Northern Hemisphere stratospheric winds in higher midlatitudes: longitudinal distribution and long-term trends

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Abstract

The Brewer-Dobson circulation (BDC, mainly meridional circulation) is very important for the stratospheric ozone and, thus, for the overall state of the stratosphere. There are some indications that the meridional circulation in the stratosphere could be longitudinally dependent, which would have impact on ozone distribution. Therefore here we analyse the meridional component of the stratospheric wind at northern middle latitudes to search for its longitudinal dependence. The analysis is based on the NCEP/NCAR-1 (National Center for Environmental Prediction and the National Center for Atmospheric Research), MERRA (Modern Era-Retrospective Re-Analysis) and ERA-Interim (European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim) reanalysis data. The well-developed two-core structure of strong but opposite meridional winds, one at each hemisphere at 10 hPa at higher northern middle latitudes, and a less-pronounced five-core structure at 100 hPa are identified. In the peak areas of the two-core structure the meridional and zonal wind magnitudes are quite comparable. The two-core structure at 10 hPa is practically identical for all three different reanalyses in spite of different time periods covered. The two-core structure is not associated with tides. However, the two-core structure at the 10 hPa level is related to the well-pronounced Aleutian pressure high at 10 hPa. Zonal wind, temperature and ozone mixing ratio at 10 hPa also exhibit the effect of Aleutian high, which affects all parameters of the northern middle stratosphere. Long-term trends in meridional wind in “core” areas are significant on the 99% level. Trends are negative during the period of ozone depletion development (1970-1995), while they are positive after the ozone trend turnaround (1996-2012). They are independent of sudden stratospheric warming occurrence and the quasi-biennial oscillation (QBO) phase. The influence of the 11-year solar cycle on stratospheric winds has been identified only during the west phase of QBO. The well-developed two-core structure in the meridional wind illustrates limitations of application of zonal mean concept in studying stratospheric circulation.

1. Introduction

Stratospheric winds play a main role in stratospheric chemistry through transporting long-lived species, but they also could create transport barriers which could isolate the polar vortex in winter (Shepherd, 2007, 2008). Simultaneously with chemical processes, trace gas distribution moderates the radiative forcing in stratospheric region. The changes of stratospheric wind (strengthening of westerly polar vortex and its poleward shift) are coupled with ozone depletion and temperature changes (Scaife et al., 2012). For example, the unprecedented ozone loss in the Arctic in 2011 was caused by extreme meteorology (e.g., Pommereau et al., 2013). The Antarctic ozone hole intensification over the 1980–2001 period is not solely related to the trend in chemical losses, but more specifically to the balance between the trends in chemical losses and ozone transport (Monier and Weare, 2011a). One of the most studied circulation structures in the stratosphere is the Brewer-Dobson circulation. The detail description of this circulation can be found in Butchart (2014). Many model studies reveal an acceleration of the residual mean circulation and Brewer-Dobson circulation due to increasing greenhouse gas (GHG) concentration (Oberlander et al., 2013, Lin and Fu, 2013, Oman et al., 2009). However, age of air data does not confirm a simple pattern of reduction of age of air as a consequence of the Brewer-Dobson circulation (BDC) intensification (Engel et al., 2009; Stiller et al., 2012). Monier and Weare (2011b) found some weakening of northern winter Brewer-Dobson circulation in polar region in reanalysis ERA-40 (ECMWF Re-analysis for 40 years) and R-2 (NCEP-DOE Reanalysis 2). The changes of stratospheric wind (strengthening of westerly polar vortex and its poleward shift, changes in the Brewer-Dobson circulation) are coupled with ozone depletion and also temperature changes. Possible interactions between changes in the stratosphere dynamics and climate changes in the troposphere have been described by Hartmann et al. (2000), Scaife et al. (2012) and Deckert and Dameris (2008). The stratospheric Quasi-biennial Oscillation (QBO) and downward feedback from the stratospheric vortex to tropospheric weather systems have been reported to be relevant both in the context of weather prediction and climate (Baldwin and Dunkerton, 1999; Baldwin et al., 2003; Sigmond et al., 2008; Marshall and Scaife, 2009; Wang and Chen, 2010). Moreover, stratospheric wind (zonal and meridional) affects vertically propagating atmospheric waves which control the transport circulation in the stratosphere and mesosphere (Holton and Alexander, 2000).

It is generally believed that the meridional wind component is in the stratosphere much weaker than the zonal wind component. However, as we show later, it is not always the case. Many studies have been working with zonal mean winds. The Northern Hemisphere has pronounced distribution of continents, mountain regions and oceans, which reflects in the troposphere and also in the stratosphere. Some phenomena introduce longitudinal differences into wind pattern, for example El-Nino Southern Oscillation - ENSO (e.g., Weare, 2010). The total ozone in the winter higher middle latitudes has a strong longitudinal dependence, the maximum-minimum difference being more than 100 D.U. (e.g., Mlch, 1994). **Demirhan Bari et al. (2013) found longitudinal dependence of residual winds in the stratosphere and through impact on the Brewer-Dobson circulation some effects on stratospheric ozone and water vapour in the stratosphere for 2001-2006. So**

there are reasons for studying longitudinal dependence of meridional wind and other parameters in the stratosphere based on long-term re-analysis data series, what we are doing in this paper.

Our study of longitudinal distribution of meridional and zonal wind, which we found to be substantial, should reveal where the meridional wind might be substantial component of the total horizontal wind. The results could have an impact on BDC circulation in terms of longitudinal distribution, which is very important for the ozone transport at. The distribution of meridional wind is very important for wave propagation in the stratosphere (Matsuno, 1970, Kodera et al., 1990). Therefore here we investigate longitudinal distribution of meridional and also zonal component of stratospheric winds at northern middle latitudes. Impact of QBO or Sudden stratospheric warmings (SSWs) which is mainly waved driven is also studied.

