Evaluation of the HOMME Dynamical Core in the Aquaplanet Configuration of NCAR CAM4: Rainfall

SAROJ K. MISHRA

Department of Computer Science, University of Colorado, and National Center for Atmospheric Research,* Boulder, Colorado

MARK A. TAYLOR

Sandia National Laboratories, Albuquerque, New Mexico

RAMACHANDRAN D. NAIR AND PETER H. LAURITZEN

National Center for Atmospheric Research,* Boulder, Colorado

HENRY M. TUFO

Department of Computer Science, University of Colorado, and National Center for Atmospheric Research,* Boulder, Colorado

JOSEPH J. TRIBBIA

National Center for Atmospheric Research,* Boulder, Colorado

(Manuscript received 18 May 2010, in final form 21 December 2010)

ABSTRACT

The NCAR Community Climate System Model, version 4 (CCSM4), includes a new dynamical core option based on NCAR’s High-Order Method Modeling Environment (HOMME). HOMME is a petascale-capable high-order element-based conservative dynamical core developed on the cubed-sphere grid. Initial simulations have been completed in an aquaplanet configuration of the Community Atmosphere Model, version 4 (CAM4), the atmospheric component of CCSM4. The authors examined the results of this simulation and assessed its fidelity in simulating rainfall, which is one of the most important components of the earth’s climate system. For this they compared the results from two other dynamical cores of CAM4: the finite volume (FV) and Eulerian (EUL).

Instantaneous features of rainfall in HOMME are similar to FV and EUL. Similar to EUL and FV, HOMME simulates a single-peak intertropical convergence zone (ITCZ) over the equator. The strength of the ITCZ is found to be almost the same in HOMME and EUL but more in FV. It is observed that in HOMME and EUL, there is higher surface evaporation, which supplies more moisture to the deep tropics and gives more rainfall over the ITCZ. The altitude of maximum precipitation is found to be at almost the same level in all three dynamical cores. The eastward propagation of rainfall bands is organized and more prominent in FV and HOMME than in EUL. The phase speed of the eastward propagation in HOMME is found to be higher than in FV. The results show that, in general, the rainfall simulated by HOMME falls in a regime between that of FV and EUL. Hence, they conclude that the key aspects of rainfall simulation with HOMME falls into an acceptable range, as compared to the existing dynamical cores used in the model.

1. Introduction

General circulation models (GCMs) are an effective tool to improve our understanding of the present and past climate as well as to predict the future climate. The present-day numerical models have yet to capitalize on the enormous computing power made available by petascale-capable high-performance computers. The GCMs broadly
consist of two components, namely, the dynamical core and the physical parameterization suite. The dynamical core numerically solves the system of partial differential equations that governs the fluid motion, while the physics package provides the numerous forcing terms used in these equations.

To take advantage of the high-performance computing, improvement of the dynamical core used in the present-day GCM is of paramount importance. Currently, most of the operational dynamical cores use latitude–longitude-based grids. The grid lines cluster at the pole, creating a potentially severe Courant–Friedrichs–Lewy (CFL) restriction on the time step. There are many successful techniques to handle this pole problem; however, most of them (e.g., polar filters) substantially degrade parallel scalability by limiting the model to one-dimensional domain decomposition strategies. However, future evolution of the Community Climate System Model (CCSM) into an earth system model requires a highly scalable and accurate formulation of the dynamics of the atmosphere.

The High-Order Method Modeling Environment (HOMME) is a highly scalable, global hydrostatic atmospheric modeling framework (Dennis et al. 2005; Nair and Tufo 2007; Nair et al. 2009). Recently, HOMME has been integrated into the Community Atmosphere Model (CAM), the atmospheric component of the CCSM. HOMME relies on a cubed-sphere grid, where the earth is tiled with quasi-uniform quadrilateral elements, free from polar singularities. HOMME is the first dynamical core ever that allows for full two-dimensional domain decomposition in CAM.

Recent performance comparisons of CAM–finite volume (CAM-FV) and CAM-HOMME (A. Mirin 2010, personal communication) show that at the resolution used here, CAM-FV is twice as fast as CAM-HOMME on 32 processor cores of the JaguarPF Cray XT-5 at Oak Ridge National Laboratory. Because of CAM-HOMME’s increased scalability, CAM-HOMME starts to outperform CAM-FV on 512 cores and higher. CAM-HOMME achieves a maximum integration rate of 82 simulated years per day (SYPD) on 2700 cores, compared to CAM-FV’s maximum of 50 SYPD on 3328 cores. At higher resolutions, the improvements due to increased scalability become larger. At one-quarter-degree resolution, on the Intrepid Blue Gene (BG)/P system at Argonne National Laboratory, CAM-HOMME can achieve 12 SYPD on 86,400 cores, while CAM-FV achieves its maximum rate of 2.5 SYPD on 53,248 cores (Dennis et al. 2011, manuscript submitted to Int. J. High Perform. Comput. Appl.)

