Response to the comments of the referee 1

Notes on the correlation between SSWs and solar activity

By Ekaterina Vorobeva

Dear Referee,

Thank you a lot for your constructive suggestions. We tried to follow your comments and suggestions.

Specific comments.

Referee writes: "There are, of course, further proxies for solar activity."

In order to satisfy the referee and to enlarge an area of paper's application, we add four proxies (solar 3.2 cm, 8 cm, 15 cm, and 30 cm fluxes) in Table 1.

Referee note: "A positive correlation between MSSW and F10.7 is a statistical result which does nothing state about the mechanism of connection."

We have similar notation in the Summary section, i. e.: "Note that the correlation is necessary but not a sufficient condition for a relationship between the two phenomena".

Referee notes: " There occurs a possible bias due to decreasing strength of the solar cycles (from cycle 21 to cycle 24 now) and the simultaneous increasing cooling of the middle atmosphere due to growing CO2 concentration (e.g. Berger and Lübken, 2011) and a general trend in stratospheric ozone by increase of the concentration of some minor constituents such as methane, N2O and other greenhouse gases. This entails a trend in the composition independent of solar activity"

The separation of the effects of long-term changes in solar cycle and long-term changes of anthropogenic greenhouse gases (GHGs) and ozone-depleting substances (ODSs) on the middle atmosphere still remains unsolved problem. Yes, generally speaking, joint declining of solar cycle and growth of GHGs and ODSs may produce bias in correlation. But according with current knowledge, there is no statistically significant impact of anthropogenic changes on frequency of SSWs (e. g. Butchart et al., 2000; SPARC CCMVal, 2010; Mitchell et al., 2012; Hansen et al., 2014, Ayarzagüena et al., 2018). Moreover, some of recent works show increase of the SSWs frequency (e.g., Huebener et al., 2007; Charlton-Perez et al., 2008; Bell et al., 2009; Schimanke et al., 2013; Ayarzagüena et al., 2013). Thus, in last case, the join effect of negative trend in solar cycle strength and positive trend of GHGs may just reduce positive correlation, but cannot be its cause.

We add similar notation into the section Discussion.

Referee writes: "Please define and explain in more detail the expression "normalized" (line 109)."

We rewrote line 109 in order to explain the expression "normalized" used in the text. Due to the limitation of paper size, we do not describe in detail a process of using a norm factor but we present the reference where one can find it.

Referee writes: "Chapter 2 should be split inserting Chapter 3 "Discussion" after line 123. Summary is then Chapter 4."

Chapter 2 was split into Chapter 2 "Data, Method, and Result" and Chapter 3 "Discussion". In addition, we expanded Chapter 3 "Discussion" according to the referee's comments and suggestions.

Referee writes: "However, it should be mentioned that already the step from Figure 1b to 1c entails a statistical uncertainty which decreases with the number of solar cycles."

We noted this fact right after the equation (1).

Referee writes: "The references ... are missing in the Text. (It is not necessary to quote Labitzke so often, your paper deals with the influence of the F10.7 flux upon the occurrence rate of MSSW, not with the connection between the occurrence rate of MSSW and the phase of the QBO.)"

Thank you for this remark. We removed the references missing in the text.

Referee writes: "Authors beginning with Sh… should be quoted after Sc… in the list of references (e.g.Shepherd after Scherhag)."

Thank you for this remark. We rewrote the list of references in alphabetical order.

Referee writes: "The reference Charlton et al., 2007 is double. Line 91: Charlton et al., 2007."

The reference in Line 91 was changed to Charlton et al., 2007.

Referee writes: "Line 24/25: A corresponding mesospheric cooling has been found shortly after. The SSW starts with a mesospheric cooling before the SSW occurs in the stratosphere."

Currently, there are no unique opinion on time delay between SSW and mesopause cooling. Some authors state that they coincide (e. g. Zülicke et al., 2018). We do not touch this question in our short note and do not want make any strong statements on this subject.

Referee writes: "Line 72 What is meant with: "One of the strongest effects on the nature of Earth comes from the sun…"?"

The author wanted to notice the solar influence on the Earth's atmosphere. Line 72 was rewritten to clarify the point.

Referee writes: "Line 78/80…without to consider a relation to QBO…"

Corrected according to the reviewer's comment.

Referee writes: "Line 123 Not only: "different periods", but also different bins, different solar proxies."

We added other possible reasons for the difference of correlation coefficients.

Thank you a lot for taking the time to review the manuscript.

With respect,

Ekaterina Vorobeva.

