Effect of a solar flare on a traveling atmospheric disturbance

Liying Qian, Alan G. Burns, Hanli Liu, and Phillip C. Chamberlin

Received 5 April 2012; revised 31 August 2012; accepted 5 September 2012; published 13 October 2012.

[1] It is known that the sudden injection of energy during geomagnetic storms can excite atmospheric gravity waves (AGWs) or traveling atmospheric disturbances (TADs). Together with large-scale circulation, these AGWs/TADs transport energy and momentum away from their sources. In this paper, we investigate possible involvement of AGWs/TADs during solar flares. Model simulations of an X17 flare that occurred on October 28, 2003 shows that AGWs/TADs contributed to flare energy transport from the sunlit South-Pole region to the nightside equatorial region in 3–4 h, resulting in ~10% nightside equatorial neutral density enhancement in the upper thermosphere. These nightside AGWs/TADs have a phase speed on the order of ~750 m/s and a horizontal wavelength on the order of 4000 km. Enhanced solar heating to the thermosphere through enhanced ionization during flares occurs on the entire dayside, with the spatial scale of the increased solar heating being too large to excite AGWs/TADs. Further analysis revealed that strong localized enhancement of Joule heating was produced during the October 28, 2003 flare. This sudden injection of the localized heating, together with preexisting AGWs/TADs excited by moderate geomagnetic activity prior to the flare, produced intensified AGWs/TADs, which propagated energy and momentum to the equatorial region. On the other hand, model simulations showed that, under assumed geomagnetically quiet conditions, strong localized enhancement of Joule heating and AGWs/TADs were not produced during the flare. This interplay between geomagnetic activity and solar flares can be a challenge to space weather monitoring, specification, and forecasting.


1. Introduction

[2] Observations, theoretical analysis, and modeling studies have demonstrated that atmospheric gravity waves (AGWs) or traveling atmospheric disturbances (TADs) can be generated by the Lorentz force of auroral electrojet currents and heat input due to Joule heating and energetic particle precipitation [e.g., Hines et al., 1974; Yeh and Liu, 1974; Richmond, 1978, 1979; Hocke and Schlegel, 1996]. These large-scale waves propagate in the thermosphere and have horizontal phase speeds between 400 m/s and 1000 m/s, horizontal wavelengths greater than 1000 km, and periods between 30 min and 3 h [e.g., Hocke and Schlegel, 1996]. These waves transfer momentum and energy from high latitudes to mid- and low latitudes during geomagnetic storms, and are dissipated by physical processes including ion drag, molecular viscosity, and thermal conduction [e.g., Richmond, 1978]. Waves with smaller scales and slower phase speeds are more easily damped and thus are confined to mid-high latitudes, whereas waves with larger scales and faster phase speeds can reach low latitudes. AGWs/TADs manifest themselves in the ionosphere as traveling ionosphere disturbances (TIDs) observed as oscillations in ionospheric parameters such as electron density and total electron content, and, in fact, TADs have been mainly observed through observations of TIDs from ionospheric measurements [e.g., Hocke and Schlegel, 1996]. Recently, Bruinsma and Forbes [2007] elucidated morphology and characteristics of TADs using thermosphere neutral density measured by accelerometers onboard the CHAMP satellite. They found that the TADs on 20 May 2003 had typical dayside amplitudes ~20–30% and propagated equatorward from the northern hemisphere (southern hemisphere) auroral region with phase speeds on the order of 730 m/s (460 m/s) and horizontal wavelengths on the order of several thousand kilometers.

[3] The excitation of these gravity waves depends on the spatial and temporal properties of their sources [e.g., Richmond, 1978; Hocke and Schlegel, 1996]. Since sudden injection of energy in the auroral region during geomagnetic storms can excite AGWs/TADs, will sudden injection of energy during solar flares also excite AGWs/TADs? With increasing demand for global specification and forecast of space weather, it is timely and important to address this question and understand whether AGWs/TADs play a role...
2. Model Description