HOMME simulations presented in this paper use the physics package of CAM, version 4 (CAM4) (Neale et al. 2010), in the aquaplanet configuration. Since rainfall is one of the most important components of the earth’s climate system, its simulation is examined in this paper. Here the simulated rainfall from HOMME has been compared with FV and Eulerian (EUL) dynamical cores.

The organization of the paper is as follows. Section 2 briefly outlines model details and section 3 describes the simulation details. Results are presented in section 4, followed by the summary and conclusions in section 5.

2. Brief description of CAM4

The CAM4 is the sixth generation of atmospheric general circulation models (AGCMs) developed by the atmospheric modeling community in collaboration with the National Center for Atmospheric Research (NCAR). The source code, documentation, and input datasets for the model are freely available from the CAM Web site (www.ccm.ucar.edu/models/ccsm4.0/cam/). Since a detailed description of CAM4 is given in Neale et al. (2010), we will not discuss the details of model here. Nevertheless, certain aspects of the model relevant to this work are explained in the following.

CAM4 has been designed to produce simulations with reasonable accuracy for various dynamical cores and horizontal resolutions. For this study, FV, EUL, and HOMME dynamical cores were used at 1° equivalent resolutions in the horizontal and 26 levels in the vertical. The model uses the hybrid vertical coordinate, which is terrain following at the earth’s surface, but reduces it to pressure coordinate at higher levels near the tropopause.

a. CAM4 physics

All three dynamical cores use the same physical parameterization package, consisting of moist precipitation processes, clouds and radiation processes, surface processes, and turbulent mixing processes. Each of these, in turn, is subdivided into various components. The moist precipitation processes consist of the deep convective, shallow convective, and stratiform components. The deep convective processes are parameterized by the revised version of the Zhang–McFarlane convection scheme, in which the calculation of CAPE has been modified to include the effect of entrainment dilution (Neale et al. 2008). In addition, in the revised version, convective momentum transport parameterized by Gregory et al. (1997) has been included (Richter and Rasch 2008). The shallow convective process is parameterized by Hack (1994). The parameterization of the stratiform processes in CAM4 is described in Rasch and Kristjansson (1998) and Zhang et al. (2003). In the default configuration of the model, the parameterizations are applied over a time interval of 1200 for EUL, 1800 for FV, and 1800 s for HOMME.
b. CAM4 dynamical cores

The EUL dynamical core is a three-time-level spectral transform applied at T85 truncation on a $256 \times 128$ quadratic grid. Moisture transport in EUL is done using a monotonic semi-Lagrangian method, which is time split into horizontal and vertical directions. The trajectory calculation used for moisture transport uses a quasi-cubic interpolation. A detailed scientific documentation of the EUL dynamical core is given in the CAM3 scientific documentation (Neale et al. 2010).

CAM FV integrates the quasi-hydrostatic equations of motion in flux form. The horizontal spatial discretization grid is based on a “CD” grid approach that involves a half-time-step update on the Arakawa C grid that provides the time-centered winds to complete a full time step on the Arakawa D grid (Lin and Rood 1997). In the vertical, a floating Lagrangian coordinate is used that is initialized from a standard hybrid-sigma vertical coordinate (Eulerian grid). The Lagrangian vertical coordinate “floats” for several consecutive time steps (the default setup for this study is four time steps) before a vertical remapping transfers the prognostic variables back to the Eulerian reference grid. The vertical remapping procedure is formulated so that it conserves total energy (Lin 2004). The advantage of the floating Lagrangian coordinate approach is that the equations of motion in each layer reduce to two-dimensional shallow-water equations; hence, only two-dimensional operators are needed. The two-dimensional advection operator used in CAM-FV follows the Lin and Rood (1996) scheme. The water variables (specific humidity, cloud liquid water, and ice) and tracers are transported on longer time steps than that used for the momentum, thermodynamic, and continuity equation for air (the setup in this study is four dynamic time steps per tracer time step) using supercycling (e.g., Lin 2004). The Lin and Rood (1996) advection scheme applies a combination of the piecewise constant method and the piecewise parabolic method (PPM; Colella and Woodward 1984) in its dimensionally split one-dimensional operators. The stability properties of this configuration (and others) are discussed in detail in Lauritzen (2007). The moisture transport in CAM-FV is computed with the Lin and Rood (1996) transport scheme, which is a flux-form finite-volume scheme, formulated in terms of one-dimensional operators. The flux operators are based on the PPM (Colella and Woodward 1984) that are formally third-order accurate on uniform grids, and hence the implementation on the regular latitude–longitude grid is formally second order.
The damping and dispersion properties of the scheme are discussed in Lauritzen (2007). Monotonicity is enforced using reconstruction function filtering in each coordinate direction, which prevents negative undershoots in each coordinate direction. The discretization in CAM FV is such that vorticity modes at the grid scale are controlled through subgrid-scale function limiters in the advection operator. Divergent modes, however, are not controlled at the grid scale through limiters wherefore explicit second-order divergence damping is applied to the momentum equations. To stabilize the model in the presence of gravity waves, one-dimensional polar filters are applied along latitudes. More information on CAM-FV and the performance in idealized tests can be found in Lauritzen.
et al. (2010). Diffusion in CAM-FV is through the monotonicity constraints in the advection operator as well as explicitly added divergence damping (Neale et al. 2010).

