Global observations of thermospheric lunar tidal winds

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Abstract

We present direct observations of the semidiurnal lunar tide zonal winds at 250 km and 350 km during low solar activity in 2007-2008, and 2010-2011. The migrating semidiurnal lunar tide, or M_2 , is a global feature with amplitudes of about 10 m s^{-1} at equatorial latitudes, and 20 m s^{-1} at high latitudes. Amplitude maxima appear twice yearly, between February and April and between August and November. M_2 amplitudes during 2007-2008 are about 50% stronger than those during 2010-2011. These magnitudes are consistent with numerical predictions in WACCM-X. However, only one annual global-scale maximum is simulated during January–March.

Keywords: tide, semidiurnal, thermosphere, lunar

1. Introduction

Atmospheric lunar tides are global-scale oscillations driven by the gravitational force exerted by the moon (Chapman and Lindzen, 1970), and by tidally-induced vertical motions of the ocean and solid earth (Vial and Forbes, 1994). Variations in the moon's orbit, along with the motion of the earth relative to the

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moon give rise to a spectrum of lunital frequencies (Siebert, 1961). The most significant of these is the M_2 lunar semidiurnal tide, with a zonal wavenumber of 2, and a period of 12.42 solar hours, or one half of a lunar day. Dynamically speaking, lunar tides are global scale, vertically propagating inertia-gravity waves whose amplitudes increase with altitude up to about 10 m s^{-1} at meteor heights. The predicted vertical wavelength of the classical main M_2 mode is about 100 km (Chapman and Lindzen, 1970).

Interest in the lunar tides has intensified in recent years owing to their apparent role in linking sudden stratospheric warming events (SSW) to ionospheric variability. Several studies have associated SSW with enhanced lunar variability in the equatorial electrojet and vertical plasma drifts (Fejer et al., 2010, 2011), and in the geomagnetic field (Yamazaki et al., 2012). Pedatella et al. (2012) reported global lunar tide amplification of 50-60% in the NCAR Whole Atmosphere Community Climate Model (WACCM) during SSW simulations. Forbes and Zhang (2012) observed lunar tidal enhancements in the mesosphere and thermosphere during January 2009, when significant SSW occurred. Using the Global Scale Wave Model (GSWM), they showed that with zonal mean winds and temperatures attending SSW, a normal mode appears at 12.43 hours that would enhance the M_2 12.42-hour response.

Because of the close proximity between lunar and solar tidal frequencies, and the weaker amplitudes of the lunar tides, isolating M_2 in data presents a challenge. Very long records of ground-based observations are required in order to effectively resolve lunar and solar tides. M_2 winds have been inferred from mesospheric radar measurements spanning intervals ranging from 10–20 years (Stening et al., 1987; Stening and Vincent, 1989; Stening and Jacobi, 2001; Sandford et al., 2006; Niu et al., 2007). M_2 wind amplitudes maximize near 10 m s^{-1} in the lower thermosphere. Observed vertical wavelengths ranged between 17 and 80 km.

The separation between solar and lunar tidal periods becomes more pronounced when these phenomena are observed from a satellite frame of reference (Forbes et al., 2013). A wave with zonal wavenumber m and frequency σ (in

radians per day) with respect to the Earth is viewed from a low Earth orbiting satellite as an oscillation with an aliased frequency

$$k_s = \frac{|c_0| m - \sigma}{\sqrt{1 + c_0^2}} \quad (1)$$

(Salby, 1982). c_0 is the rate at which observations drift around a latitude circle, and is -2π radians day⁻¹ for satellites in a sun-synchronous orbit. When viewed from this platform, the migrating solar semidiurnal tide with $m = 2$ and a period of 12 hours (.5 days) registers as an invariant feature ($k_s = 0$), while the lunar semidiurnal tide (with $m = 2$ and a period of 12.42 hours) will have an apparent period of roughly 15 days ($k_s = 0.067$). Thus, polar- and low-orbiting satellite data are particularly well-suited to the study of global lunar tides. Forbes et al. (2013) exploited these properties to document lunar tides in mesospheric and lower thermospheric temperatures, and in thermospheric densities during the solar minimum period of 2007–2010. Zhang and Forbes (2013) examined M_2 winds between 80–100 km from the UARS High Resolution Doppler imager (HRDI).

