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Key Points:

- Ten secondary waves (SWs) due to interactions between diurnal tides and ultrafast Kelvin waves (UFWK) are identified and quantified
- A triad between two UFWK and DE3 is discovered
- The SWs modify the way that the lower atmosphere couples with the ionosphere

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Exploring Wave-Wave Interactions in a General Circulation Model

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Abstract Nonlinear interactions involving Kelvin waves with (periods, zonal wave numbers) = (3.7d, $s = -1$) (UFWK1) and = (2.4d, $s = -1$) (UFWK2) and $s = 0$ and $s = 1$ quasi 9 day waves (Q9DW) with diurnal tides DW1, DW2, DW3, DE2, and DE3 are explored within a National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIME-GCM) simulation driven at its ~ 30 km lower boundary by interpolated 3-hourly output from Modern-Era Retrospective Analysis for Research and Applications (MERRA). The existence of nonlinear wave-wave interactions between the above primary waves is determined by the presence of secondary waves (SWs) with frequencies and zonal wave numbers that are the sums and differences of those of the primary (interacting) waves. Focus is on 10–21 April 2009, when the nontidal dynamics in the mesosphere-lower thermosphere (MLT) region is dominated by UFWK and when identification of SW is robust. Fifteen SWs are identified in all. An interesting triad is identified involving UFWK1, DE3, and a secondary UFWK4 = (1.5d, $s = -2$): The UFWK1-DE3 interaction produces UFWK4, the UFWK4-DE3 interaction produces UFWK1, and the UFWK1 interaction with UFWK4 produces DE3. At 120 km the dynamic range of the reconstructed latitude-longitude zonal wind field due to all of the SW is roughly half that of the primary waves, which produced them. This suggests that nonlinear wave-wave interactions could significantly modify the way that the lower atmosphere couples with the ionosphere.

1. Introduction

It is now widely recognized that vertically propagating waves serve to dynamically couple the lower atmosphere to the upper atmosphere and ionosphere (e.g., see recent review by Liu, et al., 2016). The wave spectrum consists primarily of gravity waves (GW), solar and lunar tides, planetary waves (PWs), and ultrafast Kelvin waves (UFWK). Vertically propagating tides and UFWK grow in amplitude with height and achieve their maxima between about 80 and 120 km (Forbes et al., 2008, 2009; Gan et al., 2014; Gasperini, Forbes, & Hagan 2017; Lieberman et al., 2013; Talaat & Lieberman, 1999; Zhang et al., 2006), the atmospheric region referred to as the mesosphere-lower thermosphere (MLT). At subauroral latitudes UFWK and tides often dominate the dynamics of this region.

For later reference, for solar thermal tides we adopt the notation DWs (SWs), DEs (SEs) for a westward or eastward propagating diurnal(semidiurnal) tide, respectively, with zonal wave number = s . For a terdiurnal tide, we replace D or S with T, and for zonally symmetric ($s = 0$) oscillations we use D0, S0, and T0.

Between about 100 and 150 km, winds associated with the waves move plasma across magnetic field lines, generating electric fields and currents. The currents produce magnetic field variations that can be measured by magnetometers on the ground. The electric fields map to higher regions of the ionosphere (approximately 200–1,000 km) where they redistribute plasma vis-a-vis $\mathbf{E} \times \mathbf{B}$ drifts. Tides and UFWK with the longer vertical scales ($> \sim 50$ –75 km) penetrate to 200 km and beyond (e.g., Forbes, 2000; Forbes et al., 2014; Oberheide et al., 2011) and further affect plasma densities by driving composition variations and transporting plasma along magnetic field lines (e.g., England et al., 2010; He et al., 2011). Significant neutral atmosphere temperature, wind, and density variability also accompanies the wave spectrum throughout the ionosphere-thermosphere-mesosphere (ITM) system (100 to approximately 500 km).

The upper atmosphere and ionosphere variability, or near-Earth *space weather* that is driven by waves of lower atmosphere origin has practical consequences. Variations in plasma and neutral densities impact the

integrity of high-frequency tracking, communications, surveillance, and geolocation systems; Global Navigation Satellite System signals; and satellite ephemeris predictions pertinent to orbital debris prediction, collision avoidance, and reentry. The practical relevance of this component of space weather to our 21st century society motivates and intensifies our need to understand the basic physical processes underlying the variability of the ITM.

Elucidating and understanding the origins of day-to-day variability face a couple of major challenges. Ground-based observations are limited by poor geographical coverage, and space-based observations are limited by orbital sampling, particularly with regard to local time. For instance, MLT observations made from the ground provide evidence that an important source of GW variability occurs through modulation by tides (e.g., Beldon & Mitchell, 2010; Fritts & Alexander, 2003; Isler & Fritts, 1996; Thayaparan et al., 1995). Tides in turn are known to be modulated by PW (Beard et al., 1999; Huang, Liu, Lu, et al., 2013; Huang, Liu, Zhang, et al., 2013; Kamalabadi et al., 1997; Pancheva et al., 2000, 2002; Pancheva & Mitchell, 2004). However, the sparse geographical coverage of these measurements precludes a global perspective. Space-based evidence of PW-tide interactions exist (Forbes & Moudden, 2012; Forbes & Zhang, 2017; Gasperini et al., 2015; Gasperini, Forbes, Doornbos, & Bruinsma, 2017; Pedatella & Forbes, 2012) that provide a global view, but the methodologies that are necessarily employed often yield multiple solutions, which cannot be explicitly deconvolved.

General circulation models have provided some important insights into wave-wave interactions (Chang, Palo, & Liu, 2011; Gan et al., 2017; Moudden & Forbes, 2011; Nguyen et al., 2016; Palo et al., 1999; Pedatella, Liu, & Hagan, 2012). These are mainly confined to PW-tide interactions since such models do not have the spatial resolution to resolve the smaller-scale (tens of kilometers) part of the GW spectrum. PW-tide simulations have addressed quasi 2 day wave (Q2DW) interactions with SW2 (Palo et al., 1999) and DW1 (Chang, Palo, & Liu, 2011; Nguyen et al., 2016); quasi 6 day wave (Q6DW) interactions with DW1, DE2, and DE3 (Pedatella, Liu, & Hagan, 2012) and with DW1 and SW2 (Gan et al., 2017); and UFKW-DE3 interactions (Gasperini, Forbes, & Hagan, 2017). These studies confirm that PW-tide interactions yield two secondary waves (SWs) each with the sum (+) or difference (−) of both frequency and zonal wave number of the two primary waves, in agreement with theoretical prediction (Teitelbaum & Vial, 1991, hereafter TV91). That is, the interaction between any nontidal wave (frequency = $\delta\Omega$ and zonal wave number = m) and any tide (frequency = $n\Omega$ and zonal wave number = s) gives rise to (+) and (−) SW as follows (TV91):

$$\cos(\delta\Omega t + m\lambda) \times \cos(n\Omega t + s\lambda) \rightarrow \cos[(n \pm \delta)\Omega t + (s \pm m)\lambda], \quad (1)$$

where $\Omega = 2\pi\text{day}^{-1}$, $t = \text{UT (days)}$, $\lambda = \text{longitude}$, $\delta = \text{days}/T$, and T is the nontidal wave period in days.

In addition, SWs are found to propagate as independent oscillations and the SW may propagate into the thermosphere even if the PW remains confined to lower altitudes. Furthermore, the SWs do not necessarily occur where primary wave amplitudes are large. In fact, SW observed in the MLT can be excited at much lower altitudes and benefit from their exponential growth with height resulting in significant MLT amplitudes (Nguyen et al., 2016).

