: green dot-dash).

Figure 3 illustrates the total cloud cover in the 25-65N latitude band both zonal mean (first column), inside the refined region (second column) and outside (third column). CAM4 has a large difference in cloud fraction between the region inside and outside of the mesh (black). CAM5 (blue) and CAM-CLUBB (red) have almost identical cloud fractions inside and outside of the mesh.

Figure 4 illustrates the same type of table, but for longwave cloud radiative effects (forcing). In CAM4 (black), cloud forcing differs by 5Wm-2 (20%) inside and outside of the variable mesh region. CAM5 (blue) varies by 0.5Wm-2, and CAM-CLUBB (red) by 0.1Wm-2.

Total Cloud Fraction

	CFRC	TOTAL AVG / SDEV	INSIDE AVG / SDEV	OUTSIDE AVG / SDEV
CAM4	cam4_ne120 (*)	0.577 / 0.096	0.576 / 0.098	0.577 / 0.095
	cam4_ne30	0.675 / 0.077	0.680 / 0.078	0.674 / 0.077
	cam4_neVAR_NH01	0.656 / 0.098	0.573 / 0.097	0.673 / 0.090
	cam4_neVAR_NULL	0.673 / 0.088	0.674 / 0.087	0.673 / 0.088
CAM-CLUBB	cam5club_ne120 (*)	0.693 / 0.050	0.702 / 0.053	0.692 / 0.049
	cam5club_ne30	0.731 / 0.046	0.733 / 0.047	0.730 / 0.046
	cam5club_neVAR_NH01	0.696 / 0.049	0.695 / 0.050	0.696 / 0.049
	cam5club_neVAR_NULL	0.698 / 0.049	0.697 / 0.048	0.698 / 0.050
CAM5	cam5_ne120	0.728 / 0.086	0.732 / 0.087	0.728 / 0.086
	cam5_ne30	0.750 / 0.090	0.751 / 0.091	0.750 / 0.090
	cam5_neVAR_NH01	0.730 / 0.089	0.726 / 0.088	0.730 / 0.089
	cam5_neVAR_NULL	0.735 / 0.089	0.733 / 0.089	0.735 / 0.089

Figure 3: Total cloud cover in the 25-65N latitude band for aquaplanet runs with full physics. Shown are the zonal mean (first column), inside the refined region (second column) and outside (third column). Variable mesh simulations are highlighted for CAM4 (black), CAM5 (blue) and CAM-CLUBB (red)

Long Wave Cloud Forcing

	LWCF	TOTAL AVG / SDEV	INSIDE AVG / SDEV	OUTSIDE AVG / SDEV
CAM4	cam4_ne120 (*)	22.813 / 4.711	22.912 / 4.707	22.793 / 4.711
	cam4_ne30	28.785 / 5.384	28.664 / 5.349	28.809 / 5.391
	cam4_neVAR_NH01	28.865 / 5.988	24.557 / 5.015	29.729 / 5.791
	cam4_neVAR_NULL	30.166 / 5.803	30.504 / 5.930	30.098 / 5.775
CAM-CLUBB	cam5club_ne120 (*)	22.043 / 4.670	22.325 / 4.636	21.987 / 4.674
	cam5club_ne30	22.890 / 5.226	23.019 / 5.298	22.864 / 5.211
	cam5club_neVAR_NH01	22.474 / 5.180	22.574 / 5.070	22.454 / 5.202
	cam5club_neVAR_NULL	22.794 / 5.169	22.549 / 5.007	22.842 / 5.199
CAM5	cam5_ne120	26.324 / 4.886	26.494 / 4.872	26.290 / 4.888
	cam5_ne30	27.930 / 5.441	28.299 / 5.674	27.856 / 5.390
	cam5_neVAR_NH01	26.871 / 5.406	26.437 / 5.118	26.958 / 5.458
	cam5_neVAR_NULL	27.408 / 5.490	27.374 / 5.550	27.414 / 5.478

Figure 4: Same as Figure 3 for longwave cloud forcing (radiative effect) in the 25-65N latitude band

Thus CAM5 and CAM-CLUBB are quite stable in mid-latitude cloud systems, CAM-CLUBB slightly more so. At least in terms of an aquaplanet configuration.

4. Aquaplanet Equatorial Refined Mesh: Full Physics

Finally, experiments have been conducted with a refined mesh region in the tropics, again using an aquaplanet configuration. The mesh is centered on the equator and extends 60 deg of longitude and 60 deg of latitude. This is indicated as the red lines on Figure 5.

