The Atmospheric Tide: Detergents of the Upper Atmosphere -- Just Add Water and Stir Vigorously

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Abstract

Atmospheric tides are global scale oscillations observed in all regions of the atmosphere. A previously developed numerical model, the Global-Scale Wave Model (GSWM) (Hagan, 1993) simulates the diurnal and semidiurnal tides from the ground to 120 km and beyond. We compared GSWM tidal simulations to ground-based radar data obtained during two of the Lower Thermospheric Coupling Study (LTCS) campaigns in order to evaluate the ability of the model to capture the salient features of the tides observed in the mesosphere and lower thermosphere during July.

Introduction

The upper atmosphere can be a very violent place, where wind velocities fluctuate greatly with time, reaching speeds in excess of 100 ms\(^{-1}\). These fluctuations play important roles in the transportation of energy from one area of the atmosphere to another. They also dominate the dynamics of the mesosphere and lower thermosphere, joining these regions inseparably. Atmospheric tides are the heart and soul of the fluctuations, carrying in their veins the heat necessary for the survival of their species at the surface of the earth and beyond. As these tides grow with height, they obtain greater and greater horizontal velocities, until they reach a critical value. At this point, they dissipate, depositing precious momentum to the background winds, other waves, and even undiscovered sources that can boggle the mind. Oddly enough, these tides are largely dependent upon thermal forcing by water vapor in the troposphere and ozone in the stratosphere (Fig. 1A).

As detergent couples polar and non-polar substances to remove grease from clothing, atmospheric tides couple the different regions of the atmosphere. The tides lift the energy away from the heated areas and transport energy to the places in need of it. In the same way detergent is key to understanding what’s going on in your laundry, the tides are vital to understanding the mesosphere and lower thermosphere (MLT).
Atmospheric Theory

One can describe the atmosphere in terms of layers, each layer having a temperature profile different from the previous. The troposphere, for example, is a layer going from the ground to about 10 km. Figure 2 shows a typical middle latitude temperature profile. From this figure we see that this layer’s temperature decreases at a rate of about 10Kkm⁻¹. The stratosphere is a layer in which the temperature increases due to the presence of ozone (O₃), a heating mechanism described later. The stratosphere extends from 10 km to about 50 km. Next, is the mesosphere, a region of the coldest temperatures in the earth’s atmosphere. It extends from 50 - 80 km. Then, there is the thermosphere, a layer of increasing temperature, lying above the mesosphere at 80 km.

There are two competing physical processes which determine the ratio of invariable gaseous constituents of the atmosphere with height. These processes are molecular diffusion and mixing by fluid motion. Molecular diffusion predominates above 100 km, having very little effect on the MLT. However, the second process, fluid motion is due to the movement of large air parcels within and/or between different layers of the atmosphere (Wallace and Hobbs, 1977). This process predominates below 100 km, and it is only in that area that the air is, for the most part, homogenous (Wallace and Hobbs, 1977). All of this holds true for these chemicals in the atmosphere. However, components like ozone (O₃) and water vapor (H₂O(ν)) are highly variable in both space and time (Wallace and Hobbs, 1977). Despite these gases being only trace elements in the atmosphere, they play vital roles in the heating of the stratosphere and troposphere, respectively.

Because the sun can heat only what faces it, only half of the atmosphere receives heat at a time. If one considers the different layers of concentric spheroids, the sun heats only half of these spheroids at a time, as well. As the temperature of each region of the atmosphere absorbs heat, the constituent gases expand. Conversely, on the dark, unheated side, the gases contract as the temperatures fall. One may find it also important to note that the pressure gradients associated with temperature differences generate winds. The difference in temperature induces a “tide” that follows its heating source, the sun, passing over each location once every 24 hours (Fig.1C). However, a tide has a much broader implication than the simple heating of the atmosphere due to the absorption of solar radiation. To atmospheric scientists, a solar tide is a planetary-scale periodic fluctuation in temperature, density, pressure, and velocity (Forbes, 1995).

