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

Michal Kozubek, Peter Krizan, Jan Lastovicka

Institute of Atmospheric Physics ASCR, Bocni II, 14131 Prague, Czech Republic
Correspondence to: M. Kozubek (kom@ufa.cas.cz)

Abstract

Stratospheric winds can be affected by many factors like tropospheric North Atlantic Oscillation (NAO), stratospheric Quasi-biennial Oscillation (QBO) or Sudden Stratospheric Warming (SSW) and solar activity. The behaviour and trends of total horizontal wind, and of its meridional component, is analysed based on the NCEP/NCAR reanalysis data. The influence of NAO on trend in total horizontal wind is significant in the lower stratosphere (100 hPa) in Atlantic sector; the trend is also affected by QBO, whereas influence of SSW is rather minor and observable only in the middle stratosphere (10 hPa). The most important result of this study seems to be the longitudinal distribution of the meridional wind component. We identify in winter (January) a well-developed two-core structure of strong but opposite winds, one at each hemisphere at 10 hPa, and a less-pronounced four-core structure at 100 hPa. The two-core structure at 10 hPa is practically identical in three different reanalyses, NCEP/NCAR, ERA-Interim and MERRA. This structure is not associated with tides. However, the two core structure at the 10 hPa level appears to be related to the well-pronounced Aleutian pressure high at 10 hPa. The well-developed two-core structure illustrates limitations of application of zonal mean concept in studying stratospheric circulation.

Keywords: Stratospheric dynamics, meridional wind, long-term trend, longitudinal distribution, solar activity

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 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 and R-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 affects vertically propagating atmospheric waves which control the transport circulation in the stratosphere and mesosphere (Holton and Alexander, 2000). The stratosphere is influenced also by solar activity (e.g., Gray et al., 2010 and references herein). Therefore it is important to study the stratospheric circulation and the impact of climate change on this circulation.

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 changed in the mid-1990s, we analyse some trends separately for time periods before and after the mid-1990s.

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 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). Some phenomena even disappear when we study zonal mean values (e.g., Lastovicka, 2003). On the other hand, to our best knowledge the longitudinal differences of meridional wind in the stratospheric climatology have not yet been studied. Therefore we investigate longitudinal distribution of meridional component of stratospheric winds at middle latitudes. A strong effect has been found at the 10 hPa level.

The paper focuses on two topics: (1) Connection of stratospheric total horizontal wind to other phenomena like Quasi-biennial Oscillation (QBO), Sudden Stratospheric Warming (SSW) or North Atlantic Oscillation (NAO). (2) Longitudinal distribution of meridional wind component at different pressure levels without zonal averaging (zonal averaging is usual for this type of analysis) and possible reason for its behaviour; as far as we know, such an analysis have not yet been done. The meridional wind is very important; the Brewer-Dobson circulation, which transports ozone from tropics to polar region, is meridional circulation.

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; Rufenacht et al., 2012) and from space by the High Resolution Doppler Imager (HRDI) on UARS covering 10–35 km and 60^{o}S–60^{o}N, using the molecular oxygen A- and B-bands (Ortland et al., 1996). However, direct wind measurements do not provide sufficiently long and homogeneous global data series, therefore we use in the paper reanalysis data, namely NCEP/NCAR-1 reanalysis (further on NCEP/NCAR). 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). According to Kozubek et al. (2014) stratospheric winds from the NCEP/NCAR reanalysis are slightly better than those from ERA-40 and ERA-Interim reanalysis. Moreover, neither ERA-40, nor ERA-Interim separately covers the whole period 1970-2012. On the other hand, general pattern and long-term changes of stratospheric winds in all three 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. 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/, NAO is taken from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim.

When studying longitudinal distribution of meridional winds, we use the NCEP/NCAR reanalysis and for confirmation of results also MERRA (downloaded from http://disc.sci.gsfc.nasa.gov) and ERA Interim (Dee et al., 2011) reanalyses. The results are similar even though not quite identical.

The analysis is focused on middle latitudes (50°, 52.5°, 55°N) at two pressure levels 100 and 10 hPa. These two pressure levels represent the dynamics and conditions in the lower (100 hPa) and middle (10 hPa) stratosphere at middle latitudes. The three selected latitudes represent middle latitude band from 49°N to 56°N. Its advantage is that it consists mainly of land, not ocean, i.e. geographic data coverage even before satellite era seems to be relatively good, better than in majority of other latitudinal bands. We analyzed these three latitudes separately to show the detail changes in each of the three latitudes but usually the results are quite similar, therefore we present them predominantly only for one latitude. We mostly use daily data from 00 UTC but for one analysis we have to choose also 06 and 12 UTC (analysis of diurnal and semidiurnal tidal effects). The selected latitudes are separated into four sectors (0°E-90°E – European sector, 90°E-180°E – Asian sector, 180°W-300°W – Pacific-American sector, and 300°E-360°E – Atlantic sector). The wind speed is calculated from gridded u and v components. In analyses we have used either total horizontal wind, or u (zonal) and v (meridional) components separately. As for trend/correlation analysis, we also present some results for 42.5 and 62.5^{o}N to broaden latitudinal range studied. The longitudinal distribution of meridional wind is investigated for the 20-60^{o}N latitude band.

We look for time development in each sector at both pressure levels. The statistical significance threshold of trends has been set on 95% level (using standard MATLAB routine), which is the standard significance level for analyses in meteorology (wind, temperature, etc.). We compare behaviour of wind speed in different sectors. Then we divide data of the whole period into several groups according to QBO, NAO or solar cycle influence. We again compute trends separately for all these groups with significance threshold 95%. These analyses have been done for total horizontal wind speed or for meridional component, respectively. The significance has been also calculated at the 99% level in some cases. For investigation of longitudinal distribution of meridional wind we have computed averages through the whole period (1970-2012) for every grid point from 20°N to 60°N and for every month. Comparison of wind speed distribution in 100 and 10 hPa at 00 UTC or wind speed distribution at 00, 06 and 12 UTC (06 and 12 for analysis of diurnal and semidiurnal tides) separately for meridional components has been done.

3. Results

3.1. Long-term trends in total horizontal winds

In this section we would like to show the influence of different stratospheric/ tropospheric phenomena on the long-term evolution of the stratospheric total horizontal wind speed. Figure 1 shows time development of winter averages (October-March) of total horizontal wind speed for different geographical sectors of 52.5°N. We have done analysis also for two other latitudes (50°N and 55°N) and the results were very similar (not shown here). The top panel presents results for 100 hPa. The behaviour of Atlantic sector (300°W-360°W) is different from other sectors (Pacific-American, Asian and European). There is significant positive trend (95% level) since 1970 till 1996 and negative trend after 1996 in the Atlantic sector. The peak value of wind speed and turnaround of trend in 1996 coincide with the total ozone trend turnaround in northern middle latitudes (e.g., Harris et al., 2008). The trends in other three sectors are insignificant, if any. Generally stronger winds occur in Atlantic sector, especially after 1985. At pressure level 10 hPa no significant trend can be found. The behaviour is rather chaotic and qualitatively similar for all four sectors. There are stronger winds in Atlantic (300°W-360°W) and European (0°E-90°E) sectors, in some years the wind is two times stronger in Atlantic than Asian sector (42 m/s and 17 m/s, respectively for 1998). To have broader latitudinal coverage, the analysis shown in Fig. 1 is repeated for latitudes 42.5°N and 62.5°N for Atlantic sector in Fig. 2. It reveals a similar behaviour of wind speed at 10 hPa as in Fig. 1 (no significant trend if any). At 100 hPa we also cannot see any significant trend contrary to Fig. 1. Thus a clear long-term change/trend in total horizontal wind seems to be confined to the Atlantic sector and higher middle latitudes (49°N-56°N). Therefore further on we focus on higher midlatitudes and the Atlantic sector.