The method of bispectral analysis has been occasionally used to provide evidence for PW-tide interactions in connection with ground-based measurements (Clark & Bergin, 1997; Kamalabadi et al., 1997; Rüster, 1994). In addition to the (+) and (−) frequencies arising in (1), nonlinear interactions can also give rise to phase relationships between primary and SW that emerge from higher-order spectral techniques such as bispectrum and bicoherence analysis (Beard et al., 1999). Beard et al. (1999) review the application of these methods and conclude that they are not always reliable as the primary means for detecting nonlinear interactions within the MLT, but instead, they are more useful as *confirmation* that nonlinear interactions exist and are responsible for any attendant SW. Following the practice of other recent PW-tide and UFKW-tide interaction studies noted above, we rely on the specificity of periods and zonal wave numbers in the context of equation (1), along with evidence indicating the presence of potential primary waves, to identify whether or not a given wave is a SW. In contrast to analyses of ground-based observations, global space-based observations and general circulation models provide the important additional constraint of sum (+) and difference (−) *zonal wave numbers* to provide confidence in identifying SW resulting from nonlinear wave-tide interactions.

The present work is motivated by a number of previous observational and modeling studies that demonstrate the importance of UFKW in vertically coupling the MLT with the thermosphere and ionosphere at low

latitudes (Chang et al., 2010; Chang, Liu, & Palo, 2011; England et al., 2012; Gasperini et al., 2015; Gasperini, Forbes, Doornbos, & Bruinsma, 2017; Gu et al., 2014; Liu et al., 2013, 2015). Since UFKW are excited by convective processes in the troposphere, they carry the signal of tropospheric variability (including intraseasonal oscillations) to the MLT (Miyoshi & Fujiwara, 2006) and to the thermosphere and ionosphere as well. However, with the exception of the UFKW-DE3 modeling study of Gasperini, Forbes, and Hagan (2017), we do not know to what extent UFKWs interact with the full tidal spectrum to produce SWs that add complexity to the *E* region wind system that communicates its variability to the ionosphere through the generation of electric fields.

Herein, we explore the output of a thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (TIME-GCM) driven by reanalysis data at its lower boundary near 30 km, to address this topic of UFKW-tide interactions. The focus is on April 2009, when the prevalent waves are UFKW and diurnal and semidiurnal solar thermal migrating and nonmigrating tides, as detailed below in section 3.1. We seek to learn the extent to which SWs are produced through interactions between primary waves within the wave spectrum; the nature of the SW temperature and wind oscillations and their symmetry about the equator; the vertical wavelengths and zonal wave numbers of the SW; which SWs propagate into the 100–150 km dynamo region with the potential of generating electric fields; and what degree of spatial-temporal complexity is added to the wave spectrum by the presence of SW.

The following section describes the model adopted for the present study. Section 3 reports on our results followed by discussion and conclusions in section 4.

2. MERRA-Forced TIME-GCM

The TIME-GCM is one of a series of global time-dependent National Center for Atmospheric Research (NCAR) models developed to simulate the circulation, temperature, electrodynamics, chemistry, and compositional structure of the upper atmosphere and ionosphere. The TIME-GCM is a global grid point model that calculates neutral gas heating, dynamics, photoionization, electrodynamics, and the compositional structure of the middle and upper atmosphere and ionosphere from first principles for a given solar irradiance spectrum. The TIME-GCM inherently accounts for atmospheric tides that are excited by the absorption of ultraviolet and extreme ultraviolet radiation in the middle and upper atmosphere. Upward propagating waves excited in the troposphere are specified at the 30 km lower boundary of the TIME-GCM (see below). The upper boundary of the TIME-GCM for this solar minimum simulation is near 500 km. Subgrid-scale gravity waves are necessary for realistic simulations of the mesopause region and are parameterized with a modified Lindzen (1981)-type scheme that is extended to include molecular damping effects in the lower thermosphere. See Roble and Ridley (1994), Roble (1995), and Roble et al. (1988) for a more complete description.

We employ a TIME-GCM simulation covering all of 2009 that is forced at its lower boundary of ~30 km by interpolated 3-hourly dynamical fields from Modern-Era Retrospective Analysis for Research and Applications (MERRA) as described in Häusler et al. (2014, 2015). This simulation uses the high-resolution version of the TIME-GCM, corresponding to $2.5^\circ \times 2.5^\circ$ in latitude and longitude, four grid points per scale height in the vertical direction, and 60 s time step, although only hourly histories are archived. The high-resolution simulation is necessary in order to resolve the waves of interest in this study. We used $F_{10.7}$ values and cross-cap potentials based on *Kp* indices to nominally represent solar radiative and high-latitude forcing during this solar minimum and largely geomagnetically quiescent year.

An attribute of TIME-GCM is that it extends sufficiently deep into the atmosphere to couple with MERRA at an altitude (approximately 30 km) where the latter benefits from an abundance of assimilated data. TIME-GCM is seamlessly coupled to the thermosphere and ionosphere, so that the vertical propagation of both primary and SWs is fully modeled, as well as their effects on both the dynamo generation of electric fields and on *F* region ionization distributions (i.e., equatorial ionization anomaly).

MERRA is a NASA satellite-era reanalysis that uses a version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) (Rienecker et al., 2011). It has a horizontal resolution of 1.25° , temporal resolution of 3 h, and 42 vertical levels from 1,000 hPa to 0.1 hPa (~64 km). It is a physics-based weather prediction model constrained by global data. It was chosen for this investigation due to its comprehensive nature, especially in terms of the hydrological cycle, which is relevant to tidal and UFKW forcing. There is a large number of papers that have used MERRA to study regional and global climate, various types of wave coupling, precipitation, stratospheric water vapor, global energy, and water budgets, and some sort of

validation is part of all of these studies. In particular, a study by Lindsay et al. (2014) evaluates seven different reanalysis products (including several versions of National Centers for Environmental Prediction, European Centre for Medium-Range Weather Forecasts, and MERRA) and finds MERRA to outperform the others. Diurnal tides in MERRA were also validated by Sakazaki et al. (2012). A particular strength of MERRA is the availability of 3-hourly data, whereas other publicly available reanalysis/assimilation products are 6-hourly, precluding resolution of semidiurnal tidal components.

TIME-GCM/MERRA for April 2009 was analyzed to verify that, in terms of periods and zonal wave numbers, amplitudes, and temporal variability, the modeled tides and UFKW conform sufficiently well with observations for the simulation to serve as a realistic laboratory to investigate UFKW-tide interactions. This evidence is provided in the following section.

3. Results

3.1. Identification of Nonlinear Interactions and Secondary Waves (SWs)

As noted in section 1, we chose to analyze April output from TIME-GCM/MERRA2009 due to the prevalence of UFKW with periods between 2 and 4 days during this period; in addition, various tides present in the model appear to be modulated at UFKW periods. This latter point is illustrated in Figure 1, where daily amplitudes of temperature and zonal and meridional wind amplitudes are illustrated for the larger-amplitude tides present during April 2009, namely, DW1, SW2, and DE2. Here we seek to elucidate and better understand the nonlinear interactions between UFKW and these tidal components, the nature of the SW that exist as a result of these interactions, and to what extent the SWs contribute to the total dynamical state.

An initial exploration of the April 2009 model data was performed by constructing zonal wave number versus period spectra to ascertain the waves that were present. Spectra were constructed for the whole month, and for three consecutive 10 day intervals during the month, at altitudes of 80, 90, 100, 110, and 120 km, and at latitudes of -30° , 0° , and $+30^\circ$. This range of heights was chosen due to the greater possibility of detecting SW due to exponential growth from their source, since most measurement techniques capable of detecting SW operate within this height regime, and due to the potential relevance to ionospheric coupling at the highest altitudes. The range of latitudes chosen recognizes that UFKW-tide interactions are most likely to occur at low latitudes. Line spectra were also constructed for each zonal wave number to aid in identification of wave periods. The spectra for the 11–20 April 10 day interval were somewhat more robust in terms of the presence of SW, and all of the following analysis pertains to this 10 day period. (Although frequency resolution was better for the full 30 day spectrum, spectral peaks were diminished in amplitude, either due to reduced phase coherence of the waves during the full month or their relatively low amplitudes during the remainder of April.)