Notes on the correlation between SSWs and solar activity

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Abstract

A correlation between solar activity and normalized occurrence rate of sudden stratospheric warmings (SSWs) has been found. As a proxy for solar activity, the ~~F~~10.7 cm solar radio flux has been used. In order to find the correlation, we derived a normalized occurrence rate of MSSWs based on both ERA40/ERA-Interim dataset and NCEP data. Based on this distribution, we calculated the correlation coefficient, which amounts to 0.63 ~~0.6314~~, with a significance of 90.68% for ERA40/ERA-Interim, and 0.55 ~~0.5455~~ for NCEP-NCAR-I, with a significance of 83.80%. Additionally, we calculate correlation coefficients for Lyman-alpha flux and sunspot numbers with the analogous method for the same period.

Keywords: Middle atmosphere – composition and chemistry; Waves and tides; Middle atmosphere dynamics

1. Introduction

In the middle of the last century, Scherhag (1952) and Scrase (1953) independently found an incident of sudden stratospheric warming (SSW). A corresponding mesospheric cooling has been found shortly after (Quiroz, 1969). The SSW effect is manifested in sudden and short (several days) increase in temperature (up to 60 K) in the stratosphere and joint cooling in the mesosphere at high and middle latitudes during winter. More strict definition of SSW one can find in ~~any~~ reviews on this subject (e.g. Butler et al., 2015). According ~~with~~ to current knowledge (see e.g. Shepherd et al., 2014; Zülicke et al., 2018; and references therein) the genesis of the effect goes from mesopause at high latitudes toward stratosphere at middle latitudes with peak of intensity around 65° N. There are two types of sudden stratospheric warmings: minor warmings and major warmings. Minor warmings also consist of the temperature increase, but at 10 hPa it is about 30 K smaller than for major warmings. The main difference is that unlike to the major warming, during the minor one, the zonal wind weakens but does not reverse the direction (e.g. Labitzke, 1981). In this study, we consider just major sudden stratospheric warming effect.

SSW events play a rather important role in atmospheric investigations not only because these pronounced events have impacts on all processes in the middle atmosphere but also because they provide a natural examination of our understanding of atmospheric interactions. The first step to understanding the nature of SSWs was the theory of planetary waves (PWs) propagation by Charney and Drazin (1961), who derived the dispersion relationship for vertically propagating Rossby waves. The theoretical explanation was proposed by Dickinson (1968a,b; 1969a,b) and consists of an interaction of PWs which penetrate into the winter middle atmosphere and affect general mean circulation when they dissipate. Steady dissipating waves can weaken the zonal mean flow and maintain the winter stratosphere above radiative equilibrium temperatures (Dickinson, 1969b). This theory was confirmed by model simulations (Matsuno, 1970, 1971). Currently, this explanation is generally accepted; nevertheless, we should note that there are alternatives. For example, based on model simulations, Peters (1985 a,b) found that SSW-like effects may occur due to nonlinear wave–wave interactions. However, the role of wave–wave interaction during SSWs is not clear until the present time. Recently, Gavrilov et al. (2017) have touched upon this problem.

Since SSWs have been observed and modeled in numerous works (e.g. Holton, 1976; Schoeberl, 1978; Tao, 1994; Siskind et al., 2005; Smith et al., 2011, and references therein), the topic has attracted genuine interest in all fields of atmospheric science. Using a 3D model, Sonnemann et al. (2006) studied the distributions of minor chemical species in the mesopause region in time of SSWs. The most-detailed investigation of the variability of the hydroxyl airglow layer during SSWs has been represented in the work of Shepherd et al. (2010). The response of OH* and the infrared atmospheric band has been found by satellite observations (Gao et al., 2011), and Shepherd et al. (2014) investigated the impact of this phenomenon on distributions of CO and NO_x based on a joint analysis of model simulation and satellite observations. The impact of SSWs on the secondary ozone layer has been highlighted in the work of Tweedy et al. (2013) based on model simulations and in the work Smith et al. (2009) based on the SABER instrument onboard the TIMED satellite. The temperature and dynamic structure of the mesopause region during sudden stratospheric warmings were investigated by reanalysis data (Siskind et al., 2010) and based on a global circulation model ~~by~~ (Zülicke and Becker, 2013). A large number of works are devoted to the role and propagations of gravity waves in times of SSWs (Limpasuvan et al., 2011, 2012; McLandress et al., 2013; de Wit et al., 2014; Ern et al., 2016). Recently, an effect on the troposphere (Hinssen et al., 2011) and equatorial latitudes has been found (Bal et al., 2017). More about SSWs and related fields can be found in reviews of this subject (e.g. Holton, 1980; McIntyre, 1982; Plumb, 2010; Butler et al., 2015).