Time series of total horizontal wind speed for the Atlantic sector and higher middle latitudes and of NAO index are compared in Fig. 3. NAO is selected because it influences the winds in the Atlantic sector and above selected range of latitudes in the troposphere and its effect is expected to be observed also in the lowermost stratosphere (100 hPa). Figure 3 shows that trends in winds and NAO for three different periods (1958-1970, 1971-1995 and 1996-2009) are similar in tendency, a negative tendency before 1970, a positive tendency for 1970-1995, and a negative tendency after 1995. While the trends of winds are significant, the trends of NAO are insignificant (except for the last period where we can find significant negative trend) mainly due to large scatter of data. Thus the different trend behaviour of total horizontal wind at 100 hPa in the Atlantic sector compared to other sectors is influenced by NAO, which is tropospheric phenomenon located in the North Atlantic Ocean region.

Now we show winter (December-February only) trends for two periods (1970-1995 and 1995-2012). This analysis will show us the influence of different stratospheric phenomena (QBO or SSW) on the stratospheric winds (dynamics). We have to start at 1970 because before this year the reliability of NCEP/NCAR reanalysis data is lower (Kozubek et al., 2014). We use daily data for two periods 1970-1995 and 1996-2012, as in about 1995 the trend in the northern midlatitude total ozone was changed (e.g. Harris et al., 2008) and we want to test possible impact of this change on stratospheric winds. The results are presented in Table 1. We divide data into several groups. The first two groups show results for winters when either major SSW occurs or does not occur (the standard WMO definition is used for SSW). This analysis should reveal the influence of major SSW on dynamics in different sectors of middle latitudes. The statistically significant trends (95% level) at 100 hPa for all three analysed latitudes are found mainly in the Atlantic sector. Generally positive trend is seen in 1970-1995 and negative one in 1995-2012 which agree with previous studies (Lorenz and DeWeaver, 2007, Lastovicka et al., 2010, Reinsel et al., 2005). At 10 hPa there are no statistically significant trends for group with major SSWs but again a positive tendency in 1970-1995 and a negative tendency in the second period are observed. The second group without major SSWs reveals again positive tendency in the first period and negative one in the second. However, contrary to group with major SSWs, we can find several significant trends in both periods, even though weaker than corresponding trends at 100 hPa. These results indicate that major SSWs at 10 hPa support a tendency to absence of significant trends. No substantial impact of major SSWs on trends in winds is found for 100 hPa; trends with and without major SSWs are very similar.

The third and fourth groups in Table 1 show trends for years when the east or west phase of QBO occur, respectively. At 100 hPa we can found significant trend mainly for period 1970-1995 in Atlantic and European sectors. Again we can found change from positive (in the first period) to negative (in the second period) trends, which is well pronounced for the west phase of QBO, whereas there is no systematic change for the east phase of QBO. There is no typical behaviour at 100 hPa for the east or west phase of QBO. At 10 hPa the tendency to change from positive (1970-1995) to negative (1995-2012) trends can be seen for both phases of QBO but again it is more pronounced for the west phase of QBO. There are almost no differences between trends in the east and west QBO phases for positive trends in 1970-1995 but negative trends in 1995-2010 in European and Atlantic sectors are much more negative for the west phase of QBO. Thus the results show that for both pressure levels trends and their change in the mid-1990s are evidently better pronounced for the west than east phase of QBO. We have done similar analysis separately for each month; the results are similar to the whole winter results (December-February). We calculated the statistical significance of all trends in Table 1 also on the 99% level. However, only four trends (out of 192) are significant at this level, probably due to limited length of data sets.

It should be mentioned that Monier and Weare (2011b) found some strengthening of northern polar jet in October-December and weakening in January-March. However, our analysis of total horizontal wind at northern higher middle latitudes reveals similar trends for October-December and January-March.

3.2. Impact of solar cycle on total horizontal winds

Another analysis, which has been done, is comparison between years in the solar cycle maximum and minimum in different QBO phases. This analysis will show the connection between solar cycle and stratospheric dynamics (QBO and wind speed). Stratospheric dynamics and chemistry is influenced by solar activity especially at higher levels. We show winter (October-March) differences for different groups.

The results for total horizontal wind speed are shown on the first two panels 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 all studied sectors. The differences are significant mainly in Atlantic sector. 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 4 m/s) in all studied sectors. These differences are mainly significant in European and Atlantic sector. Differences between QBO east and QBO west phase in solar maximum are mainly positive but insignificant.

The differences are generally smaller at 100 than at 10 hPa. We cannot find a systematic structure for differences between QBO east and QBO west phase for solar maximum or minimum. The results for differences between solar minimum or solar maximum are mainly positive (except two insignificant cases) for QBO east or west phase. Again the significant values can be observed mainly in Atlantic or European sectors.

The two bottom panels show the same analysis as top ones but for v (meridional) wind component. An analysis for zonal wind component may be found in many studies but we have not found in literature such an analysis for meridional component. The differences are slightly smaller than for total horizontal wind. At 10 hPa we cannot find any specific features for all four groups. We can see only a few significant values in different sectors. At 100 hPa we can find significant differences for all four groups mainly in Pacific-American and Atlantic sector. This analysis was done also for each month or different period (i.e. October- December or January- March) and the biggest differences have been found in December and January. These results confirm that solar activity influence the total horizontal wind (i.e. essentially zonal wind) mainly in higher part of the stratosphere (10 hPa) and predominately in European and Atlantic sectors. The meridional wind is influenced mainly at lower part of the stratosphere (100 hPa).

3.3 Longitudinal distribution of stratospheric meridional winds

Because we have found different signs in different sectors during the previous analysis of meridional wind component (see Tab. 2, bottom panels), we have computed the whole possible period averages of this component for each grid point from 60°N to 20°N for January at 10 hPa. 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. 4. The top panel show results for NCEP/NCAR, middle for ERA Interim and bottom for MERRA reanalysis. The behaviour of different reanalyses is similar in major features; the results for NCEP/NCAR slightly differ due to much longer averaging period. Figure 4 reveals at 10 hPa for January a core of strong poleward wind on the east hemisphere of the middle and higher latitudes for. This poleward wind changes into equatorward wind core on the west hemisphere at 10 hPa (similar amplitude as on the east hemisphere). Both the poleward and equatorward peaks (centres of the cores taken as 100°E-150°E and 130°W-80°W at 10 hPa) are statistically significant at 99% level (in fact at even higher level) for NCEP/NCAR reanalysis. The results of similar analysis for 100 hPa are shown in Fig. 5. 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 are two cores with negative (equatorward) and two cores with positive (poleward) values; the four-core structure is less pronounced than the two core structure at 10 hPa. The same analysis, but for July, is shown in Fig. 6. 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, especially at 10 hPa. At 100 hPa there is again a tendency to four-core patterns but at lower latitudes than in January. We have done the same analysis for higher pressure level of 5 hPa and the differences between east and west hemisphere have been growing with increasing height.

Figure 7 show averages over the period 1957-2012 for January at 10 hPa pressure level but we compare 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 geopotencial height because of dynamics reason. Figure 8 shows a distribution of geopotential height at 10 and 100 hPa. 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. 9 for all three reanalyses, confirms 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 points like 60°N, 135°E both wind components are approximately equal. In summer there is no well pronounced Aleutian pressure high in the geopotential height field and, therefore, no two-core structure in meridional wind is observed. At 100 hPa at least on the western hemisphere (not at eastern one) the distribution of geopotential height (high or low pressure centres on Fig. 8) resembles the four-core structure in winds in Fig. 5 but again this structure is less pronounced than that at 10 hPa. 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. 6).

4. Discussion

The results concerning long-term trends in the total horizontal wind are mainly focused on the Atlantic sector of higher middle latitudes (49°N-56°N) because other analysed latitudes (42.5°N and 62.5°N) do not reveal any significant trend. Pronounced trends at higher middle latitudes are confined to Atlantic sector and 100 hPa level (not 10 hPa), which suggests some role of NAO. The results coincide with the result of Scaife et al. (2005) that NAO as a tropospheric phenomenon affects zonal winds in the lower stratosphere (and vice versa); we added to that finding that contrary to the lower stratosphere, trends in total horizontal winds in the middle stratosphere (10 hPa) are not influenced significantly by NAO. Figure 3 shows that both changes of trends in stratospheric wind at 100 hPa in Atlantic sector around 1995 and 1970 are coincident with changes of trends in NAO. Our results also show that QBO as a stratospheric phenomenon, which influences the stratosphere at all heights, affects trends (95% level) at both the 100 and 10 hPa levels, whereas major sudden stratospheric warming (SSW), which is substantially better developed at 10 hPa than at 100 hPa, affect trends measurably only at 10 hPa. The influence of QBO and SSWs and their combination on the stratosphere has been discussed in many papers, e.g. recently by Watson and Gray (2014). The influence of QBO on global stratospheric circulation, so called Holton-Tan effect, has first been observed by Holton and Tan (1980); our results are qualitatively consistent with Holton-Tan rule. Mechanisms of influence of the above individual factors on trends in stratospheric winds remain a challenge for future investigations.

