Impact of Variable-Resolution Meshes on Midlatitude Baroclinic Eddies Using CAM-MPAS-A

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ABSTRACT

The effects of a variable-resolution mesh on simulated midlatitude baroclinic eddies in idealized settings are examined. Both aquaplanet and Held–Suarez experiments are performed using the Model for Prediction Across Scales-Atmosphere (MPAS-A) hydrostatic dynamical core implemented within the National Science Foundation–Department of Energy (NSF–DOE) Community Atmosphere Model (CAM-MPAS-A). In the real world, midlatitude eddy activity is organized by orography, land–sea contrasts, and sea surface temperature anomalies. In these zonally symmetric idealized settings, transients should have an equal probability of occurring at any longitude. However, the use of a variable-resolution mesh with a circular high-resolution region centered at 30°N results in a maximum in eddy kinetic energy on the eastern side and downstream of this high-resolution region in both aquaplanet and Held–Suarez CAM-MPAS-A simulations. The presence of a geographically confined maximum in both simulations suggests this response is mainly attributable to CAM-MPAS-A’s ability to resolve eddies via the model dynamics as resolution increases. However, in the aquaplanet simulation, a secondary maximum in eddy kinetic energy is present, which is probably linked to the resolution dependencies of the CAM physics. These mesh responses must be considered when interpreting real-world variable-resolution CAM-MPAS-A simulations, particularly in climate change experiments.

1. Introduction

Variable-resolution (or multiresolution) approaches to simulating regional climate offer an appealing modeling framework in which areas of interest can be simulated at high resolution while maintaining consistent dynamics and physics that are usually lacking in traditional regional climate models (e.g., Déqué et al. 1994; Wang et al. 2004; McGregor 2005; Fox-Rabinovitz et al. 2006; McGregor 2013). However, this very consistency highlights an ongoing modeling challenge: model results are often strongly dependent on resolution and solutions do not necessarily converge as resolution increases (e.g., Boville 1991; Pope and Stratton 2002; Duffy et al. 2003; Williamson 2008). In quasi-uniform simulations, resolution dependency can be tuned away (if sufficient computing resources exist to do so) or simply acknowledged. In a variable-resolution setting, however, resolution dependencies cannot be ignored because they can introduce anomalous circulations that affect the quality of the entire simulation (Lorant and Royer 2001; Rauscher et al. 2013). This resolution dependency can arise as a result of the model physics (e.g., O’Brien et al. 2013; Williamson et al. 1995), such as the parameterization of cumulus convection, but also from the model dynamics (e.g., Wan et al. 2008).

The effects of these scale dependencies on variable-resolution simulations are apparent in aquaplanet simulations performed recently using a multiscale modeling approach—the new Model for Prediction Across Scales-Atmosphere (MPAS-A) dynamical core coupled with the Community Atmosphere Model (CAM-MPAS-A; Neale 2010). By their design, aquaplanet simulations should be zonally and hemispherically symmetric (Neale and Hoskins 2000), at least in a statistical sense. However, the use of a variable-resolution mesh with a circular high-resolution region on the equator results in large zonal asymmetries in the precipitation and circulation fields, particularly in the tropics (Rauscher et al. 2013). These same circulation asymmetries are largely absent...
in a variable resolution performed with idealized physics, suggesting that in the tropics, the scale dependencies rest within the CAM model physics (Hagos et al. 2013; O’Brien et al. 2013; Rauscher et al. 2013). Further evidence that the CAM physics are responsible can be found in variable-resolution aquaplanet simulations performed with a different dynamical core, the Spectral Element dynamical core and the same CAM physics (CAM-SE). These simulations display similar precipitation and circulation anomalies in the tropics (Levy et al. 2013; Zarzycki et al. 2014).

