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Numerical Techniques and Cloud-Scale Processes for High-Resolution Models

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LONG-TERM GOALS

The long-term goal of this project is to design and evaluate the components that will comprise a next generation mesoscale atmospheric model within the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]). It is anticipated that in order to meet future Navy requirements, next generation approaches to numerical techniques and physical parameterizations will be needed.

OBJECTIVES

The objectives of this project involve the development, testing, and validation of new numerical techniques such as spectral element techniques and monotonic advection methods. The overarching objective is to develop methods for high-resolution numerical weather prediction applications for horizontal grid increments at 1 km or less.

APPROACH

Our approach is to follow a methodical plan in the development and testing of a nonhydrostatic microscale modeling system that will leverage the existing COAMPS and new model prototypes. Our work on numerical methods will involve investigation of spatial and temporal discretization algorithms that are superior to the current generation leap-frog, second-order accurate numerical techniques presently employed in COAMPS and many other models; these new discretization methods will be developed and implemented. We would like to use numerical methods that have already been developed and tested in other communities, such as computational fluid dynamics, and apply these to high-resolution numerical weather prediction applications. Validation and evaluation of the modeling system will be performed using datasets of opportunity, particularly in regions of Navy significance.

[1] COAMPS® is a registered trademark of the Naval Research Laboratory.

WORK COMPLETED

1. Spectral element 2D prototypes.

Spatial resolution required to adequately resolve features of interest can be easily determined for the finite difference model where the grid spacing is constant. Even with varying resolution (e.g. commonly used vertically stretched grid) the grid spacing is increasing monotonically with the distance away from the area of interest. The non-uniform spacing of nodal points used for the spectral element model makes the same task less straightforward. The difference between the minimum and maximum distance between adjacent nodal points within the same element is proportional to the polynomial order. The *h-p* parameter space, where *h* is number of elements in the horizontal direction and *p* is polynomial order was mapped out to span nominal horizontal resolution from 200 to 10000 m.

Numerical solutions to the linear, hydrostatic flow over an idealized mountain and an analytic solution for the vertical momentum flux were used to calculate the normalized l_2 norm. An overall error, speed of convergence and computational cost were assessed, the latter two compared to the numerical solutions obtained with a finite difference model.

There is no analytical solution for our chosen test case involving moisture (squall line with warm microphysics). Storm stages, checked at two different times (3000 and 6000 s) differ depending on the polynomial order and nominal grid spacing. In addition, dimensional viscosity was added to the model to ensure stability and realism of the solution since there is no subgrid-scale mixing. The initial value of viscosity was constant in all cases, regardless of the time step chosen. Tests with various values of viscosity were performed to assess convergence of solutions. Symmetry tests were performed to assess sensitivity of the storm development to the initial warm bubble location in relation to the non-uniformly spaced nodal points.

2. WENO (Weighted Essentially Non-Oscillatory) methods

Atmospheric models require numerical methods that can accurately represent the transport of tracers with steep gradients, such as those that occur at cloud boundaries or the edges of chemical plumes. In atmospheric sciences, the most widely used numerical techniques for this type of problem are flux-corrected transport or closely related flux-limiter methods. The limiters are typically designed to prevent the development of new extrema in the concentration field. This will preserve the non-negativity of initially non-negative fields, which is essential for the correct simulation of cloud microphysics or chemical reactions. One serious systematic weakness of flux limiter methods is that they also tend to damp the amplitude of extrema in smooth regions of the flow, such as the trough of a well-resolved sine wave. To avoid this problem, we have been investigating the application of WENO (Weighted Essentially Non-Oscillatory) methods to tracer transport in atmospheric models. WENO methods are widely used in many disciplines, but scarcely been tested in atmospheric applications. WENO methods preserve steep gradients while simultaneously avoiding the dissipation of smooth extrema by estimating the value of the solution in a way that heavily weights the smoothest possible cubic polynomial fit to the local function values. Where the solution is well resolved, all possible cubic interpolants are weighted almost equally. Near a steep gradient, those interpolants are almost completely ignored.