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 also reversal of trends in the lower stratospheric wind (100 hPa). 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 is the reason why we focused on dynamical factors which could be behind the change of trends of both ozone and wind. Moreover, whereas ozone trend occurs more or less everywhere at higher middle latitudes, the lower stratospheric wind trend appears to be basically confined to the Atlantic sector, which points to dynamical factor NAO. In this context it might be of some interest that the primary explanatory variable of behaviour of ozone laminae (lower stratosphere phenomenon) observed at Payerne in Switzerland is NAO (Lastovicka et al., 2014).

Perhaps the most important result offers the analysis of geographic distribution of meridional component of stratospheric wind in the form of the well-pronounced two-core structure at 10 hPa in winter. This two-core structure is provided by NCEP/NCAR, ERA-Interim and MERRA reanalyses in a very similar form despite different time periods used (Fig. 4). We have not found in literature any analysis of meridional wind geographic distribution without zonal mean averaging. 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. 7). However, the geopotential height analysis reveals probable reason for this longitudinal distribution. The well-developed large Aleutian high at 10 hPa in Fig. 8 can block the zonal flow (see Fig. 9) 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. This is in qualitative agreement with the behaviour of meridional wind in Fig. 4. This feature can probably explain the longitudinal distribution of meridional winds at 10 hPa.

Such pronounced longitudinal distribution of meridional wind documents limitations of application of zonal means in examining stratospheric circulation.

We also identify statistically significant trends (99% level) in peaks of both cores at 10 hPa (Table 3). These trends are negative in period 1970-1995 and positive in 1996-2012 for both cores independent of the phase of QBO or occurrence of major SSW. Table 1 shows for 10 hPa a 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.

As for 100 hPa, the distribution of geopotential heights at the western hemisphere perhaps seems to support the observed four-core longitudinal distribution of winds but such effect is largely absent at the eastern hemisphere. Further investigations of origin of the two-core and four-core longitudinal structure of stratospheric winds will be done in near future but even these basic results show that we have to be careful when zonal mean averages are used for analyses, because in such a way we can miss important information. The problem with zonal averages is well known but they are still used too often.

5. Conclusions

Analysis of northern wintertime NCEP/NCAR reanalysis data at 100 and 10 hPa levels in higher middle latitudes (49-56^{o}N) reveals influence of stratospheric (QBO) and particularly tropospheric (NAO) phenomena on the trends in total horizontal winds in the stratosphere. It also exhibits a reversal of trends in winds in the mid-1990s in accord with change of trend in ozone, which is however probably caused by dynamical factors, which affect both win and ozone. Stronger trends in total horizontal wind observed at 100 hPa (not at 10 hPa) in Atlantic sector are related to trends in NAO. Even though NAO is a tropospheric phenomenon, it can affect the dynamics at least in the lower stratosphere. The other analyzed latitudes (42.5°N and 62.5°N) do not show any significant trend so we can conclude that this effect appears to be confined to higher midlatitudes. The effect of QBO, which means much more pronounced trend and its change in the west phase of QBO than in the east phase, is evident in both pressure levels. Major sudden stratospheric warmings (SSWs) support tendency to absence of significant trends in total horizontal winds at 10 hPa; they have no detectable impact on trends in winds at 100 hPa. Mechanisms to explain these observations remain to be a challenge for future investigations.

The stratospheric total horizontal winds in the winter northern middle latitudes were examined also separately for years of the solar cycle minimum and maximum under different QBO conditions. These results (Table 2) confirm that solar activity influences the total horizontal wind mainly at higher part of the stratosphere (10 hPa) and predominately in European and Atlantic sectors. The meridional wind is influenced mainly at lower part of the stratosphere (100 hPa).

The geographic distribution of meridional component of stratospheric wind in winter (January) is shown in Fig. 4 and 5 for 20-60^{o}N. It reveals well pronounced longitudinal distribution of winds at latitudes above 30^{o}-35^{o}N with two cores of strong but opposite meridional winds, one at each hemisphere (eastern and western) at 10 hPa, and a less pronounced four-core structure at 100 hPa. Reanalyses NCEP/NCAR, ERA-Interim and MERRA provide the same pattern. In summer such a well-pronounced core structure is absent (Fig. 6). The two-core structure at 10 hPa is not caused by tides as it is demonstrated by Fig. 7. We have identified the strong and well-developed large Aleutian pressure high at 10 hPa (Fig. 8), which is capable to explain qualitatively the two-core structure in the longitudinal distribution of meridional wind. The longitudinal distribution of zonal wind at 10 hPa (Fig. 9), trends in the total horizontal wind in Fig. 3, strength of two cores in Table 3, and strength of the blocking Aleutian high provide a pattern consistent with the two core structure of longitudinal variation of meridional wind at 10 hPa and its interpretation through the blocking Aleutian high. This illustrates limitations of approach via zonal mean values when studying circulation.

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).

References

Baldwin, M.P., and Dunkerton, T.J.: Propagation of the arctic oscillation from the stratosphere to the troposphere, J. Geophys. Res., 104, 30937-30946, 1999.

Baldwin, M., Shuckburgh, D. Norton, E., Thompson, and W., Gillett, G.: Weather from the stratosphere? Science, 301, 317-318, 2003.

Butchart, N.: The Brewer-Dobson circulation, Rev. Geophys., 52, 157-184, 2014

Deckert, R., and Dameris, M.: Higher tropical SSTs strengthen the tropical upwelling via deep convection, Geophys. Res. Lett, *35*(10), 2008.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis:

configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137, 553–597, 2011.

Engel, A., Möbius, T., Bönisch, H., Schmidt, U., Heinz, R., Levin, I., Atlas, E., Aoki, S., Nakazawa, T., Sugawara, S., Moore, F., Hurst D., Elkins J., Schauffler S., Andrews A., and Boering K.: Age of stratospheric air unchanged within uncertainties over the past 30 yr. Nat. Geosci., 2, 28–31, doi:10.1038/ngeo388, 2009.

Gray, L.J., Beer, J., Geller, M., Haigh, J.D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G.A., Shindell, D., van Geel, B., and White, W.: Solar influences on climate, Rev. Geophys., 48, RG4001, doi: 10.1029/2009RG000282, 2010.

Harris, N. R. P., Kyrö, E. Staehelin, J., et al.: Ozone trends at northern mid- and high latitudes — A European perspective, Ann. Geophys., 26, 1207–1220, doi: 10.5194/angeo-26-1207-2008, 2008.

Hartmann, D. L., Wallace, J. M., Limpasuvan, V., Thompson, D. W., and Holton, J. R.: Can ozone depletion and global warming interact to produce rapid climate change? Proc. Nat. Acad. Sci., 97(4), 1412-1417, 2000.

Hildebrand, J., Baumgarten, G., Fiedler, J., Hoppe, U.-P., Kaifler, B., Lubken, F.-J., and Williams, B. P.: Combined wind measurements by two different lidar instruments in the Arctic middle atmosphere, Atmos. Meas. Tech., 5, 2433–2445, 2012.

Holton, J.R., and Hsiu-Chi Tan. The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. J. Atmos. Sci., 37 (10), 2200-2208, 1980.

Holton, J. R., and Alexander, M. J. The role of waves in transport circulation of the middle atmosphere. Geophys. Monogr. Ser., vol. 123, AGU, Washington DC, 21-35, 2000.

Kistler, R., Collins W. Kalnay, E., et al. The NCEP 50-year reanalysis: Monthly means CDrom and documentation. Bull. Am. Meteorol. Soc. 82 (2), 247-267, 2001.

