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Key Points:

- DE3 and UFKW propagate to the thermosphere from below
- Nonlinear wave-wave interactions produce large secondary waves
- Vertically propagating waves are larger than geomagnetic/solar effects

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Wave coupling between the lower and middle thermosphere as viewed from TIMED and GOCE

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Abstract Vertical coupling between the lower and middle thermosphere due to the eastward propagating diurnal tide with zonal wave number 3 (DE3) and the 3.5 day ultra-fast Kelvin Wave (UFKW) is investigated using Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics-Sounding of the Atmosphere using Broadband Emission Radiometry (TIMED-SABER) temperatures near 100 km and Gravity field and steady-state Ocean Circulation Explorer (GOCE) neutral densities and zonal winds near 260 km. The analysis is performed between $\pm 45^\circ$ latitude during 2011, when reliable and continuous measurements are available. With geomagnetic and solar effects removed, DE3 and the UFKW are identified as dominant sources of day-to-day variability at both heights. Evidence is found for the vertical propagation of DE3 and the UFKW from the lower to middle thermosphere over a range of time scales. Over 60% of the variance due to DE3 and the UFKW at 260 km is traceable to variability occurring at 100 km. The not exact agreement is thought to be due to the influences of wave-wave interactions, zonal mean winds, dissipation, and inherent transience that interfere with one-to-one mapping of structures between 100 and 260 km. Spectral and temporal analyses of the SABER and GOCE data also reveal the presence of sidebands due to the modulation of DE3 by the UFKW. These secondary waves are responsible for up to 10% to 20% of the longitudinal and day-to-day variability. Overall, vertical propagating waves together with sidebands from DE3-UFKW nonlinear interactions are responsible for 60% to 80% of the total variability, while geomagnetic and solar effects correlated with ap and $F_{10.7}$ account for less than 20% of the variance.

1. Introduction

The vertical coupling of solar tides and other waves from the lower atmosphere to the thermosphere and ionosphere has been a topic of intense research in the past decade [Yigit and Medvedev, 2015]. Global-scale solar tides, planetary waves, gravity waves, and Kelvin waves around 100–150 km generate electric fields in the E region due to the dynamo action of tidal winds. These electric fields map along equipotential magnetic lines and drive $E \times B$ plasma drifts in the F region, which cause temporal and spatial variability in the E region tides to transfer to the F region plasma [e.g., Jin et al., 2008; Kil et al., 2007, 2008; Liu et al., 2007; Liu and Watanabe, 2008]. The vertical propagation of some of these wave components to the upper thermosphere (300–400 km [Forbes et al., 2009b; Hagan et al., 2009]) also directly modulate neutral and plasma densities [He et al., 2011; England et al., 2010]. Altogether the above wave influences drive a component of space weather.

Atmospheric solar tides are global oscillations of temperature, density, and wind fields induced by the daily cyclic absorption of solar energy in the atmosphere, with periods being subharmonics of one solar day. They can be described by the expression: $A_{n,s} \cos(n\Omega t + s\lambda - \phi_{n,s})$, where t is time, Ω is the rotation rate of the Earth, λ is longitude, n denotes a subharmonic of a solar day, s is the zonal wave number, $A_{n,s}$ the amplitude, and $\phi_{n,s}$ the phase (defined as the time of maximum at zero longitude). Eastward (westward) propagation corresponds to $s < 0$ ($s > 0$). In local time $t_{LT} = t + \lambda/\Omega$, the previous expression becomes: $A_{n,s} \cos(n\Omega t_{LT} + (s-n)\lambda - \phi_{n,s})$. The eastward nonmigrating diurnal tide with zonal wave number 3 (DE3) in the mesosphere/lower thermosphere (MLT) region is a major driver of the wave-4 structure in the ionosphere, and its signature has been detected in thermosphere neutral densities and temperatures. It is excited in the tropical troposphere by latent heat release in deep convective clouds, and it is a large source of variability in the mesosphere/lower thermosphere (MLT) region [Hagan et al., 1997; Hagan and Forbes, 2002; Oberheide et al., 2011]. The first symmetric mode of DE3 is the largest component [Truskowski et al., 2014] and is a Kelvin wave that is known to propagate higher into the thermosphere due to its vertical wavelength of ~ 56 km [Oberheide et al., 2011]. The strongest DE3

Figure 1. Example of fits to GOCE residuals and daily $F_{10.7}$ and 3 h ap indices for a geomagnetic active period (day of year (DOY) 269–274), around the equator (latitude $\pm 12^\circ$). (a) The $F_{10.7}$ (magenta line) and ap (green line) values. (b) The residual winds (black line) and (c) their fits (red line). In this 5 day period, the variance captured by the fits to wind (density) is 0.31 (0.39), indicating that $\sim 31\%$ ($\sim 39\%$) of the variance in the winds (densities) is linked to geomagnetic solar activity.

tends to occur during the months of July to November, with maximum DE3 amplitude at the equator around 15 m/s in the zonal winds at 95 km [Talaat and Lieberman, 1999; Forbes et al., 2003b].