To test temporal stability of longitudinal distribution, long-term trends at latitudes of the most pronounced latitudinal structures are calculated. Ozone concentration in the northern middle latitudes changed its trend in the mid-1990s (e.g., Harris et al., 2008). Since ozone is the main heater of the stratosphere via absorption of solar radiation, this turnaround of ozone trend had to affect more or less also behaviour of other stratospheric parameters, and it affects even the mesosphere and lower thermosphere (e.g., Lastovicka et al., 2012). Since ozone trends in the northern middle latitudes changed in the mid-1990s (e.g., Harris et al., 2008), trends in the stratospheric dynamics are expected to be altered by the ozone recovery and thus trends in the periods before and after the mid-1990s are examined separately.

SSW and the QBO are known to have important impact on the stratosphere including its circulation (Limpasuvan et al. 2004, Naito and Hirota, 1997, Labitzke and van Loon, 1988). The stratosphere is influenced also by solar activity (e.g., Gray et al., 2010 and references herein). Impact of these phenomena on stratospheric circulation,

particularly on the observed longitudinal structures in meridional wind, deserves attention and analysis.

The paper focuses on two topics:

(1) Longitudinal distribution of meridional wind component at different pressure levels and possible reason for its behaviour. Therefore it will be supported by calculating the longitudinal distribution of geopotential height and of zonal wind component. This will be accompanied by trend analysis of observed longitudinal structures. The results are described in Section 3.1.

(2) Trend analysis of stratospheric total horizontal wind and meridional component with connection to Quasi-biennial Oscillation (QBO), Sudden Stratospheric Warming (SSW) (mainly wave driven) and solar activity. The results are described in Section 3.2.

The structure of the paper is as follows. In Section 2 the data and methods are described. Then, in Section 3 the results of analysis are shown and in Section 4 they are briefly discussed. Section 5 summarizes conclusions.

2. Data and methods

Stratospheric winds have been measured from the ground using active and passive techniques (Hildebrand et al., 2012; Rüfenacht et al., 2012) and from space by the High Resolution Doppler Imager (HRDI) on the Upper Atmospheric Research Satellite UARS covering 10–35 km and 60^{o}S–60^{o}N, using the molecular oxygen A- and B-bands (Ortland et al., 1996) or Baron et al. (2013) who derive winds from SMILE (Superconducting Submillimeter-Wave Limb-Emission Sounder). However, direct wind measurements do not provide sufficiently long and homogeneous global data series.

Therefore when studying longitudinal distribution of meridional or zonal wind we use in the paper three independent reanalysis data, namely reanalyses NCEP/NCAR-1 (National Center for Environmental Prediction and the National Center for Atmospheric Research, further on NCEP/NCAR), MERRA (Modern Era-Retrospective Re-Analysis) and ERA-Interim (European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim). The NCEP/NCAR reanalysis was described in detail by Kistler et al. (2001). This reanalysis provides data from 1948 onwards, but data is more reliable from 1957 onwards, when the first upper-air observations were established, and from 1979 onwards, due to the beginning of satellite date assimilation. Data is available on the 2.5° to 2.5°grid at 00, 06, 12 and 18 UTC. Vertical resolution is 28 levels with the top of the model at 2.7 hPa. The NCEP/NCAR analysis system efficiently assimilates upper-air observations but it is only marginally influenced by surface observations because model orography differs from reality (Kistler et al., 2001). The ERA-Interim is described in Dee et al., 2011. Data is available from 1979 on the 0.75° to 0.75°grid at 00, 06, 12 and 18 UTC. Vertical resolution is 60 levels with the top of the model at 1 hPa. The MERRA reanalysis is described and downloaded from http://disc.sci.gsfc.nasa.gov. Data is available from 1979 on the 1.25° to 1.25°grid at 00, 06, 12 and 18 UTC. Vertical resolution is 42 levels with the top of the model at 0.1 hPa.

According to Kozubek et al. (2014) stratospheric winds from the NCEP/NCAR reanalysis are better for long term trend analysis than those from ERA-40 and ERA-Interim reanalysis if we take into account the length of available period. Neither ERA-40, nor ERA-Interim, nor MERRA separately covers the whole period 1958-2012. On the other hand, general pattern and long-term changes of stratospheric winds in NCEP/NCAR, ERA-40 and ERA-Interim reanalyses (except for the last four years of ERA-40) are very close each other since about 1970 (Kozubek et al., 2014), therefore it is sufficient to use only one of these three reanalysis for trend analysis. The 10.7cm solar radio flux (from http://www.esrl.noaa.gov/psd/data/correlation/solar.data) is used for the solar cycle analysis (solar max and solar min). The QBO data at 50 hPa is taken from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/ and SSW data is taken from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/northpole/index.html

For investigation of longitudinal distribution of meridional wind, zonal wind or geopotential height we have computed averages throughout the period 1970-2012 for every grid point from 20°N to 60°N and for every month. Analysis of wind speed distribution in 100 hPa (where we can identify influence of troposphere and study dynamics near tropopause) and 10 hPa (which is a representative level for the middle stratosphere and major stratospheric warming determination) at 00 UTC or wind speed distribution at 00, 06 and 12 UTC (06 and 12 for examining possible influence of diurnal and semidiurnal tides) separately for meridional component has been done for all three reanalyses.

The trend analysis is focused on middle latitudes (50°- 60°N) again at pressure level 10 hPa in order to investigate the behaviour of wind in the two-core structure area. We analyse connection between QBO or SSW with dynamics (stratospheric wind) and solar activity with QBO at 10 hPa. In trend analyses we have used either total horizontal wind or v (meridional) components separately. The total horizontal wind speed is calculated from gridded u and v components.

The selected latitudes are separated into four sectors (100°E-160°E – poleward wind core, 160°E-140°W- sectors affected by Aleutian height, 140°W-80°W – equatorward wind core and 80°W-100°E –sector not affected by two-core structure, see Fig. 1).

We look for trends or differences between different groups in each sector at 10 hPa. The statistical significance threshold of trends has been set on 95% level, which is the standard significance level for analyses in meteorology (wind, temperature, etc.), and in trend analysis also on 99% level. We divide data of the whole period into several groups according to QBO (east or west QBO phase) or solar cycle influence (solar maximum years and solar minimum years) and for a trend analysis we divided data into two periods (1970-1995 with decreasing ozone and 1995-2012 with increasing ozone). We compute trends separately for all these groups with significance threshold 95% or 99%.

