Response of the thermosphere and ionosphere to an ultra fast Kelvin wave

Loren C. Chang,1 Scott E. Palo,1 Han-Li Liu,2 Tzu-Wei Fang,3 and Chin S. Lin4

Received 15 March 2010; revised 25 April 2010; accepted 28 April 2010; published 28 August 2010.

1 Ultra Fast Kelvin (UFK) waves are eastward propagating planetary waves with periods between 3 and 5 days, which are capable of penetrating into the thermosphere and ionosphere where they may modulate phenomena occurring in this region. A sensitivity study has been conducted to examine the effect of an Ultra Fast Kelvin wave on the thermosphere and ionosphere using the NCAR Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) under June solstice solar minimum conditions. It is found that realistic ultra fast Kelvin waves with amplitudes in the MLT region of approximately 20–40 m s⁻¹ in zonal wind fields and 10–20 K in temperature fields, can result in approximately 8–12% perturbations in hourly neutral density at 350 km, as well as hourly total electron content (TEC) perturbations of 25–50% in regions corresponding to the equatorial ionization anomalies (EIAs), with the largest relative changes resolved during the nighttime due to the lower electron densities. The electrodynamical calculations in the model were then disabled to identify the relative importance of ionospheric electrodynamics and direct wave propagation in generating the aforementioned changes. The subsequent results show that changes in thermospheric neutral density are relatively insensitive to the presence of the dynamo electric field, while UFK wave modulation of the dynamo accounts for most of the TEC perturbations due to changes of ionospheric vertical plasma drift.


1. Introduction

2 Upwards coupling of waves and tides from the mesosphere and lower thermosphere (MLT) region into the upper thermosphere and ionosphere have been of great interest in recent years, particularly in the context of the eastward propagating s = 3 nonmigrating diurnal tide (DE3). Signatures of DE3 have been detected in the ionosphere F-region, thermosphere neutral densities and exosphere temperatures (Immel et al., 2006; Lühr et al., 2007; Forbes et al., 2009), in addition to those of other migrating and nonmigrating tidal components (Forbes et al., 2008). In addition to atmospheric tides, which occur at harmonics of a solar day, planetary waves with periods of multiple days have also been observed in the ionosphere. Haldoupis et al. (2004) detected periodicities in sporadic E critical frequencies near the 2, 5, 10, and 16 day periodicities of the Rossby normal modes known to occur in the lower and middle atmosphere. Ultra fast Kelvin waves with periods between 3 and 5 days have also been detected in ionospheric minimum virtual height (h'F) [Takahashi et al., 2006] and maximum critical frequency (foF2) [Takahashi et al., 2007]. Similar periodicities were also resolved in the variation of F layer electron densities [Fagundes et al., 2005], evening F-layer virtual height [Fagundes et al., 2009a], as well as equatorial spread F [Fagundes et al., 2009b]. Fagundes et al. [2009a] attributed these oscillations in ionospheric parameters with periods of days to the influence of propagating planetary waves, characterizing them as traveling planetary wave ionospheric disturbances.

3 The primary focus of this study is the transmission of ultra fast Kelvin waves into the thermosphere and ionosphere. Kelvin waves are eastward propagating planetary waves that are excited sporadically in the lower atmosphere by tropical convective activity. Propagating upwards through the equatorial middle atmosphere, Kelvin waves are confined to low latitudes by the Coriolis force, with the equator serving as a waveguide. A distinctive feature of such equatorial Kelvin waves in the middle and lower atmosphere is that they are symmetric about the equator in zonal wind and temperature fields, but are virtually absent in low latitude meridional winds - a consequence of the geostrophic balance that exists in the meridional wind fields. Kelvin waves with periods longer than about 6 days are classified as slow and fast Kelvin
waves, with periods of 10–20 days and 6–10 days, respectively. Such slow and fast Kelvin waves have relatively short vertical wavelengths and are usually confined to altitudes below the stratopause [Salby et al., 1984]. However, ultra fast Kelvin (UFK) waves have periods in a band ranging from roughly 3 to 5 days, and vertical wavelengths in the range of 30 km or more for zonal wavenumber 1, increasing with wave frequency. This allows such waves to penetrate into the MLT region or higher altitudes, driving changes further up in the thermosphere and ionosphere [Lieberman and Riggin, 1997; Forbes, 2000].

Fast and ultra fast Kelvin waves were observed by Salby et al. [1984] in satellite temperature measurements from Nimbus-7 LIMS, with the latter identified for the first time. Eastward propagating zonal wavenumber 1 disturbances with periods between 3.5–4.0 days as well as 6.7–8.6 days were resolved, with shorter periods occurring higher up in the stratosphere. The structure and dispersion characteristics of the identified waves were found to be in agreement with those of Kelvin modes, and displayed signs of Doppler shifting by mean winds resulting in altered vertical wavelengths. Satellite wind observations from the High Resolution Doppler Interferometer (HRDI) by Lieberman and Riggin [1997] found signatures of UFK waves with periods around 3 days and zonal wavenumbers (s) 1–3, coherent in latitude and altitude. An s = 1 UFK wave event in late July 1994 was observed to occur in the aforementioned study, maximizing at the equator around 105 km altitude with zonal wind amplitudes as high as 60 m s⁻¹. Radar observations of UFK waves at near-equatorial radar sites have shown zonal wind amplitudes in the range of 10–30 m s⁻¹ around 90 km altitude, with durations around 10–20 days [Riggin et al., 1997; Younger and Mitchell, 2006; Takahashi et al., 2007].