Kelvin waves are eastward and vertically propagating waves trapped at low latitudes by the Coriolis force. They were first observed in the atmosphere by Wallace and Kousky [1968], and numerous theoretical studies on their origin followed [e.g., Holton, 1970, 1972, 1973; Chang, 1976]. The source of these waves was identified with unsteady convective heating in the tropical troposphere [Holton, 1972]. Holton [1992] described Kelvin waves using linear theory in the absence of mean winds as oscillations with zero velocity across the equator and Gaussian symmetric structure in latitude and maxima in zonal wind, temperatures, and density at the equator. Kelvin waves are grouped in three classes [Wallace and Kousky, 1968]: slow Kelvin waves that occur in the stratosphere (~ 15 – 50 km) at periods of 10–20 days, fast Kelvin waves found in the stratosphere and mesosphere (~ 20 – 100 km) at periods of 6–10 days, and ultra-fast Kelvin waves (UFWK) with periods of 3–6 days that can propagate to higher altitudes given their longer vertical wavelength [Salby et al., 1984; Canziani et al., 1995; Lieberman and Riggan, 1997; Forbes et al., 2009a]. Using equatorial radar wind measurements from 1993 and 1997, Yoshida et al. [1999] showed that UFWK amplitudes vary significantly throughout the year, with two annual peaks of increased activity: one around March–May and another around July–November. Using global-scale wave model simulations, Forbes [2000] showed that a UFWK with period of 3 days and zonal wave number of 1 (eastward) could reach amplitudes of 10–25 K in temperature and 10–40 m/s in zonal wind in the lower thermosphere. Forbes [2000] also showed the vertical wavelength of the UFWK to be ~ 58 km. Gu et al. [2014] found similar UFWK amplitudes in Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics-Sounding of the Atmosphere using Broadband Emission Radiometry (TIMED-SABER) temperatures.

Figure 2. Zonal wave number versus period spectrum for 2011 at the equator (latitudes $\pm 12^\circ$) (a) before and (b) after the removal of geomagnetic and solar effects for (from top to bottom) GOCE density, GOCE wind, and SABER temperature, respectively. The spectrum was created by least squares data from both ascending and descending nodes. Positive (negative) zonal wave numbers correspond to westward (eastward) waves. There is evidence of a strong UFKW in both SABER and in GOCE with period of 3.5 days and zonal wave number -1 . Note the significant reduction of the 10 day periodicity with zonal wave number 0 after filtering out geomagnetic and solar effects.

There is increasing evidence that different components of the wave spectrum interact with each other to produce secondary waves. For instance, *Palo et al.* [1999] demonstrate the generation of secondary waves due to the interaction between the westward propagating semidiurnal tide with zonal wave number 2 (SW2) and the quasi 2 day wave (Q2DW); *Wang et al.* [2011] discuss generation of the westward propagating terdiurnal tide with zonal wave number 3 (TW3) from the westward propagating tide with zonal wave number 1 (DW1) and SW2; *Hagan et al.* [2009] and *Oberheide et al.* [2011] demonstrate the production of the eastward propagating semidiurnal tide with zonal wave number 2 (SE2) and the stationary planetary wave 4 (SPW4) from the DE3-DW1 interaction; and *Moudden and Forbes* [2013] interpret the observation of terdiurnal nonmigrating tides in terms of interactions between diurnal and semidiurnal nonmigrating tides.

As explained by *Teitelbaum and Vial* [1991], planetary wave (PW) interactions with tides yields secondary waves defined by the sum and difference of the frequencies and zonal wave numbers in the primary waves, in the following manner: $[\cos(\delta\Omega t + m\lambda) \cos(n\Omega t + s\lambda)] = 1/2 \cos[(n + \delta)\Omega t + (s + m)\lambda] + 1/2 \cos[(n - \delta)\Omega t + (s - m)\lambda]$, where $\delta\Omega$ and m are the planetary wave's frequency and zonal wave number, respectively. In a time frequency spectrum, the secondary waves appear as two sidebands on either side of the tide with a shift in frequency equal to the planetary wave's frequency $\delta\Omega$.

In the present context the TIMED and GOCE satellites sample the atmosphere in a way that does not allow time domain determination of tidal components, since their orbits are quasi Sun synchronous (GOCE) or slowly precessing (TIMED). However, *Moudden and Forbes* [2010] developed a method (explained in section 2) whereby PW-tide interactions can be revealed in such situations. We will employ that method here to quantify the UFKW modulation of DE3.