RESULTS

1. Spectral element 2D prototypes.

The normalized l2 norm error is lowest for the nominal resolution less than or equal to 1 km (Figure 1). Large error in the lower left portion of the same figure is due to the poorly resolved topography and error introduced with inexact integration when the polynomial order is too low. The convergence to the final solution is achieved quickly for cases with coarser nominal resolution of 2000 and 3000 m (yellow and green lines, respectively in Figure 2), while simulations with finer nominal resolution converge at or around 12 hours. The most important factor in the final error is the nominal horizontal grid spacing, where all the cases can be grouped into two clusters: quickly converging with less accuracy and slowly with more accuracy. Note that the errors calculated with the finite difference model keep decreasing with increasing resolution, but even with the finest resolution (500 m, solid gray line with diamonds) the error is comparable to the error obtained with the spectral element model with the nominal resolution of 2000 m.

The finite difference model is computationally cheaper for a given nominal resolution (Figure 3). The increase of computational cost per increased resolution is comparable for both models. While the resolution refinement results in a monotonic decrease of the error for the finite difference model, thus justifying the cost, which is not the case for the spectral element model. Increasing the nominal resolution from 3000 to 2000 m, or 1000 to 500 m, yields only marginal error reduction, with an increased computational cost. The biggest accuracy yield happens when reducing the average resolution from 2000 to 1000 m (more than an order of magnitude).

The nominal horizontal resolution of 2000 m is too coarse, or the effective diffusion combined with a larger time step is too weak, resulting in larger storm clouds with weaker positive virtual potential temperature perturbations compared to those obtained with finer resolutions (Figure 4, right panel). More consistent results were simulated with both 500 and 1000 m nominal resolutions (Figure 4, left and middle panel, respectively).

Smaller time step required by finer resolution results in applying diffusion more often. In order to balance the effective diffusion, it was increased for 1000 m (larger time step compared to 500 m) comparing the results (Figure 5, right panel) to the original 500 m (Figure 4, left panel). The narrower updraft section of the cloud is now more comparable. Similarly, a decrease in diffusion for the 500 m simulation resulted in a broader updraft section (Figure 5, left panel), compared to the original 1000 m case (Figure 4, middle panel).

The initial location of the warm bubble, which triggers the storm, is important for the symmetry of the fully developed storm. When the bubble is centered, such that the nodal spacing to the left and right are equal, the storm will remain symmetric in the absence of wind shear. If the nodal spacing is not equal, the storm develops a tilt, similar to simulations with the environmental wind shear (not shown).

2. WENO (Weighted Essentially Non-Oscillatory) methods

The WENO based selective monotonic advection (SMA) scheme (Blossey and Durran 2007) was fully implemented in COAMPS in FY 2009. In addition, a semi-Lagrangian option (Skamarock 2006; Blossey and Durran, 2007) was also implemented in order to offset the extra computational costs required

for the SMA scheme. Both the semi-Lagrangian and Eulerian versions of the SMA scheme were tested and compared with the currently available 2nd- and 4th-order finite difference advection schemes for a variety of idealized test problems. In addition, both SMA schemes were evaluated in the full COAMPS numerical weather prediction (NWP) mode over two 15-day periods: 1-15 January 2008 for an eastern Pacific domain and 1-15 May 2008 for a domain containing the continental United States (CONUS). The CONUS test was configured with a 9-km horizontal resolution domain extending from the Rocky Mountains to the East Coast nested within a 27-km horizontal resolution domain containing the entire CONUS region. Several highlights from the 9-km domain will be discussed below.

One issue with any finite difference scheme is the presence of overshoots and undershoots in regions of steep gradients. For fields that are required to be positive definite, such as moisture, any negative values generated must be filled in order to maintain a physically meaningful solution. Skamarock and Weisman, 2006 have shown that the cumulative effect of filling negative values of moisture can lead to a positive bias in precipitation. They demonstrate that a positive definite advection improves this bias by eliminating the necessity to fill negative values. The impact of the positive definite SMA scheme on the COAMPS precipitation bias is shown in Fig. 6. Plotted is the 24-h accumulated precipitation model bias as a function of the accumulated precipitation for the fourth-order advection (black), Eulerian SMA scheme (blue), and semi-lagrangian SMA scheme (red). Here the time step of the semi-lagrangian scheme is three times that of the Eulerian scheme. The 24- and 48- hr forecasts, sampled from the 9-km CONUS domain for the 1-15 May 2008 time period, are compared with the Stage-IV gridded precipitation data set (Lin and Mitchell 2005). Bias values less than 1 indicate a negative bias, 1 is no bias, and values greater than 1 indicate a positive bias. While the each scheme shows and increasing bias as a function of accumulated precipitation, both the Eulerian and semi-Lagrangian SMA schemes have a lower bias than the fourth-order advection scheme. This is especially true for larger precipitation thresholds.

