INTRODUCTION

As a result of the perceived motion of the Sun around the Earth causing a diurnal cycle of solar heating, atmospheric waves with a period of a day and harmonics of a day are excited near the earth’s surface. These tides, especially diurnal, semidiurnal, and terdiurnal, which migrate westward with the sun and propagate primarily vertically but also horizontally through the atmosphere, have been the subject of numerous studies. Less attention has been given to those tides of higher order than terdiurnal (tides with a periods of less than eight hours) but recent studies using simulations from whole atmosphere models, which extend from the earth’s surface up through the thermosphere, have shown the effects of these higher order tides in the middle and upper atmosphere. Simulations from the Kyushu General Circulation Model (GCM) used by Miyoshi et. al,[2009] revealed a causal relationship between migrating tides with periods of four to six hours and the generation of the solar terminator wave in troposphere/stratosphere which propagates up through the thermosphere. And simulations from the Whole Atmosphere Model (WAM) used by Akmaev et. al, [2009], reveal contributions to the thermospheric Midnight Temperature Maximum (MTM) by these same tides with periods of less than eight hours. Here, we use the extension of the Whole Atmosphere Community Climate Model (WACCM-X) to examine these higher order tides in the upper atmosphere and investigate connections with the lower atmosphere. We also examine simulations from the WAM model used by Akmaev above to compare to the WACCM-X results.

MODEL DESCRIPTIONS AND SIMULATIONS

There are a number of whole atmosphere models currently under development, many based on models used in climate and weather prediction for the lower atmosphere. Two of these models WACCM-X and WAM, are used for this study. WACCM-X is an extension of the Whole Atmosphere Community Climate Model (WACCM), which is based on the Community Atmosphere Model (CAM), the atmospheric component of the coupled Community Earth System Model (CESM). The version used here is modified WACCM3/CAM3 and has interactive chemistry based on the Model for OZone And Related chemical Tracers (MOZART) and a finite volume dynamical core. Ion chemistry is also included but ion and electron transport related to the electric and magnetic fields are not. Electron and ion energy equations are not solved, the electron and ion temperatures are equal to the neutral temperature, and electrodynamics are not included. The upper boundary of WACCM-X is in the upper thermosphere near 500 kilometers with 81 vertical levels and a vertical resolution of half of a scale height in the mesosphere and thermosphere. The horizontal resolution is 1.9° in latitude by 2.5° in longitude and the time step length is 5 minutes.

WACCM-X was run for 12 months under solar minimum and quiet geomagnetic conditions with a temporal resolution of 1 hour. The initial conditions for this run were the result of a one-year spin-up simulation. Temperature and zonal and horizontal winds in the thermosphere were examined for seasonal and spatial characteristics.

WAM is an extension of the medium-range weather prediction Global Forecast System (GFS) model as part of the Integrated Dynamics in the Earth’s Atmosphere (IDEA) project. It is the neutral atmosphere component of the coupled IDEA model and extends to the top of the thermosphere. WAM has a spectral dynamical core and an upper boundary near 600 kilometers. Vertical resolution is a quarter scale height above the troposphere and horizontal resolution is 1.8° latitude and longitude. The model can be run, as is routinely done with GFS, with data assimilation at specified intervals.

Simulations were done for 15 months with hourly output for low solar activity and quiet geomagnetic conditions and the last 12 months are used in this analysis. This produces results to be interpreted as climatology since no data assimilation is done beyond the initialization at a particular date. Temperature and horizontal winds were examined and compared to the WACCM-X simulations.

RESULTS AND DISCUSSION

A study was conducted to illustrate the characteristics and source of the MTM in the WACCM-X model and compare to those from the WAM model as well as previous observations. Figure 1a shows the March 13 WACCM-X simulation of temperature at an approximate altitude of 285 kilometers. In this one day plot, the maximum near the equator around 21:30 LT and the v shaped extension to higher latitudes is a simulation by WACCM-X of the MTM under equinox conditions. This feature has been observed by numerous groups and previously simulated in the WAM model [Akmaev et al., 2009]. One note here is the lack of a sizeable minimum in WACCM-X before the MTM, with the minimum being much clearer in WAM and observations.