The 120 km temperature spectrum over the equator shown in Figure 2 is representative of the solar tides, UFKW, and SW present in the simulation. The two largest tides in the spectrum at 120 km, DE2 (19 K) and TW3 (22 K), were removed in this depiction to better highlight the smaller waves in the spectrum. Figure 2 also contains most of the SWs found in a wider search that includes other heights and latitudes. A complement to Figure 2 was also prepared where the y axis is frequency instead of period, to better highlight SW with periods less than 1 day, but this did not lead to discovery of any additional SW.

A population of waves are identified as primary waves if interactions among waves in this population produce a second population of different waves in accord with (1), but the reverse is not true. The second population of waves are the secondary waves. Generally, secondary waves also have no known source of excitation except for interactions among primary waves. As with any definition, there are a few special cases, and these will be pointed out in the course of the following discussion. In the case of tides, identification as a primary wave is corroborated by knowledge about their sources within the atmosphere (e.g., Hagan & Forbes, 2002, 2003; Zhang et al., 2010a, 2010b). Furthermore, in order to limit the scope of this paper to the interactions most likely to be of practical significance, we focus attention only on primary-stage interactions, that is, interactions between primary waves. Secondary- or tertiary-stage interactions involving interactions between secondary waves and primary waves or other secondary waves are not considered here, although they can in some cases measurably influence the wave dynamics (e.g., Huang, Liu, Zhang, et al., 2013; Walterscheid & Vincent, 1996).

The full list of primary waves leading to SW through wave-wave interactions according to (1) is provided in Table 1. The corresponding list of SW and the wave-wave interactions that lead to them are provided in Table 2. The quasi 9 day waves $s = 0$ and $s = 1$ are indicated as Q9dW0 and Q9dW1, respectively, and are assumed to be primary waves. The various SW(i) spectral peaks are identified by their corresponding index i in Figure 2.

Figure 1. Latitude versus day of month plots illustrating day-to-day variability in a few representative tides from TIME-GCM/MERRA2009 at 120 km: DW1 (top row), SW2 (middle row), and DE2 (bottom row). The fields plotted are amplitudes of temperature (left column), zonal wind (middle column), and meridional wind (right column).

Note that the spectral peaks corresponding to $i = 1, 2$, and 14 do not appear in Figure 2, but they were found in spectra at other heights and/or latitudes. Although not as clearly identifiable as would exist in observational data, the spectra did exhibit something similar to a background noise level of ≤ 1 K at 100 km and ≤ 2 K at 120 km. Rejecting spectral peaks less than twice these upper-limit values led to the 15 SWs listed in Table 2, which were quite prominent in the spectrum and occurred at periods and zonal wave numbers consistent with interactions between the waves in Table 1. The corresponding confidence levels are given in the caption of Figure 2. There were also a few peaks that were not identifiable.

There are some uncertainties associated with the wave periods attached to each spectral peak in Table 2. First, the frequency resolution for a 10 day spectrum using hourly data is 0.1d^{-1} , which translates to periods of order 0.10d for periods near 1 day. Second, the UFKWs listed as primary waves in Table 1 at nominal periods of 3.7d (UFKW1) and 2.4d (UFKW2) do not have well-defined peaks but instead occur between about 3.4d – 4.1d (UFKW1) and 2.2d – 2.6d (UFKW2) (half-amplitude widths). This is consistent with our previous experience with UFKW in both the model and observational data (Gasparini et al., 2015) that the periods of UFKW are not fixed, as they are highly transient. Consider, for example, UFKW1 interacting with a diurnal tide. The (+) and (–) frequencies are $(1 + 1/3.4)\text{d}^{-1} = 1.29\text{d}^{-1}$, $(1 + 1/4.1)\text{d}^{-1} = 1.24\text{d}^{-1}$, $(1 - 1/3.4)\text{d}^{-1} = 0.71\text{d}^{-1}$, and $(1 - 1/4.1)\text{d}^{-1} = 0.76\text{d}^{-1}$, resulting in a range of periods 1.24d – 1.29d for the (+) SW and 1.32 – 1.41d for the (–) SW. Uncertainties attached to identification of SW from this source are therefore potentially of similar order to that associated with the frequency resolution. The SW periods listed in Table 2 are only identified as SW if their

Figure 2. Period versus zonal wave number(s) spectrum of TIME-GCM/MERRA2009 temperatures at 120 km during 10–20 April 2009. $s < 0$ ($s > 0$) denote eastward (westward) propagating. The numbers correspond to SW in Table 2. Although SW(1), SW(2), and SW(14) are not visible in this spectrum, they do occur at other heights and/or latitudes. The two largest waves in this spectrum, DE2 and TW3, are omitted to better highlight the SW. With the amplitude cutoffs quoted in the text, minimum confidence levels were 90% for SW(1)–SW(2), SW(6), and SW(14)–SW(15); 95% for SW(4) and SW(10)–SW(13); and 99% for SW(3), SW(5), and SW(7)–SW(9).

periods fall within the bounds set by the above uncertainties; of course, matching SW zonal wave numbers with those expected based on (1) sets an important additional constraint to the SW identification.

Tables 1 and 2 also include vertical wavelengths for each of the primary and secondary waves, respectively. Due to the influences of background winds, temperatures, and dissipation, vertical wavelengths vary with latitude and height. The tabulated vertical wavelengths are based on phase gradients between 70–75 km and about 110 km and at latitudes (usually between about $\pm 15^\circ$) where maxima occur and structures are well behaved. Vertical wavelengths for primary waves are discussed briefly in the following section, and vertical wavelengths are considered in light of the theory of TV91 in section 3.4.

Although semidiurnal tides exhibit day-to-day variability over periods of several days during April 2009 (see, in particular, SW2 in Figure 1), no secondary waves due to semidiurnal tide-UFW interactions met the identification criteria described above. Table 2 therefore does not include any secondary waves due to semidiurnal tide-UFW interactions, and SW2 and other semidiurnal tides are absent from Table 1. This result may simply be specific to the 11–20 April 2009, period chosen for analysis.

3.2. Primary Wave Structures and Comparisons With Observations

In this subsection, the mean height versus latitude structures of the primary waves during 10–20 April 2009 (Table 1) are presented; structures of the SW are presented in section 3.3 For the primary waves, comparisons

are provided with available observational data to verify the realism of the model amplitudes. For the SW, the focus is on amplitudes relative to the primary waves and their degree of penetration into the 100–150 km dynamo region, where they are capable of producing electric fields that impact the ionosphere. Relative to the latter point, much of the emphasis will be placed on wind amplitudes. In some cases temperature amplitudes are shown for primary waves in order to facilitate comparisons with available wave determinations in the literature, while the zonal component of the wind is generally shown since many of the waves are the atmospheric manifestation of Kelvin waves with relatively small meridional wind amplitudes. Our intent is to provide a limited yet representative sampling of the primary and SW structures.

