A Comparison of Mesh Refinement in the Global MPAS-A and WRF Models Using an Idealized Normal-Mode Baroclinic Wave Simulation

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(Manuscript received 23 December 2013, in final form 13 June 2014)

ABSTRACT

Idealized normal-mode baroclinic wave simulations are conducted to examine the impact of continuous mesh refinement compared with stepwise changes in resolution using nested grids. The nested-grid results are produced using the Advanced Research Weather Research and Forecasting (WRF-ARW) Model, hereafter ARW, and the continuous refinement results are produced using the atmospheric component of the Model for Prediction Across Scales-Atmosphere (MPAS-A). For the nested domain simulations with the ARW, variants of both one-way and two-way nesting techniques are examined. Significant reflection and distortion of waves are evident in results using one-way nesting, with the error increasing with decreasing boundary-update frequency. With continuous updating of the boundary conditions in one-way and two-way nesting, wave distortion is still evident near the lateral boundaries but the distortion is much less than with infrequent boundary updates. The conformal Voronoi meshes in MPAS provide a much smoother transition between mesh resolutions. Variable-resolution mesh MPAS-A simulations, using different transition zones between high- and low-resolution regions, are compared with the results from the ARW simulations. In the MPAS-A simulations, there is no significant reflection of gravity waves, suggesting that continuous mesh refinement can eliminate distortions that tend to occur along the boundaries of nested meshes.

1. Introduction

Most atmospheric models use rectangular elements as the basis of their spatial discretization, and a common approach to introduce locally refined regions is the use of nested grids as implemented in, for example, the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008). Models that use unstructured meshes can often be configured to include local refinement by configuring elements in such a way that the transition between coarse and fine-resolution regions is smooth as is done within the Model for Prediction Across Scales (MPAS; Skamarock et al. 2012). Some models permit a coordinate transformation (grid remapping) such that their grid is smoothly varying while allowing for some concentration of elements in a local region [e.g., the Nonhydrostatic Icosahedral Atmospheric Model (NICAM); Tomita 2008; Fox-Rabinovitz et al. 2008]. Modeling systems employing nested grids and those that use smooth grid transformations will likely possess very different error characteristics associated with the refinement techniques, and we explore these different characteristics in this paper.

Nested grid applications make use of limited-area models (LAMs) that are widely used in numerical weather prediction and regional climate modeling to obtain higher-resolution simulations in regions of interest. There are two approaches to running LAMs that are commonly used. The first approach is called one-way nesting, in which the lateral boundary conditions for a simulation using a limited-area model are interpolated in both time and space from a previously completed (coarser grid) simulation or analysis. The second approach is called two-way nesting, where both the coarse and fine grids are integrated simultaneously, with the coarse grid supplying boundary conditions for the fine grid (LAM) at each coarse-grid time step, along with the replacement of the coarse-grid solution with the fine-grid solution in the fine-grid region every coarse-grid time step. One-way nesting is used almost

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DOI: 10.1175/MWR-D-14-00004.1

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exclusively in operational numerical weather prediction (NWP) and regional climate applications; given its increased complexity, two-way nesting is used primarily in research applications.

There are several potential problems associated with grid nesting. Nest boundaries introduce discontinuous changes in spatial resolution between the LAM and the coarser-grid driving model. For a typically used spatially refinement ratio of 3, two-thirds of the spatial wave-number spectrum present on the fine mesh are absent on the coarse mesh. On inflow boundaries this means the flow must spin up the small-scale structures. A more serious problem occurs at outflow where waves in the upper two-thirds of the wavenumber space must be filtered or else may be spuriously reflected back into the fine-grid domain or aliased onto the coarse grid. Here “inflow” and “outflow” refer to the direction of propagation for each wave mode rather than the direction of the fluid flow. Additionally, both one-way and two-way nesting require temporal interpolation. For two-way nesting the temporal interpolation may have only a small effect if the ratio of coarse- to fine-grid time steps is not large. For one-way nesting it is common to interpolate fine-grid boundary values using coarse-grid data updated at time intervals much larger than the fine-grid time step. Similar to the spatial interpolation issue, temporal interpolation can also cause spurious reflection and aliasing at the lateral boundaries of the fine grid. These problems have given rise to a number of approaches for specifying the nest lateral boundary conditions and to spatial and temporal filtering on the nested grid in the vicinity of its lateral boundaries (e.g., Warner et al. 1997; Harris and Durran 2010).

