Final Report

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Project Title: Development of an Adaptive Vertical Grid Scheme for Large Scale Models

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Report Sections/Contents:

1. Overview of Project

In recent years the combination of increasing computational capability and uncertainties in climate simulations due to clouds (or more broadly un- or under-resolved processes that must be approximated or parameterized) has led to enhanced interest in higher resolution global and regional models. In simple terms, the expectation is that significantly better simulations can be obtained by resolving cloud scale motions and relying less on cloud parameterizations. However, simulations capable of resolving cloud scale motions on global or large regional domains are computationally challenging. Simulations run on small domains (where very fine grids can be applied) have demonstrated that horizontal grid spacing of less than 1 km and vertical grid spacing as small as 10 m are required to simulate stratocumulus clouds. From a climate modeling perspective, accurately capturing stratocumulus and the transition between stratocumulus and cumulus is critical because of the large role that these clouds play in the Earth radiation balance. The computational burden of cloud resolving models increases rapidly as the number of grid points increases. Consequently, decreasing the grid spacing in order to resolve boundary layer cloud processes adequately is (at best) marginally practical for large domain regional models or global cloud resolving models. One potential approach to increasing resolution with only modest increases in computational costs is to use an adaptive grid. In this approach, additional grid points are added to the relatively coarse model base grid only where needed as determined by the model simulation itself.

The objective of this research project was to implement and evaluate an adaptive vertical grid in the Multiscale Modeling Framework (MMF) climate model. In the MMF, a two-dimensional or small three-dimensional cloud resolving model is embedded into each grid cell of the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM), replacing most of the cloud parameterizations normally used by CAM.

2. Significant Results

The first step of the proposed research project was to implement a previously published algorithm for an adaptive vertical grid (called the adaptive Z-grid or AZG, Marchand and Ackerman 2011) into the latest "offline" version of the System for Atmospheric Modeling (SAM), the cloud resolving model (CRM) used in the MMF, and then to port this change into the MMF itself. This coding activity turned out to be much more difficult than originally anticipated. In particular, an insidious error in the calculation of the moist-static-energy when a new layer was added to the adaptive grid proved difficult to find. The error resulted in moist-static-energy not being conserved, and over the course of a few simulated days, the error caused clouds to evaporate resulting in a net loss of low cloud. The error was present in the original offline model, but only when the AZG was used in a full MMF (where large scale forcing is not prescribed) did the error become apparent.

With this error fixed, sensitivity testing of the adaptive vertical grid (AVG) approach began in earnest during the third year of the project. A number of short (10 to 14 day) runs were undertaken to evaluate the MMF-AVG, examining the effect of various code configurations including thresholds used to adjust when adaptive layers are added, and the impacts of horizontal domain size and horizontal grid spacing.

The results of the AZG simulations were somewhat disappointing. Figure 1 compares the amount of low cloud produced by the MMF-AZG model with observations from the NASA MISR instrument. Panel a shows the MISR global distribution of low cloud amount on a two-degree grid. The model output is shown for three configurations. Panel b shows the MMF simulation using a 52 level grid with a fixed vertical grid (labeled AZG0 L52). Panel c shows results with the AZG scheme turned on using the same initial 52 level grid, and allowing a maximum of 30 additional levels and nominal thresholds (labeled AZG5 L52). Panel f shows results using a fixed grid with 219 vertical levels (labeled AZG5 L219). The L219 simulation has a nominal 12.5 m resolution through most of the boundary layer, and is equal to the finest resolution allowed in the AZG5 L52 simulation. It is only in the last 6 months (since I obtained access to the NSF XSEDE COMET computer) that I could undertake a simulation with L219 layers. This simulation took more than five times longer to complete as compared to the AZG5 L52 simulation.

Panel h provides perhaps the best summary of the simulated low cloud amount, and compares the zonal mean low cloud fraction where the black line is the MISR observations, the red dashed line is the AZG0 L52 simulation, the green dashed line is the AZG5 L52 simulation, and the blue dashed line is the AZG0 L219 simulation. Panel h highlights the large under-prediction of low cloud in the host model (AZG0 L52), which is common to many climate models. In fact, the low-cloud deficiency shown here for AZG0 L52 is worse than in most published MMF runs because the embedded CRM horizontal resolution has been reduced to 250 m from the more customary 4 km, and it has been established by several researchers that low-cloud amounts are reduced in the MMF as the horizontal resolution is made finer (Chang et al. 2010, Marchand and Ackerman 2010). The AZG5 L52 run shows only a modest increase in the amount of low cloud. While a positive result, the total amount of low cloud remains far below observed amounts. However, even when using the MMF with 219 layers and a nominal 12.5 m vertical grid spacing low cloud amount does not increase very much.