Figures 3–6 illustrate height versus latitude structures pertaining to the DW1, DW2, DE2, DE3, UFW1, UFW2, Q9dW0, and Q9dW1 primary waves. For the tides and UFW, the illustrated structures were obtained by fitting TIME-GCM/MERRA2009 output over the 10–20 April 2009 period, while the Q9dW0 and Q9dW1 structures were obtained by fitting over the whole month of April. One of the difficulties faced in assessing the realism of the illustrated amplitudes is that observational data are generally not ideally suited for model comparisons. In the case of ground-based measurements, day-to-day variability of tides can be measured and from which 10 day means can be constructed, but zonal wave numbers cannot be identified. This means that diurnal tidal components (e.g., DW1, DW2, DE2, and DE3) at a given location cannot be distinguished. Similarly, also UFW1

Table 1
Primary Waves Leading to Interactions in Table 2

Wave	Period (days)	Zonal wave number (s)	Mean vertical wavelength (km)
DW1	1.0	1	32
DW2	1.0	2	32
DW3	1.0	3	32
DE2	1.0	−2	60
DE3	1.0	−3	46
UFW1	≈ 3.7	−1	45
UFW2	≈ 2.4	−1	52
Q9dW0	~ 9	0	75
Q9dW1	~ 9	1	120

Table 2
Secondary Waves Resulting From Interactions Between Primary Waves in Table 1

Secondary wave (SW) identifier	Observed (calculated) period (s)	Mean vertical wavelength (km)	Wave interaction Sum (+) or difference (–)
SW(1)	0.79d (0.79d), $s = 0$	xx	[UFWK1 x DW1 (+)]
SW(2)	1.37d (1.37d), $s = 2$	xx	[UFWK1 x DW1 (–)]
SW(3)	0.83d (0.79d), $s = -3$	xx	[UFWK1 x DE2 (+)]
SW(4)	1.40d (1.40d), $s = -1$	xx	[UFWK1 x DE2 (–)]
SW(5)	0.71d (0.70d), $s = 1$	68	[UFWK2 x DW2 (+)]
SW(6)	0.69d (0.70d), $s = 2$	40	[UFWK2 x DW3 (+)]
SW(7), UFWK3	1.67d (1.72d), $s = -1$	70	[UFWK2 x DE2 (–)]
SW(8), UFWK4	1.60d (1.45d, 1.36d), $s = -2$	41	[UFWK1 x UFWK2 (+)], [UFWK1 x DE3 (–)]
SW(9)	0.50d (0.50d), $s = -2$	72	[DE3 x DW1 (+)]
SW(10)	0.50d (0.50d), $s = -1$	55	[DE3 x DW2 (+)], [DE2 x DW1 (+)]
SW(11)	0.88d (0.90), $s = 1$	31	[Q9DW0 x DW1 (+)]
SW(12)	1.17d (1.12d), $s = 1$	32	[Q9DW0 x DW1 (–)], [Q9DW1 x DW2 (–)]
SW(13)	0.88d (0.90d), $s = 2$	32	[Q9DW0 x DW2 (+)], [Q9DW1 x DW1 (+)]
SW(14)	1.17d (1.12d), $s = 2$	31	[Q9DW0 x DW2 (–)]
SW(15)	0.90d (0.90d), $s = 3$	28	[Q9DW1 x DW2 (+)]

Note. Ill-defined vertical wavelengths are denoted as xx.

Figure 3. Height versus latitude structures of a few primary waves that interact with UFWK to produce secondary waves: Top row: DW1 temperature amplitudes (left) and phases (right). Bottom row: DW1 zonal wind amplitudes (left) and DW2 zonal wind amplitudes (right). Phases are defined as longitude of maximum at 0000 UT.

Figure 4. Same as Figure 3 but for DE2 and DE3 in place of DW1 and DW2, respectively.

and UFKW2 cannot be distinguished in ground-based measurements. For space-based measurements, local time precession of the orbit generally means that derived tides represent averages over periods much longer than 10 days, that is, 60 days for the TIMED satellite and 36 days for UARS. Since phases can vary with time, amplitude reduction can occur when deriving average tides over these longer time intervals.

To better inform us about the utility of the satellite observations, two comparisons were made. First, 60 day and multiyear (2002–2010) mean tidal temperatures from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) measurements at 110 km over the equator (Truskowski et al., 2014) were compared with those computed for 2009 using the identical methodology. Amplitudes for DW1, DW2, DE3, and DE2 during 2009 generally exceeded the multiyear mean values by only ~10–20%, while those for DW3 were about twice as large as the multiyear mean values. Second, 10 day mean and 60 day mean tides were calculated from TIME-GCM/MERRA2009 and compared; 10 day mean tides were consistently about 25% larger than the 60 day mean tides in keeping with the finding previously reported by Häusler et al. (2014, 2015). In the following, SABER-derived tides (except for DW3) from several sources that use TIMED observations are discussed without regard to year or multiyear averaging, but keeping in mind that they likely underestimate 10 day mean values by about 25%. It seems reasonable to assume that tides derived from UARS data similarly underestimate 10 day mean values, but by some amount less than 25%.

Figure 3 illustrates temperature amplitudes and phases for DW1 and zonal wind amplitudes for DW1 and DW2. DW1 generally maximizes during March–April, and DW1 temperature measurements are available from SABER data (Gan et al., 2014; Truskowski et al., 2014). Amplitudes of 16 K at 95 km (Gan et al., 2014) and 16 K at 100 km (Truskowski et al., 2014) are consistent with the 17 K and 20 K values depicted in Figure 3 if one takes into account the 25% factor noted above. DW1 zonal wind amplitudes measured by the High Resolution Doppler Imager instrument on UARS yield values of 40 ms^{-1} at 95 km, which are somewhat larger than the 25–30 ms^{-1} values in Figure 3, and may benefit from 36 day versus 60 day averaging. In terms of vertical structure, TIME-GCM/MERRA2009 indicates a DW1 temperature peak near 110 km. SABER DW1 temperatures peak near 100 km according to Gan et al. (2014), although the Zhang et al. (2006) result, which is a 120 day mean, reveals a peak near 115 km. In this regard the Gan et al. (2014) results should be taken as more credible,

Figure 5. Same as Figure 3 but for UFKW1 and UFKW2 in place of DW1 and DW2, respectively.

since they used a more recent version of SABER data, and the inversion technique is less reliable above 110 km. In conclusion, TIME-GCM/MERRA2009 appears to reasonably approximate, and possibly underestimate, the observed DW1 in the MLT.

Observed DW2 amplitudes are generally largest during September–March and near minimum during April, whereas TIME-GCM/MERRA2009 DW2 is large during September–December and April–May. April DW2 zonal wind magnitudes from UARS observations (Forbes et al., 2003; Oberheide et al., 2006) maximize at about $4\text{--}6\text{ ms}^{-1}$ between about between 15 and 35° latitude in each hemisphere, significantly lower in amplitude than the $10\text{--}15\text{ ms}^{-1}$ values shown in Figure 3. However, Oberheide et al. (2006) show amplitudes of 16 ms^{-1} during February. SABER DW2 temperature amplitudes during April peak at about $2\text{--}4\text{ K}$ over the equator near 105 km altitude (Gan et al., 2014; Truskowski et al., 2014), whereas TIME-GCM/MERRA2009 DW2 temperature (not shown) also peaks at 105 km but with an amplitude of $12\text{--}14\text{ K}$. SABER temperature amplitudes during 2009 do not exceed 8 K, but the 25% factor suggests that 10 day mean DW2 amplitudes of 10 K are attainable. We conclude that TIME-GCM/MERRA2009 considerably overestimates observed DW2 amplitudes during April but provides a reasonable characterization of this wave during other parts of the year.