There have been a number of studies examining the effects of lateral boundary conditions in LAMs. Leduc and Laprise (2009) investigated the sensitivity of domain size to errors arising from the lateral boundary conditions in regional climate simulations, and found a strong dependency of the errors on the distance of the lateral boundaries from the region of interest. Caron (2013) found that these errors can propagate as fast as external gravity waves and can contaminate the entire solution in a finite time. The frequency at which lateral boundary conditions are updated can be another potential problem affecting nested-grid simulations. In most LAMs, the boundary values are linearly interpolated over relatively long time intervals from global model data, and this can lead to unrealistic synoptic forcing as shown by Tudor and Termonia (2010). Harris and Durran (2010) document the deficiencies of one-way nesting based on an idealized case in a one-dimensional shallow-water model, but they suggest that one-way nesting can still be an attractive method for running a high-resolution mesoscale model for short-term forecasts (see their Table 1).

Warner et al. (1997) suggested that two-way interactive nesting reduces noise observed at the boundaries.
in one-way nested simulations and generally produce smaller errors than one-way nesting. For long integrations (e.g., regional climate applications), the two-way nesting approach allows for upscale influences to the coarse grid and helps keep the solutions on the two grids (coarse and fine) coupled. The decoupling of the solutions can be a major problem in the one-way approach and have led to the development of techniques such as spectral nudging to keep the large scales correlated (Miguez-Macho et al. 2005).

We adopt a variant of the Jablonowski and Williamson (2006) baroclinic wave test case that uses the most unstable normal mode (Park et al. 2013, hereafter P13) to investigate the issues related to variable-resolution grids and domain nesting. Since baroclinic waves are a key feature of midlatitude weather phenomena, this idealized analysis has direct relevance to atmospheric applications. We compare the results between one- and two-way nesting in the limited-area Advanced Research Weather Research and Forecasting (WRF-ARW) Model (hereafter ARW) (Skamarock et al. 2008), using the uniform resolution (latitude–longitude grid) global WRF Model simulations as a reference. Recently, Skamarock et al. (2012) introduced a new global atmospheric model, the Model for Prediction Across Scales-Atmosphere (MPAS-A), which supports variable-resolution meshes called Spherical Centroidal Voronoi Tesselations (SCVTs). We examine the behavior of the idealized baroclinic wave in MPAS simulations on a variable-resolution grid and demonstrate how these grids alleviate many of potential problems associated with lateral boundary conditions in LAMs. Our paper is organized as follows. In section 2, the model setup and description of the test case are presented. The structure and evolution of the normal mode in nested- and variable-resolution grids are compared in section 3, and section 4 summarizes the results of our study.

2. Experimental setup

We simulate the most unstable normal mode for an idealized growing baroclinic wave as described by P13. Based on the analytic initial conditions proposed by Jablonowski and Williamson (2006), P13 extended their test case to examine the normal-mode baroclinic wave evolution and found that wavenumber 9 was the most unstable normal mode. The symmetry of the wavenumber-9 normal-mode solution allows us to easily identify deviations in the solutions brought about by nested- or variable-resolution meshes. Here we use the same configuration as P13 but we increase the number of vertical layers to 50 and we do not include moisture. The vertical grid is stretched, with the vertical grid size varies from 82 m near the surface to approximately 900 m near...
the model top in MPAS, and from 110 m near the surface to approximately 1.2 km near the domain top in WRF.

