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Changes in the zonal mean flow, temperature, and planetary waves observed in the Northern Hemisphere mid-winter months during the last decades

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ABSTRACT

Four sets of data: the UK Met Office, Modern Era Retrospective-analysis for Research and Applications (MERRA), Japanese 55-year Reanalysis data (JRA-55), and ERA-Interim data (ERA) have been used to estimate the climatic variability of the zonal mean flow, temperature, and Stationary Planetary Waves (SPW1, SPW2) from the troposphere up to the lower mesosphere levels. The composites of the meteorological fields during mid-winter month have been averaged over the first (1995–2005) and second (2006–2016) 11 years intervals and have been compared mainly paying attention to interannual and intraseasonal variability. Results show that changes in the mean fields and SPW2 are weaker and statistical significance of these changes is lower in comparison with the changes observed in the intraseasonal variability of these characteristics. All data sets demonstrate a decrease of SPW1 amplitude at the higher-middle latitudes in the lower stratosphere and opposite effect in the upper stratosphere. However, there is an increase of the intraseasonal variability for all meteorological parameters and this rise is statistically significant. The results obtained show that UK Met Office data demonstrate stronger changes and increase of the intraseasonal variability in comparison with other data sets.

1. Introduction

An increased interest of scientists in the stratosphere-troposphere coupling has been noticed in recent years. And now it is impossible to neglect the stratospheric impact on tropospheric processes, since visible changes in stratospheric circulation lead to specific consequences on weather and climate change (Robock, 2001; Wallace and Thompson, 2002). Most of investigations are dedicated to ozone concentrations in the stratosphere (Gabriel et al., 2007; Smyshlyaev et al., 2016). Ozone and other radiatively active trace gases content is one of the most important factors affecting the temperature and therefore dynamical regime of this atmospheric region. However, an individual analysis of temperature variability is necessary since stratospheric temperature trends help to mark out the anthropogenic effect and natural processes that influence the climate (Hansen et al., 1997). It is well known that both low and middle troposphere have warmed while the stratosphere has cooled (Golitsyn et al., 1996; Ramaswamy et al., 2001; Beig et al., 2003) what is proved with all available data sets. It is obvious that the dynamical regime and behavior of planetary waves in response to stratospheric temperature variability require the monitoring and permanent diagnostics process. The stationary planetary waves (SPWs) are generated by the orography and difference between ocean and land heating; they propagate into the stratosphere and impact on the mean flow and temperature in the middle atmosphere.

Weber and Madden (1993) obtained climatology of the SPWs and normal-mode Rossby waves in the lower atmosphere using European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. Kanukhina et al. (2007, 2008) analyze of the long-term changes in the zonally averaged temperature, wind, geopotential height and wave activity of SPWs during NCEP/NCAR reanalysis time interval of 1959–2002 and show an increase in the amplitude and intra-seasonal variability of SPW with wave number 1, which is noticeable in the boreal stratosphere during Northern Hemisphere winter. Pogoreltsev et al. (2009) demonstrate that the significant variability of mean zonal flow and temperature is observed at the upper levels of stratosphere. The entire NCEP/NCAR reanalysis data allowed studying five intervals of 11-years but having maximum at 10 hPa pressure level (altitude of about 30 km). Modern reanalysis products enable scientists to accomplish different tasks and make a conclusion about dynamical situation at the heights of mesosphere. Therefore, the question, of whether the obtained tendencies

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remain at present comes up.

In present study the climatic variability observed in the last two decades (1995–2005 and 2006–2016) is examined using the UK Met Office (Swinbank and O'Neill, 1994), Modern Era Retrospective-analysis for Research and Applications (MERRA) (Rienecker et al., 2011), Japanese 55-year Reanalysis data (JRA-55) (Kobayashi et al., 2015), and ERA-Interim data (ERA) (Dee et al., 2011). The purpose of this investigation is to check whether the climatic trends obtained in the previous studies continue or even do not persist in the recent years and to calculate the changes of zonal mean flow, temperature, and activity of SPWs observed in the upper stratosphere and lower mesosphere. The estimations of changes in the intraseasonal variability of these meteorological characteristics during midwinter months in Northern Hemisphere are also performed.