DW3 is not mentioned much in the literature, but it does consistently appear in SABER spectra (Forbes et al., 2008; Truskowski et al., 2014). DW3 is thus a regular feature of the MLT although it does vary considerably from year to year (Forbes et al., 2008). TIME-GCM/MERRA2009 shows a temperature peak of $3\text{--}4\text{ K}$ for DW3 over the equator near 100 km (not shown) and an amplitude of $2\text{--}3\text{ K}$ at 110 km. Multiyear spectra at 110 km show amplitudes of order $2\text{--}3\text{ K}$ at 110 km (Truskowski et al., 2014) but during April 2009, values as high as 8 K are seen at 100 km and 110 km. TIME-GCM/MERRA2009 amplitudes of DW3 thus do occur during individual years, and investigation of its potential influences in the present context and with the modeled amplitudes constitutes a meaningful exercise.

Figure 4 illustrates temperature amplitudes and phases for DE2 and zonal wind amplitudes for DE2 and DE3. Truskowski et al. (2014) show an amplitude of 3 K at 110 km between about $\pm 20^\circ$ latitude for DE2 during April, while Forbes et al. (2008) indicate its peak height to lie between 110 and 115 km. The DE2 amplitude at similar latitudes and 110 km in TIME-GCM/MERRA2009 is 12 K, and a broad peak exists between 115

Figure 6. Height (30–100 km) versus latitude ($\pm 50^\circ$) structures of quasi 9 day primary wave amplitudes in TIME-GCM/MERRA2009. Top row: $s = 0$ (Q9dW0) and $s = 1$ (Q9DW1) zonal wind amplitudes. Bottom row: $s = 0$ (Q9dW0) and $s = 1$ (Q9DW1) temperature amplitudes.

and 140 km. Truskowski et al. (2014) do indicate DE2 amplitudes at 110 km to exceed 6 K during June–July and December–January. TIME-GCM/MERRA2009 thus overestimates DE2 by at least 75%.

DE3 temperature amplitudes from SABER exhibit a primary maximum during July–September and a secondary maximum during March–April (Truskowski et al., 2014). At 110 km, SABER temperature analyses reveal an amplitude of 6–9 K at 110 km for April (Gan et al., 2014; Liu et al., 2015; Truskowski et al., 2014), whereas TIME-GCM/MERRA2009 amplitudes are of order 10–11 K at 110 km (not shown). SABER DE3 temperatures peak near 110 km, whereas those from TIME-GCM/MERRA2009 exhibit a broader peak between 110 and 130 km (not shown). For DE3 eastward wind amplitudes over the equator for April, Talaat and Lieberman (1999) find values of 5 ms^{-1} at 100 km and 10 ms^{-1} between 112 and 118 km, which can be compared with the $\sim 7 \text{ ms}^{-1}$ and 14 ms^{-1} amplitudes depicted in Figure 4. Forbes et al. (2003) and Oberheide et al. (2006) indicate DE3 zonal wind amplitudes of order $6\text{--}8 \text{ ms}^{-1}$ at 95 km, in good agreement with Figure 4. Figure 4 also shows peak values of DE3 zonal wind to occur between 115 and 130 km, whereas UARS observations indicate a peak height for DE3 zonal wind at 110–115 km (Lieberman et al., 2013). Overall, DE3 appears to be reasonably characterized within TIME-GCM/MERRA2009.

Figure 5 depicts temperature amplitudes and phases for UFKW1 and zonal wind amplitudes for UFKW1 and UFKW2. SABER temperature measurements reveal UFKW with periods near 3 days with zonal wave numbers of $s = -1, -2$, and -3 throughout the year (Liu et al., 2015; Gasperini et al., 2015; Gasperini, Forbes, Doornbos, & Bruinsma, 2017). Our interest here focuses on UFKW with $s = -1$ as primary waves. These waves exhibit significant intraseasonal and interannual variability (Gasperini, Forbes, Doornbos, & Bruinsma, 2017) with peak amplitudes typically in the range of 4–8 K at 110 km. Specific to April 2009, UFKW amplitudes range between 2 and 6 K at 98 km (Liu et al., 2015). The above SABER analyses of UFKW are performed within 10 day (Liu et al., 2015) and 15 day (Gasperini et al., 2015; Gasperini, Forbes, Doornbos, & Bruinsma, 2017) windows, which compares well with the 10 day window used for TIME-GCM/MERRA. For TIME-GCM/MERRA UFKW1 (UFKW2, not shown) temperature amplitudes are roughly 4 K (4 K) at 98 km and 5 K (7 K) at 110 km, in good agreement with the observations.

Finally, good agreement was found between theory (e.g., Truskowski et al., 2014), TIME-GCM/MERRA2009 and the aforementioned data sources concerning vertical wavelengths of the above primary waves. Vertical wavelengths change with latitude and height due to the effects of background temperature and wind structures

and dissipation, but on average vertical wavelengths for DW1–DW3 are of order of 25–30 km, ~60 km for DE2, and ~45–55 km for UFKW and DE3. The overall conclusion to be drawn from the above comparisons is that TIME-GCM/MERRA2009 captures tidal and UFKW amplitudes and structures in reasonable accord with observations and thus can provide realistic insights into UFKW-tide interactions, the nature of resulting SW, and impacts on the broader dynamical system.

Two of the primary waves listed in Table 1 are the Q9DW0 and Q9DW1 planetary waves. The Q9DW1 in SABER data was recently studied by Forbes and Zhang (2015), who termed it a Q10DW1 since the mean period was closer to 10 days, and this wave is commonly referred to as the 10 day normal mode in the literature. Similarities exist between the Q9DW1 temperature structure in Figure 6 with the March results in Figure 2 of Forbes and Zhang (2015) in that there are two maxima in height at middle to high latitudes in each hemisphere, with minimum values near the equator. This is consistent with the Q10DW1 normal mode, which is antisymmetric about the equator. Above about 90 km in both SABER data and TIME-GCM/MERRA2009, deviations from this behavior occur with significant amplitudes in the low-latitude region. Forbes and Zhang (2015) suggest that this may be the manifestation of the first symmetric mode of the Q10DW1 induced by the mean wind field. Q10DW1 temperature amplitudes in Figure 6 are roughly consistent with those in Forbes and Zhang (2015) for April, although they are a factor of 2 to 4 smaller than those that occur during other parts of the year. Perhaps, more relevant to the problem at hand is the Q9DW1 wind structure illustrated in Figure 6, which overlaps in many ways with those depicted in Figures 3–5, and with amplitudes that are comparatively nonnegligible; thus, conditions for nonlinear interaction appear to exist. Nevertheless, the overall importance of Q9DW1 may be underestimated in TIME-GCM/MERRA2009 during April.

Zonally symmetric ($s = 0$) oscillations have not been widely studied in the MLT region. Pancheva et al. (2009) analyzed SABER temperature data for October 2003 to March 2004 and first revealed the existence of $s = 0$ oscillations in the MLT region. They showed $s = 0$ temperature oscillations that mainly occur above 100 km at amplitudes of order 4–10 K, with periods between about 5 and 25 days and without well-defined seasonal variation. Pancheva et al. (2009) speculated that the strong oscillations above 100 km were connected with GW dissipation modulated by the planetary waves at lower levels. Amplitudes below 100 km were only of order 1–2 K. Forbes and Zhang (2015) also produced results for $s = 0$ oscillations in temperature, which remain unpublished. For April 2009, they found temperature amplitudes of order 1–2 K between 60 and 100 km in the Southern Hemisphere and between 90 and 100 km in the Northern Hemisphere. TIME-GCM/MERRA2009 thus slightly overestimates the observed Q9DW0 and provides a more symmetric depiction. As with Q9DW1, Q9DW0 zonal winds extend to low to middle latitudes and thus could, in principle, interact nonlinearly with the other primary waves in Table 1 and Figures 3–5.