HOMME uses the continuous Galerkin spectral finite-element method (Taylor and Fournier 2010), often abbreviated as the spectral element method (SEM). This method is designed for fully unstructured quadrilateral meshes. The current configurations in CAM are based on the cubed-sphere grid. The main motivation for the inclusion of HOMME is to improve the scalability of CAM by introducing quasi-uniform grids, which require no polar filters (Taylor et al. 2008). HOMME is also the first dynamical core in the CAM that locally conserves energy in addition to mass and two-dimensional potential vorticity (Taylor 2011). HOMME represents a large change in the horizontal grid as compared to the other dynamical cores in CAM. Almost all other aspects of HOMME are based on a combination of well-tested approaches from the Eulerian and FV dynamical cores. For tracer advection, HOMME is modeled as closely as possible on the FV dynamical core. It uses the same conservation form of the transport equation and the same vertically Lagrangian discretization (Lin 2004). The HOMME dynamics are modeled as closely as possible on the Eulerian dynamical core. They share the same vertical coordinate, vertical discretization, hyperviscosity-based horizontal diffusion, top-of-model dissipation, and solve the same moist hydrostatic equations. The main differences are that HOMME advects the surface pressure instead of its logarithm (to conserve mass and energy), and HOMME uses the vector-invariant form of the momentum equation instead of the vorticity-divergence formulation. The time stepping in HOMME is a form of dynamics/tracer/physics subcycling, achieved through the use of multistage second-order-accurate Runge–Kutta methods. The tracers and dynamics use the same time step, which is controlled by the maximum anticipated wind speed; however, the dynamics uses more stages than the tracers to maintain stability in the presence of gravity waves.

The moisture transport in CAM-HOMME is computed with the same vertically Lagrangian approach (Lin 2004) as used in CAM-FV, and the former uses the monotone vertical remap from (Zerroukat et al. 2005). The transport within the Lagrangian surfaces is done using the locally mass-conserving spectral element discretization (Taylor and Fournier 2010), combined
with a sign-preserving limiter (Taylor et al. 2009). The spectral element advection operator is fourth-order accurate on the cubed-sphere grid with very little diffusion, so additional scale-selective mixing is added via the same hyperviscosity term used in the dynamics (Neale et al. 2010). The spatial diffusion used in CAM-HOMME is modeled on that used in CAM-Eulerian. CAM-HOMME uses the same hyperviscosity operator, and the 1° results presented here use the same hyperviscosity coefficient as T85 CAM-Eulerian. The hyperviscosity operator is solved explicitly and time split from the rest of the dynamics, using a mixed finite-element integrated-by-parts formulation (Neale et al. 2010).

3. Simulation details

For the examination of the performance of HOMME in NCAR CAM4, we carried out a set of simulations with HOMME, FV (the default dynamical core of CAM4), and EUL. All the simulations were performed in the aquaplanet configuration of CAM4. In this configuration, all the land points are replaced by ocean points, such that the surface drag coefficients, albedo, and evaporation characteristics are homogeneous over the globe. A further simplification is obtained by fixing the solar declination to its value on 21 March, which puts the sun overhead at the equator. This produces another desirable simplification by providing approximate hemispheric symmetry of insolation forcing. The experiments have been performed with a zonally symmetric SST profile as a lower boundary condition. The distribution of SST used in the simulation is given in Eq. (1), which is the same as the control SST used by Neale and Hoskins (2000):

$$T_S(\lambda, \phi) = \begin{cases} 
27[1 - \sin^2(3\phi/2)] & -\pi/3 < \phi < \pi/3 \\
0 & \text{otherwise}
\end{cases}, \quad (1)$$

where, $T_S$ is sea surface temperature (°C), $\lambda$ is longitude, and $\phi$ is latitude.

The initial condition for all simulations was from a previous aquaplanet simulation. All the simulations were performed for 24 months, and the last 18 months

Fig. 5. Zonally averaged time-mean (a) TRF, (b) DRF, (c) SRF, and (d) LRF from FV, EUL, and HOMME with 1200-s physics time step.
were considered for the analysis. The default physics tunings were used for all the simulations. The monthly and daily model outputs have been analyzed to understand various issues pertaining to the steady (time mean) and transient (temporally varying) characteristics of the simulated climate.

