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The stratospheric response to external factors based on MERRA data using linear multivariate linear regression analysis

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Abstract

The stratosphere is influenced by many external forcings (natural or anthropogenic). There are many studies which are focused on this problem and that is why we can compare our results with them. This study is focused on the variability and trends of temperature and circulation characteristics (zonal and meridional wind component) in connection with different phenomena variation in the stratosphere and lower mesosphere. We consider the interactions between the troposphere–stratosphere-lower mesosphere system and external and internal phenomena, e.g. solar cycle, QBO, NAO or ENSO using multiple linear techniques. The analysis was applied to the period 1979–2012 based on the current reanalysis data, mainly the MERRA reanalysis dataset (Modern Era Retrospective-analysis for Research and Applications) for pressure levels: 1000–0.1 hPa. We do not find a strong temperature signal for solar flux over the tropics about 30 hPa (ERA-40 results) but the strong positive signal has been observed near stratopause almost in the whole analyzed area. This could indicate that solar forcing is not represented well in the higher pressure levels in MERRA. The analysis of ENSO and ENSO Modoki shows that we should take into account more than one ENSO index for similar analysis. Previous studies show that the volcanic activity is important parameter. The signal of volcanic activity in MERRA is very weak and insignificant.

1 Introduction

The Sun activity changes in the different timescale. The most studied is approximately eleven years (from 9 to 14 years) (Lean et al., 1997) cycle. The possible influence to the Earth's atmosphere or surface climate is a matter of debate for a long time (Pittock, 1978; Shindell et al., 2001; Gray et al., 2010). The understanding of possible mechanism is still very poor in comparison with other climate forcing aspects (Houghton et al., 2001; Myhre et al., 2013). One of the main problems of the solar impact to the

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climate is that the changes of total solar irradiance (TSI) during solar cycle are only 0.1 % and it is questionable how these small changes can influence the atmospheric processes. The effects of solar changes on the stratosphere have been examined by the observational or theoretical studies in the previous years (Labitzke, 2001; Labitzke et al., 2002; Haigh and Blackburn, 2006; Randel et al., 2009; Hood et al., 2010; Hood and Soukharev, 2012). These studies used different method to show the solar influence and cover various periods and areas. Several dataset from Free University of Berlin (FUB) data (Labitzke, 2001), NCEP-NCAR reanalysis (Kalnay et al., 1996) and ERA-40 reanalysis (Crooks and Gray, 2005; Frame and Gray, 2010), radiosonde stations observation (Labitzke and van Loon, 1988) or satellite Stratospheric Sounding Unit (SSU) observation (Scaife et al., 2000) were used for these analysis.

Regression analysis was applied by (Hood, 2003) to NCEP-NCAR reanalysis data and he found a maximum positive response (1.6 K) at about 48 km decreasing to ~ 1 K at 32 km. The El Nino Southern Oscillation (ENSO), the Quasi-Biennial oscillation (QBO), the North Atlantic Oscillation (NAO) and volcanic activity were not taken into account in earlier regression studies. Hood et al. (2010) included extratropical wave forcing into the analysis. Crooks and Grey (2005) applied multiple linear regression analysis taking into account NAO, ENSO, QBO and the volcanic effects to extract stratospheric response to solar variability from the ERA-40 reanalysis data for the period 1979–2001 (update until 2008 can be found in Frame and Grey, 2010). They found a positive temperature response (about 0.5 K) in the lower stratosphere shifted by about 25° from the equator while over the equator they found only a non significant minimum. They considered that this effect is rather similar to the structure of QBO (non-linear interaction between QBO and solar signal cannot be accounted for by multiple linear regression analysis). They also found a corresponding solar signal in zonaly averaged zonal wind. Claud et al. (2008) used linear multiple regression analysis for temperature from SSU observations and FUB database. They found that during the solar maximum temperature is usually higher by about 0.5 K for low and mid-latitudes than in solar minimum and polar vortex is also cooler (by 2–4 K) during solar maximum. Randel and

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Wu (2007) showed that tropical stratosphere internannual variability (ozone and temperature) is controlled partly by QBO. Smith and Matthes (2008) also found a strong dependence of presence QBO on solar signal in tropics.

