AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL065671

Key Points:
- A compressed B_z within SIR resulted in sudden high-latitude energy injection
- Sudden energy injection generated gravity waves in the auroral regions
- A wave almost traveled around the Earth once horizontally in the thermosphere

Correspondence to:
J. Guo and X. Feng,
jpguo@spaceweather.ac.cn;
fengx@spaceweather.ac.cn

Citation:
Guo, J., J. M. Forbes, F. Wei, X. Feng, H. Liu, W. Wan, Z. Yang, C. Liu, B. A. Emery, and Y. Deng (2015), Observations of a large-scale gravity wave propagating over an extremely large horizontal distance in the thermosphere, *Geophys. Res. Lett.*, *42*, 6560–6565, doi:10.1002/2015GL065671.

Received 4 AUG 2015
Accepted 4 AUG 2015
Accepted article online 7 AUG 2015
Published online 28 AUG 2015

Observations of a large-scale gravity wave propagating over an extremely large horizontal distance in the thermosphere

Jianpeng Guo[1], Jeffrey M. Forbes[2], Fengsi Wei[1], Xueshang Feng[1], Huixin Liu[3], Weixing Wan[4,5], Zhiliang Yang[6], Chaoxu Liu[1], Barbara A. Emery[7], and Yue Deng[8]

[1]SIGMA Weather Group, State Key Laboratory of Space Weather, NSSC, Chinese Academy of Sciences, Beijing, China, [2]Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado, USA, [3]Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Fukuoka, Japan, [4]Key Laboratory of Ionospheric Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [5]Beijing National Observatory of Space Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, [6]Department of Astronomy, Beijing Normal University, Beijing, China, [7]High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA, [8]Department of Physics, University of Texas, Arlington, Texas, USA

Abstract In this paper we report the detection of a large-scale gravity wave propagating over an extremely large horizontal distance in the thermosphere on 28 July 2006. Specifically, after being launched at the northern auroral region on the dayside, this wave propagated equatorward with phase speeds on the order of ~720 m/s and finally almost traveled around the Earth once horizontally in the thermosphere prior to dissipation. The time taken to dissipate is about 15.5 h. It is the farthest-traveling large-scale gravity wave currently tracked by satellite measurements, made possible by a sudden injection of energy in an unusually clean propagation environment. This experiment of opportunity serves as an important step in furthering our theoretical understanding of gravity wave propagation and dissipation in the thermosphere.

1. Introduction

It is generally accepted that although a wide spectrum gravity waves can be excited at high latitudes by impulsive auroral processes, only low-frequency fast moving waves (with wavelengths of several thousand kilometers) can propagate over large distances in the thermosphere [e.g., *Francis*, 1975; *Richmond*, 1978; *Mayr et al.*, 1990; *Bruinsma and Forbes*, 2010]. However, how far these waves can travel in the thermosphere prior to dissipation remains an open question. This is partly because of the limited temporal and spatial resolution of ground-based and satellite observations tracking gravity wave propagation in the thermosphere [*Mayr et al.*, 1990; *Forbes et al.*, 1995]. It is also partly due to lack of a complete theoretical description of realistic gravity wave dissipation (due to molecular viscosity, thermal conduction, ion drag, nonlinear saturation, and radiative damping *Yiğit et al.* [2008] and *Yiğit and Medvedev* [2015]) for such transient events. In addition, it is difficult to isolate and track individual disturbances within all of the remaining thermosphere variability.

One way of addressing this question is to search for well-defined gravity waves that have propagated large distances from auroral sources using current measurements and then evaluate theoretically their propagation and dissipation in the thermosphere. Toward this end, our initial efforts focused on identifying large-scale (>~1000 km) gravity waves utilizing neutral densities derived from accelerometer measurements on the polar-orbiting CHAMP and GRACE satellites [see *Guo et al.*, 2014]. Within this search, we have discovered the farthest-traveling large-scale gravity wave reported to date, which is the subject of the present paper. This wave was excited in the northern auroral region on the dayside on 28 July 2006 by sudden energy injection (Joule heating and particle precipitation) due to a compressed southward magnetic field component within a stream interaction region (SIR) and almost traveled around the Earth once horizontally in the thermosphere before being dissipated. The following section describes the data utilized in the present study, and section 3 provides our results. A brief discussion of the results follows in section 4.

