Comparison of diurnal tide in models and ground-based observations during the 2005 equinox CAWSES tidal campaign


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In this study, ground-based observations of equinox diurnal tide wind fields from the first CAWSES Global Tidal Campaign are compared with results from five commonly used models, in order to identify systematic differences. WACCM3 and Extended CMAM are both self-consistent general circulation models, which resolve general climatological features, while TIME-GCM can be forced to approximate specific conditions using reanalysis fields. GSWM is a linear mechanistic model; while GEWM is an empirical model derived from ground-based and satellite observations. The models resolve diurnal tides consistent in latitudinal structure with observations, dominated by the upward propagating (1,1) mode. There is disagreement in the magnitudes of the tidal amplitudes and vertical wavelengths, while differences in longitudinal tidal variability indicate differences in the nonmigrating tides in the models. These points suggest inconsistencies in model forcing, dissipation, and background winds that must be examined as part of a coordinated effort from the modeling community.

1. Introduction

The mesosphere and lower thermosphere (MLT) region of the Earth’s atmosphere extends between roughly 50–120 km altitude, and forms what is often considered to be the transition region between the electrically neutral, turbulence driven lower atmosphere and the charged, rarefied gases of the ionosphere and near Earth space. The dominant global scale dynamical features of this region are the atmospheric tides – persistent global scale oscillations with periods at harmonics of a solar day, forced by periodic insolation of water vapor by IR radiation and latent heat release in the troposphere, as well as UV absorption by ozone in the stratosphere (Hagan, 1996). Though they are relatively small in the troposphere and stratosphere source regions, the tides then propagate upward, growing in amplitude as the atmospheric density decreases, until they are dissipated in the lower thermosphere by turbulent and molecular diffusion (Hagan et al., 1995; Ortland and Alexander, 2006).

The tides are categorized by period, with the diurnal tide having a period of 24 h, the semidiurnal tide having a period of 12 h, and so on. Tides of these specific periods may be further subdivided into migrating and nonmigrating tides based upon...
their zonal wavenumbers and phase velocities. Migrating tides have zonal wavenumbers such that they propagate westward at the same rate as the apparent motion of the Sun. On the other hand, nonmigrating tides have zonal wavenumbers such that their phase velocities are not Sun-synchronous. In a simplified atmosphere, the latitudinal structure of each tidal component can be decomposed as being a sum of Hough modes – orthogonal solutions to Laplace’s tidal equation. These modes may propagate vertically away from their source regions, or can be trapped (evanescent) modes, which decay away from their excitation regions.

The diurnal tide represents the response of the atmosphere to the largest component of solar heating, and is the primary target for this study. From past observations (Hays and Wu, 1994; Burragle et al., 1995; Wu et al., 2006, 2008), it is known that the diurnal tide is dominated at low latitudes by the migrating diurnal tide (zonal wavenumber $s=1$), which itself is dominated by the upward propagating diurnal $(1,1)$ Hough mode, accounting for a primary peak in tidal temperature fields at the equator, with secondary peaks near $35^\circ$ latitude; and peaks in horizontal wind fields around $20–30^\circ$ latitude in both hemispheres. Evanescent modes dominate the diurnal tidal response at mid to high latitudes. Additionally, diurnal tidal amplitudes exhibit a regular seasonal amplitude variation, maximizing at the equinoxes and minimizing at the solstices.

Though the migrating tides are usually dominant, nonmigrating tides can also be important in certain times and regions, superimposing with the migrating tides to create longitudinal tidal variability when observed from ground stations at different longitudes along the same latitude circle. Using GSWM runs incorporating latent heat release due to deep tropical convection in the troposphere, Hagan and Forbes (2002) found that in addition to modulating the radiatively excited migrating diurnal tide, latent heat release was also responsible for forcing eastward propagating diurnal tides with wavenumbers $2$ and $3$ ($s=–2,–3$), westward propagating diurnal wavenumber $2$ ($s=–2$), as well as diurnal standing ($s=0$) oscillations. Various nonmigrating tides, such as the $s=2$ nonmigrating diurnal tide (Oberheide et al., 2002), and the $s=1$ nonmigrating semidiurnal tide may also be forced by nonlinear interactions between the migrating tides and stationary planetary waves (Chang et al., 2009). Similarly, numerical experiments by Hagan et al. (2009) have shown that migrating and nonmigrating tides of the same period may also interact with each other to produce stationary planetary waves.