Figure 5 presents a map of the mean tropical precipitation rate from these variable mesh simulations. CAM4 (Figure 5-right) has high precipitation in the refined region, CAM5 (Figure 5-center) has less precipitation in the high-resolution region and is more uniform, and CAM-CLUBB (Figure 5-left) has high precipitation both inside and outside of the high-resolution region.

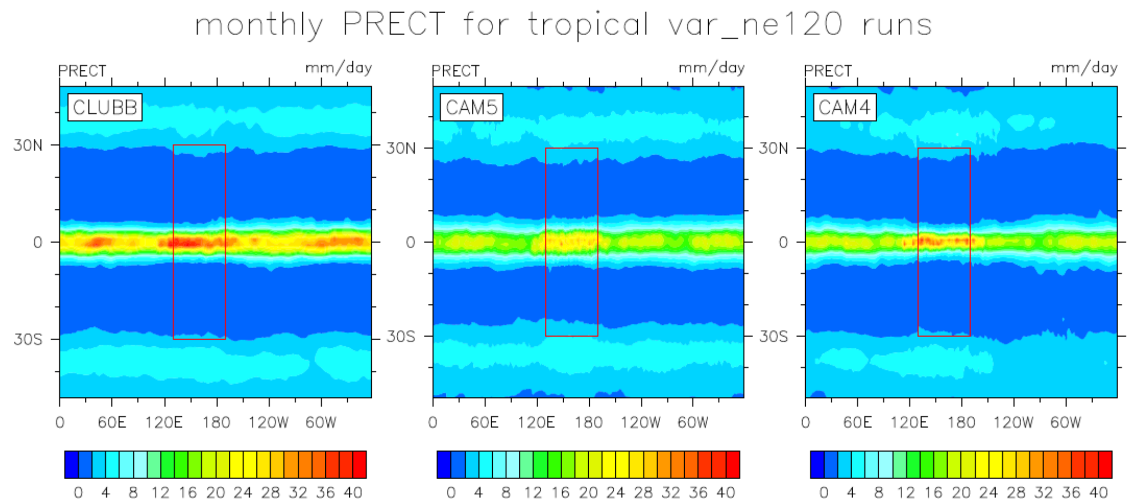

Figure 5: Total mean tropical precipitation rate (mm/day) from variable mesh aquaplanet simulations with different physics packages: CAM-CLUBB (left), CAM5 (center) and CAM4 (right)

The total precipitation (PRECT) is more stable inside and outside the high-resolution region along the equator in CAM-CLUBB than in other configurations. Figure 6 illustrates that the large scale (PRECL) and convective (PRECC) precipitation are very different inside and outside of the high-resolution region in all three simulations.

This probably should be the case. The timestep is the same in both regions, so the convective relaxation time in relation to the timestep is the same. But the vertical velocity forcing supersaturation for the large scale condensation is going to be different in the high resolution region: likely higher, driving more condensation. Since the condensation in the macrophysics is generally not limited with a timescale, it removes water right away. This would increase stratiform precipitation in the refined regions. More condensation done by the stratiform scheme with fixed precipitable water means less available for convection.

This occurs in all three schemes, but the balance in CAM-CLUBB seems more appropriate: because the total is more similar. This yields higher confidence in the performance of the scheme at high resolutions.

Finally we show sets of vertical profiles of the different tendency terms averaged over the high resolution region (solid lines) and outside of the high resolution region (dashed lines) in Figure 7 for temperature (T) and figure 8 for humidity (Q). The different terms are for the total (DTCOND and DCQ for temperature and humidity respectively), the macro and microphysics (MPDT and MPDQ, this includes all condensation from CLUBB), the shallow convection (CMFDT and CMFDQ: note CLUBB does not have any separate shallow convection, this is in MPDT and MPDQ) and tendencies for the deep convection (ZMDT and ZMDQ).