While the tropical response was examined in Rauscher et al. (2013), the midlatitude response to the variable-resolution (VR) mesh in these simulations has yet to be explored. This represents a critical gap since variable-resolution Atmospheric Model Intercomparison Project (AMIP) simulations using CAM-MPAS-A are planned for North America (Leung et al. 2013), and correctly interpreting these real-world results requires an understanding of the impact of the use of the VR mesh itself on the simulations. Baroclinic eddy activity is a primary driver of midlatitude climate dynamics. Localized regions of baroclinic eddy activity (i.e., storm tracks) are identified by regions of maximum eddy kinetic energy (Hoskins and Valdes 1990). In the real world, storm tracks are organized by orography land–sea contrasts, and regional sea surface temperature (SST) gradients (Hoskins and Valdes 1990; Chang and Orlanski 1993; Brayshaw et al. 2009). In idealized experiments that lack any zonal asymmetry in boundary conditions, baroclinic eddy activity should have an equal probability of occurring at any longitude (Inatsu et al. 2003).

In variable-resolution idealized simulations using CAM-MPAS-A this may not be the case. Increasing horizontal resolution has been shown to increase eddy kinetic energy in Held–Suarez, aquaplanet, and real-world simulations (Boville 1991; Boyle 1993; Wan et al. 2008; Williamson et al. 1995). The Held–Suarez results suggest that this is a dynamical response since wave activity may be strengthened by resolving smaller-scale motions (Wan et al. 2008). Further, diabatic heating responses to the physics resolution dependencies in the midlatitudes cannot be ruled out. Extratropical SST gradients and anomalies affect storm tracks (Kaspi and Schneider 2011; Inatsu et al. 2002; Lu et al. 2010), and indirect responses to tropical heating anomalies caused by the variable-resolution mesh may also occur through tropical–midlatitude Rossby wave propagation (e.g., Hoskins and Karoly 1981; Jin and Hoskins 1995). It, therefore, seems likely that the variable-resolution mesh may impact the zonal distribution of baroclinic activity (i.e., storm tracks). If so, are these artificial storm tracks attributable to the CAM-MPAS-A model dynamics or physics or a combination of responses to both?

We examine the response of midlatitude baroclinic eddies to a variable-resolution mesh in a series of aquaplanet experiments performed with MPAS-A (Ringler et al. 2010, 2011) implemented within CAM. Three quasi-uniform CAM-MPAS-A simulations were run with horizontal grid spacings of approximately 30, 120, and 240 km; these are described in Rauscher et al. (2013). In addition, we performed a set of VR simulations with the high-resolution region centered at 30°N. In the VR simulations, we varied the grid spacing of the coarse-resolution region to give ratios of 4 (30–120 km) and 8 (30–240 km). These VR simulations differ from the CAM-MPAS-A VR simulation presented in Rauscher et al. (2013), which has its high-resolution region centered on the equator. We also performed a series of Held–Suarez simulations to investigate whether the midlatitude responses to the VR mesh can be attributed to the model physics or dynamics.

Section 2 contains a brief description of the models used (CAM and MPAS-A) and the experimental design. An overview of the circulation and precipitation anomalies associated with the variable-resolution mesh is presented in section 3, while transient eddy statistics are discussed in section 4. Finally, discussion and conclusions are presented in section 5.

2. Models and experimental design

We employ the National Science Foundation–Department of Energy (NSF–DOE) CAM (Neale 2010) with version 4 physics and 26 vertical levels coupled to the MPAS-A, as described in Rauscher et al. (2013). The source code, documentation, and input datasets for CAM are available online at http://www.cesm.ucar.edu/models/cesm1.0/cam/ The standard version 4 physics suite is used, including the mass flux scheme of Zhang and McFarlane (1995) for deep convection.