Before comparing numerical results between the ARW nested grids and the variable-resolution MPAS-A Voronoi meshes, we conducted control simulations using a constant horizontal resolution in WRF and a quasi-uniform mesh in MPAS-A. The global version of the ARW (Skamarock et al. 2008) is tested with coarse (Δ = 0.9°, 93 km at the equator; WRF-C) and fine (Δ = 0.3°, 31 km at the equator; WRF-H) horizontal resolution. Similarly MPAS-A simulations are produced on two quasi-uniform mesh with either 70,562 cells (Δ ~ 90 km; MPAS-C) or 655,362 cells (Δ ~ 30 km; MPAS-H).

Model configuration information for the WRF single domain and nested simulations are summarized in Table 1 (left column) and Table 2, respectively. The ARW nested-grid configuration, plotted in Fig. 1, is used for the one- and two-way nesting experiments. In one-way nesting, we consider four different cases that differ in how lateral boundary values are updated. For the one-way offline nesting (WRF-1wayOFF), commonly called downscaling and widely used in LAMs, boundary values for the nested grid are specified from larger-scale simulations that have already been conducted or from preexisting analyses. For this experiment, we update lateral boundary values every 6 h and then interpolate between these times to provide boundary values for the grid at each time step. On the other hand, the lateral boundary values for the high-resolution domain in WRF-1wayOFF.2H and WRF-1wayON are updated every 2 h and every coarse-domain (WRF-C) time step, respectively. The online nesting option (WRF-1wayON) is very similar to two-way nesting test (WRF-2way) except the results on the nested grid are not fed back to the coarse grid (WRF-C). In WRF, this online nesting is easily achieved by turning off the interpolation of fine-grid fields back to the coarse grid in the two-way nesting configuration. The fine-grid domain is located in the region of 20°–80°N, 30°W–30°E.

![Variable-resolution meshes for the (a) MPAS-TRW and (b) MPAS-TRN configurations, plotted using meshes that are 4 times coarser than those used in the experiments for display purposes. Full-resolution meshes in the highlighted areas for (c) MPAS-TRW and (d) MPAS-TRN.](image-url)
and the grid refinement ratio of 1:3 is used for all cases except for the WRF-1wayOFF.X1 cases. In WRF-1wayOFF.X1, the nested grid boundary values are taken from the high-resolution global WRF (WRF-H) and no spatial interpolation is required to provide boundary data for the nested domain. For the nested domains, lateral boundary regions are comprised of one specified and four relaxation rows as described in Skamarock et al. (2008, see their Fig. 6.1).

The MPAS configurations using quasi-uniform and variable-resolution meshes are summarized in Table 1 and Table 3, respectively. Two different cases are examined for the variable-resolution meshes. Both meshes have the same cell size range, from 90 km in the coarse mesh region to 30 km in the area of the nested WRF domain, but with two different transition zone widths. The wider (MPAS-TRW) and narrower (MPAS-TRN) transition-zone meshes are shown in Fig. 2. Both MPAS-TRW and MPAS-TRN have a circular region of high resolution centered at (50°N, 0°) with a radius of 38°. The variable meshes of MPAS are computed using the density function,

$$\rho(x) = \frac{1 - \gamma}{2} \left[ \tanh \left( \frac{\beta - \|x_c - x\|}{\alpha} \right) + 1 \right] + \gamma,$$  \hspace{1cm} (1)