While appearing intermittently throughout the year, UFK wave amplitudes have been observed to display two annual peaks, though the exact times corresponding to increased UFK wave activity have been found to be variable from year to year. Using equatorial radar wind data from 1993–1997, Yoshida et al. [1999] determined that the first peak in UFK wave activity occurred in January–March during the first two years of observations, but later shifted to March–May. The second peak was observed to be irregular, spreading between July–November. A relation between the UFK waves and the westward phases of the mesospheric semiannual oscillation (MSAO) in February–April and August–October has been suggested, though analysis of radar wind data by Tsuda et al. [2002] found the time between UFK wave activity peaks and MSAO westward wind peaks to be variable from year to year.

Modeling studies by Forbes [2000], using Global Scale Wave Model (GSWM) results calibrated to match observed UFK wave amplitudes in the mesosphere and lower thermosphere, indicated that an ultra fast Kelvin wave with a period of 3 days and with zonal wavenumber 1, could attain amplitudes of 10–25 K in lower thermosphere temperature fields and 10–40 m s⁻¹ in the zonal wind fields of the same region. Additionally, the classical vertical wavelength of the UFK wave was also found to be Doppler shifted upwards by westward mean winds from 56 km to around 70 km, allowing the wave to penetrate well into the lower thermosphere. Simultaneous observations of mesospheric wind fields, h’F, and foF2 by Takahashi et al. [2007] detected signals at UFK wave periodicities in the ionosphere at the same time a UFK wave was observed to occur in mesosphere zonal wind fields, providing observational evidence that UFK waves do have the potential to couple further upwards from the MLT region.

Several coupling mechanisms have been proposed as being capable of connecting perturbations in the MLT region to the upper thermosphere and ionosphere, two of which will be explored in the context of the UFK wave. These mechanisms are modulation of the ionospheric electrodynamicstics and direct propagation of the wave upwards into the upper thermosphere.

Perturbations of zonal wind fields in the vicinity of the of the ionosphere E-region, located around 90–120 km altitude, can generate additional polarization electric fields, which add to the background large scale electric field. This has been suggested as the coupling mechanism for tidal and planetary wave signatures in the ionosphere F region [Immel et al., 2006; Lühr et al., 2007; Takahashi et al., 2007]. Takahashi et al. [2007] also suggested that modulation of the F-region dynamo by a UFK wave might also be a mechanism in explaining UFK wave signatures observed in h’F and foF2, if the waves were capable of penetrating into the 150–200 km altitude range. It has also been suggested that nonmigrating tidal perturbations may extend all the way from the MLT into the upper thermosphere, and it is this direct wave propagation that is responsible for tidal signatures resolved in the neutral thermosphere and exosphere [Forbes et al., 2009], though mechanistic model results by Pogoreltsev et al. [2007] showed that planetary waves, including the UFK wave, were dissipated before reaching the ionospheric F2 layer.

In this study, we seek to quantify the relative contribution of these two mechanisms in the context of UFK induced variability to both thermosphere neutral densities and total electron content.

2. Methodology

In order to estimate thermosphere and ionosphere changes due to a UFK wave, and identify the relative contributions of the aforementioned coupling mechanisms, the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) [Roble and Ridley, 1994; Hagan and Roble, 2001] developed at the National Center for Atmospheric Research is utilized. The TIME-GCM spans a vertical domain extending from approximately 30 km in the stratosphere, up to approximately 450 km in the thermosphere during solar minimum conditions. A 5 × 5° horizontal grid, with two points per scale height in the vertical direction, and a time step of two minutes is utilized for this study. The effects of gravity waves in the TIME-GCM are parameterized according to the linear saturation theory of Lindzen [1981], and computed in accordance with the background wind fields. The electrodynamic calculations follow magnetic apex coordinates [Richmond, 1995], and may be deactivated if desired, a feature that will be utilized to understand the importance of wind dynamo modulation in transmitting the UFK wave signal into the thermosphere and ionosphere. The lower boundary of the model allows for planetary waves to be excited by means of periodic perturbations in geopotential height.
Background atmosphere conditions in the TIME-GCM are set to perpetual northern hemisphere summer conditions (day 180), in accordance with the time of year during which the largest UFK wave amplitudes tend to be observed [Tsuda et al., 2002; Forbes, 2000]. Solar activity is low ($F_{10.7} = 75$), and geomagnetic conditions are quiet. Migrating atmospheric tides are forced at the model lower boundaries using monthly profiles from the Global Scale Wave Model (GSWM) [Hagan and Forbes, 2002, 2003]. Nonmigrating tides and planetary waves other than the UFK wave are not used for this study. Prior to the start of the numerical experiments, the model was run for 10 days until a diurnally reproducible state was achieved.