3. Results

3.1 Longitudinal distribution of stratospheric meridional winds

The whole possible period averages of meridional wind component for each grid point from 60°N to 20°N for January at 10 hPa have been computed. For comparison we have computed these averages for three reanalyses (MERRA for period 1979-2012, ERA Interim for 1979-2012 and NCEP/NCAR for 1958-2012). The results are shown in Fig. 1. The top panel show results for NCEP/NCAR, middle for ERA Interim and bottom for MERRA reanalysis. The behaviour of different reanalyses is quite similar in major features despite the different length of time intervals. Figure 1 reveals at 10 hPa for January a core of strong poleward wind on the eastern hemisphere of the middle and higher latitudes. This poleward wind changes into equatorward wind core on the western hemisphere at 10 hPa (similar amplitude as on the eastern hemisphere). Both the poleward and equatorward peaks (centres of the cores taken as 100°E-160°E and 140°W-80°W at 10 hPa) are statistically significant at 95% and 99% level for NCEP/NCAR reanalysis. The results of similar analysis for 100 hPa are shown in Fig. 2. Generally winds are stronger at 10 hPa (up to 20 m/s) than at 100 hPa (up to 10 m/s). At 100 hPa there is a five-core structure, which is much less pronounced than the two-core structure at 10 hPa. The same analysis is shown in Fig. 3 for July at 10 hPa. This analysis reveals that the observed two-core structure at 10 hPa occurs only in winter. The winds are weaker than in January and the distribution is much less compact compared with

January. We have done the same analysis for higher pressure level of 5 hPa and the differences between the eastern and western hemispheres (two-core structure) have been found to grow with increasing height.

Figure 4 shows climatology based on NCEP/NCAR reanalysis over the period 1958-2012 for January at 10 hPa pressure level for data from 00 UTC (top panel), 06 UTC (middle panel) and 12 UTC (bottom panel). There are almost no differences in main features. Therefore we can conclude that the two-core structure with opposite meridional winds is not caused by diurnal or semidiurnal tides. The other possibility for this structure could be dynamical reasons which are discussed in the next paragraph.

Wind field is closely associated with distribution of geopotential height because of dynamical reasons. Figure 5 shows a distribution of geopotential height at 10 hPa again for all three reanalyses. The Aleutian pressure high centred at about 40°-55°N, 180°E is well developed at 10 hPa. This height can block the zonal winter eastward winds. This results in poleward meridional flow on front side and in equatorward meridional flow on the backside as a consequence of flow along the massive anticyclone. This coincides with the observed two-core structure at 10 hPa with the poleward meridional component of wind on the eastern hemisphere and the equatorward meridional component on the western hemisphere. The behaviour of zonal wind at 10 hPa, shown in Fig. 6 for all three reanalyses, reveals substantial weakening of zonal wind in the region of Aleutian pressure height; together with strengthening of meridional component it results in non-zonal, oblique wind flow. In some locations like 60^{o}N, 135^{o}E both wind components are approximately equal. The summertime distribution of geopotential heights at 10 hPa does not display any well-pronounced structure and, therefore, no pronounced structure is developed in meridional wind (Fig. 3). At 100 hPa on the western hemisphere (not at eastern one) the distribution of geopotential height resembles the five-core structure in winds in Fig. 2 but again this structure is much less pronounced than that at 10 hPa (not shown here).

3.2. Impact of solar cycle, SSW and QBO on trends in wind

Further analysis, which has been done, is comparison between years in the solar cycle maximum and minimum in different QBO phases and trends in different dynamics situations (SSW or no SSW years, east or west QBO years). This analysis is focused on latitudes where two-core structure at 10 hPa was identified (50°N-60°N). It should reveal potential connections between solar cycle, stratospheric dynamics (wind speed) and wave activity driven SSW, all that under potential influence of QBO. Stratospheric dynamics and chemistry is influenced by changes in ozone concentration so we analyze separately the total horizontal wind in period 1970-1995 with decreasing ozone and 1995-2012 with increasing ozone. We show trends for different groups (with and without major SSW years and east or west QBO phase years) for December-February (DJF), as in January we can see the strongest two-core structure. We analyse total horizontal wind as well as meridional component separately to find which component is more affected by different drivers. The trends of meridional wind are shown in Table 1. We can identify change of the trends in all four sectors for all four groups (positive one for period 1970-1995, negative one for 1996-2012). The trends are significant on 99% level (in a few cases only at 95% level) in the two sectors where the core structure occurs. There are only a few significant trends (95% level) in the other two sectors.

The results on connection of solar cycle and dynamics with the total horizontal wind speed are shown on the top panel of Table 2. At 10 hPa we can observe a positive difference (by 2-5 m/s) between solar minimum and maximum for the west QBO in both sectors where core´s occur. The differences are significant at 95% level. The differences are smaller and insignificant in the other two wind sectors. The east QBO does not reveal a systematic or significant difference; moreover sometimes wind in solar maximum is stronger than in solar minimum. We can observe negative differences between QBO east and QBO west phase in solar minimum (up to 3 m/s) in all studied sectors. These differences are again mainly significant in two core sectors. Differences between QBO east and QBO west phase in solar maximum are mainly positive but insignificant.

The bottom panel shows the same analysis as top one but for v (meridional) wind component. The differences are smaller than for total horizontal wind. We cannot find any specific features for all four groups. We can see only a few significant values in different sectors.

The analysis was done also for each month separately and the biggest differences have been found in December and January. These results show that solar activity influences the total horizontal wind (i.e. mainly zonal wind) mostly in higher part of the stratosphere (10 hPa) and predominately in the two core sectors.