3.3. Secondary Wave Amplitude Structures

In Figures 7–9 we depict the zonal wind amplitude structures of most of the SWs listed in Table 2. The top row of Figure 7 depicts the (+) and (–) SW resulting from interaction between UFKW1 and DW1, namely, SW(1) = [0.79d, 0] and SW(2) = [1.37d, W2], where the content within the bracket provides the period in days, direction of zonal propagation (east or west) and the magnitude of zonal wave number; 0 denotes a zonally symmetric oscillation. The bottom row of Figure 7 is the (+) SW resulting from interactions between UFKW2 and DW2 and DW3, respectively: SW(5) = [0.71d, W1] and SW(6) = [0.69d, W2]. SW(5) and SW(6) have the most coherent amplitude and phase (not shown) structures, extend more prominently into the 100–150 km region, and thus are likely to have the greatest ionospheric impacts through the generation of dynamo electric fields. SW(5), the largest amplitude SW in Figure 7, is more symmetric like in terms of phase with a mean vertical wavelength of about 75 km. The phase structure of SW(6) is more asymmetric about the equator, with a vertical wavelength near 40 km.

The top row of Figure 8 depicts the (+) and (–) SW resulting from interaction between UFKW1 and DE2: SW(3) = [0.83d, E3] and SW(4) = [1.40d, E1]. The bottom row of Figure 8 illustrates SW(7) = [1.67d, E1], which is the (+) wave from the UFKW2–DE2 interaction, and SW(8) = [1.60d, E2] (calculated from (1) to be [1.45d, E2]), which is the (+) wave produced by UFKW1 interacting with UFKW2. SW(8) at [1.36d, E2] also arises as the (–) SW from the UFKW1–DE3 interaction. We note the larger amplitudes of the SW in Figure 8 compared with those in Figure 7. SW(7) and SW(8) share some common characteristics with UFKW1 and UFKW2. These SWs have phase structures that are symmetric like about the equator, especially above 110 km. They also have temperature structures that are equatorially centered, and given their similarity with the zonal wind structures in Figure 8, we conclude that they are Kelvin waves. All of this should not be surprising, since UFKW1, UFKW2, and DE2

Figure 7. Height versus latitude structures of zonal wind amplitudes of four SWs resulting from UFKW-tide interactions: Top row: SW(1) and SW(2). Bottom row: SW(5) and SW(6). Refer to Table 2 for periods and zonal wave numbers of these SWs and the nonlinear interactions that produced them.

are all basically Kelvin waves, albeit distorted about the equator to some degree. In the following, we will refer to SW(7) and SW(8) as UFKW3 and UFKW4.

The three waves UFKW1, UFKW4, and DE3 form an interesting triad. As indicated above the model UFKW4 = [1.36d, E2] can arise from UFKW1 interacting with DE3. UFKW4 can in turn interact with DE3 [1.0d, E3] to produce [3.23d, E1] $\approx$ UFKW1 as a (−) SW. Moreover, [0.96d, E3] $\approx$ DE3 is the (+) SW arising from the UFKW1–UKFW4 interaction. We note that the second interaction mentioned here is one of those exceptions where we consider a secondary wave interacting with a primary wave.

Figure 9 illustrates most of the waves resulting from interaction between either Q9DW0 or Q9DW1 and DW1 or DW2: SW(11) = [0.88d, W1], SW(12) = [1.17d, W1], SW(13) = [0.88d, W2], and SW(14) = [1.17d, W2]. The amplitudes of these waves also exceed those in Figure 7. Referring to Table 2 for details, we note that more than one interaction may be involved in producing SW(12) or SW(13) but that SW(11) results from the (+) Q9DW–DW1 interaction, and SW(14) results from the (+) Q9DW0–DW2 interaction. With the exception of SW(14), the zonal wind structures of all of these SWs are similar to those of DW1 and DW2 plotted in Figure 3. SW(11)–SW(14) all have temperature and phase structures similar to DW1 and DW2. These waves are essentially sidebands of DW1 and DW2, and it should not be surprising that they share the same amplitude and phase structures.

SW(9) = [0.5d, E2] = SE2, SW(10) = [0.5d, E1] = SE1, and SW(15) = [0.90d, W3] are not plotted since this would not bring additional relevant information to the discussion. SE2 is a well-known product of DE3–DW1 interaction as first reported in Hagan et al. (2009) and is also known to be excited directly in the troposphere (Hagan & Forbes, 2003). Therefore, we have not considered SE2 to be a SW here. Truskowski et al. (2014) put forth arguments that SE1 is not excited in the lower atmosphere, but perhaps through nonlinear interaction involving SE2 and a stationary planetary wave with $s = 1$. Table 2 asserts the additional possibilities that SE1 is a SW that can arise from DE3–DW2 or DE2–DW1 interactions.

Figure 8. Same as Figure 7 but for SW(3), SW(4), SW(7), and SW(8) in place of SW(1), SW(2), SW(5), and SW(6), respectively.

3.4. Secondary Wave Phase Structures

In their theoretical work on PW-tide interaction, TV91 introduced the simple exponential dependence $\exp(k_{SW}z)$ for the vertical structures of the secondary waves where k_{SW} is the vertical wave number of the (+) or (−) SW and z is altitude. Following Spizzichino (1969) and similar to (1), this leads to the relation $k_{SW} = k_T \pm k_\delta$ where k_{SW} , k_T , and k_δ are the vertical wave numbers of the sum and difference secondary waves, the tide, and the nontidal modulating wave, respectively. A similar relationship for the secondary wave phases (omitted from (1) can also be deduced: $\phi_{SW} = \phi_T \pm \phi_\delta$, and which sometimes accompanies (1) in the literature. The vertical wave number relationship is more conveniently written in terms of vertical wavelengths (Pancheva & Mitchell, 2004):

$$\lambda_{SW} = \frac{\lambda_T \lambda_\delta}{\lambda_\delta \pm \lambda_T}. \quad (2)$$

Pancheva and Mitchell (2004) applied (2) to observations of 23 day and 15 day modulations of the semidiurnal tide in the MLT over Esrange (68°N, 21°E). They found good agreement between observed vertical wavelengths of secondary waves and those calculated from (2). They furthermore noted that although the SW had relatively close frequencies $((2 \pm \delta)\Omega)$, the vertical structures are quite different. It is apparent from the nature of (2) that the (−) SW vertical wavelength will always be larger than that of the (+) SW.

Given the success of Pancheva and Mitchell (2004), (2) was applied to the current population of primary waves and SWs, without any success in virtually all cases. As one example, consider interactions between UFKW1 ($\lambda \approx 45$ km) and DE2 ($\lambda \approx 60$ km) (refer to Figures 4 and 5), which lead to (+) SW(3) and (−) SW(4). The mean vertical wavelength for DE2 represents an average based on the equator (76 km) and +20° latitude (43 km). Note that the amplitude and phase structures of these primary waves are reasonably well behaved, except for two obvious breaks in smooth phase progression for DE2. Applying relation (2) using a 60 km mean vertical wavelength for DE2 yields vertical wavelengths of 26 km for SW(3) and −180 km for SW(4). The negative vertical wavelength implies a trapped or evanescent solution as opposed to vertically propagating. Using the values of 76 km and 43 km for DE2 yields vertical wavelengths for SW(3) and SW(4) of 45 km and −110 km, and 22 km and 967 km, respectively. Actual temperature amplitude and phase structures for SW(3) and SW(4) are

Figure 9. Height versus latitude structures of zonal wind amplitudes of four SWs resulting from interactions between the 9 day oscillations with $s = 0$ (Q9dW0) and $s = 1$ (Q9dW1) and the DW1 and DW2 tides. Top row: SW(11) and SW(12). Bottom row: SW(13) and SW(14). Refer to Table 2 for periods and zonal wave numbers of these SWs and the nonlinear interactions that produced them.

illustrated in Figure 10. We note that the phase structures below about 100 km are rather complex, and it is not even possible to identify a representative mean value for the vertical wavelengths of these waves, which is why no value is provided in Table 2. SW(4) does emerge as a well-defined Kelvin wave-type oscillation above 110 km, and this transition will be discussed further below.