Under the aforementioned settings, hereafter referred to as the default model run, the 3 day period $s = 1$ UFK wave was forced in the TIME-GCM in the following manner: TIME-GCM was executed at steady state (no lower boundary planetary wave forcing) for the first 10 days of the experiment, UFK wave forcing was then applied for a duration of 10 days between days 190–200, then turned off and the model allowed to run on for an additional 20 days until day 220. Two lower boundary forcing amplitudes were utilized with geopotential height perturbations of 17 meters (high UFK forcing) and 10 meters (low UFK forcing), selected to produce a range of UFK wave amplitudes representative of past studies, as will be detailed in the following. Together, the high and low UFK wave forcing settings provide a better understanding of how thermosphere and ionosphere perturbations in TIME-GCM scale with UFK wave amplitude.

Figures 1 and 2 show the amplitudes and phases of the resulting 3 day $s = 1$ UFK wave as a function of latitude and altitude on the day immediately following the ten days of forcing in TIME-GCM (day 201), computed via a linear least-squares fit with 6 day sliding window. Consistent with the calibrated GSWM results of Forbes [2000], the UFK wave amplitudes maximize in the lower thermosphere between 100–120 km. The vertical wavelength is approximately 50 km, and the phase progression is downwards, indicative of upwards energy propagation. For the high UFK forcing case, the maximum amplitude of 41 m s$^{-1}$ in the zonal wind fields near 100 km is consistent with the upper bound established in the calibrated GSWM study of 40 m s$^{-1}$, as are the maximum

![Figure 1](image1.png)

Figure 1. (left) Amplitudes and (right) phases of the ultra fast Kelvin wave forced in TIME-GCM using high UFK forcing settings, as a function of latitude and altitude, for model day 201. Planetary wave fields shown correspond to (top) zonal wind (amplitude contours of 5 m s$^{-1}$), (middle) meridional wind (amplitude contours of 1 m s$^{-1}$), and (bottom) temperature (amplitude contours of 5 K). Phase contours are 30°.
temperature field amplitudes, which are 22 K around 115 km in TIME-GCM, compared to 25 K in GSWM.

[14] Figure 3 shows the UFK wave amplitudes as function of latitude and time for high and low UFK forcing at 90 km, corresponding to the altitude of past ground-based radar observations of UFK waves [Riggin et al., 1997; Younger and Mitchell, 2006; Takahashi et al., 2007]. The zonal wind amplitudes of the high UFK wave at 90 km are around 29 m s⁻¹, which is similar to the range of 25–30 m s⁻¹ for the 3.5 day period UFK wave detected by Takahashi et al. [2007] in meteor radar observations at the same altitude.

[15] The UFK wave in the low UFK forcing case exhibits similar spatial structure as the strong forcing case, with maximum amplitudes of roughly 22 m s⁻¹ in zonal wind fields around 100 km, and 13 K in temperature fields around 115 km, representative of the lower range for UFK waves in the calibrated GSWM runs of Forbes [2000]. The zonal wind amplitudes for the low UFK wave at 90 km are around 16 m s⁻¹, which is lower than that observed by Takahashi et al. [2007].

[16] With both high and low UFK forcing, the meridional wind amplitudes of the UFK wave are smaller than the zonal wind amplitudes in the MLT region, though the latitudinal structure of the meridional wind fields transitions to a form with peaks in the high latitudes above roughly 100 km. This transition is again consistent with the results of Forbes [2000], who attributed the change in meridional structure to the increasing molecular dissipation in the thermosphere.

[17] From these results we conclude that both the high and low UFK wave events utilized in this study are realistic, and consistent with both the upper and lower ranges of UFK wave amplitudes established by past observational and modeling studies.

3. Results: Thermosphere and Ionosphere Sensitivity

[18] We now examine changes in neutral density at 350 km in the presence of the ultra fast Kelvin wave from the default model run, in order to establish the degree to which such a UFK wave can alter the neutral thermosphere. Figure 4 shows the percent change of neutral densities at 350 km in the TIME-GCM with a UFK wave present, relative to a control default run with no UFK wave. The results for the high UFK are shown as a function of latitude and universal time at 0° longitude in the contour plot in the upper panel. The line plot in the lower panel shows the percent change for the high and low UFK forcing levels at the equator for the local value
Figure 3. (top) Zonal wind (2 m s\(^{-1}\) contours), (middle) meridional wind (0.5 m s\(^{-1}\) contours), and (bottom) temperature (1 K contours) amplitudes of the ultra fast Kelvin wave forced in TIME-GCM with (left) high and (right) low UFK forcing, as a function of latitude and time, at 90 km altitude.
The spatial structure of the neutral density change was consistent for both high and low levels of UFK forcing, though the magnitude differed.

The temporal and spatial signature of the UFK wave is clearly visible in the neutral density changes in the time following the onset of wave forcing on day 190, including the 3 day period of the UFK wave, as well as the largest changes occurring about the equator. Although wave forcing is present only between days 190–200, the maximum changes in neutral density occur about 4 days after forcing has ceased, illustrating the time delay between the model lower boundary and the 350 km level. Locally, the neutral densities at the equator can vary by as much as 12% from the control run values with high UFK forcing, and 8% with low UFK forcing. There is also a minor decrease in global mean neutral densities at 350 km by approximately 3% at high UFK forcing, and 8% with low UFK forcing. This is also a minor decrease in global mean neutral densities at 350 km by approximately 3% at high UFK forcing, leading to a slight downward trend in the local neutral density changes. After the UFK wave forcing is turned off, the neutral densities gradually return towards the unperturbed values in the control default run, though minor differences on the order of 1% are still resolved 20 days after UFK wave forcing has ceased.