~~One of the strongest effects on the nature of Earth comes from the sun~~ Solar irradiance strongly affects the Earth’s atmosphere and climate (Seppälä et al., 2014); hence, naturally, the question of what the effect of solar variations on the SSW occurrence rate arises. The strongest solar variation is the 11-year solar cycle. Labitzke and van Loon (1990) did not find any significant correlation between the 11-year solar cycle and MSSWs based on their analysis of the ~~F~~10.7 cm solar radio flux. Nevertheless, Labitzke (2004, and references therein) showed that such a correlation exists for MSSW events distributed by phases of QBO (quasi biennial oscillation). This is partially in contradiction with work of Sonnemann and Grygalashvyly (2007), who found such a correlation without ~~a relationship~~ considering a relation to QBO phases based on an analysis of Lyman-alpha flux and sunspot numbers. The reason for the discrepancy is either the difference in fluxes or methods.

We decided to narrow this gap in the knowledge and conduct an analysis of the solar radio flux at 10.7 cm (F10.7 ~~flux~~). However, based on SSW statistics and F10.7 data ~~radio flux~~, we derived a normalized occurrence rate for MSSW events. The data, method, and results are described in Sect. 2, the discussion is presented in Sect. 3 followed by concluding remarks in the last section.

2. Data, Method, and Result

We investigate the statistical connection between MSSWs and solar activity. As a proxy for solar activity, we use the ~~F~~10.7 cm solar radio flux (http://lasp.colorado.edu/lisird/data/noaa_radio_flux/). Because MSSWs are phenomena that commonly occur from December until March (Charlton et al., 2007 ~~Charlton and Polvani, 2007~~), we calculated monthly mean values of F10.7 ~~radio flux~~ for December, January, February, and March through the entire period from 1958 to 2013. The lowest mean F10.7 ~~radio flux~~ value did not fall below 67 solar flux units (sfu). The uppermost value did not exceed 267 sfu. We chose a difference of 25 sfu for the flux subdivision (8 subintervals) and calculated a number of monthly mean F10.7 ~~radio flux~~ values which fell into each subinterval (Fig. 1a).

Next, we calculated the mean F10.7 ~~flux~~ values for the month prior to the MSSWs' central day (the day when zonal mean zonal wind at 10 hPa becomes negative). In this study, we used two databases of central day. The first database combines the central day of MSSW events from ERA-40 reanalysis for the period 1958 to 1979 (14 events) and ERA-interim reanalysis for the period 1979 to 2013 (23 events) (Butler et al., 2017). The central days by NCEP-NCAR-I reanalysis (35 events) (Butler et al., 2017) were used as the second database. Then, we calculated the number of MSSWs that occurred in each F10.7 ~~radio flux~~ subinterval (Fig. 1b) based on two databases of central day. The dependence of MSSWs on F10.7 ~~flux~~ is rather negative (Fig. 1b), but we should take into account that the distribution of wintertime monthly averaged values of F10.7 ~~flux~~ is non-uniform. The values corresponding to low solar activity occur most often, and values corresponding to high solar activity are rare. Hence, for calculations of correlation between MSSW and F10.7, ~~MSSW occurrence rate should be normalized~~ number of MSSWs at given solar activity should be normalized by the duration of the solar activity in the respective phase. A detailed description of this procedure is presented in (Sonnemann and Grygalashvyly, 2007). We calculated the MSSWs' occurrence rate normalized ~~to~~ by the occurrence rate of F10.7 ~~flux~~ values as shown in (Sonnemann and Grygalashvyly, 2007):

$$\mathrm{R}^i = \frac{\left(\mathrm{N}^i_{\mathrm{MSSW}} \big/ \mathrm{N}^i_{\mathrm{F10.7}}\right) \sum \mathrm{N}^i_{\mathrm{MSSW}}}{\sum \left(\mathrm{N}^i_{\mathrm{MSSW}} \big/ \mathrm{N}^i_{\mathrm{F10.7}}\right)}, \quad i = 1, \ldots, 8, \tag{1}$$

where $\mathrm{N}^i_{\mathrm{F10.7}}$ and $\mathrm{N}^i_{\mathrm{MSSW}}$ are the number of F10.7 ~~flux~~ values and number of MSSWs in subinterval i, respectively. Note that calculation by Eq. (1) entails a statistical uncertainty which decreases with the number of solar cycles.

