Error Growth in a Whole Atmosphere Climate Model

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ABSTRACT

It has been well established that the atmosphere is chaotic by nature and thus has a finite limit of predictability. The chaotic divergence of initial conditions and the predictability are explored here in the context of the whole atmosphere (from the ground to the thermosphere) using the NCAR Whole Atmosphere Community Climate Model (WACCM). From ensemble WACCM simulations, it is found that the early growth of differences in initial conditions is associated with gravity waves and it becomes apparent first in the upper atmosphere and progresses downward. The differences later become more profound on increasingly larger scales, and the growth rates of the differences change in various atmospheric regions and with seasons—corresponding closely with the strength of planetary waves. For example, in December–February the growth rates are largest in the northern and southern mesosphere and lower thermosphere and in the northern stratosphere, while smallest in the southern stratosphere. The growth rates, on the other hand, are not sensitive to the altitude where the small differences are introduced in the initial conditions or the physical nature of the differences. Furthermore, the growth rates in the middle and upper atmosphere are significantly reduced if the lower atmosphere is regularly reinitialized, and the reduction depends on the frequency and the altitude range of the reinitialization.

1. Introduction

The nonlinear equations describing the atmosphere are known to be a deterministic chaotic system, which has been extensively studied since Lorenz (1963). A characteristic feature of such systems is that small errors introduced in the initial conditions grow exponentially with time until they “saturate.” This exponential error growth fundamentally limits the predictability of numerical models. This error growth has been thoroughly studied in the context of tropospheric model predictability (e.g., Kalnay 2003).

In recent years, there has been increasing development of general circulation models (GCMs) and mechanistic models of the middle and upper atmosphere, and also models that extend from the earth’s surface to the middle or upper atmosphere. Examples of the former include the National Center for Atmospheric Research (NCAR) Thermosphere, Ionosphere, Mesosphere, and Electrodynamics General Circulation Model (TIME-GCM) (e.g., Roble 2000), the ROSE model (Rose and Brasseur 1989; Smith et al. 2003), and the Met Office (UKMO) Stratosphere–Mesosphere Model (SMM) (Gray et al. 2003). The lower boundaries of these models are specified, either by reanalysis data or by idealized formulation, to account for planetary waves and tides. TIME-GCM extends from the stratosphere (≈30 km) to the upper thermosphere, and the vertical ranges of ROSE and SMM are 15–110 km and 16–80 km, respectively. Examples of the latter include the Middle Atmosphere Circulation Model at Kyushu University (MAMKU) (Miyahara et al. 1993), the Canadian Middle Atmosphere Model (CMAM) (Beagley et al. 2000), the Navy Operational Global Atmospheric Prediction System–Advanced Level Physics–High Altitude (NOGAPS-ALPHA) model (McCormack et al. 2004), the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA) (Schmidt et al. 2006), and the NCAR Whole Atmosphere Community Climate Model (WACCM) (Garcia et al. 2007). The primary goals of these models are to explore the coupling of different atmospheric regions; the coupling of dynami-

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cal, chemical, radiative, and electrodynamical processes; and the implication of these couplings for lower, middle, and upper atmosphere variability on various temporal scales. The error growth in these models is still not well understood. For example, the stratosphere and mesosphere display vacillations and even chaotic features in some models as the amplitude of the planetary wave forcing increases (Yoden 1987a,b; Scaife and James 2000; Gray et al. 2003), consistent with the classical theory by Holton and Mass (1976), whereas the TIME-GCM with realistic forcing from reanalysis data shows little or no vacillation or error growth (T. Matsuo 2008, personal communication, hereafter MAT). It is thus desirable to further study the error growth in the extended models and the middle/upper atmosphere models and how the error growth rates in different atmospheric regions may affect each other. The data assimilation of the middle and upper atmosphere, which is becoming increasingly important with the growing amount of ground-based and satellite observations of the middle/upper atmosphere, also requires better understanding of the error growth in the extended models.

The error growth in the WACCM is explored in this paper. A brief description of the model is given in section 2. The error growth in WACCM, its dependence on atmospheric regions, model resolution and model domain, and possible mechanisms controlling the error growth are then discussed in section 3. Conclusions are given in section 4.