Figure 7 compares the morphology of the 2-km AGL cloud-water mixing ratio field for a pair of COAMPS simulations taken from the 9-km CONUS domain and initialized 00 UTC 14th May 2008. This period was chosen due to the presence of a developing cyclone, trailing cold front, and active convection over the Midwest. As the cold front progressed through Texas, Oklahoma, and Arkansas and into the Gulf Coast states, radar imagery indicated several developing lines of severe thunderstorms (not shown). Both the fourth-order advection scheme and Eulerian SMA scheme indicate this line of thunderstorms at 00 UTC 15th May (24-hr forecast; Fig. 7a and b). However, over the next 12 hours, as the line progresses into Louisiana and Mississippi, the SMA scheme is better able to maintain a coherent linear structure in the cloud field (Fig. 7d) compared to the fourth-order advection scheme were the cloud field is much more disjoint and consists of individual blobs of cloud-liquid water (Fig. 7c). The cloud field present in the simulation with the SMA scheme is more consistent with the precipitation field from the observed radar imagery (not shown); however, an objective verification comparison of the cloud fields in the two schemes has not been completed.

IMPACT/APPLICATIONS

COAMPS is the Navy's operational mesoscale NWP system and is recognized as the key model component driving a variety of DoD tactical decision aids. Accurate mesoscale prediction is considered an indispensable capability for defense and civilian applications. Skillful COAMPS predictions at resolutions less than 1 km will establish new capabilities for the support of the warfighter and Sea Power 21. Operational difficulties with weapon systems such as the Joint Standoff Weapon (JSOW) have been

documented in regions with fine-scale topography due to low-level wind shear and turbulence. Improved high-resolution predictive capabilities will help to mitigate these problems and introduce potentially significant cost saving measures for the operational application of JSOW. The capability to predict the atmosphere at very high resolution will further the Navy sea strike and sea shield operations, provide improved representation of aerosol transport, and will lead to tactical model improvements. Emergency response capabilities and Homeland Security issues within the DoD and elsewhere, such as LLNL, will be enhanced with the new modeling capability.

TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-120) that focus on the transition COAMPS to FNMOC. The improvements to the COAMPS dynamical core have been transitioned to the SPAWAR 6.4 project and subsequently to operations as a result of the marked improvement in the geopotential height bias statistics.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling, boundary layer studies, and topographic flows and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS.

