Lunar tide contribution to thermosphere weather

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Abstract As the utilization of low-Earth orbit increases, so does the need for improved ephemeris predictions and thus more accurate density models. In this paper we quantify the density variability of the thermosphere attributable to the lunar gravitational tide, a potentially predictable component of variability not included in any operational density prediction models to date. Using accelerometer measurements from the GOCE satellite near 260 km altitude, the level of lunar tidal density variability is shown to be about half that associated with the low level of geomagnetic variability that occurs about 75% of the time (Kp ≤ 3), thus constituting an element of “space weather.” Our conclusion is that the lunar tide ought to be considered for inclusion in contemporary density models of the thermosphere for operational ephemeris predictions. Some suggested first steps are included in the conclusions of this paper.

1. Introduction

According to NASA web sites on orbital debris, there are approximately 500,000 objects of various sizes orbiting our planet, most of them inactive debris and many in low-Earth orbit (< 1000 km) where atmospheric drag exerts its influence. About 20,000 of these objects are large enough to be tracked. As the number of objects continues to increase and human activity in space expands, accuracy requirements for orbital prediction and collision avoidance are expected to become increasingly stringent. This translates directly to increased requirements on the accuracy of density prediction.

A variety of empirical density models have been developed over the past 50 years that capture the salient features of seasonal-latitudinal, local time, solar, and geomagnetic variability of thermosphere density. Efforts are just beginning within the community to develop physics-based models that assimilate real-time data to enable thermosphere weather prediction in much the same way that weather is predicted near Earth’s surface. However, at present the predictive capabilities of such models are inherently limited due to our current inability to accurately predict the solar and geomagnetic conditions that drive density variability in the thermosphere. In this paper we quantify the thermosphere density variability due to a source that has not yet been included in any density prediction models to date, the lunar gravitational tide. We demonstrate that the lunar tide is sufficiently large to warrant inclusion in either empirical or first-principles density models, especially since the lunar tide is to some degree predictable. We also demonstrate that the lunar tide contains a degree of variability and thus constitutes an element of “space weather.” This variability serves to challenge first-principles models on the one hand and on the other sets limits on the potential accuracy of predictions from empirical models based on climatology.

The study of atmospheric lunar tides has a long history, much of which is reviewed in Chapman and Lindzen [1970]. Prior to the satellite era, observations of the lunar atmospheric tide were predominantly made from the ground. Since the period of the main lunar tidal component as observed from the ground (M₂, 12.42 h) is close to that of the solar semidiurnal tide (S₂, 12.00 h) and its amplitude is small in comparison to S₂ as well as other geophysical variability, relatively long data sets were required to extract the lunar tide. The types of data that were typically available were surface pressure [e.g., Haurwitz and Cowley, 1969], ionosonde measurements of the ionosphere [e.g., Matsushita, 1967b], and ground magnetometer measurements that revealed the lunar variations in ionospheric currents [e.g., Matsushita, 1967a, Bartels and Johnston, 1940].

According to theory [e.g., Lindzen and Hong, 1974], lunar tidal oscillations ought to increase with height until attenuated by molecular dissipation around 100–150 km; penetration to higher altitudes continues with somewhat less but still appreciable amplitudes. Ground-based radars have taken advantage of this increase with altitude and have been used to reveal the lunar tide around 90–100 km [e.g., Stening...
et al., 1997] at a few locations around the globe. However, only recently have satellite measurements been used to delineate the lunar tide on a global scale. Zhang and Forbes [2013] used High-Resolution Doppler Imager wind measurements from the Upper Atmosphere Research Satellite to examine the lunar tide between 80 and 100 km and made comparisons with the most recent model simulations [Forbes et al., 2013]. Good agreement with global scale wave model (GSWM) phases was obtained, but the model overestimated the observed lunar tidal amplitudes by about 30%. In the Forbes et al. [2013] study, mean lunar tides were extracted from SABER temperatures between 80 and 110 km, from CHAMP satellite accelerometer measurements of density near 500 km, and from GRACE satellite accelerometer measurements of density near 500 km. The retrieved lunar tidal signatures are between ±60° latitude and averaged over the solar minimum period 2008–2010 as a function of month. These results revealed lunar tidal amplitudes of order 5–10 K for temperature and 10–15 m/s for both zonal and meridional winds in the lower thermosphere and of order 5–10% at orbital altitudes, enough to impose nonnegligible day-to-day variability on the IT system. The Forbes et al. [2013] study occurs amidst a resurgence in interest in the lunar atmospheric tide [e.g., Lühr et al., 2012; Paulino et al., 2013; Pedatella et al., 2012b], particularly as a vehicle for imprinting the variability associated with sudden stratospheric warnings (SSWs) at high latitudes during Northern Hemisphere winter on the low-latitude ionosphere [e.g., Fejer et al., 2010, 2011; Pedatella et al., 2012a; Stening, 2011; Yamazaki et al., 2012]. It appears that the changes in middle atmosphere circulation accompanying the SSWs facilitate propagation of the lunar tide to the thermosphere, perhaps as a result of changing the resonance properties of the atmosphere [Forbes and Zhang, 2012]. Changes in lower thermosphere lunar tidal temperatures and upper thermosphere lunar tidal densities are observed to be of order 20–30 K and 15–20%, respectively [Forbes and Zhang, 2012], during such events. Thus, it appears that the lunar semidiurnal tide has now assumed a role as a significant contributor to both ionosphere and thermosphere “space weather.”