4. Discussion

The results on longitudinal distribution of meridional and zonal component of stratospheric wind show that the meridional wind forms a well pronounced two-core structure at 10 hPa in winter. This two-core structure is revealed by NCEP/NCAR, ERA-Interim and MERRA reanalyses in a very similar form despite different time periods used (Fig. 1). The wintertime longitudinal distribution at 10 hPa can be explained neither by diurnal, nor by semidiurnal tides, because there are no differences between the longitudinal distribution of meridional winds at 00, 06 and 12 UTC (Fig. 4). However, the geopotential height analysis reveals the reason for this longitudinal distribution. The well-developed large Aleutian high at 10 hPa in Fig. 5 can block the zonal flow (see Fig. 6) and pushes the winter eastward winds to flow with substantial poleward component on the western side of the Aleutian pressure high and back equatorward on its eastern side. Comparison of Figs. 1 and 6 shows that zonal component of stratospheric wind is almost equal to the meridional component in some area. This phenomenon could results in the wave propagation changes in this part of the stratosphere (at 10 hPa, i.e. Matsuno, 1970, Kodera et al., 1990) and could affect other wave driven phenomena like SSW. The results show that the deep (upper) branch of Brewer-Dobson circulation is affected by the longitudinal distribution of meridional wind which can affect the distribution of total ozone. Therefore Fig. 7 shows longitudinal distribution of ozone and also temperature at 10 hPa in the middle latitudes (20°-60°N). This distribution is consistent with the two-core structure of meridional wind – in the eastern hemisphere, where the intensified poleward meridional wind transports warmer air and more ozone towards higher latitudes (60°N), the temperature and to a less extent ozone concentration are increasing there; in the western hemisphere core the opposite meridional transport reduces temperature and ozone at higher middle latitudes. Thus all studied parameters, meridional wind, geopotential height, zonal wind, temperature and ozone agree in main features of the longitudinal variation and provide an internally consistent pattern of longitudinal variation in the middle stratosphere (at 10 hPa). This result illustrates limitations of applicability of zonal mean approach. To find the main driver of these changes, in future we have to analyze the processes in the lower and higher levels of the atmosphere. To our best knowledge the longitudinal structure of middle stratosphere circulation at middle latitudes has not yet been studied except for Bari et al. (2013), who simulated with HAMMONIA model for 2001-2006, January a longitudinal structure of residual winds, which resembles our results. They found impact of that longitudinal structure on the Brewer-Dobson circulation and distribution of stratospheric ozone and water vapour. Hamilton et al. (2004) found in equatorial latitudes significantly weaker peak-to-peak amplitude of the quasi-biennial oscillation (QBO) in zonal wind over the South American sector than over the rest of the equatorial band. Investigation of the longitudinal dependence of stratospheric zonal winds during SSW events with model HAMMONIA (Miller et al., 2013) demonstrates the asymmetry of the climatological winter and of single events.

We identify statistically significant trends (mostly on 99% level) in both core sectors at 10 hPa (Table 1). These trends are negative (weakening of meridional wind) in 1970-1995 (increasing ozone content) and positive (strengthening of meridional wind) in 1996-2012 (decreasing ozone content) for both cores independent of the phase of QBO or occurrence of major SSW. We also identify the tendency to slight strengthening of the total horizontal wind in 1970-1995, which is consistent with weakening of cores of meridional wind – both features can be caused by some weakening of the blocking Aleutian pressure high at 10 hPa. Opposite trends/tendencies in 1996-2012 are consistent with some strengthening of the blocking Aleutian pressure high. This is confirmed by trends in central part of the blocking Aleutian pressure high; -34.6 m/year for 1970-1995 and + 38.3 m/year for 1996-2012, both being significant at the 95% level. The trends are mostly insignificant in other two sectors (sector not affected by the two-core structure). So we can conclude that the two-core structure affects the trend of the meridional component, which is independent of SSW and QBO. The analysis was done separately for periods before and after the mid-1990s, when the ozone trend at northern middle latitudes reversed. This analysis confirms similar reversal of trends in the stratospheric wind. However, ozone serves here as indicator rather than cause of the trend change. Statistical and modelling studies carried out in the European FP5 project CANDIDOZ show that the main cause of this change in ozone trends results from changed dynamical behaviour (Harris et al., 2008). This conclusion is supported by behaviour of ozone laminae (Lastovicka et al., 2014).

The above results are the reason why in section 3.2 we investigate potential effect of some dynamical factors (SSW and QBO), which could be behind the change of trends of both ozone and wind. The change of the meridional wind trend (from positive to negative in mid 90s) occurs independently on SSW or QBO (Table 1). We can connect this with changes of ozone trends. The trends in core structure areas are significant (mainly 99% level) for all four SSW/QBO combinations. In areas not affected by core structure, more significant trends (95% level) occur for years with than without major SSWs. This result could indicate that the abnormal conditions in the stratosphere during SSW can affect meridional wind trends (B-D circulation and ozone transport) in areas where meridional wind is weak.

According to Shindell et al. (1999) the changes of the upper stratospheric wind are caused partly by changes in the solar irradiance. The impact of the 11-yr solar cycle, sometimes in the combination with the QBO, on the stratosphere is described in many papers (i.e. Salby and Callahan, 2000, Labitzke and Kunze, 2009, Limpasuvan et al. 2004, Naito and Hirota, 1997, Labitzke and van Loon, 1988). The influence of solar activity on total horizontal wind is shown in Table 2. Our results agree with results of other authors but we specify dependence of solar effect on longitude. The most statistically significant differences can be found again in the two-core sectors. The differences are larger in higher latitudes. This result agrees with previous studies that higher latitudes are more affected by changes in solar activity. The analysis of meridional component does not show any specific features so we can conclude that solar activity affects mainly total horizontal wind.

5. Conclusions

Based on data from reanalyses NCEP/NCAR, ERA-Interim and MERRA, the longitudinal distribution of meridional component of stratospheric wind in winter (January) has been examined for 20-60^{o}N. It reveals well pronounced longitudinal distribution of meridional wind at latitudes above 45^{o}N with two cores of strong but opposite meridional winds, one at each hemisphere (eastern and western) at 10 hPa, and a much less pronounced five-core structure at 100 hPa. All three reanalyses provide the same pattern. In summer such a well-pronounced core structure is absent. The two-core structure at 10 hPa is not caused by tides as no differences exist between 00, 06 and 12 UTC results. We have identified the strong and well-developed large Aleutian pressure high at 10 hPa, which is capable to explain qualitatively the two-core structure in the longitudinal distribution of meridional wind. Longitudinal distribution of zonal wind, temperature and ozone content is consistent with that of meridional wind and geopotential height, i.e. the middle stratosphere as a whole displays a significant longitudinal distribution at higher middle latitudes. Our results illustrate limitations of approach via zonal mean values when studying the northern midlatitude middle stratosphere.