2. Data and method

To investigate changes observed during two last decades (1995–2016) in the large-scale dynamics of the winter stratosphere in the Northern Hemisphere, four sets of data have been selected: the UK Met Office, MERRA, JRA-55, and ERA. Using several data sets is necessary to check whether all the data have the same tendency and to provide us with more detailed and reliable information on the stratospheric dynamics (Sakazaki et al., 2012; Dingzhu et al., 2015). The considered time interval has been divided into two sub-intervals of 11 years to exclude the impact of the 11-year solar cycle (Baldwin and Dunkerton, 2005; Kuchar et al., 2015), i.e., 1995–2005 and 2006–2016. This quantity of years is supposed to be enough to capture the observed climatological distribution of meteorological parameters in the stratosphere (Scaife et al., 2000).

The composites of the meteorological fields such as stationary planetary waves with zonal wave number $m = 1$ and $m = 2$ (SPW1 and SPW2), zonally averaged temperature, and mean zonal wind averaged over the first (1995–2005) and second (2006–2016) 11 years intervals have been calculated and compared mainly paying attention to intraseasonal and interannual variability.

By averaging over three winter months (DJF), the mean values and intraseasonal standard deviations for each winter have been calculated. Thus the intraseasonal standard deviations characterize the atmospheric variability within the winter months. Averaged over every investigated winter parameters have been averaged over two decades to calculate the composites and interannual standard deviations. To obtain the SPW1 and SPW2 amplitudes and phases, the Fourier decomposition is used of. Applying the Least Squared approach, the characteristics of these planetary waves have been calculated.

The composites of the mean zonal wind, temperature, amplitudes and phases of SPW1, and SPW2 in the geopotential height averaged over midwinter months (December–February) have been created separately for first and second eleven years. The estimations of the differences between two composites and statistical significance of obtained differences have been calculated. Additionally the same analysis was performed for each winter month separately – December, January, and February. To estimate the statistical significance of these differences, the so-called Welch *t*-test has been used (Welch, 1947). This technique has been successfully applied to analyze the differences in composites by Naoe and Shibata (2010), Inoue et al. (2011), and Pogoreltsev et al. (2015).

3. Results

3.1. Zonal wind and temperature

Zonally averaged zonal wind and temperature have been calculated for two time intervals to estimate their interannual variability within the considered 11-year sub-intervals. After that the difference in composites between 2006–2016 and 1995–2005 has been calculated. The result of the differences for mean zonal wind and temperature averaged over winter months (December–February) is demonstrated in Fig. 1 (a), (c) columns. Fig. 1 (b), (d) columns show interannual variability of zonal wind and temperature during 22 years. Both meteorological characteristics have been calculated using the UK Met Office, MERRA, JRA-55, and ERA data sets and are presented, respectively. It is seen that difference in the mean zonal wind obtained with MERRA, JRA-55, and ERA data are quite similar. UK Met Office reanalysis demonstrates a slight increase in rates of zonal wind variability during the last 11 years at upper stratosphere levels and at 50N-80N latitudes. However, all these tendencies are statistically insignificant (except the UK Met Office data with P of about 70%, here P is the significance level at which the hypothesis that the means are equal is disproved).

Composites for temperature difference represent the statistically significant decrease at the upper stratosphere levels in the UK Met Office data at 40 km with the significance level 95%. Results for other data sets are quite similar, though MERRA data show some decrease of temperature at levels higher than 45 km (Fig. 1c).