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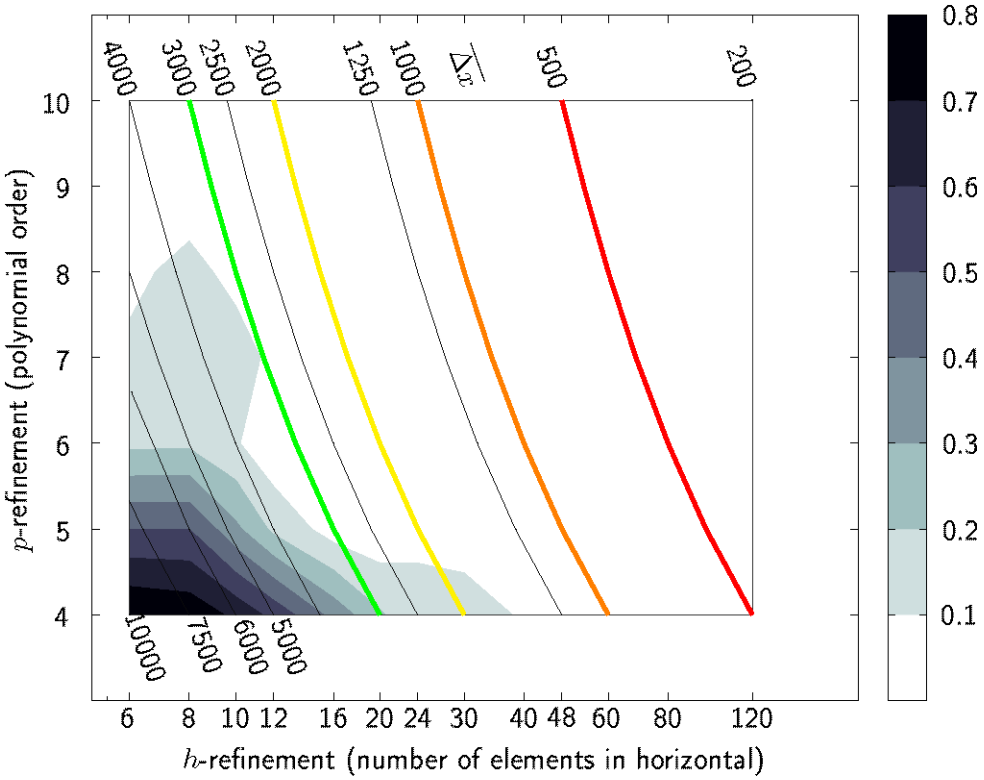

Figure 1. Normalized l_2 norm distribution (shaded contours, c.i. 0.1) of the vertical momentum flux as a function of the polynomial order (p) and number of elements in horizontal (h) . Red, orange, yellow and green lines connect cases with the same average resolution of 500, 1000, 2000 and 3000 m, respectively.