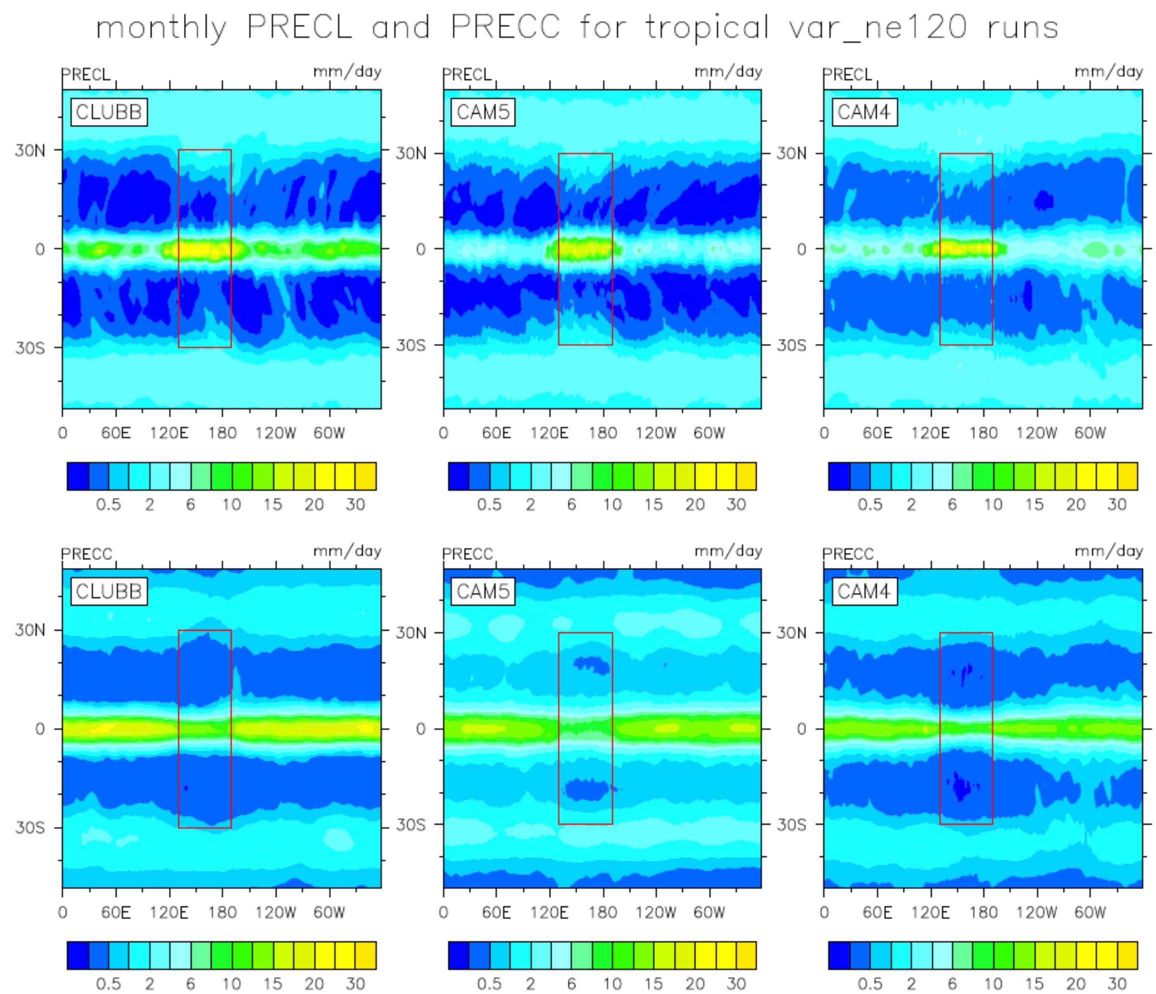

Figure 6: Tropical precipitation rates as in Figure 5 from variable mesh aquaplanet simulations. Top row: large scale precipitation, bottom row, convective precipitation.

Notable in Figure 7 is that the total heating tendency from moist processes is basically the same inside and outside of the high-resolution region. Deep convection contributes more outside of the region than inside. Note that the averages do not quite seem to balance: in this preliminary figure MPDT is a residual and there may be another term in the equation that was missed that may be compensating. But the total (black) should be correct. CAM4 and CAM5 have larger differences in the heating profile inside and outside of the refined region: in CAM5 the sign of the microphysical temperature tendency changes.