2.1. NCAR TIE-GCM

The TIE-GCM is a first-principles upper atmosphere general circulation model that solves the Eulerian continuity, momentum, and energy equations for the coupled thermosphere/ionosphere system. It utilizes a spherical coordinate system fixed with respect to the rotating Earth, with latitude and longitude as the horizontal coordinates and pressure surface as the vertical coordinate. It has a horizontal resolution of 5° × 5°. The pressure interfaces are defined as \( P_{\text{lev}} = \ln(P_0/P) \), where \( P_0 \) is a reference pressure at \( 5 \times 10^{-4} \) µPa. The model has 29 pressure surfaces covering the altitude range from \( \sim 97 \) km to \( \sim 700 \) km, with \( \text{lev} \) ranging from \( -7 \) to \( 7 \) and a vertical resolution of one half scale height. The external forcing of the TIE-GCM are solar irradiances, parameterized using the \( F_{10.7} \) index or supplied by measurements or empirical models [Solomon and Qian, 2005]; auroral electron precipitation [Roble and Ridley, 1987] and ionospheric convection driven by the magnetosphere-ionosphere current system (Weimer model) [Weimer, 2005]; and the amplitudes and phases of tides from the lower atmosphere [Hagan et al., 2001]. For the investigation in this paper, high temporal (1 min) flare spectra (0–190 nm with 1 nm resolution) estimated by the Flare Irradiance Spectral Model (FISM) [Chamberlin et al., 2007, 2008] will be used as solar input to the TIE-GCM. Solar wind data (\( B_x, B_y, B_z \), solar wind velocity, and solar wind density) from the OMNI database (http://cdaweb.gsfc.nasa.gov/istp_public/) will be used as input for the Weimer model.

2.2. FISM Solar Flare Model

The FISM (Flare Irradiance Spectral Model) is an empirical model developed for space weather applications. It uses the Geostationary Operational Environmental Satellites (GOES) X-Ray Sensor (XRS) 0.1–0.8 nm channel, Thermosphere Ionosphere Mesosphere Energetics and Dynamics Solar EUV Experiment (TIMED/SEE) [Woods et al., 2005], Solar Radiation and Climate Experiment SOLar STellar Irradiance Comparison Experiment (SORCE/SOLSTICE) [McClintock et al., 2000], and F10.7 as inputs, to estimate the solar X-ray and EUV irradiances at wavelengths from 0 to 190 nm at 1 nm resolution with a temporal resolution of 60 s [Chamberlin et al., 2007, 2008]. The temporal resolution is high enough to model thermosphere and ionosphere variations due to solar flares [Qian et al., 2010, 2011; Qian and Solomon, 2011; Qian et al., 2012].

3. Results

We conducted investigations of the thermosphere response to an X17 flare that occurred on 2003301 (10/28/2003). Based on GOES X-ray (0.1–0.8 nm) data, the X17 flare started at \( \sim 11:00 \) UT, peaked at \( \sim 11:10 \) UT, and decayed about 1 h later at \( \sim 12:00 \) UT. Geomagnetic activity on both October 28, 2003 and October 27, 2003 were between low and moderate (Kp \( \sim 3 \)). The TIE-GCM was run using FISM daily spectra starting 25 days prior to October 28, 2003. The model output at the beginning of October 28, 2003 was used as initial conditions to conduct two model runs. In the first run the model used FISM flare spectra for October 28, 2003 (flare run), whereas it used FISM daily spectrum (excluding flares) for October 28, 2003 in the second run (no-flare run). In both runs, realistic geomagnetic input, i.e., solar wind data (\( B_x, B_y, B_z \), solar wind velocity, and solar wind density) from the OMNI database was used as input for the Weimer model to calculate effects of geomagnetic activity. Hereafter, we will refer to the flare run with the realistic geomagnetic forcing as case #1 and the no-flare run with the realistic geomagnetic forcing as case #2. The difference fields from these two model runs (case #1 minus case #2) represent effects of the solar flare, which were used to look at possible signatures of AGWs/TADs during the flare event.

