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Comparison of the long-term trends in stratospheric dynamics of four reanalyses

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Abstract. Since the long-term trends of different atmospheric parameters have been already studied separately in many papers, this study is focused on the stratospheric wind (zonal and meridional components) and temperature over the whole globe at 10 hPa during 1979–2015. We present the trends for the whole winter (October–March), for each individual month of winter and separately for the period before and after the ozone trend turnaround during the mid-1990s. The change of ozone trends has a clear impact on trends in other investigated stratospheric parameters. Four reanalyses (MERRA, ERA-Interim, JRA-55 and NCEP-DOE) are used for comparison. Every grid point is analysed, not zonal averages. The comparison of trends in meridional wind, which is closely connected with Brewer–Dobson circulation, shows a good agreement for all four reanalyses (main features and amplitudes of the trends) in terms of winter averages, but there are some differences in individual months, particularly in trend amplitude. These results could be important for studying dynamics (transport) in the whole stratosphere.

Keywords. Meteorology and atmospheric dynamics (climatology general circulation middle atmosphere dynamic)

1 Introduction

Stratospheric temperature and winds and their trends are very important parts of global changes. They can give us an overview of natural or anthropogenic mechanisms in global warming, troposphere–stratosphere coupling and Brewer–Dobson circulation. The temperature in the stratosphere is also important for understanding ozone variability, trends and future changes (WMO, 2006, 2010). Temperature trend analysis is a standard diagnostics tool for evaluating climate models (e.g. Eyring et al., 2006; Garcia et al., 2007).

The major problems in the understanding and validating temperature and wind changes in the stratosphere and lower mesosphere are the uncertainties and homogeneity of observational datasets. The longest observational datasets of temperature from radiosondes cover the period from the late 1950s, but they are usually only up to the 10 hPa. Another problem with the radiosonde and rocketsonde datasets is the limited spatial coverage. Rocketsondes can reach high altitudes but their observations are expensive and irregular basis.

Satellite measurements of the temperature in the higher atmospheric levels like the stratosphere and mesosphere are available for more than 30 years. Thompson et al. (2012) showed that stratospheric measurements from the Stratospheric Sounding Unit (SSU) developed by different groups are inconsistent with their earlier SSU data versions. Zou and Qian (2016) presented well inter-calibrated and merged SSU and advanced microwave sounding unit (AMSU) observations available from the NOAA/STAR group and reported together with Randel et al. (2016) and Seidel et al. (2016) the linear trend during 1979–2015 to be a cooling, which increased with altitude from the lower stratosphere (from ~ -0.1 to -0.2 K decade^{-1}) to the middle and upper stratosphere (from ~ -0.5 to -0.6 K decade^{-1}).

General circulation model simulations are based on the understanding of radiative, dynamical and chemical processes not only in the stratosphere but generally in the whole atmosphere. According to Ramaswamy et al. (2001), the models try to capture the most important links between the stratosphere, the troposphere and the mesosphere. They show us the global pattern of temperature climatology, trends and variations for different periods. As was mentioned above, the analyses of observations are used for verification of each model. The problem with numerical climate models is dif-

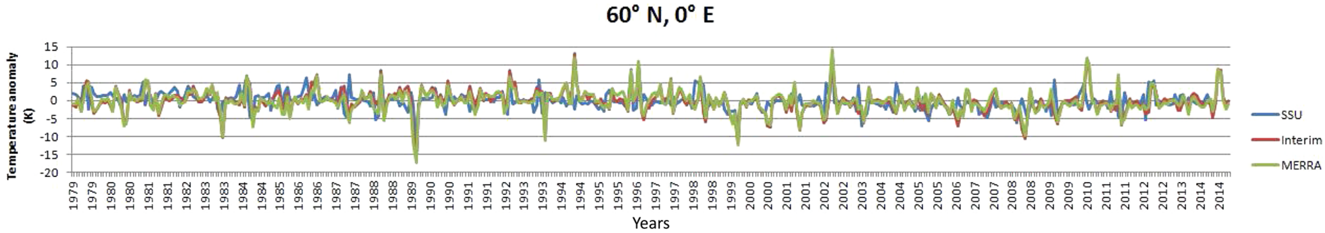

Figure 1. Temperature anomaly time series of MERRA reanalysis (red), ERA-Interim (blue) and SSU (derived by STAR from SSU with AMSU-A, green) for grid point 60° N and 0° E.

ferent parameterizations of processes in the atmosphere. The models reveal cooling in the whole stratosphere.

An analysis of wind behaviour and trends in the stratosphere is even more difficult than temperature analysis because wind observations in the upper stratosphere and lower mesosphere are very scarce and the existing ones are not available on a regular basis. The novel ground-based microwave Doppler wind radiometer (WIRA) is the only instrument that provides wind observations between 35 and 70 km altitudes with satisfying long-term continuity (Rüfenacht et al., 2012, 2014). Direct measurements of zonal and meridional wind are the best way to observe stratospheric dynamics.

Various analyses of changes in the stratospheric wind (e.g. strengthening of polar vortex or variations of the Brewer–Dobson circulation) can be found in many papers (e.g. Shepherd, 2007, 2008; Scaife et al., 2012; Butchart, 2014 or Ray et al., 2014). Changes of the stratospheric wind are connected with temperature and ozone variations. Bari et al. (2013) found longitudinal dependence of residual wind in the stratosphere and the global distribution of ozone and water vapour in the stratosphere and mesosphere for 2001–2006. Kozubek et al. (2015) observed a pronounced longitudinal dependence of stratospheric meridional winds at higher latitudes for 1979–2012.

For our paper we use reanalysis datasets because they cover both hemispheres in regular grid scheme. The advantages of these datasets are that they are available on a daily and monthly basis without any gaps from 1979 until present. The reanalyses cover various time intervals, have different grid resolutions and apply different methods for data assimilation (Courtier et al., 1998; Parish and Derber, 1992). According to Kozubek et al. (2014), Masaki (2008) and Fujiwara et al. (2017), there are some differences between individual reanalyses in the stratosphere as well as between reanalyses and observations, but these differences are not crucial. The problem of jumps in data series might be more severe at higher altitudes because comparison of various reanalyses revealed that the largest differences in global mean temperatures between reanalysis datasets occur above 10 hPa, with many showing large step changes coincident with changes in the global observing system (Maycock et al., 2016). Coy et al. (2016) found good agreement between observations from Singapore and the MERRA reanalysis. Utilization of more reanalyses can show us if the major structures in trend analyses are comparable or if they differ from each other, i.e. reliability of obtained trends.

We focus on the longitudinal distribution of temperature or wind characteristics. The longitudinal distribution of trends is important because the behaviour of various parameters can be different in different sectors (e.g. Atlantic sector, Pacific sector). The majority of temperature or wind trend analyses are focused on the zonal averages of analysed parameters, but we lose information about the longitudinal distribution using zonal averages. We mainly analyse trends in meridional winds and their differences in different months or periods, which might be important for understanding the behaviour and evolution of Brewer–Dobson circulation. Kozubek et al. (2015) showed differences between meridional wind trends in the different sectors of the Northern Hemisphere at 10 and 100 hPa at 20–60° N. Here we extended the analysis to the whole globe.

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

2 Data and methods

We used four reanalyses for comparison. ERA-Interim (European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim; for which a detailed description can be found in Dee et al., 2011), MERRA (Modern Era Retrospective-analysis for Research and Applications; details in Reichle, 2012), NCEP/DOE (NCEP-DOE Reanalysis 2; details in Kanamitsu et al., 2002) and JRA-55 (Japanese 55-year Reanalysis; details in Kobayashi et al., 2015). All these reanalyses are available for the period from 1979 until present, but we only analysed the 1979–2015 period in our study. For NCEP/DOE, we used 2.5° × 2.5° grid resolution and for the rest we used higher resolution 1.25° × 1.25°.