Figure 5 shows the percent change in hourly total electron content (TEC) between 90 km altitude and the TIME-GCM upper boundary (approximately 450 km) with UFK wave forcing relative to the control default run for all local times at selected longitudes. The longitudes shown correspond to regions where the magnetic equator is near the geographic equator (160°W), south of the geographic equator (75°W), and north of the geographic equator (0° and 120°E). Again, the contour plots correspond to changes resulting from high UFK forcing, which is similar in spatial structure to changes resulting from low UFK forcing. While changes in TEC as high as 50% (25%) are resolved at high (low) UFK forcing, these occur between 2000–2400 LT at the longitudes examined. The changes are particularly large in the equatorial ionization anomalies on the southern side of the magnetic equator. The 3 day periodicity of the UFK wave is again prominent in the TEC changes, with maximum changes resolved around 3–4 days following the end of UFK wave forcing.

To better understand the local time dependence of the relative changes in TEC, the averaged daytime TEC values were computed as the mean between 0600 and 1800 LT for each day, while the nighttime values were computed as the mean between 1800 and 0600 LT the following day, and the relative changes shown in Figures 6 and 7, respectively. While this averaging reduces the magnitude of the relative TEC changes, compared to the hourly values, the significance of daytime and nighttime TEC changes can be established using this method.

Changes in daytime TEC of roughly 15% occurred with high UFK forcing and 10% with low UFK forcing, occurring in the low latitudes. The changes in nighttime TEC
are 25% with high UFK forcing and 15% with low UFK forcing. As will be shown in the next section, the UFK wave is capable of modulating wind fields at ionosphere F region altitudes as suggested by Takahashi et al. [2007], and may produce changes the post-sunset vertical drift (the pre-reversal enhancement) and nighttime ionosphere. Similarly, Fagundes et al. [2009a] attributed traveling planetary wave ionospheric disturbances observed in evening F-layer virtual height during solar maximum to planetary wave modulation of the pre-reversal enhancement electric field. However, the pre-reversal enhancement is relatively weak or absent during summer solstice under low solar activity conditions [Scherliess and Fejer, 1999] as utilized for the TIME-GCM runs shown here, and was not found to be significant in the model results. Thus, the larger changes in the nighttime TEC may mainly be due to the smaller nighttime electron densities. The absolute changes in TEC and its relation to the ionospheric dynamo mechanism will be discussed in the following section.

4. Electrodynamic Modulation Versus Direct Propagation

The degree to which the UFK wave signature is transmitted into the thermosphere and ionosphere directly or through electrodynamic interaction is now examined. Two

Figure 5. Contour plots showing % change in hourly total electron content in model runs with high UFK wave, relative to control run without UFK wave at longitudes of (a) 160°W, (b) 75°W, (c) 0°, and (d) 120°E, as function of latitude and time. Line plots show TEC difference at geographic equator for high (red line) and low UFK (blue line). Dashed orange line denotes magnetic equator in apex coordinates.
additional model runs of TIME-GCM are performed with and without UFK wave forcing (at both high and low UFK forcing levels) in the same manner as in the default run, but with the ionosphere wind dynamo electric fields disabled in both cases. Although the overall distribution of electron densities in the ionosphere will differ significantly without the presence of the dynamo electric fields, the use of a control run with no dynamo effects ensures that the relative change between the wave forcing and control run will illustrate perturbations attributable solely to the presence of the UFK wave.

Figure 8 shows the change induced by a UFK wave in neutral densities at 350 km with no ionospheric electrodynamics calculations. Compared to the neutral density results with the electrodynamics turned on (Figure 4), the lack of the electrodynamical processes does not have a significant effect on the resolved neutral density perturbations attributed to the UFK wave, with maximum relative changes of 10% at the equator in the high UFK forcing case without dynamo electrodynamics, compared to 12% with dynamo electrodynamics. This indicates that the perturbations of thermosphere neutral densities at 350 km are caused by direct propagation of the UFK wave rather than by modulation of the E-region wind dynamo or by ion drag through the perturbations in ionospheric ion density.

[24] Figure 8 shows the change induced by a UFK wave in neutral densities at 350 km with no ionospheric electrodynamical calculations. Compared to the neutral density results with the electrodynamics turned on (Figure 4), the lack of the electrodynamical processes does not have a significant effect on the resolved neutral density perturbations attributed to the UFK wave, with maximum relative changes of 10% at the equator in the high UFK forcing case without dynamo electrodynamics, compared to 12% with dynamo electrodynamics. This indicates that the perturbations of thermosphere neutral densities at 350 km are caused by direct propagation of the UFK wave rather than by modulation of the E-region wind dynamo or by ion drag through the perturbations in ionospheric ion density.