Figure 1 shows the difference in vertical neutral wind between the flare run (case #1) and the no-flare run (case #2) at 12:40 UT, one hour and 40 min after the flare onset at 11:00 UT, in the southern hemisphere. Over-plotted are the vectors of neutral horizontal wind changes between the flare run and the no-flare run. These flare-enhanced winds are plotted for the altitude of 400 km. AGWs/TADs are shown in the vertical wind with an amplitude on the order of 2 m/s.
(~30% of the background vertical wind) that propagated from the polar region to both dayside and nightside with a large ring-like longitudinal extend. On the nightside, these AGWs/TADs had a horizontal wavelength on the order of 4000 km and a phase speed on the order of 750 m/s in the upper thermosphere. Dayside wavelength and phase speed are similar to those on the nightside. In addition, Figure 1 shows that the sudden injection of heating in the dayside by the flare caused a flow divergence in the dayside and convergence in the nightside, and equatorward meridional wind enhancement was on the order of 40 m/s (~10% of the total background wind) in the nightside due to the heating in the sunlit South-Pole region. These enhanced neutral winds also transport energy and momentum from the sunlit area to the nightside. Equivalent North-Pole depiction of Figure 1 (not shown) shows that there was nearly no nightside equatorward enhancement of neutral wind and very weak AGWs/TADs in the northern hemisphere (winter hemisphere).

Figure 2 shows altitude-latitude cross sections of changes (case #1 minus case #2) of vertical wind, neutral temperature, and neutral density at 12:40 UT, 90 min after the flare onset at 11:00 UT, and at 15:00 UT, nearly 4 h after the flare onset. It is evident from Figure 2a that AGWs/TADs in the southern hemisphere (summer hemisphere) were stronger and propagated faster, whereas AGWs/TADs in the northern hemisphere (winter hemisphere) were weaker and propagated more slowly. Solar zenith angle effects likely played an important role in the hemisphere difference of wave amplitudes, and the resulting difference in equatorward enhancement of neutral winds can cause the hemisphere difference in the phase speeds of the waves. At 12:40 UT, 90 min after the flare onset, neutral temperature and density enhancements at midlatitude in the southern hemisphere are on the order of 3% (~40 K) and 18% in the upper thermosphere, respectively. At 15:00 UT, nearly 4 h after the flare’s onset, these enhancements of neutral temperature (~3%)
and neutral density (~18%) reached the equatorial area.

[10] So what are the mechanisms that generate the AGWs/TADs shown in Figure 1 and Figure 2? There are strong temperature gradients along solar terminators, especially the terminator in the South-Pole region, and sudden heating during onset of solar flares could trigger waves. Although waves in Figure 2a appear to have a split around 70°S and propagate in both directions and thus could suggest a wave source near the terminator, the ring-like wave morphology shown in Figure 1 suggests otherwise. We noticed that there was moderate geomagnetic activity (Kp ~ 3) prior to the onset of the flare, and IMF $B_y$ and $B_z$ both experienced large changes from being negative to being positive shortly before the onset of the flare and remained to be large positive (5–10 nT) during the flare. The auroral morphology of the waves shown in Figure 1 strongly suggests that geomagnetic activity may play a role in the AGWs/TADs shown in Figures 1 and 2. In order to find out whether the geomagnetic activity played such a role, we set geomagnetic activity to be quiet throughout the day and repeated the two model runs. The quiet geomagnetic conditions were chosen as: $B_x = 0$, $B_y = 0$, $B_z = 0$, $\nu = 400$ km/s, $\rho = 4$ cc. Hereafter, we refer to the flare run under the assumed geomagnetically quiet conditions as case #3 and the no-flare run under the assumed geomagnetically quiet conditions as case #4. We examined vertical wind since vertical wind is one of characteristic features in the auroral region and of gravity waves. Figure 3a shows the vertical wind at 10:50 UT from the flare run using realistic geomagnetic forcing (case #1), 10 min before the onset of the flare. The corresponding $B_y$ and $B_z$ are shown in Figure 3b. Prior to the flare, $B_z$ fluctuated between being negative and being positive whereas $B_y$ was negative. Shortly before the flare’s onset, both $B_y$ and $B_z$ experienced large changes from being negative to being positive and remained to be the large positives shown in Figure 3b during the flare. Figure 3c shows the vertical wind at 10:50 UT from the flare run under the assumed magnetically quiet conditions (case #3). Both $B_y$ and $B_z$ are zero throughout the day. Figure 3a shows that there were AGWs/TADs generated by geomagnetic activity prior to the onset of the flare, as opposed to Figure 3c, when there were no AGWs/TADs under the quiet geomagnetic conditions prior to the onset of the flare.