In this paper we provide evidence that DE3 and a 3.5 day UFKW are prominent oscillations in both TIMED/SABER temperatures at 100 km and densities and winds measured by accelerometer on the GOCE satellite near 260 km during 2011. Moreover, the evidence strongly suggests that both DE3 and the UFKW propagate from 100 km to 260 km and that they undergo nonlinear interactions, producing secondary waves in this height regime. We furthermore quantify the total contributions of waves to the total density and wind variability measured by GOCE and demonstrate that it exceeds the variability that is attributable to geomagnetic and solar variability, as measured through least squares regression on ap and $F_{10.7}$. Our results therefore

Figure 3. Time series of daily DE3 amplitudes for (a) GOCE density, (b) GOCE wind, and (c) SABER temperature. Large day-to-day and seasonal variability exists, with maxima around DOY 30–50, DOY 100–200, DOY 240–280, and DOY 310–350. Amplitudes up to 10% are found in the densities, 19 m/s in the winds, and 20 K in the temperatures. There is evidence of vertical propagation of DE3 from 100 km to 260 km.

point to the importance of lower atmosphere coupling as an important contributor to the thermosphere weather, at least in the absence of major solar-driven variability.

In section 2 we provide a description of the data used, the methodology followed, and its limitations. In section 3.1 we provide evidence for the vertical propagation of DE3 and the UFKW; in section 3.2 we show evidence of nonlinear DE3-UFKW interactions; in section 3.3 we discuss implications for longitudinal variability; while in section 3.4 we quantify the relative importance of vertically propagating waves and geomagnetic solar effects. In section 4 we provide the conclusions.

2. Data and Methodology

For this study, we used global temperatures (version 1.04) at 100 km from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument aboard the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) satellite (<http://saber.gats-inc.com/data.php>), and density and zonal wind at 260 km from the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission [Rebhan *et al.*, 2000]. TIMED was launched in 2001 in a slowly precessing orbit, covering 24 h of local time in 60 days (when considering both ascending and descending nodes), while GOCE was launched in 2009 in a 6:00/18:00 local time Sun-synchronous orbit. Due to the lack of out-of-plane orbit control, GOCE started a slow local time drift, such that in 2011 the local solar time at the ascending node drifted to ~18:58. Each day both TIMED and GOCE sample 360° of longitude within steps of ~24° for each node.

We performed our analysis for the year 2011, when almost gapless data exists and small errors are found in both SABER and GOCE (except for the first 24 days and the last 7 days of the year for GOCE). We focused on latitudes between $\pm 45^\circ$, where DE3 and the UFKW reach their largest amplitudes, and sampling is not affected by yaw maneuvers for TIMED, leading to an almost continuous time series coverage in UT and longitude.

SABER kinetic temperatures are derived from CO₂ measurements made by the limb-scanning infrared radiometer (method detailed by Mertens *et al.* [2001]). GOCE thermosphere neutral density and cross-track winds (version 1.2) are derived using ion thruster data combined with the accelerometer and star camera data products [Doornbos, 2013, Doornbos *et al.*, 2013a, 2013b; Bruinsma *et al.*, 2014], following five steps: (1) estimation of the biases in the gradiometer common-mode accelerations using GPS tracking data, (2) conversion of ion thruster activation data to accelerations, (3) modeling of radiation pressure accelerations based on orbit and attitude information, (4) removal of radiation pressure and ion thruster accelerations from the

Figure 4. Time series of 30 day running means of daily DE3 amplitudes for (a) GOCE density, (b) GOCE wind, and (c) SABER temperature. Vertical propagation of DE3 is even more evident than in Figure 3, given the steady state approximation.

acceleration data, and (5) iterative adjustment of wind direction and density inputs of an aerodynamic model of the satellite until the modeled aerodynamic accelerations match the observations.

In order to highlight the waves and at least partially quantify solar and geomagnetic influences, we used multiple linear regression to fit the raw data to daily $F_{10.7}$ and 3 h ap values on 15 day windows, stepping forward 1 day at the time. We then removed these fits from the raw data and analyzed the resulting residuals for wave content. Figure 1 shows an example of the fit for a geomagnetically active period, where ap - $F_{10.7}$ effects account for $\sim 31\%$ and $\sim 39\%$ of the total variability at 260 km in the winds and densities, respectively. These fits for the whole year are used in section 3.4 to assess the relative importance of thermospheric variability attributed to waves from below versus that connected with solar and geomagnetic forcing.

As discussed by Zhang *et al.* [2006], the slow local time precession of most low-orbiting satellites represent a major limitation of utilizing satellite-based measurements to derive atmospheric tides. The difficulties involved fall into the categories of sampling and aliasing. The sampling issue is caused by the inherent variability of the atmospheric system within the 24 h local time precession period of the satellites: if the local time structure of the atmosphere evolves over the precession period, the derived tides are an average over that period. The aliasing issue is due to the zonal mean aliasing into the derived tidal field. If the atmosphere is sampled by a satellite in a slowly precessing orbit, the changing zonal mean is perceived as a local time change, leading to spurious tidal harmonics. Different methods have been used to circumvent these issues [e.g., Lieberman, 1991; Forbes *et al.*, 1997, 2003a; Talaat and Lieberman, 1999; Oberheide and Gusev, 2002], each one with its advantages and drawbacks. In particular, Lieberman [1991] and Oberheide and Gusev [2002] estimated daily diurnal tides by taking differences between ascending and descending node measurements that are 12 h or less apart in local time. We employ a similar method to SABER and GOCE data in order to derive daily amplitudes of DE3. Assuming that the main components to the observed longitudinal wave-4 structure are DE3 and SE2, and given that the semidiurnal tide has same phase at opposite nodes, we extract daily amplitudes of DE3 as the wave-4 of ascending minus descending differences divided by 2. The main source of error is represented by aliasing of TE1 and DW5 into the wave-4 structure, causing uncertainties ranging from $\sim 5\%$ during the Northern Hemisphere summer to $\sim 30\%$ during the Northern Hemisphere winter (according to Oberheide *et al.* [2011]).