We compared temperature anomaly time series of the reanalyses MERRA and ERA-Interim with well-intercalibrated and merged SSU and AMSU observations (Ver-

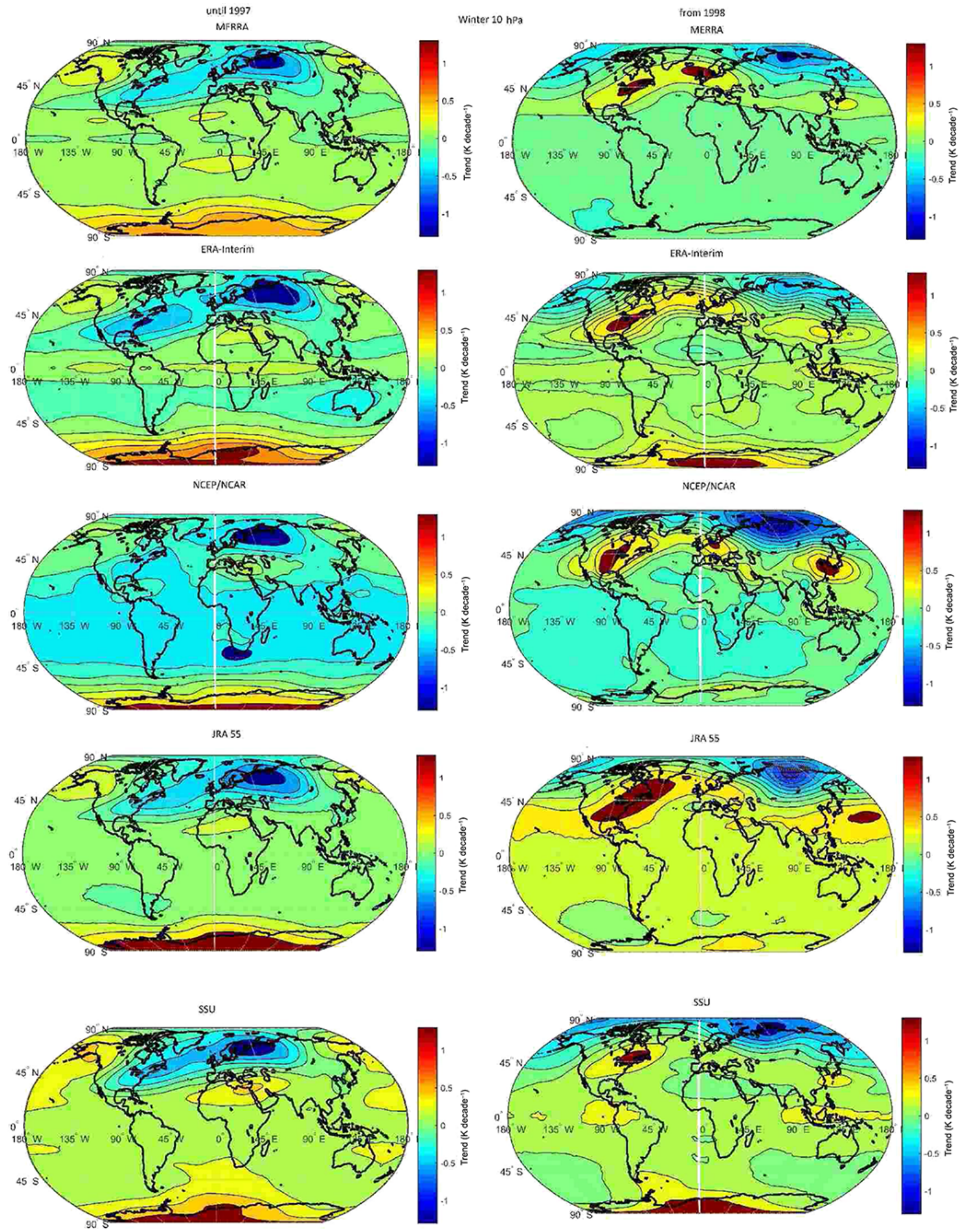

Figure 2. Temperature trends (K decade^{-1}) for the winter season (October–March) at 10 hPa from MERRA, ERA-Interim, NCEP/NCAR, JRA-55 reanalyses and SSU channel 1 (top to bottom). Left panels show 1979–1997, right panels show 1998–2015 and statistical significance (95 %) is highlighted by white dots.

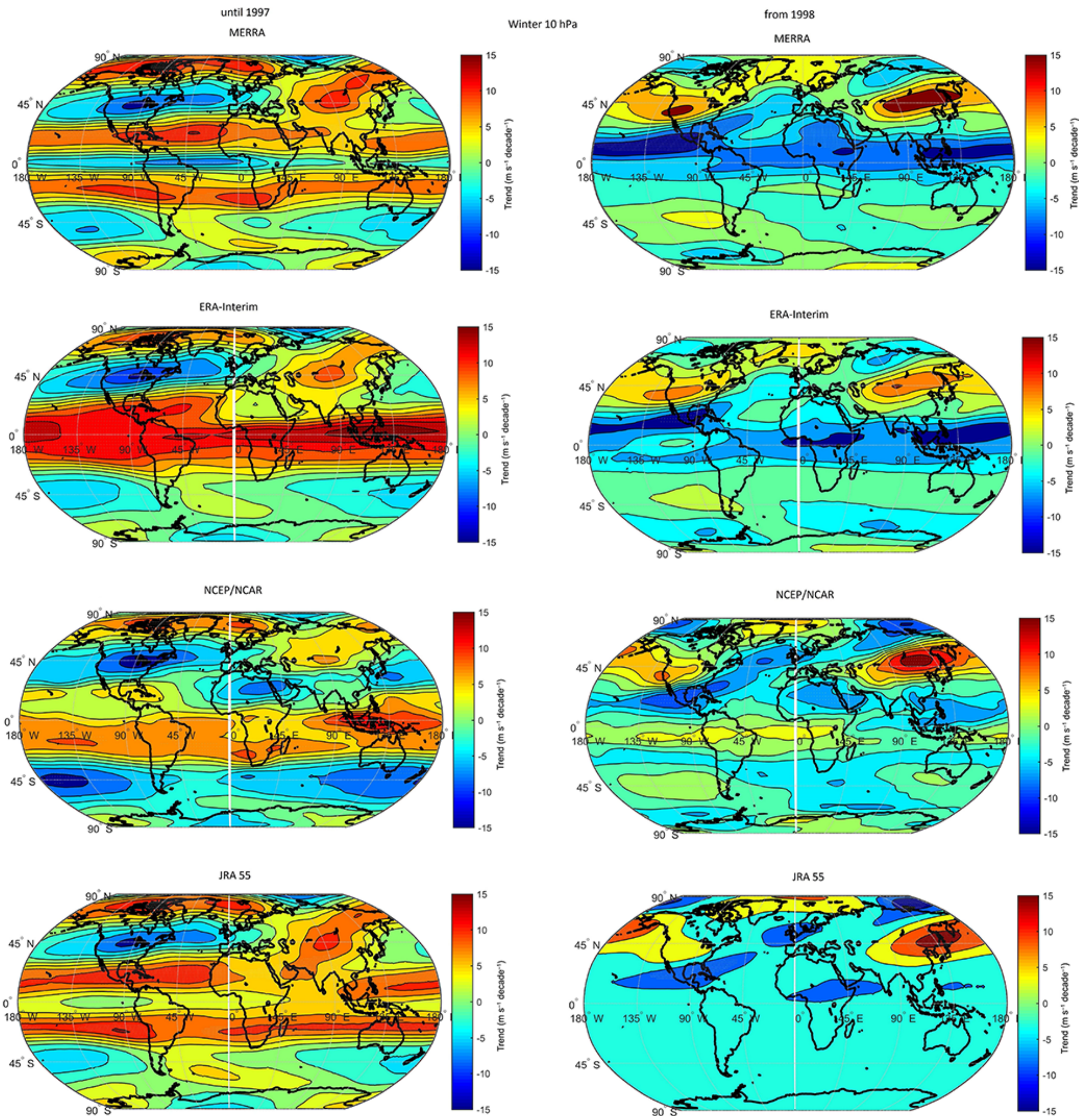

Figure 3. Zonal wind trends (m s^{-1} $decade^{-1}$) for the winter season (October–March) at 10 hPa from MERRA, ERA-Interim, NCEP/NCAR and JRA-55 reanalyses (top-to-bottom). Left panels show 1979–1997, right panels show 1998–2015 and statistical significance (95 %) is highlighted by white crosses.

sion 3) available from the NOAA/STAR group, presented by Zou and Qian (2016) for 10 well-spread grid points in the middle latitudes (40–60° N). Simple grid point time series provide more information than global or zonal means because as we pointed out above, we can lose important information from zonal averaging. The comparison of these temperature anomaly time series shows that the agreement of SSU 1 (channel 1, derived from merging SSU and AMSU-A) and reanalyses at 10 hPa is good. An example is shown in Fig. 1, which shows the temperature time series anomaly for grid point 0° E, 60° N, at 10 hPa.