Besides observations and reanalyzes a number of numerical simulations were used for better understanding of the mechanisms behind solar influence on the middle atmosphere conditions. The first conceptual model which includes downward propagation of direct solar UV effects was introduced by (Hines, 1974) and then extended by various authors (Kodera, 1995; Hood et al., 1993; Kodera and Kuroda, 2002). The Global Circulation Models are able to reproduce the main features of the observed atmospheric variability modes (NAO, QBO or ENSO) but they cannot capture all details (e.g., Gray et al., 2005; Matthes et al., 2006). That is why the fully coupled Chemistry models are used on annual or monthly time scales (Rozanov et al., 2004; Matthes et al., 2004). Reasonable agreement of the observations with model simulation was showed by (Chiodo et al., 2012; Austin et al., 2008; Schmidt et al., 2010). WACCM model is general circulation model with very high resolution in the stratosphere and interactive chemistry but Chiodo et al. (2014) found out that strong model response to solar irradiance variability presented by Chiodo et al. (2012) is an artefact caused by the applied statistical approach and disappears if the volcanic eruptions are not included in the model run.

In this paper we analyze MERRA data using multiple linear regressions technique to compare the atmospheric response to solar variability with the results obtained from other reanalyses datasets (ERA-40, NCEP-NCAR and ERA-Interim). The main advantage of MERRA is that it produces data continuously from 1979 without any gaps and covers atmosphere from 1000 up to 0.1 hPa allowing to analyze processes not only in the troposphere or stratosphere but also lower part of the mesosphere. This analysis shows interesting results especially for the solar flux because we can expect strong solar signal in the higher layer of the atmosphere. We take into account the most important stratospheric/tropospheric mechanisms like NAO, QBO, ENSO, ENSO Modoki and solar cycle. All these phenomena have large influence on the behaviour of the

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stratosphere and that is why they are included into our model. We focus mainly on the dynamical part so we analyzed temperature, zonal and meridional wind, which is very important for studying Dobson–Brewer circulation. The structure of the paper is as follow. In Sect. 2 the data and methods are described. Then, in Sect. 3 the results of analysis are shown and briefly discussed. The summary and discussion of our results is given in Sect. 4.

2 Data and methods

We use MERRA reanalysis monthly averaged data derived from 6 hourly analyses for the period 1979–2012 downloaded from http://disc.sci.gsfc.nasa.gov. The resolution of the reanalysis data is $0.5^{\circ} \times 0.667^{\circ}$. These reanalysis data is available up to 0.1 hPa. We use a standard linear multiple regression method with autoregressive model (used by Gray et al., 2005) to show the temperature, zonal and meridional wind response to different forcings. We consider 10.7 cm radio solar flux (from http://www.esrl.noaa.gov/psd/data/correlation/solar.data), NAO index (from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim), ENSO Index (from http://www.esrl.noaa.gov/psd/data/correlation/mei.data), which should represent conventional El Nino with warming in the eastern Pacific and Modoki index (EMI) which represents El Nino with warming in the central Pacific. The last phenomenon is QBO at 50 and 10 hPa (from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/). We have done analysis where volcanic eruptions were included but the signal was weak and insignificant (see Fig. 7) and the differences between model with and without volcanic eruption were negligible. That is why decided to exclude volcanic eruptions from our regression model.

We used annual averaged data (T, u, v) which has been deseasonalized by subtracting the mean of each month from monthly data for the period January 1979–December 2012 according to Crooks and Gray, 2005. We have tried two ways to remove autocorrelation. First, we used Durbin–Watson test for auto-correlation treatment

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of our analysis. Second, we followed a Box–Jenkins pre-whitening procedure (Box and Jenkins, 1980). This was applied on the time-series of the simulated phenomena and of the predictors (ENSO, F 10.7 cm, etc.). The results show that the atmospheric response to all analyzed forcings is insensitive to the use of an autoregressive term. The statistical significance is computed using standard MATLAB routine. This routine considers possible influence of autocorrelation on the statistical significance estimate. The results show zonal mean of each analyzed parameter from 90° S to 90° N. The Fig. 1 shows the monthly values of physical parameters like NAO, QBO (50 and 10 hPa), ENSO, EMI or 10.7 cm solar flux for period 1979–2012 which were included into our regression model and we can see that the analyzed period covers almost 3 solar cycles.