The MPAS multiresolution approach differs from previous multiresolution approaches that utilize stretched grids (e.g., Fox-Rabinovitz et al. 1997; Déqué et al. 2005; Lorant and Royer 2001; Fox-Rabinovitz et al. 2006; McGregor 2013). In these approaches, in the mesh is deformed through a continuous mapping and, as a result, the mesh is topologically unchanged as the resolution varies. Thus, increased resolution in one region comes at the expense of decreased resolution in another region. To overcome this limitation, MPAS uses Spherical Centroidal Voronoi Tessellations (SCVTs). These meshes are also referred to as geodesic grids, icosahedral grids, or hexagonal grids. Within MPAS, local mesh refinement is achieved through the specification of a single scalar density function that results in higher resolution where this density function is large and lower resolution where this density function is small (Ringler et al. 2011). Meshes can
be configured with multiple high-resolution regions, and increases in resolution in one region do not need to be balanced by coarser resolution elsewhere. The result is a mesh with smooth transitions: Fig. 1 shows a transition region for one of the meshes used here, with a grid spacing of approximately 30 km in the high-resolution region centered at 30°N, 0°, and 240 km in the coarse-resolution region.

These multiresolution SCVTs are paired with a recent generalization of the C-grid staggering to Voronoi tesselations (Thuburn et al. 2009; Ringler et al. 2010), which guarantees a realistic simulation of geostrophic adjustment (Thuburn et al. 2009) along with exact mass, tracer, and potential vorticity conservation and energy conservation to within truncation error (Ringler et al. 2010). MPAS-A utilizes the WeatherResearch and Forecasting Model vertical and time discretization (Skamarock et al. 2008). A detailed description of the MPAS-A hydrostatic solver can be found in Park et al. (2013).

Two types of idealized experiments are performed: aquaplanet (Neale and Hoskins 2000) and Held–Suarez (Held and Suarez 1994). The aquaplanet simulations are configured following Neale and Hoskins (2000), with the “control” SST (in °C) distribution prescribed as follows:

\[ T_s(\lambda, \phi) = \begin{cases} 
27 \left[ 1 - \sin^2 \left( \frac{3\phi}{2} \right) \right] & \text{if } -\frac{\pi}{3} < \phi < \frac{\pi}{3}, \\
0 & \text{otherwise.} 
\end{cases} \]  

(1)

In the aquaplanet simulations, there are no landmasses or seasons (insolation is equinoctial), but the full suite of CAM physics is used. In Held–Suarez simulations, the full model physics are replaced by prescribed forcing and dissipation, thus removing the effects of the physics parameterizations on the solution (Held and Suarez 1994). By comparing aquaplanet to Held–Suarez simulations, we can determine the differing resolution dependencies of the model physics and dynamics.

In these experiments (Table 1), CAM-MPAS-A is configured with three different quasi-uniform resolution (QUR) meshes with grid spacings of approximately 30, 120, and 240 km and two VR meshes. The QUR experiments are described in detail and evaluated in Rauscher et al. (2013). (The high-resolution regions of the VR meshes employed here are outlined in Fig. 3.) The high-resolution region spans about 60° latitude and longitude, and is centered at 30°N; the grid spacing transitions to the coarser resolution over 20° of latitude–longitude. This central latitude of 30°N was chosen to be the same as in real-world AMIP variable-resolution simulations planned for North America (Leung et al. 2013), with the goal that these VR simulations could help to inform their interpretation. The two VR meshes are distinguished by the grid spacing in their respective coarse-resolution regions. In one simulation, it is 120 km, giving a ratio of 4 between the coarse resolution and fine resolution (referred to as ×4). In the other simulation, this ratio is 8, as the coarse region has grid spacing of about 240 km (×8).

Each simulation was run for 5 yr, with the first 6 months discarded for spinup, leaving 4.5 years for analysis. Typically a Held–Suarez (H–S) simulation is run for 1200 days,
Table 1. List of CAM-MPAS-A simulations. Aquaplanet (Held–Suarez) simulations are abbreviated with APE (H–S). Mesh ratio refers to the ratio between the finest and coarsest grid spacing in a mesh, where \( \times 1 \) indicates a quasi-uniform mesh.