Table 1. Correlation Coefficients Between Daily and Monthly DE3 in SABER Temperature, GOCE Density, and GOCE Wind Around the Equator and for the Whole Year (Latitude $\pm 12^\circ$)

Correlation	DE3 Daily	DE3 Monthly
Temperature and density	0.57	0.64
Density and wind	0.83	0.86
Temperature and wind	0.66	0.75

Figure 2 presents the zonal wave number versus period spectrum for 2011 around the equator before (Figure 2a) and after (Figure 2b) the removal of geomagnetic and solar effects for GOCE and SABER data. The largest short-period wave in both SABER and GOCE data after the removal of ap - $F_{10.7}$ fits is found to be the UFKW with a period of 3.5 days and zonal wave number -1 (eastward). The large 10 day periodicity with zonal wave number 0 present in the raw data (Figure 2a) is significantly reduced by removing fits with ap and $F_{10.7}$ (Figure 2b), suggesting its link to geomagnetic and solar effects. In fact, this periodicity is likely related to recurrent geomagnetic activity and high-speed solar wind streams near 9 day period, the signature of which has been reported in both TIMED temperature data near 110 km [Jiang *et al.*, 2014] and CHAMP density data near 400 km [Lei *et al.*, 2008].

Daily amplitudes of the UFKW are derived by least squares fitting residuals in 15 day running windows (15 day means shifted 1 day at the time). This is performed according to the expression: $y(t, \lambda) = \bar{y} + A \cos[2\pi(t/T) - m\lambda]$, where t is UT time, λ is longitude (in radians), $\bar{y}$ is the zonal mean, A is the amplitude, T is the period (3.5 days), and m is the zonal wave number (-1). The amplitude of the UFKW is taken as the maximum amplitude in that particular 15 day window. The length of the window is chosen such that at least four full cycles are required to fully capture a wave with a 3.5 day period.

In order to diagnose the UFKW and DE3 interaction, we use a method developed by Moudén and Forbes [2010] for Mars and later applied to Earth [Forbes and Moudén, 2012], involving the use of pseudolongitude series. This method is detailed below.

Figure 5. Same as Figure 3, but for the UFKW with period of 3.5 days and zonal wave number -1 . (a) Amplitudes up to 7% are found in the densities, (b) 6 m/s in the winds, and (c) 11 K in the temperatures, with maxima at low latitudes around DOY 40–90 and DOY 170–220.

Figure 6. Same as Figure 4, but for the UFKW. Similarly to DE3, vertical propagation is more evident, with two maxima around DOY 40–90 and DOY 170–220.

The time longitude dependence of a PW can be expressed as $\cos(\delta\Omega t + m\lambda)$ and that of a tide as $\cos(n\Omega t + s\lambda)$. (i.e., $\delta\Omega \approx 0.3 \text{ day}^{-1}$, $m = -1$ correspond to the eastward propagating UFKW with zonal wave number 1; while $n = 1$, $s = -3$ corresponds to the diurnal eastward propagating tide with zonal wave number 3 (DE3)). In this context, negative (positive) zonal wave numbers correspond to eastward (westward) propagating waves. From a Sun-synchronous satellite orbit the above expressions become $\cos(\delta\Omega t_{\text{LT}} + (m - \delta)\lambda)$ and $\cos(n\Omega t_{\text{LT}} + (s - n)\lambda)$; hence, waves with the same values of $|m - \delta|$ or $|s - n|$ alias into each other. Using the theory formulated by Teitelbaum and Vial [1991], Moudden and Forbes [2010] show that the modulation of a tide by a PW generates two secondary waves with longitudinal wave numbers $(s - n) \pm (m - \delta)$. Additionally, Forbes and Moudden [2012] demonstrate that the effect of slow local time precession is negligible. Moudden and Forbes [2010] demonstrate these conclusions by creating spectra with respect to pseudolongitude, instead of time. Pseudolongitude P is defined as $P = \lambda + 2\pi c$, where λ is longitude and c is the number of cycles around Earth. In other words, an increment of 2π is added to the real longitudes every time the initial longitude (that of the first orbit in the time series) is crossed again by the satellite. In a pseudolongitude spectrum, PW peaks are located at $|m - \delta|$, tides at $|s - n|$, and secondary waves due to PW-tide modulation at $|(s - n) \pm (m - \delta)|$. Accordingly, the UFKW ($m = -1$, $\delta \approx 0.3$) and DE3 ($s = -3$, $n = 1$) interact to produce secondary peaks at $|(-3 - 1) \pm (-1 - 0.3)| = |-4 \mp 1.3| = 2.7$ (sideband 1) and 5.3 (sideband 2). Sideband 1 has a period of $[\Omega(n - \delta)]^{-1} = 1.43$ days and zonal wave number of $(s - m) = (-3 + 1) = -2$, while sideband 2 has a period of $[\Omega(n + \delta)]^{-1} = 0.77$ days and zonal wave number $(s + m) = (-3 - 1) = -4$.