In addition to reflecting the nature of forcing phenomena occurring at lower levels, the tidal response in the MLT region also has implications for thermosphere and ionospheric phenomena occurring far above the mesosphere and lower thermosphere. Tidal perturbations with longer vertical wavelengths are more resistant to dissipation, and can penetrate into the lower thermosphere. The signatures of such tidal components can be transmitted further up into the upper thermosphere and exosphere through interaction with the E-region dynamo, or through direct upward propagation (Oberheide and Forbes, 2008). Evidence of such tidally modulated phenomena has been found in observations of equatorial F region anomaly (Immel et al., 2006), as well as in exospheric temperatures derived from satellite drag data (Forbes et al., 2009).

Clearly, understanding the atmospheric tides observed at their peak amplitudes in the MLT region can help to shed light on the energetics and dynamics of regions both above and below the MLT. This makes the understanding of tidal structure and variability in the MLT region on seasonal and shorter day-to-day time scales, important to the understanding of the atmosphere as a whole. Such an effort necessitates the use of observations that are global in scale, with local time coverage sufficient to unambiguously resolve the tides over short time scales. At the present time, satellite-borne tidal observations can provide global scale coverage in the MLT region, but require very long integration times due to their slow rates of local time precession. Conversely, ground-based instruments can provide excellent resolution of day-to-day changes in the tide, but are limited in spatial coverage. As a result of these limitations, the use of tidal observations from multiple ground-based locations, as well as both space and ground-based observational platforms is desired. Examples of such studies include Yuan et al. (2010), which combined observations from TIMED/SABER and sodium lidar; as well as Ward et al. (2010), which examined the consistency between tidal signatures in TIMED satellite data, ground-based observations, and the Extended Canadian Middle Atmosphere Model.

In the following study, we expand on the work of Ward et al. (2010) by comparing multiple ground-based observations of the diurnal tide from the CAWSES Global Tidal Campaigns to results from five different atmospheric models. The objective is to examine the capabilities of current models in resolving the diurnal tide, and highlight commonalities and shortcomings amongst the models.

### 2. Observations

The CAWSES Global Tidal Campaigns are intended to provide periods of coordinated global scale observations of the atmospheric tides, involving multiple ground and space-based instruments. A total of four observational campaigns were conducted between 2005 and 2008, corresponding to the four seasons (Ward et al., 2010). In this study, we focus on ground-based observations from the first campaign, which took place during the equinox conditions of September/October 2005. In particular, we examine results from 14 ground-based instruments in various regions around the globe, shown in Fig. 1 and listed in Table 1. These diurnal tidal observations are then compared with tidal results from five different atmospheric models, which will be further examined in the following section.

The ground-based instruments utilized in this study include lidar, medium frequency (MF), and meteor (MR) radar stations, the characteristics of which are briefly summarized. MF and MR radars have long been utilized in studies of MLT wind fields, and function by measuring backscatter off of ionized structures in the MLT region, which are advected with the background wind fields, thus acting as tracers. MR utilizes ionization trails from ablating micro-meteors, while MF radars measure backscatter from gradients and fluctuations in the ionospheric D region (Khattatov et al., 1996; Hocking and Thayaparan, 1997; Riggan et al., 2003). Barring hardware failures, these radar systems are capable of continuous operation over long periods of time, making them attractive for long-term climatological studies.

Lidars are a more recent development in MLT observations. The CSU sodium lidar at Fort Collins is utilized in this study, and can provide profiles of MLT winds and temperatures through backscatter from sodium atoms resulting from meteor ablation in the region (She et al., 2002, 2003). The resulting wind and temperature profiles have high vertical resolution ($0.5$ km for the lidar dataset utilized here, compared to $2–4$ km for the radar datasets), allowing for the study of smaller scale structures and transient features, such as gravity waves. However, such lidars are limited by weather conditions and have shorter continuous operating times on the order of days to roughly one week (Yuan et al., 2010). In this particular case, the lidar was in operation for roughly seven days. Generally speaking, MF and MR radars are capable of long duration observations, while current lidar systems provide higher vertical resolution over a shorter time period.
3. Model descriptions

Computer models are of great use in interpreting observations of tidal structure and variability, as well as for conducting numerical experiments in a controlled environment. Modeling efforts to date can be roughly classified as either empirical or physics-based models, the latter of which includes both general circulation models (GCMs) and comparatively simpler mechanistic models. For this study, we examine tidal results from five different models, which are described in the following.

