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The 11-year solar cycle in current reanalyses: A (non)linear attribution study of the middle atmosphere~~Solar cycle in current reanalyses: (non)linear attribution study~~ales(r4,tc3;r2,sc1)

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Abstract

This study focusses on the variability of temperature, ozone and circulation characteristics in the stratosphere and lower mesosphere with regard to the influence of the 11-year solar cycle. It is based on attribution analysis using multiple nonlinear techniques (Support Vector Regression, Neural Networks) besides the multiple linear regressiontraditional linear[ales](r4,tc4) approach. The analysis was applied to several current reanalysis datasets for the 1979-2013 period, including MERRA, ERA-Interim and JRA-55, with the aim to compare how this type of data resolves especially the double-peaked solar response in temperature and ozone variables and the consequent changes induced by these anomalies. Equatorial temperature signals in the lower and upper stratosphere were found to be sufficiently robust and in qualitative agreement with previous attributionobservational[ales](r4,sc29) studies. The analysis also pointed to the solar signal in the ozone datasets (i.e. MERRA and ERA-Interim) not being consistent with the observed double-peaked ozone anomaly extracted from satellite measurements. Consequently the results obtained by linear regression were confirmed by the nonlinear approach through all datasets, suggesting that linear regression is a relevant tool to sufficiently resolve the solar signal in the middle atmosphere. Furthermore, the seasonal evolution of the solar response was also discussed in terms of dynamical causalities in the winter hemispheresthe seasonal dependence of the solar response was also discussed, mainly as a source of dynamical causalities in the wave propagation characteristics in the zonal wind and the induced meridional circulation in the winter hemispheres[ales](r3,c6). The hypothetical mechanism of a weaker Brewer Dobson circulation at solar maxima[ales](r3,c6) was reviewed together with discussion of polar vortex behaviourstability[ales](r4,sc25).

1 Introduction

The Sun is a prime driver of various processes in the climate system. From observations of the Sun's variability on decadal or centennial time scales, it is possible to identify temporal patterns and trends in solar activity, and consequently to derive the related mechanisms of the solar influence on the Earth's climate (e.g. Gray et al., 2010). Of the semi-regular solar cycles, the most prominent is the approximate 11-year periodicity which manifests in the solar magnetic field or through fluctuations of sunspot number, but also in the total solar irradiance (TSI) or solar wind properties. For the dynamics of the middle atmosphere, where most of[ales](r2,sc2) ozone production and destruction occurs, the changes in the spectral solar irradiance (SSI) are the most influential, since the TSI as the integral over all wavelengths exhibits variations of orders lower than the ultraviolet part of the spectrum (Lean, 2001). This fact was supported by original studies (e.g. Labitzke, 1987; Haigh, 1994) that suggested the solar cycle (SC) influence on the variability of the stratosphere. Gray et al. (2009) have shown, with the fixed dynamical heating model, that the response of temperature in the photochemically controlled region of the upper tropical[ales](r3,c7) stratosphere is approximately given 60% by direct solar heating and 40% due to indirect effect by the ozone changes.

Numerous ~~observational~~[ales](r4,sc29) studies have identified temperature and ozone changes linked to the 11-year cycle by multiple linear regression. The use of ERA-40 reanalysis (Frame and Gray, 2010) pointed to a manifestation of annually averaged solar signal in temperature, exhibited[ales] predominantly around the equator with amplitudes up to 2 K around the stratopause and with a secondary amplitude maximum of up to 1 K in the lower stratosphere. Soukharev and Hood (2006), Hood et al. (2010) and Randel and Wu (2007) have used satellite ozone data sets to characterize statistically significant responses in the upper and lower stratosphere. The observed double-peaked ozone anomaly in the vertical profile around the equator was reproduced, nevertheless the concerns about physical mechanism of the lower stratospheric response was expressed (Austin et al., 2008).~~The observed double-peaked ozone anomaly in the vertical profile around the equator was confirmed by the simulations of coupled chemistry climate models (Austin et al., 2008).~~[ales](r3,c3,c8)

The ozone and temperature perturbations associated with the SC have an impact on the middle atmospheric circulation. They produce a zonal wind anomaly around the stratopause (faster subtropical jet) during solar maxima through the enhanced meridional temperature gradient. Since planetary wave propagation is affected by the zonal mean flow (Andrews and McIntyre, 1987), we can suppose that a stronger subtropical jet can deflect planetary waves propagating from higher latitudes. Reduced wave forcing can lead to decreasing/increasing or upwelling/downwelling motions in the equatorial or higher latitudes respectively (Kodera and Kuroda, 2002). The Brewer-Dobson circulation (BDC) is weaker during solar maxima (Kuroda and Kodera, 2001)~~(Gray et al., 2010)~~[ales](r2,s6) although this appears to be sensitive to the state of the polar winter. Observational studies, together with model experiments (e.g. Matthes et al., 2006) suggest a so-called "Top-Down" mechanism where the solar signal is transferred from the upper to lower stratosphere, and even to tropospheric altitudes.

Statistical studies (e.g. Labitzke et al., 2006; Camp and Tung, 2007) have also focused on the lower stratospheric solar signal in the polar regions and have revealed modulation by the Quasi-Biennial Oscillation (QBO), or the well known Holton-Tan relationship (Holton and Tan, 1980) modulated by the SC. Proposed mechanisms by Matthes et al. (2004, 2010)[ales](r2,sc4) suggested that the solar signal induced during early winter in the upper equatorial stratosphere propagates poleward and downward when the stratosphere transits from a radiatively controlled state to a dynamically controlled state involving planetary wave propagation (Kodera and Kuroda, 2002). The mechanism of the SC and QBO interaction, which stems from reinforcing each other or canceling each other out (Gray et al., 2004) has been verified by WACCM3.1~~recent~~[ales] model simulations (Matthes et al., 2013). These proved the independence of the solar response in the tropical upper stratosphere from the response dependent on the presence of the QBO in lower altitudes. However, fully coupled WACCM-4 model simulations by Kren et al. (2014) raised the possibility of occurrence by chance of the observed solar-QBO response in the polar region.[ales](r2,sc5)

~~Observational and modeling studies over the past two decades have fundamentally changed our understanding of wave processes and the coupling between the middle atmosphere and tropospheric conditions (**?**). It has been shown that the stratosphere plays a significant and active role in tropospheric circulation on various time scales (**???**). A deeper understanding of the mechanisms of communication between the middle atmosphere and troposphere~~

~~contributes to better climate change predictions. However, a number of questions about the coupling processes with regard to solar signal perturbation have to be answered.~~[ales] (r4,sc2) It has been shown that difficulties in the state-of-the-art climate models arise when reproducing the solar signal influence on winter polar circulation, especially in less active sun periods (Ineson et al., 2011). The hypothesis is that solar UV forcing is too weak in the models. Satellite measurements indicate that variations in the solar UV irradiance may be larger than previously thought (Harder et al., 2009). However, the measurements by Harder et al. (2009) from SORCE satellite may have been affected by instrument degradation with time and so may be overestimated in the UV (Ermolli et al., 2013). They have also concluded that the SORCE measurements probably represent the upper limit in the magnitude of the SSI variation. Consequent results of GCMs, forced with the SSI from the SORCE measurements, have shown larger stratospheric response than for NRLSSI dataset. Thus, coordinated work is needed to have reliable SSI input data for GCM simulations (Ermolli et al., 2013), and also to propose robust conclusions concerning SC influence on climate (Ball et al., 2014).[ales] (r3,c9;r4,sc3)