where $x_c$ is the location of center and $x$ lies on the sphere. The MPAS-TRW and MPAS-TRN meshes have the coefficient with $[\alpha, \beta, \gamma] = [0.148, 0.784, (1/3)^{4}]$ and $[0.038, 0.717, (1/3)^{6}]$, respectively. Equation (1) is similar
to that used in Ringler et al. (2011) except we have corrected the leading coefficient on the right-hand side of the equation. These transition zones span approximately 30° in MPAS-TRW (Fig. 2a) and 10° in MPAS-TRN (Fig. 2b). These variable-resolution SCVTs are discussed in more detail in section 3. As shown in Tables 1 and 3, WRF and MPAS-A use very similar numerical configurations. They both use a third-order Runge–Kutta scheme (Wicker and Skamarock 2002) for time integration and a two-dimensional Smagorinsky scheme for diffusion. A gravity wave–absorbing layer (Klemp et al. 2008) is employed near the model top (5 km, approximately five levels) in both models to reduce wave reflection. Three-dimensional divergence damping with the coefficient of $\beta_d = 0.1$ and a vertically implicit off-centering parameter ($\beta_s = 0.1$) are used in both WRF and MPAS-A tests (Klemp et al. 2007). In MPAS-A, a small amount of fourth-order hyperdiffusion ($K_4$) is additionally employed because there is no implicit diffusion for the horizontal momentum variables in MPAS-A. The hyperdiffusion coefficient is scaled by $(\Delta/\Delta_f)^3$ where $\Delta$ is the mesh spacing and $\Delta_f$ is the mesh spacing for the fine region. For the WRF simulations, a polar filter is used at latitudes poleward of 80° to avoid the nested grid, which requires a very small time step in WRF.

Fig. 4. Vertical velocity and horizontal wind vectors at 850 hPa at (a),(c) day 5 and (b),(d) day 7: (top) WRF-C and (bottom) WRF-H.
We compute the linear normal mode using the technique described in P13 and the WRF-C configuration, results are saved on 40 vertically interpolated isobaric levels. WRF and MPAS-A are initialized by interpolation from this isobaric level analysis.

3. Results

a. WRF single domain

Figure 3 shows the surface pressure and potential temperature at the lowest half level from the WRF-C and WRF-H simulations at days 5 and 7. During this evolution, the minimum and maximum surface pressures are comparable between coarse- and high-resolution WRF simulations, but there are significant differences in the surface pressure in the vicinity of cold front. There are stronger temperature gradients along the tail of the surface cyclone in WRF-H (Fig. 3c) compared to WRF-C (Fig. 3a), and by day 7 a secondary cyclone is developing in the cold-frontal region in WRF-H but not in WRF-C. The secondary cyclone is associated with high-latitude, high potential vorticity that has been advected south during the evolution of wave.

The vertical velocity and horizontal wind vectors for WRF-C (top) and WRF-H (bottom) at 850 hPa are shown in Fig. 4. Although the baroclinic wave structures are very similar in WRF-C and WRF-H, the intensities of the vertical velocities are noticeably different between

![Figure 5. Vertical velocity at 200 hPa at (a),(c) day 5 and (b),(d) day 7: (top) WRF-C and (bottom) WRF-H.](image-url)
the two cases. In the mature stage at day 5, a low-level jet is developing along the southern part of the cyclone and cold front (∼50°N, 0°). In the wave breaking stage at day 7, ascending and descending regions are separated in the eastern and western sectors of the baroclinic wave, respectively. Differences are also evident in the smaller scales at this time. In the northwestern part of the breaking wave (∼65°N, 5°W), there is more small scale variation in WRF-H (Fig. 4d) than in WRF-C (Fig. 4b). Other mesoscale waves are more prominent in the upper-level jet as shown in Fig. 5 depicting the vertical velocity at 200 hPa. Although the intensities of the waves at day 5 are similar in Figs. 5a,c, mesoscale waves are beginning to emerge in WRF-H. At day 7, the vertical velocity pattern and intensities in WRF-H (Fig. 5d) are quite different from WRF-C. In the WRF-C results shown in Fig. 5b, there are very weak small-scale waves near 60° latitude, and there are two separate regions of ascent around latitudes 58° and 43°N. In contrast to the coarse-grid simulation, the high-resolution normal-mode simulation has two different wave-source regions. One source produces small wave packets that are appearing in the northeastern section of the baroclinic wave. These waves resemble the inertia–gravity waves discussed by Zhang (2004), Plougonven and Snyder (2007), and Waite and Snyder (2009), where
the simulations were on the $f$ plane. In these previous simulations of idealized baroclinic waves, the excitation of gravity waves was shown to occur in the unbalanced upper-tropospheric jet, which is consistent with the location of wave generation in our simulations. The shape and structure of the gravity waves are quite comparable to the gravity waves found in the simulations of Plougonven and Snyder (2007) and Waite and Snyder (2009), though detailed analysis is beyond the scope of this study. The second wave source is in the southern part of the baroclinic wave ($\sim 43^\circ$N, $5^\circ$W) and is quite strong but not as well organized. These waves are related to the generation of the secondary cyclone mentioned earlier.