3.1. General circulation models: extended CMAM, WACCM3 & TIME-GCM

Two fully nonlinear, time-dependent GCMs are utilized in this study: version 3 of the NCAR Whole Atmosphere Community Climate Model (WACCM3); the Extended Canadian Middle Atmosphere Model (Extended CMAM). Both models are fully nonlinear, and capable of integrating the full set of primitive equations to resolve the global variation of the tides as a function of time. There are however, several distinct differences between the models.

Extended CMAM (Fomichev et al., 2002; Du et al., 2007) extends from the surface to roughly 210 km. The governing equations are solved in spectral space, with dependent variables expanded horizontally in spherical harmonics through wavenumber 32 (T32). This corresponds to a horizontal grid of approximately \( \frac{\pi}{6.0} \), while the vertical resolution varies from 150 m near the surface to 2 km near the tropopause, and 3 km in regions further above. Tidal oscillations are self-consistently generated from short and long wave radiation absorption, large-scale condensation, and convective heating. Nonorographic gravity waves are parameterized using the Doppler spread parameterization of Hines (1997a,b).

WACCM3 (Garcia et al., 2007) extends from the surface to roughly 150 km altitude. The dynamical core of WACCM3 is derived from that of NCAR's Community Atmosphere Model, version 3 (CAM3), which uses a finite volume method for evaluating the primitive equations in physical space. The horizontal resolution of the model as run for this study was \( \frac{\pi}{6.0} \), with 66 vertical levels corresponding to a resolution of approximately 1.1 km in the troposphere, 1.75 km at the stratopause, and 3.5 km above 65 km. The tides are forced self-consistently through long and shortwave heating, while a modified Lindzen scheme detailed in Garcia et al. (2007) is used to parameterize the effects of gravity waves.

Unlike the Extended CMAM and WACCM3, the NCAR Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) (Roble and Ridley, 1994; Hagan and Roble, 2001; Yamashita et al., 2010), is a time-dependent model with a lower boundary around 30 km, and extends upward to approximately 500 km in the thermosphere. The horizontal resolution is similar to that of WACCM3 at \( 2.5 \times 2.5' \), with a vertical resolution of approximately 1.5 km in the MLT region. Waves and other phenomena propagating upward from below the 30 km lower boundary must be implemented using GSWM model fields, reanalysis data, or specified explicitly by the user. Though the model does not extend to the tidal forcing regions in the troposphere, the use of a lower boundary in the stratosphere allows for more flexibility in terms of the numerical experiments that can be performed, as certain lower atmospheric forcing may be customized or eliminated altogether.

The diurnal tide and planetary waves in this particular run of TIME-GCM are forced at the lower boundary solely using ECMWF data. The tides are forced self-consistently through long and shortwave heating, while a modified Lindzen scheme detailed in Garcia et al. (2007) is used to parameterize the effects of gravity waves.

3.2. Mechanistic models: Alaska and Trivandrum

The time-dependent mechanistic model, the Alaska model, runs from the surface to approximately 200 km. The governing equations are solved using a spectral representation through truncation wavenumber 48 (T48). This corresponds to a horizontal grid of \( \frac{\pi}{4.8} \), while the vertical resolution varies from 500 m near the surface to 1 km near the stratopause, and 2 km in regions further above. Tidal oscillations are self-consistently generated from atmospheric heating, nonorographic gravity waves are parameterized using the Doppler spread parameterization of Hines (1997a,b).

The Trivandrum model extends from the surface to approximately 150 km altitude. The governing equations are solved using a spectral representation through truncation wavenumber 48 (T48). This corresponds to a horizontal grid of \( \frac{\pi}{4.8} \), while the vertical resolution varies from 500 m near the surface to 1 km near the stratopause, and 2 km in regions further above. Tidal oscillations are self-consistently generated from atmospheric heating, nonorographic gravity waves are parameterized using the Doppler spread parameterization of Hines (1997a,b).
reanalysis fields at the same 2.5° resolution as the TIME-GCM horizontal grid, corresponding to the first month of the first tidal campaign (September 2005), with the intention of approximating actual atmospheric conditions and tidal forcing during that time. This is in contrast to past TIME-GCM studies, such as Hagan and Roble (2001), which used GSWM seasonal values for tidal forcing at the lower boundary, or coupled the TIME-GCM lower boundary to another general circulation model (CCM3) (Liu and Roble, 2002). While quasi-realistic forcing of planetary waves at the TIME-GCM lower boundary has also been implemented in the past with NCEP Reanalysis fields (Liu and Roble, 2005), this method cannot be used for tidal forcing, due to the once per day resolution of the NCEP fields. The four times daily time resolution of the ECMWF fields makes it an attractive candidate for replacing GSWM seasonal fields for the purposes of forcing the diurnal tide in TIME-GCM to approximate a specific period of time, though the time resolution is still insufficient to accurately excite the semi-diurnal tide. As such, TIME-GCM is the only model examined in this study that is forced by conditions particular to the September 2005 time period, with the other models representing climatological results.