There is an interplay between variability due to the lunar tide and variability associated with geomagnetic disturbances that makes isolation of the lunar tide difficult. As shown by Forbes and Zhang [2012] and Park et al. [2012], the periodicity of the M2 lunar tide from the perspectives of the CHAMP and GRACE orbits is close to 13.5 days, due to local time precession of the orbital planes. This 13.5 day periodicity can at times coincide with that of recurrent geomagnetic activity at Earth, which is related to the distribution of coronal holes on the rotating Sun and the high-speed solar wind streams emanating from them [Tsurutani et al., 1995b; Mursula and Zieger, 1996; Lei et al., 2008; Tulasi Ram et al., 2010]. Recurrent geomagnetic activity tends to occur predominantly in the declining phase of any given solar cycle [Tsurutani et al., 1995a]. The same periodicity can also often be found in solar flux indices such as the 10.7 cm solar radio flux [Donnelly and Puga, 1990]. Forbes et al. [2013] managed this problem by focusing on solar minimum years, where these effects are smaller, and also by taking advantage of the fact that the 13.5 day variations of lunar and geomagnetic origin are not phase coherent; by performing multiyear binning in lunar time, the geomagnetic contributions average out and a clear lunar signal emerges. However, when we attempted to isolate the lunar signal in the time domain, it was virtually impossible to unambiguously separate these two 13.5 day variations, except during periods such as sudden stratospheric warnings when the lunar tide was unusually amplified [Forbes and Zhang, 2012] or during a few periods of exceptionally quiet or easily identified geomagnetic variations.

In this paper we bring a new data set to bear on the lunar tidal problem provided by accelerometer measurements on the GOCE (Gravity and Steady-State Ocean Circulation Explorer) satellite. GOCE is in a near-circular Sun-synchronous (dawn/dusk) orbit near 260 km. Its measurements of densities and winds (see section 2 for details) provide a “middle thermosphere” perspective on upward propagating waves from lower altitudes, complementing extensive measurements by the TIMED spacecraft below 110 km and by the CHAMP and GRACE satellites in the 350–550 km height region. Figure 1 provides motivation for the current study in the context of the GOCE density measurements. Shown are samples of longitude-averaged percent residuals from 15 day running mean densities at each latitude. This suppresses variability at time scales greater than about 15 days. The examples shown are for two 60 day intervals, one covering April–May 2010 and the other for January–March, 2012. The solid line indicates the latitude-averaged residuals, the red dots depict the residuals of the daily mean Kp from its 15 day running mean, and the black dotted curve is a 14.77 day sinusoidal oscillation, i.e., the lunar tide periodicity as seen from the GOCE orbit. We note first of all that the density fluctuations can be quite large on the order of 20–30%. In addition, there are visible correlations between the density fluctuations in both Kp and the lunar tide. In particular, during May 2010 the lunar tide and Kp variations are visibly correlated with each other. These results raise several questions:
To what degree do the lunar tide and geomagnetic activity account for the density variability displayed in Figure 1, and what is the relative importance of each? Can the lunar tide and geomagnetic activity variations be effectively separated? And, might there be a variation in \( Kp \) that can be physically attributed to the lunar tide? We seek to answer these questions in the present paper. Our method of data analysis in support of this goal is described in the following section, while results are provided in section 3.

2. Data and Method of Analysis

2.1. Thermosphere Density and Neutral Wind Measured by GOCE

The data employed in this study consist of thermosphere neutral densities and cross-track winds from GOCE, the Gravity Field and Steady-State Ocean Circulation Explorer \[\text{Rebhan et al., 2000}\]. GOCE was launched on 17 March 2009 and had its reentry on 11 November 2013 after 1700 days of normal operation. In order to achieve its very challenging gravity field mission objectives, GOCE was launched into a near-circular orbit at the relatively low altitude of 260 km. This altitude is interesting to thermospheric research since no other single satellite provides measurements at this altitude spanning multiple years.