[25] Citing work by Volland and Mayr [1977], Forbes [2000] noted that the solutions to Laplace’s tidal equation corresponding to the meridional structure of Kelvin waves in the highly dissipative thermosphere approached a distinctive thermospheric mode, with meridional structure altered from
that in the lower atmosphere. The characteristics of the UFK wave in the thermosphere were given as latitudinally uniform zonal wind fields, as well as meridional wind and temperature fields proportional to the sine and cosine, respectively, of latitude.

Figures 9 and 10 show the amplitudes of the UFK wave at 350 km in the model runs with and without the ionosphere wind dynamos, at both high and low UFK forcing levels. The UFK wave at 350 km displays similar time evolution to the values from the default run at 90 km (Figure 3). To the first order, the meridional structure of the UFK wave in Figures 9 and 10 resembles that described by Forbes [2000], particularly in the meridional wind and temperature fields, and indicates that the UFK wave continues to influence the neutral thermosphere above 150 km. In the context of the DE3 and DE2 nonmigrating diurnal tides, Forbes et al. [2009] noted that the meridional structure and time evolution of the tidal perturbations in exospheric temperature strongly resembled those resolved in SABER temperatures at 110 km, citing this as evidence of vertical propagation of the nonmigrating tides from the lower thermosphere directly into the exosphere.

While this also appears to be the case for the UFK wave, given that thermosphere zonal winds in the equatorial upper thermosphere were measured to be in the range of 100–150 m s\(^{-1}\) [Liu et al., 2006], the zonal wind amplitudes of around 10 m s\(^{-1}\) (6 m s\(^{-1}\)) of the high (low) UFK wave at 350 km do not appear to be as significant as the wave 4 signatures attributed to the presence of DE3 during its August maximum by Lühr et al. [2007], who observed maximum

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**Figure 7.** Same as Figure 5, but for daily nighttime averaged TEC.
Zonal wind amplitudes of 20–30 m s\(^{-1}\) in August 2004 CHAMP accelerometer measurements. It is possible, however, that the wave 4 signatures in the CHAMP observations include contributions from tidal components other than DE3, which are then aliased into the wave 4 pattern due to the near constant local time sampling of the CHAMP spacecraft [Lühr et al., 2007; Forbes et al., 2008, 2009]. Additionally, we note that predictions of DE3 amplitudes in the upper thermosphere by Oberheide and Forbes [2008] using the method of Hough mode extensions found maximum August zonal wind amplitudes of around 6 m s\(^{-1}\), compared to a monthly mean wind speed of 13 m s\(^{-1}\) from CHAMP. Finally, we note that away from its annual peak during August, DE3 amplitudes are significantly smaller [Oberheide and Forbes, 2008; Forbes et al., 2008]. Additional model runs under March equinox conditions (not shown) corresponding to the other peak in observed UFK wave activity [Yoshida et al., 1999] showed UFK wave amplitudes and neutral density perturbations of magnitudes comparable to those in the June solstice conditions shown here. It is therefore possible, that UFK waves may drive short term variations in thermospheric neutral densities comparable to or exceeding those driven by DE3, particularly if DE3 is in a weaker state. Additional work is needed however, to ascertain the significance of the UFK wave relative to other tides or planetary wave components in the neutral thermosphere during other times of year.

Some differences do exist between the two model runs, as well as with the classical solution. The UFK wave zonal winds show peaks around 60°N and 30°S when the dynamo is turned on, compared to around 30° latitude in both hemispheres when the dynamo is turned off. Similarly, the UFK meridional winds maximize around 60° latitude when the dynamo is turned on, compared to near the poles when the dynamo is turned off, the latter being closer to the thermospheric mode solution of Volland and Mayr [1977]. In contrast, the UFK response in temperature fields is virtually unchanged by the lack of the dynamo electrodynamics. The consistency shown between the UFK wave response both with and without the dynamo at larger spatial scales indicates that there is very little dependence between the presence of the dynamo, and vertical UFK wave propagation into the thermosphere. However, the smaller scale changes involving the locations of the peaks in UFK horizontal wind fields, as well as the slightly smaller UFK wave amplitudes without the dynamo indicate that dynamo electrodynamics can still have a second order effect on the UFK wave structure in the upper thermosphere. It is noted again that the meridional structure of UFK wave meridional wind amplitudes at 350 km more closely approximates the cosine structure predicted by classical theory for the thermosphere [Volland and Mayr, 1977; Forbes, 2000] when dynamo electrodynamics are turned off. Since classical theory does not consider electrodynamic effects, this suggests that the changes in UFK wave structure can likely be attributed to differences in ion drag with and without calculation of the electrodynamic processes.