Table 2. Same as Table 1, but for the UFKW^a

Correlation	UFKW Daily	UFKW Monthly
Temperature and density	0.57	0.72
Density and wind	0.72	0.84
Temperature and wind	0.80	0.88

^aNote that most of these values are greater than the ones in DE3 (Table 1). No explanation for this was found.

Figure 7. (a) Whole year pseudolongitude spectrum for SABER temperature, (b) time series of DE3, (c) UFKW, (d) sideband 1, and (e) sideband 2. The interaction between DE3 (marked in red) and the UFKW (marked in blue) generates the sideband 1 and sideband 2 (both marked in black). The sidebands (Figures 1d and 1e) show large variability, similarly to DE3 and the UFKW, and tend to maximize when both DE3 and the UFKW have large amplitudes. The sidebands reach amplitudes up to 7 K, comparable to the amplitude of the UFKW.

3. Results

3.1. Vertical Propagation of DE3 and the UFKW

Figure 3 shows daily DE3 amplitudes for GOCE density (Figure 3a), GOCE wind (Figure 3b), and SABER temperature (Figure 3c) for the entire year. Amplitudes up to 10% are found in the densities, 19 m/s in the winds, and 20 K in the temperatures. The intraseasonal variability of DE3 is very similar at 100 km and 260 km, with maxima at low latitudes around DOY 30–50, DOY 100–200, DOY 240–280, and DOY 310–350. The presence of DE3 at both heights, the common intraseasonal variability, and the similar amplitudes are clear indications that vertical propagation is occurring. The vertical propagation of DE3 is even more apparent when looking in Figure 4, which shows 30 day running means of the daily values plotted in Figure 3. For each day (and

Figure 8. Same as Figure 7, but for GOCE density at 260 km. The sidebands due to the UFKW-DE3 interaction are clearly visible also in GOCE density and reach amplitudes up to 4%.

latitude bin) we calculated 30 day means and created an array of means by stepping forward 1 day at the time. Eliminating a lot of day-to-day variability, this method provides a quasi steady state view. The latitudinal structures result somewhat smoothed by applying monthly means, giving the impression that for this case, the maxima occur closer to the equator than for the daily values. Additionally, most of the day-to-day variability is removed and the amplitudes are significantly reduced. The apparently different latitudinal structures can only be attributed to the fictitious effect introduced by taking monthly means, and no contamination by other wave components is possible. The correlation coefficient over the entire year between DE3 in SABER temperatures at 100 km and DE3 in GOCE winds at 260 km is 0.66 for daily values and 0.75 for the 30 day running means (see Table 1). No link with season, level of geomagnetic activity, or zonal mean winds was found. Generally, DE3 tends to have a symmetric latitude structure with maximum around the equator due to the prevalence of its first symmetric mode (which is a Kelvin wave and thus is symmetrical around the equator).

Figure 9. Same as Figure 7, but for GOCE wind at 260 km. The sidebands due to the UFKW-DE3 interaction are clearly visible also in GOCE wind and reach amplitudes up to 7 m/s, comparable to the amplitudes of the UFKW.

The presence of other Hough modes, such as the first antisymmetric mode, can alter such symmetric structure and give rise to maxima at low latitudes, instead of the equator [Forbes *et al.*, 2003a]. This is likely the cause of the low-latitude peaks evident in Figure 3.

As shown in Figure 2 and already discussed in section 1, after $F_{10.7}$ and ap effects are removed from the raw data, the UFKW with $(\delta\Omega)^{-1} = 3.5$ days and $m = -1$ emerged as the most prevalent short-period wave both at 100 km and 260 km. Figure 5 shows daily UFKW amplitudes for GOCE at 260 km and SABER at 100 km. Amplitudes up to 7% are found in the densities (Figure 5a), 6 m/s in the winds (Figure 5b), and 11 K in the temperatures (Figure 5c), with maxima at low latitudes around DOY 40–90 and DOY 170–220. Vertical propagation of the UFKW appears clear, especially observing the common intraseasonal variability and similar amplitudes. (Note that although daily values are presented, the UFKW is calculated using 15 day moving