The mean of the entire month of March WACCM-X simulations is shown in figure 1b. Here, the MTM is less apparent than in the plot of one day. The lack of a clear minimum prior to the MTM here and on March 13 is mostly due to the equatorial occurrence time, 21:30 LT, being biased earlier in the evening than the typical previously observed and modeled MTM occurrence time around midnight. This causes merging of the MTM with the sharp diurnal gradient of temperature and tends to cause the equatorial minimum typically preceding the MTM to be difficult to simulate in the one day in figure 1a and even more so in the monthly mean in figure 1b. As seen in figure 1c, which is the WAM March monthly mean temperature near 285 kilometers, simulation of the minimum preceding the MTM is not an issue, with the equatorial MTM occurrence time near midnight and a clear minimum a few hours earlier.

A better way to examine the MTM in WACCM-X would be to look along the v shaped propagation to higher latitudes at a later local time when the MTM in WACCM-X is occurring later than the large diurnal temperature gradient. This is accomplished in Figure 1d, which shows longitude profiles of temperature at a latitude of 20°N latitude near 285 km and 9 UT, one line for each daily WACCM-X simulation, in the month of March. Apparent is the considerable day-to-day variation in magnitude and variation in small-scale features. These variations were also seen in the WAM model results from Akmaev et al, [2009]. Also, similar to WAM, WACCM-X simulations have secondary peaks around 20 LT and 03 LT. In contrast to WAM is the time of occurrence of the MTM in WACCM-X simulations. WACCM-X shows the MTM occurring one to two hours before midnight at 20°N in March whereas WAM has the time as less than an hour after midnight at this latitude and time of year. This temporal difference, which was also seen at the equator, could possibly be related to an issue with the phase of tides in WACCM-X. Also different from WAM is the magnitude of the MTM. WACCM-X maximum values are in the 50K range and WAM has values upwards of 100K. The known low migrating tidal amplitudes of WACCM-X discussed in previous studies may explain this amplitude difference.

As mentioned above, Akmaev et al., [2009] showed a clear simulation by WAM of the thermospheric MTM near 285 kilometers but also noted the significant contribution to this feature by zonal wavenumbers 3 and greater. This was further examined in the simulations from WACCM-X and WAM. Performing a longitude one-dimensional spectral analysis and reconstruction of temperature gives the results shown in figures 2a and 2b for WACCM-X and WAM, respectively. These are similar to that shown for WAM in Akmaev et al., [2009] except the zonal wavenumbers for WACCM-X are divided into three levels of contribution, zonal wavenumbers 1-3, 1-6, and 1-9 as opposed to the 1-3, 1-12, and all for the previous WAM analysis. Even with the lack of a clear minimum before the MTM feature at 21:30, it is still apparent, near 285 kilometers at the equator, migrating tides of zonal wavenumbers 4-6 are large contributors to the MTM feature in WACCM-X in figure 2a. This is also seen in figure 2b for WAM where contribution from zonal wavenumbers 4-6 is significantly larger than that of zonal wavenumbers 7-9. It is also encouraging that the secondary peak after midnight, which is not affected by the large temperature gradient before midnight, is clear in WACCM-X and WAM.

Additional details of contribution to the MTM by these higher zonal wavenumbers can be obtained by further examining the characteristics of zonal wavenumbers in the WACCM-X and WAM models. Using the results of the one-dimensional FFT performed in longitude as described above, temperature amplitude variations with wavenumber can be examined. As shown in figure 3a, near the equator the temperature amplitude of the March monthly mean at 285 kilometers has expected large magnitudes for zonal wavenumbers 1 and 2 but a clear peak can also be seen at zonal wavenumber 5 for both WACCM-X and WAM, which is significantly larger than that of the surrounding zonal wavenumbers 4 and 6. So, for the zonal wavenumbers 4-6 contribution to the MTM shown in figures 5 and 6, the main contributor for WACCM-X and WAM appears to be zonal wavenumber 5. Additionally, zonal wavenumber 3 is larger than zonal wavenumber 2 in WAM but this is not seen in WACCM-X. Since the migrating terdiurnal tide is a significant mechanism in WAM for producing the MTM, a smaller zonal wavenumber 3 in WACCM-X would seem to at least partially explain the overall lower magnitude of the MTM compared to WAM

Further examination of reconstructed temperature gives a better quantitative idea of this zonal wavenumber 5 peak. Vertical profiles of reconstructed temperature for zonal wavenumbers 4-6 are shown in figures 3b-d. The relative peak of zonal wavenumber 5 at 285km, as seen in figure 3a, is apparent in figure 3c with a magnitude of above 10K in WACCM-X and WAM. This is in contrast to the less than 10K and less than 6K for zonal wavenumbers 4 (figure 3b) and 6 (figure 3d) respectively. Also, the vertical structure of zonal wavenumber 5 reveals increasing magnitude with altitude through the thermosphere for both WACCM-X and WAM not seen in zonal wavenumber 4, which does not continuously increase through the thermosphere. The magnitude of wavenumber 5 is nearly twice as large as that of wavenumber 4 near the top of the models. The magnitude of wavenumber 6, especially in WAM, also approaches or exceeds that of wavenumber 4 in the thermosphere, increasing with altitude.

