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# Studying Manifestations of 2008–2011 Sudden Stratospheric Warmings in East-Siberia and European Russia

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## Abstract

*This paper presents a study of variations in atmospheric temperature at the mesopause and lower thermosphere (MLT) heights on the mid-latitudes in different longitudinal sectors during the 2008-2011 sudden stratospheric warming events. The research has been made on the data of ground-based and satellite temperature measurements. We analyzed variations of upper mesosphere temperature at ~87 km inferred from OH (6,2) airglow observations at two mid-latitude observation points: the ISTP Geophysical Observatory (East Siberian region, 52°N, 103°E) and the Zvenigorod Station (European region, 56°N, 37°E). Satellite data on atmospheric temperature vertical profiles obtained by the EOS Aura Microwave Limb Sounder (MLS) were involved.*

*We conducted a regression and correlation analysis of the day-to-day stratosphere and mesopause temperatures during the SSW events. The SSW manifestations were revealed to influence on the mesopause region in the East Asian longitude zone in a more complex way than in the European one. In the European longitudinal zone the mesopause temperature decreased almost simultaneously with the stratospheric temperature rise; in all these SSW events, when the stratospheric temperature increased by ~ 30 K, the temperature in the mesopause decreased by ~ 20 K. In East Asia, there was no stable trend in the mesopause temperature response to the SSW. These results may exhibit an SSW possible longitudinal effect on the thermal and dynamic regimes of the middle and upper atmosphere.*

*Key words: temperature, stratospheric warming, upper mesosphere, hydroxyl emission, ground-based and satellite measurements*

## 1. Introduction

Winter sudden stratospheric warming (SSW) is one of the most dramatic meteorological phenomena in the middle atmosphere. During a SSW, polar stratospheric temperatures rise and the zonal-mean zonal flow weakens dramatically over a short time period. Stratospheric warming can be said to be major when the zonal-mean zonal winds at 60°N and 10 hPa become easterly during winter and the 10-hPa zonal-mean temperature gradient between 60°N and 90°N becomes positive *(Charlton et al.,* 2007*)*. According to WMO definition, if no reversal of the westerlies is observed but only a rapid temperature increase, at least of 25°C within one week in the upper stratosphere in any area of winter time hemisphere, the event is defined to be a minor warming (*Labitzke*, 1977).

Thermodynamic regime disturbances during significant winter stratospheric warmings cover a wide range of heights from the troposphere to the upper mesosphere and the lower thermosphere *(Labitzke,* 1972*).* Mesospheric coolings are known to be associated with SSWs. The key mechanism, initially proposed by *Matsuno* (1971) and now widely accepted, is the growth of upward propagating planetary waves from the troposphere and the interaction between the transient wave and the mean flow. The interaction decelerates and/or reverses the eastward winter stratospheric jet and also induces a downward circulation in the stratosphere causing adiabatic heating and an upward circulation in the mesosphere causing adiabatic cooling. SSWs influence gravity wave propagation and transmission in the middle atmosphere. As *Holton* (1983) pointed out, the reversal of stratospheric winds reduces/eliminates the flux of gravity waves entering the mesosphere. Accordingly, the reduction in gravity wave drag causes a reduced meridional circulation and, hence, a cold mesosphere.

*Liu and Roble* (2002) predicted mesospheric cooling extending up to the heights of ~ 110 km with a secondary warming between 110–170 km. *Siskind et al.* (2010) explain that stratospheric wind shears during the SSW suppress the upward propagation of gravity waves into the mesosphere.

Experimental results confirming the SSW impact on MLT region were presented in (*Myrabo et. al*., 1984*; Matveeva & Semenov*, 1985*; Walterscheid*, 2000). Using the data on OH rotational temperature, the authors revealed the mesopause temperature decrease.

However, association between SSW events and the MLT region is not fully understood. Questions about the timing of stratospheric and mesospheric disturbances remain. *Myrabo et al*. (1984) report a 1–2 day delay in the mesospheric response to a stratospheric event, and *Hernandez* (2004) suggests the mesosphere cooling be a 1–2 month leading indicator of stratospheric warmings, while the model result of *Liu and Roble* (2002) indicates little, if any, phase lag or lead between the temperature anomalies in the mesosphere and stratosphere. *Hoffman et al.* (2007) found that the onset of the mesospheric cooling, accompanied by a reversal of the mesospheric circulation from eastward to westward winds during the major SSW in 2005/2006, occurred some days before the changes in the zonal circulation in the stratosphere, indicating a downward propagation of the circulation disturbances from the MLT region to the stratosphere during the SSW events. *Mbatha et al.* (2010) observed a similar reversal of the mean zonal wind at the MLT approximately 7 days before the reversal at 10 hPa, during the Southern SSW in September 2002.