Kozubek, M., Laštovička, J., and Križan, P.: Differences in mid-latitude stratospheric winds between reanalysis data and versus radiosonde observations at Prague, Ann. Geophys., 32, 353-366, doi: 10.5194/angeo-32-353-2014, 2014.

Lastovicka, J.: Non-zonality of ozone response to geomagnetic storms and Furbush decreases of cosmic rays. Adv. Space Res., 32 (9), 1793-1802, 2003.

Lastovicka, J., Krizan, P., and Kozubek, M.: Long-term trends in the middle atmosphere dynamics at northern middle latitudes – one regime or two different regimes? Atmos. Chem. Phys. Discuss., 10, 2633-2668, doi: 10.5194/acpd-10-2633-2010, 2010.

Lastovicka, J., Solomon, S.C., and Qian, L.: Trends in the Neutral and Ionized Upper Atmosphere, Space Sci. Rev., 168, 113–145, doi: 10.1007/s11214-011-9799-3, 2012.

Lastovicka, J., Krizan, P., and Kozubek, M.: Long-term trends in the northern extratropical ozone laminae with focus on European stations, J. Atmos. Sol.-Terr. Phys., 120, 88-95, http://dx.doi.org/10.1016/j.jastp.2014.09.006, 2014.

Lin, P., and Fu, Q.: Changes in various branches of the Brewer–Dobson circulation from an ensemble of chemistry climate models. J. Geophys. Res. Atmos, 118(1), 73-84, 2013.

Lorenz, D. J., and DeWeaver, E. T.: Tropopause height and zonal wind response to global warming in the IPCC scenario integrations. J. Geophys. Res. Atmos (1984–2012), 112(D10), 2007.

Marshall, A. G., and Scaife, A. A. Impact of the QBO on surface winter climate. J. Geophys. Res. Atmos., 114(D18), 2009, doi: 10.1029/2009JD011737

Mlch, P.: Total ozone response to major geomagnetic storms during non-winter periods. Studia geoph. Geod., 38 (4), 423-429, 1994.

Monier, E. and Weare, B. C.: Climatology and trends in the forcing of the stratospheric ozone transport, Atmos. Chem. Phys., 11, 6311-6323, doi: 10.5194/acp-11-6311-2011, 2011a.

Monier, E. and Weare, B. C.: Climatology and trends in the forcing of the stratospheric zonal-mean flow, Atmos. Chem. Phys., 11, 12751-12771, doi:10.5194/acp-11-12751-2011, 2011b.

Oberländer, S., Langematz, U., & Meul, S.: Unravelling impact factors for future changes in the Brewer-Dobson circulation. J. Geophys. Res. Atmos, *118*, 10,296-10,312, 2013.

Oman, L., Waugh, D. W., Pawson, S., Stolarski, R. S., & Newman, P. A.: On the influence of anthropogenic forcings on changes in the stratospheric mean age. J. Geophys. Res. Atmos *(1984–2012)*, *114*, D03105, 2009 DOI: 10.1029/2008JD010378.

Ortland, D. A., Skinner, W. R., Hays, P. B., Burrage, M. D., Lieberman, R. S., Marshall, A. R., and Gell, D. A.: Measurements of stratospheric winds by the High Resolution Doppler Imager, J. Geophys. Res., 101, 10351–10363, 1996.

Pommereau, J.-P., Goutail, F., Lefèvre, F., Pazmino, A., Adams, C., Dorokhov, V., Eriksen, P., Kivi, R., Stebel, K., Zhao, X., and van Roozendael, M.: Why unprecedented ozone loss in the Arctic in 2011? Is it related to climate change?, Atmos. Chem. Phys., 13, 5299-5308, doi: 10.5194/acp-13-5299-2013, 2013.

Reinsel, G. C., Miller, A. J., Weatherhead, E. C., Flynn, L. E., Nagatani, R. M., Tiao, G. C. and Wuebbles D. J.: Trend analysis of total ozone data for turnaround and dynamical contributions, J. Geophys. Res., 110, D16306, doi: 10.1029/2004JD004662, 2005

Rufenacht, R., Kampfer, N., and Murk, A.: First middle atmospheric zonal wind profile measurements with a new ground-based microwave Doppler-spectro-radiometer, Atmos. Meas. Tech., 5, 2647–2659, 2012

Scaife, A. A., Knight, J. R., Vallis, G. K., and Folland, C. K. A stratospheric influence on the winter NAO and North Atlantic surface climate, Geophys. Res. Lett., 32 (18), 2005, DOI: 10.1029/2005GL023226

Scaife, A. A., Spangehl, T., Fereday, D. R., Cubasch, U., Langematz, U., Akiyoshi, H., Slimane, B., Breasicke, P., Butchard, N., Chipperfield, M. P., Gettelman, A., Hardiman, S. C., Michou, M., Rozanov, E. and Shepherd, T. G.: Climate change projections and stratosphere–troposphere interaction. *Climate Dynamics*, *38*(9-10), 2089-2097, 2012

Shepherd, T.G. Transport in the middle atmosphere. J. Meteorol. Soc. Jpn. II, 85B,

165-191, 2007.
Shepherd, T.G. Dynamics, stratospheric ozone, and climate change. Atmos. Ocean, 46, 117-138, 2008.
Sigmond, M., Scinocca, J. F, and Kushner, P. J. Impact of the stratosphere on the tropospheric climate change. Science, 301, 317-318, 2008.
Stiller, G. P., von Clarmann, T., Haene,l F., Funke, B., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., Lossow, S., and Lopez-Puertas, M.: Observed temporal evolution of global mean age of stratospheric air for the 2002 to 2010 period. Atmos. Chem. Phys., 12, 3311–3331, www.atmos-chem-phys.net/12/3311/2012/, 2012.
Wang, L., and Chen, W. Downward arctic oscillation signal associated with moderate weak stratospheric polar vortex and the cold December 2009. Geophys. Res. Lett., 37, L09707, 2010, DOI: 10.1029/2010GL042659
Watson, P. A. G., and Gray, L. J. How does the quasi-biennial oscillation affect the stratospheric polar vortex? J. Atmos. Sci., 71 (1), 391-409, 2014.
Weare, B. C.: Tropospheric-stratospheric wave propagation during El Niño-Southern Oscillation, J. Geophys. Res., 115, D18122, doi: 10.1029/2009JD013647, 2010.

Table 1: Winter (December-February only) trends (m/s per year) of total horizontal 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. Top panel 100 hPa, bottom panel 10 hPa. 70-95 means 1970-1995 and 95-12 means 1995-2012. Significant trends on 95% level are highlighted by bold numbers.