GOCE thermosphere neutral density and wind speed are derived using ion thruster data combined with accelerometer and star camera data products \[\text{Doornbos, 2013, Doornbos et al., 2013a, 2013b; Bruinsma, 2013}\]. GOCE is in a 96.70° inclination Sun-synchronous dusk-dawn (≈18.6 h/6.6 h) orbit. The ascending or upleg part of the orbit is on the duskside, and the descending or downleg portion is on the duskside. Due to its high inclination, the cross-track winds are very near in the zonal direction except near the poles. The currently available GOCE data extend from November 2009 to May 2012 with some missing periods.

2.2. Method of Analysis

The purpose of this study is to demonstrate the lunar tide contribution to thermosphere weather. It is well-known that thermosphere variability is well related to the geomagnetic disturbances driven by solar wind and changes in the solar EUV radiation, which are often proxied by \( Kp \) and \( F_{10.7} \), respectively. These relationships are embodied in such empirical models as MSISE90 \[\text{Hedin, 1991}\], NRLMSISE-00 \[\text{Picone et al., 2003}\], and many predecessor models developed in the prior three decades. During different parts of a solar cycle, these two drivers can vary differently on scales ranging from days to months. Figure 2 shows the Lomb-Scargle periodograms \[\text{Lomb, 1976; Scargle, 1982}\] of \( Kp \) (top panel) and \( F_{10.7} \) (bottom panel) for 2003–2005 during the downside of solar cycle 23 (blue curves) and for 2010–2011 during the upside of solar cycle 24 (red curves). \( Kp \) is characterized by very prominent peaks near 9.0 days and 13.5 days during the downside of solar cycle 23, the expected behavior for recurrent geomagnetic activity \[\text{Tulasi Ram et al., 2010}\]. However, during the upswing of solar cycle 24, \( Kp \) is fairly quiet in terms of oscillations with periods shorter than 25 days. Figure 2 (bottom) shows that the short-term oscillations of \( F_{10.7} \) with periods under 20 days are negligible during both of the above time intervals. The GOCE data availability from November
Figure 2. Lomb-Scargle periodograms of (top) $Kp$ and (bottom) $F_{10.7}$. The blue curves denote the downside of solar cycle 23 which spanned from 2003 to 2005; the red curves denote the upside of solar cycle 24 which spanned 2010 and 2011.

2009 to May 2012 is thus optimum for minimizing the aliasing that can occur between geomagnetic and lunar variability.

During any given day, from the viewpoint of a Sun-synchronous satellite, the local times of the upleg measurements around a zonal circle are all the same, as are those for the downleg measurements. The lunar phase angle, which is the angle formed by the vectors from the center of the Earth to the Sun and the Moon, respectively, does not change much ($< 12^\circ$) either. It follows that lunar time, which can be calculated from solar local time and the lunar phase angle, is also contained within a narrow range in a zonal circle. The lunar tide we are interested in is the predominant longitude-independent migrating tide, $M_2$. Thus, the first step of our data processing is to bin the raw satellite data into $3^\circ$ latitude bins for either leg of each day and then take the zonal mean. No more than 5 of the 15 orbits of each leg can be missing, and the $\geq 10$ zonal points are interpolated into 15 evenly spaced longitude grids to ensure that the calculated (unweighted) zonal mean is free of bias. When the zonal mean is determined, all the longitude-dependent tides and planetary waves originating from the lower atmosphere are essentially removed.

A daily time series is now obtained for each bin indexed by leg and $3^\circ$ latitude interval. The 15 day running mean is then subtracted from each point centered at the 15 day window of the time series, leaving a time series of residuals that will be referred as primary residuals in this paper. The density residual at the center point is also divided by the 15 day mean and multiplied by 100 to yield the relative density as a unit of percent. Again, no more than 5 of the 15 days can be missing in the data for the 15 day running mean to be calculated and included to ensure that the background trends are consistently free of bias. From the formula detailed in Forbes et al. [2013] and Zhang and Forbes [2013], the period of the $M_2$ tidal oscillation viewed from a Sun-synchronous satellite like GOCE is 14.77 days. The $M_2$ signatures are thus absent in the 15 day running mean but remain in the residuals. On the other hand, all the long-term variations are removed in this way; these include not only geophysical variations such as the semiannual variation but also biases associated with solar radiation pressure modeling, satellite drag coefficient modeling, etc. In this second step, we only utilize data in days where the daily mean of 3-hourly $Kp$ is less or equal to 3 to avoid geomagnetically active conditions.