4. Results

a. Instantaneous distribution

Figure 1 shows the horizontal distribution of the total precipitation at the surface from FV, EUL, and HOMME. The left column of the figure shows the instantaneous features, and the right column shows the time-mean features. For the study of the instantaneous features, several snapshots were analyzed and the basic characteristics were found to be similar. One representative instant has been arbitrarily chosen for illustration. The stormlike zonally oriented structures in the tropics and baroclinic wavelike meridionally oriented structures in the mid-latitudes are evident in all three dynamical cores (see the left column). The interactions between the tropics and extratropics show up prominently in the instantaneous patterns. The time-mean features shown in the right column are the average of the instantaneous features. The intertropical convergence zone (ITCZ) appears over the equator saliently. The dry zones over the subtropical highs are distinct. The secondary rainfall zones over midlatitude storm tracks are also distinct in all three dynamical cores. The notable difference is that the ITCZ in EUL and HOMME is comparatively sharper and more confined to the equator than in FV. By and large, the horizontal distribution of rainfall is found to be similar in all three dynamical cores.

Since the HOMME dynamical core is based on the cubed-sphere grid, it is desirable to examine the wave 4 signal from the simulations. In Fig. 2, the difference in
the time-averaged precipitation and its zonal mean is shown. However, no signature of the wave 4 is evident in the plot. This indicates that the simulation is devoid of such noise, and the length of integration is long enough. The other two dynamical cores are based on a latitude–longitude grid and known to be free of wave 4 noise.

b. Mean state

In this section we compare the time-mean state of precipitation from FV, EUL, and HOMME. Figure 3 shows the zonally averaged time-mean surface reaching total rainfall (TRF) for the three dynamical cores. We find that the peak of the ITCZ is over the equator in all three cases. The morphology of the ITCZ is found to be similar. However, there is notable difference in the magnitude of the TRF. Over the equator, the TRF in EUL and HOMME is higher than in FV. The mean TRF over the equator in FV is approximately 18 mm day$^{-1}$, whereas in EUL and HOMME it is around 25 mm day$^{-1}$. The difference is approximately 40% of the mean value of FV. However, there is almost no difference in TRF between EUL and HOMME. Since TRF constitutes three components—namely, deep convective rainfall (DRF), shallow convective rainfall (SRF), and large-scale rainfall (LRF)—in the following we analyze them individually.

Figure 4 shows the zonally averaged time-mean surface reaching DRF, SRF, and LRF for FV, EUL, and HOMME. All three components are found to be higher in EUL than in FV. Among the three components, the difference in DRF between EUL and FV dominates the other two components. On the contrary, the comparison between FV and HOMME indicates that DRF is almost same for both of them, whereas the other two components are higher in HOMME than in FV. The difference in LRF between HOMME and FV is nearly double of the difference in SRF. In other words, the higher TRF in EUL is primarily due to more DRF, whereas in HOMME it is mainly due to more LRF.

Since rainfall simulation is sensitive to time step (Williamson and Olson 2003; Mishra et al. 2008) and is different in the three dynamical cores, we will examine its contribution to the differences in the simulations. To do so, we carried out two additional simulations with FV and HOMME with 1200 s. Figure 5 shows the zonally averaged time-mean precipitation from the three simulations. It is noticed that TRF is largely similar in EUL and HOMME and more than in FV. Higher TRF in

### Table 1. Global mean total rainfall from the three dynamical cores.

<table>
<thead>
<tr>
<th>Dynamical core</th>
<th>Global mean TRF (mm day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FV</td>
<td>2.888</td>
</tr>
<tr>
<td>EUL</td>
<td>3.024</td>
</tr>
<tr>
<td>HOMME</td>
<td>2.948</td>
</tr>
</tbody>
</table>
EUL is primarily due to more DRF, whereas in HOMME it is mainly due to more LRF. The result is similar to that seen in the simulations with default time steps. This infers that the difference in the simulations with the three dynamical cores is not due to different physics time steps, rather the difference associated with the formulation of the dynamical cores and their indirect effects through the physics parameterization. However, TRF is found to be marginally increasing with the reduction of time step, which is due to the enhancement in LRF. This result is in agreement with Mishra et al. (2008). They showed that TRF and LRF increase with a decrease in time step and the impact is less severe in the smaller time step regime.

The surface-reaching rainfall is the vertical integral of the net precipitation production at each model level. The net precipitation production at any level is the condensation minus the reevaporation of precipitation and cloud liquid water at that corresponding level. In Fig. 6, the vertical distribution of the net precipitation production is shown for FV, EUL, and HOMME. The first column shows the vertical distribution of the TRF production. Similarly, the second, third, and fourth columns show the vertical distribution of DRF, SRF, and LRF, respectively. The figure shows that in all three cases, the net TRF production is vertically extended over the entire troposphere, except for a few near-surface and top-of-the-model layers. The latitudinal extent and vertical distribution of TRF looks alike in the three dynamical cores. The altitude of peak TRF occurs around the same level. However, there is a notable difference in their magnitudes—that is, TRF in EUL and HOMME is more than in FV—which is in agreement with the preceding discussion. In all three cases, DRF occurs in the lower and midtroposphere, accompanied by reevaporation of precipitation and cloud liquid water in the upper troposphere. The third column shows that there is very little SRF in FV, as compared to that found in EUL and HOMME. In all three dynamical cores, the SRF production occurs in the mid- and lower troposphere with peaks near 600 hPa. From the fourth column, it can be seen that LRF occurs in the middle and upper troposphere. The peak of the LRF occurs near 500 hPa in all three cases. There is considerable amount of reevaporation of LRF seen in the lower troposphere and near-surface layers. Overall, the vertical distribution of precipitation production is similar in the three dynamical cores.

