The Study of the Ionospheric Dynamics during Strong Sudden Stratospheric Warmings in the Russia's Arctic Region

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Abstract— The behavior of the ionosphere in Russia's Arctic region during periods of strong sudden stratospheric warmings was investigated using data from the international network of phase dual-frequency GPS/GLONASS receivers, global ionospheric maps (GIM) of the total electron content (TEC) and vertical sounding data. Six events of major stratospheric warmings that have occurred in the Northern hemisphere over the last decade were considered. In order to identify the possible response of the high-latitude ionosphere to SSW events, we carried out the analysis of the total electron content and F2-layer electron density deviation from the background level. Spatial and temporal distributions of the amplitude of diurnal TEC variations were also studied. The dynamics of the high-latitude ionosphere at the points near the SSW zone during the periods of warmings was found to differ from the regular. We also revealed that the events of major SSWs are usually accompanied by a decrease in amplitude of diurnal TEC variations during the SSW development stage and by an increase in amplitude, which may be observed at latitudes of up to $\sim 75^\circ$N after the SSW peak.

1. INTRODUCTION

A sudden stratospheric warming (SSW) is a significant unexpected increase in temperature (up to 50° or more) in the winter polar and subpolar stratosphere. It lasts for several days or weeks and covers most of the hemisphere. Major (strong) warmings are characterized by the reversal of the meridional temperature gradient sign over the hemisphere; besides, the western direction of the stratospheric zonal circulation changes to the eastern one. Weakening or destruction of the circumpolar vortex, determining the dynamics of the polar and subpolar middle atmosphere in winter, is also observed.

It is believed that the SSW development is connected with intensification and penetration of planetary waves to the stratosphere from the troposphere and with their interaction with the western stratospheric flow. This interaction results in the dissipation of waves and in the release of large amounts of wave energy, which leads to an increase in the stratospheric temperature [1]. In turn, wave activity intensification and significant changes in the atmospheric circulation during SSW periods may have an impact on ionospheric plasma. Various ionospheric effects of SSWs are identified and analyzed in the equatorial [2–4] and mid-latitude [4] regions. According to [5], remarkable abnormality of regular dynamics of the total electron content (TEC) is observed during SSWs in the mid-latitude ionosphere.

Since the state of the unlit winter polar ionosphere under quiet geomagnetic conditions is determined mainly by the dynamics of the neutral atmosphere, it is natural to expect that such large-scale phenomena as SSWs have to influence its behavior. Therefore, the purpose of this work was to study ionospheric disturbances in Russia's Arctic region during stratospheric warmings in 2006–2013.

2. SUDDEN STRATOSPHERIC WARMINGS IN 2006–2013

In 2006–2013, six major stratospheric warmings occurred in the Northern hemisphere. The peaks (maximums) of these events (day of the zonal wind reverse at a level of 10 hPa) were registered in the following winters: on January 21, 2006; on February 24, 2007; on February 22, 2008; on January 24, 2009; on February 9, 2010; on January 6, 2013. All SSW events, except for the warming of 2009, were accompanied by an increase in intensity of stationary planetary waves with zonal number 1 (SPW1) [6]; the amplitude of these waves characterizes the degree of the polar circulation displacement. During such stratospheric warmings, the polar cyclone moved to lower latitudes and the polar anticyclone was formed. The centers of these SSWs (the region of the most significant increase in the stratospheric temperature) were located in the Asian region of Russia. The SSW in winter 2008/09 was accompanied by an increase in the intensity of SPW2 determining the polar vortex splitting. During this event, there was a division of the circumpolar vortex into two alternating pairs of cyclones and anticyclones. The center of this warming was located over the Northern part of the Atlantic Ocean. Minor SSWs were registered almost every winter.

It should also be noted that the years chosen for the study were characterized by a relatively low solar and geomagnetic activity; geomagnetic disturbances were not recorded during the periods of the maximum development of the SSWs under consideration.