At the Earth's surface, the detection of the SC influence is problematic since there are other significant forcing factors, e.g. greenhouse gases, volcanoes and aerosol changes (e.g. Chiodo et al., 2012)~~(Gray et al., 2010)~~[ales] (r2,sc8), as well as substantial variability attributable to internal climate dynamics. However several studies (van Loon et al., 2007; van Loon and Meehl, 2008; Hood and Soukharev, 2012; Hood et al., 2013; Gray et al., 2013; Scaife et al., 2013)~~(van Loon et al., 2007; van Loon et al., 2008; van Loon et al., 2012; van Loon et al., 2013; v~~ detected the solar signal in sea level pressure or sea surface temperature which supports the hypothesis of a troposphere-ocean response to the SC. The studies (e.g. Hood and Soukharev, 2012) suggest a so-called "Bottom-Up" solar forcing mechanism t.~~T~~[ales] (r3,c10)hat contributes to the lower ozone and temperature anomaly in connection with the lower stratosphere deceleration of the BDC. However, the results presented by Chiodo et al. (2014) suggest the contribution of SC variability could be smaller since two major volcanic eruptions are aligned with solar maximum periods and also given the shortness of analysed time series (in our case 35 years). These concerns related to the lower stratospheric response of ozone and temperature derived from observations has already been raised (e.g. Solomon et al., 1996; Lee and Smith, 2003). However, another issue is whether or not the lower stratospheric response could depend on the model employed in the simulations (Mitchell et al., 2015b).[ales](r2,sc8;r4,sc17;r3,c3)

The observed double-peaked ozone anomaly in the vertical profile around the equator was confirmed by the simulations of coupled chemistry climate models (Austin et al., 2008).

Several past studies (e.g. Soukharev and Hood, 2006; Frame and Gray, 2010; Gray et al., 2013; Mitchell et al., 2014)~~(e.g. Soukharev and Hood, 2006; , 2010; , 2013)~~[ales](r2,sc11+c1) used multiple linear regression to extract the solar signal and separate other climate phenomena like the QBO, the effect of aerosols, North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO) or trend variability. Apart from this conventional method, it is possible to use alternative approaches to isolate and examine particular signal components, such as wavelet analysis (Pisoft et al., 2012, 2013) or empirical mode decomposition (Coughlin and Tung, 2004). The nonlinear character of the climate system also suggests potential benefits from the application of ~~alternative,~~[ales] full nonlinear attribution techniques to study of properties and interactions in the atmosphere. However, such nonlinear methods~~techniques~~[ales] have been used rather sporadically in the atmospheric sciences (e.g. Walter and Schönwiese, 2003; Pasini et al., 2006; Blume and Matthes, 2012), mainly due to their several disadvantages such as the lack of explanatory power (Olden and Jackson, 2002).

To examine middle atmospheric conditions, it is necessary to study reliable and sufficiently vertically resolved data. Systematic and global observations of the middle atmosphere only began during the International Geophysical Year (1957-1958) and were later expanded through the development of satellite measurements (Andrews and McIntyre, 1987). Supplementary data come from balloon and rocket soundings, though these are limited by their vertical range (only the lower stratosphere in the case of radiosondes) and the fact that the in situ observations measure local profiles only. By assimilation of these irregularly distributed data and discontinuous measurements of particular satellite missions into an atmospheric/climatic model, we have modern basic datasets available for climate research, so called reanalyses. These types of data are relatively long, globally gridded with a vertical range extending to the upper stratosphere or the lower mesosphere and thus suitable for 11-year SC research. In spite of their known limitations (such as discontinuities in ERA reanalysis – McLandress et al., 2014), they are considered an extremely valuable research tool (Rienecker et al., 2011). Coordinated intercomparison has been initiated by the SPARC community to understand current reanalysis products, and to contribute to future reanalysis improvements (Fujiwara et al., 2012). Under this framework the paper by Mitchell et al. (2014) has been published where 9 reanalysis datasets were examined in terms of 11-year SC, volcanic, ENSO and QBO variability. Complementing their study, we provide comparison with nonlinear regression techniques here, assessing robustness of the results obtained by Multiple Linear Regression (MLR). Furthermore, EP-flux diagnostics are used to examine solar-induced response during winter season in both hemispheres, and solar-related variations of assimilated ozone are investigated.[ales](r1,c1;r2,sc11+c1;r3,c5;r4,c4)

The paper is arranged as follows. In section 2 the used datasets are described. In section 3 the analysis methods are presented along with regressor terms employed in the regression model. Section 4 is dedicated to the description of the annual response results. In subsection 4.1.1 solar response in MERRA reanalysis is presented. Next, in subsection 4.1.2 other reanalyses are compared in terms of SC. Comparison of linear and nonlinear approaches is presented in subsection 4.1.3. Section 4.3. describes monthly evolution of SC response in the state variables. Section 5 is aimed at dynamical consequences of the SC analysed using the EP-flux diagnostics.[ales](r4,sc4)

2 Datasets

Our analysis was applied to the most recent generation~~to the last generation~~[ales](r2,sc12) of three reanalysed datasets: MERRA (Modern Era Reanalysis for Research and Applications, developed by NASA) (Rienecker et al., 2011), ERA-Interim (ECMWF Interim Reanalysis) (Dee et al., 2011) and JRA-55 (Japanese 55-year Reanalysis) (Ebita et al., 2011). We have studied the series for the period 1979-2013. All of the datasets were analysed on a monthly basis. The Eliassen–Palm (EP) flux diagnostics (described below) was computed on a 3-hourly basis from MERRA reanalysis and subsequently monthly means were produced. Similar approach has been already used by Seviour et al. (2012) and Mitchell et al. (2015a). The former study proposed that even 6-hourly data are not only necessary but should also be sufficient to diagnose tropical upwelling in the lower stratosphere.The Eliassen–Palm (EP) flux diagnostics (described below) was analysed on the daily basis and subsequently monthly averages were produced.ales(r2,c2,sc13;r4,tc1;r3,c11) The vertical range extends to the lower mesosphere (0.1 hPa) for MERRA, and to 1 hPa for the remaining reanalysesales. The horizontal resolution of the gridded datasets was $1.25°$x$1.25°$ for MERRA and JRA-55 and $1.5°$x$1.5°$ for ERA-Interim respectively.

In comparison with previous generations of reanalysesreanalysisales, it is possible to observe a better representation of stratospheric conditions. This improvement is considered to be connected with increasing the height of the upper boundary of the model domain (Rienecker et al., 2011). For example, tTales(r3,c11)he Brewer-Dobson circulation was markedly overestimated by ERA-40, an improvement was achieved in ERA-Interim, but the upward transport remains faster than observations indicate (Dee et al., 2011). Interim results of JRA-55 suggest a less biased reanalysed temperature in the lower stratosphere relative to JRA-25 (Ebita et al., 2011).

In addition toExcept forales(r3,c11) the standard variables provided in reanalysis, i.e. air temperature, ozone mixing ratio and circulation characteristics – zonal, meridional or omega velocity, we have also analysed other dynamical variables. Of particular interest were the EP flux diagnostics -= a theoretical framework to study interactions between planetary waves and the zonal mean flow (Andrews and McIntyre, 1987). Furthermore, this framework allows the study of the wave propagation characteristics in the zonal wind and the induced (large scale) meridional circulation as well. For this purpose the quasi-geostrophic approximation of Transformed Eulerian Mean (TEM) equations were used in the form employed by Edmon Jr et al. (1980), i.e. using their formula (3.1) for EP flux vectors, (3.2) for EP flux divergence and (3.4) for residual circulation. These variables were then interpolated to a regular vertical grid. For the visualization purposes the EP flux arrows were also scaled via the formula (3.13) in (Edmon Jr et al., 1980). The script was publicly released (Kuchar, 2015).~~For this purpose the quasi-geostrophic approximation of Transformed Eulerian Mean (TEM) equations was used, in the form employed by (Edmon Jr et al., 1980).~~[ales](r2,c2,sc13;r4,tc1)