b. MPAS quasi-uniform mesh

Figure 6 shows the vertical velocity and wind vectors at 850 hPa from MPAS-A using quasi-uniform grids (top for MPAS-C and bottom for MPAS-H). The patterns are quite similar to the WRF results at high latitudes. However, at low latitudes, the MPAS results display a somewhat sharper gradient of vertical velocity at the cold front (Fig. 6c) and stronger vertical velocity in the secondary cyclone (Fig. 6d) than in the WRF simulations (Figs. 5c and 5d, respectively).

The overall structures and intensities for the vertical velocity at 200 hPa from MPAS-A (Fig. 7) are quite similar to those exhibited in WRF (Fig. 5). Slightly
more small-scale variations are produced in the southern part of the positive vertical velocity area at day 5 in MPAS-H (Fig. 7c) compared to WRF-H (Fig. 5c), but at day 7 MPAS-C (Fig. 7b) does not display any of the mesoscale waves that are weakly evident in WRF-C (Fig. 5b). This again may be related to the smaller grid spacing at high latitudes in WRF that we mentioned earlier. In WRF-C, the longitude interval is comparable to MPAS-C near the equator (~90 km), but it has only half the grid spacing (~45 km) at 60°N where inertia–gravity waves are generated in this study.

c. WRF nesting test

The results from the high-resolution regional nested domains are shown in Figs. 8–11 for the same times and levels as in Figs. 4 and 5. Figure 8 is from the WRF-1wayOFF experiment. At the lower level, abrupt changes of vertical velocity occur along the east and west lateral boundaries at day 5 (Fig. 8a) and day 7 (Fig. 8b). More interestingly, small-scale variations are propagating through the negative vertical velocity region from the eastern outflow boundary at day 5 (Fig. 8a) and also...
through the positive vertical velocity region at day 7 (Fig. 8b). As confirmed by Figs. 4a and 4b, these waves are not physical. The errors are more serious in the upper-level vertical velocity field as shown in Figs. 8c and 8d. The artificial positive velocities are significant along the lateral boundaries, even the south and north lateral boundaries, and significant noise is evident throughout the domain. The overall pattern of the positive and negative vertical velocities in the baroclinic waves is not significantly contaminated in the interior of the domain at 850 hPa in the WRF-1wayOFF compared to that from WRF-H, whereas at the upper level in WRF-1wayOFF, the vertical velocity field is highly corrupted.

To assess the impacts of the time interval at which the nested domain lateral boundary values are updated to the error in the one-way nested solutions, the results from WRF-1wayON (update frequency is every time step) and WRF-1wayOFF.2H (update frequency is every 2 h) are shown in Figs. 9 and 10. In WRF-1wayON, the vertical velocity perturbations along the lateral boundaries are significantly reduced (Figs. 9a,b) compared to WRF-1wayOFF (Fig. 8). This reduced error is also apparent in the gravity waves present at upper levels as seen in
Figs. 9c and 9d. Although significant distortions of the baroclinic wave are still evident at the upper level in the vicinity of the eastern (outflow) boundary, the overall structure of the normal mode is reasonably represented within the interior of the domain.