<table>
<thead>
<tr>
<th>Type of simulation</th>
<th>Quasi-uniform (QUR) or variable resolution (VR)</th>
<th>Mesh ratio</th>
<th>Approx horizontal resolution (native) (km)</th>
<th>No. 2D grid points (native)</th>
<th>Hyperviscosity</th>
<th>Approx horizontal resolution (regridded)</th>
<th>No. 2D grid points (regridded, meridional grid points ( \times ) zonal grid points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APE</td>
<td>QUR</td>
<td>( \times 1 )</td>
<td>240</td>
<td>10,242</td>
<td>( 5 \times 10^{15} )</td>
<td>1.9(^{\circ}) lat ( \times ) 2.5(^{\circ}) lon</td>
<td>96 ( \times ) 144</td>
</tr>
<tr>
<td>APE</td>
<td>QUR</td>
<td>( \times 1 )</td>
<td>120</td>
<td>40,962</td>
<td>( 5 \times 10^{15} )</td>
<td>0.9(^{\circ}) lat ( \times ) 1.25(^{\circ}) lon</td>
<td>192 ( \times ) 288</td>
</tr>
<tr>
<td>APE</td>
<td>VR</td>
<td>( \times 8 )</td>
<td>30</td>
<td>65,562</td>
<td>( 5 \times 10^{12} )</td>
<td>0.23(^{\circ}) lat ( \times ) 0.31(^{\circ}) lon</td>
<td>768 ( \times ) 1152</td>
</tr>
<tr>
<td>APE, H–S</td>
<td>VR</td>
<td>( \times 4 )</td>
<td>240–30</td>
<td>65,538</td>
<td>( 5 \times 10^{12} ) to ( 5 \times 10^{15} ) scaled</td>
<td>0.23(^{\circ}) lat ( \times ) 0.31(^{\circ}) lon</td>
<td>768 ( \times ) 1152</td>
</tr>
<tr>
<td>APE, H–S</td>
<td>VR</td>
<td>( \times 4 )</td>
<td>120–30</td>
<td>102,402</td>
<td>( 5 \times 10^{12} ) to ( 5 \times 10^{14} ) scaled</td>
<td>0.23(^{\circ}) lat ( \times ) 0.31(^{\circ}) lon</td>
<td>768 ( \times ) 1152</td>
</tr>
</tbody>
</table>

3. Global response to mesh refinement

As noted in the introduction, without tuning, most climate models display some sensitivity to changing horizontal resolution. In the case of CAM, this is expressed as increasing tropical precipitation and circulation strength with resolution, irrespective of the dynamical core used (Williamson et al. 1995; Abiodun et al. 2008). This is demonstrated in Fig. 2, which shows differences in vertically integrated moisture and 925-hPa winds between the QUR 30- and 240-km simulations. Moisture is greater in tropical regions (and reduced in midlatitudes) at higher resolution, whereas low-level winds appear to be strengthened (e.g., tropical easterlies and low-level midlatitude westerlies). In a VR setting, these resolution sensitivities lead to precipitation and circulation anomalies that have a global effect on the simulation.

This global effect is illustrated in the top four panels of Fig. 3, which show departures from the zonal mean precipitation (shaded), 250-hPa eddy streamfunction, and 250-hPa velocity potential for the two variable-resolution aquaplanet simulations (\( \times 4 \) right, \( \times 8 \) left). Departures from the zonal mean measure deviations from the expected symmetry\(^1\) as an indication of the VR mesh effects on the solution. A positive precipitation anomaly is present on the southwestern periphery of the high-resolution region near the equator, as the southern boundary of the high-resolution region is located in the tropics. This precipitation anomaly results in part from changes in wind speed and moisture content as the VR solution “adjusts” to the high-resolution region. The associated diabatic heating anomaly located on the equator from \( 0^\circ \) to \( 60^\circ \)W (Fig. 4) initiates a Gill-type response, as indicated by the anticyclonic circulation to the northwest of the positive heating anomaly. A similar

\(^1\) It is impossible to obtain an exactly zonally symmetric climate from any mesh that is not exactly zonally symmetric (i.e. cubed-sphere, hexagonal-icosahedral, and triangular meshes), even for quasi-uniform configurations.
but more hemispherically symmetric response was found in VR simulations with the high-resolution region centered on the equator (Hagos et al. 2013; Rauscher et al. 2013).