3.2. Linear mechanistic model: GSWM

We also examine the 2002 version of the linear mechanistic Global Scale Wave Model (GSWM-02) (Hagan et al., 1999; Hagan and Forbes, 2002). Unlike the aforementioned general circulation models, which numerically integrate the full set of perturbation equations forward in time and space, the GSWM solves a simplified set of linear equations under the assumption of steady-state conditions and sinusoidal behavior in longitude and time, with prescribed time independent background winds derived from High Resolution Doppler Imager (HRDI) observations, as well as prescribed background temperatures, forcing, and dissipation (in the form of Rayleigh friction and eddy diffusivity coefficients). This produces wave amplitudes and phases as a function of latitude and altitude for each specified frequency and wavenumber pair under the prescribed forcing and background conditions, and is useful in understanding the effects of changes in these parameters on tidal structure. However, GSWM cannot capture tidal components or variability generated by nonlinear interactions due to the linearized nature of the equations solved. For this study, we use the diurnal tidal results of GSWM-02, which include both the migrating ($s=1$) and 12 nonmigrating diurnal tidal components from zonal wavenumbers $s=6$ to $-6$. The horizontal resolution of 3.0 × 5.0° and the vertical resolution of the model are less than 1 km in the MLT region.

3.3. Empirical model: GEWM

The Global Empirical Wind Model (GEWM) (Portnyagin and Solovjova, 2000; Portnyagin et al., 2004; Portnyagin, 2006) is a two-dimensional model of the migrating diurnal tide, semi-diurnal tide, and mean horizontal wind derived from a network of 46 ground-based MF and MR radar stations, as well as observations from the HRDI and WINDII (wind imaging interferometer) instruments aboard the UARS spacecraft. The ground-based observations span a broad latitude range from 80°N through 90°S, while HRDI measurements equatorward of 45°, and WINDII measurements equatorward of 45° were utilized. Systematic biases between the horizontal winds measured by the various instruments were identified with respect to the MR measurements, which were assumed to be the most accurate. Correction factors were then applied to the data to minimize the aforementioned biases (Portnyagin et al., 2004). The resulting empirical model covers 80–100 km altitude, with a latitude resolution of 5°. We utilize the results of GEWM-II in the following study, which provides monthly amplitudes and phases for the migrating diurnal tide as a function of latitude and altitude (Portnyagin, 2006), derived from uncorrected MR, HRDI, and WINDII data, and with MF data scaled upward above 88 km altitude.

4. Processing methodology

At each observational station, and the nearest model gridpoint in WACCM3, Extended CMAM, and TIME-GCM, hourly averaged zonal and meridional winds from each altitude level over the entire two month campaign were fit to a basis function containing the diurnal, semi-diurnal, and ter-diurnal tides using a linear least-squares fitting routine:

$$F(t) = \sum_{\sigma=1}^{3} A_{\sigma} \cos(\sigma \Delta t + \phi_{\sigma})$$

This provides tidal amplitudes ($A_{\sigma}$) and phases ($\phi_{\sigma}$) as a function of height for each individual ground-station and at the nearest model gridpoint. Errors were computed from the fit covariances.

Output from GSWM already provides diurnal tide amplitudes and phases at all model latitude, longitude, and altitude gridpoints, while GEWM provides the amplitudes and phases of the migrating diurnal component with respect to latitude and altitude.