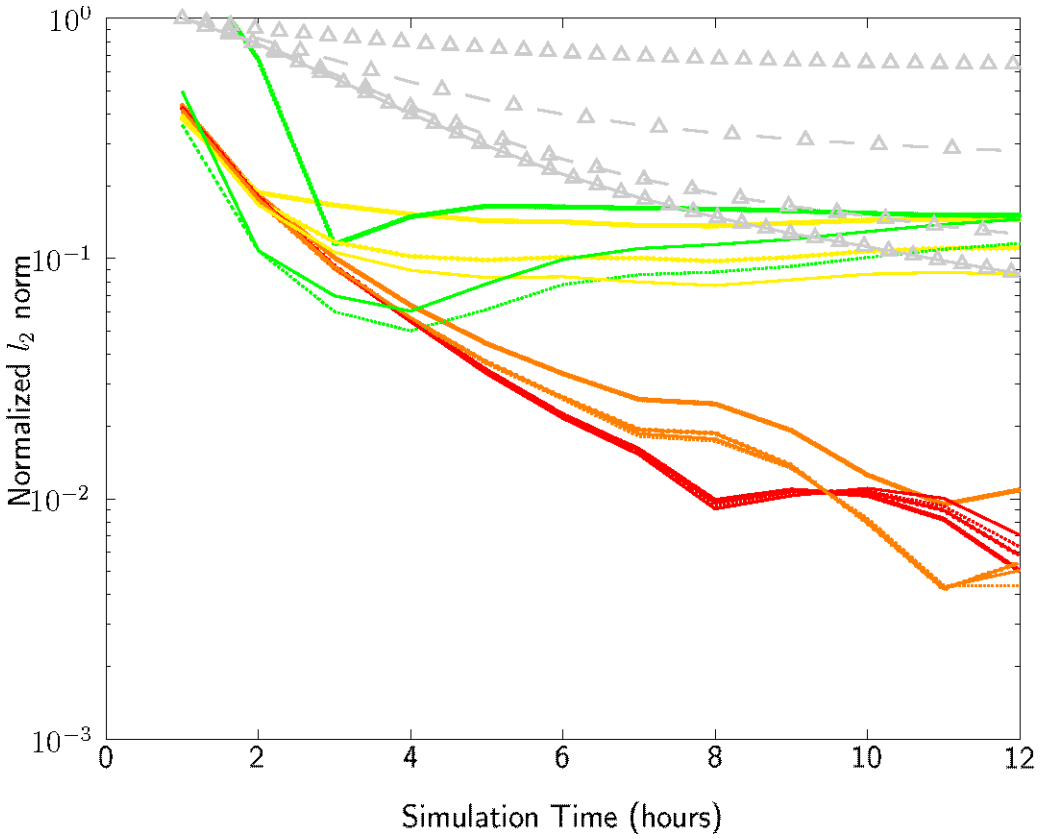

Figure 2. Time evolution of the normalized l_2 norm of the vertical momentum flux (output every hour, starting at t=1 h). Results based on simulations with the same horizontal resolution are grouped by a line color: green (3.0 km), yellow (2.0 km), orange (1.0 km) and red (0.5 km). Line styles depict the polynomial order of basis functions: thick solid (p=4), dotted (p=6), dashed (p=8) and thin solid (p=10). In addition, gray lines with diamonds represent results obtained with a finite difference model: solid, short dashed, long dashed and dotted stand for grid spacing of 500, 1000, 2000 and 3000 m, respectively.

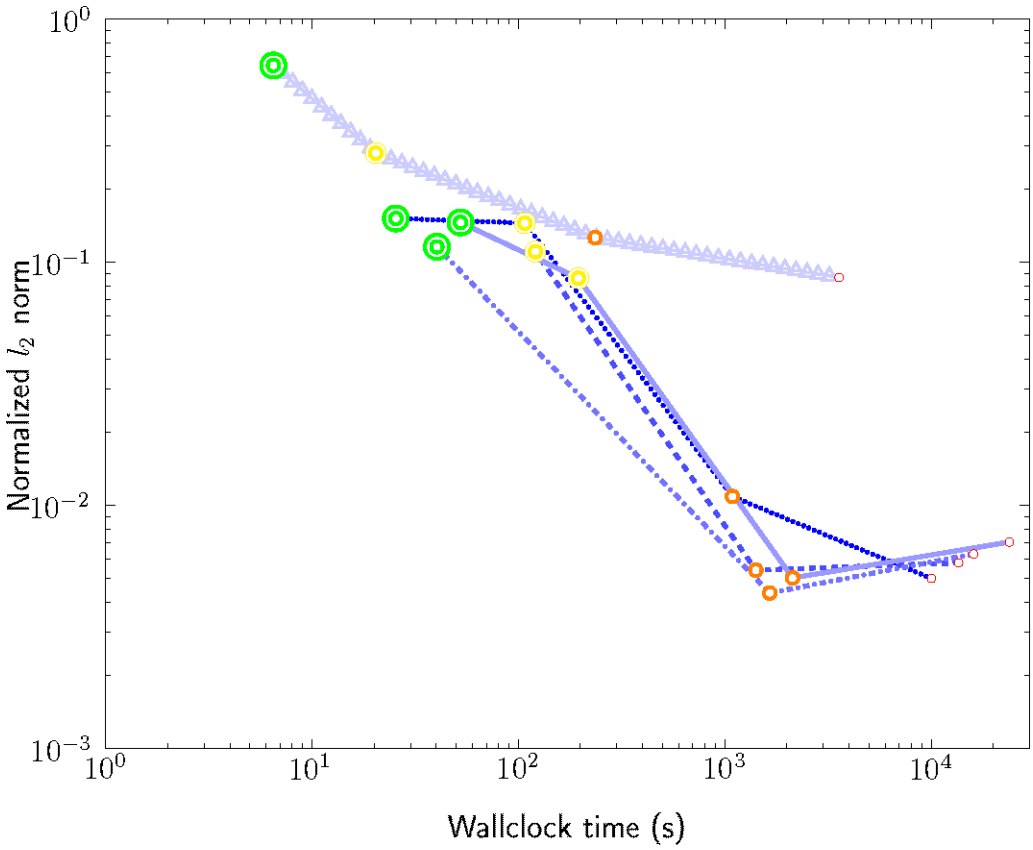

Figure 3. Normalized l_2 norm of the vertical momentum flux as a function of computational time. Results obtained with the spectral element model are: solid, dashed, dot-dashed, and dotted lines for p=4, p=6, p=8 and p=10, respectively. The lightest blue line with triangles represents the finite difference model. Simulations with different resolutions are represented with small red circles (500 m), orange circles with wide rings (1000 m), yellow circles with thick inner and thin outer rings (2000 m) and green circles with two thick rings (3000 m).