2. Model description

In this study, both the Community Atmosphere Model, version 3 (CAM3) (Collins et al. 2004) and the Whole Atmosphere Community Climate Model based on CAM3 and with interactive chemistry (WACCM3) are used. CAM3 is the latest in a series of global atmosphere models developed at NCAR and is the atmospheric component of the Community Climate System Model (CCSM). The upper boundary of CAM3 is at 3.5 hPa (~38 km) with 26 vertical levels. WACCM3, on the other hand, extends from the earth’s surface to the lower thermosphere (5.1 × 10^{-6} hPa, approximately 140 km). WACCM3 has 66 vertical levels with vertical resolution 1.1–1.75 km in the troposphere and stratosphere and half-scale height (2–3.5 km) in the mesosphere and lower thermosphere. The dynamics and the advection of constituents are handled by the finite volume dynamical core of CAM3. Modules from the Model for Ozone and Related Chemical Tracers (MOZART) (Brasseur et al. 1998), which include both neutral and ion chemistry, are incorporated in WACCM3 so that interactive chemistry–dynamics is implemented in the model. Mesospheric and thermospheric processes such as exothermic heating, non-LTE radiative transfer, gravity wave drag, molecular diffusion, constituent ionization, joule heating, and ion drag are also included in WACCM3, with modules adapted from TIME-GCM (e.g., Roble 2000). A detailed description of WACCM3 can be found in Garcia et al. (2007). In this study, WACCM3 is run with two different horizontal resolutions: 4° × 3° and 1.9° × 2.5°, and CAM3 with 1.9° × 2.5°.

3. Analysis of model results

3.1 General error growth in WACCM

Figure 1 shows the zonal mean temperature at 82°N and zonal mean zonal wind at 62°N, both at 10 hPa, from ten WACCM3 simulations of the months of December, January, and February. One of the simulations (referred to as the base case) shows a minor stratospheric sudden warming in late December and a major warming in late January. The other simulations are otherwise identical to the base case, except that perturbations of different physical natures are introduced into various atmospheric regions. For example, random perturbations are introduced to the initial zonal wind field in the troposphere, stratosphere, or mesosphere in some of the simulations. The magnitude of gravity wave momentum flux in the parameterization scheme is slightly adjusted in another simulation. The solar F10.7 flux or the geomagnetic Kp index are slightly altered in other simulations. Regardless of the different nature and location of these perturbations, the zonal mean temperature and zonal wind from all of these cases diverge from each other, and the divergence (error growth) becomes apparent about 15–20 days after the perturbations are first introduced and becomes saturated at about 30 days. It should be noted that the frequency of major stratospheric sudden warming in WACCM3 is about 0.1–0.2 (once or twice in ten winter simulations), lower than the observed frequency of roughly once every other year. This low frequency is reflected in Fig. 1. Additional perturbation simulations, as well as multiple-year runs using WACCM3, also display this low frequency of major stratospheric warming. The cause of this low frequency is not clear and still under investigation.

The magnitude of the error after saturation varies in different atmosphere regions. Figure 2 shows the differences in zonal wind and meridional wind between one perturbed case and the base case at a specific longitude 50 days after the start of the simulations. It is evident that the differences are largest in the winter
stratosphere and also in the mesosphere regardless of season. The differences in the summer stratosphere, on the other hand, are minimal. Differences in the troposphere are small compared to those in the summer stratosphere and mesosphere but still significant relative to the typical wind magnitude in the troposphere. This regional dependence of the error is qualitatively similar among all cases, with or without stratospheric sudden warming. Figure 3 shows the standard deviation of zonal wind along longitude, averaged over December–February, calculated from one of the simulations. The standard deviation is large in the troposphere, winter stratosphere, and the mesosphere/lower thermosphere. Comparison of Figs. 2 and 3 suggests that the

![Zonal mean temperature and zonal wind plots](attachment:image.png)

**Fig. 1.** Zonal mean (a) temperature at 82°N and (b) zonal wind at 62°N at 10 hPa from 10 WACCM simulations of December–February.
error growth is closely related to the atmospheric variability. In regions where the variability is weak, such as the summer stratosphere where planetary waves are weak, the error growth is weak. On the other hand, the error growth is strong in regions where the planetary waves are strong (mesosphere and winter stratosphere).