5. Results

5.1. Latitude variation

Fig. 2 shows the model and observed diurnal tidal amplitudes as a function of latitude at 90 km for the zonal and meridional wind fields during September/October 2005. The diurnal tidal amplitudes for all of the models except GEWM were computed at each latitude and longitude grid point, then averaged zonally for each model latitude grid point. As no phase information was included in the average, this method will not eliminate the effects of tidal components with nonzero zonal wavenumbers, which would otherwise average out to zero when integrated over 360° of longitude. The contribution of both migrating and nonmigrating components to the overall diurnal tide is also manifested in the form of differences in tidal amplitudes from observations at similar latitudes, but different longitudes. This longitudinal variability can be seen in the observations near 20°S. The two stations near 40°N (Platteville MF radar and Fort Collins lidar) are located relatively close to one another. Differences between these two sites are attributable to differing observational lengths, with the lidar being active for roughly seven days, while the MF radar was active for much of the two month campaign. When the MF radar data was sampled only during the times when the lidar was active, the resulting tidal results demonstrated good agreement between the two instruments.

With the exception of TIME-GCM (dot-dashed line), all of the models resolve the expected bimodal structure with tropical peaks commonly associated with the diurnal (1,1) wind expansion functions in both horizontal wind fields, consistent with the observational data. However, the models differ significantly from one another on the magnitude of the tidal amplitudes in the low latitudes: GSWM and Extended CMAM display the largest amplitudes with peaks exceeding 50 m/s, WACCM3 and GEWM are intermediate with peak amplitudes in the vicinity of 15–30 m/s, while TIME-GCM displays the smallest peak amplitudes, around 10–15 m/s. Additionally, the latitude at which the tropical peaks
occur also varies, with the peaks in WACCM3 generally occurring at lower latitudes compared to the other models, especially in the Northern Hemisphere.

Using generalized Hough modes, Ortland (2006) found that a narrowing of the migrating diurnal tidal peaks could be attributed to the presence of an eastward equatorial zonal mean zonal wind jet. This may be a factor in the narrower horizontal wind peaks found in WACCM3, though further comparison of the background wind fields of the various models is needed to confirm this. It is also worth noting that Ortland (2006) also found that increased dissipation resulted in a broadening of the tidal peaks, though again, this requires analysis of the different gravity wave parameterizations utilized in the GCMs, which is beyond the scope of this study.

The diurnal tidal amplitudes and phases in the zonal and meridional wind fields as a function of height are shown in Fig. 3 for observations and model gridpoints nearest to the Kauai MF radar station (22°N, 200°E), which is located near the Northern Hemisphere tropical peak of the diurnal (1,1) Hough mode. The difference in tidal amplitude between the models is again significant throughout the entire domain, with GSWM and Extended CMAM showing the largest amplitudes and TIME-GCM displaying the smallest amplitudes. The amplitudes in WACCM3 and GEWM are closest to the observed amplitudes throughout most of the observational domain. In the case of GEWM this is not unexpected as GEWM was derived in part from ground-based observational data. It has been noted that the magnitude of MLT winds observed by the satellite-borne HRDI instrument were generally larger than those measured by MF radar (Burrage et al., 1996; Khattatov et al., 1996). Given that the magnitude of GSWM Rayleigh friction coefficients were tuned based upon diagnostics using HRDI diurnal wind climatologies (Hagan et al., 1999), this may explain the larger GSWM amplitudes compared to GEWM and radar at this location.

Causes for some of the aforementioned differences between the models and observations may be revealed through examination of the tidal phase structure. The slopes of the tidal phases reveal the vertical wavelengths of the diurnal tide resolved by the various models and observations. Past studies have shown that tidal vertical wavelengths are affected by eddy diffusion and momentum deposition in the MLT region from gravity wave breaking. Gravity wave momentum forcing can increase or decrease tidal amplitudes, depending upon the phase of the forcing relative to the tide, while also shortening the tidal vertical wavelength by locally advancing the tidal phases. On the other hand, gravity wave induced eddy diffusion has been found to increase tidal vertical wavelengths, while providing tidal dissipation (Ortland and Alexander, 2006). Numerical experiments by Ortland and Alexander (2006) have found that the overall effects of these two gravity wave mechanisms on the tide are highly dependent upon the gravity wave parameterization and source spectrum utilized. Additionally, the tidal vertical wavelengths are also affected by the background zonal mean zonal winds, though any increase or decrease is highly dependent upon the structure of the mean winds (Ortland, 2006). Finally, the overall diurnal tidal vertical wavelength at a particular location is also dependent upon the superposition of the migrating and nonmigrating tidal components that comprise the total diurnal tide, as well as the superposition of the different meridional modes of each tidal component. Therefore, differences in tidal vertical wavelength might also be the result of different migrating and nonmigrating tidal amplitudes due to differences in tidal forcing.