3 Results

In Fig. 2 we can observe ENSO signal for zonal wind (right panels), temperature (middle panels) and meridional wind (left panel). The statistical significance has been computed on the 95 % level. The temperature response is the strongest in the polar region (70°–90° N at about 10 hPa). In this region we can find a significant positive signal up to 1 K. The insignificant positive response (about 0.6 K) is also visible from 1 hPa about 70° S. There is very weak negative signal over the equator at 10 hPa. Zonal wind analysis shows that there is a strong significant response (up to 1.5 $\mathrm{m\,s^{-1}}$) over the subtropical region (25° N and S) at 100 hPa and over the equator at 30 hPa. Negative signal can be found over the equator at pressure level 1 hPa. The results agree with (Chen et al., 2009; Calvo and Marsh, 2011; Calvo et al., 2008). We cannot find any significant response in meridional wind analysis (left panels).

The Fig. 3 shows the same as Fig. 2 for NAO response. There is a significant negative temperature signal (0.8 K) in the polar region (from 60° N) at 100 hPa and over the equator (about 200 hPa). The positive signal (up to 1 K) can be found at higher altitude (from 10 hPa). Zonal wind analysis shows a significant positive signal (about

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1.5 m s^{-1}) north from 50° N almost through the whole troposphere and stratosphere and weaker negative signal over the equator at 30 and 0.5 hPa (agree with Baldwin et al., 1994). Surprisingly we identify significant positive signal of NAO at middle stratosphere about 60° S. Meridional wind analysis shows similar results as for zonal wind. NAO affects predominately higher north latitudes but the positive response is evident just from 30 hPa not through the whole stratosphere. These results confirm the theory that NAO effects can be detected mainly over the high northern latitudes, but NAO could be influenced by the volcanic activity. That is why the NAO signal could be affected by this activity more than others parameters (can explain significant temperature signal over the equator) but our model with included volcanic activity do not confirm this possibility.

The response of temperature and wind to QBO at 50 hPa is illustrated in Fig. 4. There is significant positive temperature signal over the equator at 30 hPa and in the subtropics (30° N and S) at 5 hPa. A negative response is visible over the equator at about 5 hPa. Similar results can be observed for the zonal wind analysis. Significant positive signal is located over the equator between 30–10 hPa. If we look at the meridional wind analysis the situation is not as clear as for zonal wind. The strongest positive signal is located at about 3 hPa north from the equator (10° N) and there are several weaker but significant positive or negative signal in the area 20° N. The positive signal at about 1 hPa from 60° N could be connected with the temperature response. The results again show that QBO affect stratosphere and maybe troposphere mainly over the equator (Naujokat, 1986; Randel et al., 1999; Ern and Preusse, 2009).

Analysis of ENSO Modoki Index can be seen in the Fig. 5. ENSO Modoki is connected with sea surface temperature (SST) in the central and eastern Pacific and it has distinct teleconnections and affects many parts of the world (the West Coast of USA, South Africa etc.). The detail description of main features and teleconnections can be found in (Ashok et al., 2007; Yeh et al., 2009). We identify positive temperature signal at higher latitude (80° N) at about 1 hPa and negative from 50–80° S. Zonal wind shows a strong negative signal from 300 hPa in the area 60–30° S and over the

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equator at 5 hPa. Positive signal can be found over the equator at 30 hPa (agree with Xie et al., 2012). We can see that ENSO Modoki affects different regions than classical ENSO phenomenon. The strongest signal can be found in the middle latitudes (Southern Hemisphere) and we cannot find the zonal wind signal in the tropics and subtropics as for the classical ENSO.

The last parameter which is included into our model is the 10.7 cm solar flux (Fig. 6). The strongest significant temperature signal is located in the upper stratosphere (over 2 hPa). This signal is positive almost through whole analyzed area. We can also identify weak but significant positive trend over from 40° S to 40° N at about 40 hPa. In the zonal wind analysis we can find a significant negative response over the equator above 1 hPa. The stronger positive signal which can be seen in the subtropics area (30° N and S) at high stratosphere (higher than 1 hPa) is mainly statistically insignificant. The analysis of meridional wind shows positive significant signal over the equator at pressure level 300 hPa and then higher than up from 0.5 hPa at 50° S and 20° N hPa. The significant negative trend has been found around 20° S at 0.5 hPa so there is big gradient (big change of response) at this pressure level. The results for solar flux analysis are similar to (Frame and Gray, 2010) in zonal wind where we have found two centres of positive response in subtropics near the stratopause and weaker negative signal in the southern polar region at about 10 hPa. We do not find so strong temperature response over the tropics about 30 hPa but we have found strong positive signal near stratopause in the almost whole analyzed area (Frame and Gray, 2010 found positive signal just over the tropics at 1 hPa region).