The results from updating the lateral boundary values every 2 h (WRF-1wayOFF.2H) are shown in Fig. 10. As in WRF-1wayON, significantly reduced errors are observed compared to WRF-1wayOFF (Fig. 8), although unphysical small-scale variations and strong vertical velocities along the lateral boundaries are still present. Lateral boundary conditions provide the large-scale forcing from which small-scale structures develop in the nested domain. Denis et al. (2002) indicated that the boundary update interval was sufficiently small if it is smaller than one-quarter of the wave period. In this experiment, the baroclinic wave period is approximately 40 h, thus updating the boundary values every 6 h satisfies the Denis et al. criterion and should provide proper synoptic forcing for the fine-resolution grid. However, comparison between Fig. 8 and Fig. 10 suggests that this update frequency is not small enough to capture the generation and propagation of mesoscale waves in the nested domain.

**Fig. 10.** (a),(b) 850-hPa wind vectors and vertical velocity and (c),(d) 200-hPa vertical velocity at (left) day 5 and (right) day 7 for WRF-1wayOFF.2H.
Figure 11 shows that the results from WRF-2way are similar to those with one-way online nesting, except that the abrupt changes in the vertical velocity in the vicinity of lateral boundaries in WRF-2way are noticeably reduced compared to the results of WRF-1wayON. At day 7 in Fig. 11d, there are two inertia–gravity wave packets in the northern region of the baroclinic wave train. The two inertia–gravity wave packets contained in the figure are not identical and their amplitudes are weaker than WRF-H. To investigate these weakened waves further, a vertical cross section from WRF-2way is plotted in Fig. 12 together with the WRF-H results. The top panels of Fig. 12 depict the vertical wind on day 6 at 200 hPa and the bottom panels display the vertical velocity cross sections along the line AA’ from WRF-H in Fig. 12a and line BB’ from WRF-2way in Fig. 12b. Contour fields from outside the nested region in Fig. 12b are taken from the coarse domain of WRF-2way. For the WRF-H results shown in Fig. 12c, the gravity waves curve to the cyclonic side of the jet and propagate northward, as found by Zhang (2004, see Figs. 6c,d in their paper). On the other hand, for WRF-2way in Fig. 12d, gravity waves are connected to the western lateral boundary even at large distances from that boundary. Because of the influence of
the lateral boundary region, the intensity of the secondary cyclone is overestimated (Fig. 11b near “B” label) and artificial upward propagation of the inertia–gravity waves is apparent at this time.

To further illustrate the differences between experiments, time series of maximum vertical velocity are shown in Fig. 13a (WRF-1wayOFF nesting is not shown because of the large amount of noise during its evolution). Compared to WRF-C, stronger vertical velocities arise in WRF-H and in the nested simulations after day 4 because the smaller scales are better resolved. However, there are large differences between WRF-H and the nested simulations when the baroclinic wave enters its mature stage. Although WRF-2way and WRF-1wayON results follow the WRF-H results very well until day 4.2, large peaks of vertical velocity arise around days 4.5, 5.5, and 6.75 compared to WRF-H. To investigate the source of these peaks, the location of maximum vertical velocity at days 4.5, 5.5, and 6.75 are marked in Fig. 13b. The maxima for WRF-2way (red crosses) and WRF-1wayON (blue triangles) are all located along the eastern and western boundaries, and have no correlation with the correct location as represented by WRF-H (black circles).

d. Lateral boundary values from WRF-H

An additional experiment (WRF-1wayOFF.X1) is carried out in which lateral boundary values are taken...
from WRF-H (as opposed to WRF-C). In this case, since there is no horizontal resolution gap between the nested grid and its parent, only temporal interpolation is required to provide the lateral boundary conditions. The simulation results at the lower and upper levels are shown in Fig. 14, and they are virtually indistinguishable to those in Fig. 8 for WRF-1wayOFF. Even though lateral boundary values are being used at coincident grid points from WRF-H, the results in Fig. 14 are very similar to those produced by using boundary values interpolated from a coarse grid. With a 2-h update frequency, the noise is significantly reduced (WRF-1wayOFF.X1.2H in Fig. 15), and the results are comparable to WRF-1wayOFF.2H in Fig. 10. Together with the results described previously in section 3c, these results indicate that inadequate update frequencies for lateral boundary values can produce significant errors similar to those produced by spatial interpolations required in high-resolution nested simulations. Note that some of the amplitude differences between the results given in Figs. 10d and 15d suggest that additional spinup time is necessary in WRF-1wayOFF.2H to generate gravity waves, likely because there is little small-scale information in interpolated boundary values from WRF-C.