						100 hPa							
latitude	50°N				52.5°N				55°N				
sector	0-90	90-180	180-300	300-360	0-90	90-180	180-300	300-360	0-90	90-180	180-300	300-360	
70-95	**0.07**	-0.02	0.06	**0.15**	0.06	-0.04	0.06	**0.16**	0.05	-0.02	0.06	**0.12**	**major SSW**
95-12	-0.13	0.00	-0.22	**-0.60**	-0.15	0.01	-0.26	**-0.64**	-0.18	-0.05	-0.29	**-0.57**	
70-95	0.11	0.04	0.09	0.20	0.12	-0.01	**0.14**	0.27	0.11	-0.01	0.09	0.25	**no SSW**
95-12	-0.14	-0.01	-0.19	**-0.55**	-0.09	-0.06	**-0.18**	**-0.53**	-0.12	0.00	-0.26	**-0.55**	
70-95	**0.10**	**-0.18**	-0.01	0.09	0.07	**-0.20**	-0.02	**0.09**	0.06	**-0.18**	-0.03	0.09	**east QBO**
95-12	-0.26	**0.10**	0.08	**-0.35**	-0.26	**0.07**	0.04	-0.43	-0.27	0.00	-0.01	**-0.48**	
70-95	**0.05**	0.02	**0.11**	**0.26**	0.08	0.03	**0.14**	**0.28**	0.10	0.04	0.15	**0.28**	**west QBO**
95-12	0.04	0.05	-0.27	**-0.54**	-0.06	-0.08	**-0.36**	**-0.62**	-0.18	-0.22	-0.43	**-0.68**	
						10 hPa							
	50°N				52.5°N				55°N				
	0-90	90-180	180-300	300-360	0-90	90-180	180-300	300-360	0-90	90-180	180-300	300-360	
70-95	0.00	0.05	0.03	0.01	-0.01	0.07	0.04	0.04	-0.01	0.09	0.05	0.08	**major SSW**
95-12	0.16	-0.06	-0.25	-0.16	0.08	-0.11	-0.28	-0.21	-0.02	-0.13	-0.31	-0.26	
70-95	0.05	0.04	0.09	**0.11**	0.00	0.07	0.08	**0.14**	0.07	**0.14**	0.04	**0.17**	**no SSW**
95-12	-0.07	**-0.15**	**-0.19**	-0.06	-0.08	0.00	**-0.24**	-0.12	0.06	-0.07	**-0.20**	**-0.18**	
70-95	**0.16**	0.15	0.02	0.11	**0.22**	0.17	0.04	0.20	**0.29**	0.20	**0.08**	0.29	**east QBO**
95-12	0.15	-0.27	-0.33	0.07	0.00	-0.31	**-0.40**	-0.07	-0.19	-0.31	-0.47	-0.26	
70-95	**0.23**	0.04	0.10	**0.22**	**0.22**	0.05	0.11	**0.26**	0.20	0.07	0.12	**0.28**	**west QBO**
95-12	-0.43	-0.36	-0.21	-0.55	**-0.56**	-0.45	-0.25	**-0.60**	**-0.65**	-0.51	-0.32	**-0.65**	

Table 2: Winter (October-March) differences of wind speed (m/s) for different latitudes and sectors. Top half shows total horizontal wind speed for two pressure level, bottom half v (meridional) wind component for two pressure levels. 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				**52.5°N**				**55°N**				**latitude**
	0-90	**90-180**	**180-300**	**300-360**	**0-90**	**90-180**	**180-300**	**300-360**	**0-90**	**90-180**	**180-300**	**300-360**	**sector**
(min/east)-(min/west)	-1.07	-0.03	-1.45	**-2.63**	**-1.93**	-0.33	**-1.83**	**-3.52**	**-2.78**	-0.73	**-2.16**	**-4.33**	**10 hPa**
(max/east)-(max/west)	0.33	**-0.56**	1.46	1.35	0.66	-0.42	1.17	**1.72**	1.08	-0.27	0.80	**1.88**	
(min/west)-(max/west)	**2.02**	0.51	1.55	**2.82**	**2.56**	0.80	1.81	**3.75**	3.15	1.14	**2.01**	**4.42**	
(min/east)-(max/east)	0.62	**1.04**	-1.36	-1.15	-0.03	0.89	-1.19	-1.49	-0.71	0.68	-0.94	**-1.79**	
(min/east)-(min/west)	0.03	-0.10	0.45	**1.04**	0.11	-0.11	0.57	1.14	0.22	-0.05	**0.68**	**1.19**	**100 hPa**
(max/east)-(max/west)	**-1.32**	-0.89	0.04	0.09	**-1.34**	**-0.94**	-0.01	0.18	-1.27	-0.85	-0.05	0.18	
(min/west)-(max/west)	0.04	0.12	0.78	0.53	-0.08	0.19	**0.87**	0.73	-0.16	0.23	**0.92**	**0.92**	
(min/east)-(max/east)	**1.39**	0.91	1.19	1.48	1.38	1.02	1.45	**1.69**	1.33	1.04	1.66	**1.93**	
(min/east)-(min/west)	-0.01	**-0.64**	0.60	-0.29	-0.11	-0.73	**0.79**	-0.31	-0.26	**-0.84**	1.01	-0.31	**10 hPa v**
(max/east)-(max/west)	-0.38	0.15	0.09	**0.43**	-0.40	0.14	0.10	**0.59**	-0.43	0.17	0.14	**0.70**	
(min/west)-(max/west)	-0.17	**1.18**	-0.73	-0.05	-0.20	1.36	**-0.86**	0.05	-0.18	**1.57**	-0.99	0.08	
(min/east)-(max/east)	0.19	0.39	-0.22	**-0.77**	0.09	0.49	-0.17	**-0.85**	-0.01	0.57	**-0.11**	**-0.92**	
(min/east)-(min/west)	0.02	-0.03	0.25	**-0.52**	0.04	-0.10	0.37	**-0.69**	0.05	-0.17	**0.49**	-0.84	**100 hPa v**
(max/east)-(max/west)	-0.14	0.13	-0.24	**0.44**	-0.16	0.16	**-0.30**	0.52	-0.17	0.21	-0.34	**0.58**	
(min/west)-(max/west)	-0.04	0.09	-0.31	**0.57**	-0.11	0.17	**-0.45**	0.80	-0.16	0.24	**-0.58**	**1.02**	
(min/east)-(max/east)	0.12	-0.06	0.18	**-0.39**	0.09	-0.08	**0.21**	-0.41	0.05	-0.13	0.25	**-0.40**	

Table 3: Winter (December-February only) 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; the remaining one is significant at the 95% level.

10 hPa			
latitude	55°N	55°N	
sector	100°E-150°E	130°W-80°W	
70-95	**0.57**	**0.54**	**major SSW**
95-12	**-0.61**	**-0.67**	**major SSW**
70-95	**0.43**	**0.51**	**no SSW**
95-12	**-0.6**	**-0.49**	**no SSW**
70-95	0.39	**0.42**	**east QBO**
95-12	**-0.48**	**-0.46**	**east QBO**
70-95	**0.41**	**0.55**	**west QBO**
95-12	**-0.54**	**-0.62**	**west QBO**

