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Traveling ionospheric disturbances observed by Kharkiv and Millstone Hill incoherent scatter radars near vernal equinox and summer solstice

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ABSTRACT

We present the results of comparative study of traveling ionospheric disturbances (TIDs) obtained at middle latitudes of different longitudinal sectors during two coordinated observational campaigns. The joint measurements were conducted near the vernal equinox and summer solstice in 2016 using Kharkiv (49.6 N, 36.3 E) and Millstone Hill (42.6 N, 288.5 E) incoherent scatter radars. The same methods and software were used for analysis of both data sets to ensure consistency. We found that TIDs with periods of 40–80 min are observed during all measurements and concentrated predominantly near the sunrise and sunset terminators over both sites. There is no obvious relationship between the observed wave processes and variations in the auroral electrojet. Absolute and relative amplitudes, time of appearance, durations and phase differences of TIDs show strong height and seasonal variability. Relative amplitudes are substantially greater over Millstone Hill, whereas higher absolute amplitudes are observed over Kharkiv. During the summer solstice, the overall wave activity is smaller than during vernal equinox. Additional joint observations are needed to identify the seasonal and longitudinal dependences of TID characteristics.

1. Introduction

Traveling ionospheric disturbances (TIDs) represent a key dynamic process of energy transfer in horizontal and vertical directions, and are one of the important sources of ionospheric variability. Although they have been studied for extended period of time, the sources of TIDs remain a matter of a debate. Multiple experimental and modeling studies point to mechanisms related to space weather and auroral activity (Bristow et al. (1996); Hocke and Schlegel (1996)). However, a large body of work also favors tropospheric and atmospheric origins of TIDs (Boška and Šauli (2001); Xiao et al. (2007)). Acoustic gravity waves (AGWs) play a key role in coupling of different atmospheric regions through momentum and energy transfer, and most of quiet-time TIDs are thought to be the manifestations of AGWs at ionospheric heights (Vadas and Nicolls (2009); Nygrén et al. (2015); Negrea et al. (2016)). There is some evidence of non-AGW-induced TIDs being observed. Such TIDs can be generated by slow magnetohydrodynamic and magnetogradient waves (Burmaka et al. (2006)), electrodynamic instability (Kotake et al. (2007)) and auroral phenomena (Kirchengast (1997)).

The AGW/TID events are originated by numerous high energy sources. The observations have shown that the main natural origins of these processes are geomagnetic storms (Borries et al. (2009); Nishioka et al. (2009)), solar terminators (Song et al. (2013)), solar eclipses (Jones et al. (2004); Burmaka and Chernogor (2013)), earthquakes (Astafyeva and Afraimovich (2006)), volcanic eruptions (Cheng and Huang (1992)), typhoons (Xiao et al. (2007)), tsunamis (Artru et al. (2005)), cold tropospheric fronts (Boška and Šauli (2001)), ocean circulation (Djuth et al. (2010)), etc. There are evidences of artificial sources of AGW/TIDs, such as nuclear explosions (Zhang and Tang (2015)), rocket launches (Burmaka et al. (2006)) and ionospheric HF heating (Chernogor et al. (2015)).

A variety of space- and ground-based facilities is used to detect AGW/TIDs and estimate their characteristics, with a widespread usage of the remote sensing techniques (Dymond et al. (2011); MacDougall and Jayachandran (2011); Frissell et al. (2014)). Significant progress in understanding TID generation, propagation and dissipation have been made using optical and radio facilities: all-sky imagers (Candido et al. (2008)), ionosondes (Boška and Šauli (2001); Kozlovsky et al. (2013); Negrea

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et al. (2016)), SuperDARN HF radars (Bristow et al. (1996); Frissell et al. (2014)), Doppler radars (Jones et al. (2004); Chum et al. (2012)), radio interferometers (Jacobson et al. (1995)), middle and upper atmosphere radars (Oliver et al. (1997)), incoherent scatter radars (ISRs) (Galushko et al. (1998); Vadas and Nicolls (2009); Djuth et al. (2010); Vlasov et al. (2011); Nicolls et al. (2014); Chernogor et al. (2015)) and GPS/GNSS receivers (Astafyeva and Afraimovich (2006); Kotake et al. (2007); Tsugawa et al. (2007); Borries et al. (2009); Song et al. (2013)).

Over the past two decades, comprehensive theoretical studies have significantly contributed to understanding of AGW propagation, damping and dissipation in the thermosphere (Vadas (2007)). These theoretical estimates demonstrate a good agreement with experimental results and enable explanation of the behavior of AGW-induced TIDs by considering viscosity, thermal diffusivity and vertical gradient in the background wind velocity (Vadas and Nicolls (2009); Nicolls et al. (2014)).

Broadly speaking, TIDs can be categorized in two groups: large-scale TIDs (LSTIDs) and medium-scale TIDs (MSTIDs). LSTIDs have characteristic periods of 1–2 h and horizontal wavelengths of the order of 1000 km (Hocke and Schlegel (1996)). MSTIDs have periods of 15–60 min and horizontal wavelengths of several hundred kilometers, and propagate southwestward at night and generally equatorward during the daytime (Kotake et al. (2007)). LSTIDs are thought to be mostly originated in the auroral zone during variations of geomagnetic activity (Borries et al. (2009)). But they were also observed over China at dawn and associated with sunrise terminator source (Song et al. (2013)). MSTIDs are mostly induced by local sources located both in the lower and upper atmosphere (see Tsugawa et al. (2007); Hernández-Pajares et al. (2012)). However, similar wave signatures were also detected during geomagnetic storm (Nishioka et al. (2009)). The sources of TIDs remain an open question.