The height distribution of SSW-related mesosphere cooling events has not been well established yet. Thus, (*Siskind et al*., 2005) using the SABER temperature data revealed that mesospheric temperatures between 0.7 hPa and 0.01 showed a significant anticorrelation with stratospheric temperatures during SSW. However, for pressures <0.01 hPa, this anticorrelation breaks down and near 0.002 hPa, which is the pressure associated with the OH emission peak, the correlation coefficient is close to zero or slightly positive, in disagreement with the calculations from *Liu and Roble* (2002).

The purpose of this paper is to study variations in atmospheric temperature at the MLT heights during winter stratospheric warmings in 2008-2011. The key feature of this study is that they are based on measurement data of the atmosphere in different longitudinal zones: Irkutsk (52°N, 103°E) and Zvenigorod (56°N, 37°E).

## *2. Analyzed data*

Data on the variations of mesopause temperature obtained from ground-based spectrographic measurements of the OH emission (834.0 nm, band (6-2)) at the Institute of Solar-Terrestrial Physics (ISTP) Geophysical Observatory (52°N, 103°E, near Irkutsk) and Zvenigorod Station (56°N, 37°E). Mesopause temperature is determined using the OH(6-2) emission spectra. The spectra allow to determine OH rotational temperature that corresponds to the atmospheric temperature at the mesopause height (height of the emission layer maximum is about 87 km (*Khomich et.al*., 2008)). Measurements and data processing at both observatories have been carried out by the same method (*Perminov et al*., 2007, *Khomich et.al*., 2008).

High-transmission diffraction spectrographs with CCD-matrix detectors allow recording of the night sky emission spectrum in the near infrared region with high spectral (~ 0.2-0.3 nm) and temporal (~ 2-5 min) resolutions are used. The field of view of used spectrographs provides a spatial resolution at the height of the OH emission about 20 km. To determine the OH rotational temperature, we used the first 3 lines of P-branch of the OH(6-2) vibration-rotation band. The accuracy of the temperature measurements is 2 K.

Satellite data on vertical temperature distribution in the stratosphere-mesosphere from Microwave Limb Sounder (MLS) aboard the EOS Aura (http://disc.sci.gsfc.nasa.gov/Aura/overview/data-holdings/MLS/index.shtml) have been used. The Aura spacecraft has near polar, sun-synchronous orbit at 705 km with a ~ 100-min period. MLS scans the Earth's limb in the forward direction of flight, viewing microwave emissions at the 118 GHz – 2.5 THz spectral regions. The vertical resolution of these data is about 3 km, and the spatial coverage is near-global (-82° to +82° latitude), with each profile spaced 1.5° (about 165 km ) along the orbit track (roughly 15 orbits per day). These measurements have been used to derive vertical profiles of various atmospheric components, relative humidity and temperature of the atmosphere. According to Schwartz et al. 2008, temperature precision is 1 K or better from 316 hPa to 3.16 hPa, degrading to 3 K at 0.001 hPa. The vertical resolution is 3 km at 31.6 hPa, degrading to 6 km at 316 hPa and to 13 km at 0.001 hPa.

National Centers for Environmental Prediction (NCEP) annual data for the Northern Hemisphere. The NCEP/NCAR Reanalysis data set is a continually updating gridded data set representing the state of the Earth's atmosphere, incorporating observations and numerical weather prediction (NWP) model output dating back to 1948. It is a joint product from the NCEP and the National Center for Atmospheric Research (NCAR). We used data for the Northern Hemisphere (http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data.html). These data represent an archive of various meteorological parameters for 150-10 hPa atmospheric heights for the period of 1 January 1979 until present. We analyzed the daily atmospheric temperature at 10 hPa for this whole period. For the analysis, we chose the temperature at the North Pole and the zonal temperature for 60-90ºN and 50ºN.