3 Methods

To detect variability and changes due to climate-forming~~external climate~~[ales] factors, such as the 11-year SC, we have applied an attribution analysis based on Multiple Linear Regression (MLR) and two nonlinear techniques. The regression model separates the effects of climate phenomena that are supposed to have an impact on middle atmospheric conditions. Our regression model of a particular variable X as a function of time t, pressure level p, latitude φ and longitude λ[ales](r4,sc5) is described by the following equation:

$$\begin{aligned}X(t,z,\varphi,\lambda) = &\sum_{i=1}^{12}\alpha_i(z,\varphi,\lambda)+\beta(z,\varphi,\lambda)\,t\\ &+\gamma(z,\varphi,\lambda)\,\mathrm{SOLAR}(t)+\delta_1(z,\varphi,\lambda)\,\mathrm{QBO}_1(t)\\ &+\delta_2(z,\varphi,\lambda)\,\mathrm{QBO}_2(t)+\delta_3(z,\varphi,\lambda)\,\mathrm{QBO}_3(t)\\ &+\varepsilon(z,\varphi,\lambda)\,\mathrm{ENSO}(t)+\zeta(z,\varphi,\lambda)\,\mathrm{SAOD}(t)\\ &+\eta(z,\varphi,\lambda)\,\mathrm{NAO}(t)+e(t,z,\varphi,\lambda).\end{aligned} \tag{1}$$

After deseasonalizing which can be represented by α_i indices for every month in a year, the individual terms represent~~we have applied~~[ales](r2,sc14) a trend regressor t either in linear form or including the Equivalent Effective Stratospheric Chlorine (EESC) index (this should be employed due to the ozone turnover trend around the middle of the 90s), t~~. T~~[ales](r2,sc14)he SC ~~is~~[ales] represented by the 10.7 cm radio flux as a proxy for solar ultraviolet variations at wavelengths 200-300 nm that are important for ozone production and radiative heating in the stratosphere, and[ales](r3,c14) which correlates well with sunspot number variation (the data were acquired from Dominion Radio Astrophysical Observatory (DRAO) in Penticton, Canada).

We have also[ales] included the quasi-biennial proxies as another stratosphere-related predictor. Similar studies have represented the QBO in multiple regression methods in several ways. Our approach involves three separate QBO indices extracted from the each~~MERRA~~[ales](r4,sc reanalysis. These three indices are the first three principal components of the residuals of our linear regression model (1) excluding QBO predictors applied to the equatorial zonal wind. The approach follows the paper by Frame and Gray (2010), or the study by Crooks and Gray (2005) to avoid contamination of the QBO regressors by the solar signal or other regressors[ales](r4,sc6). The three principal components explain 49%, 47% and 3% of the total variance for the MERRA; 60%, 38% and 2% for the JRA-55; 59%, 37% and 3% for the ERA-Interim[ales](r4,sc6). The extraction of the first two components reveals a 28 month periodicity and an out-of phase relationship between the upper and lower stratosphere. The out-of phase relationship or orthogonality manifests approximately in a quarter period shift of these components. The deviation from the QBO quasi-regular period represented by the first two dominant components is contained in the residual variance ~~of 4%~~[ales]. Linear regression analysis of the zonal wind with the inclusion of the first two principal components reveals a statistically significant linkage between the third principal component and the residuals of this analysis. Furthermore, the regression coefficient of this QBO proxy was statistically significant for all variables ~~tested for a~~[ales] p-value < 0.05 (see below for details about significance testing~~statistical significance~~[ales] techniques). Wavelet analysis for the MERRA[ales] demonstrates three statistically significant but non-stationary periods exceeding the level of the white noise wavelet spectrum (not shown): an approximate annual cycle (a peak period of 1 year and 2 months), a cycle with a peak period of 3 years and 3 months and a long-period cycle (a peak period between 10 and 15 years). Those interferences can be attributed to the possible non-linear interactions between the QBO itself and other signals like the annual cycle or long-period cycle such as the 11-year SC at the equatorial stratosphere.

The El Niño Southern Oscillation is represented by the Multivariate ENSO index (MEI) which is computed as the first principal component of the six main observed variables over the Pacific Ocean: sea level pressure, zonal and meridional wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky (NCAR, 2013). The effect of volcanic eruptions is represented by the Stratospheric Aerosol Optical Depth (SAOD). The time series was derived from the optical extinction data (Sato et al., 1993). We have used globally averaged time series in our regression model. The North Atlantic Oscillation has also been included through its~~in the respective~~[ales] index derived by ~~a~~[ales] rotated principal component analysis ~~technique~~[ales] applied to the monthly standardized 500-hPa height anomalies obtained from the Climate Data Assimilation System (CDAS) in the Atlantic region between 20°N-90°N (NOAA, 2013).

The robustness of solar regression coefficient has been tested in terms of including or excluding particular regressors in the regression model, e.g. NAO term was removed from the model and resulting solar regression coefficient was compared with the solar regression coefficient from the original regression setup. The solar regression coefficient seems to be highly robust since neither the amplitude nor statistical significance field was not changed significantly when NAO or QBO_3 or both of them were removed. However, cross-correlation analysis reveals that the correlation between NAO and TREND, SOLAR and SAOD regressors is statistically significant, but small (not shown).[ales](r1,c3,c4;r3,c13;r4,sc7)

The multiple regression model via eq. (1) has been used for the attribution analysis, and supplemented by two nonlinear techniques. The MLR coefficients were estimated by the least squares method. To avoid the effect of autocorrelation of residuals and to obtain the Best Linear Unbiased Estimate (BLUE) according to the Gauss-Markov theorem (Thejll, 2005), we have used an iterative algorithm to model the residuals as a second-order autoregressive process. Durbin-Watson test confirmed that this setup was sufficient to model most of the residual autocorrelations in the data.~~we have used an iterative algorithm to model the residuals as a second-order autoregressive process. The Durbin-Watson statistic has been used to detect the autocorrelation of the error terms from the regression model.~~[ales](r2,sc15)

As a result of the uncorrelated residuals, we can suppose the standard deviations of the estimated regression coefficients not to be diminished (Neter et al., 2004). The statistical significance of the regression coefficients was computed with a t-test.

The nonlinear approach, in our case, consisted of Multi Layer Perceptron (MLP) and the relatively novel epsilon[ales](r4,sc9) Support Vector Regression (ε–[ales](r4,sc9)SVR) technique with the threshold parameter $\varepsilon = 0.1$[ales](r4,sc9) ~~in our case~~[ales](r4,tc9). The MLP as a technique inspired by the human brain is~~highly complex and~~[ales](r4,sc8) capable of capturing non-linear interactions between inputs (regressors) and output (modelled data) (e.g. Haykin, 2009). The nonlinear approach is achieved by transferring the input signals through a sigmoid function in a particular neuron and within a hidden layer propagating to the output (a so called feed–[ales](r3,c16)forward propagation). The standard error back–[ales](r3,c16)propagation iterative algorithm to minimize the global error has been used.