Figure 11 shows the zonal wind fields of the UFK wave at high UFK forcing near the equator, at 0° longitude. The downward phase progression of the UFK wave is clearly
Figure 9. Ultra fast Kelvin wave amplitudes as function of latitude and time in TIME-GCM at 350 km for (left) high and (right) low UFK forcing. Amplitudes shown for (top) zonal wind, (middle) meridional wind, and (bottom) temperature, with ionosphere wind dynamo turned on.
Figure 10. Same as Figure 9, but with wind dynamo electrodynamics turned off.
visible, with vertical wavelengths of around 50 km below roughly 120 km, implying a vertical phase velocity of roughly 17 km day\(^{-1}\). The vertical wavelength of the UFK wave increases with altitude, becoming evanescent above 150 km. This variation in vertical wavelength is coincident with the rapid decay of wave amplitudes above roughly 150 km due to increasing dissipation. Pogoreltsev et al. [2007] noted in their simulations of upwards propagating planetary waves that the ultra fast Kelvin wave is rapidly damped out in the lower thermosphere below about 150 km. While a significant decrease in UFK wave amplitude is resolved in TIME-GCM above 150 km, the UFK wave amplitudes continue to extend upwards into the thermosphere, albeit at smaller amplitudes.

[30] Direct propagation of the UFK wave above 150 km may not be the only possible explanation for the wave amplitudes in the TIME-GCM neutral thermosphere at 350 km. It is interesting to note from Figure 4, that changes in neutral density are resolved at 350 km in the days immediately following the beginning of UFK wave forcing on day 190, with a pronounced 3 day periodicity being resolved by day 194. Although UFK waves have large group velocities of 10–12 km day\(^{-1}\) [Miyoshi and Fujiwara, 2006], the time delay of 4 days is faster than would be expected for the UFK wave to propagate from the lower boundary at 30 km to the region above 150 km, where the vertical wavelength approaches infinity. It is possible that the earlier changes maybe a reflection of displacements in the vertical column of geopotential height due to the presence of the UFK wave in the lower and middle atmosphere.

[31] Figure 12 shows the change in hourly TEC in TIME-GCM due to the UFK wave when the electrodynamic calculations are turned off. Compared to the hourly changes of up to 50% (27%) resolved in the default model run with high (low) UFK forcing (Figure 5), the TEC here varies by less than 10% (5%) at maximum. The 3 day periodicity of the UFK wave is less dominant, with sub-diurnal perturbations becoming more prominent. This corresponds to a reduction by roughly a factor of 5 compared to the cases where dynamo electrodynamics are included in the model run.

[32] From this, it is clear that most of the UFK wave induced change in TEC from the default run can be attributed to modulation of the ionospheric electric fields through the wind dynamo mechanism by the UFK wave, rather than in-situ forcing or advection by the upwards propagating UFK wave. The dynamo electric fields in TIME-GCM extend throughout the E and F regions, and are relatively constant in the vertical direction during the daytime.

[33] Some indication of how the UFK wave modulates the E-region wind dynamo to generate the TEC changes resolved in the default model run with dynamo electrodynamics turned on can be seen by examining the changes in vertical plasma drift, which is sensitive to the zonal and meridional wind fields in the dynamo region [Fang et al., 2008; Liu et al., 2010]. Figure 13 shows the change in vertical drift at 0° longitude between the default run with and without the high UFK wave, as well as the change in zonal wind fields at selected altitudes spanning the E-region between 100–140 km (also with high UFK forcing). The 3 day periodicity of the UFK wave is apparent in both the vertical drift and the zonal wind fields, while the changes in vertical drift associated with the UFK wave are quite broad, extending about the equator to about 60° latitude. The phases of the UFK wave zonal winds change in altitude due to its upwards propagating nature, as illustrated previously in Figure 11. The vertical drift

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Ultra fast Kelvin wave zonal wind fields at 2.5°S and 0° longitude as function of altitude and time, for high UFK forcing. Contours of 5 m s\(^{-1}\).}
\end{figure}
remains mostly constant throughout the E- and F-regions, and represents the integrated effect of the UFK wave driven changes to the zonal wind fields of the dynamo region.

It is interesting to note that due to the increasing vertical wavelengths of the UFK wave towards 150 km, the phase difference of the zonal wind variation at adjacent altitude levels decreases. However, the eastward electric field which generates the upward vertical drift is a global scale phenomenon, making it impossible to estimate the perturbations of the upward drift through analyzing the perturbations of zonal wind at a specific altitude and longitude. Nonetheless, it is apparent that the ionospheric vertical drift is being affected by the UFK wave in the mesosphere and lower thermosphere region.

A global view of the relation between vertical drift and TEC changes in TIME-GCM is shown in Figure 14, which shows global snapshots of 120 km vertical drift, as well as the absolute change in 120 km vertical drift and TEC with high UFK forcing, as a function of geographic latitude and solar local time. The time steps shown correspond to 1800UT on day 202 and 9 hours later at 0300UT on day 203, which are representative of some of the strongest local changes in dayside and nightside TEC, as well as vertical drift, during the entire model run. From the 120 km vertical drift fields and changes in Figures 14a–14d, the largest absolute changes in vertical drift are resolved near the terminators on the magnetic equator, with maximum values of 8–10 m s$^{-1}$. Comparing the changes in vertical drift to changes in TEC (Figures 14e and 14f),

Figure 12. Same as Figure 5, but with wind dynamo electrodynamics turned off.
regions of enhanced upwards (downwards) drift correspond to regions of increased (decreased) TEC. The zonal wavenumber 1 structure of the ultra fast Kelvin wave is clearly visible in both the difference fields of vertical drift and TEC.