Figure 10. (a) The pseudolongitude spectrum centered on DOY 160 and constructed using 21 days (from DOY 150 to DOY 170) of SABER temperatures. The UFKW peak at ~ 1.3 cycles (marked in blue), the DE3 peak at 4 cycles (marked in red), and their sidebands at ~ 2.7 cycles and at ~ 5.3 cycles (sidebands 1 and 2, both marked in black) are all evident. The reconstructed signal is shown: (b) the observations, (c) the sum of wave-1 and wave-2, (d) wave-3, (e) wave-4, (f) the UFKW, (g) the secondary peaks, (h) the sum of wave-1 to wave-4, (i) the sum of wave-4 and the UFKW, (j) the sum of wave-1 to wave-4 and the UFKW, and (k) the total fit, which includes the DE3-UFKW interactions. The total fit (Figure 10k) reproduces very well the observations (Figure 10b).

windows; hence, each day actually combines data from 15 days). Similar to DE3, the comparison is improved by looking at 30 day running means, which are shown in Figure 6. Table 2 lists the correlation coefficients between the UFKW in SABER and GOCE. Correlation coefficients of 0.80 for daily values and 0.88 for running means are found between temperatures and winds.

The presence of a strong DE3 and UFKW both at 100 km and 260 km, and the common day-to-day and seasonal variability, is evidence of the vertical propagation of these waves from the lower to the middle thermosphere. The not exact agreement is likely caused by the effect of wave-wave interactions, zonal mean winds, dissipation, and inherent transience that interfere with one-to-one mapping of structures between 100 km and 260 km. Some of the discrepancies between the two heights can also be explained by differences between the temperature and density fields (where the latter is in some sense related to the integral of the temperature field).

Note that estimating the vertical wavelengths of DE3 and the UFKW from TIMED-SABER and GOCE data presents significant difficulties due to satellite sampling limitations and is beyond the scope of this paper.

Table 3. Variance Around the Equator (Latitude $\pm 12^\circ$) for Each Wave Component Described in Figures 10–12^a

Variance	SABER Temperature	GOCE Density	GOCE Wind
Wave 1–2	0.167	0.187	0.233
Wave 3	0.157	0.152	0.119
Wave 4	0.292	0.318	0.227
UFWK	0.253	0.356	0.159
Secondary peaks	0.235	0.193	0.210
Wave 1–4	0.556	0.504	0.705
Wave 4 + UFWK	0.356	0.567	0.394
Wave 1–4 + UFWK	0.687	0.643	0.756
Total fit	0.814	0.922	0.925

^aThe total fit includes wave-1 to wave-4, the UFWK, and the DE3-UFWK interactions. Note that 80% (90%) of the variance in SABER (GOCE) can be explained by upper propagating waves.

3.2. Nonlinear Wave-Wave Interactions

Utilizing the method of *Moudden and Forbes* [2010], we analyzed the GOCE and SABER data looking for evidence of nonlinear interactions between DE3 and the UFWK. As discussed in sections 1 and 2, in a fixed local time frame DE3 appears as longitudinal wave-4 ($|s - n| = |-3 - 1| = 4$), hence creating a peak at four cycles in a pseudolongitude spectrum, while the UFWK with $\delta\Omega = 3.5^{-1}$ days and $s = -1$ generates a peak at near 1.3 cycles ($|m - \delta| = |-1 - 3.5^{-1}| \approx \sim 1.3$). The modulation of DE3 by the UFWK produces two sidebands given by the sum and differences of the zonal wave numbers and frequencies [*Forbes and Moudden*, 2012]. In the UT-longitude frame [*Teitelbaum and Vial*, 1991] the sideband waves are the sum (sideband 2) and difference (sideband 1) waves with periods of 1.43 and 0.77 days and zonal wave numbers -2 and -4 , respectively. In a pseudolongitude spectrum these waves appear as one peak at ~ 2.7 cycles (sideband 1) and another at ~ 5.3 cycles (sideband 2). Thus, even though the sideband waves cannot be directly resolved by the satellite sampling, they appear in the pseudolongitude spectra. As emphasized by *Moudden and Forbes* [2010], this methodology only provides insights for interactions between PWs and nonmigrating tides. Sideband peaks for PW interactions with migrating tides fall on top of the PW peak.

Evidence of UFWK modulation of DE3 is found in both SABER and GOCE, as presented in Figure 7 for SABER temperature, Figure 8 for GOCE density, and Figure 9 for GOCE wind. Figure 7a shows the yearly averaged pseudolongitude spectrum for SABER temperatures, followed by the daily amplitudes of DE3 (Figure 7b), UFWK (Figure 7c), sideband 1 (Figure 7d), and sideband 2 (Figure 7e). Looking at the spectrum in Figure 7a it is easy to detect the wave-4 peak at four cycles (mainly due to DE3), the UFWK peak at 1.3 cycles and the DE3-UFWK interaction at ~ 2.7 cycles (sideband 1) and ~ 5.3 cycles (sidebands 2). These peaks are also evident in GOCE density (Figure 8a) and GOCE wind (Figure 9a).