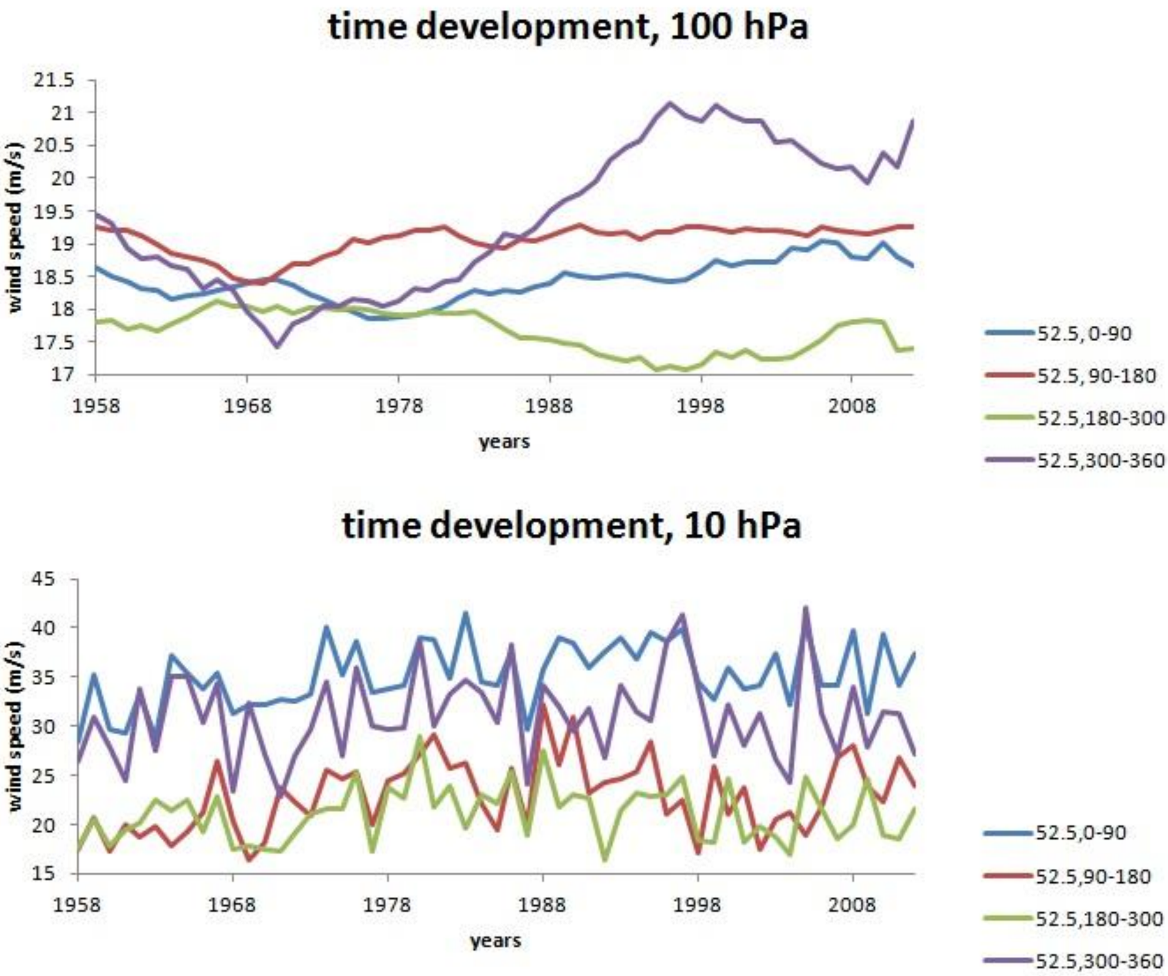

Figure 1: Time development - winter averages (October-March) of total horizontal wind speed in four different sectors of 52.5°N for period 1958-2012. Top panel is for 100 hPa, bottom panel for 10 hPa.

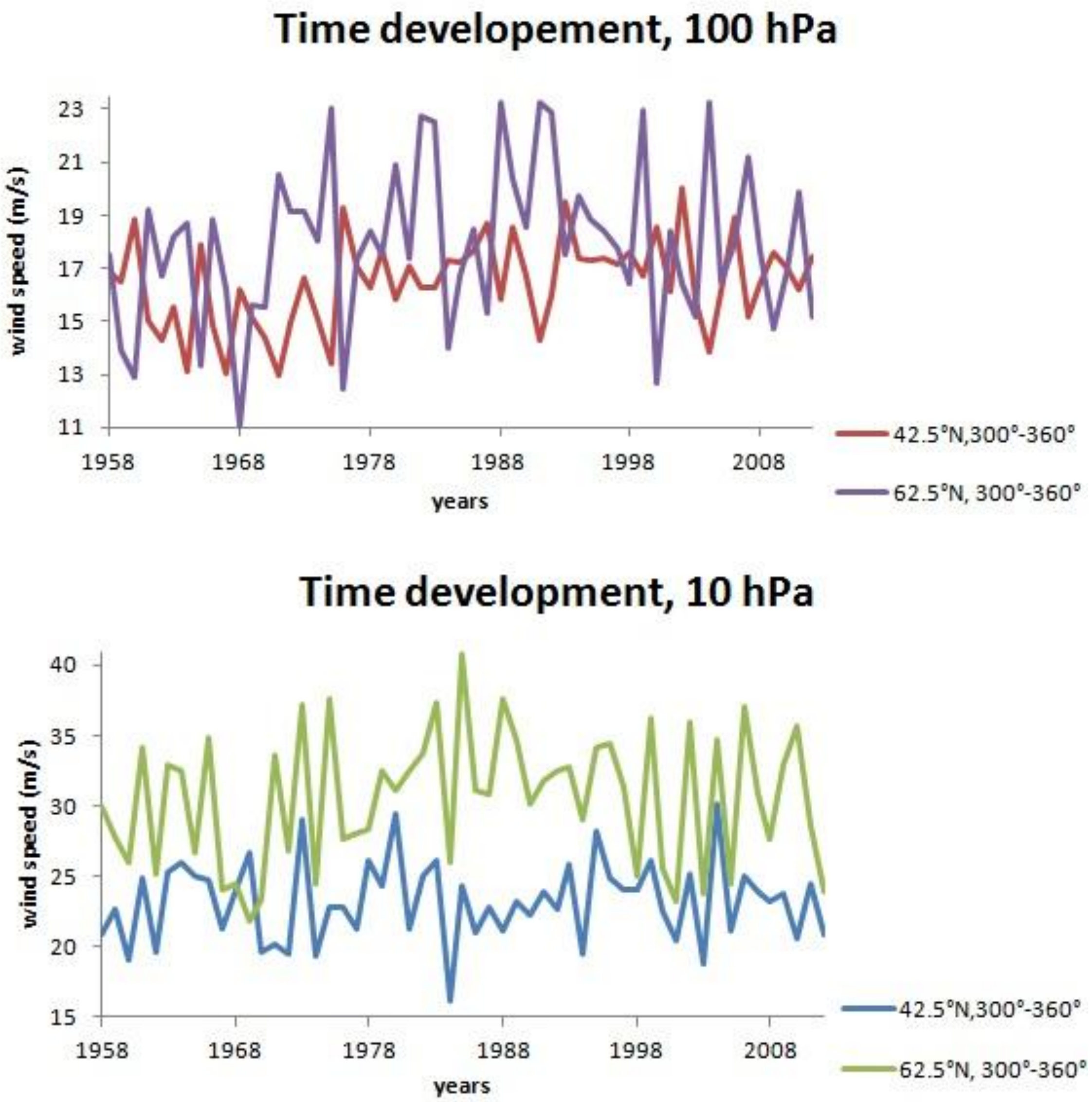

Figure 2: Time development - winter averages (October-March) of total horizontal wind speed in Atlantic sector (300°-360°E) of 42.5°N and 62.5°N for period 1958-2012. Top panel is for 100 hPa, bottom panel for 10 hPa.

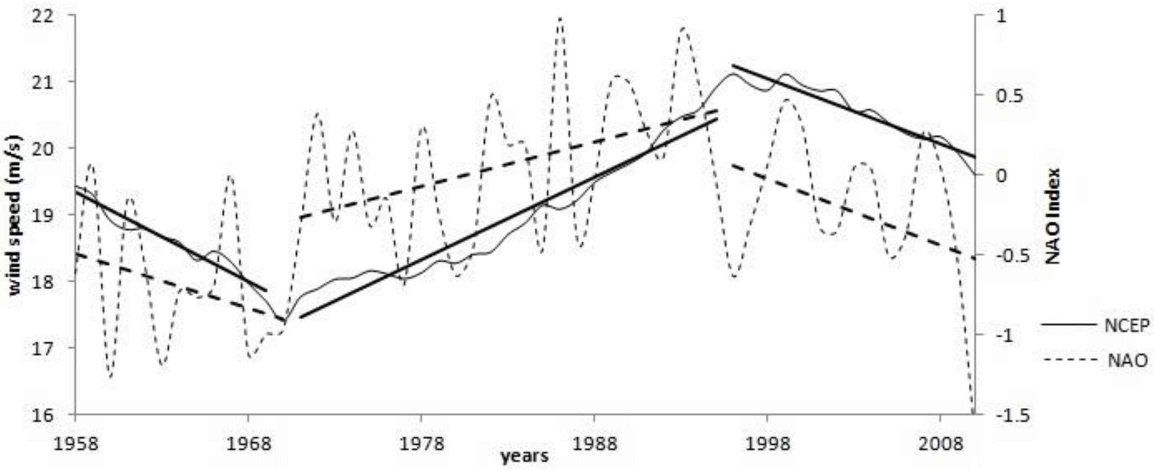

Figure 3: Comparison of total horizontal wind speed (solid line) at 100 hPa, 52.5°N, sector 300°E-360°E NCEP/NCAR reanalysis and NAO index (dashed line) for three different periods.