The period 1979–2015 is divided into two sub-periods, 1979–1997 and 1998–2015, to investigate connection of the changes of different parameter trends with total ozone turnaround in northern middle latitudes (Harris et al., 2008). We also checked the sensitivity of trends to the selection of break point year, and the results show that the differences are insignificant (less than 0.5 m s^{-1} $decade^{-1}$). We calculate linear trends for winter months (October–March) of each sub-period at several pressure levels and their statistical significance (95 %) using the standard linear regression MATLAB routine. Then we focus on the trend separately for each month from November until February at 10 hPa because we

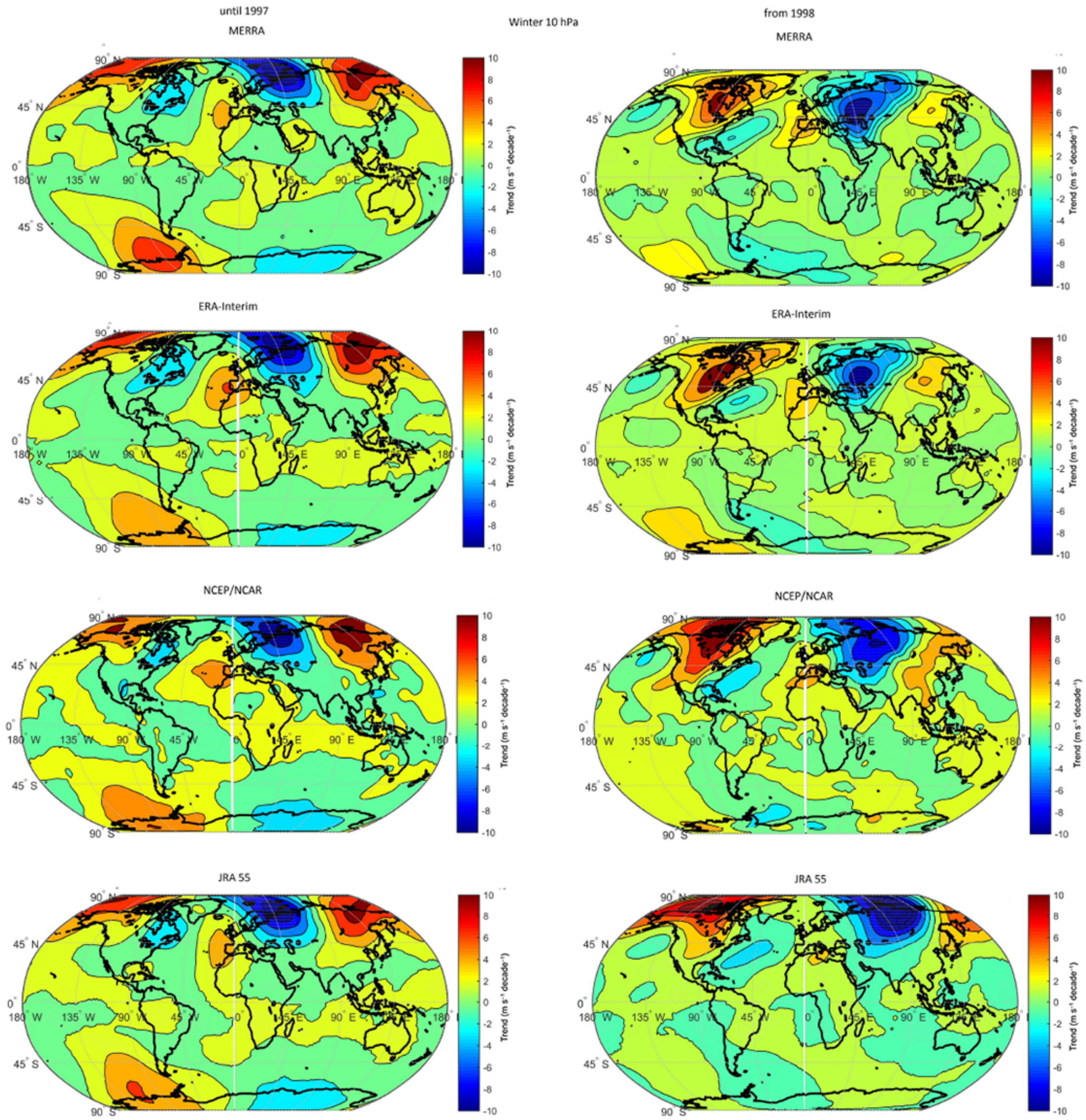

Figure 4. The same as Fig. 3 but for meridional wind trends ($m\,s^{-1}$ decade^{-1}).

can compare all four reanalyses in this pressure level. This level also represents the stratospheric conditions well (e.g. dynamics). For this pressure level we also compute the differences between each month for the month-to-month development and differences between two sub-periods for every month.

The results for temperature (T), zonal (u) and meridional (v) wind are compared for all four reanalyses.

3 Results

Let us begin with trends at 10 hPa. Figures 2–4 show the trends in temperature, zonal and meridional wind, respectively, at 10 hPa for all four reanalyses and SSU channel 1

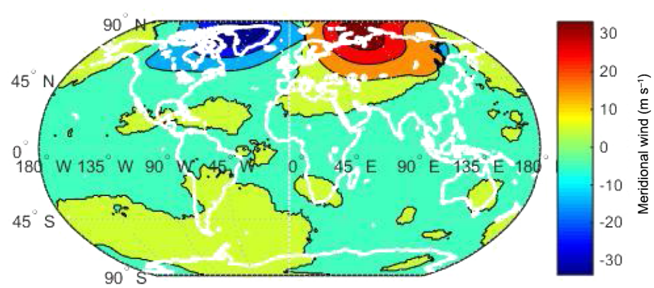

Figure 5. Meridional wind ($m\,s^{-1}$) climatology for January from 1998 to 2015 in the MERRA reanalysis.

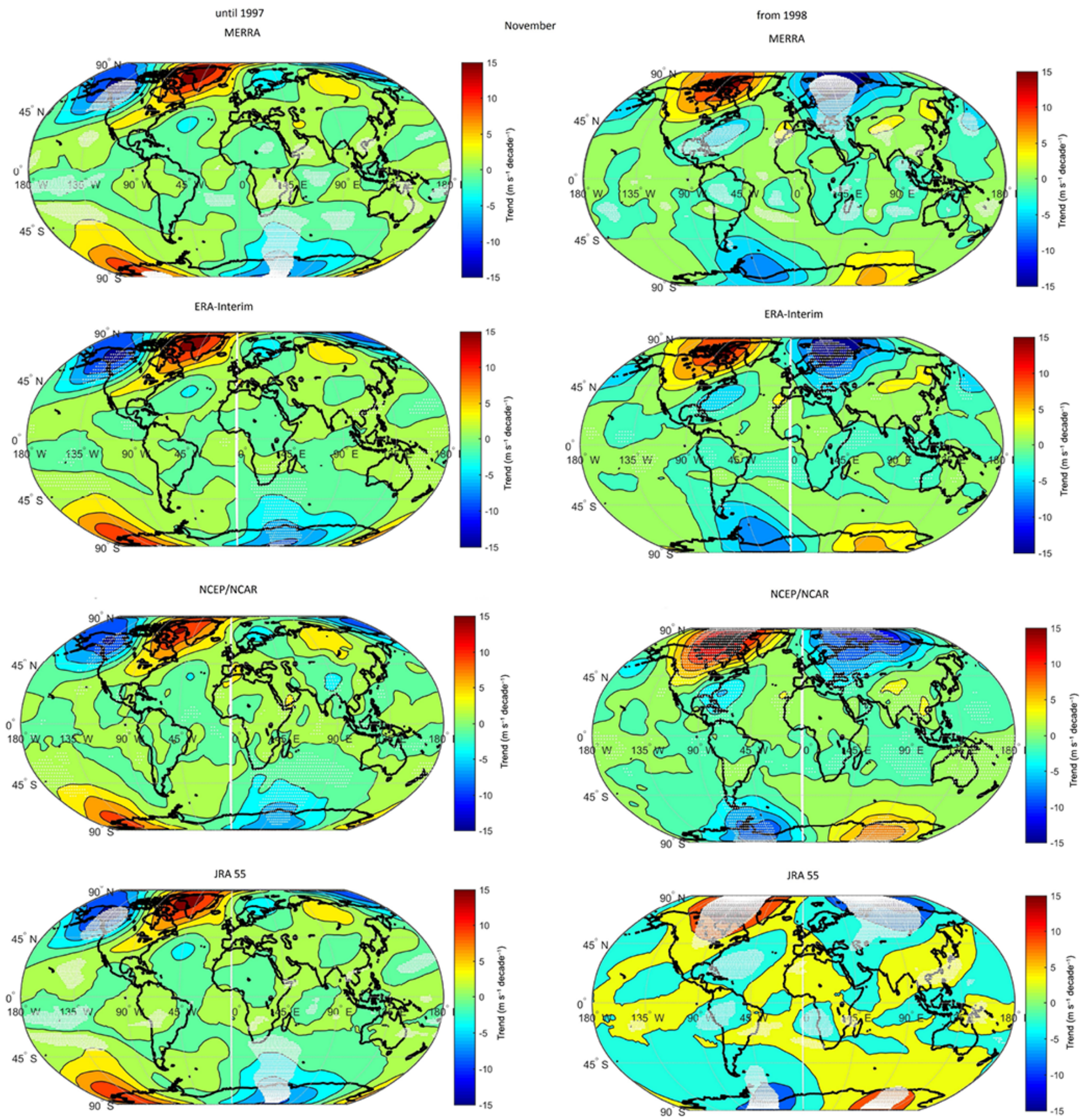

Figure 6. Meridional wind trends (m s^{-1} $decade^{-1}$) for November at 10 hPa from MERRA, ERA-Interim, NCEP/DOE and JRA-55 reanalyses. Left panels show 1979–1997 and right panels show 1998–2015. Statistical significance (95 %) is highlighted by white crosses.