3. *NMF2* DYNAMICS IN NORILSK

To study the behavior of the polar ionosphere during the periods of SSWs, the vertical sounding data obtained at Norilsk ionosonde (88.3°E, 69.3°N) were used. From the initial data of the maximum electron concentration in the F2 layer (NmF2) we calculated series of deviations from the background level: $dNmF2_i(t) = NmF2_i(t) - \langle NmF2\rangle_i(t)$. Background magnitudes $\langle NmF2\rangle_i(t)$ were calculated by averaging the *NmF2* values for 15 geomagnetically quiet days before and 15 days after each current day: $\langle NmF2\rangle_i(t) = \frac{1}{30}\sum_{i-15}^{i+15} NmF2_i(t)$. Daily-temporal dynamics of the obtained deviations in winters 2006–2013 is shown by colors in Figure 1. On each panel, the local time is scaled vertically, while days from January to February of each year (from December to February

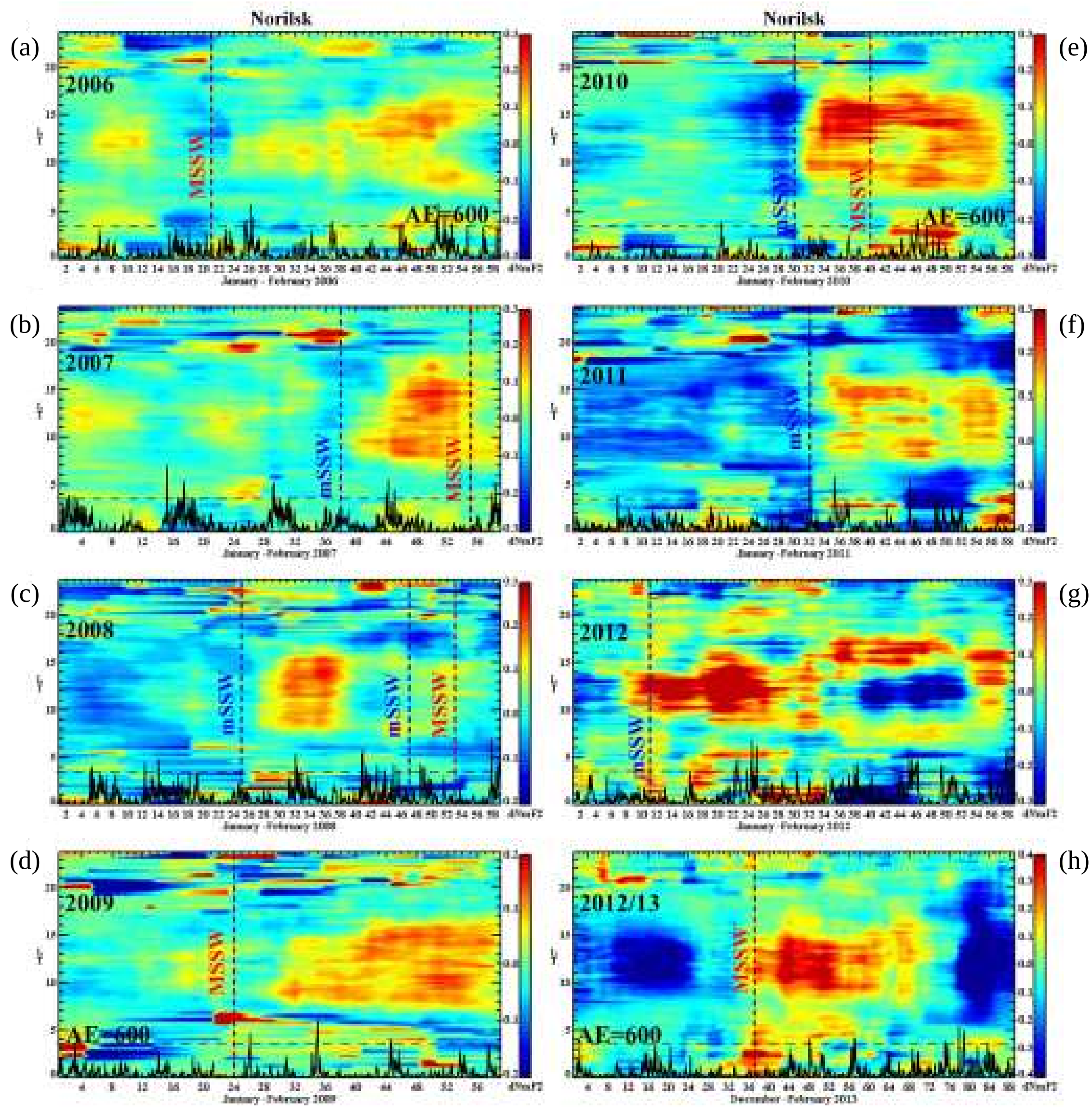


Figure 1: The dynamics of *NmF2* deviations from the background level. The red dotted lines show peaks of major SSWs (MSSW); the blue ones, maxima of minor SSWs (mSSW). Variations of AE index are depicted on each panel by black solid line.