Thermospheric winds play an important role in ionosphere-thermosphere coupling, through dynamo generation and transport of plasma along magnetic field lines. Motivated by the apparent significance of the lunar tide for stratosphere-ionosphere coupling, the purpose of this paper is to document the contribution of M_2 to thermospheric zonal winds. We analyze winds from the CHALLENGING Minisatellite Payload (CHAMP) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) missions during the years surrounding the 2009 solar minimum. Monthly mean M_2 behavior is presented in CHAMP and GOCE zonal winds, and compared with simulations of M_2 in the extended WACCM model, or WACCM-X. Our findings indicate that M_2 is a climatological feature of the thermospheric wind near solar minimum, that exhibits interannual variability and possible sensitivity to the background wind.

2. Data and Analysis

2.1. CHAMP

CHAMP was a 10-year mission managed by the GeoForschungsZentrum (GFZ) in Germany. The primary mission goals were mapping of Earth's magnetic and gravity fields, and the collection of refraction data for characterizing the troposphere and the ionosphere. Although CHAMP was not designed for studies of the thermosphere, it carried a Spatial Triaxial Accelerometer for Research (STAR) that measured nongravitational forces acting on the spacecraft, among which the drag is dominant (Bruinsma et al., 2004). Cross-track winds have been derived from acceleration values by Liu et al. (2006) and Doornbos et al. (2010). This study uses the wind dataset derived by Doornbos et al. (2010), distributed at http://thermosphere.tudelft.nl/accelldrag/data.php?cat=CH_PN_R02.

CHAMP was stabilized in a circular, near-polar orbit starting at about 450 km in 2000 and descending to 265 km by September 2010. Between roughly 65°S and 65°N, CHAMP ground-relative orbit tracks are aligned north-south, implying that the crosswind orientation is east-west, or zonal. Daily measurements are fixed in local solar time, with a separation of approximately 12 hours between the ascending and descending node observations. The orbital precession of CHAMP ($c_0 \sim -6.3$ radians day⁻¹) results in 12 hours of lunar local time coverage within 13.3 days.

CHAMP winds have been computed for 2003–2008. This study utilizes winds in 2007 and 2008, the available years closest to the 2009 solar minimum (see Figure 1). Our analysis begins with the formation of daily longitudinal averages of the east-west crosswind, binned in latitude and segregated by ascending and descending parts of the orbit. We follow the strategy described by Forbes et al. (2013), which is based on the property that according to (1), M_2 is viewed by CHAMP as an oscillation of the zonal mean zonal wind ($\overline{U}$) with a period of roughly 13.3 days. It is important to bear in mind that the M_2 tide is considerably weaker than the time-mean and the solar migrating tidal winds, which are also represented in the daily longitudinal averages (Lieberman et al.,

2013). We therefore filter these components by subtracting 14-day averages of the zonal mean zonal wind from each daily value. The “residual” zonal mean zonal winds, denoted $\overline{U}_{res}$, are binned in lunar local time, and composited over 54-day blocks in order to average over 18–24 hours of local solar time. At each latitude, a 12-hour harmonic (M_2) is fit to the lunar local time composites.

2.2. GOCE

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) was a European Space Agency (ESA) satellite intended to map the Earth’s gravity field in unprecedented detail. The mission commenced on March 17, 2009 and ended November 11, 2013 when the spacecraft re-entered Earth’s atmosphere. We examined M_2 GOCE winds between November 2009–July 2011, when solar flux conditions were fairly similar to the CHAMP data analysis period. (See Figure 1.) Data are distributed at <https://earth.esa.int/web/guest/missions/esa-operational-missions/goce/goce-thermospheric-data>

The primary onboard instrumentation was a highly sensitive gravity gradiometer consisting of three pairs of accelerometers which measured gravitational gradients along three orthogonal axes. To gain the best possible measurements, the satellite was stabilized in an extremely low orbit (255 km above Earth), where it was subjected to air drag. This drag was compensated by an electric ion engine that generated carefully calculated thrust. Accelerometer and thrust activation data were used to detect the aerodynamic force on the satellite. Cross-winds and density were determined by iterating wind and density inputs to an aerodynamic model of the satellite, until the modeled aerodynamic accelerations matched the observations (Doornbos et al., 2013).