The trends of meridional wind are found to be significant in the two core sectors independently on SSW or QBO and mainly insignificant in sectors not affected by two-core. In the period of ozone depletion evolution (1970-1995) the meriodional wind in cores weakens, whereas in the period of recovering ozone concentration (1996-2012) it is also recovering. The influence of solar cycle can be seen mainly for the west phase of QBO.

Acknowledgements

Authors acknowledge support by the Grant Agency of the Czech Republic, grant P209/10/1792, by the Ministry of Education, Youth and Sports of the Czech Republic, grant LD 12070, and by the COST ES1005 project (TOSCA).

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Table 1: Winter (December-February) trends (m/s per year) of meridional wind speed for two periods (1970-1995 and 1996-2012). Major SSW- only years when the major SSW (according to WMO definition) occur, no SSW – years when no SSW occurs, east QBO - only years when the east phase of QBO occurs, west QBO - only years when the west phase of QBO occurs. Pressure level10 hPa. 70-95 means 1970-1995 and 95-12 means 1995-2012. Significant trends on 99% level are highlighted by bold numbers and red; significant trends on 95% level are in italics and green.

					10 hPa								
latitude	50°N				55N				60°N				
sector	**100°E-160°E**	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	**100°E-160°E**	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	**100°E-160°E**	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	
70-95	**0.52**	*0.21*	*0.49*	0.15	**0.57**	0.15	**0.54**	0.12	**0.60**	0.11	**0.55**	0.10	**major SSW**
95-12	**-0.61**	-0.19	**-0.63**	-0.10	**-0.61**	*-0.27*	**-0.67**	-*0.24*	**-0.64**	*-0.22*	**-0.59**	*-0.26*	
70-95	**0.39**	*0.23*	**0.46**	*0.20*	**0.43**	0.19	**0.51**	0.15	**0.49**	0.16	**0.56**	*0.18*	**no SSW**
95-12	**-0.71**	-0.08	**-0.42**	-0.05	**-0.6**	-0.11	**-0.49**	-0.08	**-0.64**	-0.13	**-0.56**	-0.1	
70-95	0.37	0.14	0.35	0.09	*0.39*	*0.17*	**0.42**	*0.19*	**0.43**	0.19	**0.48**	0.23	**east QBO**
95-12	**-0.44**	*-0.24*	**-0.40**	*-0.19*	**-0.48**	-0.16	**-0.46**	-0.11	**-0.53**	-0.12	**-0.51**	-0.09	
70-95	**0.34**	*0.19*	**0.49**	*0.20*	**0.41**	*0.24*	**0.55**	0.21	***0.39***	*0.25*	**0.59**	*0.27*	**west QBO**
95-12	**-0.50**	-0.08	**-0:64**	-0.04	**-0.54**	-0.12	**-0.62**	-0.09	**-0.57**	-0.17	**-0.68**	-0.12	

Table 2: Winter (December-February) differences of wind speed (m/s) for different latitudes and sectors. Top panel shows total horizontal wind speed for 10 hPa, bottom panel v (meridional) wind component for 10 hPa. Min-east: years under solar minimum and the east phase of QBO conditions; min-west: years under solar minimum and the west phase of QBO, the same for solar maximum conditions. Significant trends on 95% level are highlighted by bold numbers.

	50°N				**55°N**				**60°N**				**latitude**
	100°E-160°E	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	**100°E-160°E**	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	**100°E-160°E**	**160°E-140°W**	**140°W-80°W**	**80°W-100°E**	**sector**
(min/east)-(min/west)	**-1.07**	-0.08	**-1.47**	-0.03	**-1.89**	-0.28	**-1.73**	-0.23	**-2.77**	-0.57	**-2.05**	-0.53	**10 hPa**
(max/east)-(max/west)	0.33	-0.27	1.26	-0.46	0.66	-0.42	1.17	-0.44	1.04	-0.18	0.76	-0.27	
(min/west)-(max/west)	**2.02**	0.38	**1.39**	0.51	**2.76**	**0.81**	**1.84**	0.72	**3.19**	**1.08**	**2.23**	1.01	
(min/east)-(max/east)	0.62	**0.96**	**-1.36**	**1.02**	-0.39	0.75	-1.19	0.81	-0.71	0.64	-0.92	0.56	
(min/east)-(min/west)	-0.01	0.34	**-0.63**	0.60	-0.11	-0.29	-0.73	**0.79**	-0.26	**1.14**	**-0.84**	**1.12**	**10 hPa v**
(max/east)-(max/west)	-0.38	0.2	0.15	0.09	-0.40	-0.52	0.14	0.10	-0.43	0.18	0.17	0.14	
(min/west)-(max/west)	-0.17	0.42	**1.17**	-0.73	-0.20	-0.17	**1.39**	**-0.86**	-0.18	-0.95	**1.57**	**-0.99**	
(min/east)-(max/east)	0.19	-0.29	0.39	-0.22	0.09	-0.11	0.49	-0.17	-0.01	-0.17	0.57	-0.11	