All that should remain in the residuals after this processing, mainly, are $Kp$- and $F_{10.7}$-related variations in addition to those due to the lunar tide. In order to better isolate the lunar tide, the $Kp$- and $F_{10.7}$-related variations are first removed. This is done in 45 day moving windows by fitting the $Kp$ and $F_{10.7}$ residuals (also obtained from 15 day running means) in a least squares sense to the residuals of relative density or cross-track wind. The $Kp$ and $F_{10.7}$ fit is then subtracted from the relative density or wind residuals to produce a set of “secondary residuals,” which should be relatively free of $Kp$ or $F_{10.7}$ variations. Next, we fit $M_2$ in
3. Results

3.1. Separation of the Lunar Tide From $Kp$ and $F_{10.7}$ Variations

We begin by illustrating some typical fits to primary and secondary residuals and providing a sense of their quality. In Figure 3, the top row corresponds to relative density at dawn and 18°S latitude on 3 September 2011, while the bottom row is for zonal wind at dusk and 24°S latitude on 18 September 2011. Figure 3 (left column) illustrates the $Kp + F_{10.7}$ fit (blue curve) to primary residuals in relative density or zonal wind (black curve). Figure 3 (middle column) illustrates the $M_2$ fit (blue curve) to the 3 day running mean secondary residuals. The correlation coefficient $R$ of each fit is labeled on the top of each panel. Figure 3 (right column) illustrates the spectra of the primary residual (black curve), the spectra of $Kp + F_{10.7}$ fit (black dotted curve), and the spectra of secondary residuals (blue curve).

In the specific case dated 3 September 2011, the relative density residuals correlate fairly well with the $Kp + F_{10.7}$ residuals. After the $Kp + F_{10.7}$ contributions are removed, the secondary residuals fit well with $M_2$ oscillation with an amplitude of 4.3% and correlation coefficient $R = 0.74$. The spectra of secondary residuals show a strong peak at the $M_2$ oscillation period, well above the 95% confidence level. This reveals that the primary residuals are “contaminated” by the $Kp + F_{10.7}$ contributions; the real $M_2$ signature is present but obscured by the density variability caused by $Kp + F_{10.7}$. The GOCE zonal wind panel in Figure 3 (bottom row) dated 18 September 2011 shows a similar situation but with less $Kp + F_{10.7}$ contribution.

3.2. Spectral Verification

Figure 4 shows the spectra of secondary residual time series (solid black) of the whole year of 2011 at 18°S latitude for both relative density (top row) and zonal wind (bottom row) and for both dusk (left column) and dawn (right column) as labeled on the top of each panel. These are compared with the spectra of $Kp$ residuals (dotted) of the same year. Significant $M_2$ peaks are only seen in the spectra of secondary residuals of
GOCE relative density or zonal wind and not in the Kp spectra. Although the M2 peaks are not as significant as those of individual 45 day time windows, the peaks at dusk for both relative density and zonal wind reach the 95% confidence level. This set of full year spectra shows that the sample fitting cases in Figure 3 are not isolated or intermittent throughout the year.

Figure 5 shows the latitude-dependent spectra of secondary residuals during the whole year of 2011, in the latitude range 80° S to 80° N, for both relative density (left column) and zonal wind (right column) and for both dusk (top row) and dawn (bottom row). The 95% confidence level of the periodogram contour is 8.86 which is the same as the 95% confidence level of Kp as indicated by the horizontal dotted lines. The vertical dotted lines indicate the M2 period of 14.77 days viewed from GOCE. Significant and distinct M2 peaks are seen in all four panels but are within ±40° latitudes, and the peaks in the right panels for zonal wind are more confined to lower latitudes than the densities. The M2 peaks in relative density at both dusk and dawn stand out uniquely in their own panel while those in zonal wind are accompanied by some sidebands; these sidebands, which also appear in Figure 4, may be associated with annual, semiannual, or solar flux modulations of the zonal wind vis-a-vis ion drag effects that more directly affect the wind field than the density field. Low-latitude zonally symmetric ionization variations at periods near 16 days have also been connected with the dynamo generation of electric fields by planetary waves [e.g., Forbes and Leveroni, 1992; Pedatella et al., 2009], and such effects may also be appearing in these spectra.

3.3. Lunar Tide and Geomagnetic (Kp) Variability in Density

Figure 6 shows the amplitudes of M2 with 95% fitting confidence at both dusk (top row) and dawn (bottom row) and in both relative density (left column) and zonal wind (right column), as labeled on the top of each panel. Each panel includes M2 amplitudes for the whole time window from November 2009 to May 2012. The full-length vertical white stripes common to all panels indicate time intervals when GOCE data are missing or removed by our processing criteria, while the irregular white areas are where the fitting confidence levels fall below 95%. In Figure 6 (top left) for relative density at dusk, large M2 amplitudes are seen from December to February in southern latitudes and from May to June in northern latitudes. The peaks around September are not so obvious and concentrated. Overall, the M2 response appears in both hemispheres when it exists, and there is a tendency for minima to occur at low latitudes. In Figure 6 (bottom left) for relative density at dawn, a similar distribution pattern is shown but with more obvious September peaks and...
Figure 5. Latitude-dependent spectra of secondary residuals for the whole year of 2011 for both (left column) relative density and (right column) zonal wind and for both (top row) dusk and (bottom row) dawn. The 95% confidence level of the periodogram contour is 8.86 which is about the same as the 95% confidence level of $Kp$ as indicated by the horizontal dotted lines. The vertical dotted lines indicate the $M_2$ period which is 14.77 days viewed from GOCE.