(temperature only) over the whole winter (October–March) for the two periods 1979–1997 and 1998–2015.

Figure 2 shows the trend in temperature. The statistical significance (95 %) is highlighted by the white dots. Generally we observe a good agreement in terms of the signature of trends for all four reanalyses and SSU, but the magnitudes are somewhat different. The results show mainly negative trends up to -1.2 K $decade^{-1}$ in the first period, especially in the middle and higher latitudes of the Northern Hemisphere. NCEP/DOE displays more negative trends at low latitudes than other reanalyses and SSU. In the second period there are predominantly positive trends up to 0.4 K $decade^{-1}$ in the middle and higher latitudes. The main features are similar, except for MERRA and ERA-Interim, where the negative trend core over the Eurasian continent is weaker than for the other two reanalyses, SSU being between these two groups. Substantial longitudinal differences in temperature trends occur at northern higher latitudes.

Figure 3 shows the same as Fig. 2, except for SSU (no wind data), but for zonal wind trends. NCEP/DOE, JRA-55 and MERRA show similar features (distribution, local areas of positive or negative trends) on the Northern Hemisphere and over the Equator in the first period. However, results for ERA-Interim show a strong positive significant trend up to 15 m s^{-1} $decade^{-1}$ in the equatorial region, which is not observed in the other reanalyses. The results for the second pe-

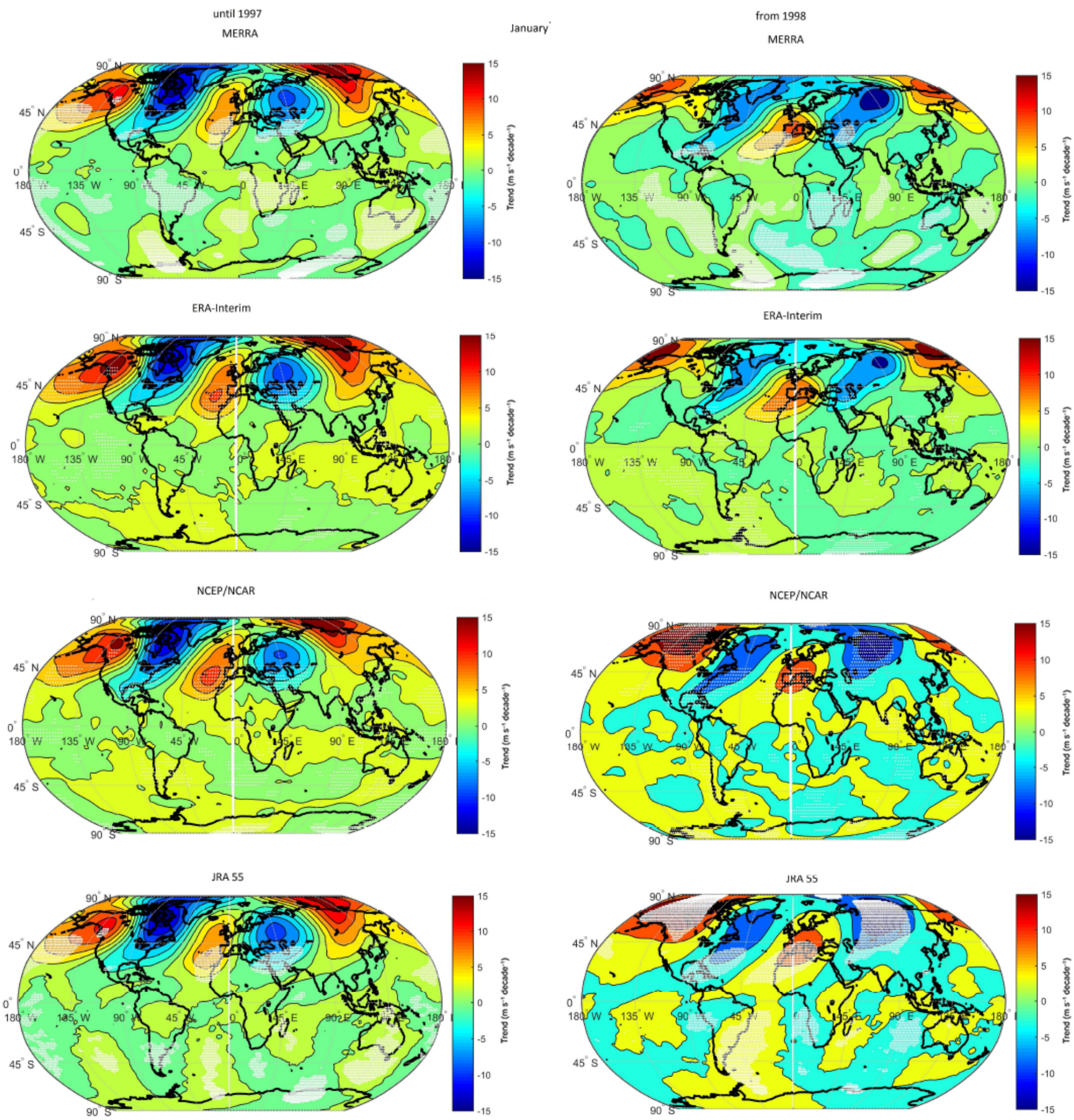

Figure 7. The same as Fig. 6 but for December. Statistical significance (95 %) is highlighted by white crosses.

riod are similar for all four reanalyses, with mostly negative trends up to $-10\,\mathrm{m\,s^{-1}}$ decade^{-1}. The second period shows one positive trend core over China and another one over the northern USA and related part of Pacific Ocean, which have different magnitudes for different reanalyses.

Figure 4 shows the meridional wind trends. The results are very similar in main features for both periods and all four reanalyses. We have to be careful with interpretation of the results because the climatology of meridional wind shows that we have core sectors with northward wind and southward wind (Kozubek et al., 2015). We can say that there is a positive trend in the northward wind sector and a significant negative trend in the southward wind sector during the second period (1997–2015), meaning a strengthening of the meridional wind for both sectors. In the first period, the situation is not clear because the position of negative and positive trend cores is not consistent with the position of climatological wind cores. The climatology of meridional wind for 1979–2015 is shown in Fig. 5.

The next four figures (Figs. 6–9) show the meridional wind trend ($\mathrm{m\,s^{-1}}$ decade^{-1}) for individual months (November–February) of all four reanalyses (ERA-Interim, JRA-55, MERRA and NCEP/DOE) at 10 hPa. We can say that the major features are very similar for all four reanalyses. Differences can be found in the amplitude of trend in different months. These differences are up to $1\,\mathrm{m\,s^{-1}}$ decade^{-1}. There are no regular structures of trends in the middle and higher latitudes during the first period for November, De-