for winter 2012/2013, Figure 1(h)) are scaled horizontally. The red vertical dashed lines mark peak days of major SSWs; the blue ones, the days when the largest increase in stratospheric temperature at 10 hPa (∼30 km) was observed in the region of Norilsk during the minor warmings.

Figure 1 shows that negative daytime *NmF2* deviations are registered during the warming development phase; i.e., values of the maximum F2-layer concentration are low relative to the background level in these periods. For most events, *NmF2* deviations in the evening and morning hours are, on the contrary, positive. After the SSW maximum, significant positive *NmF2* deviations are observed near midday within 10–15 days. It indicates the considerable excess of the electron concentration relative to background values. Such behavior of *dNmF2* is typical for all SSW events under study, except for the warming of winter 2008/09. After this SSW peak, *dNmF2* values in the daytime are negative, and the intensity of deviations is significantly lower compared to the values recorded during other SSWs (Figure 1(d)). This may be due to the differences of 2008/09 event described in Section 2.

Note that the above ionosphere variations were not observed during major SSWs in late winter (2007, 2008, Figures 1(b), (c)). This may be due to the fact that lighting of the polar ionosphere and the electron density substantially increased by the end of the winter (relative to the levels characteristic for unlit conditions). Therefore, the state of the ionosphere starts to be largely controlled by variations in solar radiation, and weak effects associated with the neutral atmosphere do not appear.

4. TOTAL ELECTRON CONTENT

Analysis of the total electron content variations was carried out using data from the phase dual-frequency GPS/GLONASS receivers [7] located in the area under study. The series of vertical TEC were calculated from the initial data with the method described in [8]. Figure 2 presents the example of the distributions obtained at high-latitude stations NRIL (88.36°E, 69.36°N) and TIXI (128.86°E, 71.63°N) in January–February 2010.

The Figure 2 indicates that a slight decrease in the TEC daily maximum and an increase in the nighttime TEC values were observed during the warming development. After the SSW peak, TEC was increasing considerably during 5–6 days: daytime *Iv* values are almost twice as high as TEC magnitudes registered before the warming peak. The TEC behavior was the same during the periods of other major SSWs, except for the events that took place in late winter. Thus, in general, the dynamics of TEC and *NmF2* during the periods of SSWs is similar.

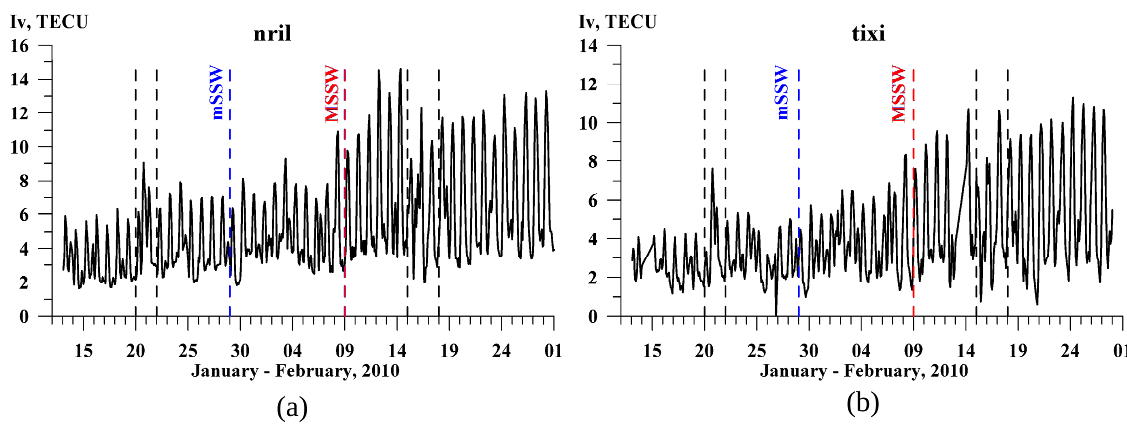
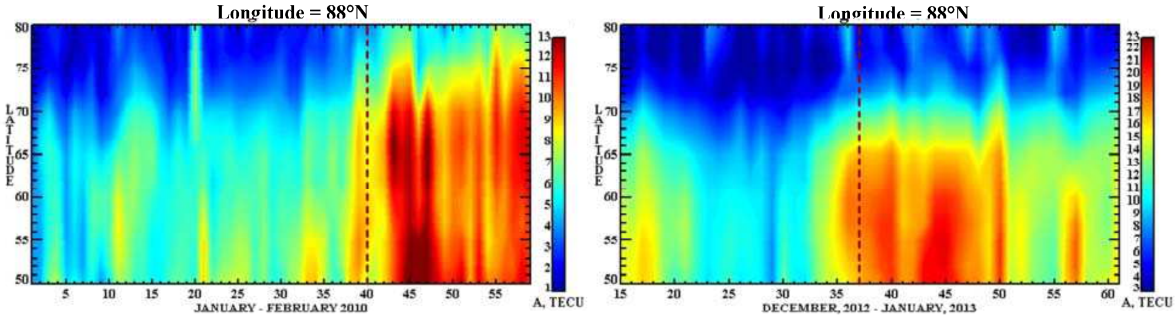