Fig. 1c illustrates dependence between the normalized occurrence rate of MSSWs and the values of F10.7 ~~flux~~ according to Eq. (1) for ERA and NCEP-NCAR-I databases. We conducted the correlation analysis for the normalized occurrence rate of MSSWs and the F10.7 ~~flux~~ values with 8 subdivisions (Fig. 1d). The correlation coefficient equals 0.63 ~~0.6314~~ for the ERA case and 0.55 ~~0.5455~~ for the NCEP-NCAR-I case. The significance amounts to 90.68% and 83.80% for ERA and NCEP-NCAR-I, respectively. The results demonstrate a distinct statistical connection between the normalized MSSW events and the F10.7 ~~flux~~ values. Our correlation coefficients are smaller than those of Sonnemann and Grygalashvyly (2007), probably, because we use different solar proxies, subdivisions and periods.

3. Discussion

~~It is not the aim of this contribution to discuss consequences and reasons, but a~~ A possible explanation for the correlation is the impact of solar activity either on PWs strength and activity or on propagation conditions (e.g. Arnold and Robinson, 1998; Fröhlich and Jacobi, 2004). Recently, Koval et al. (2018) found that solar activity might affect meridional temperature gradients and consequently change the vertical structure of the zonal wind and PWs' propagation conditions. This may point to a potential explanation. Another one possibility to explain obtained correlation is the interaction of cosmic rays (which anti-correlate with solar activity) with atmosphere, and, particularly, with stratosphere, and have an impact on climate (see Fig. 7 in (Usoskin, 2017), Fig. 3 in (Seppälä et al., 2014) and corresponding discussions). In addition, a variation in the ozone concentration over a solar cycle (Keating et al., 1987; Hartogh et al., 2011) could influence the occurrence rate of MSSWs by changing of the thermal structure of the middle atmosphere.

The separation of the effects of long-term changes in a solar cycle and long-term changes of anthropogenic greenhouse gases (GHGs) and ozone-depleting substances (ODSs) on the middle atmosphere remains an unsolved problem. In general, joint declining of solar cycle and growth of GHGs and ODSs may produce bias in correlation. However, according to current knowledge, there is no statistically significant impact of anthropogenic changes on the frequency of SSWs (e. g. Butchart et al., 2000; SPARC CCMVal, 2010; Mitchell et al., 2012; Hansen et al., 2014, Ayarzagüena et al., 2018). Moreover, some of the recent works show enhancement of the SSWs frequency under GHGs and ODSs forcing (e.g., Huebener et al., 2007; Charlton-Perez et al., 2008; Bell et al., 2009; Schimanke et al., 2013; Ayarzagüena et al., 2013). Thus, the joint effect of negative trend in solar cycle strength and positive trend of GHGs may just reduce positive correlation, but cannot be its cause.

The ~~F~~10.7 cm solar radio flux is not the only proxy for solar activity. Most used proxies, which differs by ~~the~~ nature from the F10.7, are Lyman-alpha flux and sunspot numbers (Bruevich et al., 2014; Mei et al., 2018), and also 3.2 cm, 8 cm, 15 cm, 30 cm solar fluxes (Dudok de Wit et al., 2014; Vaishnav et al., 2019). Thus, the information about correlation coefficients for the same database and method potentially can be useful to identify possible reasons of correlation. Hence, such correlation coefficients with corresponding significance are calculated and stored in the Table 1. We have not found any clear dependence neither correlation coefficients nor significance on solar radio flux wavelength.

4. Summary

We investigated the statistical relationship between solar activity and occurrence rate of major sudden stratospheric warmings (MSSWs). For this purpose, the ~~F~~10.7 cm solar radio flux has been used as a proxy for solar activity. The calculations have been performed based on two datasets of central day (NCEP-NCAR-I and combined ERA) for the period from 1958 to 2013. The analysis of calculations was based on the normalized MSSW occurrence rate. The analysis revealed a positive correlation between MSSW events and solar activity with a correlation coefficient equals 0.63 ~~0.6314~~ for the ERA dataset ~~case~~ and 0.55 ~~0.5455~~ for the NCEP-NCAR-I dataset ~~case~~. Note that the correlation is necessary but not a sufficient condition for a relationship between the two phenomena. The nature of the correlation is still not clear, and further investigations in this direction are necessary.

Data availability.