## *3. Results and discussion*

In January-February 2008, January 2009 and January 2010, there were very intense, long-time winter SSWs covering a large part of the Northern Hemisphere. The SSW in January 2011 was less intense, however, well-pronounced in zonal stratospheric temperature at 50N. SSWs in 2008-2009 were among the most intense events in the Northern Hemisphere since 1978. Fig. 1 presents variations of daily stratospheric temperature at 10 hPa geopotential level for the North Pole (90ºN) and zonal mean temperature for 60-90ºN and 50ºN according to the NCEP annual data for the Northern Hemisphere. Red arrows show periods of the analyzed SSW events. The January–February 2008 period was characterized by four SSWs, the SSW events in January being minor warmings, the last warming, at the end of February 2008, being a major warming (*De Wachter et.al.,* 2011). The major stratospheric warming in January 2009, when the stratospheric temperature reached record-breaking values, was an especially remarkable event. This event was the strongest and most prolonged on record and was associated with a vortex split (*Manney et al*., 2009a). The SSW in January 2009 has been described in a number of publications (*Labitzke*, 2009, *Harada et al*. 2009). Stratospheric warmings in January 2010 and January-February 2011 were minor warmings. Preliminary analysis of 2008-2010 SSW events was performed in *(Medvedeva et.al.,* 2011).

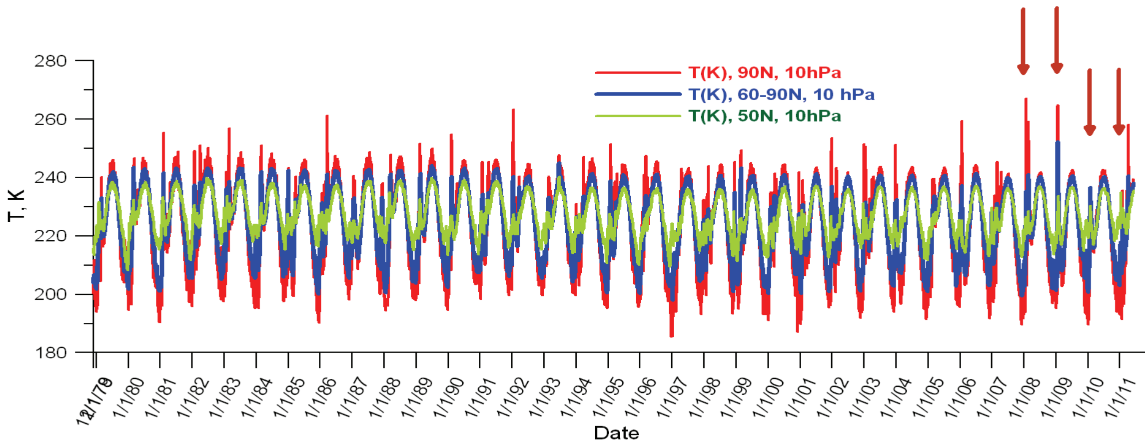


Fig. 1. Daily stratospheric temperature at 10 hPa geopotential level for the North Pole (red), 60-90ºN (blue) and 50ºN (green), NCEP data. Red arrows – periods of analyzed SSW events.

During the 2008–2011 SSWs, stratospheric temperature disturbances of large spatial scales were observed (Fig. 2). There were temperature disturbances in almost the entire middle atmosphere and significant changes in the vertical distribution of temperature. Under quiet conditions and with no SSWs observed, the winter stratospheric temperature at the 10hPa isobaric level is ~ 210 K. The largest temperature increases were observed in the stratosphere at altitudes of 40-50 km. The cooling of the atmosphere recorded at MLT heights was distributed very irregularly in height and time.