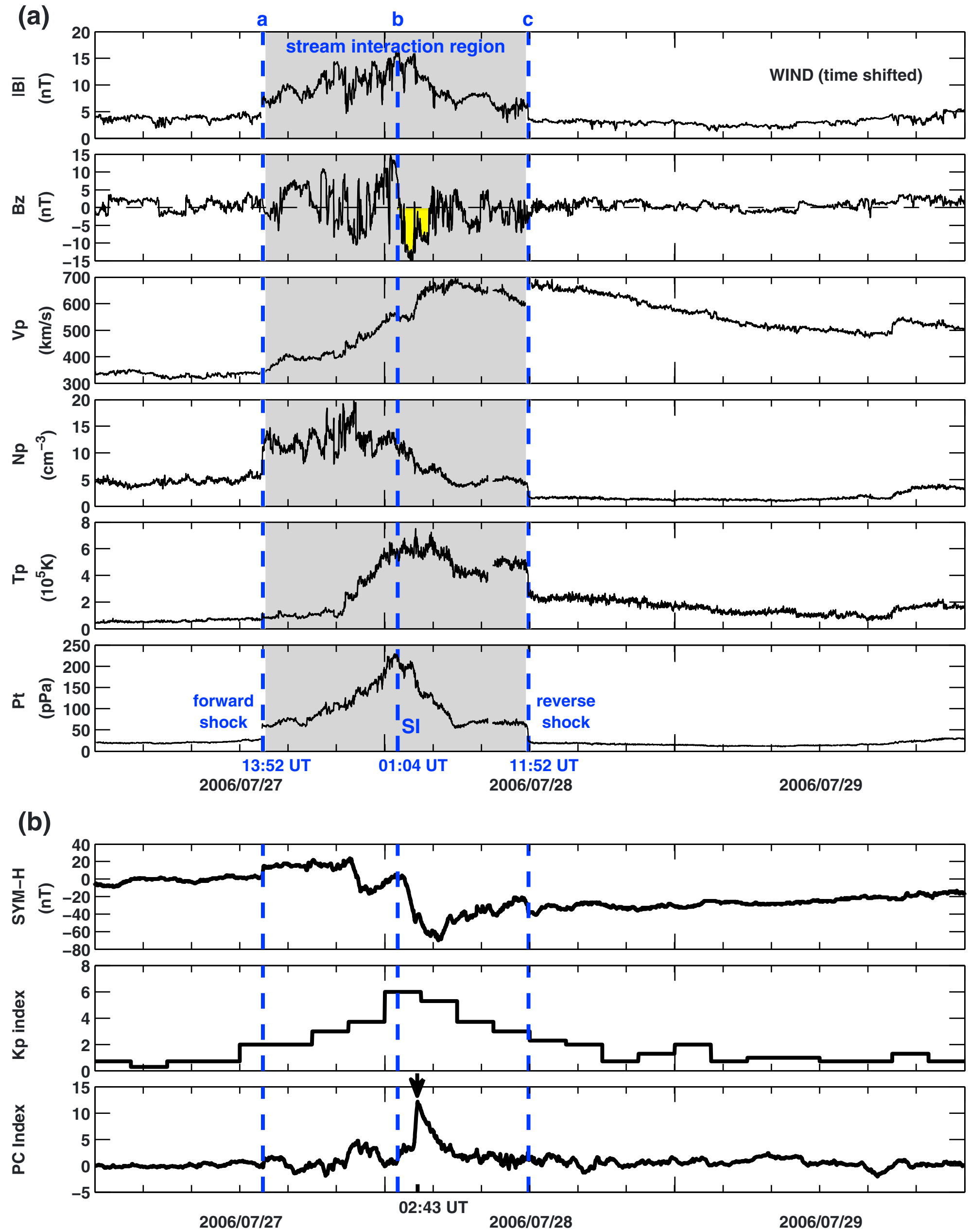

Figure 1. (a) The in situ observation of a SIR by WIND during 27–29 July 2006. From top to bottom: magnetic field magnitude (|B|), southward magnetic field (B_z) in geocentric solar magnetospheric (GSM) coordinates, proton velocity (V_p), proton density (N_p), proton temperature (T_p), and total perpendicular pressure (P_t). All these parameters are shifted 50 min to the nose of the magnetopause. Dashed lines a and c mark a pair of forward-reverse shocks bounding the SIR (gray-shaded region); dashed line b marks the stream interface (SI). The yellow-shaded interval corresponds to the compressed southward B_z component. (b) The resultant geomagnetic activity ($SYM-H$, Kp, and PC indices). The arrow marks the sudden increase in PC index with a peak occurring at 0243 UT on 28 July.