The Support Vector Regression technique belongs to the category of kernel methods. Input variables were nonlinearly transformed to a high-dimensional space by a radial basis (Gaussian) kernel, where a linear classification (regression) can be constructed (Cortes and Vapnik, 1995). However, cross-validation must be used to establish a kernel parameter and cost function searched in the logarithmic grid from 10^{-5} to 10^{1} and from 10^{-2} to 10^{5} respectively[ales](r4,sc9). We have used 5-fold cross-validation to optimize the SVR model selection for every point in the dataset as a trade-off between the recommended number of folds (Kohavi, 1995) and computational time. The MLP model was validated by the holdout method since this method is more expensive in order of magnitude compared to computational time. The datasets were separated into a training set (75% of the whole dataset) and a testing set (25% of the whole dataset). The neural network model was restricted to only one hidden layer with the maximum number of neurons set up to 20.[ales](r4,sc9)

The earlier mentioned lack of explanatory power of the nonlinear techniques in terms of complicated interpretation of statistical models (Olden and Jackson, 2002)[ales](r4,sc10) mainly comes from nonlinear interactions during signal propagation and the impossibility to directly monitor the influence of the input variables. In contrast to the linear regression approach, the understanding of relationships between variables is quite problematic. For this reason, the responses of our variables have been modelled by a technique originating from sensitivity analysis studies and also used by e.g. Blume and Matthes (2012). The relative impact RI of each variable was computed as

$$RI = \frac{I_k}{\sum I_k}, \tag{2}$$

where $I_k = \sigma(\hat{y} - \hat{y_k})$. $\sigma(\hat{y} - \hat{y_k})$ is variance of[ales](r4,sc12) difference between the original model output $\hat{y}$ and the model output $\hat{y_k}$ when the k-input variable was held at its constant level. There are many possibilities with regard to which constant level to choose. It is possible to choose several levels and then to observe the sensitivity of model outputs varying for example on minimum, median and maximum levels. Our sensitivity measure (relative impact) was based on the median level. The primary reason comes from purely[ales](r3,c17) practical considerations - to compute our results fast enough as another weakness of the nonlinear techniques lies in the larger requirement of computational capacity. In general, this approach was chosen because of their relative simplicity for comparing all techniques to each other and to be able to interpret them too. The contribution of variables in neural network models has already been studied and Gevrey et al. (2003) produced a review and comparison of these methods.

4 Results

4.1 Annual response (MERRA)

Figure 1(a,d,g,j) shows the annually averaged solar signal in the zonal and altitudinal means of temperature, zonal wind, geopotential height and ozone mixing ratio. The signal is expressed as the average difference between the solar maxima and minima in the period 1979-2013, i.e. normalized by 126.6 solar radio flux units[ales](r3,c14;r4,sc13). Statistically significant responses detected by the linear regression in the temperature series (see Fig. 1(a)) are positive and are located around the equator in the lower stratosphere with values of about 0.5 K. The temperature response increases to 1 K in the upper stratosphere at the equator and up to 2 K at the poles. The significant solar signal anomalies are more variable around the stratopause and not limited to the equatorial regions. Hemispheric asymmetry of the statistical significance can be observed in the lower mesosphere. From a relative impact point of view (in Figs. 2(a)-(c) marked as RI), it is difficult to detect a signal with an impact larger than 20% in the lower stratosphere where the volcanic and QBO impacts dominate. In the upper layers (where the solar signal expressed by the regression coefficient is continuous across the equator) we have detected relatively isolated signals (over 20%) around $\pm 15^{\circ}$ using the relative impact method. The hemispheric asymmetry also manifests in the relative impact field, especially in the SVR field in the mesosphere.

The annually averaged solar signal in the zonal-mean of zonal wind (Figs. 1(d) and 2(d)-(f)) dominates around the stratopause as an enhanced subtropical westerly jet. The zonal wind variability due to the SC corresponds with the temperature variability due to the change of the meridional temperature gradient and via the thermal wind equation. The largest positive anomaly in the northern hemisphere reaches 4 m/s around 60 km (Fig. 1(d)). In the southern hemisphere, the anomaly is smaller and not statistically significant. There is a significant negative signal in the southern polar region and also at the equator especially in the mesosphere. The negative anomalies correspond with a weakening of the westerlies or an amplification of the easterlies. The relative impact of the SC is similarly located zonally even for both nonlinear techniques (Figs. 2(d)-(f)). The equatorial region across all the stratospheric layers is dominantly influenced by the QBO (expressed by all 3 QBO regressors) and for this reason the solar impact is minimized around the equator.

The pattern of the solar response in geopotential height (Figs. 1(g) and 2(g)-(i)) shows positive values in the upper stratosphere and lower mesosphere. This is also consistent with the zonal wind field thorough thermal wind balance. In the geopotential field, the SC influences the most extensive area among all regressors. The impact area includes almost the whole mesosphere and the upper stratosphere.

The ~~last row of~~ [ales] figure 1(j) also shows the annual mean solar signal in the zonal mean of the ozone mixing ratio (expressed as a percent change from the solar maximum to the solar minimum). By including EESC regressor term in the regresssion model~~Using the model with EESC~~[ales](r2,sc17) instead of a linear trend over the whole period (for more detailed description see methodology section)[ales](r2,sc17), we tried to capture the ozone trend change around the year 1996. Another possibility was to use our model over two individual periods, e.g. 1979-1995 and 1996-2013, but the results were quantitatively similar. The main common feature of other results is the positive ozone response in the lower stratosphere, ranging from a 1 to 3 percent change. The majority of results share the positive ozone response. In the equatorial upper stratosphere, no other relevant solar signal was detected compared to the study based on satellite measurement (Soukharev and Hood, 2006). By the relative impact method (Figs. 2(j)-(l)), we have obtained results comparable with linear regression coefficients, but especially around the stratopause the impact suggested by nonlinear techniques does not reach the values achieved by linear regression.

4.1.1 Annual response — C~~(e~~[ales](t4,tc6)omparison with JRA-55, ERA-Interim~~)~~[ales](t4,tc7)

Comparison of the results for the MERRA, ERA-Interim and JRA-55 temperature, zonal wind and geopotential height shows that the annual responses to the solar signal are in qualitative agreement (compare figures in Fig. 1). The zonal wind and geopotential response seems to be consistent in all presented methods and datasets. The largest discrepancies can be seen in the upper stratosphere and especially in the temperature field (the first row in these figures). The upper stratospheric equatorial anomaly was not detected by any of the regression techniques in the case of the JRA-55 reanalysis although the JRA-25 showed a statistically significant signal with structure and amplitude of 1-1.25 K comparable with ERA-Interim in the equatorial stratopause (Mitchell et al., 2014)[ales](r2,sc16). Furthermore~~On the other hand~~[ales], the anomaly in the MERRA~~ERA-Interim~~[ales](r2,sc16) temperature in Fig. 1(a) almost reaches the same value as in the ERA-Interim~~MERRA~~[ales] series nevertheless the upper-stratospheric equatorial signal is situated lower down at around 3 hPa (Mitchell et al., 2014)[ales](r2,sc16). However, upper-stratospheric temperature response could be less than accurate due to the existence of discontinuities in 1979, 1985 and 1998 (McLandress et al., 2014) coinciding with solar maxima. Therefore, the temperature response to solar variation may be influenced by these discontinuities in the upper stratosphere. The revised analysis with the adjustments from McLandress et al. (2014) showed in comparison with the original analysis without any adjustment that the most pronounced differences are apparent in higher latitudes and especially in 1 hPa. However, the regression coefficients decreased by about 50% when using adjusted dataset and the differences are not statistically significant in terms of 95% confidence interval. The difference in tropical latitudes is about 0.2 K/(Smax-Smin). The trend regressor t from Eq. 1 reveal large turnaround from positive trend to negative in the adjusted levels, i.e. 1, 2, 3 and 5 hPa. Other regressors do not reveal any remarkable difference. The results in Figs. 1(b,e,h,k) and 3 from raw dataset ware kept in order to refer and discuss the accordance and difference between our results and results from Frame and Gray (2010); Mitchell et al. (2014), where no adjustment has not considered as well.[ales](r3,c2,c19)