In Fig. 6, it is seen that most of the precipitation occurs within the latitudinal belt of 5°S–5°N. To make a closer comparison between the vertical profiles of precipitation, we have shown the area-averaged (5°S–5°N, 0°–360°E) time-mean precipitation production rate for FV, EUL, and HOMME in Fig. 7. The figure shows a close resemblance between the three profiles. The peak of the precipitation production occurs near 600 hPa in
all three cases. Near the surface (below 950 hPa), the net precipitation production is negative, which is because the reevaporation of falling precipitation is more in these layers. The notable point here is that there is a systematic difference in the magnitude of the precipitation production in the midtroposphere between the three cases. EUL has the largest precipitation production, FV has the smallest, and HOMME falls in between these two.

To get an overall idea about the global mean values, we analyzed these quantities for the three dynamical cores. Table 1 shows the global mean TRF from FV, EUL, and HOMME. The values are very close to each other; that is, the difference among them is on the order of 2.5% of their mean values. The global mean value for HOMME falls in between that of the other two dynamical cores.

c. Intensity and frequency

Here we show the intensity and frequency of rainfall for FV, EUL, and HOMME. For this we analyzed the daily rainfall data. Since in the preceding section we noticed that the region of significant difference is the deep tropics (10°S–10°N, 0°–360°E), we will focus primarily on this region. Figure 8 shows the frequency distribution of daily rainfall rates (left panel) and the total rainfall falling in each bin (right panel). The rainfall rates are sorted into four categories based on the intensity of rain rate, namely, dry, light, moderate, and heavy categories. Vertical lines in Fig. 8 indicate these categories. Figure 8a shows that the frequencies in the dry and heavy categories are higher in EUL and HOMME than in FV. The opposite is true in the light and moderate categories. Although the frequencies in the dry category are higher, when the frequencies were multiplied with the respective rainfall rates (accumulated rainfall), they become almost equal in the three dynamical cores (see Fig. 8b). The accumulated rainfall in the light and moderate categories is highest in FV, lowest in EUL, and intermediate in HOMME, whereas the rainfall accumulated in the heavy category is found to be higher in EUL and HOMME than in FV. Hence, the higher amount of TRF in HOMME and EUL comes from the heavy rainfall category. There appears a mismatch between Figs. 8a and 8b, which is counterintuitive, because within the categorized bin, there is an
internal shift. For example, in the heavy rainfall-rate category, the frequency in EUL is higher than in FV, whereas the accumulated rainfall in heavy category shows the opposite. We investigated by making the bin size finer in this category and noticed that there was an internal shift toward the upper end in HOMME; that is, there are more points with higher rainfall rates than in EUL in the deep tropics.

d. Time–longitude realization

The time-mean features for FV, EUL, and HOMME have been discussed in the previous section. Since the transients play a cumulative role in forming the time-mean steady state, here we discuss the transient activities. In section 4b we saw that the difference between the dynamical cores was mainly found in the equatorial belt, where most of the transient activities constitute the zonally propagating waves. Hence, we will consider this region and discuss the zonal propagation characteristics via time–longitude diagrams.

Figure 9 shows the time–longitude diagrams of rainfall over the equator (2°S–2.5°N) for 180 days. Daily data have been plotted in the figure. All of them (FV, EUL, and HOMME) show the eastward propagation. This resembles observed equatorial Kelvin waves (Wheeler and Kiladis 1999). These rainfall bands appear to move over a range of speeds and wavenumbers; however, there are distinct differences between the three cases.