The temporal development of the error in zonal wind is shown in Fig. 4. The contour plots on the left show the difference in zonal wind between a member of the simulations in which the initial perturbations are introduced near the top of the model (above 10^4 hPa, denoted by the horizontal line) and the base case. The contour plots on the right show differences for another simulation in which the initial perturbations are introduced in the lower atmosphere (below 100 hPa, denoted by the horizontal line). The difference fields are taken at a specific longitude and 62°N and 62°S. In both cases small perturbations are added to the initial zonal wind field in the corresponding regions. From the plots, the error becomes apparent first in the upper atmosphere, near the top of the model, regardless of the altitude of the initial perturbations. The error then increases and becomes larger at progressively lower altitudes, though it is consistently small in the southern (summer) stratosphere. The error becomes saturated in the whole model domain after about 30 days.

To better quantify the error growth of the model, the root-mean-square differences between zonal winds from different cases for the whole model domain and for different atmosphere regions, including the troposphere, stratosphere, and mesosphere/lower thermosphere at low latitudes, summer and winter midlatitudes, and summer and winter high latitudes, are calculated and shown in Fig. 5. Over the whole domain, the error growth nearly plateaus after 30–40 days at ~20 m s^{-1}, and the growth is similar for all the cases. For the troposphere, the error growth is quite uniform at different latitudes and saturates after ~30 days at about 10 m s^{-1}, with that at low latitudes slightly lower and at winter midlatitudes slightly higher. The error growth in the stratosphere varies significantly over latitude: The saturated error is smallest in the summer midlatitudes with the saturation level at 5 m s^{-1}, between 5 and 10 m s^{-1} at low latitudes and around 10 m s^{-1} at summer high latitudes. The relatively larger error at summer high latitudes is probably due to the eastward wind bias in WACCM in the high-latitude lower stratosphere. Because of this bias, planetary waves can propagate into this region and increase the
variability. The error growth is much larger and more variable in the winter mid to high latitudes: generally larger than 20 m s$^{-1}$ varying between 20 and 50 m s$^{-1}$. The error growth is strongest in the mesosphere and lower thermosphere (MLT) region, especially in the winter hemisphere with the error between 30 and 60 m s$^{-1}$. From the summer hemisphere to the low latitudes, the saturated error in the MLT increases from ~20 to ~30 m s$^{-1}$.

**b. Error growth due to resolved gravity waves and planetary waves**

In this section, we first examine the initial error growth. Figure 6 shows differences in zonal wind between two pairs of the ensemble members in the first 200 h at a specific location and four pressure levels from the troposphere to the MLT: between the case in which initial error is introduced in the lower atmosphere (solid line: case L) and the base case and between the case in which initial error is introduced in the upper atmosphere (dotted line: case U) and the base case. For the first 2–3 days, the error is larger at all altitudes in case L, but the error from case U becomes comparable to case L afterward. It is noted that the error in both cases shows oscillations with periods generally comparable to or smaller than the inertial period (denoted by the solid horizontal line in the plots). This suggests that the error growth is likely related to error growth in the amplitude/phase of gravity waves resolved by the model (fast modes). The period distribution of the error growth over latitude in the initial 100 h for case L is also examined, and it is found that very often the error occurs with oscillation periods lower than the inertial period (not shown).

Because gravity wave amplitude grows exponentially with altitude, the errors related to gravity waves are also expected to grow with altitude. Figure 7 shows the vertical profile of the rms error in case L (solid) and case U (dotted) 0.5, 1, 2, and 4 days after the start of the
simulations. In both cases, the error grows with altitude exponentially by two to three orders of magnitude from the lower to the upper atmosphere after 48 h. This is consistent with the growth of gravity wave amplitudes over the same altitude range. It is also noteworthy that the error in case U is initially smaller than that in case L at all altitudes but becomes statistically comparable after 2 days. For other cases in which initial error differs, it also takes about 2 days for the error to reach the same magnitude. Therefore, the exponential growth of the error with altitude and the similarity in time for the error to reach its saturation level at each altitude ex-
plain the apparent downward progression of error from the upper atmosphere regardless of the location of the initial error.