It should be noted that there exists an increase in the intraseasonal variability of the mean zonal wind during the last decades and the statistical significance of these changes at the higher-middle latitudes in the stratosphere is sufficiently high (P is greater 95%) for all data sets (Fig. 2 (a) column). An increase in the intraseasonal variability of temperature is observed at lover stratosphere levels and in 50N-70N latitude band ($P > 95\%$, Fig. 2 (c) column). A weak cooling can be observed at the upper stratosphere levels in the MERRA and ERA data sets (P is about 70%, Fig. 2 (c) column).

3.2. SPW1 and SPW2

Observed changes in the dynamical regime of the stratosphere are accompanied with the changes in the amplitude of the SPWs. Fig. 3 (a), (c) columns show the difference in the SPW1 and SPW2 amplitudes between two composites (amplitudes averaged over 2006–2016 and 1995–2005 years), while (b), (d) columns demonstrate interannual variability of SPW1 and SPW2 amplitudes during 22 years. Amplitudes are presented from the top down: the UK Met Office, MERRA, JRA-55, and ERA data sets.

The changes in the amplitudes of SPW1 averaged over mid-winter (December–February) months have an opposite sign in the lower and upper stratosphere, where consequently the weakening and strengthening is observed (Fig. 3 (a) column). This result is identical for all data sets used in the research. It is evidently that the UK Met Office data allow us to obtain the greater strengthening.

Fig. 3 (c) column illustrates a situation where SPW2 amplitudes show slight weakening in the upper stratosphere levels and a slight amplification of the amplitudes in the lower stratosphere levels and significance is low.

Considering the difference in the intraseasonal variability during winter months, it should be noted that SPW1 amplitude increases in the upper stratosphere (Fig. 4 (a) column). Fig. 4 (a), (c) columns show the difference between composites obtained for two time intervals 2006–2016 and 1995–2005 and (b), (d) columns demonstrate interannual variability of SPW1 and SPW2 intraseasonal variability during 22 years. Unfortunately, only the UK Met Office data set demonstrates the statistical significance of an increase in SPW1 intraseasonal variability with more than 90%. MERRA along with JRA-55 and ERA data sets show coincident statistically insignificant results. An increase of the intraseasonal variability of SPW2 amplitudes is observed in all data sets ($P > 90\%$). But the significance of the results obtained using the UK Met Office data is higher ($P > 95\%$) than for the rest ones (Fig. 4 (c)).

Additionally to analyze three winter months the composites for each month separately and the estimations of the changes have been performed. The results show that the most substantial (statistically significant) changes in the SPW1 and mean zonal wind are observed at the middle latitudes in the stratosphere during December for all data sets considered. The analysis of SPW1 amplitude changes enables to conclude that during the last decades the most amplitude growth has been