The largest absolute changes in TEC occur during the daylight hours between roughly 0700–1800LT. TEC changes in the model initially occur near the geomagnetic equator during the morning hours. This is manifested in Figure 14e as the 1 TECu decrease occurring between roughly 0700–0900LT. In the time between roughly 1100–1300LT, the equatorially centered changes in TEC transition away from the geomagnetic equator, with the largest absolute TEC changes resolved in regions on either side of the magnetic equator. By 0300UT the following day (9 hours later) (Figure 14f), the region of decreased TEC initially resolved in Figure 14e around 0800LT has increased in absolute magnitude, and is now located on either side of the magnetic equator. The absolute changes in TEC gradually decrease following about 1800LT, consistent with both the decreased nighttime electron densities, as well as the absence of the E-region dynamo during the nighttime. A similar temporal variation is resolved for the region of increased TEC located around 0900LT in Figure 14. The transition of the TEC changes from a single maxima above the magnetic equator after sunrise, to the bimodal form with two maxima on either side of the magnetic equator later in the day is consistent with the observed local time variation of the EIAs [Appleton, 1946; Scherliess et al., 2008]. The changes in TEC therefore correspond to a modulation of the EIAs in longitude and time by the UFK wave.

During the daytime, the TEC changes in TIME-GCM can likely be attributed to the interaction of the UFK wave with the E-region dynamo, as the strongest UFK wave amplitudes occur primarily below 150 km. However, the nighttime TEC and vertical drift changes cannot be attributed to this mechanism, as the E-region dynamo is not present during the nighttime due to recombination. As shown previously in Figures 7 and 12, the large relative changes resolved in nighttime TEC are too large to be explained by advection alone. Given that the UFK wave is still present above 150 km at reduced amplitudes, the nighttime changes in TEC and vertical drift may be driven by modulation of the F-region dynamo. Another potential mechanism is adjustment of the nightside electric fields to balance the changes induced by the UFK wave in the dayside electric field. However, the monotonic decrease in absolute TEC change suggests that the larger relative changes in nighttime TEC may simply be

![Figure 13](image-url)
a reflection of the lower nighttime electron densities. As mentioned previously, while modulation of the pre-reversal enhancement has been proposed to explain postsunset traveling planetary wave ionospheric disturbances observed during solar maximum conditions [Fagundes et al., 2009a], the pre-reversal enhancement is absent during the solar minimum solstice conditions utilized for the TIME-GCM runs shown here. This suggests that the mechanisms and effects of UFK wave induced changes to the ionosphere may vary depending upon the solar cycle.

5. Other Coupling Mechanisms

In addition to the electrodynamic interaction and direct propagation mechanisms examined here, there exist other mechanisms that have the potential to couple dynamics in the mesopause region to changes higher up in the thermosphere and ionosphere. These mechanisms include changes in gravity wave drag, as well as the propagation of child waves generated by mechanism of nonlinear interaction between planetary waves and the atmospheric tides. These two factors are briefly discussed in the context of the UFK wave.

Eddy diffusion in the mesopause region induced by breaking gravity waves have also been shown to be capable of generating changes in thermosphere composition, and thus, neutral density on a seasonal scale [Qian et al., 2009]. Smith [1996] suggested that zonal asymmetries in stratospheric winds could modulate vertically propagating gravity waves to generate planetary scale structures in the upper mesosphere found in HRDI horizontal winds. Similarly, numerical experiments by Jacobi et al. [2006] suggested that gravity wave drag modulated by the period and zonal wavenumber of the quasi-two day wave in the lower atmosphere could act to suppress the quasi-two day wave in the mesosphere and lower thermosphere. Pogorelskev et al. [2007] also partially attributed signatures of longer period planetary waves in the mesosphere and lower thermosphere region, to the filtering of gravity waves by planetary waves in the stratosphere, which then produced planetary wave in the lower thermosphere through in-situ forcing.

However, it should be noted that the UFK wave reaches significant amplitudes primarily in the mesosphere and lower thermosphere, and will have a smaller effect on gravity wave propagation compared to planetary waves with significant amplitudes at lower altitudes (i.e., the quasi-two day wave and the longer period Rossby normal modes). Eddy diffusivities in the lower thermosphere region computed self-consistently by TIME-GCM in the presence of the UFK wave showed modulation amplitudes at the 3 day \( s = 1 \) periodicity of less than 5% of the background values near 100 km. Approximating this 3 day period eddy diffusivity perturbation as a Gaussian in latitude, and applying it to the 97 km lower boundary of the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) [Richmond et al., 1992], the effect on thermosphere neutral densities and TEC were found to be negligible, with changes of less than 1%.

Qian et al. [2009] found that changes in eddy diffusivities in the mesopause region required an e-folding time on the order of 10 days to propagate into upper thermosphere neutral densities at significant magnitudes. It is clear that modulation of eddy diffusivities at the time scale of the 3 day UFK wave period is insufficient to generate the large perturbations in neutral density and TEC resolved in the TIME-GCM default run.