The variability of the solar signal in the MERRA stratospheric ozone series was compared with the ERA-Interim results. The analysis points to large differences in the ozone response to the SC between the reanalyses and even in comparison with satellite measurements by Soukharev and Hood (2006). In comparison with the satellite measurements, no relevant solar signal was detected in the upper stratosphere in the MERRA series. The signal seems to be shifted above the stratopause (confirmed by all techniques, shown in Figs. 2 and 3(j)-(l)). Regarding the ERA-Interim, there is an ozone response to the SC in the upper stratosphere. This statistically significant response indicates negative anomalies with values reaching up to 2% above the equator and up to 5% in the polar regions of both hemispheres. The negative response could be interpreted as a consequence of temperature rise leading to increased ozone losses because of the temperature dependence of the reaction rates that control the ozone balance in the upper stratosphere. This interpretation does not require that the assimilation model had included interactive ozone chemistry since in the model used for ERA-Interim the ozone as a prognostic variable is relaxed towards a photochemical equilibrium for the local value of the ozone mixing ratio, the temperature, and the overhead ozone column (Dee et al., 2011). An additional term is used to parameterize the heterogeneous chemistry. This fact together with the finding that the temperature and ozone are highly negatively correlated in the upper stratosphere, e.g. -0.93 for zonal mean between 15°S and 15°N in 1 hPa, provide reasonable explanation of the negative ozone response to the SC which is driven by temperature variability in the upper stratosphere. In the case of MERRA, while SBUV ozone profiles are assimilated with SC passed to forecast model (as ozone analysis tendency contribution), no SC was passed to the radiative part of the model. The same is also true for ERA-Interim and JRA-55 (see descriptive table of reanalysis product on SC in irradiance and ozone in Mitchell et al. (2014). Among other tendencies the dynamics and chemistry components also contribute to total tendency of ozone. These two tendencies prevent any variations in ozone analysis tendency though. Thus periods longer than 1 year are filtered out in the upper stratosphere. Only annual and semi-annual cycles are included. The SC-like periods seem to be diminishing approximately from 5 hPa except in the polar regions fro both hemispheres. The negative correlation -0.93 between sum of the tendency of dynamics and chemistry and tendency from analysis for zonal mean in the tropical upper stratosphere confirms this statement as well. This negative correlation roots from anti-phase relationship between the tendency from dynamics and chemistry. Therefore despite the fact that the analyzed ozone should contain a solar signal, the signal is very weak and is compensated by internal model variability in terms of dynamics and chemistry. Since the SBUV ozone profiles have very low vertical resolution this may also affect the ozone response to the SC in the reanalysis. These facts should be also taken into account in case of monthly response discussion of particular variables in the section 4.2.~~The negative response can be connected with a higher destruction of ozone during the solar maximum period and consequent heating of the region.~~[ales](r3,c1;r4,sc14)

The lower stratospheric ozone response~~solar signal~~[ales](r4,sc15) in the ERA-interim is not limited to the equatorial belt ±30° up to 20 hPa, as in the case of the MERRA reanalysis, and the statistical significance of this signal is rather reduced. The solar signal is detected higher and extends from the subtropical areas to the polar regions. The results suggest that the solar response in the MERRA series is more similar to the results from satellite measurements (Soukharev and Hood, 2006). Nevertheless, further comparison with independent data sets is needed to assess the data quality in detail.

4.1.2 Comparison of the linear and nonlinear approaches (MLR vs. SVR & MLP)

In this paper, we have applied and compared one linear (MLR) and two nonlinear attribution (SVR and MLP) techniques. The response of the studied variables to the solar signal and other forcings was studied using the sensitivity analysis approach i[ales](r2,sc18)n terms of averaged response deviation from the equilibrium represented by the original model output $\hat{y}$ (Blume and Matthes, 2012). This approach does not recognize a positive or negative response as the linear regression does. For this reason, the relative impact results are compared to the regression's coefficients. Using linear regression, it would be possible to assess~~analyse~~[ales](r2,sc18) the statistical significance of the regression's coefficients and a particular level of the relative impact since they are linearly proportional[ales](r2,sc18). ~~Due to a higher variance, the significance levels of the relative impact are not estimated.~~[ales](r2,sc18) A comparison between the linear and nonlinear approaches by the relative impact fields shows qualitative and in most regions also quantitative agreement. The most pronounced agreement is observed in the zonal wind (Figs. 2, 3 and 4(d)-(f)) and geopotential height fields (Figs. 2, 3 and 4(g)-(i)). On the other hand worse agreement is captured in the ozone and temperature field. In the temperature field the upper stratospheric solar signal reaches values over 20%, some individual signals in the Southern H~~northern h~~[ales](r4,sc16)emisphere even reach 40%. However, using the relative impact approach, the lower stratospheric solar signal in the temperature field (which is well established by the regression coefficient) does not even reach 20% because of the dominance the QBO and volcanic effects. These facts emphasize that nonlinear techniques contribute to the robustness of attribution analysis since the linear regression results were plausibly confirmed by the SVR and MLP techniques.

In conclusion t~~However, the statistical significance of individual responses could have been estimated by the bootstrap technique, which is quite expensive for computational time, and for this reason was not applied. T~~[ales](r4,sc18)he comparison of various statistical approaches (MLR, SVR and MLP) should actually contribute to the robustness of the attribution analysis including the statistically assessed uncertainties. These uncertainties could partially stem from the fact that the SVR and Neural network techniques are dependent on an optimal model setting which is based on a rigorous cross-validation process, which places a high demand on computing time.

The major differences between the techniques can be seen in how much of the temporal variability of the original time series is explained~~they can simulate the original time series~~[ales](r4,sc19), i.e. in the coefficient of determination. For instance, the differences of the explained variance reach up to 10% between linear and nonlinear techniques, although the zonal[ales] structure of the coefficient of determination is almost the same. To conclude, nonlinear techniques show an ability to simulate the middle atmosphere variability with a higher accuracy than cross-validated linear regression.

4.2 Monthly response (MERRA)

As was pointed out by Frame and Gray (2010), it is necessary to examine the solar signal in individual months because of a solar impact on polar-night jet oscillation (Kuroda and Kodera, 2001)~~variable solar impact throughout the year~~[ales](r2,sc20). For example, the amplitude of the lower stratospheric solar signal in the northern polar latitudes in February exceeds the annual response since the SC influence on vortex stability is most pronounced in February. Besides the radiative influences of the SC, we discuss the dynamical response throughout the polar winter (Kodera and Kuroda, 2002).

Statistically significant upper stratospheric equatorial anomalies in the temperature series (winter months in Figs. 5 and 6(a)-(d)) are expressed in almost all months. Their amplitude and statistical significance vary throughout the year. The variation between the solar maxima and minima could be up to 1 K in some months. Outside the equatorial regions, the fluctuation could reach several kelvins. The lower stratospheric equatorial anomaly strengthens during winter. This could be an indication of dynamical changes, i.e. alteration~~alternation~~[ales](r4,tc9) of the residual circulation between the equator and polar regions (for details please see section 5)~~the discussion~~[ales]. Aside from the radiative forcing by direct or ozone heating, other factors are linked to the anomalies in the upper levels of the middle atmosphere (Haigh, 1994; Gray et al., 2009). It is necessary to take into consideration the dynamical coupling with the mesosphere through changes of the residual circulation (see the ~~below~~[ales] dynamical effects discussion below[ales]). That can be illustrated by the positive anomaly around the stratopause in February (up to 4K around 0.5 hPa). This anomaly extends further down~~propagates downward~~[ales](r4,sc20) and, together with spring radiative forcing, affects the stability of the equatorial stratopause. Hemispheric asymmetry in the temperature response above the stratopause probably originates from the hemispheric differences, i.e. different wave activity (Kuroda and Kodera, 2001)[ales](r2,sc21). These statistically significant and positive temperature anomalies across the subtropical stratopause begin to descend and move to higher latitudes in the beginning of the northern winter. The anomalies manifest fully in February in the region between $60^{\circ}-90^{\circ}$N and ~~below 10 hPa and~~[ales](r4,sc21) reach tropospheric levels – contrary to the results for the southern hemisphere (see Fig. 10 in Mitchell et al., 2014)[ales](r4,sc21). The southern hemispheric temperature anomaly is persistent above the stratopause and the SC influence on the vortex stability differs from those in the northern hemisphere.