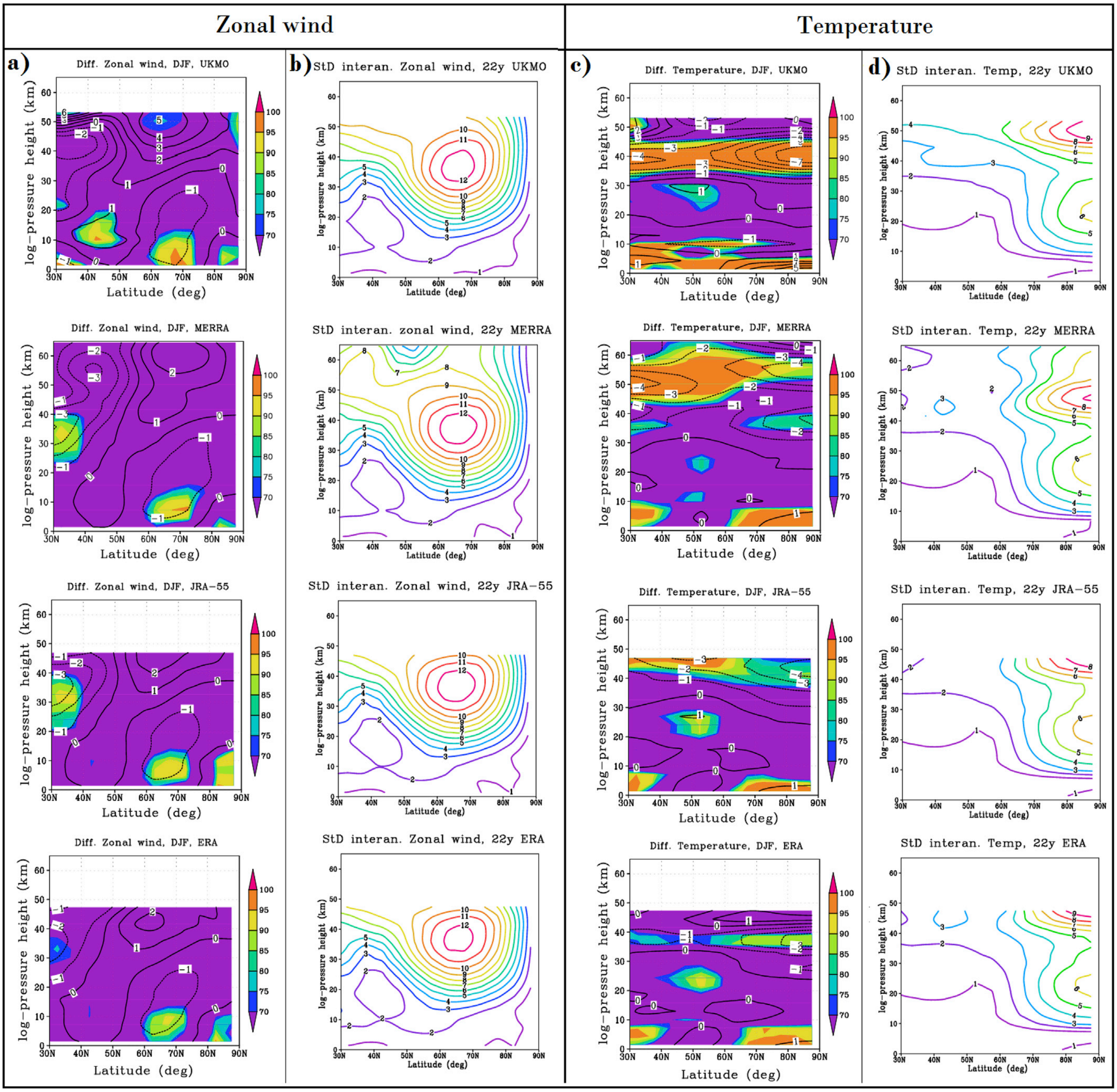

Fig. 1. The difference between 2006–2016 and 1995–2005 for the zonal mean wind and temperature averaged over winter months (DJF) - (a), (c) columns and interannual variability for the zonal mean wind and temperature during 22 years (1995–2016) - (b), (d) columns. Color scales represent the significance in percent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observed in the stratosphere at the altitudes higher than 30 km in December (not shown here). The statistical significance is about 90% for the UK Met Office data. Significance for other data sets is lower and with the smaller rates (MERRA and JRA-55: P ~70%; ERA-Interim: P~75%). In January and February the weakening of the SPW1 amplitudes has been observed during the last decades with the maximum at the higher-middle latitudes at the height of about 40 km and in February this weakening is insignificant (not shown here). In the upper stratosphere there has not been noted any essential changes in January and February. It can be assumed that the observed decrease of SPW1 activity in January is the result of a substantial intensification of the SPW1 in December that leads to the changes in the zonal mean flow and conditions of the SPW1 propagation (according to the UK Met Office data with higher significance).