An examination of subtropical trade cumulus and stratocumulus clouds in Figures 2 and 3, respectively, shows that the improvement in low cloud cover in the AZG5 L52 and AZG0 L219 simulations is most significant for trade cumulus. In Figures 2 and 3, the left panels show the distribution of clouds by cloud top height and the right panels show the cloud optical depth (essentially a measure of how bright or reflective the low clouds are). It is critical for climate model improvement that models predict the correct cloud amount and distribution cloud optical depth. The improvement in both the low cloud amount, the vertical distribution and optical depth in the trade cumulus regions (Figure 2) is striking. In regard to the observations, it should be noted that low cloud fraction for optically thin clouds (clouds with an optical depth below about three) from satellite imagers (including MISR, MODIS, GOES, etc.) are well known to be inflated for low clouds, especially in trade cumulus regions due to insufficient sensor resolution (Zhao and Di Girolamo 2006, Marchand et al. 2010). The agreement between the observations and simulations shown here is very good (much better than other climate models).

The question arises as to "why is there no significant improvement in the stratocumulus regions?" The occurrence of stratocumulus in a region is dependent on a balance among large-scale subsidence, surface fluxes, and advective tendencies with cloud-top radiative cooling and turbulent mixing being critical important. Prior to completion of the L219 simulation (and my motivation for undertaking such is that), I suspected the problem was due to advection and vertical mismatch between host model and CRM. This was because in the MMF, AVG vertical layers are added to the embedded CRM but are not added to the host model. Thus advective tendencies (passed from the host model to the CRM and vice versa) must be re-gridded. However, such re-gridding does not occur in the L219 simulation (which has similar cloud properties to the AZG simulations), demonstrating that re-gridding is not the problem. I have also examined the lower tropospheric stability (LTS) and find the model values are well in line with expectations, suggesting that subsidence is not the problem.

On the other hand, surface latent heat flux (SLHF) appears to be too low in the MMF simulations in the very coastal regions where stratocumulus clouds should be plentiful, but aren't. Figure 4 shows an expanded view of the MMF simulated (AZG0 L219) low cloud amount off the west coast of South America (where stratocumulus clouds are dominant and cloud fraction should exceed 60% over much of the region but doesn't). Comparisons of climatological SLHF from objective analysis and MMF simulations suggest the SLHF is too low near the coast (which is devoid of cloud) and too large away from the coast. This suggests that a problem with SLHF or factors that control SHLF (such as surface winds) may be an issue. In the current MMF configuration, SHLF is calculated in the host model and not calculated in the CRM, which may also be a problem.

3. Conclusions

In summary, implementation of the Adaptive Z-Grid (AZG) scheme within the Multiscale Modeling Framework (MMF) climate model was found to produce only a modest increase in low cloud amount, with much of the improvement occurring in regions dominated by trade cumulus rather than stratocumulus.

While it is disappointing that the AZG5 simulations do not show a large increase in low clouds in stratocumulus regions as was anticipated, the AZG scheme is working as it should. The adaptive grid shouldn't produce more low cloud than the model run with high vertical resolution everywhere (if it did, it would represent a serious error) and, in fact, the data show the AZG scheme (run with a maximum of 85 levels) appears to capture well model performance with 219 levels and a nominal 12.5 m resolution throughout most of the boundary layer.

The expectation going into the project was that significantly better simulations could be obtained by resolving cloud scale motions and relying less on cloud parameterizations. It is clear, however, that increasing the horizontal and vertical resolution to levels often used in stratocumulus case studies (that is, resolutions typical of large-eddy simulations) is itself not sufficient, and it remains unclear as to whether or not such resolution is necessary.

While I believe this conclusion and the material I have is sufficient for a short peer-review publication (possibly as a letter), the research to date still represents a negative result. That is, while the AVG results in some improvement, the level of improvement is not worth the additional code complexity or computational burden.

Rather, my analysis suggests the stratocumulus problem may be related to the surface latent heat flux (SLHF). I believe that it will relatively simple for me to test this hypothesis in several ways, including by simply holding fixed the surface fluxes (as a test, certainly one cannot run climate simulations in this manner). Further, I suspect that the problem might be corrected by passing the surface fluxes into the CRM (or otherwise calculating the fluxes within the CRM), such that the surface heating is applied within the CRM rather than the host model. Thus, I intend to continue working on the problem as an unfunded side activity for the next several months, at which point I will publish what has been learned. I expect to do this is Journal of Advance in Modeling Earth Systems (JAMES).