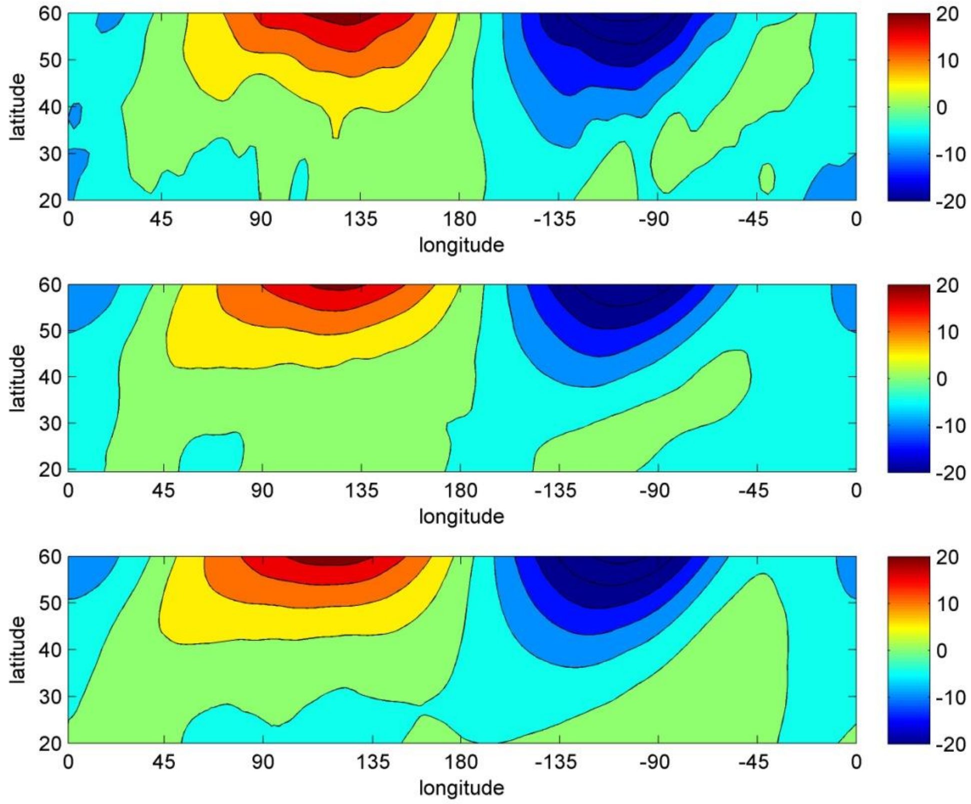

Figure 1 Plot of average meridional wind speed (m/s) component for January, 20-60°N, 180°E-180°W, 10 hPa. Top panel NCEP/NCAR (1958-2012), middle ERA Interim (1979-2012), and bottom MERRA (1979-2012). Positive values (poleward wind - red), negative values (equatorward wind - blue).

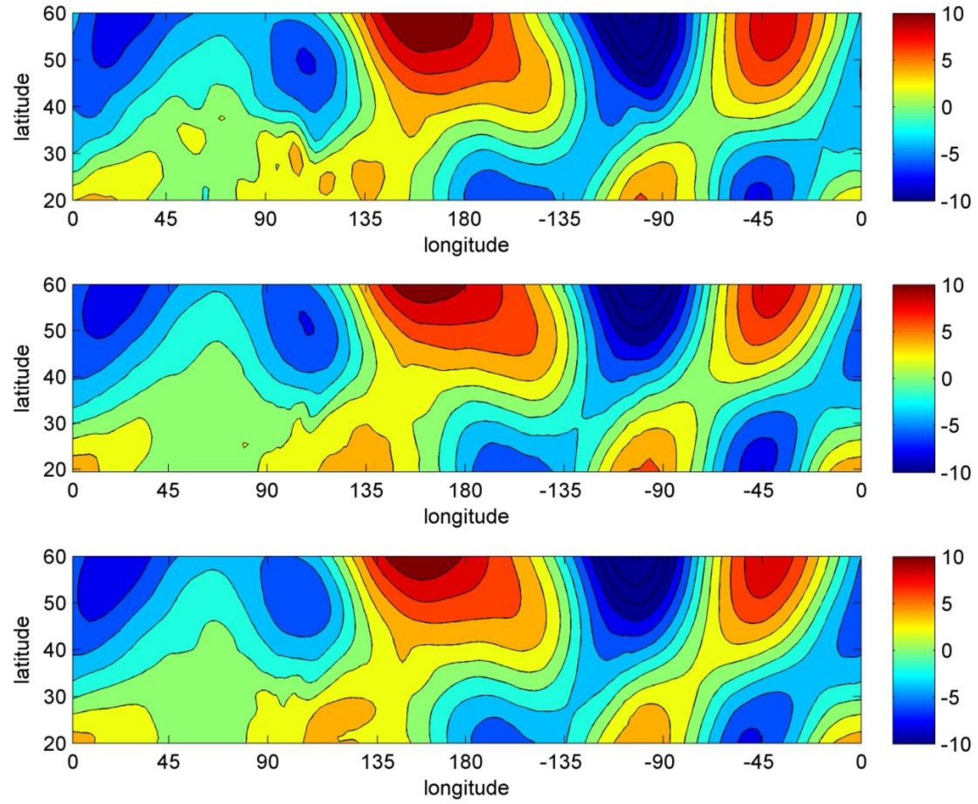

Figure 2 The same as Fig.1 but for 100 hPa.

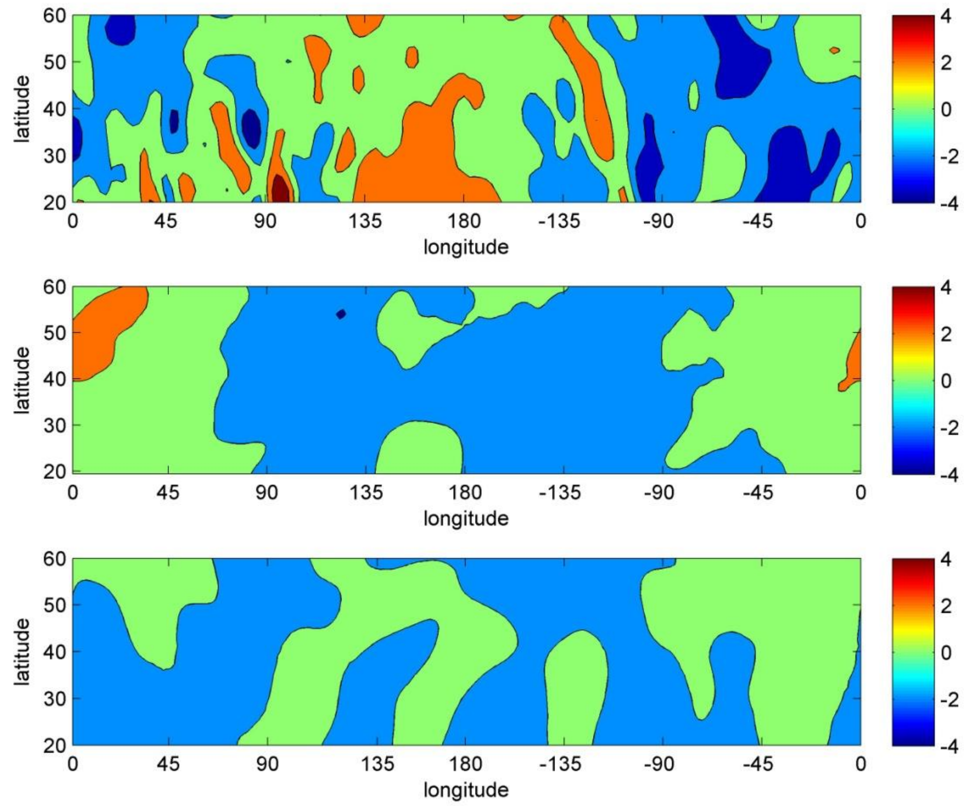

Figure 3: The same as Fig. 1 but for July. Positive values (poleward wind -red), negative values (equatorward wind - blue).