In our simulations with MPAS-A, the magnitude of the tropical response is larger in the \( \times 8 \) aquaplanet simulation, where the grid spacing ranges from 240 to 30 km, than in the \( \times 4 \) aquaplanet experiment. In the case of the \( \times 8 \) aquaplanet experiment, the response is global. The lack of a signal in the eddy velocity potential fields in the H–S simulations (bottom panels of Fig. 3) suggests that this tropical response is largely due to resolution sensitivity of the CAM physics, which has been substantiated by additional in-depth analyses of CAM simulations with different dynamical cores at varying resolutions (O’Brien et al. 2013). Further, similar variable-resolution aquaplanet experiments with a high-resolution region straddling the equator performed with the same CAM physics but with a different dynamical core, the CAM-SE, show similar asymmetries in the precipitation field (Levy et al. 2013; Zarzycki et al. 2014). A spurious (unphysical) switch from convective to resolved precipitation at higher resolution may help to drive larger vertical velocities (Williamson 2013), enhancing wind speeds in the high-resolution region and resulting in the convergence and precipitation maximum observed on the high-resolution region’s southwestern side. Interestingly, the tropical response is smaller in CAM-SE VR simulations utilizing the CAM phase 5 (CAM5) physics; this improvement may be due to the updated microphysics package (O’Brien et al. 2013; Zarzycki et al. 2014).

The effects of the VR mesh in CAM-MPAS-A are not limited to low latitudes. In contrast to the tropics, the midlatitudes tend to dry at higher resolution, as indicated in the differences between the 30- and 240-km QUR simulations (Fig. 2). However, the wind speed changes are consistent with the tropics. In the VR simulation there are two lobes of precipitation anomalies (shaded blue) on the eastern and western sides of the high-resolution region in the midlatitudes: one at about 40°N, 30°W, and the other at about 35°N, 30°E. Coincident with these precipitation anomalies are noticeable departures from the zonal mean of the temperature tendency due to moist processes (i.e., a diabatic heating response) as shown for the VR aquaplanet \( \times 8 \) simulation in Fig. 4a. Positive departures from the zonal mean (shaded red) are located on the boundaries of the high-resolution region. These differences in precipitation and diabatic heating may reflect (and for the latter, force) more transient eddy activity in the VR simulations. We examine this via the transient eddy statistics in the next section.

4. Transient eddy statistics

Storm tracks are organized by orography, land–sea contrasts, and gradients in sea surface temperature that
create strong meridional temperature gradients and diabatic heating anomalies (e.g., Hoskins and Valdes 1990; Chang and Orlanski 1993; Brayshaw et al. 2009). In the zonally symmetric world of aquaplanet, these factors are absent, and baroclinic eddies should not preferentially organize at any particular longitude (Inatsu et al. 2003). Given the precipitation and circulation asymmetries uncovered in our analysis of the tropics (Rauscher et al. 2013; Hagos et al. 2013) and the midlatitude precipitation anomalies discussed in section 3, it is natural to wonder if the presence of the variable-resolution mesh can also introduce large asymmetries into the simulation of other midlatitude climate features, such that the high-resolution region might be associated with greater baroclinic eddy activity.