The above described monthly anomalies of temperature correspond with the zonal wind anomalies throughout the year (Figs. 5 and 6(e)-(h)). The strengthening of the subtropical jets around the stratopause is most apparent during the winter in both hemispheres. This positive zonal wind anomaly gradually descends and moves poleward similar to Frame and Gray (2010) analysis based on ERA-40 data. In February, the intensive stratospheric warming and mesospheric cooling is associated with a more pronounced transition from winter to summer circulation attributed to the SC (in relative impact methodology up to 30%). However, GCMs have not yet successfully simulated the strong warming in February (e.g. Schmidt et al., 2010; Mitchell et al., 2015b). Due to the short (35-year) time series, it is possible that this pattern is not really solar in origin but is instead a consequence of internal climate variability or aliasing from effects of the two major volcanic eruptions aligned to solar maximum periods Chiodo et al. (2014).[ales](r3,c4)

In the southern hemisphere, this poleward motion of the positive zonal wind anomaly halts approximately at 60°S. For example in August, we can observe a well-marked latitudinal zonal wind gradient (Fig. 6(h)). Positive anomalies in the geopotential height field correspond with the easterly zonal wind anomalies. The polar circulation reversal is associated with intrusion of ozone from the lower latitudes as it is apparent, e.g., in August in the southern hemisphere and in February in the northern hemisphere (last rows of Figs. 5 and 6).

When comparing the results from~~of~~[ales] the MERRA and ERA-40 series studied by Frame and Gray (2010), distinct differences were found (Figs. 5(e)-(f)) in the equatorial region of the lower mesosphere in October and November. W~~, w~~[ales](r3,c20)hile in the MERRA reanalysis we have detected an easterly anomaly above 1 hPa in both months (only November shown)[ales](r4,sc23), a westerly anomaly was identified in the ERA-40 series. Further distinct differences in the zonal mean temperature and zonal wind anomalies were not found.

5 Dynamical effects discussion

In this section, we discuss the dynamical impact of the SC and its influence on middle atmospheric winter conditions. Linear regression was applied to the EP diagnostics. Kodera and Kuroda (2002) suggested that the solar signal produced in the upper stratosphere region is transmitted to the lower stratosphere through the modulation of the internal mode of variation in the polar night jet and through a change in the Brewer-Dobson circulation (prominent in the equatorial region in the lower stratosphere). In our analysis, we discussed the evolution of the winter circulation with an emphasis on the vortex itself rather than the behavior of the jets. Further, we try to describe~~deduce~~[ales](r3,c21) the possible processes leading to the observed differences in the quantities of state between the solar maximum and minimum period. Because the superposition principle only holds for linear processes, it is impossible to deduce the dynamics merely from the fields of differences. As noted by Kodera and Kuroda (2002), the dynamical response of the winter stratosphere includes highly nonlinear processes, e.g. wave mean flow interactions. Thus, both the anomaly and the total fields, including climatology, must be taken into account.

We start the analysis of solar maximum dynamics with the period of the northern hemispheric winter circulation formation. The anomalies of the ozone, temperature, geopotential and Eliassen-Palm flux divergence support the hypothesis of weaker BDC during the solar maximum due to the less intensive wave pumping. This is consistent with previous studies (Kodera and Kuroda, 2002; Matthes et al., 2006). The causality is unclear, but the effect is visible in both branches of BDC as is illustrated~~explained~~[ales] by Fig. 5 and summarized schematically in Fig. 7.

During the early Northern hemispheric (NH) winter (including November)~~November~~[ales](r2,sc22) when westerlies develop in the stratosphere, we can observe a deeper polar vortex and consequent stronger westerly winds both inside and outside the vortex. However, only the westerly anomaly outside the polar region and around 30°N from 10 hPa to the lower mesosphere is statistically significant (see the evolution of zonal wind anomalies in Figs. 5(e)-(h)). The slightly different wind field has a direct influence on the vertical propagation of planetary waves. From the Eliassen-Palm flux anomalies and climatology we can see that the waves propagate vertically with increasing poleward instead of equatorward meridional direction with height. This is then reflected in the EP flux divergence field, where the region of maximal convergence is shifted poleward and the anomalous convergence region emerges inside the vortex above approximately 50 hPa (Figs. 5(m)-(p)).

The poleward shift of the maximum convergence area further contributes to the reduced BDC. This is again confirmed by the temperature and ozone anomalies. The anomalous convergence inside the vortex induces anomalous residual circulation, the manifestation of which is clearly seen in the quadrupole-like temperature structure (positive and negative anomalies are depicted schematically in Fig. 7 using red and blue boxes respectively). This pattern emerges in November and even more clearly in December. In December, the induced residual circulation leads to an intrusion of the ozone rich air into the vortex at about the 1 hPa level (Fig. 5(s)). The inhomogeneity in the vertical structure of the vortex is then also pronounced in the geopotential height differences. This corresponds with the temperature analysis in the sense that above and in the region of the colder anomaly there is a negative geopotential anomaly and vice versa. The geopotential height difference has a direct influence on the zonal wind field (via the thermal wind balance). The result is a deceleration of the upper vortex parts and consequent broadening of the upper parts (due to the conservation of angular momentum).

Considering the zonal wind field, the vortex enters January approximately with its average climatological extent. The wind speeds in its upper parts are slightly higher. This is because of the smaller geopotential values corresponding to the negative temperature anomalies above approximately 1 hPa. This probably[ales](r2,sc23) results from the absence of adiabatic heating due to the suppressed BDC, although the differences in the quantities of state (temperature and geopotential height) are small and insignificant (see the temperature anomalies in Fig. 5(c)). It is important to note that these differences change sign around an altitude of 40 km inside the vortex further accentuating the vertical inhomogeneity of the vortex. This might start balancing processes inside the vortex, which is confirmed by analysis of the dynamical quantities, i.e. EP flux and its divergence (Fig. 5(o)). ~~A detailed description of these processes is the key to understanding the dynamics and causality of Sudden Stratospheric Warmings (SSWs) taking place in February.~~[ales](r4,sc25)

Significant anomalies of the EP flux indicate anomalous vertical wave propagation resulting in the strong anomalous EP flux convergence being significantly pronounced in a horizontally broad region and confined to upper levels (convergence (negative values) drawn by green or blue shades in Figs. 5(m)-(p)). This leads to the induction of an anomalous residual circulation starting to gain intensity in January. The situation then results in the disruption of the polar vortex visible in significant anomalies in the quantities of state in February – in contrast to January. Further strong mixing of air is suggested by the ozone fields. The quadrupole-like structure of the temperature is visible across the whole NH middle atmosphere in February (indicated in the lower diagram of Fig. 7), especially in the higher latitudes. This is very significant and well pronounced by the stratospheric warming and mesospheric cooling.

The hemispheric asymmetry of the SC influence can be especially documented in winter conditions as was already suggested in section 4.2. Since the positive zonal wind anomaly halts at approximately 60°S and intensifies over 10 m/s, one would expect the poleward deflection of the planetary wave propagation to be according to NH winter mechanisms discussed above. This is actually observed from June to August when the highest negative anomalies of the latitudinal component~~coordinates~~[ales](r4,sc26) of EP flux are located in the upper stratosphere and in the lower mesosphere (Figs. 6(m)-(p)). The anomalous divergence of EP flux develops around the stratopause between 30°S and 60°S. Like the hypothetical mechanism of weaker BDC described above, we can observe~~assume~~[ales](r3,c22) less wave pumping in the stratosphere and consequently ~~assume~~[ales](r3,c22) less upwelling in the equatorial region. In line with that, we can see in the lower stratosphere of equatorial region (Fig. 5(b) and 6(b)) a more pronounced temperature response in August (above 1 K) than in December (around 0.5 K) as already mentioned in previous observational (van Loon and Labitzke, 2000) or reanalysis (Mitchell et al., 2014) studies. Although this can point to a more weakened BDC, the residual circulation (Fig. 6(q)-(t)) as a proxy for BDC (Butchart, 2014) does not reveal this signature. Hypothetically this could be due higher role of unresolved wave processes in reanalysis (small-scale gravity waves) or due to the worse performance of residual circulation as a proxy for the large-scale transport in SH (e.g. larger departure from steady waves approximation comparing to NH), or because of the other processes than BDC leading to the temperature anomaly, e.g. aliasing with volcanic signal.~~However, the anomalies of the residual circulation pointing to a weaker BDC are not so well established as in the case of the NH winter. These mechanisms could lead to an explanation for the more pronounced temperature response to the solar signal in the equatorial region of the lower stratosphere in August for the SH winter (above 1 K) than in December for the NH winter (around 0.5 K). This is in agreement with another observational study (van Loon and Labitzke, 2000).~~[ales](r3,c22)

Overall, the lower stratospheric temperature anomaly is more coherent for the SH winter than for the NH winter, where the solar signal is not so well apparent or statistically significant in particular months and reanalysis datasets.