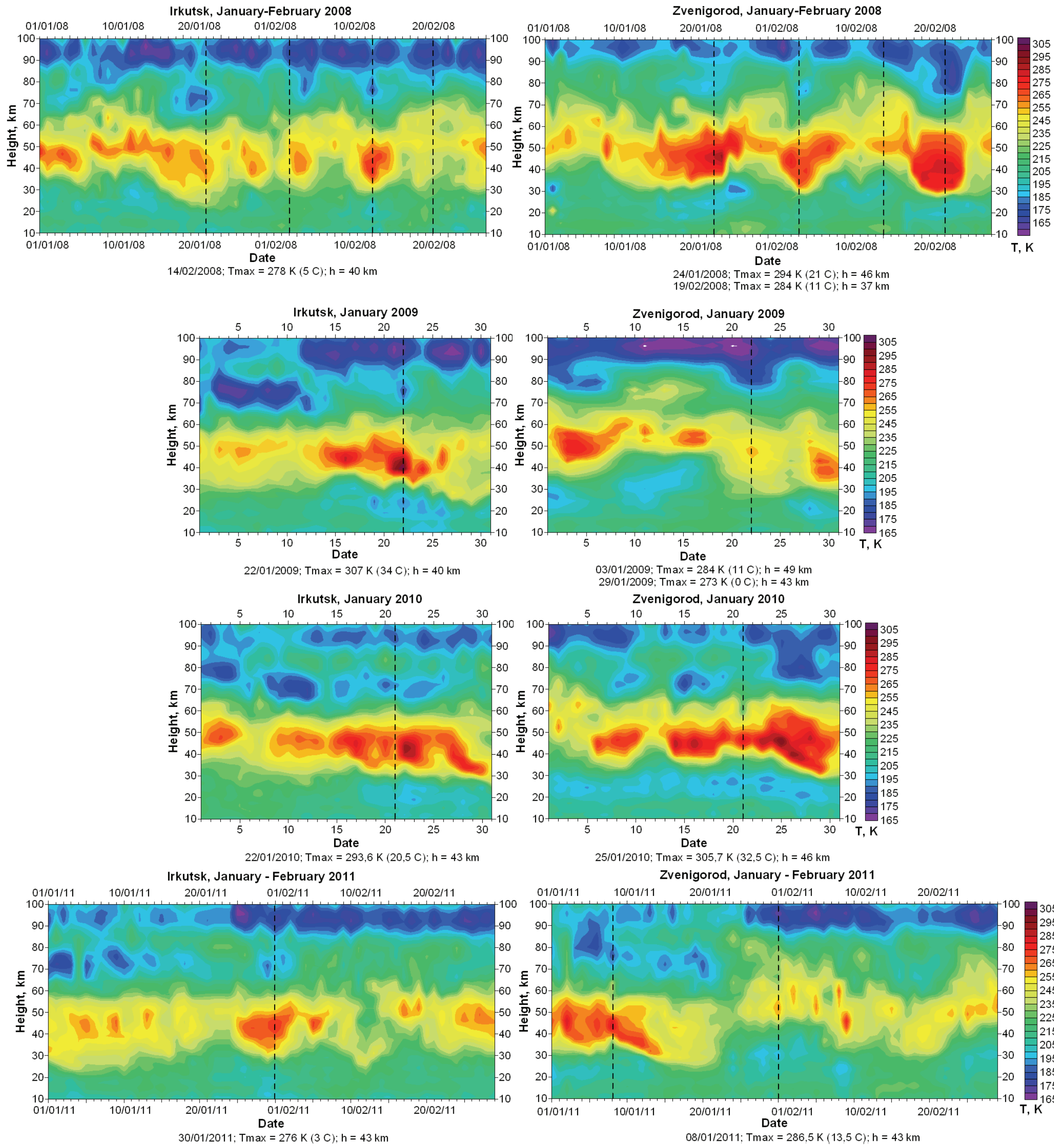


Fig. 2. Altitude-temporal maps of the atmospheric temperature distribution from the MLS AURA for the region of Irkutsk and Zvenigorod (search radius is 900 km). Dashed lines – onset of SSW events.

Fig. 3 presents variations of temperatures of the stratosphere and mesopause for the periods January-February 2008, January 2009, January 2010 and January 2011 for Irkutsk and Zvenigorod regions. The comparison of the stratosphere and mesopause temperature variations were made to perform a qualitative analysis of connection between the stratospheric temperature increase and the mesopause temperature dynamics. The MLS AURA data on temperature correspond to nighttime flights of the satellite over the regions under the study, search radius is 900 km. Satellite data on temperature were averaged over several height levels and corresponded to stratospheric heights of 3.16-1 hPa (~39-49 km) and mesospheric heights of 0.005-0.002 hPa (~84-88 km). The mesopause temperature data obtained from ground-based measurements of OH(6-2) rotational temperature corresponded to an altitude of about 87 km; we used nightly mean temperatures. No ground-based spectrographic measurements of the hydroxyl emission were made at the the ISTP Geophysical observatory in January-February 2008. The ground-based and MLS temperatures, as shown in Figure 3, have some difference in the MLT region which is in agreement with French and Mulligan (2010) who revealed that Aura/MLS exhibited a 9.9±0.4K cold bias compared with OH(6-2) temperatures.