Such activity may be identified by maxima of eddy kinetic energy (EKE), defined as \( \text{EKE} = 0.5(u'^2 + v'^2) \). Figure 5 shows departures from the zonal mean of bandpass-filtered EKE for the aquaplanet (left) and Held–Suarez experiments (right). The \( \times 4 \) experiments are shown in the top row and the \( \times 8 \) in the bottom row. In the \( \times 4 \) experiments there is no substantial response to the variable-resolution mesh. This is consistent with the behavior of the QUR experiments, as zonal means of the EKE for the QUR CAM-MPAS aquaplanet experiments show little difference between the QUR 120- and 30-km zonal means of EKE (Fig. 6). Further, maps of the departures from the zonal mean EKE for all three quasi-uniform aquaplanet experiments indicate anomalies of similar magnitude to those shown in the \( \times 4 \) experiments (Fig. 7).

However, for the \( \times 8 \) experiments, the picture is quite different. Both the H–S and aquaplanet (APE) experiments indicate an enhancement of EKE in the vicinity of the high-resolution region, although the geographical distribution differs. In the aquaplanet experiment, higher EKE is present over the entire high-resolution region, extending both upstream and downstream to cover approximately 120° of longitude. These departures from the zonal mean are at least 2–3 times larger than any zonal EKE anomalies in the quasi-uniform aquaplanet simulations (Fig. 7), and they occur over a substantially larger area (150° of longitude vs less than 60°). The lobes of higher EKE centered at about...
$30^\circ$W and $30^\circ$E coincide with the locations of the precipitation anomalies discussed in section 3; maxima of meridional heat flux ($V^\prime T^\prime$) are also similarly collocated (Fig. 4b). Elsewhere, EKE is lower than the zonal mean. In the H–S case, EKE is enhanced downstream of the high-resolution region (eastern side), again spanning about $120^\circ$, and then values are smaller than the zonal mean farther downstream. In both simulations, the reduction in EKE downstream of the maximum is consistent with Kaspi and Schneider (2011), who showed that in aquaplanet simulations, imposing a localized heating source leads to an EKE maximum but also to an EKE depression downstream (i.e., storm tracks “self-destruct” downstream).

To analyze the differences between the H–S and aquaplanet results, we use the Eady growth rate (Eady 1949), which measures how conducive the atmospheric flow is to baroclinic instability, the conversion of available potential energy into kinetic energy. The Eady growth rate ($\sigma_B$) is defined by Lindzen and Farrell (1980) as
\[ \sigma_{\text{BI}} = \frac{0.31f}{N} \frac{\partial u}{\partial z}, \]  

where \( N \) is the Brunt–Väisälä frequency, a measure of static stability, and \( \partial u/\partial z \) is the vertical wind shear, which is proportional to the meridional temperature gradient when thermal wind balance is valid. Greater values of \( \sigma_{\text{BI}} \) indicate the possibility for eddy growth and downstream development (Hoskins and Valdes 1990). Figure 8 shows vertical cross sections of the departures from the zonal mean of \( \sigma_{\text{BI}} \) averaged over 35\(^\circ\)–55\(^\circ\)N for the aquaplanet \( \times 8 \) (top) and H–S \( \times 8 \) experiments (bottom), respectively. Note that we focus on the \( \times 8 \) experiments because they clearly show storm tracks. Superimposed on the shaded \( \sigma_{\text{BI}} \) are its components, the Brunt–Väisälä frequency \( (N, \text{purple contour}) \) and \( \partial u/\partial z \) (black contour).