The F10.7 and Lyman-α solar flux data are available at http://lasp.colorado.edu/lisird/. The sunspot numbers data are accessible at https://www.ngdc.noaa.gov/stp/solar/ssndata.html. The 3.2 cm, 8 cm, 15 cm, and 30 cm solar fluxes data are available at https://spaceweather.cls.fr/services/radioflux/.

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Tables.

Table 1. Values of the correlation coefficient between solar activity and MSSWs for different proxies. The number of subintervals is the same for all calculations.

	American Sunspot numbers	Lyman-alpha flux	3.2 cm flux	8 cm flux	10.7 cm flux	15 cm flux	30 cm flux
ERA40/ERA-Interim	0.58 86.66%	0.54 83.36%	0.62 89.86%	0.44 72.32%	0.63 90.68%	0.45 74.21%	0.59 87.72%
NCEP-NCAR-I	0.49 78.00%	0.58 86.57%	0.64 91.35%	0.43 70.93%	0.55 83.80%	0.35 60.65%	0.71 95.17%

Figures.

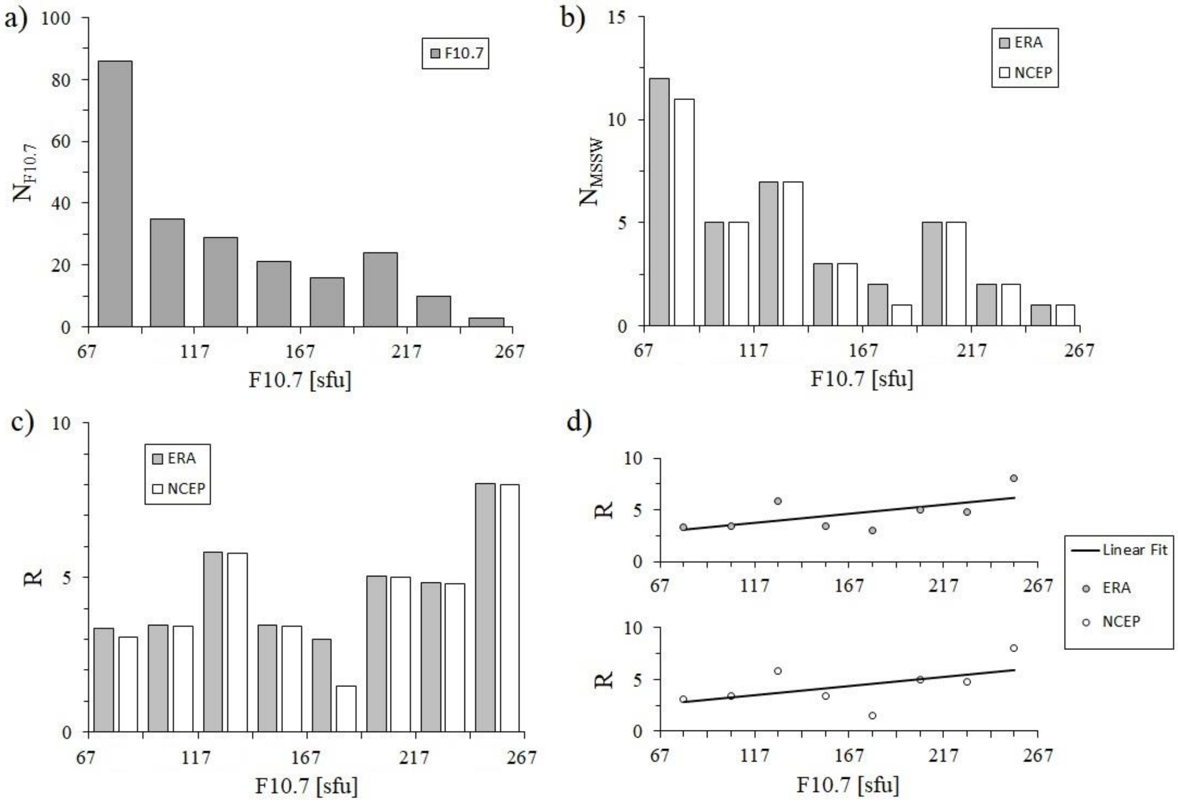

Figure 1. a) Monthly mean F10.7 ~~flux~~ values between 1958 and 2013 of 4 months between December and March; b) the number of MSWWs depending on F10.7 ~~flux~~ values; c)

normalized occurrence rate of MSSWs depending on F10.7 ~~flux~~ values; d) correlation analysis for normalized occurrence rate of MSSWs and F10.7 ~~flux~~ values.