2. CHAMP and GRACE Data

Neutral total mass densities derived from accelerometer measurements on the CHAMP and GRACE satellites are used to reveal and track gravity waves in the present study. The CHAMP satellite was launched in July 2000 at 450 km altitude in a near-circular orbit with an inclination of 87.3°. The two identical satellites GRACE-A and GRACE-B were launched in March 2002 at approximately 500 km altitude, also in near-circular but higher inclination (89.5°) orbits, with GRACE-B following approximately 220 km behind GRACE-A. The total mass densities are obtained from these accelerometer measurements using standard derivation procedures

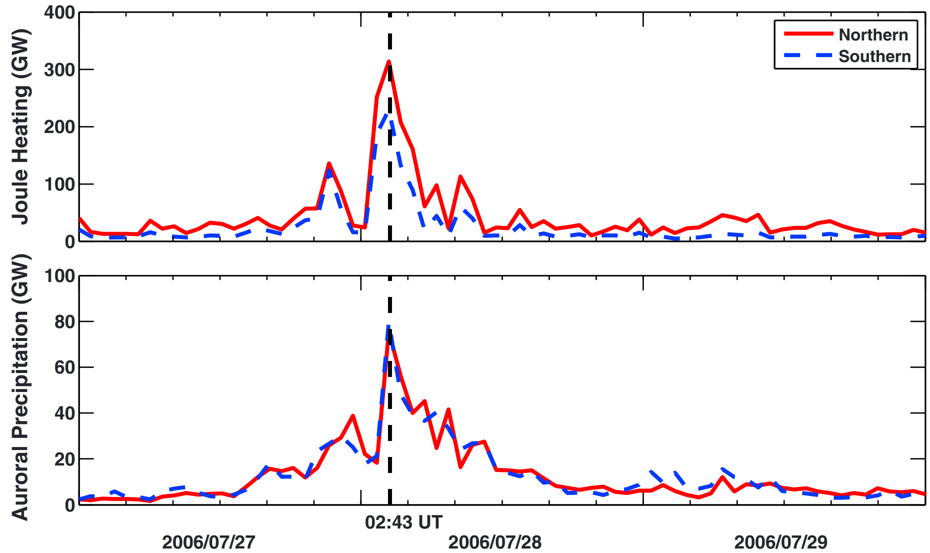

Figure 2. Variation of (top) hourly Joule heating from W05 empirical model and (bottom) hourly particle precipitation from DMSP and NOAA satellites measurements in both hemispheres during 27–29 July 2006. Vertical dashed lines indicate the time of peak Joule heating and particle precipitation, in accord with the sudden increase in the *PC* index at 0243 UT on 28 July.

[*Sutton*, 2011]. All density data are normalized to a constant altitude of 400 km using the NRLMSISE-00 empirical model [*Picone et al.*, 2002]. As the densities from GRACE-A and GRACE-B show very similar variations during the period we focused on, only the GRACE-A observations are exhibited below.

3. Results

Figure 1a shows solar wind plasma and magnetic field data from the WIND spacecraft during 27–29 July 2006 encompassing a SIR formed by a fast stream overtaking a preceding slow stream. The SIR was identified by a compression of interplanetary magnetic field (IMF) $|B|$, an increase of proton speed V_p, an increase of proton number density N_p, an enhancement of proton temperature T_p, and a significant enhancement of total perpendicular pressure P_t (defined as the sum of the magnetic pressure and plasma thermal pressure perpendicular to the magnetic field). A pair of forward-reverse shocks formed at the two edges of the SIR. A stream interface (SI), characterized by the peak of P_t, can be discerned at about 01:04 UT on 28 July (in the shifted time). At the SI, the compressed magnetic field turned southward and remained strong southward (up to −15 nT) for ∼2.5 h (yellow-shaded interval). This southward component triggered a moderate geomagnetic storm as measured by SYM-H and *Kp* indices and resulted in a sudden increase in *PC* index, starting at 02:22 UT and peaking at 02:43 UT on 28 July, which are illustrated in Figure 1b. The sudden increase in the *PC* index might imply an impulsive injection of energy in the high-latitude atmosphere. Figure 2 depicts the variation of hourly average Joule heating and auroral precipitation (electron precipitation and ion precipitation with energies < 20 keV) in both hemispheres during 27–29 July 2006. The Joule heating is calculated from the *Weimer* [2005] model (W05) driven by hourly solar wind data. The typical W05 output is a polar distribution of vertically integrated Joule heating in the Northern Hemisphere. To cover the southern hemisphere, W05 is run with the same solar wind conditions but a flipped interplanetary magnetic field (IMF) by value and a flipped dipole tilt angle, in which the interhemispheric asymmetry has been neglected. The auroral precipitation is estimated from single-pass satellite orbits of the National Oceanic and Atmospheric Administration (NOAA) and Defense Meteorological Satellite Program (DMSP) satellites [cf. *Emery et al.*, 2008]. A significant impulsive increase is revealed in both Joule heating and auroral precipitation in both hemispheres, in accord with the sudden increase in the *PC* index.