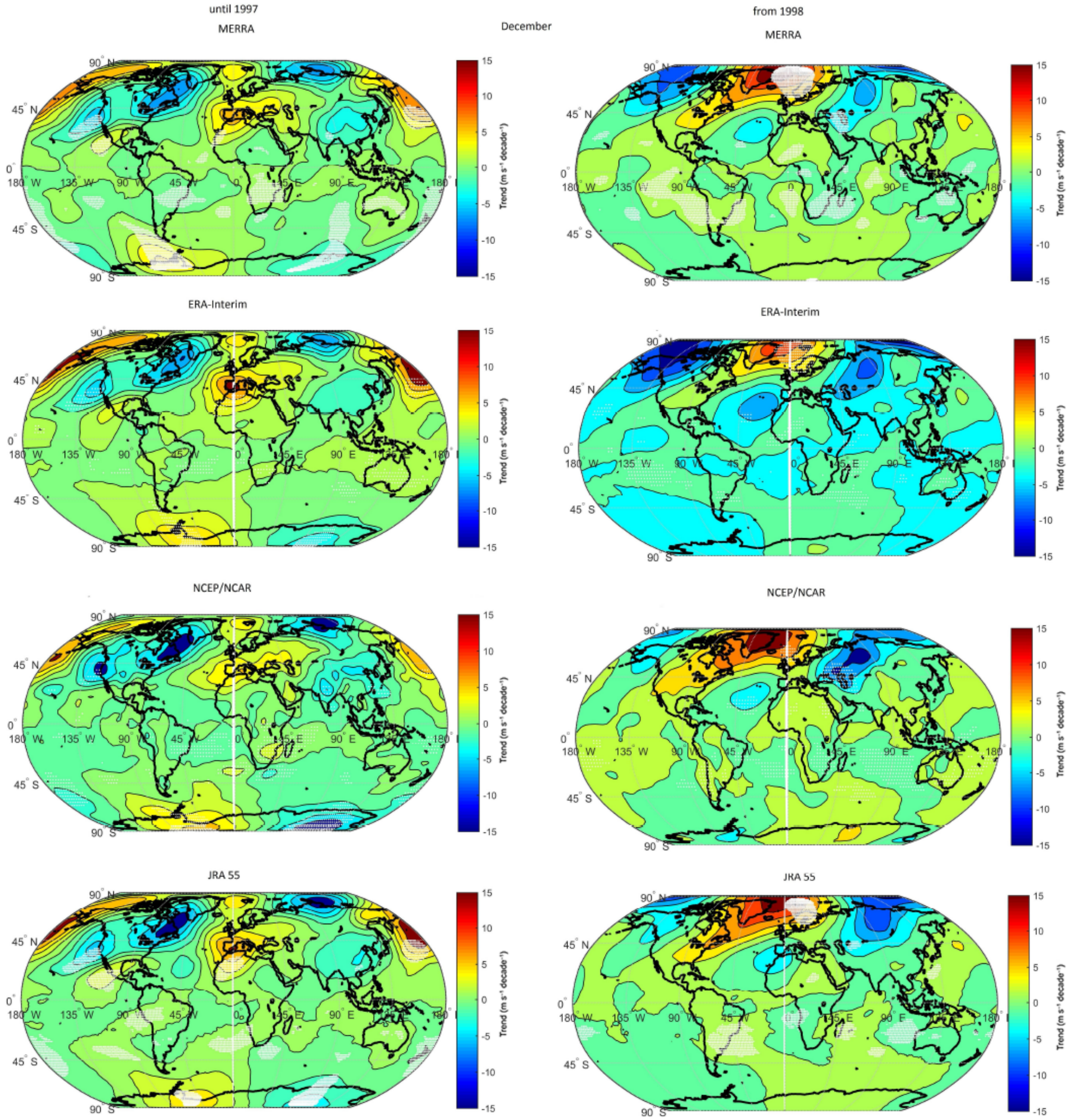

Figure 8. The same as Fig. 6 but for January. Statistical significance (95 %) is highlighted by white crosses.

cember and January. We can identify several random cores of negative or positive trends in the analysed area. JRA-55 and NCEP/NCAR display slightly more negative trends than MERRA and ERA-Interim overall. In February we observe a well-developed two-core structure that disappears in early spring (April; not shown here). The second period shows two cores for November and December, one with a significant negative trend and the other with a significant positive trend. However, as mentioned above, this means that the wind is stronger in both trend cores due to climatology. Moreover, in December we can see the change of trend from negative to positive between two periods over the Atlantic (this change is not observed in the climatology; see Kozubek et al., 2015).

The February results again show the two cores. We can identify these two cores in both periods, unlike in November–January, when we can only see them in the second period. The position is very similar in both periods. The trends are mainly significant in the second period (e.g. November for all reanalyses, January for JRA-55 and NCEP). We can observe strong insignificant trends at the 95 % level at higher latitudes. The meridional wind varies there remarkably from year to year, and this strong variability reduces the statistical significance of the observed trends.

Figure 10 shows the differences between 2 months (November and December, December and January, January and February, and finally November and February) for

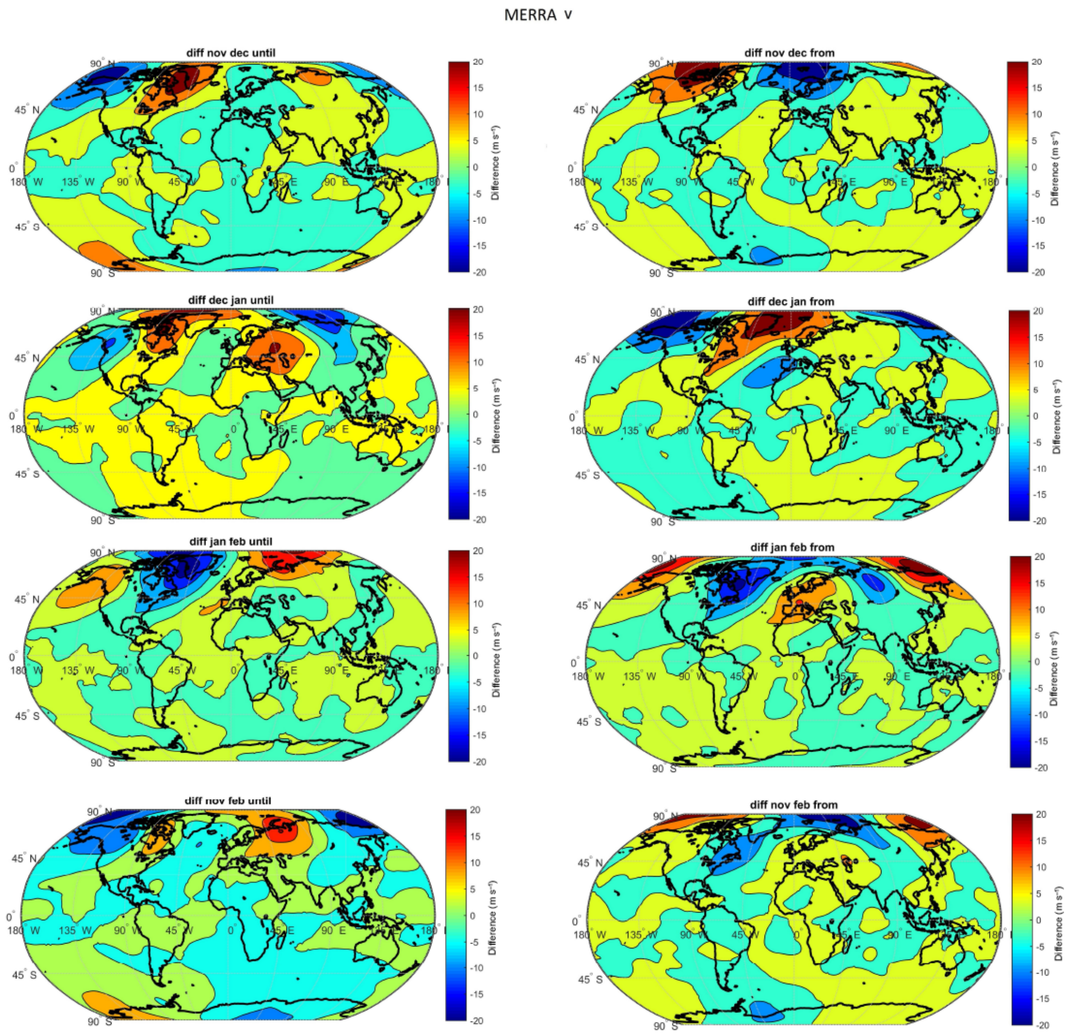

Figure 9. The same as Fig. 6 but for February. Statistical significance (95 %) is highlighted by white crosses.

MERRA reanalysis. From this figure we can see the amplitude of month-to-month variability. First there are almost no differences between two periods. This means that even if the trends can change from positive to negative and vice versa, the amplitude of month-to-month variability is largely the same. We observe big negative differences between January and February trends in both periods over the North Atlantic. This means that in February we generally identify stronger trends than in January. Conversely, we generally see weaker trends in January than in December. The differences between trends in November and February are smaller. There are generally small differences between trends at low latitudes.

Figure 11 shows the differences between two periods (before and after 1995) for each month of MERRA reanalysis. We see different behaviour for different months. Stronger trends are observed in the second period over North America and Canada for all months. Conversely, in January and February we can see positive differences (stronger trends in the first period) over Siberia.

The behaviour of other parameters (temperature and zonal wind) are shown in Figs. 12 and 13. We choose only MERRA reanalysis because the remaining three reanalyses (and also SSU data for temperature) reveal a very good agreement with MERRA results. For temperature (Fig. 12), in November we can observe a negative trend core of up to $-0.8\,\mathrm{K\,decade^{-1}}$ over the North American continent and a positive trend core of up to $0.6\,\mathrm{K\,decade^{-1}}$ over Russia in the first period. In the second period the trend cores reverse their signs. In December we do not observe the same change of trends as in November. There are negative trends over the Atlantic and a positive trend over the Aleutian Islands in the first period, but in the second period we see mainly negative trends. The biggest temperature trend change is observed between December and January in the second period. There are mainly positive trends of up to $0.6\,\mathrm{K\,decade^{-1}}$ over the middle and higher latitudes of the Northern Hemisphere in January, but as mentioned above, there are mainly negative trends over the whole analysed area in December.