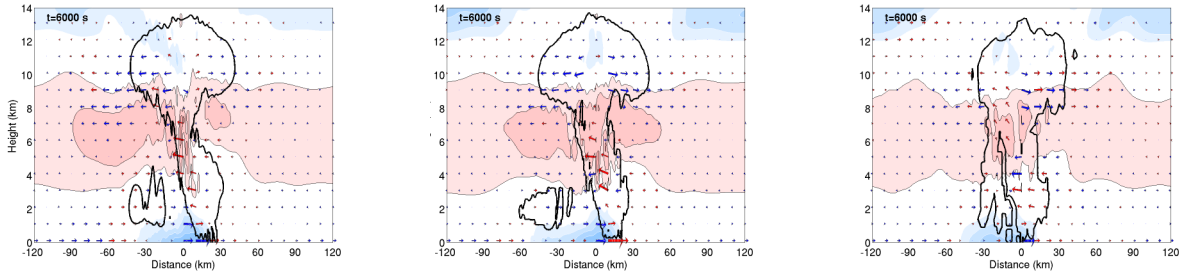

Figure 4. Squall line evolution at t=6000 s for the nominal resolution of 500, 1000 and 2000 m, in left, middle and right panel, respectively. The cloud outline is based on the mixing ratio of cloud water (10^{-5}), colored contours are virtual potential temperature perturbations (c.i. 3 K, negative/positive values are blue/red). In addition, storm relative circulation stronger than 1 m/s is depicted by arrows, blue/red for sinking/rising. Dimensional diffusivity in all cases was 200 m^2/s, time step was 0.2, 0.25 and 0.5 s for cases with nominal horizontal resolution of 500, 1000 and 2000 m, respectively.

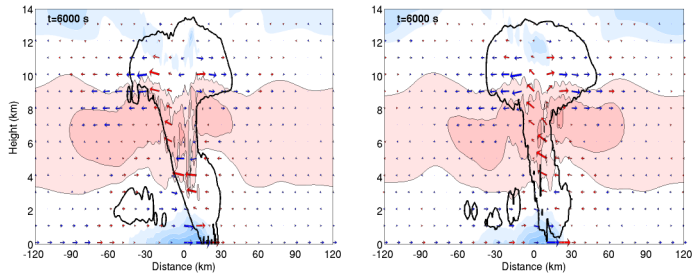

Figure 5. Same as Figure 4, except with weaker diffusivity (160 m^2/s) for the case with nominal resolution of 500 m (left panel) and stronger diffusivity (250 m^2/s) for 1000 m (right panel).