In FV, eastward-propagating organized rainfall bands appear. They propagate 360° in 30–40 days. In EUL, the rainfall appears in patches in a discrete manner. The rainfall bands are not well organized. In HOMME, streaks of well-organized rainfall are noticed. They propagate 360° in 20–30 days. Since the vertical structure of the moist heating is crucial in determining the speed of the eastward propagation, we have shown the same for the three dynamical cores in Fig. 10. The figure shows that the profiles are largely similar. All of them have most of their heating in the upper troposphere and have a top-heavy heating structure. A comparison of FV and EUL indicates that throughout the troposphere, EUL has a greater heating rate than FV. The heating profile of HOMME largely falls in between the other two dynamical cores in the lower troposphere. However, near 500 hPa, the heating in HOMME is closer to EUL and significantly more than in FV. Hence, the top heaviness in the heating profile is more in HOMME than in FV. This is associated with the faster phase speed of the eastward propagation in HOMME.

e. Associated variables

In Fig. 11, the meridional variation of surface evaporation (EVP), large-scale moisture convergence (LMC) and vertically integrated precipitable water (PWAT) is shown for FV, EUL, and HOMME. Figure 11a shows that EVP is highest for EUL, lowest for FV, and intermediate for HOMME. Over the equatorial belt, LMC is nearly the
same in EUL and HOMME and more in FV (see Fig. 11b). Local evaporation and large-scale moisture convergence are the two sources of moisture for rainfall production. A comparison of the scales in Figs. 11a,b indicates that LMC is the primary source of moisture, leading to higher rainfall over the ITCZ in EUL and HOMME than in FV. PWAT is found to be almost the same in all three dynamical cores, except over the equator, where EUL has marginally more than FV and HOMME.

In CAM4, the surface evaporation is computed as shown below (Neale et al. 2010):

\[ \text{EVP} = \rho_A |\Delta V| C_E dQ, \]  

(2)

where \( \rho_A \) is the atmospheric surface density, and \( \Delta V \) and \( dQ \) are the wind strength and moisture deficit at the lowest model level, respectively. Figure 12a shows that moisture \( Q \) at the first model level is almost the same in EUL and HOMME and lower in FV. In other words, \( dQ \) in EUL and HOMME is higher than in FV. Figure 12b shows that wind strength at the lowest level of the model is higher in EUL than in HOMME and FV over the equatorial belt. However, poleward of 5\(^{\circ}\)S/N the wind strength in EUL and HOMME is less than in FV. Hence, the higher evaporation in EUL over the equatorial belt is attributed partly to higher \( dQ \) and partly to the higher wind speed than in FV. Beyond 5\(^{\circ}\)S/N, the higher evaporation is solely due to the higher moisture deficit, since the wind speed therein is less than FV. However, the higher EVP in HOMME over the equatorial belt is primarily due to the higher moisture deficit, since the wind speed therein is almost the same as in FV.

Figure 13 shows the convective available potential energy (CAPE) for FV, EUL, and HOMME. It is seen that over the equatorial belt, EUL has significantly higher CAPE than FV and HOMME, which is approximately 135\% of the mean CAPE in FV. This is the reason for the higher amount of deep convective rainfall in EUL. However, there is no such significant difference in CAPE between FV and HOMME, leading to similar magnitudes of DRF.

The vertical profiles of area-averaged (5\(^{\circ}\)S–5\(^{\circ}\)N, 0\(^{\circ}–360\(^{\circ}\)E) time-mean relative humidity RH, specific humidity
FIG. 12. Zonally averaged time-mean (a) moisture deficit (g kg\(^{-1}\)) and (b) wind strength (m s\(^{-1}\)), at the first model level from FV, EUL, and HOMME.

\(Q\), and temperature \(T\) are compared in Fig. 14. RH is found to be lower (by \(\sim 3\%\)) in HOMME than FV, over the entire troposphere except at 900 hPa. RH in EUL is found to be higher (by \(\sim 4\%\)) in most of the layers, except those adjacent to the surface and between 900 and 700 hPa, where the opposite is true. Figures 14b and 14c show the corresponding specific humidity and temperature differences, respectively. It is seen that, in the middle

FIG. 13. Zonally averaged time-mean CAPE from FV, EUL, and HOMME.
and lower troposphere, the profile of the difference in specific humidity resembles very closely that of the difference in RH, which is further supported by the observed temperature profiles (see Fig. 14c). In the upper troposphere, the lower RH in HOMME and higher RH in EUL are mainly because of the higher temperature in HOMME and lower temperature in EUL, respectively, since the difference in $Q$ in these altitudes is almost negligible. Moisture in the boundary layer but above the surface layer (near 900 hPa) is greater in EUL than in FV and HOMME, which seems to be associated with the higher CAPE in EUL.

**f. General circulation diagnostics**

Generally the largest spatial variation of atmospheric quantities occurs in the vertical and meridional directions, so analysis of the latitude–height cross section of zonal-mean quantities is a useful exercise and provides insight into the general circulation of the atmosphere. For this we analyzed temperatures, zonal wind, vertical velocity, and specific humidity from the three dynamical cores.

