Journal of Atmospheric and Solar-Terrestrial Physics xxx (2017) 1–9

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

On statistical irregularity of stratospheric warming occurrence during northern winters

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ARTICLE INFO

Keywords:
Climatology
Stratospheric warming
Zonal-mean wind
Temperature
Planetary wave activity
Dynamical regime of the stratosphere

ABSTRACT

Statistical analysis of dates of warming events observed during the years 1981–2016 at different stratospheric altitudes reveals their non-uniform distributions during northern winter months with maxima at the beginning of January, at the end of January – beginning of February and at the end of February. Climatology of zonal-mean zonal wind, deviations of temperature from its winter-averaged values, and planetary wave (PW) characteristics at high and middle northern latitudes in the altitude range from the ground up to 60 km is studied using the database of meteorological reanalysis MERRA. Climatological temperature deviations averaged over the 60–90°N latitudinal bands reveal cooler and warmer layers descending due to seasonal changes during the polar night. PW amplitudes and upward Eliassen-Palm fluxes averaged over 36 years have periodical maxima with the main maximum at the beginning of January at altitudes 40–50 km. During the above-mentioned intervals of more frequent occurrence of stratospheric warming events, maxima of PW amplitudes and Eliassen-Palm fluxes, also minima of eastward winds in the high-latitude northern stratosphere have been found. Climatological intra-seasonal irregularities of stratospheric warming dates could indicate reiterating phases of stratospheric vacillations in different years.

1. Introduction

The coupling between the middle and lower atmosphere is extensively investigated on the base of observations and model simulations over several last decades.(e.g, Quiroz, 1975; Labitzke, 1977; Schoeberl, 1978). It is well known that sudden stratospheric warming (SSW) events are the clearest and strongest manifestation of the coupling of the stratosphere–troposphere system (Charlton and Polvani, 2007). Connected with SSWs circulation anomalies associated with strong or weak stratospheric polar vortex events can decent from the middle to the lower stratosphere where they persist, on average, for more than 2 months (e.g., Baldwin and Dunkerton, 2001) and produce substantial weather effects, for example, intense outbreaks of cold air in winter (e.g., Thompson et al., 2002). SSWs can also affect the circulation of the North Atlantic Ocean (Reichler et al., 2012), the effects of the El Niño - Southern Oscillation (ENSO) in Eurasia (e.g., Ineson and Scaife, 2009). They play an important role in stratospheric chemistry (e.g., Manney et al., 2003, 2005), transport of climate active gases and pollutants (Jiang et al., 2013; Butler et al., 2014), ozone variability in Arctic and Antarctic (e.g., Schoeberl and Hartmann, 1991). Evidences exist about SSW impacts on polar clouds in the troposphere (Kohma and Sato, 2014), on convective activity in the equatorial troposphere (e.g., Kodera, 2006), on dynamics of the mesosphere and formation of the stratopause (e.g., Siskind et al., 2007; Manney et al., 2005).

Since their first detection in 1952 (Scherhag, 1952), SSWs were extensively observed and categorized by the World Meteorological Organization. Gómez-Escolar et al. (2012) found an increase of SSW occurrence frequency in the post-satellite era from the analysis of the NCEP-NCAR and ERA-40 meteorological reanalysis datasets. The authors showed that SSWs tend to occur preferentially in January in the years 1958–1978, whereas they occur more often in December and at the end of February in years 1979–2002. Charlton and Polvani (2007) showed that typically SSWs occur in January–February with only a few SSWs occurring in November and December. Charlton and Polvani (2007) and Pawson and Naujokat (1999) demonstrated inter-annual SSW variability. They found a tendency toward reducing SSW activity during the mid-

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http://dx.doi.org/10.1016/j.jastp.2017.06.007
Received 30 December 2016; Received in revised form 16 June 2017; Accepted 18 June 2017
Available online xxxx
1364-6826/

1990s, which was not continued at the beginning of the twenty-first century. Manney et al. (2005) analyzed the interval 1958–2004 and reported about highest SSW activity between the years 1998 and 2004. Pogoreltsev et al. (2015) demonstrated the important role of nonlinear interactions of the mean flow with stationary planetary waves in the SSW formation.

Butler et al. (2015) analyzed variety of existing SSW definitions using the NCEP-NCAR and ERA reanalysis data and provided tables of dates of all major SSWs observed in years 1958–2013. Gómez-Escolar et al. (2012) analyzed the frequency distribution of SSWs during 1957–2002 from the ERA-40 reanalysis data. They found different SSW numbers in different 10-day bins. These results raised an idea that the dates of major SSWs may have non-uniform distribution even at time scales of a few weeks during the winter months. To clarify this idea in this study, we performed a climatological analysis of atmospheric characteristics related to SSW developments.

Most of the mentioned above SSW climatology studies used the NCEP/NCAR and ERA reanalysis datasets, which cover the longest period of observation in the stratosphere (since the year of 1958) with the upper boundary at the 10 hPa pressure level (approximately 30–35 km height). Recently, the Modern Era Retrospective-Analysis for Research and Applications (MERRA) database (Rienecker et al., 2011) and UK Met Office Assimilated Stratospheric Data (Swinbank and O'Neill, 1994) have been developed, which span the altitudes from the ground to 50 km (pressures up to 0.01 hPa). The analysis of 36-year (1981–2016) MERRA database (Rienecker et al., 2011) for altitudes up to 60 km was performed in the present study.