If a longitude and 24 hour two-dimensional spectral analysis is performed on WACCM-X and WAM temperature 1 hourly simulations, wavenumber and frequency can be examined. Figures 4a and 4b show zonal wavenumber 5 temperature amplitudes at different frequencies westward and eastward from WACCM-X. For most zonal wavenumbers, the westward amplitudes appear larger than the eastward amplitudes. But the obvious feature is the westward frequency 5, which is much larger at high altitudes than all other frequencies for both WACCM-X and WAM (figures 4c and 4d). For a better idea of the vertical variation of the westward zonal wavenumber 5 frequencies, density weighted temperature amplitudes are shown for WACCM-X in figure 5. At low altitudes, zonal wavenumber 5 frequency 5 migrating tide appears to be the fourth or fifth largest frequency. With increasing altitude the other frequencies decay in amplitude but frequency 5 decays much slower, especially in the thermosphere. So, at altitudes around 285 kilometers at the equator, the migrating tide with a 4.8 hour period is the dominant zonal wavenumber 5 mode.

From the one-dimensional analysis, the temperature phase for zonal wavenumbers 3-6 is shown in figures 6a/c and 6b/d for WACCM-X and WAM, respectively. A difference in the vertical wavelength of wavenumbers 4 and 5 can be seen with wavenumber 6 being more similar to 5 for both WACCM-X and WAM. A larger vertical wavelength of near 100km is clear for wavenumbers 5 and 6 relative to wavenumber 4. This, along with the slower decay of frequency 5 in figure 5, indicates the difference in zonal wavenumber 5 is not due to its source but possibly related to the higher frequency of this wave and diffusion time scales and the longer wavelength allowing the tide to propagate to higher altitudes than the lower order tides.

The variation in amplitude of zonal wavenumber 5 with latitude and height is shown in figures 7a and 7b for WACCM-X and WAM in March. A clear maximum at the equator is apparent along with smaller peaks at higher latitudes and lower altitudes. WAM has larger peaks at the equator and other latitudes and altitudes than WACCM-X.

The same FFT analysis in longitude done above for temperature was also done for zonal and meridional winds from both WACCM-X and WAM. Figure 8a is the same as figure 3a but for zonal wind amplitude and the same large zonal wavenumber 5 values are seen, in this case even large than zonal wavenumber 3 in WACCM-X. The same is shown for meridional wind in figure 8b in which all wavenumber amplitude values are smaller than those of temperature and zonal wind, with zonal wavenumber 4 being larger than zonal wavenumbers 3, 5, and 6. Figure 9 is the same as figure 7 but for zonal wavenumber 5 amplitudes of zonal wind (figures 9a and 9b) and meridional wind (figures 9c and 9d). Again, it is clear the zonal wind has similar features to temperature for both WACCM-X and WAM with a peak at the equator and smaller peaks at higher latitudes and lower altitudes. For the meridional wind, the equatorial peak is not present as in figure 9b but maxima are present around 12°N and 12°S. The southern hemisphere maximum is larger in WACCM-X whereas the northern hemisphere maximum is larger in WAM.

Since the meridional wind does not show the large zonal wavenumber 5 amplitudes at the equator seen in the zonal wind, further analysis will concentrate on the zonal wind at the equator and meridional wind at 12°N (or should I concentrate on zonal wavenumber 4 at the equator???). Similar to figure 8b, meridional wind amplitudes for zonal wavenumbers 4-6 are shown in figure 10 but at 12°N for WACCM-X and WAM in March. For zonal wavenumber 5, the amplitudes increase to values of greater than 12 but for wavenumber 4 the values are less than 10 and less than 7 for wavenumber 6. So, it appears the characteristics of meridional wind zonal wavenumber 5 at 12°N are similar to those of zonal wind and temperature at the equator.

When the same two-dimensional longitude and time analysis is done for zonal wind as for temperature for WACCM-X and WAM, results for westward zonal wavenumber 5 zonal wind are similar to temperature as shown in figures 11a and 11b. Frequency 5 becomes larger in the thermosphere and its values are higher than all other frequencies. The same is shown for zonal wind from WACCM-X in figure 11c except the density weighted zonal wind amplitudes are shown. The same altitude variation in frequency 5 is seen as in temperature with very slow decay in amplitude from the surface up through the atmosphere, especially when compared to other frequencies, once again clarifying the relationship to the higher frequency and relatively larger vertical wavelength of this tide leading to less dissipation with height.