Figure 2: The TEC at NRIL and TIXI stations in January–February 2010. The red dotted line shows the major SSW peak (MSSW); the blue one, the maximum of the minor SSW (mSSW). The black dashed lines denote days of weak geomagnetic disturbances ($kp \leq 4$).

5. THE AMPLITUDE OF DIURNAL TEC VARIATIONS

Due to the low density of GPS/GLONASS receivers in Russia's Asian region, it is difficult to obtain the TEC spatial pattern using only its direct measurements. Therefore, global ionospheric maps (GIM, ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex) were used to evaluate the spatial structure of ionospheric disturbances during the periods of SSWs. These maps contain vertical TEC data around the world with a step of 2.5° in latitude and 5° in longitude. Based on these



(a) (b)

Figure 3: The amplitude of diurnal TEC variations at longitude of Norilsk in the latitudinal belt 50–80°N. The red dashed lines mark peaks of major SSWs.

data, distributions of amplitude of diurnal TEC variations were calculated at different longitudes in the latitudinal belt 50–80°N. The amplitude of diurnal TEC variations was calculated as the difference between the daily TEC maximum and minimum. The obtained distributions of the amplitude of diurnal TEC variations at longitude of Norilsk in January–February 2010 and in December–January 2012/13 are shown in Figure 3.

The development of warmings is accompanied by a decrease in amplitude of TEC diurnal variations (Figure 3), whereas a considerable increase in amplitude is recorded after the SSW maximum. The difference between the amplitude values before and after the SSW peaks is more than 2 times. Increased values of the amplitude of diurnal TEC variations are observed during 10–15 days. It should also be noted that variations in the amplitude of diurnal TEC variations are more pronounced at lower latitudes; however, they are clearly observed up to latitudes 75°N.

6. CONCLUSION

Analysis of the behavior of the high-latitude ionosphere in winters 2006–2013 showed that, despite quiet geomagnetic conditions, significant changes in the ionospheric dynamics are observed during the periods of sudden stratospheric warmings. During the warming development phase, a decrease in diurnal *NmF2* and TEC values is observed. On the contrary, the *NmF2* and TEC nighttime values increase. This leads to the decrease in the amplitude of diurnal TEC variations. After the SSW peak, a significant growth of the parameters under study is registered for all events. The increase in the amplitude of diurnal TEC variations after the SSW maximum is shown to be observed up to 70–75°N. No ionosphere reaction can be revealed for the SSW events that occurred in late winter.

Ionospheric effects of SSW may be due to the changes of the vertical transport of molecular gas from the underlying atmosphere to the lower thermosphere, occurring near the SSW center. Besides, they can be due to the alteration of the neutral atmosphere composition, which can affect the electron concentration. Dynamics of the ionosphere can also be influenced by the increase in intensity of stationary planetary waves, accompanying the SSW events.

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