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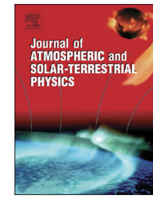

Satellite observations of wave disturbances caused by moving solar terminator

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ABSTRACT

Wave disturbances caused by moving solar terminator were studied using in situ satellite measurements. Neutral species densities measured by low-latitude satellite Atmosphere Explorer-E in the altitude range of 250–400 km were used for analysis. Wave disturbances of neutral species density with amplitudes of 2–4% were observed during few hours after passing the terminator, predominantly in time intervals of 6–9 LST and 20–23 LST. These disturbances were interpreted as the acoustic-gravity waves. Spatial scales of such waves range from few hundred to few thousand kilometers, major part of wave spectral power being concentrated in the horizontal wavelength range from 1000 km to 1200 km. It was shown that vertical and horizontal components of phase velocity of these waves coincide with vertical and horizontal components of terminator velocity, i.e. observed wave are synchronized with the terminator.

1. Introduction

Acoustic-gravity waves (AGWs) at ionospheric altitudes attract now great attention due to their important contribution into dynamics and energy of the terrestrial atmosphere. This kind of wave disturbances can be generated by various sources at different altitudes. One of the most important AGW features is ability to transfer energy in the vertical direction (Hines, 1974). The ionospheric AGWs are considered as 'originated from above', if their sources such as particle precipitation, ionospheric currents, moving solar terminator, etc. occur in upper atmosphere (Hocke and Schlegel, 1996; Somsikov and Ganguly, 1995; Kaladze et al., 2008; Lizunov et al., 2009; Fedorenko et al., 2015). On the contrary, if the waves propagate to observed altitudes from tropospheric or ground sources, they are referred to as 'originated from below' (Sauli and Boska, 2001; Rapoport et al., 2004). In addition, AGWs are conventionally divided into large-scale and medium-scale waves (Francis, 1975). Large-scale AGWs propagate at horizontal phase velocities 400–1000 m/s and have periods from 30 min to 3 h; and horizontal wavelengths above 1000 km. On the other hand, the medium-scale AGWs have phase velocities below 300 m/s and periods less than half an hour (Francis, 1975). Most of large-scale waves observed in high- or mid-latitudes are obviously 'originated from above' and correlate with geomagnetic storms (Hajkovicz, 1991; Afraimovich et al., 2001). As regards the waves 'originated from below', they appear as the medium-scale AGW since horizontal phase velocity of AGW cannot exceed velocity of sound in the atmosphere (Hines,1974), which is about 300 m/s near the ground.

Basic experimental information about AGWs at the ionospheric altitudes is obtained using numerous ground-based techniques. It is based primarily on ionospheric plasma diagnostics. Satellite in situ measurements provide global picture of AGW distribution around the entire planet. For the study of AGWs in the upper atmosphere, a low-orbit satellite equipped with neutral medium parameter sensors is required. However, a very limited number of such scientific satellites have been launched during whole history of space research; mostly these were satellites of Atmosphere Explorer and Dynamics Explorer series.

Contrary to many atmospheric AGW sources that are sporadic in nature, moving solar terminator is regular and predictable source of disturbances. Beer (1973) was first who paid attention to possible wave disturbance generation by moving terminator. Since horizontal velocity of terminator near equator is about 450 m/s, it can generate both infrasonic and gravity waves in Earth's atmosphere below approximately 180 km (Somsikov, 1983). On the contrary, at altitudes of satellite AGW observations (200–400 km), moving solar terminator can cause only gravity waves.

Today, there are a sufficiently large number of the works devoted to research of the solar terminator by the different methods (Somsikov, 2011). Experimental observations of the wave disturbances from the solar terminator have been obtained using both ground-based and satellite techniques. Statistical studies of space-time structure of medium-scale wave packets caused by the terminator have been performed (Afraimovich et al., 2009). The authors have used long-time series of total electron content (TEC)

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observations collected with the use of the Global Positioning System (GPS). They have found that those wave packets are narrow-band TEC variations with duration of 1–2 h, oscillation period 10–30 min, and wavelength about 100–300 km (Afraimovich et al., 2009).

Generation of ionospheric disturbances by the solar terminator has been confirmed experimentally using Millstone Hill incoherent scatter radar. It was found that the wave disturbances were considerably stronger at sunrise. They propagated in the horizontal plane perpendicularly to terminator with group velocity 300–400 m/s, which is approximately equal to terminator velocity in the mid-latitude ionosphere (Galushko et al., 1998).

The spatial structure of neutral atmosphere disturbances caused by the terminator has been analyzed based on measurements of the accelerometer installed on board of satellite CHAMP (Forbes et al., 2008). Neutral species density variations were within 3–5%, and horizontal wavelength was about 3000 km. It was found that wave fronts of the morning terminator in summer in the northern hemisphere are inclined to the terminator by 30° and extend from 60°S to 30°N. The authors (Liu et al., 2009) have analyzed the large-scale (3000–5000 km) wave disturbances from the terminator synchronously in neutral species density and velocity, as measured by the CHAMP satellite.