The peak at 1.0 cycle present in both SABER and GOCE could in principle be caused by D0, DW2, SW1, and SW3. D0, SW1, and SW3 are generally quite small around the equator [see *Truskowski et al.*, 2014], leaving DW2 as the probable cause of this wave-1 structure. We will leave for future investigation to explore whether this wave propagates from the mesosphere to the middle thermosphere, similar to DE3. Its interaction with the UFWK would result in peaks at 0.3 and 2.3 cycles, which are not clearly identifiable in the spectra.

Figure 7a, Figure 8a, and Figure 9a present clear evidence of nonlinear interactions between DE3 and the UFWK both at 100 km and 260 km. Figures 7b–7e, Figures 8b–8e, and Figures 9b–9e demonstrate that for periods of strong DE3 and UFWK, the interaction of the UFWK with DE3 produces sidebands that can reach amplitudes very much comparable to the amplitudes of the waves originating them (7 K in the temperatures, 4% in the densities, and 7 m/s in the winds). This suggests that nonlinear wave-wave interactions are a type of complexity that needs to be taken into consideration to accurately model thermospheric variability.

From Figures 7a–7c we notice that sideband 1 tends to have greater amplitudes than sideband 2 both at 100 km and 260 km. As previously reported, sideband 1 has a period of 0.77 days and zonal wave number -4 (compared to sideband 2 that has period 1.43 days and zonal wave number -2). As DE3-UFWK nonlinear interactions probably occur at altitudes lower than 100 km, the vertical propagation of the sidebands may depend on zonal mean winds at altitudes below 100 km (for SABER) and below 260 km (for GOCE). For

Figure 11. Same as Figure 10, but for GOCE density. Also here the total fit (Figure 10k) reproduces well the observations (Figure 10b), indicating that the sum of wave-1 to wave-4, the UFKW, and the interaction DE3-UFKW can adequately describe the latitude and longitude variability.

eastward propagating waves (such as DE3 and the UFKW), the frequency is Doppler shifted to higher absolute values in regions of westward wind and to lower absolute values in regions of eastward wind [Forbes, 2000]. In regions where dissipation is important, waves with large Doppler-shifted frequency are less effectively damped than those with smaller Doppler-shifted frequency; all other things being equal, wavefields exhibit larger amplitudes where Doppler shifting to higher absolute frequencies occurs. Generally, higher zonal wave numbers correspond to shorter vertical wavelengths and hence more susceptibility to dissipation. Thus, greater amplitudes for sideband 1 cannot be explained by interaction with the mean wind field. We have no definite explanation on why one sideband might be more readily excited than another, or why both might be excited during one period of time and not another, or why both might be excited during one period of time and not another (concerning the latter, there may be a relationship to the cross correlation between DE3 and UFKW).

3.3. Implications for Longitudinal Variability

Figure 10a shows the 21 day average pseudolongitude spectrum for SABER temperatures centered on DOY 160 (9 June 2011) and is an average of about 4 h in local time (from 11:00/23:00 on DOY 150 to 15:00/03:00 on DOY 170). We selected this period because both DE3 and the UFKW have large amplitudes, thus offering the best opportunity to investigate the longitudinal variability due to their interaction. The UFKW peak at ~1.3 cycles, the DE3 peak at 4 cycles, and their sideband peaks at ~2.7 cycles (sideband 1) and ~5.3 cycles (sideband 2) are evident in Figure 10a. Figure 10 also presents the observations (Figure 10b), sum of wave-1 and wave-2 (Figure 10c), wave-3, wave-4, the UFKW, the secondary peaks (Figures 10d–10g), the sum of wave-1

Figure 12. Same as Figure 10, but for GOCE wind. Also here the total fit (Figure 10k) reproduces well the observations (Figure 10b).

to wave-4 (Figure 10h), the sum of wave-4 and the UFKW (Figure 10i), the sum of wave-1 to wave-4 and the UFKW (Figure 10j), and the total fit including the DE3-UFKW interactions (Figure 10k). The total fit is the sum of wave-1 to wave-4, the UFKW, and the interaction between DE3 and the UFKW.

Clear longitudinal variations are apparent. The total fit (Figure 10k) reproduces well the observations (Figure 10b), indicating that the sum of wave-1 to wave-4, the UFKW, and the interaction DE3-UFKW can adequately describe the latitude and longitude variability. Comparing Figure 10k with Figure 10j, one can see the importance of secondary waves in explaining longitudinal variability. Figure 10i shows the relevance of the combined effect of the wave-4 (mainly DE3) and the UFKW, while Figures 10c–10h clarifies the relative importance of wave-1 to wave-4, the UFKW, and the combined wave-1 to wave-4 for generating longitude variations.

Similar results are found in GOCE density (shown in Figure 11) and GOCE wind (shown in Figure 12) at 260 km. Figures 11 and 12 are at fixed local time since GOCE has a Sun-synchronous dawn-dusk orbit. The variance for all the components calculated around the equator (latitude $\pm 12^\circ$) is listed in Table 3. Note that 65% of the variance in SABER temperature and 75% in GOCE wind is due to the sum of wave-1 to wave-4 and the UFKW. If we include the sidebands, this value rises to 80% for the temperatures and 92% for the winds. Although longitude variations due to the UFKW and wave-4 dominate, Figures 10 to 12, and Table 3 demonstrate that the contribution of secondary waves to the total longitude variation can be quite large and should be accounted for.