e. WRF-LAM test

We can obtain initial and boundary conditions from WRF-C to configure WRF as a LAM for any coordinate map projection. Figure 16 shows the results for surface pressure and potential temperature at the lowest half level for a regional WRF simulation using a Lambert conformal projection, a 6-h update frequency for lateral boundary value interpolation, and a 30-km horizontal grid size (left panel) in comparison to WRF-H (right panel). Since their grid sizes are comparable, the results should be quite similar. However, as in the WRF-1wayOFF results, there are significant artificial small-scale variations even in the interior of the domain. At day 5 (Fig. 16a), small-scale variations are apparent in the temperature contours in the vicinity of both the eastern and western boundaries that are not found in the WRF-H results (Fig. 16b). Asymmetries in the potential temperature fields are prominent in Fig. 16c at day 6 compared to the WRF-H results (Fig. 16d) and significantly lower surface pressure exists near the eastern boundary of WRF-LAM test. The phase speed and intensity of the cyclones in Fig. 16e are very different from the reference WRF-H results shown in Fig. 16f. At this time, the WRF-LAM simulation does not have a strong secondary cyclone as shown in WRF-H. The distortions in the WRF-LAM results are significantly larger than those occurring when the nested mesh is aligned with the coarse mesh, as in the WRF-1wayOFF results. Note that in the earlier experiment, one-dimensional interpolation is required for updating lateral boundary values because coarse domain grids are coincident with every three fine grid points. For the WRF-LAM experiments, because of different map projection, two-dimensional interpolations are necessary to provide lateral boundary values for the nested domain.
The results from the MPAS variable-resolution simulations are shown in Figs. 17 and 18. To display the fields in both the coarse- and fine-resolution regions, including transition zones, a much wider area (from 120°W to 120°E) is plotted in these figures than that plotted for the nested WRF domains. The transition zones are in the area between the two solid lines superimposed on the figures. Since MPAS-TRW has a larger transition zone than MPAS-TRN, the MPAS-TRW results have a wider region of strong vertical velocities associated with high resolution. However, the MPAS-TRW and MPAS-TRN results shown in Fig. 17 are very similar in their high-resolution regions. For example, the sharp gradient along the cold front at day 5 in Figs. 17a and 17c, and strong vertical velocities from the secondary cyclone at day 7 in Figs. 17b and 17d, are very similar between the two cases and there appear to be no significant errors due to the changing grid size.

As shown in the WRF nesting simulations, the upper-level vertical velocity provides a more stringent test of the accuracy of the model in the transition zone. Compared to the day-5 MPAS-C and MPAS-H results with high resolution.
in Figs. 7a and 7c, the MPAS-TRW results in Fig. 18a and the MPAS-TRN results in Fig. 18c show only a small amount of noise in the positive vertical velocity region located in the transition zone. At day 7, shown in Figs. 18b and 18d, both of MPAS-TRW and TRN have two sources of gravity wave generation in the high-resolution area. Although these sources do not appear in the coarse-resolution region for each case, there is no apparent reflection of waves in the transition zone. Stronger and more organized waves are apparent in the outgoing (eastern) transition zone compared to the incoming (western) transition zone in both cases.