more southern May–June peaks. Although highly dynamic patterns are seen in the distribution of the $M_2$ amplitudes in relative density, peaks do occur in the same seasons from year to year in the 2.5 year window, similar to the CHAMP and GRACE lunar tide density climatologies at 360 km and 480 km, respectively [Forbes et al., 2013].

In Figure 6 (top right), for the $M_2$ amplitudes in zonal wind at dusk, distinct peaks occur in low latitudes with some consistency between different years. They peak around $5^\circ$N and $30^\circ$S and are symmetric about $17^\circ$S. The $M_2$ of zonal wind in Figure 6 (bottom right) at dawn follows a similar pattern as Figure 6 (top right), but the latitudinal peaks move north and are symmetric about the equator. The $M_2$ amplitudes in zonal wind at high latitudes reach high values ($\sim 25–30$ m/s$^{-1}$) but are intermittent. These high-latitude regions start around $50^\circ$S in the south but $60–70^\circ$N in the north, consistent with the geographic locations of the magnetic poles. At these high latitudes, the zonal phase speed of $M_2$ gets much closer to the mean wind speeds, so variations in the background winds (diurnal, meteorological, magnetic storm related) translate into amplitude and phase variability in $M_2$; this weather-like intermittency is not unexpected and is likely the reason that no $M_2$ peaks are shown at high latitudes in Figure 5.

Figure 7 illustrates the coefficients of $Kp$ obtained from fitting the primary residuals in 45 day moving windows. These coefficients represent the percent change in density (relative to the 45 day mean) (Figure 7, left) or change in cross-track wind (Figure 7 (right), in m/s$^{-1}$) per unit change in $Kp$ at dusk (top) and dawn (bottom). We note that the results for relative density appear robust, but the cross-track wind coefficients are more intermittent. In general, for the winds, the coefficients are larger at high latitudes and are likely related to more local forcing by plasma-neutral interactions driven by convection electric fields. The latitudinal asymmetries in the wind coefficients also suggest some connection with the magnetic field configuration. On the other hand, the density coefficients tend to extend over wide latitude ranges. This is consistent with the global response to high-latitude heating for moderate $Kp$ levels that is seen in other data sets such as CHAMP [e.g., Lei et al., 2008, 2011]. A notable feature is that the $Kp$ coefficients vary between 3 and 18% per $Kp$ unit with a general trend from high to low values as the level of solar activity increases from 2010 to 2012. When viewed in terms of relative density, such behavior in terms of a preconditioned thermosphere is expected based on first-principles model results [Liu, 2013] and CHAMP data analyses [Lei et al., 2011]; that
Figure 6. The amplitudes of $M_2$ with 95% fitting confidence at both (top row) dusk and (bottom row) dawn in both (left column) relative density and (right column) zonal wind as labeled on the top of each panel. Each panel includes $M_2$ amplitudes for the whole time window from November 2009 to May 2012. The regular white stripes indicate the time periods when GOCE data are missing while the irregular white areas are where the fitting confidence levels fall below 95%.

is, for a given $K_p$ increase, the increase in relative density is greater for a lower background density (i.e., night versus day and solar minimum versus solar maximum).

Figure 7 also shows some evidence for a seasonal variation in the thermosphere response to $K_p$, with larger amplitudes during June/July. As noted in Bruinsma et al. [2006] and Forbes [2007], some degree of seasonal dependence can be understood in connection with the meridional wind field and seasonal variation in Joule heating. That is, an equatorward (poleward) wind in the solar flux-driven prestorm circulation will facilitate (hinder) the equatorward expansion of a high-latitude disturbance produced during elevated geomagnetic activity. Seasonal and diurnal variations of this circulation thus modulate the relationship between $K_p$ and thermosphere density at middle and low latitudes. In addition, the enhanced (diminished) conductivities when polar/auroral latitudes are (are not) illuminated by the Sun during local summer (winter) also result in a seasonal variation in the relation between $K_p$ and density response.