GOCE was launched in a nearly sun-synchronous orbit, with equatorial local time crossings of 18.0 (6.0) LST on the ascending (descending) portions of the orbit. (Over the lifetime of the mission, these crossing times increased by one hour and 36 minutes.) However, the lunar local time precessed by approximately 52 minutes per day, tracing out a full 12-hour cycle over a 15-day period. The analysis of GOCE data was therefore very similar to the CHAMP data. Daily

longitudinal averages of the east-west crosswind are formed, binned in latitude and segregated by ascending and descending parts of the orbit. A 15-day average of the zonal mean zonal wind is then subtracted from each daily value, to form residuals filtered of time-mean and migrating solar tidal components. Residual winds are then binned in lunar local time. To facilitate comparison with CHAMP M_2 winds, we composite GOCE winds in lunar local time bins over 54-day blocks. This averaging was undertaken for CHAMP in order to span 24 hours of local solar time; however, GOCE local times do not change significantly over this interval. At each latitude, a 12-hour harmonic is then fit to the GOCE lunar local time wind composites.

2.3. Numerical models

The observations of M_2 in thermospheric zonal wind are compared with simulations of M_2 in WACCM-X. WACCM-X extends from the surface to the upper thermosphere (2.5×10^{-9} hPa), and includes the dynamical, chemical, and physical processes that are necessary to simulate the troposphere, stratosphere, mesosphere, and thermosphere. A detailed description of WACCM-X is provided by Liu et al. (2010), and is not repeated herein. The model horizontal resolution is 1.9° in latitude and 2.5° in longitude. The vertical resolution ranges from ~ 1.5 km in the troposphere to a half scale height in the upper thermosphere. The simulations are performed under constant solar minimum ($F_{10.7} = 70$), and quiet geomagnetic conditions. The M_2 lunar tide forcing is added to WACCM-X using the approach outlined by Pedatella et al. (2012).

For the present study, we have performed a one-year WACCM-X simulation. The simulation is free-running, and thus not representative of any particular time period. We note that since we only consider a one-year WACCM-X simulation, the comparison between the simulated M_2 and that observed by CHAMP and GOCE may be impacted by interannual variability.

To understand how recurrent geomagnetic activity may alias into the observations of M_2 , we have performed additional simulations using the National Center for Atmospheric Research Thermosphere-Ionosphere-Electrodynamics Gen-

eral Circulation Model (TIE-GCM). TIE-GCM is a first principles model of the ionosphere and thermosphere, including self-consistent electrodynamics (Richmond et al., 1992). The TIE-GCM altitude domain is from ~ 97 km to 400–700 km, with the upper boundary altitude depending on solar activity conditions due to the use of a pressure coordinate system. The TIE-GCM simulations are performed with a horizontal resolution of 5° in latitude and longitude, and a vertical resolution of two points per scale height. The impact of geomagnetic activity on thermosphere zonal winds is simulated for 2007–2008 by imposing the Weimer (2005) electric potential model at high latitudes in the TIE-GCM. Realistic variability of the F10.7 cm solar flux is also included in the TIE-GCM simulations. Migrating diurnal and semidiurnal tides are specified at the model lower boundary using the climatological Global Scale Wave Model (Hagan and Forbes, 2002, 2003). Lunar tides are not included in the TIE-GCM simulations, and any variability at lunar periods can therefore be attributed to aliasing that results from periodic geomagnetic variability.