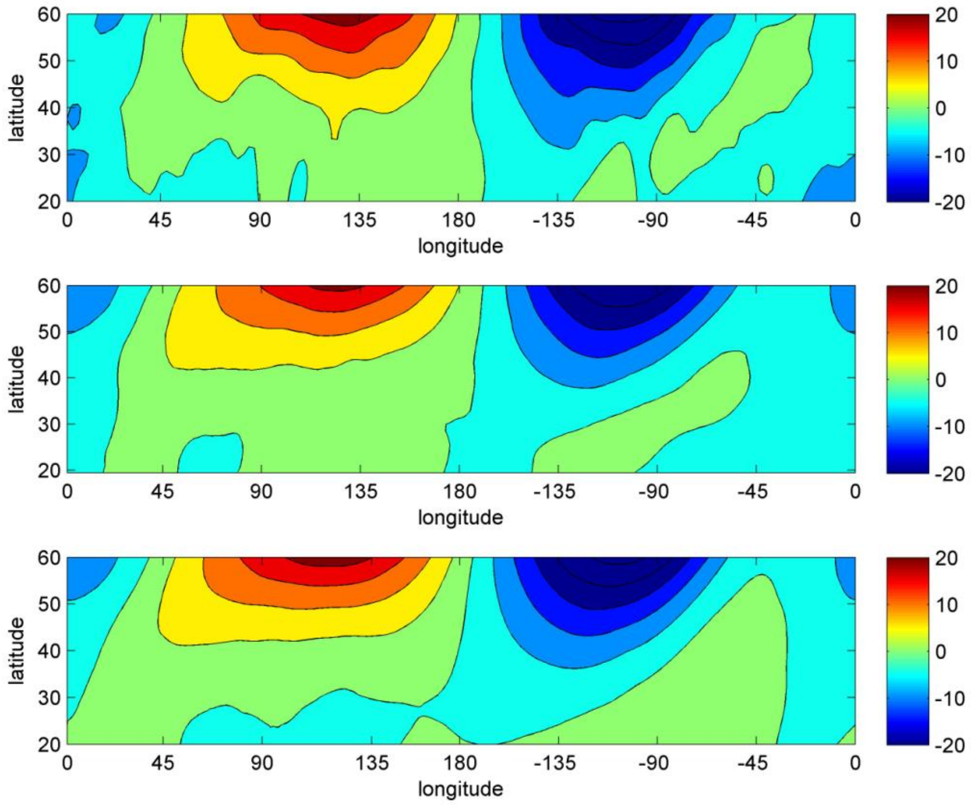

Figure 4 Plot of average meridional wind speed (m/s) component for January, 20-60°N, 180°E-180°W, 10 hPa. Top panel NCEP/NCAR (1958-2012), middle ERA Interim (1979-2012), and bottom MERRA (1979-2012). Positive values (poleward wind - red), negative values (equatorward wind - blue).

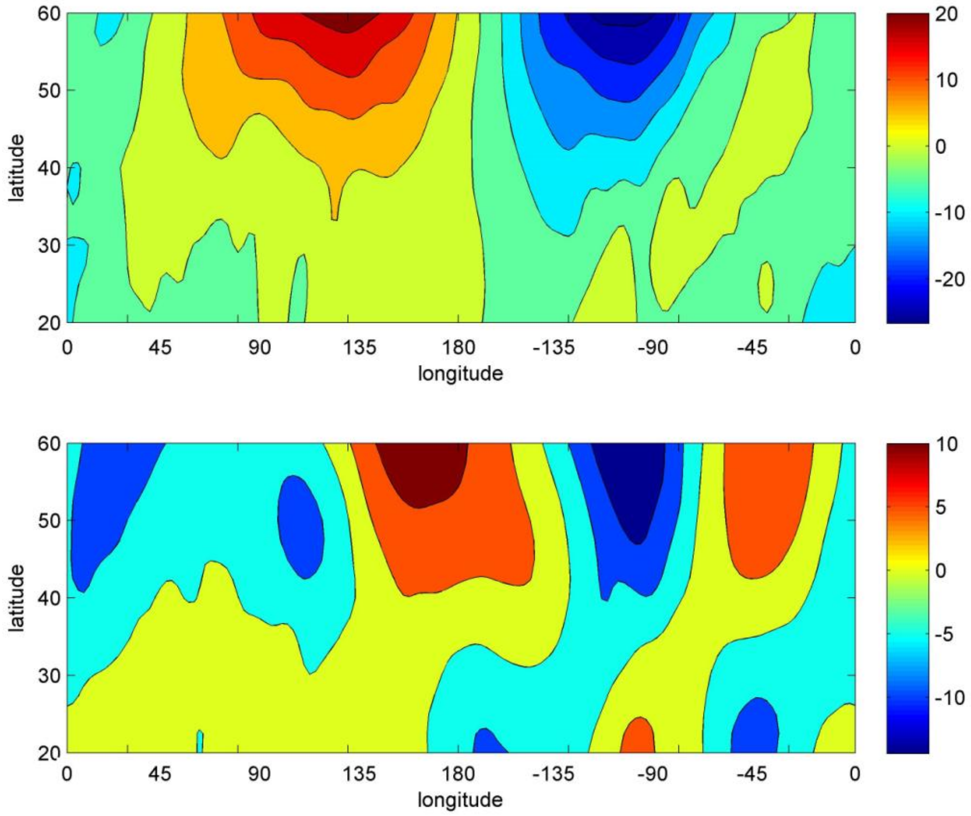

Figure 5: Plot of average meridional wind speed (m/s) component (NCEP/NCAR reanalysis) for January, 1958-2012, 20-60°N, 180°E-180°W. Top panel 10 hPa, bottom 100 hPa. Positive values (poleward wind - red), negative values (equatorward wind - blue).

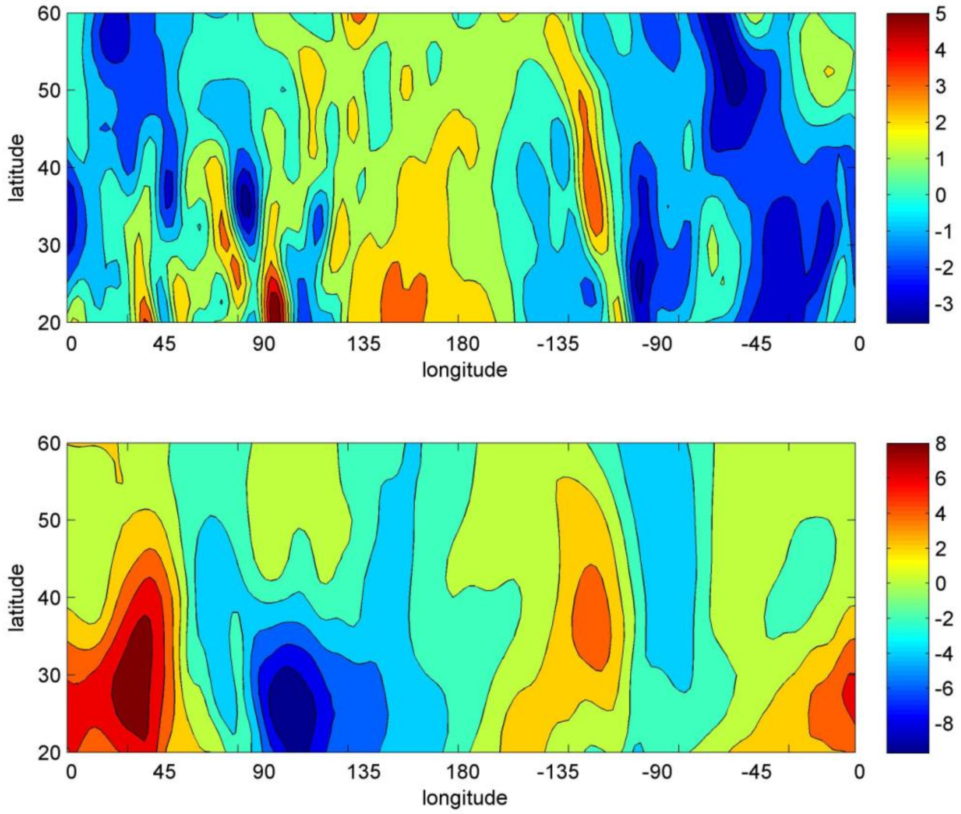

Figure 6: The same as Fig. 5 but for July. Positive values (poleward wind -red), negative values (equatorward wind - blue).