For the purpose of quantifying the lunar tide, there is one additional $K_p$ effect that must be considered, and that is exemplified by the solid black curves in Figure 7. Each of these curves represents the running $M_2$ (14.77 day or semilunar) amplitude of $K_p$ as determined by fitting to $K_p$ within 45 day moving windows. It is clear that the $M_2$ amplitude of $K_p$ is cyclic, with largest values during June/July and quasi-sinusoidal amplitude of 0.4 superimposed on a mean value of 0.4. From Figure 7, we can infer that a 0.4 change in $K_p$ generally corresponds to a 4% change in density. The question emerges, is this a magnetic activity effect or a lunar effect that should be reflected in Figure 6 as opposed to Figure 7? The possibility that geomagnetic activity might possess a lunar tide variation has in fact been suggested in the past [e.g., Wulf and Nicholson, 1949; Bell and Dufouw, 1964, 1966]. Strestik [1998] reviews much of the literature pertinent to a possible lunar tide (spring/neap) variation in geomagnetic activity and provides a thorough analysis of spectral peaks in the $A_p$ index for 1931–1991. Strestik [1998] notes that annual and semiannual modulation of the 13.5 day periodicity due to tilt of the solar dipole (such that Earth encounters a high-speed solar wind stream twice per solar rotation) give rise to peaks at 14.27 and 14.74 days, respectively (along with peaks at 13.15 and 12.69 days), which are close to the 14.77 semilunar period of interest here. Strestik points out several reasons why the above interpretation is preferred to a lunar tide variation in magnetic activity. Therefore, we conclude that we have correctly removed this variation as a $K_p$ effect and not a manifestation of the lunar tide.
Figure 7. Coefficient distributions of 95% confidence Kp fits to GOCE (left column) relative density residuals and (right column) zonal wind residuals at (top row) dusk and (bottom row) dawn. The full-length vertical white stripes common to all panels indicate time intervals when GOCE data are missing while the irregular white areas are where the fitting confidence levels fall below 95%.

Figure 8 provides a summary comparison of lunar tidal M2 and geomagnetic contributions to space weather derived from the data in Figures 6 and 7, respectively. It shows the 2.5 year (from November 2009 to May 2011) mean M2 amplitudes (in red) and corresponding mean Kp variations (Kp coefficient times Kp, in blue) in relative density (Figure 8, top) and in zonal wind (Figure 8, bottom) as functions of latitude. Each bar extends one standard deviation to either side of the mean. For relative density, the latitudinal variation is minor. Within ±40° latitude, the M2 lunar contribution is about 59.3% of the geomagnetic contribution, while from pole to pole, that ratio is 52.1%. For zonal wind, the latitudinal variation is much more. Within ±40° latitude, the M2 lunar contribution is about 171.2% of the geomagnetic contribution while from pole to pole, that ratio is 116.5%. The M2 lunar contribution is much more significant in zonal wind and relatively more significant in lower latitudes where the M2 lunar contribution is almost twice the geomagnetic contribution for zonal wind. Globally, the M2 lunar contribution is still more than the geomagnetic contribution in zonal wind and accounts for more than half of the geomagnetic contribution in relative density. The large standard deviation bars of the mean Kp variations from pole to pole indicate the global high intermittency of Kp contribution. Large standard deviation bars are also seen for the mean M2 amplitudes at high latitudes.

3.4. Consistency With Climatological Expectations
As noted earlier, a previous effort to delineate the lunar thermosphere tide [Forbes et al., 2013] involved a binning and averaging approach, with the outcome being a latitude versus month climatology of the lunar tide. The specific objective of the current work is to avoid that approach and achieve a more “dynamic” or “space weather” depiction of the lunar tide. That being said, one might ask what the current data set reveals in terms of an “average” lunar tide. There are a few difficulties that confront and answer to this question. First, according to model simulations [Forbes et al., 2013], the density variations at GOCE altitudes ~260 km are about a factor of 2 smaller than those at CHAMP and GRACE altitudes (350–500 km). Second, the amount of data currently available from GOCE is comparatively short. Third, the only data available for June/July are from 2011, and these are months where large lunar tidal amplitudes are expected based on CHAMP and GRACE results. Finally, only two local solar times are available from GOCE, leaving open the possibility of local solar time bias. These factors combine to preclude a robust result. With these caveats in mind, the average of lunar tide amplitudes displayed in Figure 6 are shown in Figure 9 (top row), with density amplitudes on the left and cross-track wind amplitudes on the right. Both dawn and dusk data are included in this average to provide a more consistent comparison with the corresponding GSWM simulations which are shown.
Figure 8. The 2.5 year (from November 2009 to May 2011) mean $M_2$ amplitudes (in red) and corresponding mean $Kp$ variations ($Kp$ coefficient times $Kp$, in blue) in (top) relative density and (top bottom) zonal wind as a function of latitude. Each bar extends one standard deviation to either side of the mean.

in Figure 9 (middle and bottom rows). The GSWM is version 09 as described in Zhang et al. [2010a, 2010b] and modified to include lunar tide forcing as described in Forbes et al. [2013]. Figure 9 (middle row) shows the corresponding GOCE results using the binning and averaging method employed in Forbes et al. [2013]; since these results take into account the phase of the lunar tide, Figure 9 (middle row) can be viewed as a vector average, whereas the amplitudes in the top row represent a scalar average. For the density results, broad similarities with the GSWM climatology are beginning to emerge, with maxima of order 4% tending to occur in the Southern Hemisphere summer and in both hemispheres during Northern Hemisphere summer. The July/August minima in the scalar-average amplitudes is notable; this may represent an undersampling of these months in the current data set or that some of the $Kp$-related variability near the $M_2$ period (solid black lines in Figure 7) in some of the windows may have included some of the lunar variation.