The time series of maximum vertical velocity for MPAS are shown in Fig. 19 and can be compared to the WRF nesting results in Fig. 13a. For the coarse-resolution test, the MPAS-C results have similar time-varying maximum vertical velocities compared to those from the WRF-C results. For the high-resolution case, the MPAS-H results have a somewhat larger vertical velocity amplitudes than those from the WRF-H results after day 4.5. In this study, all WRF simulations are conducted using a third-order horizontal advection scheme as shown in Table 1. However, the MPAS results are very comparable to WRF results generated using
FIG. 16. Surface pressure (black) and potential temperature at the lowest half level (red) for (a),(c),(e) WRF-lambert and (b),(d),(f) WRF-H: (top) day 5, (middle) day 6, and (bottom) day 7. The results from WRF-H are remapped into the lambert conformal projection. Contour intervals are 4 hPa and 10 K for surface pressure and potential temperature, respectively.
a fifth-order horizontal advection scheme for momentum and temperature (not shown).

With the variable MPAS meshes, results from both MPAS-TRN and MPAS-TRW show a very similar pattern to the results from MPAS-H. Although a small amount of noise is evident from days 3 to 5.5, the magnitude is very small compared to the nested WRF results in Fig. 13a.

4. Summary

Normal-mode baroclinic wave tests are carried out to compare results from nested domains in WRF and variable-resolution meshes in MPAS-A. For single-domain or quasi-uniform experiments, MPAS-A and global WRF show very similar results. In the high-resolution tests, both models capture the generation and propagation of gravity waves in the vicinity of the jet, which are not resolved with the coarser resolution. Secondary cyclone generation with strong vertical velocities is also obtained but only in the high-resolution tests.

One key feature for this test case is the periodic wave train (wavenumber 9 normal mode) moving into, through, and out of the high-resolution zone. Because of this periodicity, we can readily assess the behavior of the wave’s evolution in the nested domain or in a variable mesh. For the WRF-1wayOFF experiment, the baroclinic waves have significant distortion in the fine mesh domain. It is hard to find a physical connection between the upper-level and lower-level flows because of significant small-scale noise spreading throughout the domain. We also

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**Fig. 17.** Vertical velocity at 850 hPa for (a) MPAS-TRW and (c) MPAS-TRN at day 5 and (b) MPAS-TRW and (d) MPAS-TRN at day 7. The areas between the inner and outer solid lines are the transition zones for variable meshes shown in Fig. 2.
obtained similar results (with even more distortion) for WRF configured as a limited-area model. There is artificial weakening and strengthening of waves near the lateral boundaries and the secondary cyclone is not resolved well even though the resolution is comparable to WRF-H. Since most limited-area models take their lateral boundary values from global models at large time intervals, these results show potential problems with these limited-area model configurations. Furthermore, these problems can be more significant because two-dimensional interpolation is required for updating lateral boundary values when different map projections are used.

The importance of the boundary update frequency is assessed by decreasing the time interval of the lateral boundary value updates and by using the same horizontal resolution in the global and nested domain. We find that the noise in the vertical velocity is not significantly reduced unless the boundary update interval is sufficiently small. This behavior is confirmed in comparing the WRF-1wayON and WRF-2way results. Despite no influence on the coarse domain from the fine domain in the WRF-1wayON configuration, its results are very similar to those from the WRF-2way configuration. However, in both the WRF-1wayON and WRF-2way results, significant imprints from the lateral boundaries are still evident inside of the domain. Spurious waves generated at or reflecting from the lateral boundaries propagate and become superposed with the resolved waves generated within the jet.

Using the two different variable-resolution MPAS meshes, MPAS-A simulations show consistent results. Compared to the results from the quasi-uniform meshes,
the intensity and propagation of waves in the coarse- and fine-resolution regions are very similar to those in the WRF-C and WRF-H results. Throughout the transition zone, waves have reasonable structure that depend only on the local horizontal resolution and show no apparent reflections or distortions.

This study investigates the issues of lateral boundaries in regional numerical models and demonstrates an alternative approach in a global model using variable resolution. However, there are still issues to be addressed regarding the consistent treatment of physics using the variable-resolution meshes.

REFERENCES