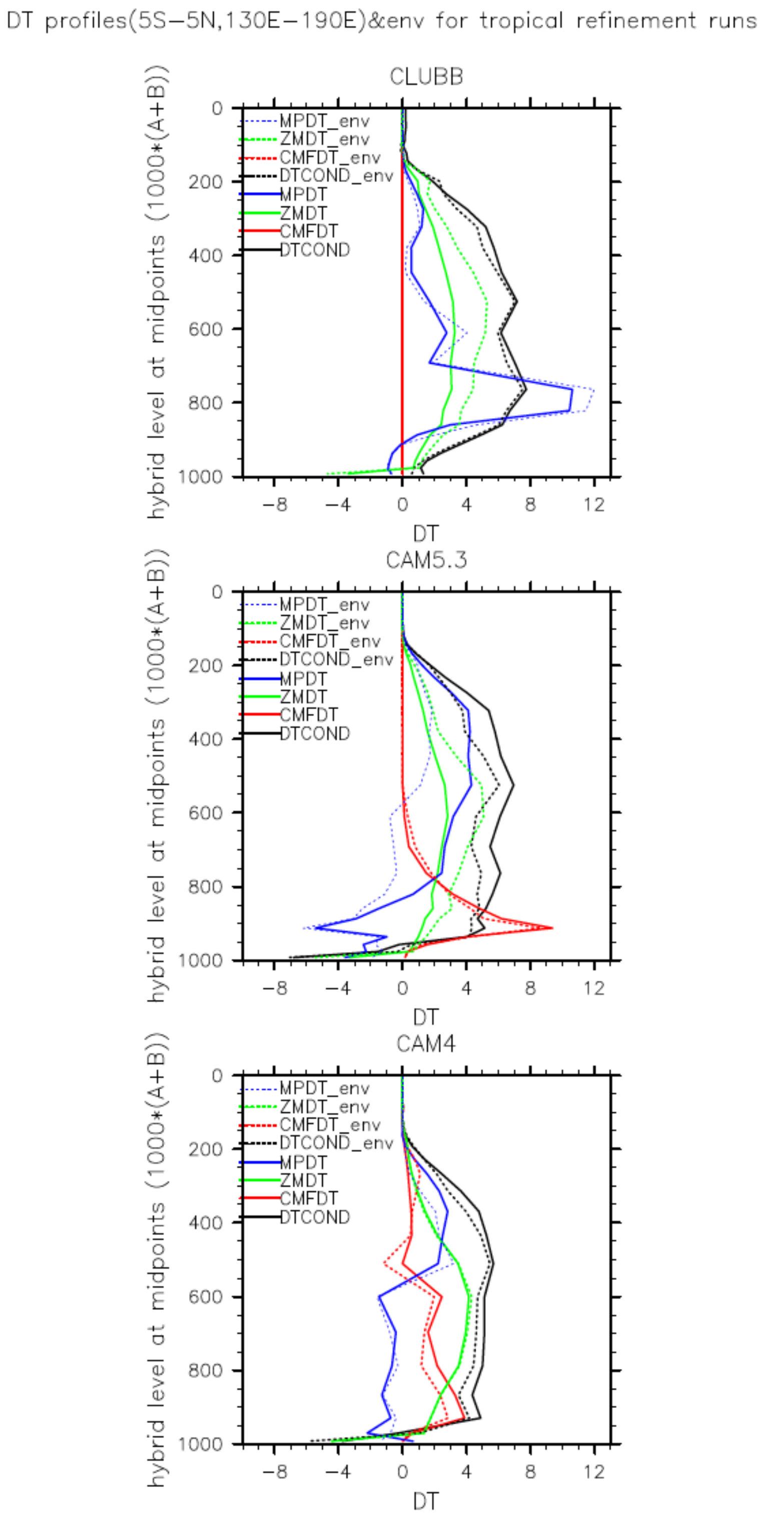

Figure 7: Temperature tendency profiles from CAM-CLUBB (top), CAM5 (middle) and CAM4 averaged over 5S-5N and inside (solid) and outside (dashed) the region of refinement. Deep convection (ZMDT: green), Shallow Convection (CMFDT: red), Large scale (macro and micro: MPDT blue), Total (black).