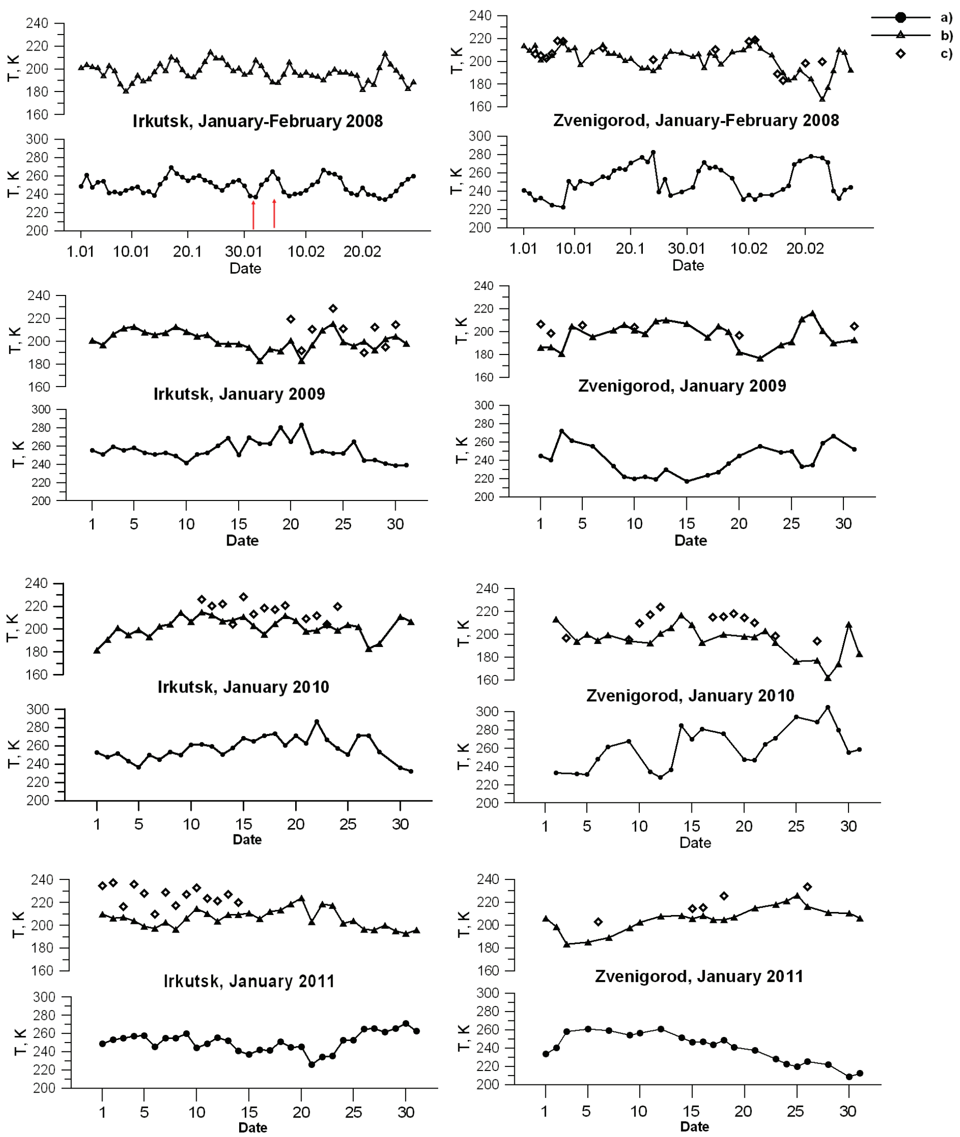


Fig. 3. Variations in the atmospheric temperature at various height levels: a )T of the stratosphere averaged for 3.16-1 hPa (~39-49 km) levels, MLS Aura data; b) T of the mesopause region averaged for 0.005-0.002 hPa (~84-88 km) levels, MLS Aura data; c) T OH (~87 km), ground-based data.

Note that over Zvenigorod, unlike over Irkutsk, a decrease (up to 30 K) in the mesopause temperature was observed during all the SSW events under consideration.

As for the Irkutsk region, the pattern is not so well-defined. Thus, during January-February 2008, oscillations of the atmospheric temperature at both the stratosphere and mesopause altitudes with ~ 6-8 day periods were observed; these oscillations were sometimes antiphased, the examples have been marked by red arrows.

To determine quantitative characteristics of the connection between day-to-day values of the mesopause and stratospheric temperatures we chose SSWs in 2008-2010 because these events were very intense, long-time winter SSWs covering a large part of the Northern Hemisphere, including both analyzed regions. So it was interesting to see if the reaction of mesopause region on such strong events for two mid-latitude regions would differ. Fig. 4 presents the results of regression analysis and the derived regression equations during the 2008-2010 SSW events for the MLS Aura measurement data only. Unfortunately, ground based measurements, due to weather conditions, are insufficient to conduct a similar analysis. So, OH rotational temperature is simply plotted by the diamonds to show that their variations are in reasonably good agreement with the observed dependences derived from the satellite data.