In the observational domain, the diurnal tide in both Extended CMAM and GSWM shows vertical wavelengths that are shorter than observations with amplitudes that exceed those in observations. In the case of Extended CMAM, it has been noted that the amplitudes of the eastward propagating components of the diurnal tide are up to a factor of three stronger than the values observed by the TIMED Doppler Interferometer (TIDI), while westward propagating components are of comparable
magnitudes. It is therefore possible that parameterizations of latent heat release and deep convection responsible for generating the eastward propagating diurnal tidal components are overestimated (J. Du, private communication, 2010). Another possibility for the larger amplitudes and decreased vertical wavelengths in CMAM may be the result of in-phase gravity wave momentum forcing, commonly associated with the Hines parameterization employed in that model (McLandress, 2002).

While similar in-phase forcing may also be possible in GSWM though the prescribed eddy diffusivity coefficients utilized in that model (Hagan and Forbes, 2002), earlier versions of GSWM showed an increase in diurnal tidal amplitudes when eddy
diffusivity was omitted (Burrage et al., 1995), indicating that the effect of eddy diffusivity in GSWM is primarily to suppress the tide. The positive real valued Rayleigh friction used to parameterize the effects of gravity wave drag in GSWM acts to reduce the tidal amplitudes with little to no effect on the vertical wavelength (Hagan et al., 1999; McLandress, 2002), and underestimated equinox Rayleigh friction coefficients could also potentially be a factor in the larger tidal amplitudes. For both models, it is also possible that the larger tidal amplitudes may be the result of increased tidal forcing in the lower atmosphere. As mentioned previously, the model zonal mean zonal winds may also play a role, though it should be noted that the prescribed zonal mean
zonal winds in GSWM were based on monthly HRDI-derived climatologies, and are therefore expected to be more realistic than the self-consistently calculated values in Extended CMAM.

It is also worth noting that TIME-GCM shows very long vertical wavelengths with very small tidal amplitudes. This suggests that the ECMWF lower boundary in this TIME-GCM run was not strong enough to force the upward propagating diurnal (1,1) mode that should dominate the diurnal tide in this region, since the dissipation scheme is the same as that used for past runs with GSWM forced tides. This underestimation may be a result of the 6 h time resolution of ECMWF not coinciding with the maximum heating signatures in the troposphere. The model vertical resolution is also connected to the strength of the resolved diurnal tide due to its relatively short vertical wavelength. However, this is

Fig. 5. Same as Fig. 3, but for Andenes meteor radar (69° N, 16° E).
unlikely to explain the smaller than expected diurnal tidal amplitudes, given that the diurnal (1,1) mode is properly resolved by TIME-GCM at identical resolutions using GSWM forcing. Consequently, it may be necessary to increase ECMWF diurnal tidal forcing in future runs of TIME-GCM.

Figs. 4 and 5 show the diurnal tidal amplitudes and phases at Platteville/Fort Collins (both near 40°N, 255°E) and Andenes (69°N, 16°E), respectively representative of the tidal responses at mid and high latitudes. While the diurnal tidal amplitudes are generally smaller than those at lower latitudes, there are still significant differences in the relative magnitudes of tidal amplitudes resolved by the various models, especially at Platteville/Fort Collins.

The Platteville MF radar observations (Fig. 4a and b), as well as GEWM, WACCM3, and TIME-GCM all show amplitudes lower than 10 m/s with few changes in the vertical direction. The nearby Fort Collins sodium lidar shows amplitudes that are somewhat larger than the MF radar, with the considerably better vertical resolution revealing a more complex vertical structure. The different observational time spans also contribute to differences between the MF radar and lidar observations. The shorter seven day period during which the lidar was operational is reflected in the larger uncertainties and broader bandwidth for the diurnal tide fitted from the lidar data. As the radar was operational almost continuously during the two month campaign, the diurnal tidal fitted from the radar data has a narrower bandwidth, and is less affected by short term tidal variability.