Numerical simulation of AGW generation by the solar terminator in the Martian atmosphere has been presented in (Forbes and Moudden, 2009). It was shown that wave fronts in horizontal plane follow the evening terminator that moves to west and are inclined to the terminator by 10–30°, horizontal wavelengths 1800–3600 km. Disturbances arise in lower atmosphere due to dust absorption of solar radiation and then propagate upwards.

In this paper, we study wave disturbances induced by the solar terminator based on in situ satellite measurements of neutral species concentration in the range of horizontal scales between 500 and 1500 km. For our investigations we have taken data of atomic oxygen $n(O)$ and molecular nitrogen $n(N_2)$ concentrations obtained by equatorial satellite Atmospheric Explorer-E (AE-E) at altitudes 250–400 km, where these gases are prevailing in the chemical composition of the atmosphere. During the period under study (see Table 1), the AE-E satellite orbit was nearly circular with inclination of 19.7°.

2. Data processing procedure

The neutral species concentrations have been measured by the satellite AE-E in frames of NACE (Neutral Atmosphere Composition Experiment) (Pelz et al., 1973). Orbit configuration of this satellite is very suitable for registration such wave disturbances. Since amplitudes of these disturbances are proportional to solar energy input, they must be maximal near the equator. Owing to small orbit inclination, the satellite is always in the low-latitude region. It is allows studying wave trains as functions of local solar time as well.

When studying wave processes using satellite measurements, it is necessary to distinguish wave disturbances against the background of other large-scale variations such as seasonal, diurnal behavior, circulation processes, etc. Nearly circular AE-E orbit minimizes large altitude density gradients and thereby permits to extract effectively the diurnal component of the density variations.

Wave disturbances were studied in terms of relative variations of atomic oxygen $\delta n(O)/\bar{n}(O)$ and molecular nitrogen $\delta n(N_2)/\bar{n}(N_2)$ concentrations, where $\bar{n}(N_2)$and $\bar{n}(O)$ are average background concentration values whereas $\delta n(N_2)$ and $\delta n(O)$ are deviations from the average values. Extraction of wave disturbances from trends was made using the moving average method. The window size was two thousand kilometers and was selected based on the consistent disturbances in various gases (Fedorenko, 2009). However, if standard spectral analysis techniques are applied regardless of physical nature, any abrupt variation in data series including discontinuities or jumps can be erroneously treated as a wave. To avoid such errors, we proceed from the next conditions:

1) Matching of waveforms in $\delta n(N_2)/\bar{n}(N_2)$ and $\delta n(O)/\bar{n}(O)$ with the correlation coefficient at least 0.8;

Table 1
Summary of all the studied events with dates and satellite orbit numbers.

Morning terminator			**Evening terminator**		
Date	Orbit number	Orbit altitude, km	Date	Orbit number	Orbit altitude, km
December 1, 1976	5283	252–250	December 2, 1976	5300	249–255
December 2, 1976	5300	249–255	December 5, 1976	5341	248–254
December 5, 1976	5340	250–247	January 19, 1977	6069	253–260
December 8, 1976	5394	245–250	January 21, 1977	6100	252–255
January 19, 1977	6070	254–259	January 24, 1977	6146	250–253
January 20, 1977	6085	253–254	January 26, 1977	6185	252–250
January 21, 1977	6101	253–256	April 19, 1977	7514	257–258
January 24, 1977	6147	251–254	April 23, 1977	7579	253–257
April 19, 1977	7514	257–258	April 23, 1977	7581	253–254
July 1, 1977	8689	281–285	April 23, 1977	7583	253–257
July 3, 1977	8725	281–285	June 30, 1977	8672	279–278
July 7, 1977	8785	278–282	July 1, 1977	8688	279–278
August 1,1977	9199	278–280	July 2, 1977	8708	277–278
August 27,1977	9608	277–276	July 3, 1977	8724	276–278
August 28,1977	9631	274–276	July 5, 1977	8756	276–278
August 30,1977	9658	273–275	July 6, 1977	8771	276–278
August 31,1977	9676	274–273	July 9, 1977	8830	276–278
October 8, 1977	10290	281–280	August 30,1977	9659	275–276
December 7, 1977	11244	262–265	December 7, 1977	11243	264–262
December 10, 1977	11301	260–263	December 10, 1977	11300	261–260
December 13, 1977	11349	280–283	December 12, 1977	11333	257–258
March 16, 1978	12821	318–319	December 22, 1977	11488	278–281
March 19, 1978	12785	318–321	March 19, 1978	12785	318–321
August 21, 1980	26652	399–398	August 16, 1980	26568	401–403
September 6, 1980	26902	398–402	August 21, 1980	26652	398–399