As a second example, consider the UFKW2-DE2 interaction, which leads to (–) SW(7) and which we previously named UFKW3. Amplitude and phase structures for SW(7) are also illustrated in Figure 10 and are very well behaved. Using the mean value of DE2 vertical wavelength of 60 km yields a vertical wavelength for SW(7) of –390 km, while the values 43 km and 76 km yield 248 km and –164 km, respectively. However, the actual average vertical wavelength of SW(7) is 75 km and does not vary significantly with latitude. Similarly, poor agreement was found for the other SW, including those associated with tidal modulation by the quasi 9 day waves. It appears that results to emerge from (2) are particularly sensitive to the differences in vertical wavelengths of the primary waves, especially when this difference is much smaller than either of the individual wavelengths. The reader can readily experiment with other SW wavelength predictions based on the data in Tables 1 and 2 and equation (2).

To understand the large disparity between (2) and results in this paper, it is instructive to elucidate the present results in the context of the original works of Teitelbaum et al. (1989, hereafter T89) and TV91. T89 investigated generation of two SWs due to nonlinear interaction between DW1 and SW2, and their approach forms the basis for TV91. The SWs were, in fact, (+) TW3 and (–) DW1 (here DW1 is coincidentally also a SW). The starting point for T89 was to solve a first-order set of thermally forced tidal equations (the linearized primitive equations) to get the height-latitude distributions of DW1 and SW2. To get the SW, T89 solved the same set of equations, this time forced by nonlinear advective terms in the momentum and thermal energy equations formed from products of the DW1 and SW2 solutions. Both sets of calculations included latitude- and height-dependent mean winds and temperature structures and resulted in amplitude and phase structures of the SW (which were also latitude and height dependent) without any reference to (2).

Figure 10. Height versus latitude structures of temperature amplitudes (top row) and phases (bottom row) of (left to right) SW(3), SW(4), and SW(7).

The T89 work was a quantitative calculation of SW generation due to interaction between two primary waves and included explicit calculation of SW vertical and horizontal structures. For the interested reader, the whole computational concept of solving a hierarchy of perturbation equations in the context of SW generation is described in a bit more detail by Forbes (2017).

The TV91 work was much less realistic, and, in fact, the main intent appears to have been mainly illustrative. The authors neglected mean winds and assumed a temperature structure dependent on height only. In addition, they made the ad hoc assumption that the SW solutions were separable in height and latitude by assuming the exponential dependence $\exp(k_{SW}z)$ on altitude. The linearized equations reduced to a second-order differential equation with latitude as the single independent variable which was solved at a single nominal height in the MLT; no vertical structures emerged from the calculation. Primary wave inputs to the second-order system of equations were not calculated as in T89. Instead, they assumed single modes (Hough functions) from classical wave theory on a sphere for SW2 and either 16 day or 8 day primary waves, each with single vertical wavelengths based on assumed equivalent depths h_n from classical theory. TV91 did not illustrate the latitude structures of the SW to emerge from this calculation. *The main point is that the relation $k_{SW} = k_T \pm k_\delta$ was an assumed input to the TV91 calculation, and did not emerge as a result of the theory or the calculation.*

The SW amplitude and phase structures to emerge from the T89 calculations possess significant latitude and vertical structure unlike any of the associated individual Hough modes for the same wave period and zonal wave number. This is because the nonlinear advective forcing terms (and their derivatives) that drive the SW equations have, by their nature, very complex latitude-height distributions (see, e.g., SW forcing distributions resulting from interaction between the 2 day wave and DW1 in Nguyen et al., 2016, their Figure 7). These forcing distributions, and their response, are also very complex and project onto multiple Hough modes spanning a range of vertical wave numbers. The response, and the Hough modes that dominate the response, evolves with height due to mean wind and dissipative filtering. This means that SW vertical wavelengths vary with height and latitude. *The conclusion is that one cannot assume a priori that wave-wave interactions lead to SW that are well expressed in terms of a single vertical wavelength, or that there is a simple relationship between the vertical wavelengths (or phases at a given height) of SW and primary waves.*

Figure 11. Latitude versus longitude reconstructions of zonal winds at 90 km based on primary waves DW1, DW2, DW3, DE2, DE3, UFKW1, and UFKW2 and the secondary waves that resulted from interactions between them: SW(1)–SW(8) and SW(10). The left and right columns correspond to two consecutive days separated by 24 h. From top to bottom the panels include primary waves only, secondary waves only, primary waves, and secondary waves combined and raw output from TIME-GCM/MERRA2009, which includes all waves contained in the simulation (minus the zonal mean at each latitude).

In terms of UFKW-tide interactions and the generation of SW, TIME-GCM/MERRA2009 is a more sophisticated version of T89 in that it solves for the primary waves, SW and background atmospheric structure (i.e., zeroth-order equations according to T89) in a fully coupled nonlinear sense. For the same reasons expressed in connection with T89, the relation between vertical wavelengths of PW and SW expressed in (2) is not expected to hold in general. This is especially true if the SW structures have evolved substantially between the primary altitudes of generation and the MLT region focused on here. As the SWs encounter eddy and molecular dissipation in the upper mesosphere and lower thermosphere, they begin to shed the higher-order short wavelength Hough modes and emerge as more well-behaved and well-defined vertically propagating waves at higher altitudes. The transition of SW(4) to a Kelvin wave-like oscillation above 110 km in Figure 10 is a good

Figure 12. Same as Figure 11 but at 120 km.

example. The successful use of (2) to predict SW vertical wavelengths by Pancheva and Mitchell (2004) may have occurred under a special set of local conditions that conformed optimally with the assumptions underlying TV91. More experimental, theoretical, and modeling work is needed to better understand the disparity in success between Pancheva and Mitchell (2004) and the results presented here.

3.5. Impact of Secondary Waves on Spatial-Temporal Variability

In this section we briefly explore the impacts of SW generation on the overall dynamics, in terms of both spatial and temporal variability. Since our focus is on UFKW-tide interactions, we consider the primary waves DW1, DW2, DW3, DE2, DE3, UFKW1, UFKW2, and the SW in Table 2 that are identified as resulting from these primary waves: SW(1)–SW(8) and SW(10). Figures 11 and 12 present results for the zonal wind at 90 and 120 km, respectively, obtained from the 10 day mean structures referred to in connection with Figures 3–8. Figure 11 (first row) shows the reconstructed latitude versus longitude structures of zonal wind for the primary waves alone, for UT = 0000 (left) and UT = 2400, 1 day later (right). Referring back to Figures 3–5, zonal wind structures are dominated by DW1, DW2, and DW3 at 90 km. The primary wave structures reflect the zonal wind

maxima that characterize these tidal components near 30° latitude and do not significantly change amplitude or phase structure from 1 day to the next. Figure 11 (second row) similarly depicts the reconstructed zonal wind field based on the aforementioned SW. We note significant departures from the latitude-longitude structures of the primary waves, although by and large still characterized by two major maxima and minima in longitude. The range of SW amplitudes ($\sim \pm 9 \text{ ms}^{-1}$) is about a factor of 6 less than that of the primary waves. Also, due to the mixture of periods and zonal wave numbers constituting the secondary waves, one can see significant changes in the structures from 1 day to the next and the longitudes of maxima/minima of major features. However, the aggregate latitude-longitude structures obtained by combining both primary and SWs do not differ much from those due to the primary waves alone, due to the relatively small amplitudes of the SW. Figure 11 (third and fourth rows) illustrates the total wave field (with the zonal mean at each latitude removed) in the simulation and provides a qualitative measure of how well the above subset of primary and secondary waves accounts for the total dynamic state at 90 km.