The vertical wavelengths in the observations, WACCM3, TIME-GCM, and altitudes below roughly 85 km in GEWM are very long, indicative of evanescent vertical structure. In contrast, the amplitudes in the Extended CMAM and GSWM are much larger, and show significant vertical variation. The Extended CMAM resolves two amplitude peaks in excess of 25 m/s at 88 and 105 km, while GSWM shows a single large peak at 105 km with an amplitude of 70 m/s. Additionally, the vertical wavelengths as determined by the phase progression of the tidal horizontal winds in Extended CMAM and GSWM are shorter than those in the observations and the other models (with the exception of GEWM above roughly 85 km), indicative of upward propagating modes. It is also noted that there is generally good agreement in the tidal phases measured by the MF radar and the lidar below roughly 95 km, though the lidar vertical profile again displays greater spatial variability.

Fig. 5a and b show observations and model results for Andenes meteor radar. The diurnal tidal response from the models and the data are much more consistent in the observational domain compared to mid-latitudes, showing amplitudes at and below 10 m/s below 95 km, and evanescent phases within approximately 5 h of one another.

From this, it is apparent that the upward propagating diurnal tidal modes in the Extended CMAM and GSWM are larger in the mid-latitudes than those in the other models and in the observations, potentially due to increased lower atmospheric forcing. In contrast, the TIME-GCM results from Kauai suggest that ECMWF forcing may be insufficient to excite the upward propagating modes even at low latitudes. This is consistent with previous analysis of the latitudinal structure of the diurnal tide in Fig. 2.

5.2. Longitudinal variation

One limitation of ground-based observations in tidal studies is their inability to distinguish the migrating tide from other nonmigrating tidal components that are also present, resulting in observations showing the superposition of all migrating and nonmigrating components, which are zonally asymmetric (Ward et al., 2010). The longitudinal variability in the diurnal tidal structure that results can be seen by comparing results from three meteor radar stations...
located at similar latitudes near the Southern Hemisphere tropical peak at 22°S: Learmonth (23°S, 114°E), Rarotonga (22°S, 200°E), and Cachoeira Paulista (23°S, 315°E).

Fig. 6 shows the zonal profiles of diurnal tide amplitude in observations and model results at approximately 92.5 km altitude from the three aforementioned locations, as well as model results from WACCM3, Extended CMAM, TIME-GCM, and GSWM at the nearest latitude gridpoints. GEWM contains only the migrating diurnal tide, and therefore does not account for longitudinal variation in tidal amplitude. The observational data shows significant differences in diurnal tidal amplitude between the three stations due to superposition of migrating and nonmigrating tides, with amplitudes largest at Cachoeira Paulista, and smallest at Rarotonga. However, the paucity of these ground-based observations precludes any definitive characterization of nonmigrating tidal variations from this ground-based perspective.

While all four models also resolve significant longitudinal variability in diurnal tidal amplitudes, the pattern of the amplitude variation in the models do not agree with observations. This suggests that the nonmigrating tides excited in the models differ from those observed during the tidal campaign, though again, this comparison is limited by the sparse distribution of the ground-based observations. It is interesting to note, however, that Extended CMAM, TIME-GCM, and GSWM display similar patterns of zonal variation. This may be due to similarities in lower atmospheric nonmigrating tidal forcing, such as that from latent heat, though this cannot be definitively stated without more detailed examination of the model forcing parameters, particularly the nonmigrating components of latent heating. Additionally, some nonmigrating tidal components may be generated through nonlinear interaction between the migrating tide and any stationary planetary waves that may be present (Oberheide et al., 2002). This may also be a factor in nonmigrating tidal generation in the three nonlinear models.

5.3. Time variation

As mentioned previously, one of the main rationales for forcing the TIME-GCM lower boundary with ECMWF Reanalysis fields is for the purpose of quasi-realistic tidal forcing. In particular, we are interested in determining how accurately TIME-GCM can reproduce the day-to-day variation of the diurnal tide using this method. Figs. 7 and 8 show the time variation of the diurnal tide horizontal wind fields at 90 km in observational data and TIME-GCM at five selected sites spanning from 69°N to 23°S. While there are occasional similarities in the time variation of the diurnal tide between the model and the observations, correlation is generally very low. Correlation coefficients between the model results and observations with zero lag time computed for all of the locations examined were less than 0.5 in nearly all cases, or were unreliable due to long observational data gaps.