Signatures near the 2, 5, 10, and 16 day periods of the Rossby normal modes have been observed in the ionospheric E- [Haldoupis et al., 2004] and F- regions [Fagundes et al., 2005], despite numerical experiments showing that most of these longer period planetary waves (excluding the quasi-two day wave) are incapable of propagating into the lower thermosphere from the stratosphere [Pogorelskev et al., 2007]. Large ionospheric variability has also been observed at low to mid-latitudes during stratospheric sudden warming (SSW) events [Goncharenko and Zhang, 2008; Chau et al., 2009]. Quasi-stationary planetary waves become large during SSWs, although they are also incapable of propagating into the the low to mid-latitude E-region. It has been proposed that the mechanism responsible for transmitting the signatures of such planetary waves into the ionosphere is through nonlinear interaction with the atmospheric tides [Haldoupis and Pancheva, 2002; Liu et al., 2010]. According to the work of Teitelbaum and Vial [1991], such a wave-tide interaction results in the generation of two sideband “child waves” with frequencies and wavenumbers that are the sum and difference of those of the interacting tide and planetary wave, which may be capable of propagating into regions where the planetary wave cannot. Superposition of the tide and the child waves results in the modulation of the tide at the period of the planetary wave. Liu et al. [2010] demonstrate numerically that the nonmigrating tides from nonlinear interaction of the quasi-stationary planetary wave and migrating tides can strongly modulate the E-region wind dynamo.

While child waves corresponding to a nonlinear interaction between the tide and the UFK wave were resolved in TIME-GCM at double resolution and found to be capable of propagating into the thermosphere, the fact that the UFK wave itself is also capable of propagating into the thermosphere at stronger amplitudes makes the contributions of such child waves much less important. We therefore conclude that the tidal modulation mechanism is much less significant in transmitting the signal of a UFK wave into the thermosphere and ionosphere, compared to the case of a planetary wave incapable of propagating into the thermosphere (e.g., the longer period Rossby normal modes).

6. Summary

A sensitivity study has been performed using the TIME-GCM to quantify the relative effects of ionosphere
wind dynamo modulation and direct vertical wave propagation, in transmitting the signature of a UFK wave into thermosphere neutral densities at 350 km and the total electron content. Both mechanisms are capable of affecting the thermosphere and ionosphere, and have been proposed to explain changes in the upper atmosphere through lower atmosphere wave coupling. Ultra fast Kelvin waves are sporadically occurring low latitude phenomena, with long vertical wavelengths allowing them to penetrate well into the thermosphere and ionosphere.

[45] The results of this study indicate that UFK wave signatures in thermosphere neutral densities at 350 km can be attributed directly to the wave propagating upwards through the thermosphere, with hourly changes around 8–12% for a UFK wave of realistic amplitudes between 20–40 m s$^{-1}$ in lower thermosphere zonal winds. Disabling the model electrodynamics results in higher order changes to the UFK wave structure in the upper thermosphere, likely attributable to differences in ion drag, but the magnitude of the relative neutral density change remains mostly unaffected. In contrast to the smaller effect on the neutral thermosphere, hourly changes in TEC can be as high as 25–50% around the equatorial ionization anomalies, particularly during the nighttime due to the lower overall electron densities. Averaged daytime TECs show relative changes of 10–15%, while averaged nighttime TECs show 15–25% relative change compared to the control run.

[46] Changes in TEC are much more sensitive to modulation of the ionospheric wind dynamos, with maximum perturbations reduced by roughly a factor of 5 when the dynamo in the model is deactivated. Analysis of vertical plasma drift changes in the E-region shows clear signatures of the 3 day UFK wave periodicity, further highlighting the effect of UFK waves in modulating the wind dynamo electric field. The resulting enhancements in upward (downward) vertical drift near the TEC result in regions of increased (decreased) TEC during the daytime hours, with absolute values of TEC changes decreasing following sunset. TEC changes are initially resolved as being roughly centered on the magnetic equator during the morning hours, but transition polewards to locations about the magnetic equator in the hours around local noon, consistent with observations of the local time variation of the EIs.

[47] Other potential coupling mechanisms such as planetary wave modulation of gravity wave drag and tidal amplitude modulation are not important in the context of the UFK wave, which has little effect on gravity wave flux, and is itself capable of propagating into the lower thermosphere at amplitudes stronger than any child waves generated through wave-tide interaction.

[48] Acknowledgments. This work was supported by NSF award ATM-0836518, and the 2009 AFRL Space Scholars Program. Han-Li Liu would like to acknowledge support by the Office of Naval Research (N00014-07-C-0209) and NASA LWS NNX08A091G. The authors wish to acknowledge Art Richmond and Wenbin Wang of NCAR, as well as Frank Marcos and Sam Cable of AFRL for their assistance and advice in this study. Robert Lynch thanks Paulo Fagundes and Hisao Takahashi for their assistance in evaluating this paper.

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L. C. Chang and S. E. Palo, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, 431 UCB, Boulder, CO 80309, USA. (loren.chang@colorado.edu)

T.-W. Fang, Center for Research in the Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309, USA.

C. S. Lin, Air Force Research Laboratory, Hanscom Air Force Base, Bedford, MA 01731, USA.

H.-L. Liu, High Altitude Observatory, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USA.