Figure 13. (a) Daily $F_{10.7}$ (magenta line) and 3 h ap (green line). (b) Variance of the total fit (black line), UFKW+DE3 (red line), UFKW (blue line), DE3 (green line), $F_{10.7}/ap$ (cyan line) for GOCE density. (c) Same as Figure 13b except for GOCE wind. The total fit includes wave-1 to wave-4, the UFKW, and the sidebands produced by the DE3-UFKW interaction. Individually, DE3 and the UFKW are responsible for 10% to 40% of the total variance, while their combined effect ranges from 20% to 60% during most of the year. The $ap/F_{10.7}$ contribution is limited to 10–20%, while the variance of the total fits ranges between 60% and 80%.

3.4. Relative Importance of Vertically Propagating Waves and Geomagnetic Solar Effects

In sections 3.1–3.3 we showed the importance of DE3, the UFKW, and their nonlinear interactions in explaining day-to-day variability. Here we seek to evaluate the relative importance of geomagnetic solar effects and vertically propagating waves in producing thermospheric variability. Since geomagnetic activity and solar flux effects are known to be relatively small below 120–150 km, we performed our analysis on GOCE data only.

Daily $F_{10.7}$ and 3 h ap values for the year 2011 are shown in Figure 13a. The variance due to $F_{10.7}/ap$ effects, DE3, UFKW, and the total fit is shown in Figure 13b for GOCE residual densities and in Figure 13c for GOCE residual winds. The total fit includes wave-1 to wave-4, the UFKW, and the sidebands produced by the DE3-UFKW interaction. Individually, DE3 and the UFKW are responsible for 10% to 40% of the total variance, while their combined effect ranges from 20% to 60% during most of the year. What we discover by looking in Figures 10b and 10c is that the $ap/F_{10.7}$ contribution is limited to 10–20%. As mentioned in section 2, geomagnetic and solar effects are likely underestimated by the $ap/F_{10.7}$ fits. This would be caused by short-period geomagnetic and solar EUV variability not captured by the ap and $F_{10.7}$ indices (which are only a partial representation of the global geomagnetic and EUV variability). These errors are embedded in the unexplained variance (difference between the total fits and the unit), which varies from 10% to 40% during most of the year. Nevertheless, the variance of the total fits ranges between 60% and 80%, indicating that the majority of thermospheric variability is caused by vertical propagating waves. This suggests that in relatively quiet geomagnetic periods, waves coming from below (and their interactions) tend to dominate the dynamics of the thermospheric system, while geomagnetic and solar effects are of secondary importance. Note that upward propagating migrating tides (and their interactions with the UFKW) are also candidate for some unexplained variance shown in Figure 13, but their effect is not the primary interest of this study and would only reinforce the conclusion that upward propagating tides represent the most significant contribution to the observed thermospheric variability.

4. Conclusions

Using SABER temperatures near 100 km and GOCE winds and densities near 260 km, DE3 and the UFKW are identified as dominant sources of day-to-day variability. We determined that over 60% of the variance in DE3

and the UFKW at 260 km can be traced back to variability occurring at 100 km. This shows that both DE3 and the UFKW propagate from the lower to the middle thermosphere. The not perfect agreement between the two heights is ascribable to additional complexities introduced by wave dissipation, the presence of zonal mean winds, wave-wave interactions, and inherent transience. We also found evidence of nonlinear interactions between DE3 and the UFKW, generating sidebands responsible for up to 10% to 20% of the day-to-day and longitudinal variability.

We determined that at low latitudes the combined effect of DE3, the UFKW, and their interactions account for 20% to 60% of the total variability. While the combined effect of wave-1 to wave-4, the UFKW, and DE3-UFKW interactions explained 60–80% of the total variability, while at most 20–40% could be ascribed to geomagnetic and solar effects.

To summarize our findings,

1. DE3 and UFKW are found to propagate from 100 km to 260 km on daily-monthly time scales and to account for large day-to-day and longitudinal variability at both heights.
2. The presence of nonlinear interactions between DE3 and the UFKW is evidenced both in the lower and middle thermosphere. DE3, the UFKW, and secondary waves due to their interaction all combine to account for over 50% of the total short-term variability, while the sum of waves 1–4, the UFKW, and the secondary waves account for up to 80% of the observed variability.
3. Between 60% and 80% of the total thermospheric variability can be traced back to vertically propagating waves and their interactions, about 10–20% is due to geomagnetic and solar effects, and 10–20% to other unexplained processes.

This study demonstrates that vertically propagating waves represent an important contribution to thermosphere variability. Additionally, nonlinear wave-wave interactions are shown to produce secondary waves with amplitudes that can be as large as the waves producing them. This demonstrates that wave-wave interactions are responsible for nonnegligible variability and should be accounted for when analyzing thermospheric variability in nonlinear models and satellite data.

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