3. Global structure of M_2

We begin by examining the evolution of $\overline{U}_{res}$ in lunar local time. This behavior is shown in Figure 2, derived from CHAMP measurements during April 2007 and 2008. The M_2 fits are juxtaposed upon $\overline{U}_{res}$ as dotted curves. The error bars shown indicate the sensitivity of $\overline{U}_{res}$ to the CHAMP measurement uncertainty, and average about 6.3 m s^{-1} . This quantity was computed by iterating the analysis method 300 times upon a prescribed combination of time-mean, solar tidal, and M_2 lunar tidal wind fields, perturbed by random fluctuations scaled by CHAMP’s measurement uncertainty of 140 m s^{-1} . The error bars connect the values of $\overline{U}_{res} \pm$ one standard deviation. The M_2 oscillation is clearly evident in many of the extratropical time traces, and is the dominant feature at 40°S , 20°S and 80°N . The uncertainty of the M_2 amplitude to the analysis method (not plotted) is about 4 m s^{-1} .

Monthly amplitudes and phases of CHAMP M_2 are plotted in Figure 3.

These determinations were made with winds from 2007–2008. Amplitudes are global in extent, and maximize during equinoxes. During the autumnal equinox a maximum of 15 m s^{-1} is centered about the equator, while the maximum of 12 m s^{-1} at vernal equinox is shifted toward the southern hemisphere. During these periods of maxima, the phase of M_2 is fairly uniform in latitude, with values between 7–8 hours. Additional maxima appear at the highest latitudes: 20 m s^{-1} in April in the southern hemisphere, and 15 m s^{-1} in the northern hemisphere. The maxima in the high southern latitudes are attended by a phase between 9–10 hours. These high-latitude phenomena will be discussed in connection to Figure 6.

Figure 4 shows monthly amplitudes and phases of M_2 derived from GOCE winds between November 2009–August 2011. While the method of analysis is identical to that used for CHAMP, we reiterate that GOCE measurements are virtually sun-synchronous, and therefore (unlike CHAMP) only two local times are represented in the processing of GOCE winds. As in the case of CHAMP M_2 , amplitudes have a global extent with twice-yearly maxima. Amplitudes are somewhat weaker than CHAMP M_2 , maximizing at 11 m s^{-1} . The first maximum of the year is centered on the equator, and occurs between January and March, compared to April as seen in CHAMP, while the fall GOCE maximum is shifted to October. An additional localized maximum is seen in July at the northern polar latitudes. Phase values range between 6–7 hours. When M_2 amplitudes are strong, which is about 1 hour earlier than seen in CHAMP M_2 .

Figure 5 is the WACCM-X counterpart to Figure 3. The figure is obtained by evaluating the time-mean wind, migrating solar diurnal and semidiurnal tides, and M_2 in WACCM at 350 km at CHAMP coordinates, and then processing the pseudo-data identically to the CHAMP values, as described in section 2.1. Some similarities can be discerned among M_2 in WACCM-X and CHAMP M_2 . WACCM-X M_2 exhibits global structure, with maximum values of 10 m s^{-1} that extend from January–March. The hour of maximum lies between 8 and 9 hours, about one hour later than in CHAMP. However, a number of differences between M_2 in CHAMP and WACCM-X are observed, including 1. The primary

WACCM-X maxima, centered in February, are located near 50°N and 50°S, as opposed to the equator as seen in CHAMP. 2. WACCM-X M₂ exhibits a localized autumnal equinox maximum in the high-latitude northern hemisphere, whereas in CHAMP the maxima are centered on the equator, and in the high-latitude southern hemisphere. 3. The global maximum in WACCM-X spanning January-February-March is actually initiated in the southern hemisphere in December.

WACCM-X M₂ winds at 260 km (not shown) are virtually identical to those at 350 km. We therefore also compare M₂ in GOCE (Figure 2) with Figure 4. The two fields are similar insofar as both show global-scale structure between January and March. However, GOCE shows a stronger maximum over the equator, and its phase precedes WACCM-X phases by about 2 hours. A maximum observed in GOCE winds in July in the northern hemisphere does not appear in WACCM-X. GOCE also exhibits a global-scale maximum in October, in contrast to the localized maximum in WACCM-X that is centered on 50°N.