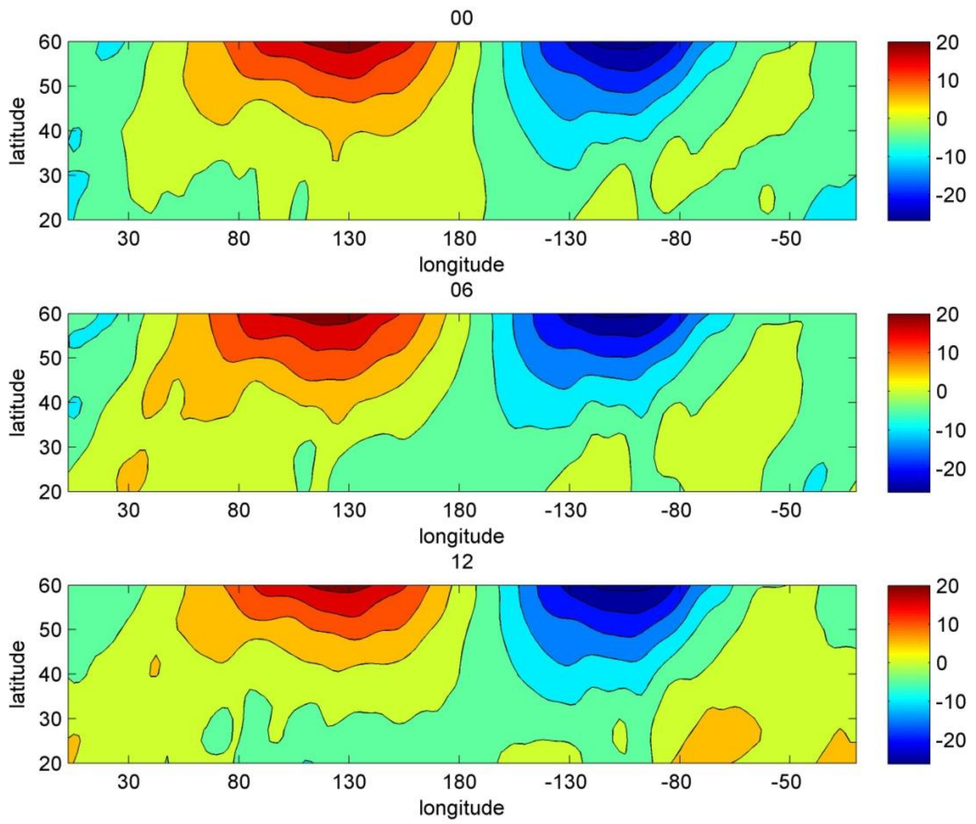

Figure 4: Plot of average meridional wind speed (m/s) component at 10 hPa for January, 1958-2012, 20-60°N, 180°E-180°W. Top panel 00 UTC, middle 06 UTC, and bottom 12 UTC. Positive values (poleward wind - red), negative values (equatorward wind - blue), NCEP/NCAR reanalysis only.

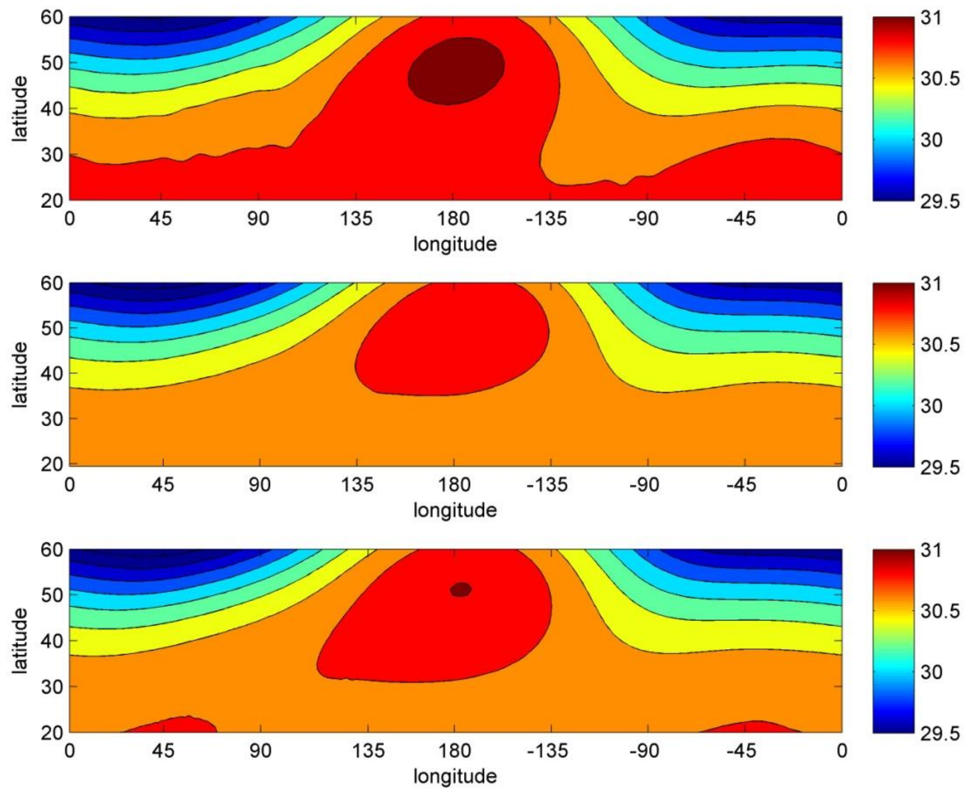

Figure 5: Plot of average geopotential height (km) for January, 1958-2012, 20-60°N, 180°E-180°W. Top panel NCEP/NCAR (1958-2012), middle ERA Interim (1979-2012), and bottom MERRA (1979-2012).