Additionally, one restriction of being considered a solar tide is that the fluctuation must be a in harmonic of a solar day (Hagan, 1995). Another restriction is the existence of a migrating component that follows the sun. Alternatively, planetary waves may be stationary or non-stationary (Forbes, 1995). The gravitational attraction (and repulsion on the opposite side) between the atmosphere of the Earth and larger astronomical masses cause some tidal forcing by virtue of inducing a bulge (Lindzen, 1990) in much the same way the moon drives the oceanic tides. However, this is only a very slight bulge, and its effects are negligible. Atmospheric tides occur in all regions of the atmosphere, including
at the surface (Lindzen, 1990). Most importantly, in the upper levels the tides dominate the dynamics of the region (Forbes, 1995) as they grow, while propagating upward. It is for this reason that, despite their source lying in the troposphere and stratosphere, they govern the MLT.

Global-Scale Wave Model

The Global-Scale Wave Model (GSWM) is a climatological model of the tides but has never been used for long-term climatological studies. It simulates the tides in both their amplitude (the greatest velocity, with the mean winds taken out) and phase (the time when the amplitude is at its maximum) for each month. The forcing caused by the water vapor in the troposphere is specified for only four months of the year (January, April, July, and October). As a result only seasonal estimates of the tides can be computed with the GSWM. The model also computes each of the three wind components separately. When mapped as a function of latitude and altitude, the results are as illustrated in Figure 3. The diurnal tide has a maximum every 24 hrs, while the semi-diurnal every 12 hrs.

Methods

During July and August of 1992 and 1994, horizontal wind velocity data were obtained from stations located at Christmas Island (2°N, 157°W), Adelaide (35°S, 138°E), and Davis (70°S, 78°E) (see Fig. 4). The velocities were compiled as hourly averages for eight days in 1992 and ten days in 1994. We converted these velocity data from two Lower Thermospheric Coupling Study (LTCS) campaigns into a time series of the meridional and zonal components at each height in the mesosphere and lower thermosphere (MLT), ranging from 70 - 100 km. To distinguish tides in the data from noise, we then used a Fast Fourier Transform (FFT) program to compute the frequency spectra from the time series. We then compared the diurnal and semi-diurnal amplitudes and phase shifts obtained in the campaign data against the outputs of the GSWM, basing the comparisons on these mappings. These comparisons will be described later.

The Radar Data

Medium frequency (MF) radars operating at 2 MHz collected wind data from 70 - 100 km at 2 km intervals, at Adelaide and Christmas Island on 30 July 1992 through 6 August 1992 (LTCS8), and the Adelaide, Christmas Island, and Davis sites operated during 29 July 1994 through 7 August 1994 (LTCS10). The radar data contains separate measurements for the meridional (north-south) and zonal (east-west) components of the wind, because wind is a vector quantity. The velocities were averages computed after an hour of collecting data. At the lower altitudes between 70 and 80 km, the radars could
only take measurements during the daytime. This limitation resulted in periods of missing data, which makes it impossible to determine diurnal variations in wind velocity for the altitudes between 70 and 80 km.

**Fast-Fourier Transforms**

We plotted the data collected by the radars in a time series (velocity vs. time) using the Interactive Data Language (IDL), so trends toward periodicity in the data (Fig. 5), as well as any gaps (Fig. 6), would become more obvious. These gaps may hinder, or at best complicate, its computation of a Fast-Fourier Transform (FFT). The FFT routine returns the frequency content of discrete data versus the amplitude of the signal. In this case, cycles per hour (hr⁻¹) versus velocity (ms⁻¹) at each respective height. In order to determine the three or four largest tidal frequency maxima on the plots, we wrote a program in IDL in order to square the values on the y-axis and plot this value (energy in m²s⁻²) versus the frequency hr⁻¹(see Fig. 7). Knowing the frequency, we then determined the period of the three or four most prominent maxima on the plot of energy versus frequency by taking the inverse of the frequency. Limitations on the range of frequencies the method detects exist, however. For example, the smallest sinusoid the FFT program can detect is the sinusoid with twice the time between samples, assuming the data is uniformly sampled, of course. This restriction destroys any consideration that the sinusoid is a harmonic of a smaller sinusoid that may, due to the sampling rate, appear ambiguous.

After using a data-fitting program to compute the phase shifts and amplitudes (with the mean taken out) from the radar data, we plotted the phase and amplitudes of the diurnal and semidiurnal tides in each wind component at each height against the phase and amplitudes GSWM simulates. Additionally, we reconstructed the plots of the diurnal and semidiurnal tides against the data to see how closely these tides represented the actual data. To make this reconstruction, we mapped the values the data-fitting program returns against the time-series of the radar data. These results will be discussed later.