6 Conclusions

We have analysed the changes of air temperature, ozone and circulation characteristics driven by the variability of the 11-year solar cycle's influence on the stratosphere and lower mesosphere. Attribution analysis was performed on the three reanalysed datasets: MERRA, ERA-Interim and JRA-55;~~last generation of reanalysed data,~~[ales](r4,sc27) and aimed to compare how these types of datasets resolve the solar variability throughout the levels where the "Top-Down" mechanism is assumed. Furthermore, the results originated in linear attribution using MLR were compared with other relevant attribution~~observational~~[ales](r4,sc29) studies and supported by nonlinear attribution analysis using SVR and MLP techniques.

The nonlinear approach to attribution analysis, represented by the application of the SVR and MLP, largely confirmed the solar response computed by linear regression. Consequently, these results can be considered quite robust regarding the statistical modeling of the solar variability in the middle atmosphere. This finding indicates that linear regression is a sufficient technique to resolve the basic shape of the solar signal through the middle atmosphere. However, some uncertainties could partially stem from the fact that the SVR and MLP techniques are highly dependent on an optimal model setting that requires a rigorous cross-validation process (which places a high demand on computing time). As a benefit, nonlinear techniques show an ability to[ales](r3,c25) simulate the middle atmosphere variability with higher accuracy than linear regression.

The solar signal extracted from the temperature field from MERRA and ERA-Interim reanalysis using linear regression has the amplitudes around 1 K and 0.5 K, in the upper stratospheric and in the lower stratospheric equatorial region, respectively. These signals, statistically significant at a p-value < 0.01, ~~can be considered sufficiently robust and they~~[ales](r4,sc28) are in qualitative agreement with previous attribution~~observational~~[ales](r4,sc29) studies (e.g. Frame and Gray, 2010; Mitchell et al., 2014)~~. since we have used the generation of reanalysed datasets extended to 2013.~~[ales](r2,sc12) The statistically significant signal was only observed in the lower part of the stratosphere in the JRA-55 reanalysis, however with similar amplitudes as the other datasets.

Similar to the temperature response, the double-peaked solar response in ozone was detected in satellite measurements (e.g. Soukharev and Hood, 2006) and in spite of that the concerns about physical mechanism of the lower stratospheric response was expressed (e.g. Austin et al., 2008).~~even confirmed by the coupled chemistry climate model simulations (e.g. Austin et al., 2008).~~[ales](r3,c24) However, the exact position and amplitude of both ozone anomalies remain a point of disagreement between models and observations. The results of our attribution analysis point to large differences in the upper stratospheric ozone response to the SC in comparison with the studies mentioned above and even between reanalyses themselves. The upper stratospheric ozone anomaly reaches 2% in the SBUV(/2) satellite measurements (e.g. Soukharev and Hood, 2006, Fig. 5) which were assimilated as the only source of ozone profiles in MERRA reanalysis. This fact is remarkable since the same signal was not detected in the upper stratosphere in the MERRA results. However, the solar signal in the ozone field seems to be shifted above the stratopause where similar and statistically significant solar variability was attributed. Concerning the solar signal in the ERA-Interim, there is a negative ozone response via a regression coefficient in the upper stratosphere although the solar variability expressed as relative impact appears to be in agreement with satellite measurements. Furthermore, the lower stratospheric solar response in the ERA-Interim's ozone around the equator is reduced in this dataset and shifted to higher latitudes. Another difference was detected in the monthly response of the zonal wind in October and November in the equatorial region of the lower mesosphere between the results for the MERRA series and ERA-40 data studied by Frame and Gray (2010). While in the MERRA reanalysis we have detected an easterly anomaly, a westerly anomaly was identified in the ERA-40 series.

A similar problem with the correct resolving of the double-peaked ozone anomaly was registered in the study of Dhomse et al. (2011) which investigated the~~in~~[ales](r3,c25) solar response in the tropical stratospheric ozone using a 3D chemical transport model. The upper stratospheric solar signal observed in SBUV/SAGE and SAGE-based data could only be reproduced in model runs with unrealistic dynamics, i.e. with no inter-annual meteorological changes.

The reanalyses have proven to be extremely valuable scientific tools (Rienecker et al., 2011). On the other hand, they have to be used with a caution for example, due the existence of large discontinuities occurring in 1979, 1985 and 1998 (McLandress et al., 2014) that translated into errors in the derived solar coefficients. For instance the revised analysis with the adjustments from McLandress et al. (2014) resulted to 0.2 K/(Smax-Smin) difference between regression coefficients in tropical latitudes of the upper stratosphere.[ales](r3,c23)

In the dynamical effects discussion, we described the dynamical impact of the SC on middle atmospheric winter conditions. ~~The main part deals with the solar influence on northern winter conditions nevertheless, southern winter anomalies were also discussed.~~[ales](r3,c25;r4,sc30) The relevant dynamical effects are summarized in schematic diagrams (Fig. 7). Both diagrams depict average conditions and anomalies induced by the SC. The first one summarizes how equatorward wave propagation is influenced by the westerly anomaly around the subtropical stratopause. The quadrupole-like temperature structure is explained by anomalous residual circulation in the higher latitudes together with the anomalous branch heading towards the equatorial region already hypothesized by Kodera and Kuroda (2002). The second diagram concludes the transition time to vortex disruption during February. Again, a very apparent quadrupole-like temperature structure is even more pronounced, especially in the polar region and seems to be more extended to lower latitudes.

Fields of residual circulation and EP flux divergence in February are showing an opposite to what would be expected from the suppressed BDC in the SC max. There is an enhanced downwelling in polar and enhanced upwelling in eq. region under 1 hPa, suggesting the need to diagnose the influence of SC on transport at least on monthly scale because the changes in the underlying dynamics (compare the upper and lower diagram in Fig. 7) would make the transport pathways more complicated.[ales](r1,c6) Since GCMs have not yet successfully simulated this pattern (e.g. Schmidt et al., 2010; Mitchell et al., 2015b) and due to the short (35-year) time series, it is possible that this pattern is not really solar in origin but is instead a consequence of internal climate variability or aliasing from effects of the two major volcanic eruptions aligned to solar maximum periods (Chiodo et al., 2014).[ales](r1,c6;r3,c4)

However, we can strongly assume that the dynamical effects are not zonally uniform, as it is shown~~supposed and presented~~[ales] here using two-dimensional (2D) EP diagnostics and TEM equations. Hence, it would be interesting~~So it would be desirable~~[ales](r4,sc31) to extend the discussion of dynamical effects for other relevant characteristics, for example, for the analysis of wave propagation and wave-mean flow interaction using the 3D formulation (Kinoshita and Sato, 2013).

This paper is fully focused on the SC influence, i.e. on decadal changes in the stratosphere and lower mesosphere, although a huge amount of results concerning other forcings was generated by attribution analysis. The QBO phenomenon in particular could be one of the points of future interest~~The QBO phenomenon could be one of them~~[ales] since the solar-QBO interaction and the modulation of Holton-Tan relationship by the SC are regarded as highly challenging, especially in global climate simulations (Matthes et al., 2013).