4 Conclusions

Multiple linear regression model has been used to identify atmospheric response to different forcing from MERRA reanalysis temperature and wind datasets. The MERRA reanalysis provides dataset up to 0.1 hPa so we can observe signal not only in the troposphere and stratosphere but also in the lower mesosphere globally for both

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hemispheres. It helps us to find a connection between different layers of the atmosphere in better resolution than previous studies. We can compare these results with the previous studies (Frame and Grey, 2010; Labitzke et al., 2002; Randel et al., 1999; Ern and Preusse, 2009; Xie et al., 2012). The results for solar flux analysis are similar in zonal wind analysis where we have found two centres of positive signal in subtropics near the stratopause and weaker negative signal in the southern polar region at about 10 hPa. We do not find so strong temperature response over the tropics about 30 hPa but we have found strong positive signal near stratopause almost in the whole analyzed area. This new features could indicate that solar forcing in the higher pressure levels is not represented well because according to Labitzke et al. (2002) we should find this signal just over the equator.

The analysis of QBO shows that the strongest signal (temperature and zonal wind) is found over the equator over the 30 hPa. These results confirm previous studies that QBO affect mainly tropics and subtropics region (Randel et al., 1999; Ern and Preusse, 2009). NAO analysis show that mainly higher latitudes of Northern Hemisphere are affected by this phenomenon and the effect can reach up the middle stratosphere. The significant signal which is observed about 60° S is not confirm by other studies (not found in ERA-40 or NCEP/NCAR reanalysis).

We can say that ENSO and EMI almost do not affect meridional wind. We can see a big difference between wind and temperature signal of classical ENSO and ENSO Modoki (not studied in previous studies). Classical ENSO affect tropics and subtropics mainly at about 100 hPa. ENSO Modoki strongest signal is found not only in tropics but also about 50° S up to 10 hPa. These results confirm previous studies that we have to consider more than one ENSO index when describing behaviour of SST and its connection with atmospheric circulation. If we take into account ENSO Modoki index effects we can improve reanalysis and model representation of real condition and real connection between different phenomena.

The volcanic activity analysis which should be important parameter (at least in WACCM) in stratospheric/tropospheric behaviour (according to Chiodo et al., 2014)

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shows surprisingly insignificant and weak signal in MERRA reanalysis. This disagreement could indicate that volcanic activity is not well represented in model or in MERRA reanalysis.

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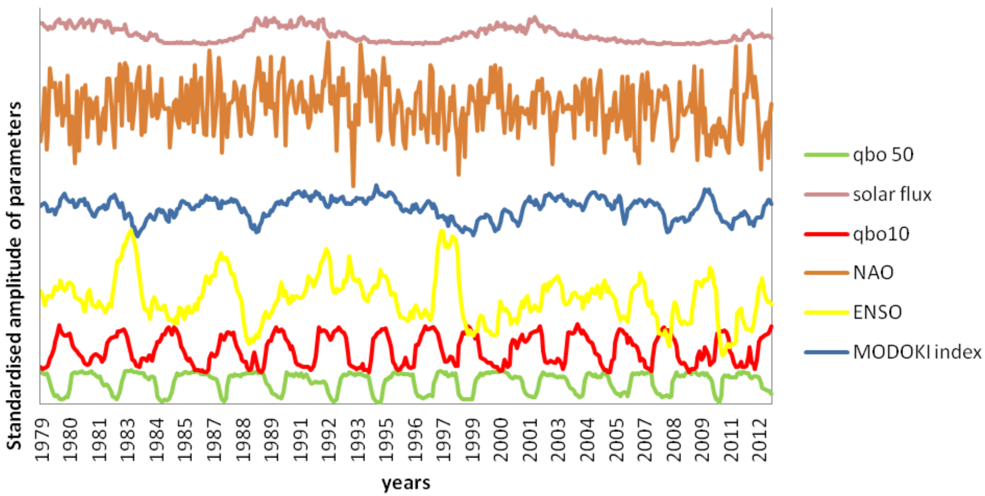

Figure 1. Time series of standardized 10.7 cm solar flux (purple line), NAO index (orange), EMI (blue), ENSO (yellow), QBO at 50 hPa (green) and QBO at 10 hPa (red).