Additionally, it is apparent that the model amplitudes resolved at sites near the low latitude peaks of the diurnal tide (Kauai and Cachoeira Paulista) are much smaller than those observed. This again indicates that the upward propagating diurnal (1,1) mode that is known to dominate the structure of the diurnal tide is not properly resolved with ECMWF forcing in TIME-GCM. Addressing the amplitude discrepancy will require comparison of the ECMWF tidal components at the lower boundary with similar GSWM seasonal values normally used to force the tides in TIME-GCM.

6. Conclusions

Diurnal tidal results from the Extended CMAM, WACCM3, TIME-GCM (with ECMWF forcing), GSWM-02, and GEWM have been compared to observations from 14 ground-based instrument sites participating in the first CAWSES Global Tidal Campaign in September and October 2005. With the exception of TIME-GCM with ECMWF forcing, all the models examined, as well as the observational data resolved a diurnal tide around 90 km altitude dominated by the bimodal structure indicative of the upward propagating diurnal (1,1) Hough mode at the low latitudes, transitioning to evanescent modes at mid to high latitudes. However, several differences between the models were also identified:

(1) Compared to the other models and observations, Extended CMAM and GSWM-02 showed much stronger tidal amplitudes and shorter vertical wavelengths near the low latitude peaks of the upward propagating diurnal (1,1) mode. The
upward propagating modes also penetrated further polewards than the other models and the observations.

(2) In contrast, low latitude tidal amplitudes in WACCM3, GEWM, and the observations were much weaker, with longer vertical wavelengths. WACCM3 also showed a much narrower latitudinal structure, with the tropical peaks in the horizontal wind fields located further Equatorward compared to the other models.

(3) TIME-GCM with ECMWF forcing did not resolve the diurnal (1,1) mode at all in the zonal wind fields, and only weakly in the meridional wind fields. Combined with the very long vertical wavelengths resolved by TIME-GCM at low latitudes, this indicates that the ECMWF diurnal tidal forcing as implemented in this particular model run is insufficient. Additionally, the correlation between the time variation of the diurnal tide resolved in TIME-GCM and observations is still quite low, though some similar features are occasionally seen.

(4) Longitudinal variation of the diurnal tidal structure at 22 S resolved by WACCM3, Extended CMAM, TIME-GCM, and GSWM-02 differs from that seen by the three radar sites located at similar latitudes, though some of the model results are similar to one another. The sparse distribution of the ground-based observations is a significant limitation on any further comparison of the longitudinal tidal variability between the models and the ground-based data.

We discuss first, the tidal response in GSWM and GEWM, which have fewer parameters and are therefore easier to analyze. The primary difference exhibited by these two models is in terms of tidal amplitude, with GSWM showing larger amplitudes and GEWM showing smaller amplitudes. This is not entirely surprising as the Rayleigh friction magnitude in GSWM was specifically tuned to produce a tidal response of similar magnitude to that observed by HRDI, which is known to resolve stronger winds than the ground-based radar results that were used to create GEWM (Burrage et al., 1996; Khattatov et al., 1996; Hagan et al., 1999).

Further validation efforts, especially in the case of the three GCMs examined, will require coordinated input from the modeling community. In this comparison, we have identified the following parameters that require further examination:

(1) The differences in tidal vertical wavelength and amplitude point to a need for comparison of the eddy diffusivities, tidal forcing, and zonal mean zonal winds in the physics-based models. In the cases of Extended CMAM, the larger tidal amplitudes and shorter vertical wavelengths may be related to the overestimation of eastward propagating diurnal tidal components due to the latent heating and deep convection parameterizations. Additionally, the Hines gravity wave parameterization employed by CMAM is also known to produce in-phase momentum forcing. In the case of GSWM, the shorter vertical wavelengths and larger amplitudes may be the result of in-phase forcing from the prescribed eddy diffusivities, or stronger lower atmospheric tidal forcing. Lower values of Rayleigh friction in GSWM might also contribute to underdamping of the tidal amplitudes. In the case of the smaller tidal amplitudes in TIME-GCM, tidal amplitudes in the ECMWF lower boundary should be compared with similar values from the other models.

(2) Differences in longitudinal variation of the tide are indicative of differences in the nonmigrating diurnal tides resolved in the various models. This in turn suggests that further comparison of the migrating and nonmigrating heating rates in the models is necessary, particularly latent heating rates, which are believed to be important in generating the nonmigrating tides. Analysis of the stationary planetary waves excited in the three nonlinear models will also be useful in ascertaining the potential for nonmigrating tidal generation via nonlinear interaction with the migrating tide.

References