Figures 3 and 4 illustrate the CHAMP and GRACE neutral densities at approximate local times of 1645/0445 and 1315/0115 h, respectively, during 27–29 July 2006. As we can see, neutral densities at high latitudes were greatly enhanced in response to the impulsive heat input (due to Joule heating and auroral precipitation) on 28 July, particularly in the Northern Hemisphere. Then large-scale wave-like structures or traveling

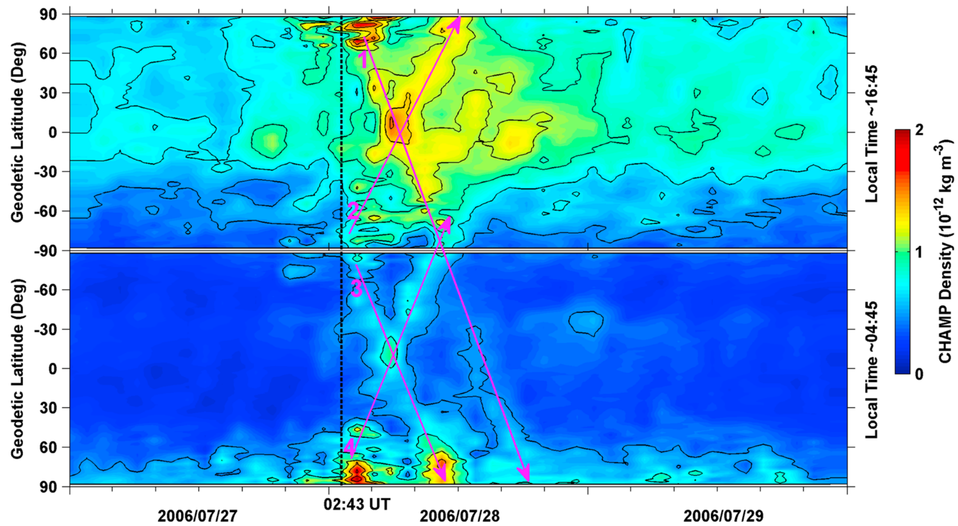

Figure 3. Latitude versus time variations of CHAMP neutral density at 400 km and near (top) 1645 LT and (bottom) 0445 LT (latitude axes in reversed order) during 27–29 July 2006. The black lines represent the contours of density with an interval of 0.25×10^{-12} kg m^{-3}. The vertical dashed line indicates the time of the peak Joule heating and particle precipitation. The magenta arrows show four large-scale gravity waves (1, 2, 3, and 4) propagating from the auroral sources to the equator and into the opposite hemisphere, even across the opposite pole. Wave 1 (launched at northern auroral regions on the dayside) propagated over much larger horizontal distances. It almost traveled around the Earth once in the thermosphere before being dissipated.

atmospheric disturbances, as manifestations of large-scale gravity waves, appeared as expected. By following maxima in the density variations from high to low latitudes and further to the opposite hemisphere, we identify two pairs of propagating large-scale waves launched from the auroral regions, one pair (wave 1 and wave 2) on the dayside and the other (wave 3 and wave 4) on the nightside, which are indicated by the magenta arrows. It is immediately clear that wave 1 traveled much larger horizontal distances in the thermosphere. Specifically, after being launched at the northern auroral region on the dayside, wave 1 propagated equatorward with phase speed on the order of ~720 m/s and encountered wave 2 near the equator, where wave interference occurred, leading to a large density increase. After the constructive interference, they passed through each other and penetrated into the opposite hemisphere. Then, wave 1 crossed the opposite pole (i.e., the southern pole) and continued to propagate on the nightside. Finally, it reached the northern pole and disappeared there. That is, it almost traveled around the Earth once horizontally in the thermosphere before being dissipated. The time taken to dissipate is about 15.5 h. To our best knowledge, it is the