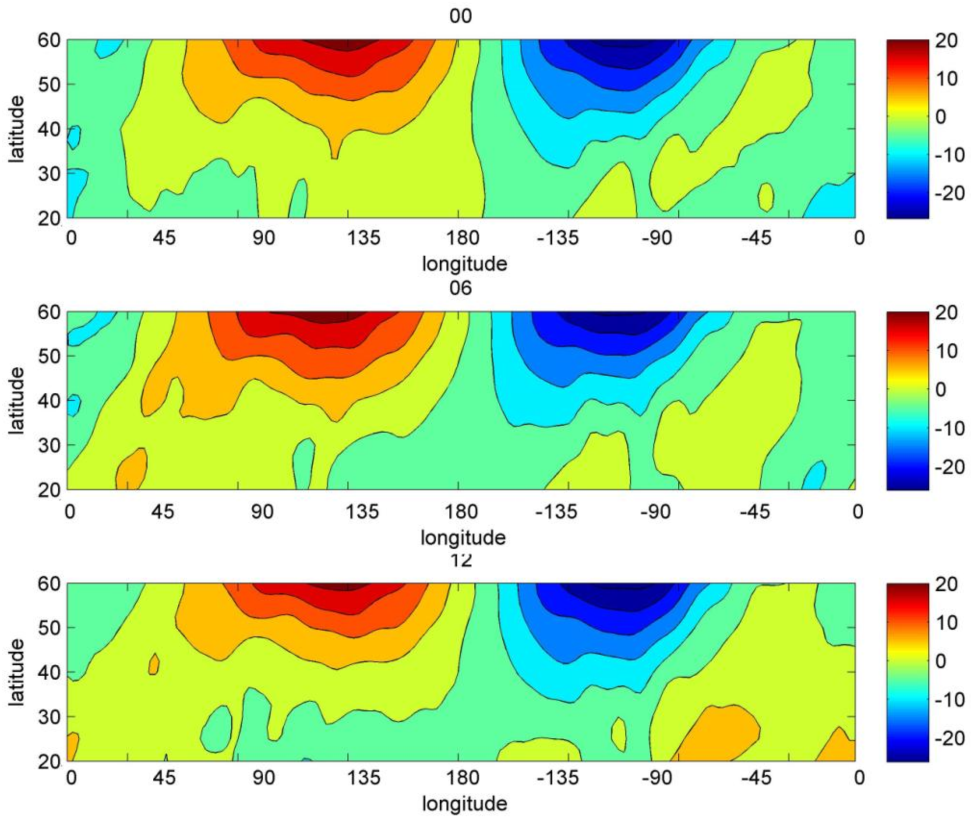

Figure 7: Plot of average meridional wind speed (m/s) component at 10 hPa for January, 1958-2012, 20-60°N, 180°E-180°W. Top panel 00 UTC, middle 06 UTC, and bottom 12 UTC. Positive values (poleward wind - red), negative values (equatorward wind - blue).

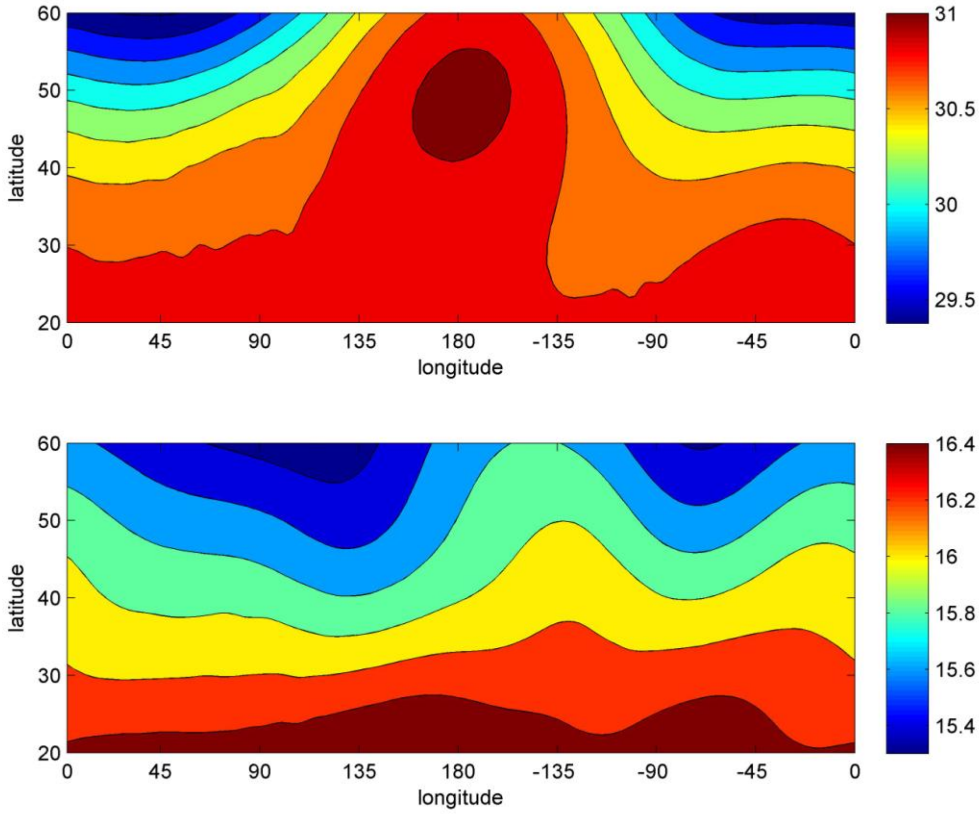

Figure 8: Plot of average geopotential height (km) for January, 1958-2012, 20-60°N, 180°E-180°W. Top panel 10 hPa, bottom 100 hPa.

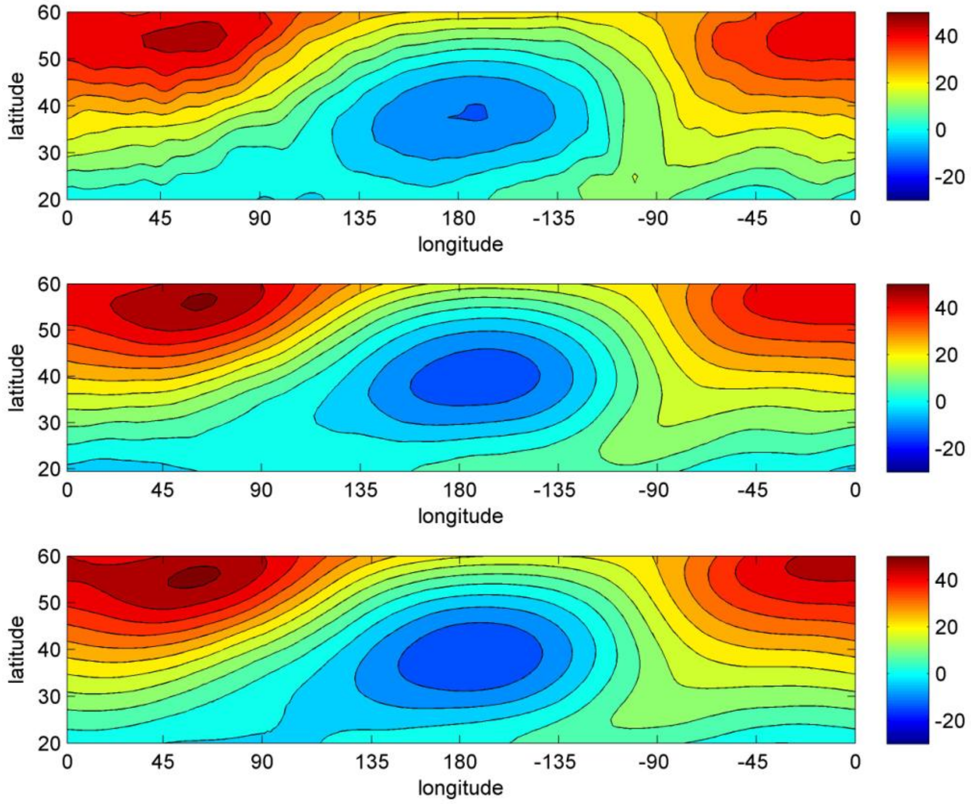

Figure 9 Plot of average zonal wind speed (m/s) component for January, 20-60°N, 180°E-180°W, 10 hPa. Top panel NCEP/NCAR (1958-2012), middle ERA Interim (1979-2012), and bottom MERRA (1979-2012). Positive values (eastward wind - red), negative values (westward wind - blue).