4. Discussion

The thermospheric M₂ tide in the zonal wind has been examined in CHAMP and GOCE data during conditions of relatively low solar activity. The global structure and magnitude of latitude versus month composites of M₂ are qualitatively similar in the two datasets. The most prominent features are low latitude M₂ amplitude maxima between 10–15 m s⁻¹ that occur twice yearly. Differences occur between the two datasets in the latitudes and timing of these maxima, and the hour of maximum in GOCE occurs about an hour earlier than in CHAMP data. In comparison, M₂ in WACCM-X exhibits only one global-scale maximum per year, occurring between January–March.

To explore the differences among the data and the model, we consider the possible influence of a 13.5-day oscillation in the K_p geomagnetic index upon $\overline{U}_{res}$, and M₂. High-speed solar wind streams from low-latitude coronal holes induce solar and geomagnetic activity at the solar rotational period (27 days)

and its subharmonics, including 13.5 days (Ram et al., 2012; Zhang et al., 2014). The 13.5-day period is close to the 13.3-day period at which M_2 is viewed by CHAMP, and the 14.7-day period that GOCE sampling associates with M_2 . Because thermospheric winds and density are sensitive to short-term geomagnetic variations (Zhang et al., 2014), we therefore attempted to quantify the leakage of a 13.5-day variation in $\overline{U}_{res}$ into M_2 .

To compute the effects of periodic geomagnetic activity on thermospheric winds, the NCAR TIE-GCM was run for 2 2-year periods (2007-2008 and 2010-2011) with realistic geomagnetic forcing, but without lunartidal forcing. Hourly model output fields were then sampled over the 2007-2008 (2010-2011) period at CHAMP (GOCE) coordinates and processed for M_2 as described in sections 2.1 and 2.1. Figure 6 presents non-lunar variability at the M_2 period in TIE-GCM (presumably due to geomagnetic sources) sampled by CHAMP. These effects are negligible at equatorial latitudes and most significant at high latitudes. Comparing Figures 3 and 6 we speculate that the K_p effect upon $\overline{U}_{res}$ may account for the high CHAMP M_2 values observed at northern hemisphere polar latitudes during February–May, and poleward of 50°S between January and April. The transition to higher values of M_2 near 40°S during vernal equinox may account for some of the asymmetry about the equator of the CHAMP equinox (March–April) maximum.

Figure 7 is the GOCE counterpart to Figure 6. As in the case of CHAMP, the effects of geomagnetic forcing upon M_2 are negligible between 40°S–40°N, and quite significant at polar latitudes, particularly in the northern hemisphere. Comparing Figures 7 and 4 suggests that aliasing of the geomagnetic-related $\overline{U}_{res}$ activity could account in part for the high-latitude extensions of GOCE M_2 during October.

The M_2 features observed in Figures 3, 4 and 5 have been influenced in part by the background conditions between the surface and the altitudes of GOCE (~ 250) and CHAMP (~ 350 km). The monthly evolution of WACCM-X $\overline{U}$, at 70 km is quite consistent overall with balanced $\overline{U}$ computed from TIMED SABER geopotential (Figure 8, left). At 100 km, WACCM-X and TIMED TIDI

$\overline{U}$ show qualitative agreement. An annual cycle appears in both datasets, with westward (eastward) $\overline{U}$ in the winter (summer) hemisphere. However, TIDI $\overline{U}$ shows this behavior only poleward of 20° , with time-mean westward $\overline{U}$ between 20°S – 20°N .