**The Trouble with Adelaide**

The data from both campaigns at the Adelaide site contained extensive periods of missing data, lasting from three days in one campaign, to four days in the other (Fig. 8). The FFT requires the data to be uniformly sampled, or else the program would close up the holes and concatenate the time-series and the sinusoids contained therein. Additionally, if we simply used the data until the point at which the gaps appeared, we would be comparing only a small bit of data against a climatological monthly average, leaving an invitation for strong biases in the comparison.
Davis, LTCS10 campaign:

The meridional component of the tides during the LTCS10 campaign are shown in Figure 12. The zonal is located in Figure 13. A noticeable discrepancy between the Davis MF data and the model reveals itself in analysis of the meridional and zonal, semi- and diurnal, amplitudes and phases. The meridional semidiurnal amplitude recorded by the radar is fairly consistent with height, while the GSWM shows a large increase with height in the amplitude. These are quite different from the comparison based on the more equatorial Christmas Island data. The GSWM’s meridional semidiurnal phase, although imitating the correct trend and rate of change with height, appears to be exactly six hours too late. As for the meridional diurnal amplitude, the model’s prediction falls mostly within the radar’s range of error, as does the meridional diurnal phase. Again, this differs greatly from the agreement between the model and radar data during the Christmas Island campaigns.

The zonal semidiurnal amplitude predicted by the model increases far more rapidly with height as compared to the MF radar data. The zonal semidiurnal phase, as recorded by the radar, closely follows the model’s prediction. The same follows for the zonal diurnal amplitude. However, the zonal diurnal phase differs from the model at heights above about 94 km.

In the case of these measurements, the diurnal and semidiurnal tides alone poorly represented the data as shown in the reconstruction (Fig. 14). Upon further examination of the frequency spectra (Fig. 15), we found a 10.5 hour wave comprising a significant portion of the data and used this, instead of the minuscule diurnal tide, in reconstructing the time-series. In this manner, we found a 10.5 hour fluctuation, which we suspected to be an oscillation similar to that detected by Hernandez (1992) at Amundsen-Scott Station (78°S, 167°E) during the period 1 August 1991 to 25 August 1991. However, upon closer examination, this fluctuation does not appear to be a tide.

Discussion

As previously mentioned, a tide is a global-scale oscillation in air pressure, density, temperature, and velocity. When drawing comparisons between winds alone only “pieces” of the tide are the basis for comparisons between the data and the GSWM. Each piece can easily be considered independent of the other, with no correlation at all between the components. Fortunately, the task of making the comparisons is not this simple. If it were, this topic would be boring and unchallenging. In fact, there is a theoretical relationship between the tidal behavior of the zonal and meridional wind components. The phase of one leads the other in the presence of a tide.

Additionally, we cannot be certain that the observed fluctuations are the actual tides themselves. We need evidence that proves that a relationship between temperature and wind exists. We also need knowledge of the global behavior of the variations in order to confirm that these are indeed tides. Unfortunately, this information is not available in our data.

Another important point is that the model is climatological. This implies that the tides will not change yearly, and that the water vapor will not fluctuate too much during
the three months over which it is collectively computed. As you can see, this might serve as a problem, especially when the tidal amplitude and phase can vary within even two years.

Some other points to consider are: 1) the model simulates tides for each month, but the data was for only eight days in one case and ten days in another. 2) the model does not try to compute the local, non-planetary interferences. Each of these points may contribute to the differences between the model and the radar measurements, but for now all explanations are merely speculative.

**Concluding Remarks**

Overall, GSWM appears adept at simulating both the meridional and zonal semidiurnal amplitude and phase components at Christmas Island. However, there exists a discrepancy between the actual MF radar data and the GSWM prediction for the meridional diurnal amplitude and phase over Christmas Island. For the most part, the radar and the model were reasonably in agreement regarding the zonal semidiurnal components. Conversely, inconsistencies between the two campaigns exist for the zonal diurnal amplitudes. The zonal diurnal phases appear to have similar trends, and are consistent in both campaigns. Despite the trends being similar, however, the model predicts them both to occur earlier than they actually do.

From the Davis site, the radar data closely fell within the range of error for both components of the meridional diurnal tide. However, the data and the model differ in their meridional diurnal components, not the semidiurnal components as seen at Christmas Island. As for the zonal semidiurnal components, the amplitude growth seems not to be as steep as the model predicts, while the phase appears to be right on track. The opposite appears to be true in the diurnal tide, however, with the amplitude being close to predicted by the GSWM, while even the phase's trend differs from the model's prediction.