[11] Figure 4 is the same as Figure 3 except for 11:30 UT, 30 min after the flare onset at 11:00 UT. For case #1, the vertical wind shows intensified AGWs/TADs (Figure 4a) compared to Figure 3a. This intensification of the waves was due to the flare. Figure 5a shows height integrated Joule

**Figure 3.** (a) Model simulated vertical wind color contour at 10:50 UT, 10 min before the onset of the X17 flare at 11:00 UT, under the realistic geomagnetic forcing based on the OMNI database (case #1). Over plotted are horizontal wind vectors; (b) the $B_y$ and $B_z$ components of the IMF on October 28, 2003; (c) model simulated vertical wind color contour at 10:50 UT, 10 min before the onset of the X17 flare at 11:00 UT, under the assumed geomagnetically quiet conditions (case #3); (d) the assumed constant $B_y$ and $B_z$ (0). The sudden changes of $B_z$ that occurred prior to the flare triggered AGWs/TADs, as shown in the vertical wind in Figure 3a. When $B_z$ was assumed to be a constant, there were no waves as shown in Figure 3c. The times around the polar plot are local times.
heating enhancement during the flare under the realistic geomagnetic conditions (case #1 minus case #2). There is localized enhanced Joule heating during the flare with spatial scale similar to the preexisting waves. This localized sudden injection of energy, together with the preexisting AGWs/TADs (Figure 3a), produced intensified AGWs/TADs (Figures 1 and 4a), which propagated energy and momentum to the equatorial region (Figure 2). On the other hand, under the assumed geomagnetically quiet conditions, there was no visible localized enhancement of Joule heating (Figure 5b) and AGWs/TADs were not produced during the flare as shown in Figure 4c. We confirmed this by examining model simulated vertical wind as well as other parameters including neutral temperature, density, and neutral refractive index.

Figure 4. (a) Model simulated vertical wind color contour at 11:30 UT, 30 min after the onset of the X17 flare at 11:00 UT, under the realistic geomagnetic forcing (case #1). Over plotted are horizontal wind vectors; (b) the $B_y$ and $B_z$ components of the IMF on October 28, 2003; (c) model simulated vertical wind color contour at 11:30 UT, 30 min after the onset of the X17 flare at 11:00 UT, under the assumed geomagnetically quiet conditions (case #3); (d) the assumed constant $B_y$ and $B_z$ (= 0). The times around the polar plot are local times.

Figure 5. (a) Model simulated changes of height integrated Joule heating responding to the X17 flare under the realistic geomagnetic activity shown in Figure 3b (case #1 minus case #2) at 11:30 UT; (b) model simulated changes of height integrated Joule heating responding to the X17 flare under the assumed geomagnetically quiet conditions shown in Figure 3d (case #3 minus case #4) at 11:30 UT. The times around the plot are local times.
composition at different times after the onset of the flare for case #3 (not shown), and found no signature of AGWs/TADs. It is important to note that there were Joule heating enhancement due to the flare in the entire dayside for both case #1 and case #3, however, they were much weaker than the localized Joule heating shown in Figure 5 for case #1, consequently, they are not visible in Figure 5. It is not clear whether it was the geomagnetic conditions during the flare, or the preexisting AGWs/TADs generated by the geomagnetic activity prior to the flare, or both, that contributed to the localized enhancement of Joule heating. The large positive $B_y$ and $B_z$ during the flare could make contributions through enhanced electric field in the polar region compared to quiet geomagnetic conditions as indicated by empirical models [Weimer, 2005]. The enhanced electric field can cause localized enhancement of Joule heating. The pre-existing AGWs/TADs could make contributions through disturbed composition, since disturbed composition can affect ionization as well as ion-neutral collision frequency, and thus affect Joule heating.

Figure 6. Comparisons of the altitude-latitude cross sections of neutral density changes at 180°E (nightside, 03:00 LT) between case #1 and case #3. (a) Simulated neutral density enhancement at 15:00 UT, 4 h after the onset of the flare at 11:00 UT, under the realistic geomagnetic forcing (case #1). (b) Simulated neutral density enhancement at 15:00 UT, 4 h after the onset of the flare at 11:00 UT, under the assumed geomagnetically quiet conditions (case #3).