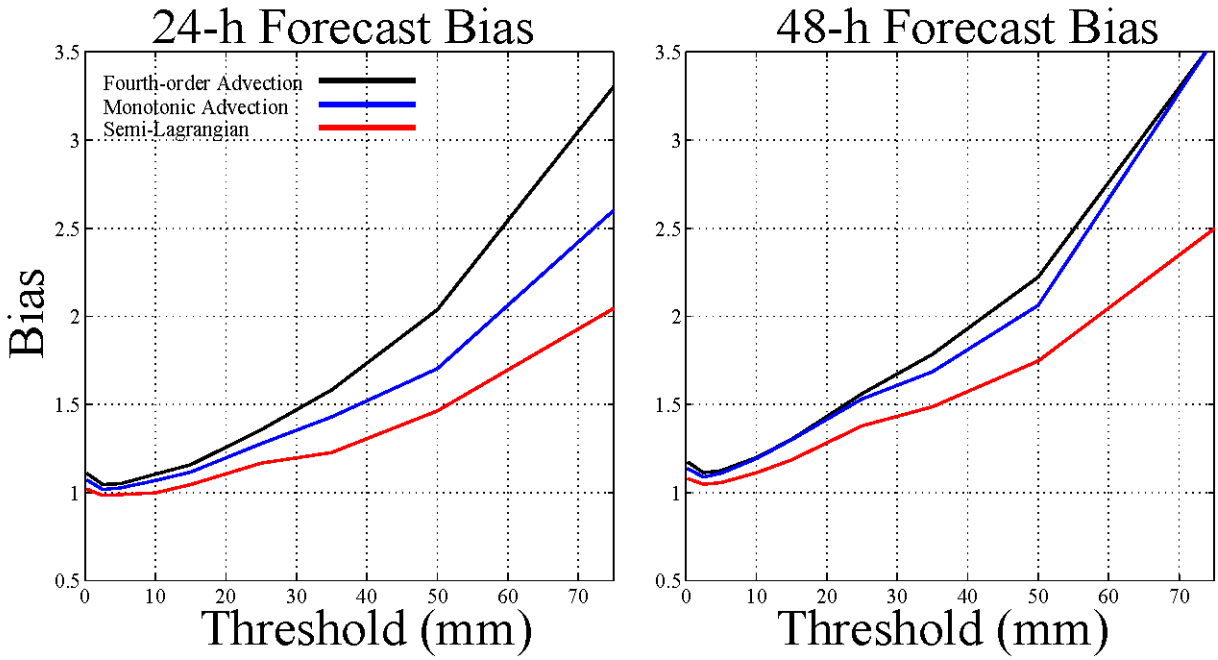

Figure 6. The COAMPS model bias of 24-h accumulated precipitation from 24- and 48-h forecasts during May 2008. The horizontal resolution is 9-km and the computational covers the continental United States east of the Rocky Mountains.

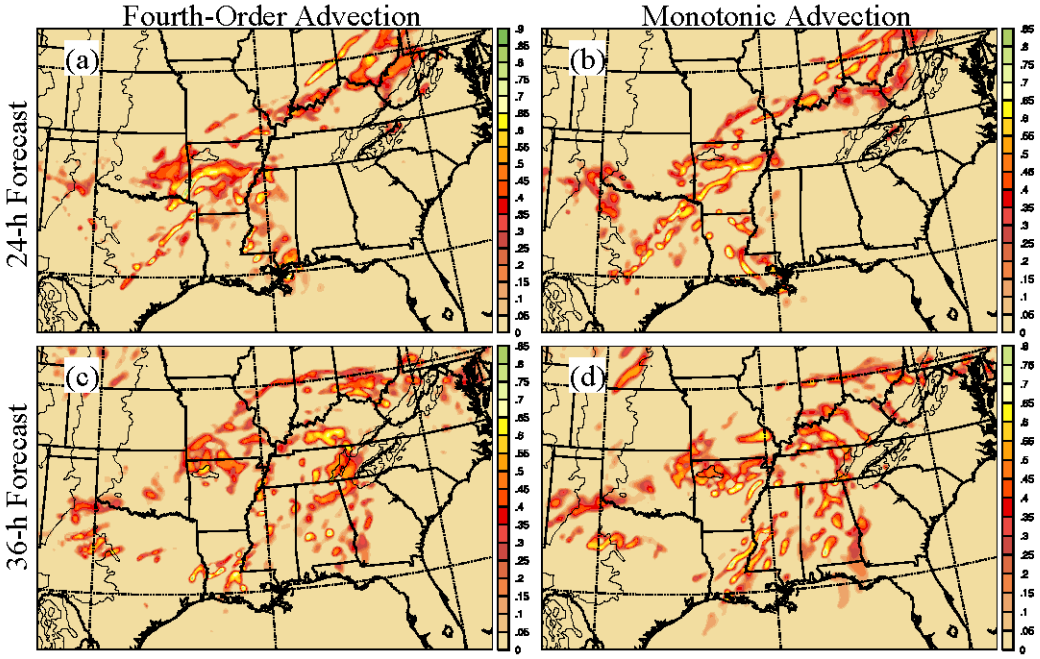

Figure 7. A pair COAMPS model forecasts for the (a, c) 4th-order advection scheme and the (b, d) WENO-based selective monotonic advection scheme. Plotted is the (a-b) 24- and (c-d) 36-h forecast of the 2-km cloud-water mixing ratio (g/kg) in a subset of a 9-km horizontal resolution domain. The model forecast was initialized 00 UTC, 14 May.