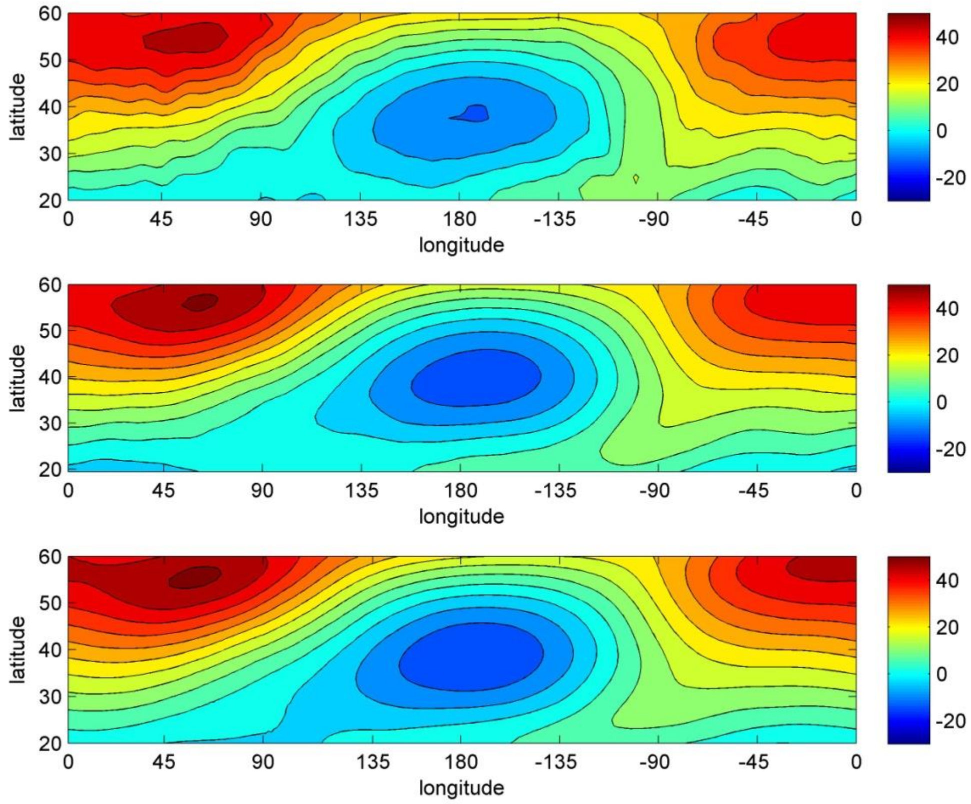

Figure 6 Plot of average zonal wind speed (m/s) component for January, 20-60°N, 180°E-180°W, 10 hPa. Top panel NCEP/NCAR (1958-2012), middle ERA Interim (1979-2012), and bottom MERRA (1979-2012). Positive values (eastward wind - red), negative values (westward wind - blue).

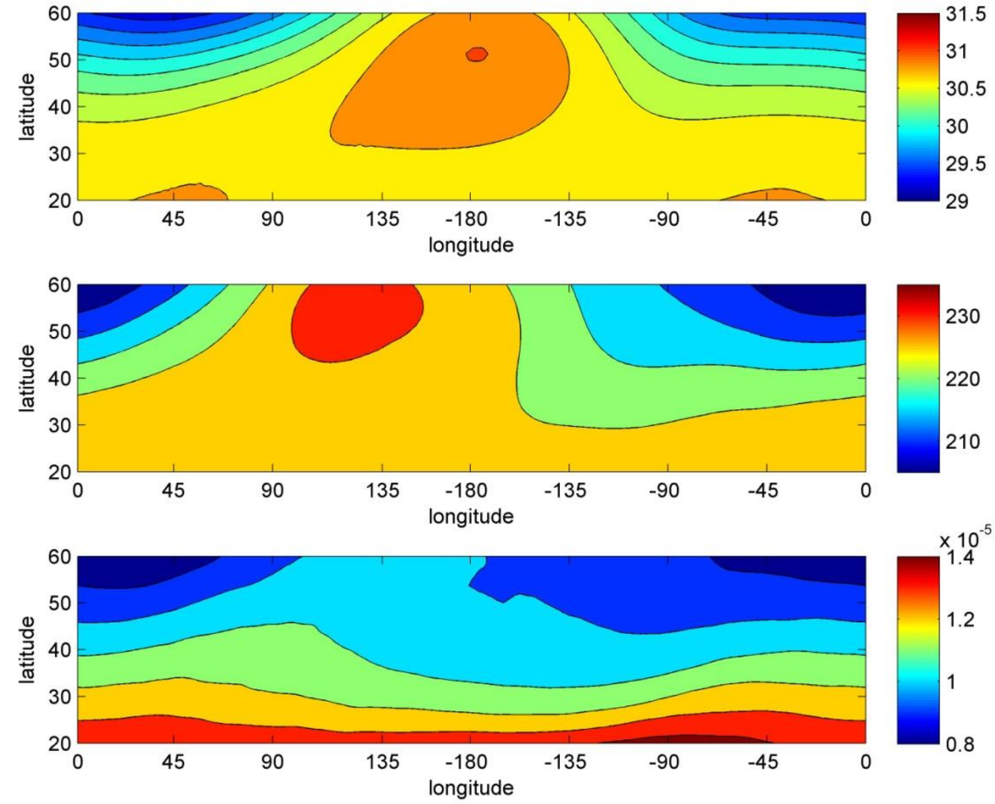

Figure 7 Plot of average geopotential height (km, top panel), temperature (K, middle panel) and ozone mixing ration (ppmv, bottom panel) for January, 20-60°N, 180°E-180°W, 10 hPa.