As well as for the SPW1, significant changes in mean zonal wind are occurred in December and at the higher-middle latitudes above 30 km. This straightness is significant for all considered data sets with the significance level of about 97%. In January and February there exists a weakening of mean zonal wind and it is not statistically significant (not shown here). The SPW2 amplitude behaves during every winter months in a following way: during December and January there is amplification in the SPW2 amplitude at middle latitudes in altitude range 15–35 km, and the reducing of the amplitude at levels higher than 35 km. All this variations are statistically insignificant. In February it is observed the significant decrease of the amplitude from 20 up to 45 km at 40N–80N latitudes, P > 90% (not shown here).

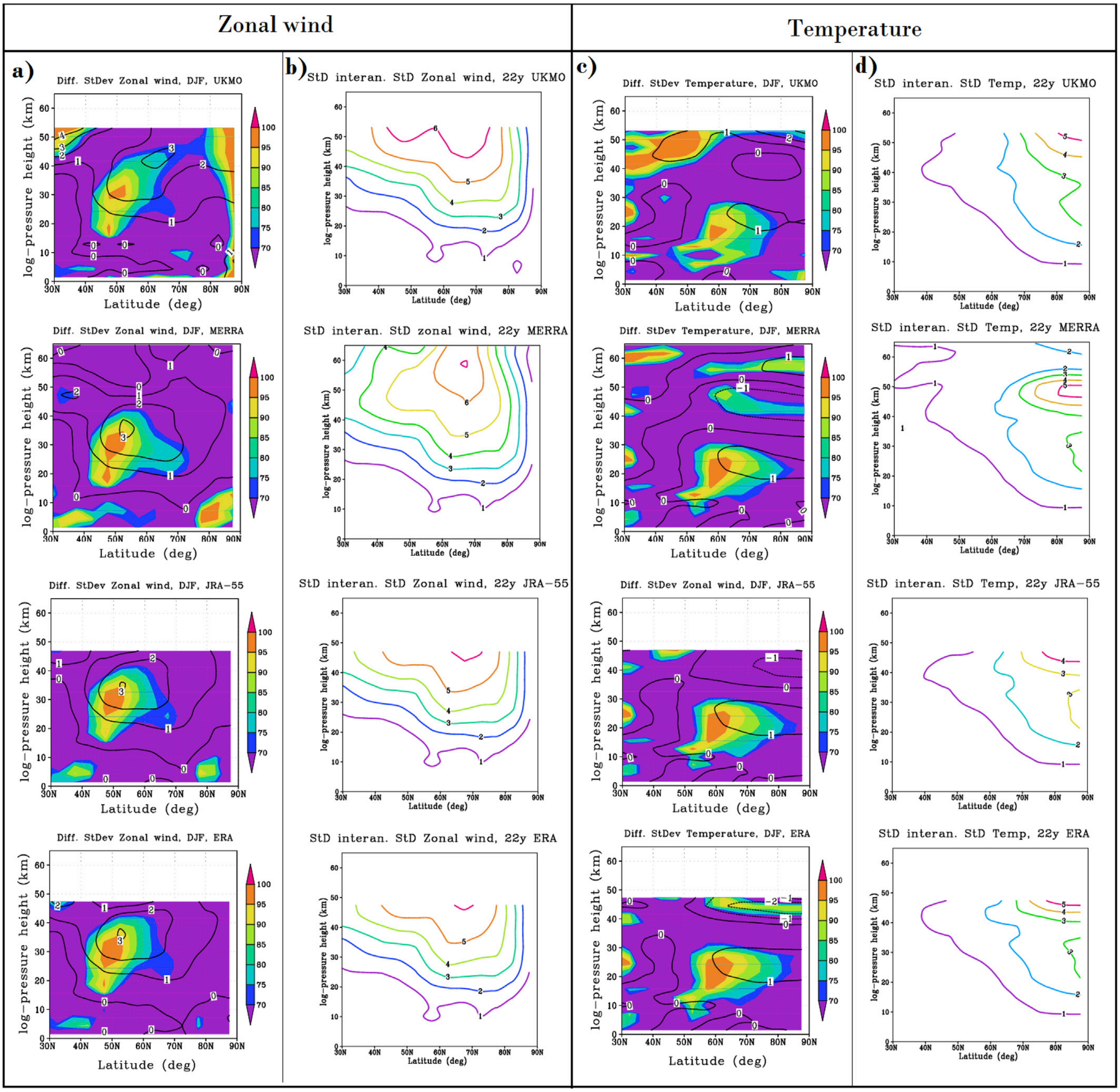

Fig. 2. The difference in intraseasonal variability (2006–2016 minus 1995–2005) for the zonal mean wind and temperature averaged over DJF - (a), (c) columns, and interannual variability of intraseasonal variability for the zonal mean wind and temperature during 22 years (1995–2016) - (b), (d) columns.

4. Conclusions

The comparison of composites obtained for the mean zonal wind, temperature, SPWs, and their interannual variability during mid-winter months calculated for 1995–2005 and 2006–2016 years using different reanalysis data sets allows us to make the following conclusions: the changes in the zonally averaged fields are weak and statistical significance of the changes is low in comparison with the changes observed in the intraseasonal variability of these fields. The strongest changes in the mean zonal wind and SPWs are observed at the higher-middle latitudes in the stratosphere; however, the statistical significance of these changes is relatively low (of about 70%) due to a strong interannual variability of stratospheric dynamics in this region. An increase of the intraseasonal variability of the mean zonal wind and temperature are observed at the middle latitudes in the lower stratosphere and the statistical significance of these changes is about 95%.

- All data sets demonstrate a decrease of SPW1 amplitude at the higher-middle latitudes in the lower stratosphere and opposite changes in the upper stratosphere.
- The SPW2 amplitude behaves in the opposite way; however, the statistical significance of the observed changes is relatively low.
- The intraseasonal variability of the SPW1 and SPW2 amplitudes increases in the middle latitude stratosphere during the last decades and this increase is statistically significant for the SPW2. These results coincide with conclusions in Pogoreltsev et al. (2009).