In Fig. 15, zonal-mean temperatures are shown from FV, EUL, and HOMME. In general, the similarity between the three distributions is remarkable. The pole-to-equator temperature difference is about 30°C at the earth’s surface. The latitudinal temperature gradient is identical in all of them. In the lower stratosphere, the temperatures increase by about 25°C from the equator to the midlatitudes; however, they decrease again with a further increase in latitude. The magnitude and altitude of the tropopause temperatures is similar in all of them. The pole-to-equator difference of the height of the tropopause in the model is similar in all three dynamical cores. In high latitudes a stable layer appears primarily because of the stabilizing effects of baroclinic waves and poleward advection of heat by the large-scale eddies. In the upper stratosphere, the decrease of temperature from equator to pole is about 25°C. We further examined the vertical profile of temperature at various latitudes from the three dynamical cores. The notable difference (not shown here) is, that over the equatorial region, the atmosphere is marginally (−0.5°C) warmer in HOMME than in FV. Between EUL and FV, EUL
has a warmer (by ~0.5°C) atmosphere in the lower troposphere and stratosphere, however, a cooler atmosphere in the middle and upper troposphere. In general, the thermal structure of the model atmosphere looks very similar in the three dynamical cores.

Figure 16 shows the longitudinal mean zonal wind for FV, EUL, and HOMME. The patterns of the lower-tropospheric easterlies and the upper-tropospheric westerlies look similar. The intensity of the jet and its spatial position agree well. It is found that the regions of largest latitudinal gradient in temperature (Fig. 15) are coincident with those of the highest vertical gradient of zonal wind in Fig. 16. This confirms that the two fields are close to a state of thermal wind balance. Similarly, the mean meridional circulation was analyzed from the three dynamical cores (not shown here). It was noticed that the positions of the ITCZ and the strongest ascent are at the same latitudes, which was anticipated. The notable differences between the three cases are the following: in EUL the circulation over the equatorial belt is marginally stronger. The rising limb of the Hadley cell shifts toward the equator in EUL, associated with strong surface winds over the equatorial belts. This strengthening of the circulation, in turn, leads to an increase in the moisture convergence in the equatorial region. However, the zonal and meridional circulation is found to be largely similar in all of them.

Zonally averaged time-mean vertical pressure velocity (omega) is shown in Fig. 17 for FV, EUL, and HOMME. A negative value of omega is associated with ascending motion, which is indicated by the dashed contours. It is observed that the ascending limb is more confined to the equator in EUL and HOMME. The latitudinal positions of the maximum omega are noticed over the corresponding locations of ITCZ, that is, over the equator. The altitude of maximum omega occurs in

Fig. 15. Zonally averaged time-mean temperature (K) for (a) FV, (b) EUL, and (c) HOMME.
the lower troposphere in all of them. Notable is the difference in the strength of omega. The strength is largely similar in EUL and HOMME but greater in FV. In Fig. 10 it was seen that the rate of moist heating over the equatorial region is higher in EUL and HOMME, which is associated with the stronger vertical velocity.

Finally, the distribution of specific humidity from the three dynamical cores is shown in Fig. 18. The very dry upper troposphere and stratosphere, the wet lower troposphere, and the dry subtropics are common in all of them. The spatial pattern of specific humidity and its magnitude are similar. It has a maximum over the surface layer of the equatorial belt and decreases with an increase in altitude and/or latitude. This is associated with the fact that the primary source of moisture—that is, surface evaporation—occurs in the lowest model level, which is strongest in the tropics and decreases with an increase in latitudes. Furthermore, the moisture sink—that is, precipitation—removes the moisture from the mid- and upper troposphere. Large-scale circulation redistributes the moisture in the atmosphere, makes it moister in the convergence zone (e.g., ITCZ), and makes it drier in the divergence zone (e.g., subtropical highs). The combined effect of the three factors governs such a distribution of the moisture in the atmosphere. The vertical and meridional gradient of the specific humidity is similar in all of them. By and large, the distribution of specific humidity is similar. However, a comparison of the vertical profiles from the three dynamical cores over individual latitudes showed marginal differences (not shown here). For instance, over the equatorial belt, the surface layer is comparatively more moist in FV, whereas in the lower troposphere (near 900 hPa) the opposite is true. However, in the upper troposphere, EUL is found to have the highest specific humidity, followed by FV, and HOMME, respectively.

5. Summary and conclusions

The High-Order Method Modeling Environment (HOMME) is a new spectral-element-based dynamical core included in the CCSM4. HOMME is a highly scalable dynamical core that achieves the conservation of mass, potential vorticity (in 2D), and moist energy. HOMME has been integrated into the Community Atmospheric Model, version 4 (CAM4), the atmospheric component of the CCSM. Initial simulations have been completed in the aquaplanet configuration of CAM4. The results have been examined to assess their fidelity in the simulation of rainfall—one of the most important components of the earth’s climate system. For this, a comparison has been made with the results from the other two existing dynamical cores of CAM4, namely, finite volume (FV) and Eulerian (EUL).

The instantaneous distribution of rainfall has been compared from the three dynamical cores. The stormlike zonally oriented structure in the tropics and baroclinic
waveline meridionally oriented structures in the midlatitudes are observed in all of them. The interactions between the tropics and extratropics show up prominently. The characteristics of the horizontal distribution of rainfall in HOMME are found to be similar to that in FV and EUL.