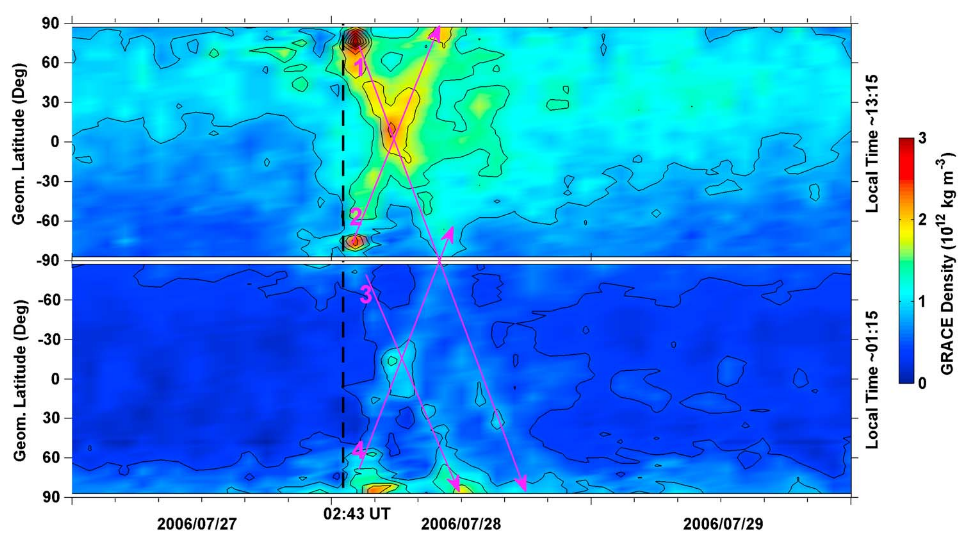

Figure 4. Same as Figure 3 but for GRACE neutral density at 400 km and near (top) 1315 LT and (bottom) 0115 LT.

longest-living and farthest-traveling large-scale gravity wave currently tracked by satellite measurements. Previous work of *Bruinsma and Forbes* [2009] reported that a far-traveling large-scale gravity wave could be tracked for 3/4 of one revolution around the Earth during the Halloween storm of 2003. Thus, our observation moves forward a step toward understanding wave dissipation and specifically how far a wave can travel in the thermosphere before being dissipated and depositing its energy and momentum into the background atmosphere.

4. Discussion

Previous studies have demonstrated that wave-like structures are often obscured by other density variability such as meridional circulation surges [*Fuller-Rowell et al.*, 1994], equatorial density anomalies [*Liu et al.*, 2007], and density perturbations due to solar terminator waves [e.g., *Forbes et al.*, 2008; *Liu et al.*, 2009] and therefore are not always distinctly visible. Such a scenario also occurred in the dayside density responses to the sudden energy injection on 28 July 2006. Fortunately, simultaneous CHAMP and GRACE observations complement each other and thus allow secure identification of the propagation of gravity waves 1 and 2. In contrast, there is very little activity on the nightside besides the wave-like structures, i.e., gravity waves were traveling in a "clean" environment with less contamination by other density variability, allowing us a chance to unambiguously track wave 1 over an extremely large horizontal distance. In order to ensure the accuracy of the identification, a filtering method of *Bruinsma and Forbes* [2009] was applied to the measured densities along the orbit. The results of relative density variations (not shown) suggest that wave 1 indeed can be tracked for one revolution around the Earth but with less clear wave signatures due to the presence of density variability from other sources. It is highly likely that many other observed large-scale waves have done the same thing as wave 1, except the details are obscured and cannot be easily extracted from the polar-orbiting measurements (with limited temporal sampling).

Detection of the farthest-traveling large-scale gravity wave poses a particular challenge for theories and models that aim to explain the properties of aurorally generated gravity wave propagation and dissipation. More discoveries of such waves from future measurements are obviously required to validate and improve physics-based models. These advances in turn would contribute to our understanding of how far aurorally generated gravity waves can travel in the thermosphere and where their energy and momentum is deposited in connection with their dissipation.

Acknowledgments

The research is supported by the Chinese Academy of Sciences (KZZD-EW-01-4), the 973 program (2012CB825601), the National Natural Science Foundation of China (41231068 and 41374187), and the Specialized Research Fund for State Key Laboratories. J. Forbes is supported by NASA Award NNX12AD26G to the University of Colorado. H.L. is supported by JSPS KAKENHI grant 15K05301, 15H02135, and 15H03733. Z.Y. is supported by the National Natural Science Foundation of China (U1231104). We acknowledge CDAWeb for access to the Wind data and the geomagnetic indices (*SYM* − *H*, *Kp*, and *PC*).