Figure 12 provides the same information as Figure 11 at 120 km. Both the primary and SWs show substantial variability from 1 day to the next; in the case of primary waves, the UFKWs are exerting their greater influence at this altitude. The dynamic range for the latitude-longitude structures due to SW alone (-20 to $+30 \text{ ms}^{-1}$) is roughly half that of the primary waves (-50 to $+35 \text{ ms}^{-1}$), a much larger fraction than at 90 km. This is due in part to the fact that DW1, DW2, and DW3 do not penetrate very effectively to 120 km and is also due to exponential growth of the SW. There may also be a small contribution due to SW generation between 90 and 120 km.

The major structural features in latitude-longitude structures for the primary waves alone reflect minor changes when the SWs are added (compare first and third rows from the top in Figure 12), but the dynamic range of the latitude-longitude zonal wind field due to primary waves alone is increased by $\sim 25\%$. However, comparison with the bottom panels of Figure 12 shows that the primary and SWs examined in this exercise represent less than half the total picture; in particular, semidiurnal and terdiurnal tides and their potential secondary waves due to UFKW interactions are omitted. Moreover, the above comparisons are performed using primary and SW structures that are 10 day averages and therefore do not fully capture the day-to-day variability that exists. A full examination of transience attached to both primary and secondary waves in the context of nonlinear wave-wave interactions in TIME-GCM/MERRA2009 is deferred to future work.

4. Summary and Conclusions

In this paper the NCAR TIME-GCM model, forced at its ~ 30 km lower boundary with 2009 output from MERRA, is used to explore nonlinear wave-wave interactions in the MLT. Focus is placed in April 2009, when the nontidal wave dynamics is dominated by UFKW. Tides during this period exhibit significant day-to-day variability over time scales of order of 3–4 days and amplitudes of about 25–50% with respect to mean values (cf. Figure 1). The existence of nonlinear wave-wave interactions between pairs of observed primary waves is determined by the presence of (+) and (–) SW predicted according to the criteria defined in Teitelbaum and Vial (1991). Since the model possesses excellent coverage in time and longitude, identification of SW is strongly constrained by the specificity of *both* their periods and zonal wave numbers. In order to limit the study to a reasonable scope, we focus attention only on secondary waves detected above a 90% confidence level, and subsequent interactions between secondary waves and primary waves or other secondary waves are not considered.

In this paper we chose to focus on the 11–20 April 10 day interval, since identification of SW peaks was more robust than in spectra covering the full month of April. Although frequency resolution was better for the full 30 day spectrum, spectral peaks were diminished in amplitude, likely due to reduced phase coherence of the waves during the full month. This is a common problem encountered in analyses of ground-based data seeking to identify secondary waves due to wave-wave interactions (Beard et al., 1999). As explained in the text, a shortcoming is that secondary waves due to semidiurnal tide-UFKW interactions were not identifiable during this 10 day period. The current study therefore focuses on diurnal tide-UFKW interactions.

Two UFKWs serve the role of primary waves in this simulation: $[3.7\text{d}, E1] = \text{UFKW1}$ and $[2.4\text{d}, E1] = \text{UFKW2}$. Zonal winds associated with UFKW1 and UFKW2 attain amplitudes of about 12 ms^{-1} at 105 km and 120 km altitude, respectively. Tides and UFKWs that serve the role of primary waves and their zonal wind amplitudes within the 110–120 km height region include DW1 (18 ms^{-1}), DW2 (10 ms^{-1}), DW3 (3 ms^{-1}), DE2 (20 ms^{-1}),

DE3 (14 ms^{-1}), UFKW1 (9 ms^{-1}), and UFKW2 (10 ms^{-1}). Amplitudes of the above tides in the model are of similar amplitude to those in observations but do not necessarily share the same seasonal-latitudinal variabilities. However, the current work is mainly aimed at exploring the nature and impacts of SW resulting from UFKW-tide interactions, and the selected simulation period provides ample opportunities to pursue this goal.

The main results of this study can be summarized as follows:

1. Nonlinear interactions and the secondary waves (SWs) that they produce are plentiful in the MLT. Considering the interactions between DW1, DW2, DW3, DE2, and DE3 with two Kelvin waves, UFKW1 and UFKW2, 10 SWs from 12 wave-wave interactions are identified. Additional SW can theoretically be generated by these UFKW-tide interactions, but they are not detected. Some waves are likely dissipated before reaching the MLT depending on their vertical wavelength or Doppler-shifted frequency. Other SW may not be excited as efficiently as the ones that are detected. Further theoretical development and modeling focusing on these issues is needed.
2. Additional five SWs originating from seven wave-wave interactions between DW1 and DW2 and the quasi 9 day waves with $s = 0$ and $s = 1$ are detected.
3. UFKW1, UFKW4, and DE3 form a triad wherein the UFKW1-DE3 interaction produces UFKW4, the UFKW4-DE3 interaction produces UFKW1, and UFKW1 interaction with UFKW4 produces DE3. This result will hopefully encourage other researchers to see if other such triads exist and to further develop theory and modeling to assess the significance of such triads on the character of the wave spectrum.
4. The three secondary waves, SW(3), SW(4), and UFKW3 in Table 2, are also discernible in the spectra at the 30 km altitude (not shown) where MERRA output is fed into the TIME-GCM. This suggests that the nonlinear interactions leading to these waves are occurring below 30 km, perhaps even in connection with latent heat forcing. These SWs can propagate to the MLT region and achieve significant amplitudes due to exponential growth. However, the same nonlinear interactions will generate these SWs between 30 km and the MLT. It is not possible within the framework of the TIME-GCM/MERRA2009 results to separate the contributions of these two sources on, for example, the amplitudes of SW(3), SW(4), and UFKW3 at 120 km.
5. It is demonstrated that the simple relation (Spizzichino, 1969; Teitelbaum & Vial, 1991) between the vertical wave number of a SW (k_{SW}) in terms of the vertical wave numbers of the interacting tide (k_T) and longer-period nontidal wave (k_δ): $k_{SW} = k_T \pm k_\delta$ cannot be expected to hold in general, since the fundamental assumptions underlying these relations are violated in the actual atmosphere or within realistic simulations such as TIME-GCM/MERRA2009. The same is true of the relative phase relationship at a given height or latitude: $\phi_{SW} = \phi_T \pm \phi_\delta$. However, there are occasions where the relationship has been demonstrated to hold (Pancheva & Mitchell, 2004), motivating the need for future theory, modeling, and experimental work to better understand these disparities.
6. At 120 km the dynamic range of the reconstructed latitude-longitude zonal wind field due SW is roughly half that of the primary waves, which produced them. The effects of such changes in *E* region winds on the *F* region ionosphere vis-a-vis dynamo-generated electric fields could turn out to be substantial, as noted by Gan et al. (2017) in connection with SW generated by 6 day wave interactions with migrating tides. However, the present result is not useful for definitive conclusions, since the effects of semidiurnal and terdiurnal tides and the secondary waves potentially resulting from UFKW interactions are omitted. In addition, the above comparisons are performed using primary and SW structures that are 10 day averages and therefore do not fully capture the day-to-day variability that exists.

The present work is an initial exploration of wave-wave interactions in TIME-GCM/MERRA2009. Further insights into the UFKW1-UFKW4-DE3 triad, semidiurnal tide-UFKW interactions, and other issues related to UFKW-tide interactions such as transience are expected to emerge from ongoing efforts involving application of time domain methodologies (such as wavelets) over the full extent of the TIME-GCM/MERRA2009 simulation. These results, as well as ionospheric impacts, will be reported in the future.

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