It is also interesting to observe from Fig. 6 that the local error of case L at 700 hPa decreases for the first 2 days and then increases afterward. The initial oscillation likely reflects the local deviation associated with gravity wave adjustment processes at or near the level where the error is introduced, and the magnitude of this oscillation decays as the local imbalance is alleviated. The error at all levels increases with time after about 2 days, indicating global error growth of the system. The error is still likely related to the gravity waves, judged from the oscillation period, although the average values over each oscillation period begin to increasingly deviate from 0. This suggests that the error on planetary scales, such as planetary waves and mean flow, is increasing. Figure 8 displays comparisons similar to those in Fig. 4, but for the amplitudes of wavenumber-1 components in the corresponding cases. Differences in propagating planetary waves are also seen in the numerical experiments. For example, the quasi-two-day wave is strong during the same period (January) in most of the WACCM simulations. However, the exact time of its appearance and the amplitude and phase of the wave are different among the ensemble members.

c. Dependence of error growth on model resolution and model domain

We have also performed ensemble simulations using the standard CAM with $1.9^\circ \times 2.5^\circ$ horizontal resolution and WACCM with $4^\circ \times 5^\circ$ horizontal resolution. As in the WACCM simulation with $1.9^\circ \times 2.5^\circ$ horizontal resolution, small perturbations are introduced at different pressure levels in the initial condition. The rms differences among zonal winds from different cases for the whole model domain and for different atmo-
sphere regions—including the troposphere, stratosphere, and mesosphere/lower thermosphere (for WACCM) at low latitudes, summer and winter midlatitudes, and summer and winter high latitudes—are calculated (Fig. 9). For all three cases, the error grows to the saturation level in about the same time (30–40 days). The saturated values averaged over the whole domain in the CAM simulations are mostly between 10 and 15 m s\(^{-1}\), smaller than those in WACCM simulations with both 1.9° and 2.5° horizontal resolutions (20–30 m s\(^{-1}\)). The larger error growth in WACCM most likely comes from the mesosphere and lower thermosphere (and in addition CAM does not have a well-resolved stratosphere). In the troposphere, the saturated values of error are quite similar for all three models (5–10 m s\(^{-1}\)), though those at southern high latitude and northern midlatitude regions from WACCM (1.9° × 2.5°) and low latitudes from CAM appear to be slightly larger. In the stratosphere, the saturated values are similar in the Southern Hemisphere and low latitudes, but those at northern midlatitudes from CAM are significantly smaller compared with both WACCM simulations. At northern high latitudes, however, the saturated error values from CAM become stronger and closer to those of the WACCM simulations (for both resolutions). Because the error growth is closely related to the strength of the planetary waves, the planetary waves at midlatitudes seem to be underestimated in CAM compared with WACCM. The saturated error values in the stratosphere from both WACCM simulations are quite similar at all latitudes. In the MLT region, the saturated error values from WACCM (1.9° × 2.5°) are generally larger than those from WACCM (4° × 5°), except at northern high latitudes where they are comparable. In the troposphere, the saturated error values from both WACCM simulations are similar, except at southern high latitudes where the simulations with higher resolutions have larger error values.

The model error growth and its dependence on the model resolution and model domain are next examined in spectral space. Figure 10 shows the zonal wavenumber power spectra of error from two pairs of WACCM (1.9° × 2.5°) and WACCM (4° × 5°) simulations at
three pressure levels in the troposphere, stratosphere, and mesosphere at 1, 3, 5, 10, 30, and 50 days after the simulations started. The magnitude and location of the initial error introduced are the same for the two sets of simulations. For both resolutions, the error growth at larger wavenumbers is initially stronger, and then the error growth at smaller wavenumbers becomes progressively more significant. This indicates that the error growth is strongest first in high wavenumbers and later in lower wavenumbers. If we interpret the high-wavenumber components as inertial gravity waves, these results are consistent with the analysis in the previous section. In the first 10 days of the simulation, the error power from WACCM (1.9° × 2.5°) is larger than that from WACCM (4° × 5°) at larger wavenumbers at all levels, with the largest difference in the mesosphere on day 1. At smaller wavenumbers, the relative strength between error power from the two sets of simulations shows more variability over time and altitude. The error power is comparable between them after the error saturates.