The above characteristics are for higher zonal wavenumbers at equinox and the same can be examined for solstice conditions. Figures 12a and 12b are similar to figures 1b and 1c but for June. Here the character of the MTM near 285 km is noticeably different than at equinox. The maximum appears earlier than at equinox and, instead of occurring near the equator, the maximum is offset toward higher northern latitudes, near 15°N for WAM and a little farther north for WACCM-X. Just as mentioned for equinox, WAM has a clear minimum prior to the near midnight maximum but WACCM-X this minimum is not present once again being mired in the large post afternoon steep temperature gradient. The magnitude of the MTM in WAM in this case is over 70K.

Since the MTM during June solstice is more apparent in the models north of the equator, further analysis will concentrate on latitude 15°N. This is also in the latitude region the NATE experiment on the Atmosphere Explorer-E found a maximum MTM magnitude at June solstice. Results from a one dimensional FFT analysis are shown in figure 12c which can be compared to figure 3a for equinox. There are clear differences between March and June with WACCM-X having a larger temperature amplitudes for zonal wavenumbers 3, 4, and 5 and smaller amplitudes for zonal wavenumbers 2 and 6. WAM, on the other hand, has larger zonal wavenumber 2, 4, and 6 but smaller wavenumber 3 and 5 amplitudes. So, for the higher zonal wavenumbers, WACCM-X still has a larger zonal wavenumber 5 than 4 or 6 but WAM has all three around the same magnitude. This still indicates a significant contribution higher zonal wavenumbers to the MTM near 15°N at solstice similar to the equator at equinox mentioned above.

Similar to figure 3, vertical profiles of reconstructed temperature are shown in figure 13 for June solstice at 15°N. In this solstice case, WACCM-X zonal wavenumber 4 and 5 temperatures have similar magnitudes in the thermosphere and tend to increase and remain constant through the top of the model. This is also true for zonal wavenumber 4 and 5 temperatures in WAM. The simulations from the two models differ for zonal wavenumber 6. In WACCM-X, zonal wavenumber 6 temperatures are less than half those of zonal wavenumbers 4 and 5. In WAM, zonal wavenumber 6 temperatures are similar to zonal wavenumbers 4 and 5 and even slightly larger near the model top.

When a two-dimensional spectral analysis is performed in longitude and time, amplitudes for wavenumber and frequency can be examined similar to that shown for equinox in figure 4. The solstice results for zonal wavenumber 5 are shown in figures 14a and 14b for WACCM-X and figures 14c and 14d for WAM. As for equinox, eastward amplitudes are smaller than westward amplitudes for both models and westward frequency 5 has the highest amplitude values in the thermosphere, larger in WACCM-X than in WAM. This is opposite to the equinox case where WAM has the larger thermospheric frequency 5 amplitudes. Another difference with equinox is the larger solstice frequency 4 thermospheric amplitudes. WACCM-X zonal wavenumber 5 density-weighted temperature amplitude profiles are shown in figure 15 for solstice similar to figure 11c for equinox. The March equinox and June solstice amplitudes are similar both showing the frequency 5 slow decay up to the top of the model. But an obvious difference, as also seen in figures 14a and 14c, is frequency 4, which is the third or fourth smallest through much of the lower and middle atmosphere but decays slower than lower frequencies up through the thermosphere in June. This decay is much faster at March equinox where frequency 4 was barely the third largest at the top of the model. So, even though the 4.8 hour period is dominant at solstice and equinox, the 6 hour period is also significant at solstice.

Figure 16 shows WACCM-X and WAM temperature phase profiles for zonal wavenumbers 3 -6 for June solstice similar to figure 6 for March equinox. In WACCM-X, zonal wavenumbers 3 and 4 have longer vertical wavelengths and zonal wavenumber 6 has shorter vertical wavelengths at solstice compared to equinox. The zonal wavenumber 5 vertical wavelengths are similar between solstice and equinox. For WAM, zonal wavenumbers 3, 4, and 6 have shorter vertical wavelengths at solstice than equinox and zonal wavenumber 5 is similar at solstice and equinox.

Similar to figure 7, the variation of zonal wavenumber 5 temperature amplitudes with latitude and height for WACCM-X and WAM is shown in figure 17 for June solstice. A large peak in WACCM-X and a few peaks in WAM are seen in the upper atmosphere near 15°N. WACCM-X has smaller peaks near 30°S and 50°S and WAM has larger peaks near 15°S and 35°S.