We estimated intra-seasonal distributions of dates of major and minor stratospheric warmings (SWs) as well as amplitudes and Eliassen-Palm (EP) fluxes of planetary wave (PW) components with zonal wavenumbers $m = 1$ and $m = 2$, EP-flux divergence, zonal-mean zonal wind and temperature deviations from its winter-mean values averaged over the 60–90° N latitudinal band at altitudes from the ground up to 60 km.

These climatological data were compared with statistical distributions of observed dates of major SSWs given as supplement to the paper by Butler et al. (2015).

2. Methods of data analysis

The term "sudden stratospheric warming" is traditionally assigned to the abrupt increases in temperature associated with zonal wind reversals at the pressure level of 10 hPa (e.g., Butler et al., 2015). Fig. 1 represents an example of temperature deviation from the winter average value (Fig. 1a) and the zonal wind (Fig. 1b) for winter months of the year 1982 obtained from the MERRA database at high latitudes. One can see sharp increase in polar stratospheric temperature in the second part of January and corresponding reversal of the zonal wind direction. However, this reversal exists at altitudes above 10 hPa level and, strictly speaking, this event can not be treated as SSW according to the WMO rules. To distinguish such events at higher stratospheric levels from traditionally discussed SSW events, we call them here as "high stratospheric warming (HSW) events".

In Fig. 1b the zero zonal wind contour appear first at altitude about 50 km on January 23. This altitude and date are considered here as the date and location of the HSW. At altitudes below 40 km the zonal wind reversal occurs 1–2 days later than that at 50 km level in Fig. 1b. Dates and heights of all HSWs obtained from the MERRA database for years 1981–2016 are given in the Supplementary Table 2 to the present paper. Fig. 1a shows the second substantial temperature increase (up to 20 K) at the end of February. One can see respective decrease in the zonal wind in Fig. 1b, however the wind does not drop below zero. One can treat such events as "minor HSW". In the Supplementary Table 2, we included such minor SSWs, for which the zonal wind drops below 10 m/s at latitude 62.5°N and mark them as "0 < u < 10". The date and altitude of minor HSW are determined using the contour of lowest zonal wind (10 m/s for Fig. 1b at the end of February).

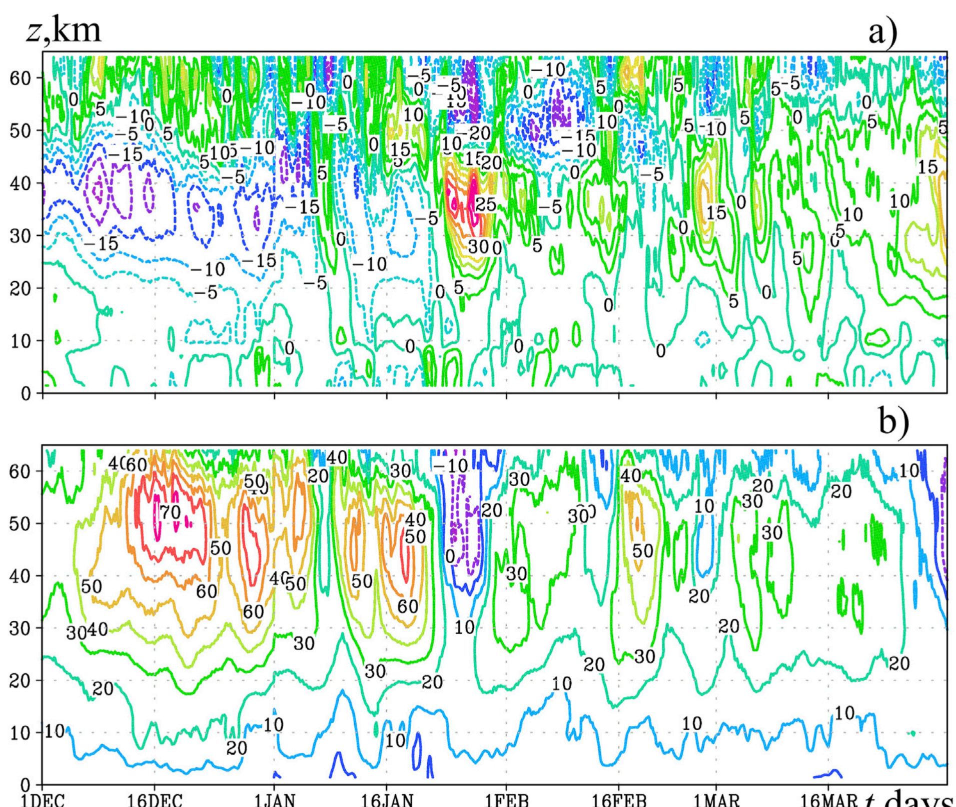

Fig. 1. Example of temperature deviation in K from the winter average value at latitude 87.5° N (a) and zonal velocity in m/s at latitude 62.5° N (b) for winter months of year 1982 obtained from the MERRA database.