The analysis of the SPW1 amplitude changes averaged over separate

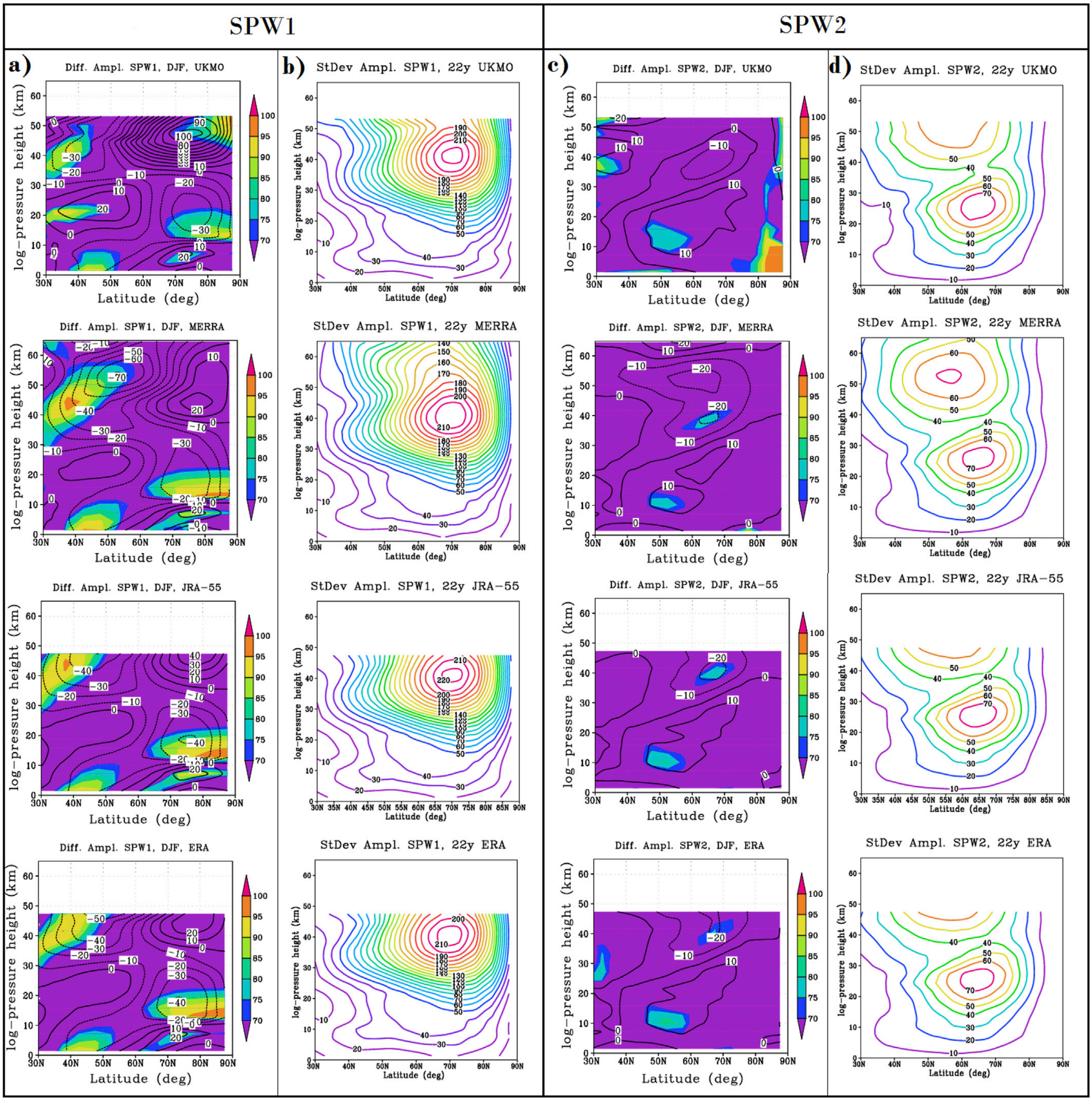

Fig. 3. The difference between 2006–2016 and 1995–2005 for the SPW1 and SPW2 amplitudes averaged over winter months (DJF) – (a), (c) columns and interannual variability for the SPW1 and SPW2 amplitudes averaged over 1995–2016 – (b), (d) columns. Four sets of data are used: UK Met Office, MERRA, JRA-55 and ERA respectively. Color scales represent the significance in percent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

months demonstrates that during the last decades the strongest growth of SPW1 amplitude has been observed in the stratosphere above the altitude of about 30 km in December. In January and February, the weakening of the SPW1 amplitude has been noted during the last decades with the maximum at the higher-middle latitudes at of about 40 km and in February this weakening is statistically insignificant. It can be assumed that the observed variations in January are the result of a substantial intensification of the SPW1 in December that leads to the changes in the mean flow and propagation conditions of the SPW1. As far as the investigated processes are substantially nonlinear it can be concluded that to understand the observed changes in the stratospheric dynamics it is necessary to analyze the seasonal evolution of dynamical processes taking into account the wave-wave and wave-mean flow interactions.

It should be noted in conclusion that all results obtained show that UK Met Office data demonstrate stronger changes and a stronger increase in the intraseasonal variability in comparison with other data sets. An additional investigation (for instance, the comparison the intraseasonal variability in reanalysis data and observations) has to be performed to make the final conclusion what data sets are more reliable to study the climatic variability.