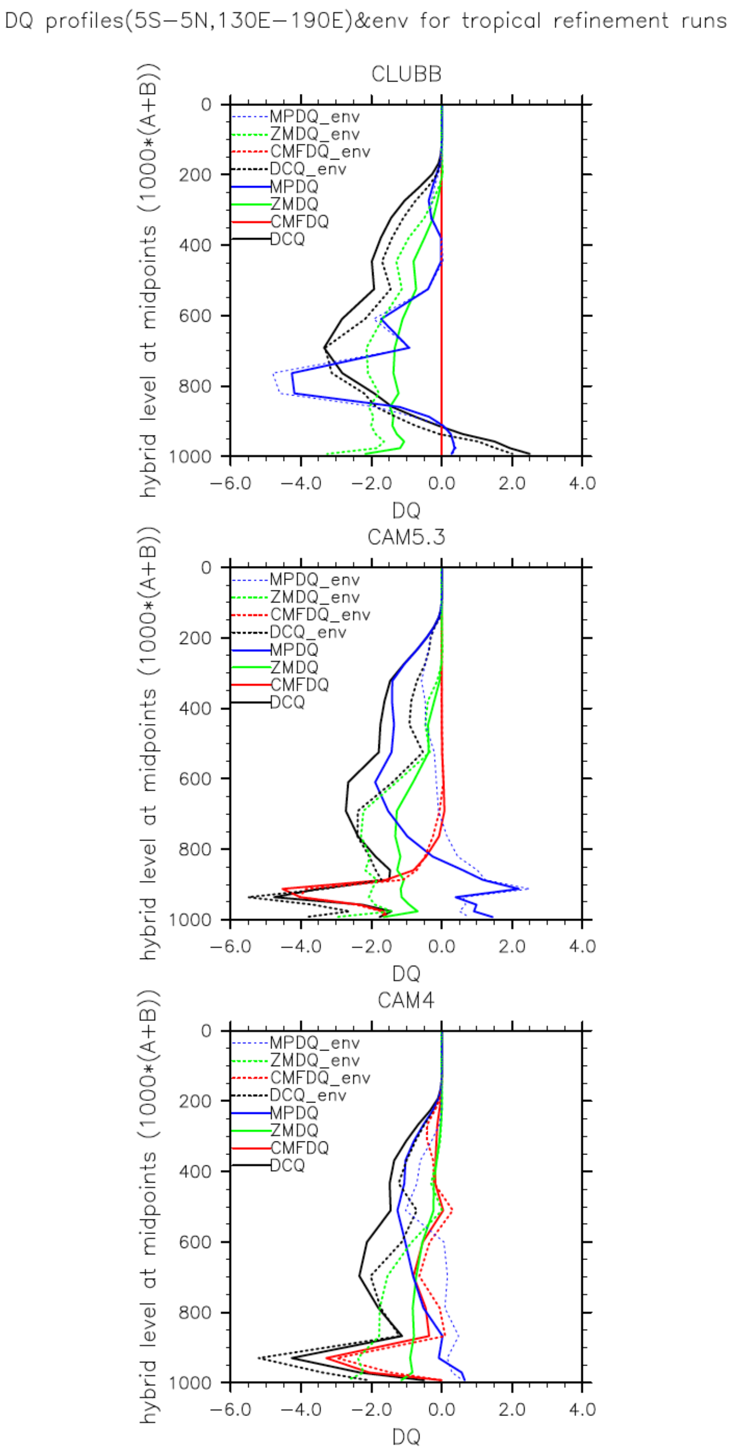

Figure 8: As for Figure 7 but for specific humidity (Q) tendency.

The humidity tendencies are shown in Figure 8. CAM-CLUBB (Figure 8-Top) has more similar humidity tendencies inside and outside of the refined region (solid and dashed black lines) than does CAM5, and is similar in magnitude to CAM4. Again, in this preliminary figure: it appears there may be a partial tendency term missing.

CAM5.3 (Figure 8 middle) has very different performance (especially of the microphysics), and note that the microphysics/macrophysics (MPDQ) and shallow convection (CMFDQ) are operating in opposition to each other: shallow convection seems to remove condensate that microphysics puts back. This may be a result of the coupling of the shallow convective detrainment in CAM5. Also note that CAM-CLUBB has its main tendency for low clouds higher (800hPa) than CAM4 or CAM5 (950hPa).

Finally, Zarzycki et al 2014c found that CAM5 physics in a variable resolution mesh at 0.25 degree produced reasonable tropical cyclones. This was also found by Wehner et al 2014 and Bacmeister et al 2014 using uniform high resolution meshes with the Finite Volume (FV) dynamical core and CAM5 physics. Zarzycki et al 2014c also note that 0.125 degree resolution produced tropical cyclones that are too strong with CAM5 physics, something also noted by Reed et al 2012. Preliminary forecast simulations of hurricane Sandy with CAM-CLUBB SE at 0.25 and 0.125 resolution indicate that intensities are lower than CAM5, but reaching appropriate magnitudes at 0.125 deg, with better evolution and growth statistics (C. Zarzycki, personal communication).