The zonally averaged time-mean rainfall has been compared for HOMME, FV, and EUL. The intertropical convergence zone (ITCZ) has a single-peak morphology in all three simulations. However, there is a considerable difference in the strength of the ITCZ. The amount of rainfall in ITCZ is found to be almost the same in HOMME and EUL, which is approximately 135% of that in FV. It is shown that the moisture deficit at the first model level (as compared to the saturation value at surface temperature) in HOMME is more in FV, which leads to higher surface evaporation. This higher surface evaporation leads to higher large-scale moisture convergence into the ITCZ, which leads to higher rainfall. The mechanism of higher rainfall in EUL is similar to the preceding, only with the following extra link: in EUL, the wind strength at the first model level is higher in FV, which is an additional factor responsible for the higher surface evaporation in EUL.

The vertical distribution of the precipitation production has been compared from HOMME, FV, and EUL. The vertical profile is found to be similar. The maximum precipitation production takes place near 600 hPa. The net precipitation production is negative below 950 hPa, which is because of the reevaporation of precipitation. Largely, the vertical structure of the precipitation is similar in all three dynamical cores.

The daily rainfall data have been examined from HOMME, FV, and EUL to study the intensity and frequency characteristics of rainfall. On the basis of intensity, rainfall is categorized as dry, light, moderate, or heavy. The notable difference is that the frequency of rainfall in the dry and heavy-intensity categories is higher in HOMME and EUL than in FV. On the contrary, in the light and moderate categories, the frequency of rainfall in EUL and HOMME is less than in FV. However, EUL and HOMME show very similar characteristics. The propagation characteristics of the rainfall band have been examined from the three dynamical cores. Well-organized coherent eastward propagation is noticed in both HOMME and FV; however, the coherence is much less in EUL.

We thus conclude that the rainfall simulated by HOMME falls in a regime somewhere in between that

Fig. 17. Zonally averaged time-mean pressure vertical velocity (Pa s$^{-1}$) for (a) FV, (b) EUL, and (c) HOMME.
of FV and EUL. Future work includes the investigation of the performance of HOMME in a real-planet framework having realistic earth geography.

Acknowledgments. Many researchers have participated in the development of HOMME. We thank Amik St-Cyr, John Dennis, Jim Edwards, Rich Loft, Rory Kelly, and Theron Voran for their contributions to the development of HOMME. We are grateful to Phil Rasch and Dave Williamson for our many fruitful discussions. The research is supported by DOE Grant DE-F402-07ER64464.

REFERENCES


Neale, R. B., and B. J. Hoskins, 2000: A standard test for AGCMs
including their physical parameterizations. I: The proposal.
——, J. H. Richter, and M. Jochum, 2008: The impact of convection
on ENSO: From a delayed oscillator to a series of events.
J. Climate, 21, 5904–5924.
——, and Coauthors, 2010: Description of the NCAR Community
[Available online at http://www.cesm.ucar.edu/models/ccsm4.0/
cam/docs/description/cam4_desc.pdf.]
Rasch, P. J., and J. E. Kristjansson, 1998: A comparison of the
CCM3 model climate using diagnosed and predicted conden-
Richter, J. H., and P. J. Rasch, 2008: Effects of convective momentum
transport on the atmospheric circulation in the Community At-
Taylor, M. A., 2011: Conservation of mass and energy for the moist
atmospheric primitive equations on unstructured grids. Numer-
ical Techniques for Global Atmospheric Models, P. Lauritzen
et al., Eds., Lecture Notes in Computational Science and
——, and A. Fournier, 2010: A compatible and conservative
Phys., 229, 5879–5895.
——, J. Edwards, S. Thomas, and R. Nair, 2007: A mass and energy
conserving spectral element atmospheric dynamical core on
1088/1742-6596/78/1/012074.
——, ——, and A. St-Cyr, 2008: Petascale atmosphere models for
the Community Climate System Model: New developments
and evaluation of scalable dynamical cores. J. Phys. Conf. Ser.,
125, 012023, doi:10.1088/1742-6596/125/1/012023.
——, A. St-Cyr, and A. Fournier, 2009: A non-oscillatory ad-
vection operator for the compatible spectral element method.
Computational Science—ICCS 2009, G. Allen et al., Eds.,
Lecture Notes in Computer Science, Vol. 5545, Springer,
273–282.
Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled
equatorial waves: Analysis of clouds and temperature
in the wavenumber-frequency domain. J. Atmos. Sci., 56,
374–399.
Williamson, D. L., and J. G. Olson, 2003: Dependence of aqua-
129, 2049–2064.
Zerroukat, M., N. Wood, and A. Staniforth, 2005: A monotonic and
positive-definite filter for a Semi-Lagrangian Inherently
Conserving and Efficient (SLICE) scheme. Quart. J. Roy.
A modified formulation of fractional stratiform condensation
rate in the NCAR Community Atmospheric Model (CAM2).