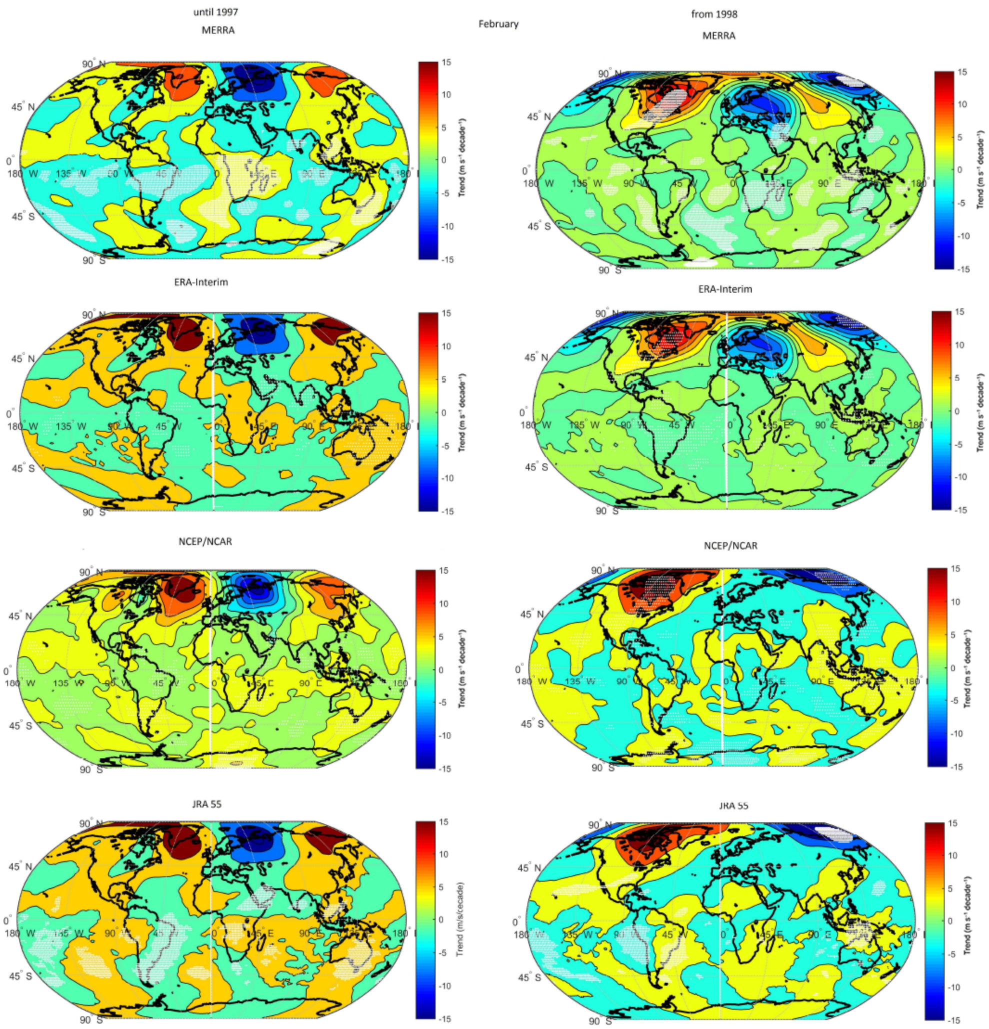

Figure 10. The difference between meridional wind trends for 2 consequent months (top to bottom: differences between November and December, differences between December and January, differences between January and February, differences between November and February) from the MERRA reanalysis at 10 hPa. Left panels show 1979–1997 and right panels show 1998–2015.

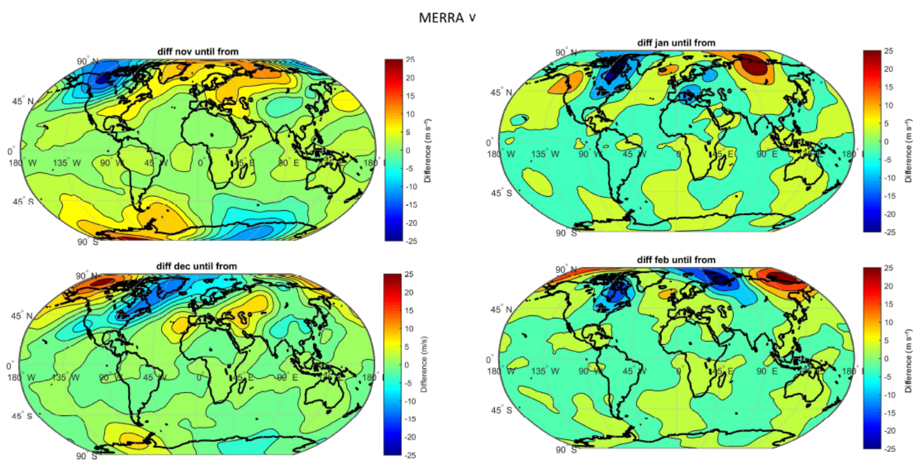

Figure 11. The difference between two periods (1979–1997 and 1998–2015) of meridional wind trends for 2 different months (difference between the first period and the second one: November – left upper panel, December – left bottom panel, January – right upper panel, February – right bottom panel) from the MERRA reanalysis at 10 hPa.

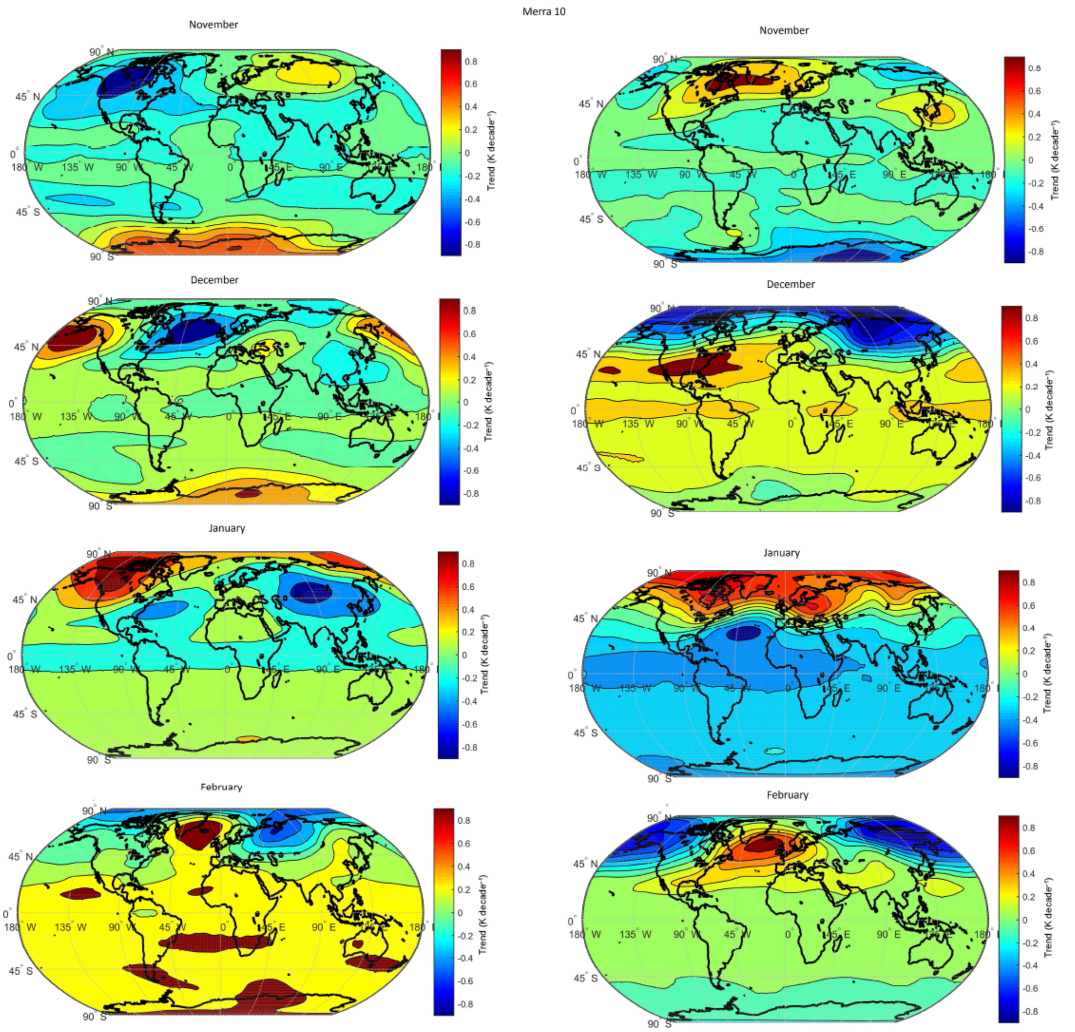

Figure 12. Temperature trends (K decade^{-1}) for different months (November, December, January and February) at 10 hPa from the MERRA reanalysis. Left panels show 1979–1997 and right panels show 1998–2015. Statistical significance (95 %) is highlighted by white dots.