5. Summary

In summary, variable mesh simulations can be an important tool for testing physical parameterizations across scales. The dynamics are stable, and the high resolution regions resemble uniform high resolution in a baroclinic test case. In aquaplanet experiments for mid-latitude storm tracks, broad scale measures of climate statistics (total cloud cover and longwave cloud radiative effect) are stable in both CAM5 and CAM-CLUBB. Cloud forcing inside and outside of refined regions in CAM-CLUBB is stable to within 0.2 Wm-2. In tropical experiments, all configurations with a common deep convection scheme have increased convective precipitation in the refined (high-resolution) region. The stratiform precipitation is reduced in the high resolution region. However, in CAM-CLUBB, the balance of the two produces more similar total precipitation inside and outside of a refined mesh region in the convergence on the equator: better than either CAM4 or CAM5. The total heating and moistening tendencies in the near equatorial region are nearly the same inside and outside of the refined mesh region in CAM-CLUBB, more so than CAM5 or CAM4.

Acknowledgements: This work was supported at NCAR by a U.S. National Science Foundation (NSF) grant for a Climate Process Team (CPT) on cloud-aerosol interactions (AGS-0968640), A NSF Earth System Modeling (EaSM) grant on multi-scale modeling (AGS-1049057) and a U.S. Department of Energy SciDAC grant on Tropical Biases (DE-SC0006702).

References:

Bacmeister, J., R. , A. Gettelman, C. Hannay, P. H. Lauritzen, J. Caron, J. E. Truesdale and M. Wehner, Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM), J. Climate, 27, 3073–3099. doi: 10.1175/JCLI-D-13-00387.1, 2014.

P. A. Bogenschutz, A. Gettelman, H. Morrison, V. E. Larson, D. P. Schanen, N. R. Meyer, and C. Craig. Unified parameterization of the planetary boundary layer and shallow convection with a higher-order turbulence closure in the community atmosphere model: single-column experiments. *Geoscientific Model Development*, 5(6):1407-1423, 2012.

Guba, O., Taylor, M. A., Ullrich, P. A., Overfelt, J. R., and Levy, M. N.: The spectral element method on variable resolution grids: evaluating grid sensitivity and resolution-aware numerical viscosity, Geosci. Model Dev. Discuss., 7, 4081-4117, doi:10.5194/gmdd-7-4081-2014, 2014.

Hack, J. J., Parameterization of moist convection in the National Center for Atmospheric Research Community Climate Model (CCM2), J. Geophys. Res., 99, 5551–5568, 1994.

Jablonowski, Christiane, and David L. Williamson. "A baroclinic instability test case for atmospheric model dynamical cores." *Quarterly Journal of the Royal Meteorological Society* 132.621C (2006): 2943-2975.

R. B. Neale, J. H. Richter, and M. Jochum. The Impact of Convection on ENSO: From a Delayed Oscillator to a Series of Events. *J. Clim.*, 21:5904-+, 2008.

S. Park and C. S. Bretherton. The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the Community Atmosphere Model.. *J. Clim.*, 22:3449-3469, 2009.

Reed, K. A., C. Jablonowski, and M. A. Taylor (2012), Tropical cyclones in the spectral element configuration of the Community Atmosphere Model, Atmos. Sci. Lett., 13(4), 303–310.

M. Wehner, K. Reed, F. Li, M. Prabhat J. Bacmeister, C.T. Chen C. Paciorek, P. Gleckler, K. Speber, W. D. Collins, A. Gettelman, C. Jablonowski and C. Algieri, The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1, J. Adv. Model. Earth Syst., 06, doi:10.1002/2013MS000276.

C. M. Zarzycki, M. N. Levy, C. Jablonowski, M. A. Taylor, J. Overfelt, and P. A. Ullrich (2014a), Aquaplanet experiments Using CAM's variable-resolution dynamical core. J. Clim., 27(14), 5481-5503. doi:10.1175/JCLI-D-14-00004.1.

C. M. Zarzycki, C. Jablonowski, and M. A. Taylor (2014b), Using variable-resolution meshes to model tropical cyclones in the Community Atmosphere Model. Mon. Weat. Rev., 142, 1221–1239. doi:10.1175/MWR-D-13-00179.1.

C. M. Zarzycki and C. Jablonowski (2014c), A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model. J. Adv. Model. Earth Syst., doi:10.1002/2014MS000352.

G. J. Zhang and N. A. McFarlane. Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Center general circulation model. *Atmos. Ocean*, 33(407-446), 1995.