4. Figures

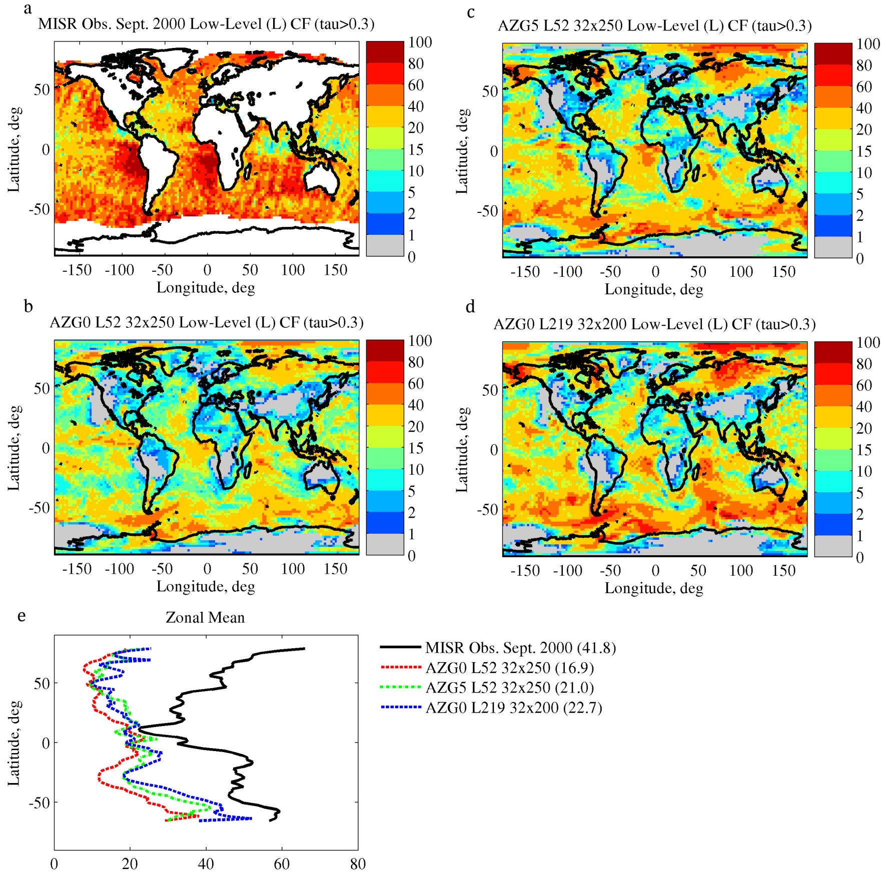


Figure 1 – Comparison of MISR observations and MMF simulations of low cloud cover with and without an adaptive grid (see text).

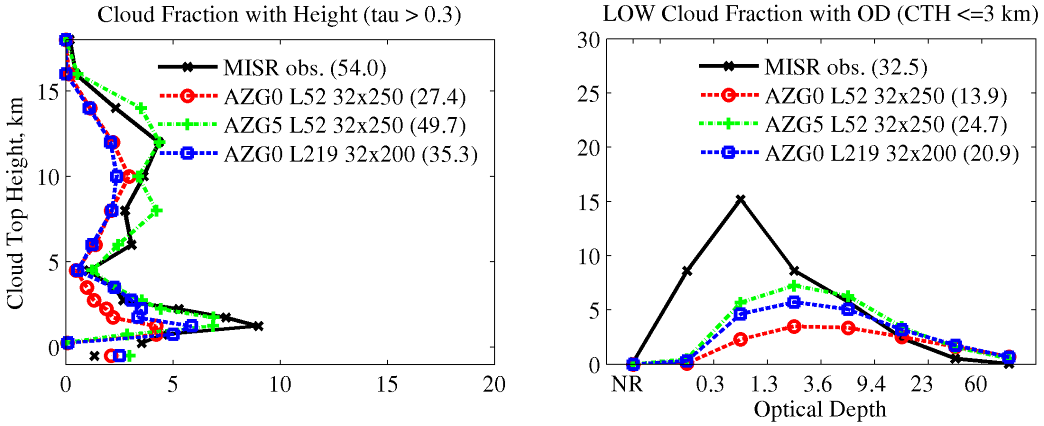


Figure 2 – Comparison of MISR observations and MMF simulations with and without an adaptive grid for the ***Hawaiian Cumulus Zone*** *(15^{o} N – 35^{o} N, 160^{o} E - 140^{o} W). Left panel is a line plot showing the vertical profile of cloud amount vs. Cloud-Top-Height (CTH) and right panel shows the distribution of Optical-Depth for low clouds (CTH < 3 km). Simulations and line colors are the same as in Figure 1, with parentheses showing total cloud fraction in the left panel and low cloud fraction in the right panel.*