Figure 13 shows the same as Fig. 12 but for zonal wind trends. We did not observe a regular structure except for a zonal structure over the equatorial region in some months (November, December or February in the first period). The trends are generally stronger (up to 15 m s^{-1} decade^{-1}) than trends for meridional wind (up to 10 m s^{-1} decade^{-1}). However, this might be a consequence of generally stronger zonal rather than meridional wind.

4 Discussion and conclusion

In this study we compare global long-term trends derived separately from four reanalyses using three parameters (temperature, zonal or meridional wind) at 10 hPa. These parameters are very important for describing the stratospheric dynamics. The reanalyses are not perfect for studying long-term trends due to possible jumps in data series, but we have compared time series at several grid points at 10 hPa with SSU satellite observations of temperature and this shows good agreement (e.g. Fig. 1). Furthermore, SSU-derived trends are well within reanalysis trends (Fig. 2). The biggest advantage of reanalyses is that we have long time series without gaps, which cover the whole globe. Of course we have to be careful, especially in the Southern Hemisphere, where not enough observations exist, or at the equatorial latitudes where reanalyses do not represent the quasi-biennial oscillation (QBO) well. Usually only climatology is used for comparison. However, the trend analysis is also important to see the changes of different parameters or to predict their future behaviour. The whole period of 1979–2015 is divided into two sub-periods, 1979–1997 and 1998–2015, to see the impact of turnround of ozone trends at northern mid-latitudes on trends in temperature and wind. We also checked the trend for the break point year 1995 and the differences are insignif-

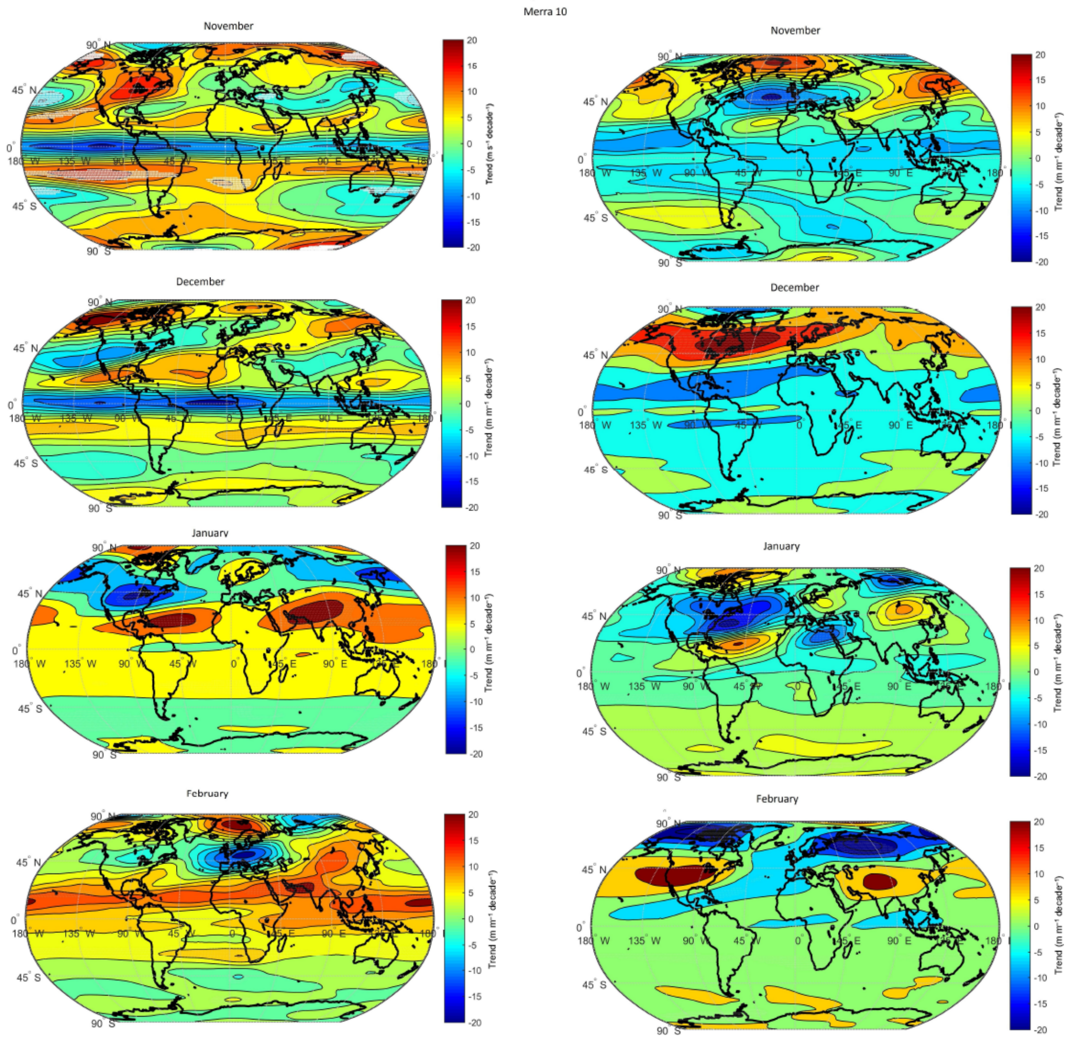

Figure 13. The same as Fig. 12 but for zonal wind trends.

icant. For every sub-period, 18 years may be regarded as a very short time series, but because of a lack of available observations or reanalysis datasets, it is not possible to use longer periods. The analysis of every grid point without zonal averaging gives us the opportunity to see the geographical–longitudinal distribution of trends.

If we compare the results for the whole winter (October–March), we find good agreement of all four reanalyses and SSU in terms of main features or amplitudes of trends at 10 hPa. This is probably caused by the averaging through the half of the year that smoothed out the differences in individual months. The changes of trend in the mid-1990s confirm the connection between the observed changes of total ozone and changes of analysed parameters. Monthly analysis shows that agreement of the main features is also good, but there are some differences in amplitude for different reanalyses. We observe month-to-month evolution of meridional wind trends during the winter months shown in Fig. 10. The results show differences between different months, especially in January and February. This could be caused mainly by the occurrence of major SSW (sudden stratospheric warming) in January and February, which affects dynamics (trends) of analysed parameters especially at 10 hPa.

The web page http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/northpole/index.html and Labitzke and Naujokat (2000) show the occurrence of SSW from 1951 to 2013. They confirm that major SSW occurs mainly in January and February but with irregular distribution. The obtained trends might also be affected by the analysed sub-period length, which might be rather short for getting reliable trends in individual months (contrary to the whole winter due to a different number of data). Computing trends for each month with and without SSW years shows us different behaviour (as we can see in Fig. 14 for meridional wind trends in February), but because we have only seven or eight values for each period, the trends or statistical significance could be strongly