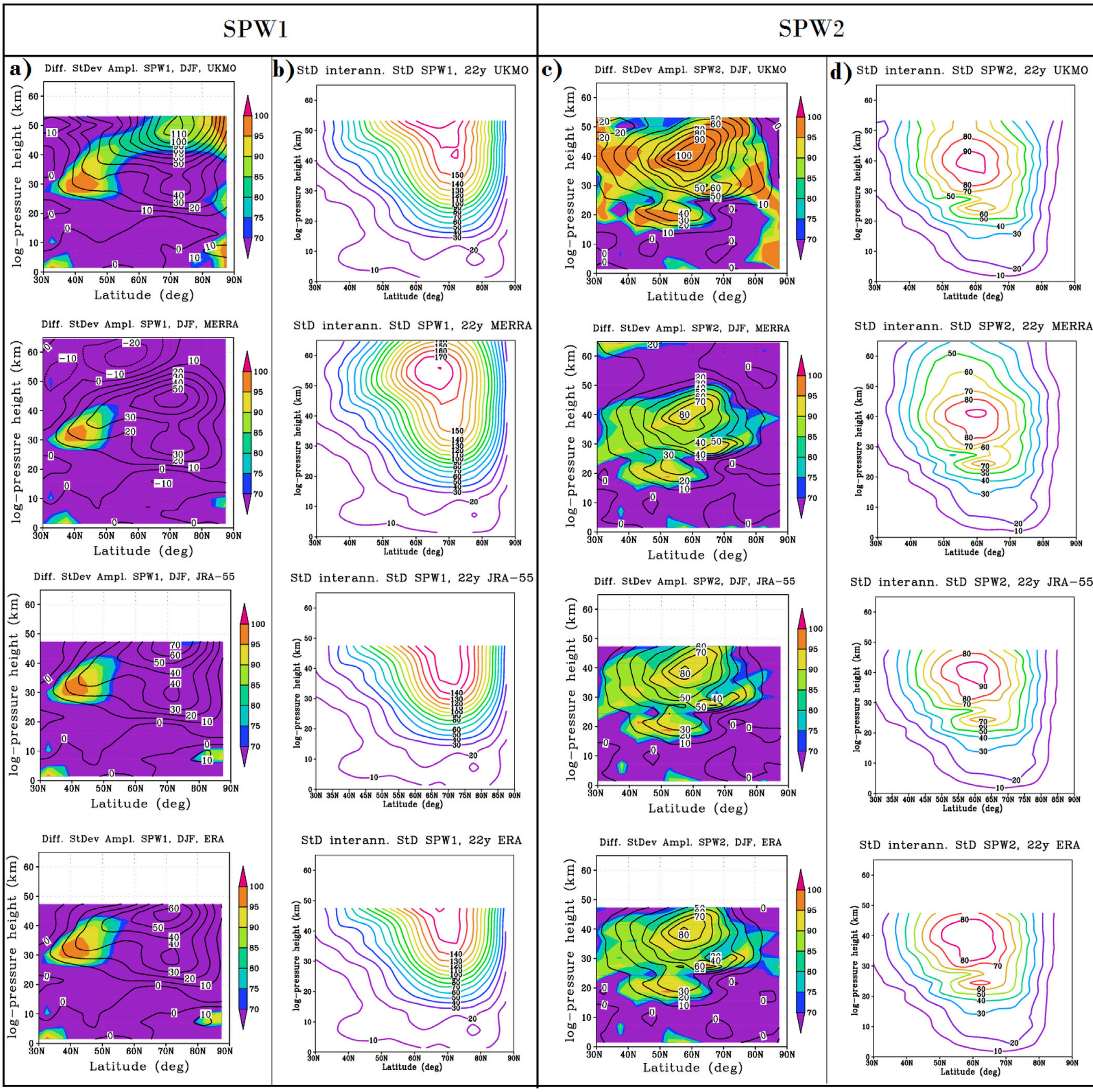

Fig. 4. The difference between intraseasonal variability (2006–2016 minus 1995–2005) for the SPW1 and SPW2 amplitude averaged over DJF ((a), (c) columns) and interannual variability of intraseasonal variability for the SPW1 and SPW2 amplitudes during 1995–2016 ((b), (d) columns).

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