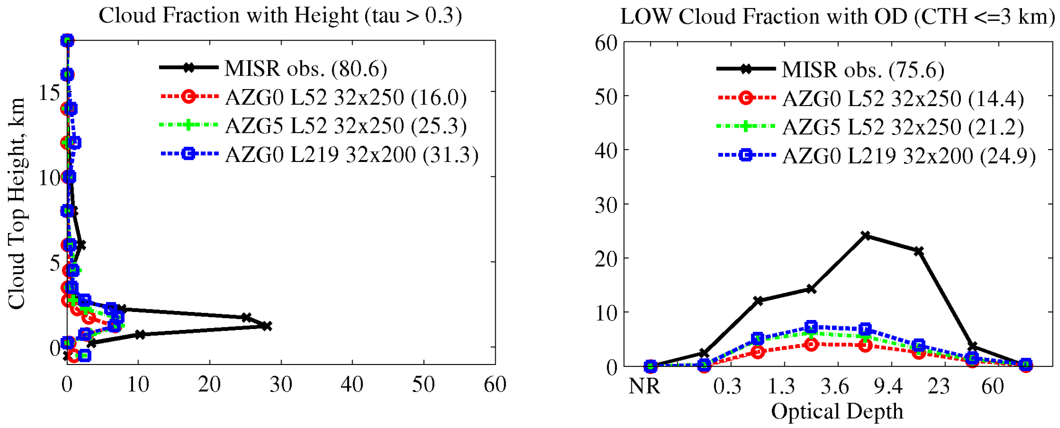
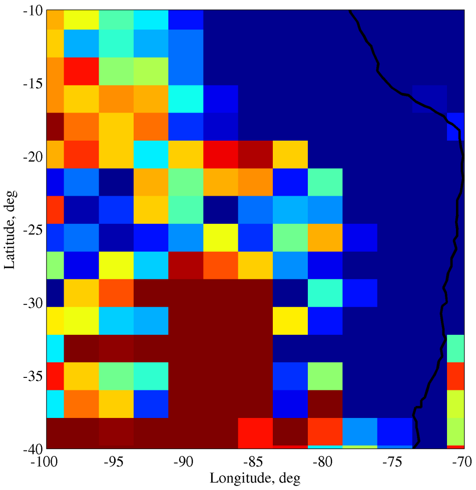
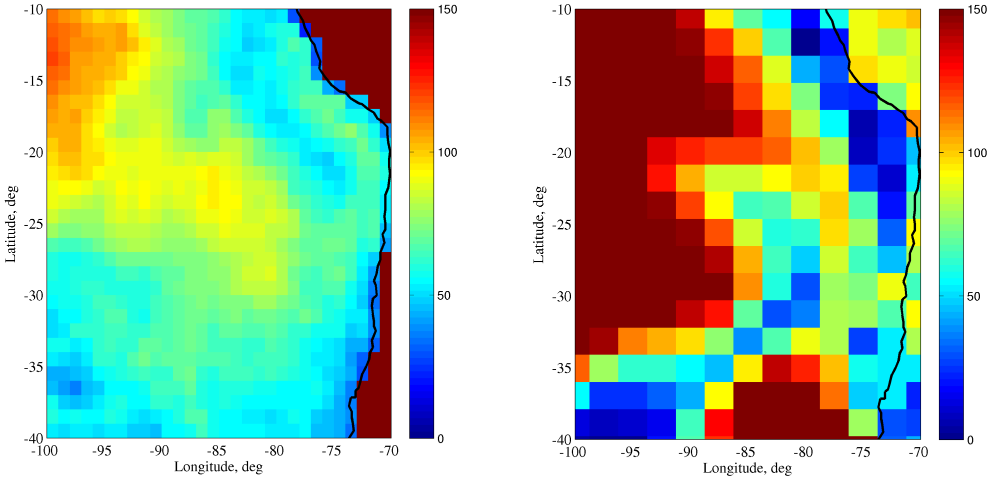


Figure 3 – Same as Figure 2 but for the ***South American Stratocumulus Zone*** *(0^{o} - 30^{o} S, 70^{o} - 100^{o} W).*



Simulated Low cloud fraction



Climatological Latent Heat Flux

MMF simulated Latent Heat Flux

Figure 4 – Top panel shows MMF simulated (AZG0 L219) low cloud fraction in ***South American Stratocumulus Zone*** *(0º - 30º S, 70º - 100º W). Lower panels show (left) expected Surface Latent Heat Flux (September climatology from Woods Hole Objective Analysis (OAFLUX) product) and (right) MMF simulated surface latent heat flux.*

5. References

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