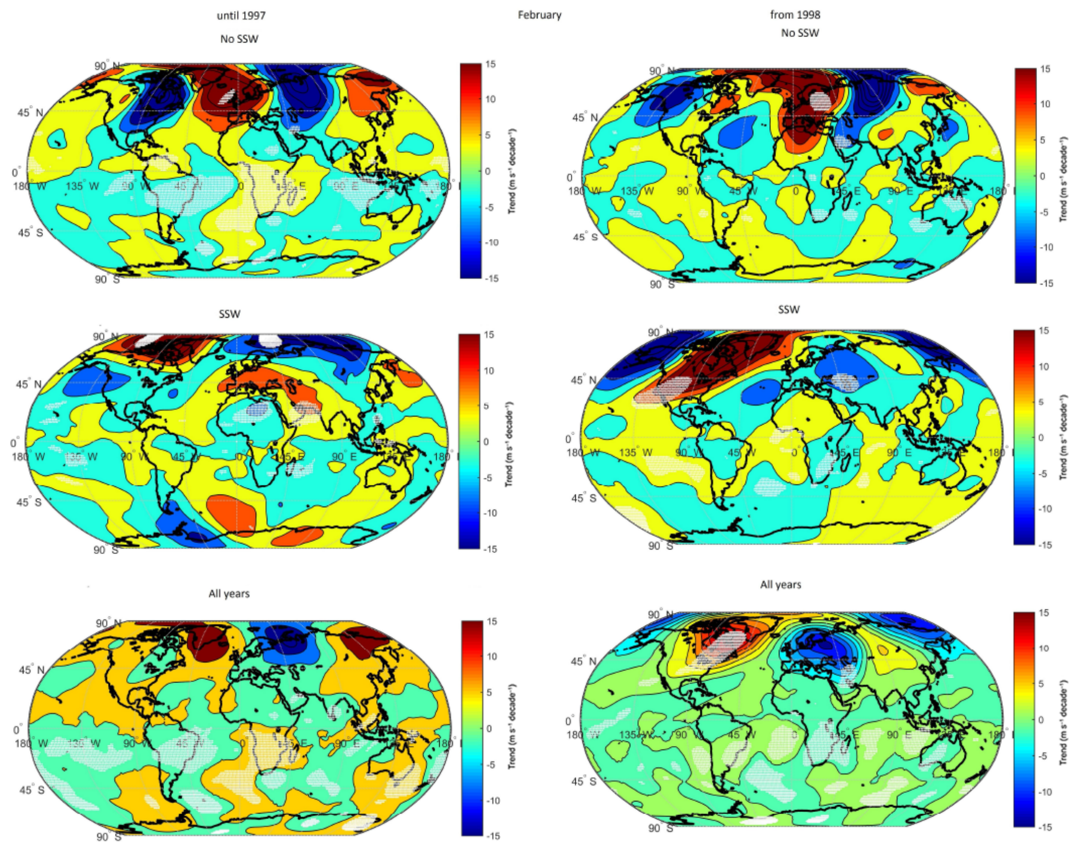

Figure 14. Meridional wind trends (m s^{-1} decade^{-1}) for February for years without SSW (top panels), years with SSW (middle panels) and all years (bottom panels) at 10 hPa from the MERRA reanalysis. Left panels show 1979–1997 and right panels show 1998–2015. Statistical significance (95 %) is highlighted by white dots.

affected. The obtained trends reveal regionally different impacts of SSW on trends, but on average the trends in meridional wind appear to be somewhat stronger and more negative in the years without SSW. From lidar measurements at Haute Provence Observatory (southeastern France), Angot et al. (2012) showed for temperature at about 40 km that temperature trends for years without SSW are more negative than trends for all years, and trends for SSW years are slightly positive, which indicates that temperature effect is detectable. Trend analysis of meridional wind for every grid point also identifies core structure, which occurs in most months. This feature points to the problem with using zonal averages for this kind of analysis.

In general, the results show that trend behaviour is similar for all four reanalyses (even though the results from Rienecker et al., 2011 show that MERRA is not intended for estimating trends on timescales longer than 5 or 10 years) but the differences between some months are especially large in some areas. This can be seen mainly between December and January or February, when SSW usually occurs, and can change the circulation of the stratosphere. The climatology of the meridional wind shows a well-developed longitudinal two-core structure at 10 hPa (Kozubek et al., 2015), but the trend behaviour usually does not copy this feature because the trends can be affected by more phenomenons (SSW, NAO, ENSO, changes of chemistry, etc.). Conversely, we can see that the change of the trends (in most cases) between the two periods follows the change of total ozone trend, which confirms the connection between meridional wind and ozone trends via the Brewer–Dobson circulation. Moreover, we can observe the strengthening of meridional wind (in most cases), which is in agreement with the strengthening of the Brewer–Dobson circulation mentioned in previous studies (Butchart, 2014). Abalos et al. (2015) derived acceleration of the tropical upwelling and global Brewer–Dobson circulation over the period 1979–2012 based on three different reanalyses, which provided similar results. This finding suggests an average acceleration of meridional circulation, which coincides with Fig. 4, where the areas of positive trends in the meridional circulation evidently prevail over areas of negative trends. We can also observe only limited areas of significant trends at the 95 % level in spite of strong trends. This could be caused by strong year-to-year variability of winds (in temperature trend we can identify more significant areas). It could also be affected by the problem with the top of the reanalysis layers. If we analyse the top reanalysis layer (NCEP/DOE), it could be affected by boundary conditions or by using extrapolation.

The analysis of temperature trends shows the core structure, especially in the first period. The problem of big change in temperature trend between December and January in the second period is probably caused by the occurrence of SSW in middle and higher latitudes, as was mentioned above. Wang et al. (2012) derived long-term trends of stratospheric temperature from SSU (Stratospheric Sounding Unit) measurements. They found that zonally averaged trends are strongest at low latitudes and weakest at high latitudes. This is generally consistent with Figs. 2 and 10 where after zonal averaging the strongest trends are observed in low-to-equatorial latitudes due to their spatial homogeneity. Conversely, stronger local trends at high latitudes roughly cancel each other out and result in a weak average trend. In general, the results agree with Randel et al. (2015, 2016), who analysed combined SSU and SABER stratospheric temperatures, and Seidel et al. (2016), who analysed stratospheric temperatures from various satellites. They both found stratospheric temperatures to reveal a negative trend (about -0.8 K decade^{-1}) from 1979 to the mid-1990s, which then changed to much smaller but still negative trends (about -0.2 K decade^{-1}). This trend change coincides with the northern mid-latitude ozone trend turnaround. Our results also reveal differences in temperature trends before and after the mid-1990s.

One relatively weak point of our analyses could be the fact that the significant area at the 95 % level is small. The reason is mainly the short time series of measurements with respect to high natural variability, particularly at higher latitudes. However, a longer dataset is not available and we are unable to separate the part caused by various interrelated meteorological processes from the observed variability, which would reduce the variability and increase the statistical significance of trend results. Therefore, we tried to look at statistical significance at the 90 % level. Figure 15 shows an example of the comparison of statistical significance of results at the 90 and 95 % levels. It is evident that the area of trends significant at the 90 % level is much larger, it covers about 50 % of the globe. The high latitudes above ~70° N, where the year-to-year variability is very high due to the occurrence of major SSWs, shows the biggest problem of our study. Nevertheless, all cores of strong trends are significant at the 90 % level; thus, we can consider the main features of trend distribution to be reasonably reliable.

We can summarize the results as follows:

1. The whole winter trend analysis for stratospheric meridional and zonal winds and temperature shows good agreement among all four reanalyses (MERRA, ERA-Interim, NCEP/DOE, JRA-55) in main features as well as for amplitudes of the trends. Temperature trends derived from SSU data agree with reanalysis-based trends.

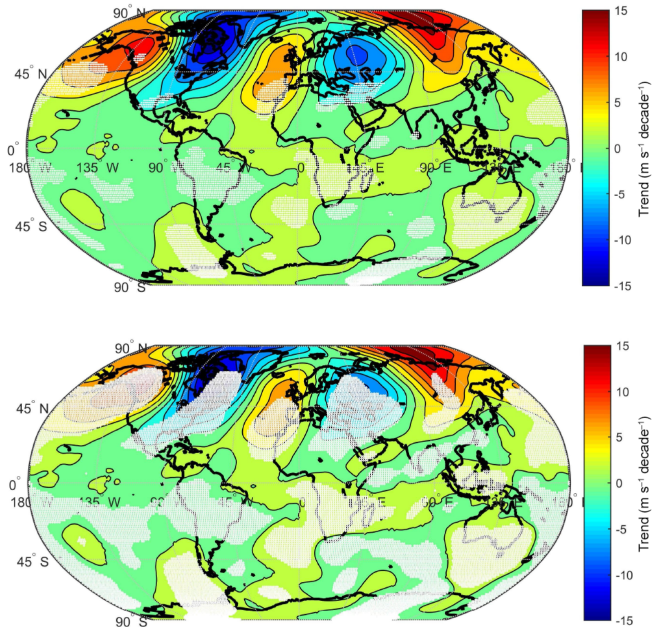

Figure 15. Meridional wind trends (m s^{-1} decade^{-1}) for January at 10 hPa from MERRA reanalysis for 1979–1997. Statistical significance (95 %) is highlighted by white crosses on the top panel and significance (90 %) on the bottom panel.

2. The change of the trends (in most cases) between two periods (before and after the mid-1990s) coincides with the change of total ozone trend in the mid-1990s, which is in line with the connection between meridional wind and ozone via Brewer–Dobson circulation.

3. There is quite a good agreement in trends in meridional wind among all four reanalyses for individual months in the main features but amplitude differences can reach up to 1 m s^{-1}.

4. There are substantial differences in trends between different months (especially December and January), partly due to the occurrence of major SSWs in January and February, which has a big effect on the stratospheric dynamics and its trends.

The next step of these investigations will be analysis of other available pressure levels with reliable data (not only one level) and comparison with the available model outputs or adding more parameters like geopotential height, relative or specific humidity, etc.

5 Data availability

The data used in this paper are available from the following sources:

– MERRA at http://disc.sci.gsfc.nasa.gov (Reichle, 2012)

- ERA-Interim at http://data-portal.ecmwf.int (Dee et al., 2011)
- NCEP/DOE2 at http:/www.esrl.noaa.gov/psd (Kanamitsu et al., 2002)
- JRA-55 at http://rda.ucar.edu/datasets/ds628.0/#! (Kobayashi et al., 2015)
- SSW: http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/northpole/index.html (Labitzke and Naujokat, 2000; Muench and Borden, 1962).

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Competing interests. The authors declare that they have no conflict of interest.

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