Both the Held–Suarez and aquaplanet simulations show enhanced baroclinicity (larger values of \( \sigma_{\text{BI}}, \text{shaded pink to red} \)) slightly to the west of the center of the high-resolution region (0\(^\circ\)) from the surface extending to midlevels. This is consistent with the high values of eddy kinetic energy located east of 0\(^\circ\) (Figs. 5c,d), as the maximum in eddy kinetic energy should be located downstream of the maximum baroclinicity as time (and hence distance) is required for the wave to develop (Kavulich et al. 2013). As with EKE, the patterns of \( \sigma_{\text{BI}} \) differ, however, in that in aquaplanet there is a wider, shallower maximum near the surface extending from 60\(^\circ\)W to 60\(^\circ\)E, while in the Held–Suarez simulation the maximum \( \sigma_{\text{BI}} \) is geographically confined to about 0\(^\circ\)–35\(^\circ\)W. The larger departures from the zonal mean of EKE and \( \sigma_{\text{BI}} \) in the
aquaplanet simulation compared to the H–S simulation may reflect in part the impact of diabatic heating associated with moist processes (Fig. 4a). Latent heat release can enhance the growth rate and amplitude of baroclinic waves (Hoskins and Valdes 1990; Chang and Orlanski 1993; Inatsu et al. 2003; Wernli et al. 2002), and indeed, a positive temperature anomaly is present from about 0\° E to 60\° E in the aquaplanet simulation (Fig. 9a). This helps to explain the stronger EKE departures from the zonal mean observed in Fig. 5 on the eastern side of the high-resolution region in aquaplanet compared to H–S.

For both simulations, the pattern of wind shear (black contour) is similar to $\sigma_{HI}$, which is to be expected as this quantity dominates $\sigma_{HI}$. This larger shear in the vicinity of the high-resolution region (in both simulations, but for H–S confined to west of 0\°) may simply reflect the higher wind speeds associated with higher horizontal resolution. There are also similarities in the distribution of static stability departures from the zonal mean (purple contour)—both the H–S and aquaplanet simulations indicate enhanced low-level stability from about 10\° to 20\°W eastward. Both simulations also show negative departures from the zonal mean of static stability near the western transition zones (around 40\°W) into the high-resolution region, with cooling aloft and some slight warming near the surface (Fig. 9b).

The interpretation of the EKE maximum on the western side of the high-resolution region (centered on 30\°W) in the aquaplanet simulation (not present in the H–S simulation; Fig. 5) is more difficult. Its absence in the H–S simulation suggests that this response is due to the resolution dependence of the physics. For the VR simulations, this decrease in moisture is illustrated in Fig. 9a, which shows departures from the zonal mean for specific humidity (purple contours), zonal wind (black contours), and temperature (shaded) averaged over 35\°–55\°N. While the changes are fairly small, reductions in specific humidity are apparent from the surface to midlevels from about 60\°W to 30\°E. In addition, the increase in zonal wind speeds that occurs in the high-resolution region implies that moisture divergence should be present on the western side of the high-resolution region in midlatitudes. Instead, there is a maximum in precipitation. Figure 4c shows a low pressure region at 60\°N, 30\°W on the poleward side of the VR region extending up and downstream of the VR region. Geostrophic balance leads to an enhancement of the jet across the entire region. Figure 4b adds support by showing enhanced heat transport at the entrance to this jet upstream of the VR region. While a tropical forcing of this geopotential low cannot be ruled out, it is not likely. This is because if it is forced in the tropics, then the geopotential at 60\°N, 30\°W would most likely be part of the Rossby wave train. Since the group velocity of this geopotential low cannot be ruled out, it is not likely. This is because if it is forced in the tropics, then the geopotential at 60\°N, 30\°W would most likely be part of the Rossby wave train. Since the group velocity of Rossby waves is always westward, the forcing would have to be located somewhat upstream of 30\°W. However, there does not appear to be a tropical source for low geopotential located westward of 30\°W.