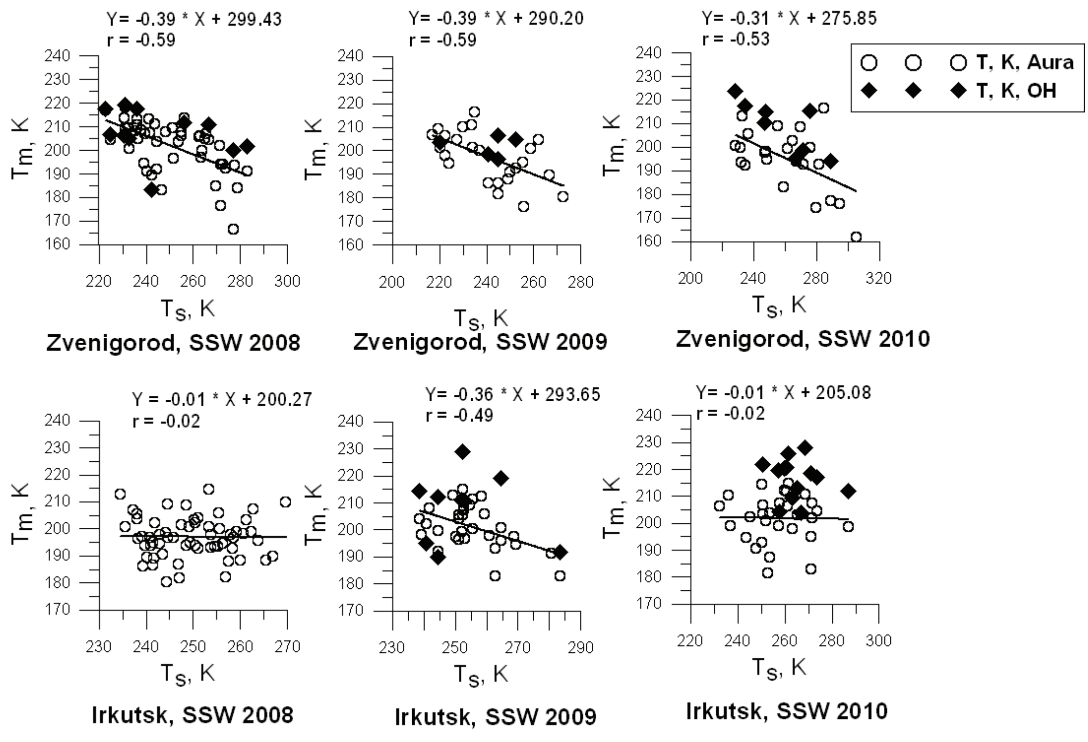


Fig. 4. Linear regression of the mesopause (Tmes, 84-88 km) and stratosphere (Tstr, 39-49km) temperature, MLS Aura data, circles. Diamonds - data of ground-based measurements.

Figure 4 shows the dependence of day-to-day values of the mesopause temperature on stratospheric temperature found for all the three analyzed SSW events in Zvenigorod and 2009 SSW event in Irkutsk. It allowed us to reveal their common features described by the following equation

$$Tmes= -(0.35\pm0.04)*Tstr + 288\pm12, \qquad r = -0.55,$$

where r is correlation coefficient.

It should be emphasized that no correlation was found between day-to-day variations in the mesopause (84-88 km) and stratospheric (39-49 km) temperatures over Irkutsk during the 2008 and 2010 SSW events. This may be caused by the fact that, according to Figure 2, the atmospheric cooling during these SSW events occurred at higher altitudes (~90-100 km) which suggests a more complicated relationship between dynamic and thermal processes in the East Asia region within these periods. In any case, these findings, as well as those by *Siskind et al*. (2005), do not correspond to the model calculations (*Liu and Roble*, 2002) suggesting a steady decrease in temperature in the MLT region up to 110 km during SSW events.

In addition, we carried out cross-correlation analysis (Fig.5) of day-to-day values of the mesopause and stratospheric temperatures during the 2008-2010 SSW events for the MLS Aura measurement data that revealed the following. In the European longitudinal zone, the mesopause temperature decreased almost simultaneously with the stratospheric temperature increase (Fig.5a). For all the three analyzed SSW events in Zvenigorod negative correlation of the stratospheric and mesopause temperatures was found; correlation coefficients were maximal at time lag=0, for all these SSWs its value was r ~ -0.6.