Figure 11 compares the zonal wavenumber power spectra of error from two pairs of WACCM (1.9° × 2.5°) and CAM (1.9° × 2.5°) simulations in the troposphere and 1, 3, 5, 10, 30, and 50 days after the simulations started. Again, the magnitude and location of the initial error introduced are the same for the two sets of simulations. It is evident that the initial error growth is much stronger in the WACCM simulations at all wavenumbers. This probably results from better representation of higher frequency gravity waves in WACCM, made possible by its extended vertical domain. When the error saturates, it is comparable in the stratosphere between the two models.

d. Control of the error growth in the middle and upper atmosphere

As seen in the simulations, the error growth in the middle and upper atmosphere is closely tied to the strength of planetary waves. This suggests at least two possible mechanisms responsible for the error growth: 1) The error originates from instability and nonlinearity in the source region of the planetary waves in the troposphere or 2) the error arises from nonlinear processes such as interactions among various planetary waves and between planetary waves and the mean flow and/or instability associated with the interactions. It is certainly possible that both could contribute to the error growth, although the relative significance of each process may differ.

To elucidate the controlling mechanisms, we perform the following numerical experiments. Two members in the WACCM ensemble simulations are chosen (referred to as A and B). As mentioned before, simulations A and B are nearly identical except for the initial conditions, which differ slightly. The initial error grows exponentially, as we have seen in the previous sections. The “hybrid” experiment (referred to as H) starts from 10 December. At altitudes above a prespecified pressure level $p_s$, the initial conditions are taken from 10 December of simulation A. Below pressure level $p_s$, the initial conditions are those from 10 December of simulation B. After the simulation starts, the model results below pressure level $p_s$ are “reinitialized” by results from simulation B at corresponding times every $\delta t$ time. We then compare the results from simulation H with simulation B above pressure level $p_s$. If the error in the middle and upper atmosphere is primarily controlled by
error growth in the source region (troposphere) or by interaction between the lower and upper atmosphere, then the results above pressure level $p_s$ from H should be similar to those from B and there should be little or no error growth. On the other hand, if the error in the upper part is primarily caused by nonlinear interactions and/or instability, then the differences between H and B are likely to grow. This is because the planetary waves are still large and a diagnostic calculation shows the existence of the necessary condition for baroclinic/barotropic instability in the upper part, and the initial conditions in H and B in the upper part are different.

Three different $p_s$ levels—50, 500, and 700 hPa—have been selected with reinitialization period $\delta t = 1$ day.
For $p_s = 50$ hPa, additional simulations have also been conducted with $\delta t$ set to 5 and 20 days. Rms differences between zonal winds from H and B above the $p_s$ pressure levels are shown in Fig. 12. The differences do not show much growth when $p_s$ is set at 50 hPa and 500 hPa with $\delta t = 1$ day, though the difference in the latter case is larger than the former case. When $p_s$ is further dropped to 700 hPa, the rms differences display strong growth similar to the differences between simulations A and B. With $p_s$ at 50 hPa and the lower part reinitialized every 5 days, the differences are larger than those from the simulation with $\delta t = 1$ day but do not show significant growth. Growth of the rms differences is evident with $\delta t = 20$ days. The “spikes” occurring at every reinitialization are likely due to the adjustment resulting from the growing incompatibility around $p_s$, and their magnitudes increase as $\delta t$ increases. These experiments thus suggest that the error growth in the
middle and upper atmosphere is closely related to the error growth in the lower atmosphere, and controlling the lower atmospheric error growth is an effective way to control the error growth in the middle and upper atmosphere.

From earlier sections, it is seen that initial error in the middle/upper atmosphere also leads to global error growth. The fact that hybrid experiments such as H effectively suppress error growth in the middle/upper atmosphere indicates that error growth from the middle/upper atmosphere may feed into the whole system through the lower atmosphere, probably via vertically propagating gravity waves. The reinitialization of the lower atmosphere, at proper height and frequency, disrupts consistent interactions across pressure level $p_r$, as well as the error growth associated with the feedback interactions of the lower and upper atmosphere.

4. Conclusions

Error growth in the whole atmosphere domain is investigated in numerical experiments using WACCM with slightly perturbed initial conditions. Measured by the rms difference over the whole domain, error growth is quite similar between pairs of these experiments regardless of the magnitude, location, or physical nature of the initial differences. The initial error growth appears to be closely related to the resolved gravity waves. Because of the exponential increase of the gravity wave amplitude, the most apparent error growth is seen initially in the upper atmosphere and progress downward with time. Later error growth is manifested at increasingly larger scales by planetary waves and the
mean flow. As a result, the error is most prominent in regions where the planetary waves are strong (winter stratosphere and MLT) as the error saturates after about 30 days. The error growth in MLT at middle and high winter latitudes and in the stratosphere at middle winter latitudes is particularly strong.