Again, modeling these tides is important in many ways. For one, if we can model the tides well, it indicates that we understand the tides to a large degree. If we understand the tides, we understand the MLT. A global MLT monitoring system is needed to confirm that the measurements are indeed global in scale, as opposed to local oscillations. Additionally, this monitoring system would make evaluations of global-scale models many times more accurate. All of this comes to mind without even mentioning that the atmospheric regions are coupled by these tides. Next time you're washing your clothes, remember the atmospheric TIDE.

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Works Cited


Figure Captions

Figure 1: Tidal heating as a function of (a) height, (b) latitude, (c) time [from (Forbes, 1995)].

Figure 2: Diagram of the average temperature profile with height over the middle latitudes [from (Iribarne, 1977)].

Figure 3: GSWM migrating diurnal tidal amplitude during July for the (a) eastward (zonal) wind amplitudes, (b) northward (meridional) wind, (c) temperature, and (d) vertical velocity.

Figure 4: Map of the radar sites.

Figure 5: Meridional wind amplitude over Christmas Island in a time-series during 29 July 1994 - 7 Aug 1994.

Figure 6: Same as 5, except for Adelaide. Note the gaps in the data.

Figure 7: Frequency spectra for Christmas Island during 29 July 1994 - 7 August 1994 at 90 km.

Figure 8: Profiles of GSWM results as compared to the radar data over Christmas Island during 29 July 1994 - 7 August 1994. Meridional component only.

Figure 9: Same as 8, except for zonal wind.

Figure 10: Same as 8, except for during 30 July 1992 - 6 August 1992.

Figure 11: Same as 9, except for during 30 July 1992 - 6 August 1992.

Figure 12: Same as 8, except for Davis.

Figure 13: Same as 9, except for Davis.

Figure 14: Mea, dirunal, and semidiurnal fits with zonal wind radar data over Davis during 29 July 1994 - 7 August 1994. Note how poorly the reconstruction fits the measurements.

Figure 15: Same as 14, except the reconstruction was made with the 10.5 hour wave replacing the diurnal tide.
Fig. 11. Schematic of (a) vertical (left), (b) latitudinal (top), and (c) diurnal (bottom) variations in tidal heating.
GWM Migrating Diurnal Tide during July
Meridional Semidiurnal Amplitude

Meridional Semidiurnal Phase

Meridional Diurnal Amplitude

Meridional Diurnal Phase

Meridional Mean Amplitude

Davis  July 29, 1994 – August 7, 1994
Zonal Semidiurnal Amplitude

Zonal Diurnal Amplitude

Zonal Mean Amplitude

Zonal Semidiurnal Phase

Zonal Diurnal Phase

Davis July 29, 1994 – August 7, 1994
T=12.24: altitude = 78

T=12.24: altitude = 80

T=12.24: altitude = 82

T=12.24: altitude = 84

T=12.24: altitude = 86

T=12.24: altitude = 88

T=12.24: altitude = 90

T=12.24: altitude = 92

T=12.24: altitude = 94

T=12.24: altitude = 96

T=12.24: altitude = 98

Measurements made at Denis
Appendix I:

Time Series for the Meridional and Zonal Wind Components

Adelaide (LTCS8, LTCS10)
Christmas Island (LTCS8, LTCS10)
Davis (LTCS10)
Appendix II:

Frequency Spectra of the Meridional Wind Components at Selected Heights

Christmas Island (LTCS8)
Davis (LTCS10)
Appendix III:

Frequency Spectra of the Zonal Wind Components at Selected Heights

Christmas Island (LTCS8)
Davis (LTCS10)
Appendix IV:

Fourier Reconstructions Made Using the Diurnal and Semidiurnal Tidal Components

Christmas Island (LTCS8, LTCS10)
T=24,12: altitude = 70

T=24,12: altitude = 72

T=24,12: altitude = 74

T=24,12: altitude = 76

T=24,12: altitude = 78

T=24,12: altitude = 80

T=24,12: altitude = 82

T=24,12: altitude = 84

T=24,12: altitude = 86

T=24,12: altitude = 88

T=24,12: altitude = 90

T=24,12: altitude = 92

T=24,12: altitude = 94

T=24,12: altitude = 96

T=24,12: altitude = 98

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