Figure 9 compares CHAMP and WACCM-X $\overline{U}$. (Time mean winds for GOCE cannot be determined due to undersampling in local time.) At low latitudes, CHAMP $\overline{U}$ is quite weak and little seasonal variation can be discerned. The most prominent feature is an annual variation away from the tropics, characterized by westward winds in the summer hemisphere and eastward winds in the winter hemisphere. Eastward winds peak at 30 m s^{-1} , while westward winds are stronger, maximizing at -70 m s^{-1} . WACCM-X $\overline{U}$ differs in many ways from CHAMP. The annual cycle is very weak, and winds are predominantly eastward, except at very high latitudes where weak westward winds are found. The strongest M_2 amplitudes are observed during periods of light winds ($|\overline{U}| \leq 10$) at 350 km. In the case of CHAMP M_2 , this juxtaposition is seen between 40°S – 30°N during vernal and autumnal equinox. In WACCM-X, light winds coincide with high M_2 at non-equatorial latitudes during January–March, in the high-latitude southern hemisphere in December, and poleward of 40°N .

5. Summary

This investigation was motivated by empirical studies that identify lunar tides as agents of stratosphere-ionosphere-thermosphere coupling. The monthly M_2 lunar tide in thermospheric zonal winds has been examined in CHAMP and GOCE data, and in WACCM-X during conditions of relatively low solar activity. The M_2 oscillation as seen in CHAMP and GOCE winds is global-scale, characterized by two separate centers of action. One of these consists of strong-amplitude features at very high latitudes, that may in part reflect spurious, non-tidal $\overline{U}_{res}$ oscillations due to geomagnetic activity at a 13.5 day subharmonic of the solar rotation. We also identify robust, low- and mid-latitude cells of M_2 with peak amplitudes ranging between 10 – 15 m s^{-1} . At 350 km (CHAMP),

these features maximize at equinox, while at 250 km (GOCE), the equinox maxima are shifted one month closer to the winter season (e. g., from March to February, and from September to October). These differences might be due to GOCE and CHAMP observing different years. Moreover, unlike CHAMP, GOCE M_2 calculations are not averaged over all local solar times.

M_2 observations were compared to predictions in WACCM-X. Amplitudes are comparable with CHAMP and GOCE, but the model exhibits only one global-scale maximum per year, occurring between January–March. While differences between CHAMP, GOCE and WACCM-X M_2 cannot be fully explained at the present time, one possible source may lie in the differences in the thermospheric zonal mean zonal wind structure. We conclude that M_2 is a climatological feature of the thermospheric wind system, with the potential to modulate transport of plasma along magnetic field lines.

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64
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Figure 1: 10.7 cm solar radio flux ($F_{10.7}$ spanning 2000–2013. Dots are daily values, solid lines are monthly mean values. Thin vertical lines bracket the intervals of CHAMP (blue) and GOCE (red) sampling.

Figure 2: Solid curves are CHAMP $\overline{U}_{res}$ plotted as a function of lunar local time in April at (a) 60°S, (b) 40°S, (c) 20°S, (d) equator, (e) 20°N, (f) 40°N, (g) 60°N and (h) 80°N. Dotted curves are M₂ fits. This vertical lines are the $\overline{U}_{res}$ values $\pm$ one standard deviation.

Figure 3: M_2 amplitude (top) and phase (bottom) as a function of latitude and month. Values are derived from CHAMP $\overline{U}_{res}$ values spanning 2006–2008. Contour interval is 1 m s^{-1} (top) and 1 hour (bottom).

Figure 4: M_2 amplitude (top) and phase (bottom) as a function of latitude and month. Values are derived from GOCE $\overline{U}_{res}$ values spanning November 2009–August 2011. Contour interval is 1 m s^{-1} (top) and 1 hour (bottom).

Figure 5: As in Figure 3, using WACCM-X values.

Figure 6: As in Figure 3, using values from the TIE-GCM. Contour values are 0–10, 15, 20, 25, and 30.

Figure 7: As in Figure 4, using values from the TIE-GCM during November 2009–August 2011. Contour values are 0–10, 15, 20, 25, and 30.

Figure 8: Left: Monthly mean $\bar{U}$ at 70 km in WACCM-X (top) and computed from SABER (bottom). Right: Monthly mean $\bar{U}$ at 100 km in WACCM-X (top) and TIDI (bottom).

Figure 9: Monthly mean $\overline{U}$ in CHAMP (top) and WACCM-X (bottom) at 350 km.