The Editor thanks one anonymous reviewer for assisting in the evaluation of this paper.

References

Bruinsma, S. L., and J. M. Forbes (2009), Properties of traveling atmospheric disturbances (TADs) inferred from CHAMP accelerometer observations, *Adv. Space Res.*, *43*, 369–376, doi:10.1016/j.asr.2008.10.031.

Bruinsma, S. L., and J. M. Forbes (2010), Large-scale traveling atmospheric disturbances (LSTADs) in the thermosphere inferred from CHAMP, GRACE, and SETA accelerometer data, *J. Atmos. Sol. Terr. Phys.*, *72*, 1057–1066.

Emery, B. A., V. Coumans, D. S. Evans, G. A. Germany, M. S. Greer, E. Holeman, K. Kadinsky-Cade, R. J. Rich, and W. Xu (2008), Seasonal, Kp, solar wind, and solar flux variations in long-term single-pass satellite estimates of electron and ion auroral hemispheric power, *J. Geophys. Res.*, *113*, A06311, doi:10.1029/2007JA012866.

Forbes, J. M., F. A. Marcos, and F. Kamalabadi (1995), Wave structures in lower thermosphere density from Satellite Electrostatic Triaxial Accelerometer (SETA) measurements, *J. Geophys. Res.*, *100*, 14,693–14,702.

Forbes, J. M., S. L. Bruinsma, Y. Miyoshi, and H. Fujiwara (2008), A solar terminator wave in thermosphere neutral densities measured by the CHAMP satellite, *Geophys. Res. Lett.*, *35*, L14802, doi:10.1029/2008GL034075.

Francis, S. H. (1975), Global propagation of atmospheric gravity waves: A review, *J. Atmos. Terr. Phys.*, *37*, 1011–1054.

Fuller-Rowell, T. J., M. V. Codrescu, R. J. Moffett, and S. Quegan (1994), Response of the thermosphere and ionosphere to geomagnetic storms, *J. Geophys. Res.*, *99*(A3), 3893–3914, doi:10.1029/93JA02015.

Guo, J., H. Liu, X. Feng, W. Wan, Y. Deng, and C. Liu (2014), Constructive interference of large-scale gravity waves excited by interplanetary shock on 29 October 2003: CHAMP observation, *J. Geophys. Res. Space Physics*, *119*, 6846–6851, doi:10.1002/2014JA020255.

Liu, H., H. Lühr, and S. Watanabe (2007), Climatology of the equatorial thermospheric mass density anomaly, *J. Geophys. Res.*, *112*, A05305, doi:10.1029/2006JA012199.

Liu, H., H. Lühr, and S. Watanabe (2009), A solar terminator wave in thermospheric wind and density simultaneously observed by CHAMP, *Geophys. Res. Lett.*, *36*, L10109, doi:10.1029/2009GL038165.

Mayr, H. G., I. Harris, F. A. Herrero, N. W. Spencer, F. Varosi, and W. D. Pesnell (1990), Thermospheric gravity waves: Observations and interpretation using the transfer function model (TFM), *Space Sci. Rev.*, *54*, 297–375.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*(A12), 1468, doi:10.1029/2002JA009430.

Richmond, A. D. (1978), Gravity wave generation, propagation, and dissipation in the thermosphere, *J. Geophys. Res.*, *83*, 4131–4145, doi:10.1029/JA083iA09p04131.

Sutton, E. K. (2011), Accelerometer-derived atmospheric densities from the CHAMP and GRACE accelerometers: Version 2.3, *Tech. Memo*, Air Force Res. Lab., Kirtland Air Force Base, New Mexico.

Weimer, D. R. (2005), Predicting surface geomagnetic variations using ionospheric electrodynamic models, *J. Geophys. Res.*, *110*, A12307, doi:10.1029/2005JA011270.

Yiğit, E., and A. S. Medvedev (2015), Internal wave coupling processes in Earth's atmosphere, *Adv. Space Res.*, *55*, 983–1003, doi:10.1016/j.asr.2014.11.020.

Yiğit, E., A. D. Aylward, and A. S. Medvedev (2008), Parameterization of the effects of vertically propagating gravity waves for thermosphere general circulation models: Sensitivity study, *J. Geophys. Res.*, *113*, D19106, doi:10.1029/2008JD010135.