The close association of the error growth with the strength of planetary waves suggests that the error growth in the middle/upper atmosphere could be controlled by error growth in the planetary wave source region in the lower atmosphere or by nonlinear interactions and instability in both lower and upper atmosphere. Results from WACCM simulations, whose lower atmosphere is periodically reinitialized by fields from a control simulation, suggest that the former (i.e., error growth in the source region in the lower atmosphere) is likely the primary controlling mechanism in this model. Reinitialization of the lower atmosphere at proper height and frequency (e.g., 500 hPa and 1-day interval) effectively suppresses error growth in the middle and upper atmosphere. Therefore, the initial error growth in gravity waves likely affects tropospheric processes on comparable scales, such as convection, and on larger scales through nonlinearity. Both will feed back on error growth at increasingly larger scales, and this “inverse cascading” in error growth may crucially impact the overall model predictability by affecting the baroclinic instability on synoptic scales in the troposphere. The error growth in the entire system is thus likely due to the chaotic behavior of baroclinic instability on synoptic scales. This interpretation is also supported by the error growth shown in spectral space (Figs. 10 and 11), which show spectral peaks at synoptic scales around wavenumber 4 when the error growth saturates. The time to reach saturation in error growth probably reflects the temporal scale of inverse cascading of the system.

Because the global error growth is independent of the location of initial error and the reinitialization of the lower atmosphere suppresses the global error growth, error introduced in the middle and upper atmosphere may affect the global error growth through the lower atmosphere. This likely explains the lack of error growth in some GCMs (e.g., TIME-GCM) that use lower boundary conditions specified by idealized perturbations or reanalysis data. On the other hand, it is known from stratosphere–mesosphere model simulations (e.g., Gray et al. 2003) that vacillations and chaotic divergence can occur when the amplitudes of the specified planetary waves are large enough, which suggests that the nonlinear interactions between planetary waves and mean flow could also be a viable mechanism for error growth. Because the ensemble of WACCM simulations shows major and minor warmings, the tropospheric forcing should be at least in the “intermediate forcing regime” described by Gray et al. (2003). However, since the frequency of major stratospheric sudden warming from WACCM is lower than the observed frequency, the planetary wave activity could be lower than reality. It is thus an interesting question whether the error growth in the upper atmosphere will be controlled by the troposphere as strongly if the model becomes more realistic in producing major stratospheric sudden warming. Furthermore, recent study (MAT) shows that the ROSE model, with a lower boundary at the tropopause, displays very different error growth using different diffusion schemes. With the lower boundary specified by reanalysis data, the largest error growth in ROSE is still much weaker than that in WACCM. The chaotic divergence thus seems to behave differently in different models. Because of the important implications for whole atmosphere predictability and data assimilation, further work is needed to understand the cause of such differences in model error growth.

The general behavior of model error growth is similar for WACCM with different resolutions, with strong error growth first at larger wavenumbers and later at lower wavenumbers. At larger wavenumbers, the error in WACCM with higher horizontal resolution is larger at all levels in the first 10 days. After about 30 days, errors from the model with both resolutions saturate. The error saturation levels are similar in the troposphere and stratosphere for the different resolutions, but those from the higher-resolution simulations are somewhat larger in most MLT regions (except at high latitudes in the winter hemisphere where they are comparable). It should be noted that the error growth here is measured by differencing members from the ensemble simulations with the same resolution but slightly perturbed initial conditions. This is different from the measure used by Tribbia and Baumhefner (2004), who differenced simulations from various spatial resolutions (T42, T63, and T106) with the one with high spatial resolution (T170) and found that the differences decrease with increasing resolution.

With the same horizontal resolution and same initial perturbation, the initial error from CAM is smaller than that from WACCM at most wavenumbers in the troposphere, probably because more gravity wave modes are resolved in WACCM with the extended vertical domain. After saturation, the errors in the troposphere from both models are quite similar, but in the winter stratosphere at midlatitudes the error from WACCM is significantly larger than that from CAM.
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