5. Discussion and conclusions

We have shown that the use of a VR mesh results in a maximum in eddy kinetic energy (EKE, i.e., a geographically confined storm track) in idealized CAM-MPAS-A simulations with zonally symmetric forcing. Without ambiguity, we can ascribe the presence of these storm tracks to the use of VR meshes. Since a maximum in eddy activity is present in the H–S experiments, the
model dynamics appear to play the primary role in its generation through the model’s ability to resolve eddies as resolution increases. However, there is a secondary EKE maximum in the \( \times 8 \) VR aquaplanet simulation that is not present in the Held–Suarez simulation, which implies that the scale dependency of the CAM physics is likely responsible. Further simulations and analyses should elucidate the exact cause of the secondary EKE maximum. Since the scale dependency of the physics appears to be reduced with the CAM5 physics compared to the CAM4 physics (O’Brien et al. 2013; Zarzycki et al. 2014), we would expect the magnitude of this secondary maximum to decrease with the CAM5 physics. Additionally, the ratio of the grid spacing between the coarse and fine resolution may not be important (Rauscher et al. 2013) so much as whether the feature of interest can be resolved at the coarser scale. Whereas in the tropics, the model moist physics are unable to adequately represent cloud and precipitation processes at any of the scales included here (O’Brien et al. 2013), simulated mid-latitude baroclinic eddy activity does not change much from 120 to 30 km, at least in CAM-MPAS-A.

These results raise the important question of whether or not these storm tracks generated in CAM-MPAS-A

![Vertical cross section of departure from zonal mean for Eady growth rate (day\(^{-1}\), shaded), \( \frac{\partial u}{\partial z} \) (s\(^{-1}\), black contours), and Brunt–Väisälä frequency (s\(^{-1}\), purple contours) for the CAM-MPAS (top) \( \times 8 \) aquaplanet and (bottom) \( \times 8 \) H–S simulations, computed with long-term monthly mean data, averaged over 35°–55°N. Red arrows show the location of the high-resolution region (approximately 30°W–30°E). Red shading indicates enhanced baroclinicity.

**FIG. 8.** Vertical cross section of departure from zonal mean for Eady growth rate (day\(^{-1}\), shaded), \( \frac{\partial u}{\partial z} \) (s\(^{-1}\), black contours), and Brunt–Väisälä frequency (s\(^{-1}\), purple contours) for the CAM-MPAS (top) \( \times 8 \) aquaplanet and (bottom) \( \times 8 \) H–S simulations, computed with long-term monthly mean data, averaged over 35°–55°N. Red arrows show the location of the high-resolution region (approximately 30°W–30°E). Red shading indicates enhanced baroclinicity.
simulations by the use of a variable-resolution mesh should be considered “added value.” The MPAS multiresolution system modeling system is being developed in order to resolve scales and processes that are currently unrepresented by global models, particularly for regional climate change applications, in a cost-effective manner (Ringler et al. 2008). From a process standpoint, the increase in EKE in the high-resolution region, which generally occurs with increasing resolution (e.g., Pope and Stratton 2002), can be considered a desirable outcome of the use of a multiresolution modeling system. The high-resolution region in the CAM-MPAS-A VR simulation is behaving as we would expect a global CAM-MPAS-A QUR high-resolution simulation to behave. However, in aquaplanet, these changes in EKE appear to be modulated by the scale-dependent physics, such that the storm track is amplified in different locations than what may be expected from the dynamics alone. In the ×8 experiments, the use of the VR mesh increases the EKE by about 20%; this difference is
similar in magnitude to future projections of increased EKE by the end of the twenty-first century in a “business as usual” climate scenario (Yin 2005).

Considering a potential application of CAM-MPAS-A to regional climate change over North America, these “mesh effects” may be removed to a first order simply by subtracting a variable-resolution control simulation from a variable-resolution climate change simulation. However, the involvement of the physics complicates this picture, as increases in specific humidity that are expected from global warming will likely alter the scale dependencies of the physics in nonlinear ways, such that differentiating the two simulations may not necessarily remove the effects of using a variable-resolution mesh in CAM-MPAS-A documented here. In such cases the value of idealized simulations becomes apparent, as we can measure the amplitude of these zonal asymmetries and use them as a first estimate of the mesh effects expected in a real-world configuration using CAM-MPAS-A. Such measurements should help to guard against the inappropriate attribution of modeling artifacts in future variable-resolution simulations using CAM-MPAS-A.

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