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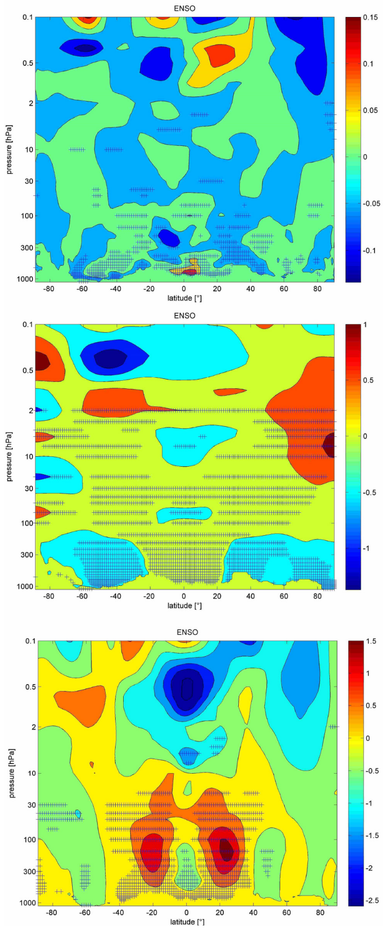

Figure 2. The annually averaged response of ENSO in meridional wind (left panels), temperature (middle panels) and zonal wind (right panels). Crosses show the statistical significance at 95 % level.

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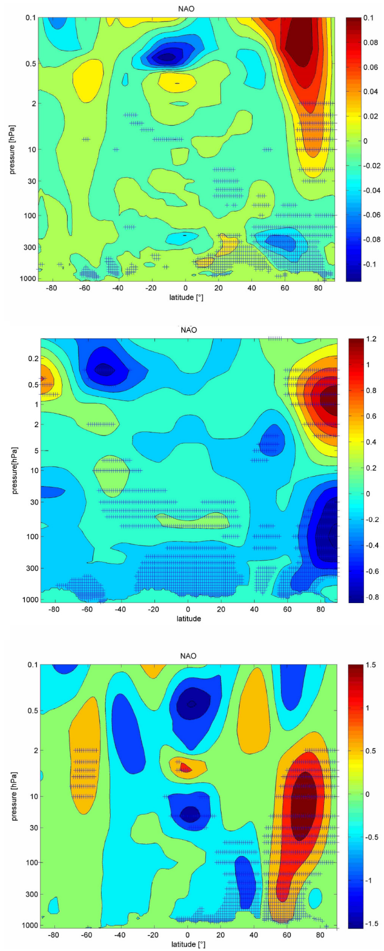

Figure 3. The same as Fig. 2 but for NAO.

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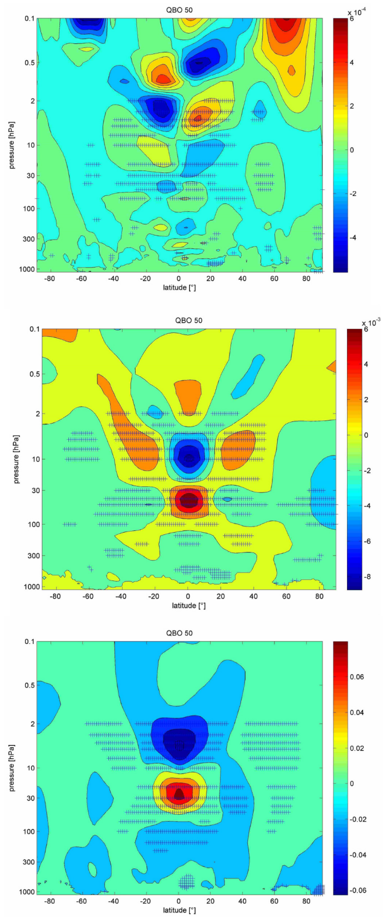

Figure 4. The same as Fig. 2 but for QBO 50 hPa.