The mean lunar tidal amplitudes in cross-track wind are shown in Figure 9 (right column). Apart from the large wind amplitudes between 30° and 80°N during January to April, the GOCE scalar and vector averages reveal consistently large amplitudes between −50° and +30° latitude during Southern Hemisphere summer, and maxima at high latitudes during Southern Hemisphere winter, with relatively little response at low to middle latitudes during Southern Hemisphere winter. These features are broadly consistent with those in the GSWM, except that the model wind maxima during Southern Hemisphere winter appear equatorward of ±60° latitude, whereas the measurements maximize poleward of ±60° latitude. These differences are likely caused in part by shortcomings in the thermosphere wind field assumed in the GSWM, especially at high latitudes, but more likely by the fact that there is missing physics in the GSWM simulation of the lunar tide. It is well-known that there are lunar variations in the plasma densities of the $F$ region [Matsushita, 1967b], in part caused by the electric fields driven by the lunar wind dynamo in the $E$ region. The lunar variations in ion drag and plasma drift should serve as a lunar tidal momentum source or sink for the wind field. There is also likely a solar local time modulation of the lunar tide [cf. Lühr et al., 2012]. These effects are not included in the GSWM, and the implications for the modeled lunar tide remain unknown; this, combined with the caveats noted previously, limits the degree to which we can interpret the GOCE lunar tidal amplitudes depicted in Figure 9.
Figure 9. The 2.5 year and dawn-dusk mean GOCE $M_2$ amplitudes derived from (top row) amplitude average and (middle row) vector averaging compared with GSWM simulation with (bottom row) $F_{10.7} = 70$ in (left column) relative density and (right column) zonal wind.

4. Concluding Remarks
4.1. Summary and Interpretation of Results
Previous investigations of the lunar atmospheric tide have mainly employed averaging over a decade or more in order to separate the lunar tidal signal from other variability. The recent study by Forbes et al. [2013] obtained seasonal-latitudinal patterns of lunar tidal density variations at 360 km and 480 km from CHAMP and GRACE accelerometer measurements, respectively, covering only 4 years (2007–2010). This was possible due to the relatively large lunar tidal signals at these altitudes, combined with the relatively low levels of additional geophysical variability (i.e., of solar and geomagnetic origin) in the data and the phase coherence of the lunar tide in contrast to variations associated with geomagnetic activity. In addition, the variability due to nonmigrating tides was averaged out, since the main semidiurnal $M_2$ tide is longitude-independent and can be derived from longitude-averaged data.

The above types of analyses provide “climatological” or “static” depictions of the lunar tide. However, despite the fact that the forcing of $M_2$ is invariant, the atmospheric response is known to be highly dynamic. For instance, the lunar tide in the thermosphere undergoes large changes in connection with sudden stratospheric warnings (SSWs) mainly in connection with middle atmosphere circulation changes that occur in the Northern Hemisphere during these disturbances [Forbes et al., 2013; Pedatella and Forbes, 2010]. Indeed, the climatological seasonal-latitudinal variability reported in Forbes et al. [2013] is driven by climatological changes in the middle atmosphere winds, as demonstrated in model simulations by these authors. As the lunar tide propagates into the thermosphere, it is subject to additional influences such as molecular dissipation, ion drag, and large background wind fields. In particular, the mean wind field above 100 km changes significantly with respect to solar and geomagnetic activity and local time, in addition to the
seasonal-latitudinal and height variations that dominate below 100 km. Above 100 km at middle and high latitudes, the zonal phase speed of the lunar tide can be of the same order or smaller in magnitude than the local wind speed; thus, the lunar tide could encounter critical levels or be Doppler shifted to higher (lower) frequencies and thus refracting its propagation and reducing (increasing) its susceptibility to dissipation. These effects will vary greatly with local time, season, magnetic activity, etc. Thus, we may expect the temporal signatures of the lunar tide in the thermosphere to depart from those anticipated based on climatology and the types of depictions that are usually offered by tidal models. It is this “dynamic” depiction of the lunar tide in the thermosphere that has been provided here using the GOCE accelerometer data for the first time. This is made possible by the high precision offered by the GOCE accelerometer compared to the lunar tide signal at 260 km, the relatively low level of solar and geomagnetic-related density variability during the period of analysis, and the fact that the lunar tide signal appears at a period of 14.77 days from the perspective of the GOCE orbit, far enough from the 13.5 day periodicity in recurrent geomagnetic activity to be unequivocally separated.