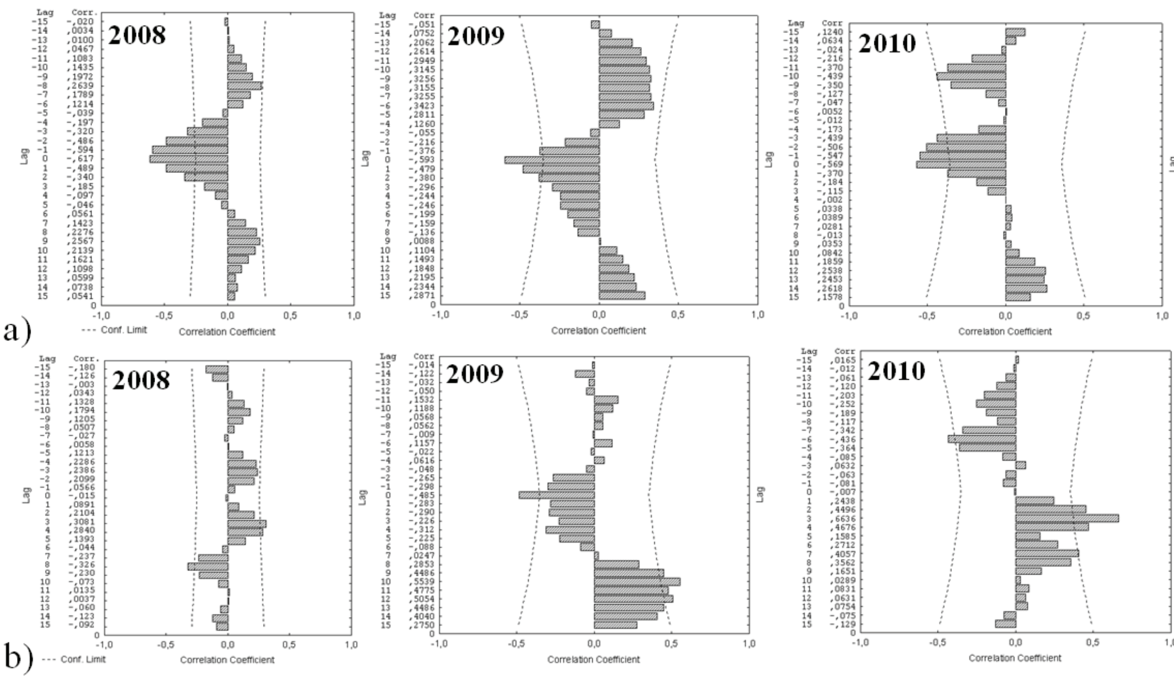


Fig. 5. Cross-correlation functions of the stratospheric (T strat, 39-49 km) and mesopause (T mes, 84-88 km) temperatures for Zvenigorod (a) and Irkutsk (b) regions, MLS Aura data. First variable: Tstrat, Lagged: Tmes, time lag=1 day. Dotted lines – 95% confidence limits.

In the East Asian longitudinal zone, no stable trend was revealed in the mesopause temperature response to the SSW (Fig. 5b). Manifestations of the SSW influence on the mesopause region in the East Asian longitudinal zone appear to be more complicated than that in the European one.

As classified by *Charlton & Polvani* (2007), there are two types of SSW events: vortex-displacement events when the stratospheric polar vortex displaces from its climatological position over the pole while preserving its integrity, and vortex splitting events when the vortex splits into two parts. According to *Matthewman et. al*. (2009), during vortex-splitting events, the vortex remains nearly barotropic with the vortex split occurring near-simultaneously over a large altitude range. In contrast, during vortex-displacement events, the vortex displacement off the pole increases with altitude above 30 km, as does the accompanying elongation of the vortex during the SSW. Splitting events are characterized by a rapid increase in the aspect ratio of the vortex a few days prior to the SSW followed by the roll-up of the elongated vortex into two distinct daughter vortices. The daughter vortices propagate rapidly apart to a distance of up to 5000 km after which they experience a retrograde rotation around their common centroid usually leading to the destruction of the weaker Canadian vortex and reformation of the main vortex around the stronger Siberian vortex. SSW in January-February 2008 and January 2010 were polar vortex displacement events (*De Wachter et. al.* 2011*, Kuttippurath1 and G. Nikulin,* 2012), whereas SSW in January 2009 was vortex-splitting event *(Manney et.al.,* 2009*)*. Probably, the revealed longitudinal differences in manifestations of the mesopause response to the analyzed SSW events are caused by a difference in the polar vortex behavior.