Just as for temperature in figure 12c, amplitudes resulting from a one-dimensional FFT in longitude for zonal and meridional wind are shown in figures 18a and 18b, respectively. Again, zonal wavenumber 5 is larger in WACCM-X than 3, 4 or 6 and larger than 4 and similar in magnitude to 3 and 6 in WAM for zonal wind. For meridional wind, zonal wavenumber 5 is larger than 3, 4, or 6 in WAM but only larger than 6 in WACCM-X.

The two-dimensional longitude and time analysis done above for temperature was also done for zonal wavenumber 5 zonal and meridional wind and results shown in figures 19 and 20, respectively, for WACCM-X and WAM. Again, westward amplitudes are larger than eastward amplitudes for both models and westward frequency 5 amplitudes are the largest, with higher values for WACCM-X than WAM. As with the solstice temperature, frequency 4 amplitudes are larger than at equinox. Figures 21a and 21b are the equivalent for zonal and meridional wind to figure 15 for temperature. Frequencies 4 and 5 are also largest as seen for temperature but frequency 4 has a larger decay in the lower and middle atmosphere than frequency 5, which has its largest decay in the thermosphere. This emphasizes that the 4.8 and 6 hour periods are significant in the thermosphere temperature and winds for zonal wavenumber 5 at solstice.

SUMMARY

Prompted by recent results from whole atmosphere models currently under development, wherein examinations were done of the role, in the mid- to upper atmosphere, of waves of harmonics of a day, or tides, we examine here these same tides in two such models, WACCM-X and WAM. These results show a connection of higher order migrating tides, greater than terdiurnal, to the temperature and winds, and in particular, the MTM feature in the low latitude thermosphere.

Examination of simulations of daily and monthly mean temperature near the equator at equinox from these two whole atmosphere models reveals both models producing an MTM feature in the thermosphere, more clearly in WAM than WACCM-X. This MTM feature has significant day-to-day and seasonal variability with characteristics being much clearer in daily data than the monthly mean. The occurrence time relative to midnight is different for the two models, with WAM being closer to midnight and WACCM-X being consistently earlier than WAM. This may partially explain the less obvious MTM feature in WACCM-X since the maximum, and more importantly the preceding minimum, can be hidden by the steep gradient in temperature from afternoon to evening. The earlier occurrence of the MTM in WACCM-X may be associated with issues related to the correct representation of migrating tidal phase in the model.

When looking at WACCM-X daily temperature for one month, it is clear there is a large day-to-day variability at the altitude of the MTM. In the WACCM-X temperature results, the magnitude of the MTM is also typically lower than that of WAM. Since Akmaev et al., [2009] pointed out migrating tides are significant contributors to the MTM, the difference in magnitude and timing compared to the WACCM-X results point to an issue with, again, phase and amplitude of these tides.

Spectral analysis reconstruction of temperature reveals this MTM is associated with large magnitudes for migrating tides with zonal wavenumbers 4-6 in both models, which is expected for WAM as noted above. For March equinox near the top of the vertical profiles, wavenumber 5 is dominant and wavenumber 6, being smaller at lower altitudes, is equivalent in magnitude to wavenumber 4.

When WACCM-X results of a two dimensional spectral analysis of temperature are examined for wavenumber 5, the westward frequency 5 tide with a period of 4.8 hours is largest in the thermosphere. Near the surface, this 4.8 hour frequency is smaller than lower frequencies but appears to decay relatively slower with altitude. This frequency also has a peak near the equator when examined in latitude and height for both models, with a larger peak in WAM than WACCM-X.

When zonal and meridional winds are examined in this same fashion, the results for zonal wind are very similar to temperature but the results for meridional wind are different. Instead of having a peak near the equator for wavenumber 5, the peak for meridional wind is near 12°N where similar results are seen as in temperature. The same large 4.8 frequency is apparent and the slow decay with altitude related to the higher frequency and relatively large vertical wavelength is clear.

Under solstice conditions the results are different but conclusions are similar for temperature and wind analyses. The MTM is shifted from the equator at June solstice, which results in the need to examine the model simulations at 15°N instead of the equator for equinox. At this latitude, the MTM appears similar to the equatorial equinox feature but the contributing higher order tides in the two models differ from each other. Wavenumbers 4 and 6 appear more significant in WAM, whereas wavenumbers 4 and 5 appear larger in WACCM-X. In either case, it is clear that the higher order tides also give large contributions to the low latitude thermosphere in solstice.