[12] Figure 6 shows comparisons of flare induced neutral density enhancement under realistic geomagnetic activity (case #1) versus density enhancement under the assumed geomagnetically quiet conditions (case #3), at 180°E and 15:00 UT. Under the assumed geomagnetically quiet conditions, as we discussed earlier, the flare did not generate AGWs/TADs, heating in the night side (Figure 6b) was then due to enhanced large–scale circulation responding to the increased solar heating to the thermosphere during the flare, with more enhancement of neutral density in the summer hemisphere. The stronger enhancement of density in the summer hemisphere was caused by more heating in the summer hemisphere and subsequent stronger enhancement of large-scale circulation. Under the realistic geomagnetic conditions (Figure 3b), the density enhancement shown in Figure 6a was caused by energy and momentum transport with contributions from both the enhanced large-scale circulation and AGWs/TADs (Figure 1). Figure 6a also shows that the AGWs/TADs transported flare energy and momentum to
2003, CHAMP and the model simulated neutral density. On October 28, AGWs/TADs addressed in this study. The spatial scale of this enhanced solar heating is too large to excite the AGWs/TADs addressed in this study. The spatial and temporal properties of sources. Enhanced solar heating to the thermosphere through enhanced ionization during a flare occurs on the entire dayside. The spatial scale of this enhanced solar heating is too large to excite the AGWs/TADs addressed in this study.

The nightside equatorial density increased ~18% compared to a ~8% density enhancement due to enhanced large-scale circulation alone. These nightside equatorial density enhancements are smaller than those in the data, and the data shows some small-scale features that are not shown in the model simulations. In addition, model simulation demonstrated that there were AGWs/TADs launched shortly before the flare and were intensified by the flare (please refer to the description regarding Figure 5), and largely dissipated in the equatorial area. These simulated wave generation, transport, and dissipation characteristics are consistent with those shown in the data. However, the simulated wave amplitudes are smaller than those in the data, and the data shows some small-scale features that are not shown in the model simulated neutral density.

4. Summary and Conclusions

[15] In this paper, we used model simulations to investigate whether AGWs/TADs play a role in energy and momentum transport during a solar flare. Model simulations of a large X17 solar that occurred on October 28, 2003 showed that AGWs/TADS were involved in transporting flare energy from the sunlit South-Pole region to the equatorial region in 3–4 h. The nightside equatorial density increased ~18% compared to a ~8% density enhancement due to enhanced large-scale circulation alone. These nightside AGWs/TADs have a phase speed on the order of ~750 m/s and horizontal wavelength on the order of 4000 km.

[16] Gravity wave excitation depends on spatial and temporal properties of sources. Enhanced solar heating through enhanced ionization during a flare occurs on the entire dayside. The spatial scale of this enhanced solar heating is too large to excite the AGWs/TADs addressed in this study. Further analysis revealed that strong localized enhancement of Joule heating was produced during the October 28, 2003 flare. In addition, the geomagnetic activity prior to the flare had excited AGWs/TADs that were present at the time of the flare. The sudden injection of the localized enhancement of Joule heating, together with the preexisting AGWs/TADs, produced intensified AGWs/TADs, which propagated energy and momentum to the equatorial region. Model simulations showed that strong localized enhancement of Joule heating was not produced during the flare under the assumed geomagnetically quiet conditions, and therefore, there were no AGWs/TADs. This interplay between magnetic activity and solar flares can be a challenge to space weather monitoring, specification, and forecasting. Future work includes understanding the mechanisms for the localized enhancement of Joule heating during the flare, to find out whether the geomagnetic activity and the preexisting AGWs/TADs both contributed to the localized enhancement of the Joule heating response to the flare.
Figure 8. (a) CHAMP nightside neutral density (01:05 LT) on October 28, 2003; (b) the corresponding nightside neutral density simulated by the TIE-GCM. The sudden increase of the GOES X-ray started at 11:00 UT, peaked at 11:10 UT, and recovered at ~12:00 UT. The TIE-GCM neutral density was sampled along the CHAMP ascending orbits (nightside part of the orbits).

[17] Acknowledgments. This research was supported by NASA grants NNX08AQ31G and NNX09A06G to the National Center for Atmospheric Research. We would also like to acknowledge the Center for Integrated Space Weather Modeling (CISM), which is funded by the National Science Foundation's STC program under agreement number ATM-0120950. NCAR is sponsored by the National Science Foundation.

[18] Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

References