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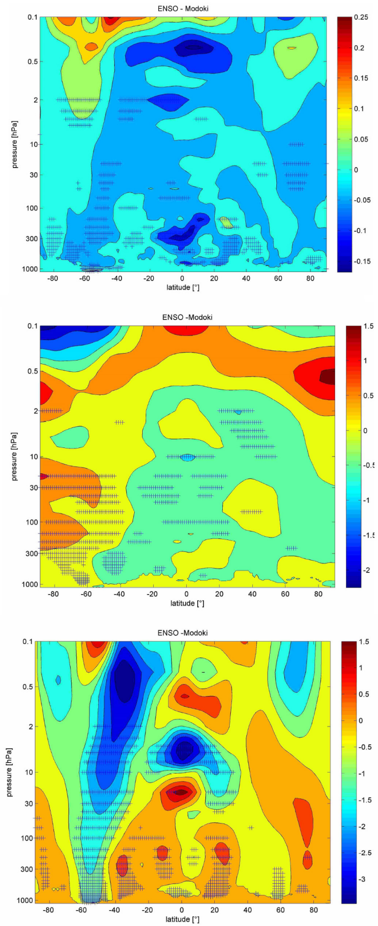

Figure 5. The same as Fig. 2 but for ENSO Modoki index.

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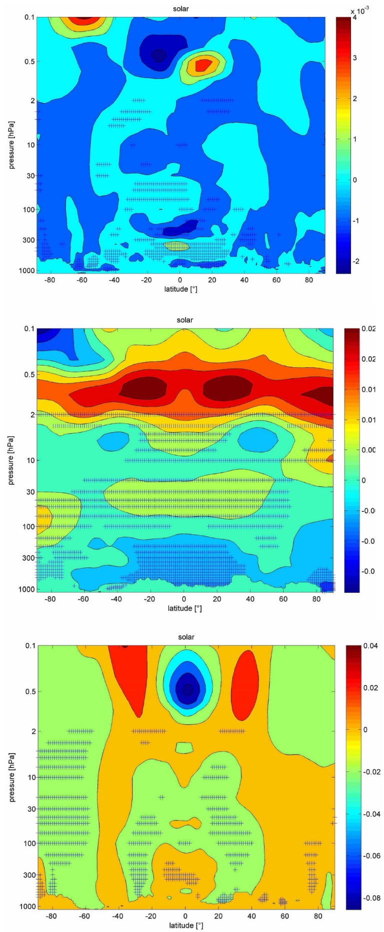

Figure 6. The same as Fig. 2 but for 10.7 cm solar flux.

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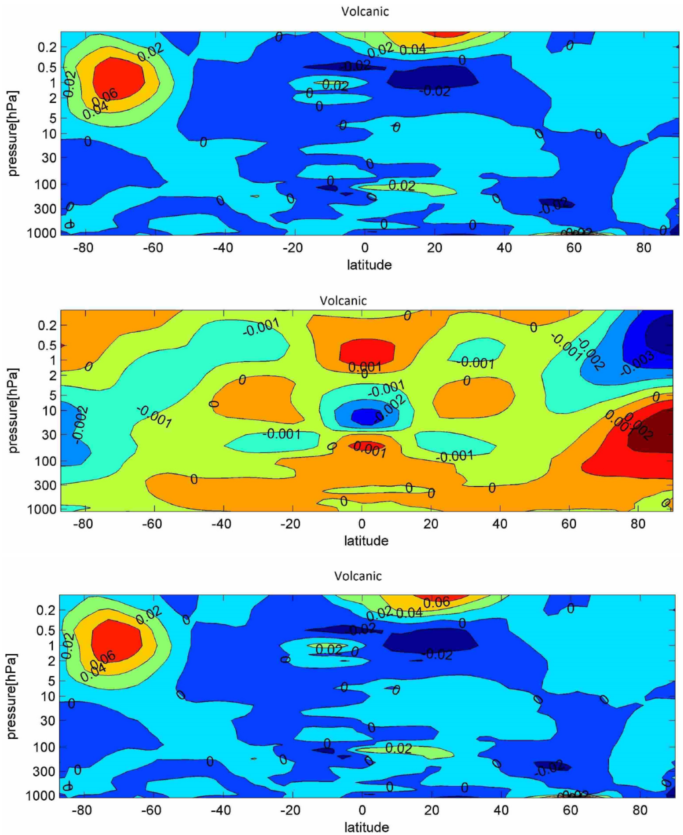

Figure 7. The same as Fig. 2 but for volcanic eruptions.

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