Although there have been numerous studies of TIDs, current knowledge is often based on observing only limited set of parameters and two-dimensional characteristics (for example, total electron content by GNSS receivers or airglow brightness by all-sky imagers). Incoherent scatter technique enables simultaneous studies of altitudinal characteristics of TIDs in several parameters like electron density (N_e), electron and ion temperature (T_e and T_i) and plasma drift (V_i), thus providing critical information needed to examine different hypothesis about association of TIDs with their sources. This technique also yields all components of wave vector, provided that the radar has the ability to operate in multi-beam mode (Vadas and Nicolls (2009); Nicolls et al. (2014)).

Significant research efforts have been devoted to the identification of TID features in a specific geographic region only. Such approach is very useful for studying individual TIDs and investigation of diurnal and seasonal dependences of their characteristics together with background ionospheric parameters. However, to examine TID behavior on a global scale and to separate contributions from global and regional sources, multi-site measurements of ionospheric plasma parameters are needed. In addition, such observations should be conducted under different ionospheric conditions to trace the evolution of TID occurrence and intensity. The important reference periods for magnetically quiet times are the equinox and solstice seasons, where the ionosphere is characterized by different states due to the annual variability of chemical and dynamical processes in geospace. Thus, description of TID features during equinox and solstice conditions is of great interest.

In this comparative study, we present simultaneous observations of TIDs by two mid-latitude incoherent scatter facilities located in different longitudinal sectors. We discuss results in the context of current understanding of TIDs and in the context of background plasma parameters that affect TID propagation and damping.

2. Facilities and methods

In March and June 2016, two joint observational campaigns were conducted using Kharkiv and Millstone Hill ISRs. The observations were made during Incoherent Scatter Coordinated Observation Days and near vernal equinox and summer solstice periods. We focus on longitudinal features in TID characteristics.

Kharkiv ISR facility (49.6 N, 36.3 E) is located in Ukraine and is the only one at middle latitudes of the Central Europe. It includes 100-m fixed, zenith-directed and 25-m fully steerable parabolic antennas, operates at 158 MHz frequency and has 2 MW peak transmit power. The calibration of electron density profiles is performed using ionosonde located in the vicinity of the ISR. More details about radar characteristics and operation modes are given by Domnin et al. (2014). Data from Kharkiv ISR are available through the Institute of ionosphere Database (http://database.iion.org.ua/). Millstone Hill ISR facility (42.6 N, 288.5 E) is located in Westford, MA, USA. It consists of zenith-directed 68-m fixed and fully steerable 46-m antennas and transmitters with operating frequency 440 MHz and the peak transmitted power 2.5 MW. Electron density is calibrated using UMass Lowell Digisonde or plasma line observations (for new experiments). Data from Millstone Hill ISR are publicly available through the Madrigal Database (http://madrigal.haystack.mit.edu/madrigal/). Both radars are capable of observations in the altitude range from 100 to 1000 km.

To assure consistency of results for Kharkiv and Millstone Hill facilities, in this study we used the same methods and software for data analysis. The main stages of data analysis are illustrated in Fig. 1. The values of electron density, ion and electron temperatures obtained from zenith measurements were chosen with time step of 1 min and 8 min for Kharkiv and Millstone Hill, respectively, and in the altitude range from 200 to 300 km. We present results only for the daytime ionosphere to avoid ambiguities related to low signal-to-noise ratio at night. In addition, we do not include V_i data due to the larger errors during V_i retrieving than for other measured parameters. As data acquired with Millstone Hill ISR zenith antenna had uneven time series due to the dwell

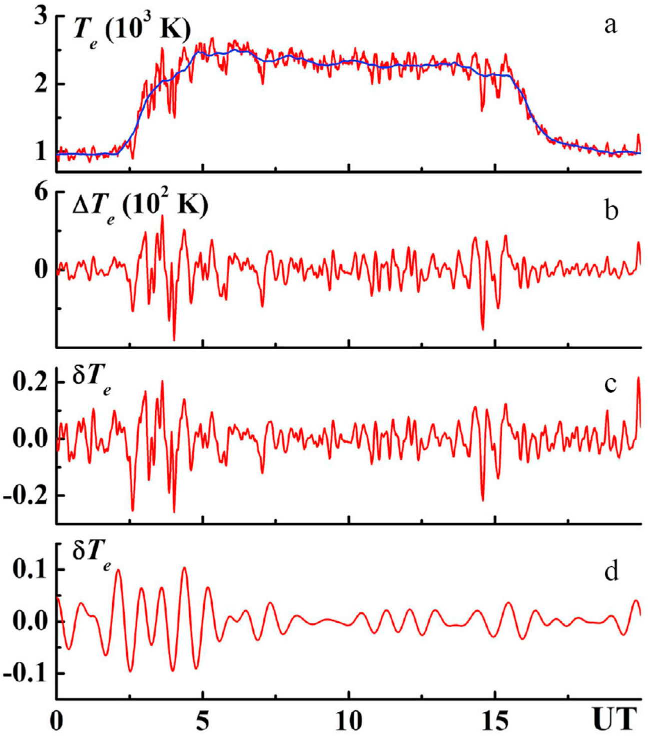

Fig. 1. Steps for data analysis to obtain TIDs in electron temperature: (a) electron temperature values (red) with trend fitted by third-order least square method using 120-min time interval (blue), (b) residuals between values and trends (absolute variations), (c) residuals normalized to trend (relative variations), (d) 40–80 min bandpass filtered relative variations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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