In this paper we have also explored the comparative effects of the Sun and the Moon on the moderate level of space weather that occurs between magnetic storms, with a focus on middle thermosphere variability as revealed by the GOCE accelerometers. We find that density and zonal wind lunar tide amplitude variabilities fall within about 5–7% and 10–25 m s\(^{-1}\), respectively, with a significant degree of intermittency. If we consider days where the mean $Kp$ is 3.0 or less (i.e., between more extreme events such as magnetic storms), then on average the density (zonal wind) variability associated with the lunar tide is about 50–60% of (equal to) that associated with geomagnetic variability. When averaging over the 2.5 year span of the GOCE data set is performed, seasonal-latitudinal patterns similar to those anticipated based on a simple linear model begin to emerge. Although several factors preclude construction of a robust climatology at GOCE attitudes at the present time, this consistency does provide some degree of validation of our time-variable results.

4.2. Relevance to Space Weather Applications

Early in this paper, we noted the potential practical relevance of our results with respect to density and orbital prediction. In this regard there are a few points worth noting. Although some local time dependencies exist (e.g., see Figure 7), the thermosphere density response to increased geomagnetic activity ($Kp$) is positive and highly correlated at different longitudes and local times around the globe. A satellite therefore generally experiences an increase in drag in connection with an increase in $Kp$ all along any given circular orbit whatever the orbital inclination. Similarly, the $M_2$ lunar tide is longitude independent and has the same phase at two local times separated by 12 h. Thus, apart from some local time differences in the amplitude of the lunar tide (e.g., see Figure 6) and some phase differences with respect to latitude [cf. Forbes et al., 2013], a polar orbiting satellite will experience an integrated drag effect of the same sign over every orbit and during the course of a day due to the $M_2$ lunar tide. In this sense, both the $Kp$ and lunar tide are effective in producing drag on a satellite. A satellite in an equatorial orbit, however, will encounter two density residual maxima and two minima due to the lunar tide, effectively canceling out the lunar tide drag effect; the situations for other orbital inclinations lie between these two extremes.

Now consider the fact that the lunar tide seen by the near-polar Sun-synchronous GOCE orbit has a period of 14.77 days. During some part of this 14.77 day cycle the lunar tide effect is to produce a net maximum increase in drag on GOCE, and 7.385 days later, it will produce a net maximum decrease in drag on GOCE. From Figure 6, this net increase can be up to about $+7\%$, and the net decrease can be up to about $−7\%$, for a total effect of about 14% change in drag over a 7.385 day period. Again, for lower inclination orbits these effects would be less. On the other hand, for a satellite in high-eccentricity orbit the drag effect of the lunar tide would be more localized at perigee and would experience the full amplitude cycle of the lunar tide density perturbation at that location. Furthermore, the period of the lunar tide oscillation seen from a given satellite orbit depends on the local time precession rate. For a circular orbit at 600 km with 74° inclination, the lunar tide period is about 12 days, for example. All of these factors would need to be taken into account if the lunar tide were incorporated into an empirical model.

Although the amplitudes associated with lunar variability in thermosphere density are modest, their relation to the phase of the Moon introduces an element of predictability. In fact, it is well established that proper phasing of a density prediction is every bit as important as getting its amplitude right [Forbes, 1972; Anderson et al., 2013]. This elevates the potential relevance of including the lunar tide in operational prediction models. Some possible next steps come to mind. First, given the results presented here and
in Forbes et al. [2013], there are sufficient data available to introduce the lunar tide into existing empirical density models in the climatological sense, that is, capturing its average seasonal-latitude structure. One could use such a model to quantify the relation between lunar tide variability and orbital prediction errors. Following on the space weather aspects of the lunar tide highlighted in the present paper, such a climatological approach will not be enough. However, it is certainly possible to include the lunar tide in existing first-principles models to ascertain the degree of temporal variability in density that is introduced by day-to-day variability associated with middle and upper atmosphere meteorology. In fact, this has already been done in the context of sudden stratospheric warmings [Pedatella et al., 2012a], although the focus was not on thermosphere density variability. As indicated in Forbes and Zhang [2012], density variations measured by the CHAMP satellite near 360 km associated with just the $M_2$ lunar tide can be of order 20% in connection with such events, underlining the importance of proceeding with such activities. The results presented here and those in Forbes and Zhang [2012] can be used to validate the level of lunar tide variability seen in such simulations.

**References**


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