The mesopause altitude changes as the stratopause altitude changes, too. We analyzed temporal variations of the ratio of the stratopause and mesopause temperatures (Fig. 6) using temperature vertical profiles of MLS Aura, one day – one profile. For each profile we chose maximal temperature in the stratosphere – it was stratopause, and minimal temperature in the mesosphere – mesopause. Then we calculated stratopause-to-mesopause temperature ratio. For example, for undisturbed winter day, 16.12.2010, for Zvenigorod according to MLS data $T_{stratopause}$=252 K, $T_{mesopause}$=198 K, $T_{stratopause} / T_{mesopause}$ = 1,28. For SSW, 28.01.2010: $T_{stratopause}$=319 K, $T_{mesopause}$=162 K, $T_{stratopause} / T_{mesopause}$ =1,97 (red arrow in the plot). The value of this ratio changed from 1.1 up to 1.9 during the analyzed SSWs. This ratio indicates the behaviour of the variation of the temperature in the stratopause and the mesopause. We believe, the observed variation of this ratio values from 1.1 to 1.9 can display the details of the interaction between these regions of the atmosphere during SSW. Therefore, this ratio could probably be used to estimate the winter mesosphere disturbance and as a quantitative characteristic of manifesting the complicated interaction processes between lower and upper atmosphere during SSW events. However, this requires further accumulation of the data on the mesopause and stratopause temperatures behavior during the SSWs.

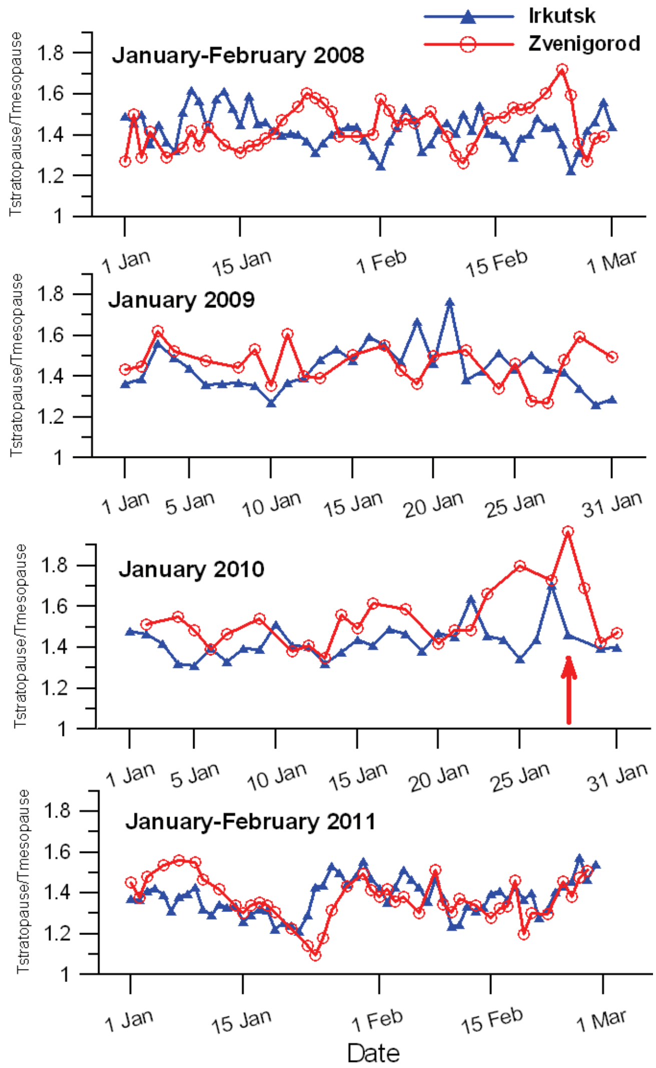


Fig. 6. Ratio of the temperatures of the stratopause and mesopause, MLS Aura data.

## 4. *Conclusions*

The analysis of the atmospheric temperature variations from ground-based and satellite data during the 2008–2011 winter stratospheric warming events revealed disturbances in the middle atmosphere from the stratosphere to the mesopause.

We obtained regression and correlation dependences of day-to-day temperatures of the stratosphere and mesopause during the SSWs. The SSW manifestations were revealed to influence on the mesopause region in the East Asian longitudinal zone in a more complex way than in the European one. In the European longitudinal zone, the mesopause temperature decreased almost simultaneously with the stratospheric temperature rise. In all these SSW events, when the stratospheric temperature increased by ~ 30 K, the temperature in the mesopause decreased by ~ 20 K. In East Asia, there was no stable tendency in the mesopause temperature response to the SSWs. Probably, the revealed longitudinal differences in manifestations of the mesopause response to the analyzed SSW events are caused by a difference in the polar vortex behavior. These results may indicate a possible longitudinal effect of SSWs on the thermal and dynamic regimes of the middle and upper atmosphere.

We analyzed the ratio of the stratopause and mesopause temperatures at the altitudes where mesopause and stratopause were located each day. This ratio could be probably used to estimate the winter mesosphere disturbance and as a quantitative characteristic of manifesting the complicated interaction processes between lower and upper atmosphere during SSW events.

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