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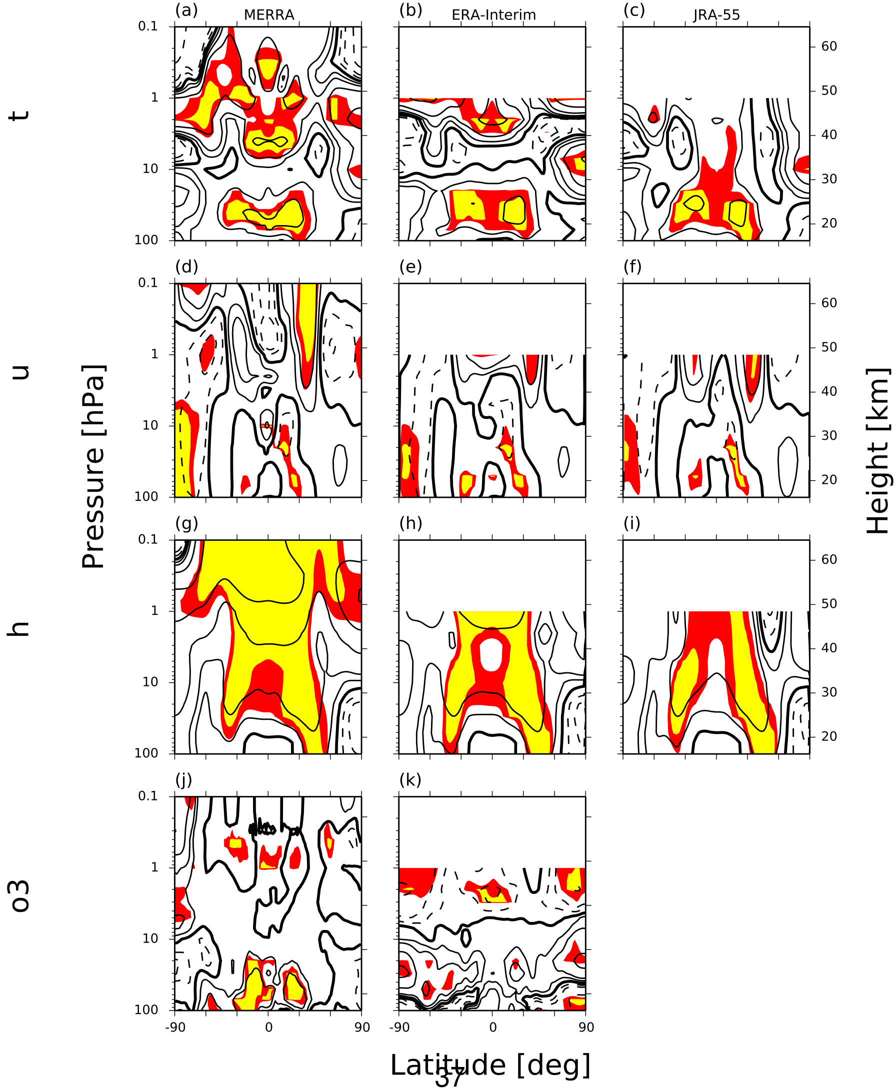


(a) MERRA
(b) ERA-Interim
(c) JRA-55
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
t
u
h
o3
Pressure [hPa]
Height [km]
Latitude [deg]
0.1
1
10
100
-90
0
90
20
30
40
50
60

Figure 1. The annually averaged response of the solar signal in the MERRA, ERA-Interim and JRA-55 zonal-mean temperature t (a)-(c), unit: [K], contour levels: $\mathbf{0}, \pm 0.25, \pm 0.5, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; zonal wind u (d)-(f), unit: [m/s], contour levels: $\mathbf{0}, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; geopotential height h (g)-(i), unit: [gpm] ~~[m]~~ [ales] (r4,tc5), contour levels: $\mathbf{0}, \pm 10, \pm 20, \pm 50, \pm 100, \pm 150$; and ozone mixing ratio $o3$ (j)-(k), unit: percentage change per annual mean, contour levels: $\mathbf{0}, \pm 1, \pm 2, \pm 5, \pm 10$. The response is expressed as a regression coefficient RC (corresponding units per S_{max} minus S_{min}). The statistical significance of the scalar fields was computed by a t-test. Red and yellow areas indicate p-values $<$ 0.05 and 0.01.

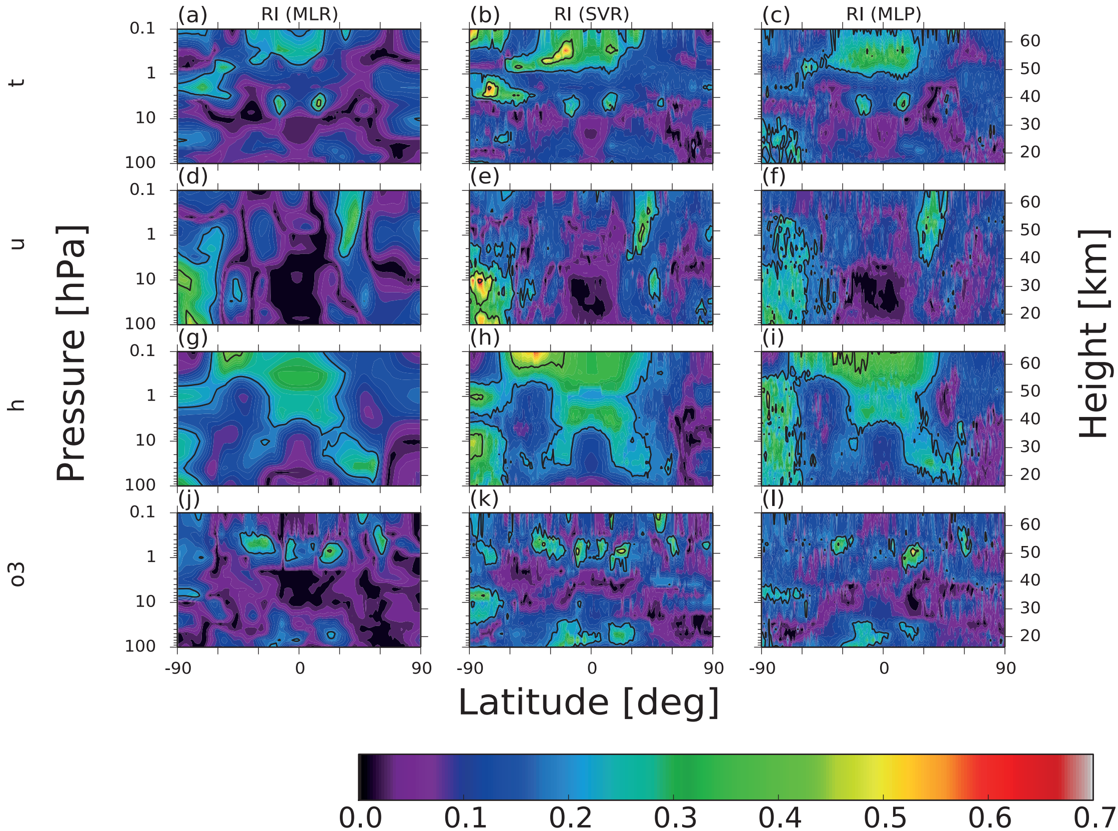


Figure 2. The annually averaged response of the solar signal in the MERRA zonal-mean temperature t (a)-(c), unit: [K]; zonal wind u (d)-(f), unit: [m/s]; geopotential height h (g)-(i), unit: [gpm] ~~[m]~~ ales (r4,tc5); and ozone mixing ratio $o3$ (j)-(l), unit: percentage change per annual mean. The response is expressed as a relative impact RI approach. The relative impact was modeled by MLR, SVR and MLP techniques. The black contour levels in the RI plots are 0.2, 0.4, 0.8 and 1.0.

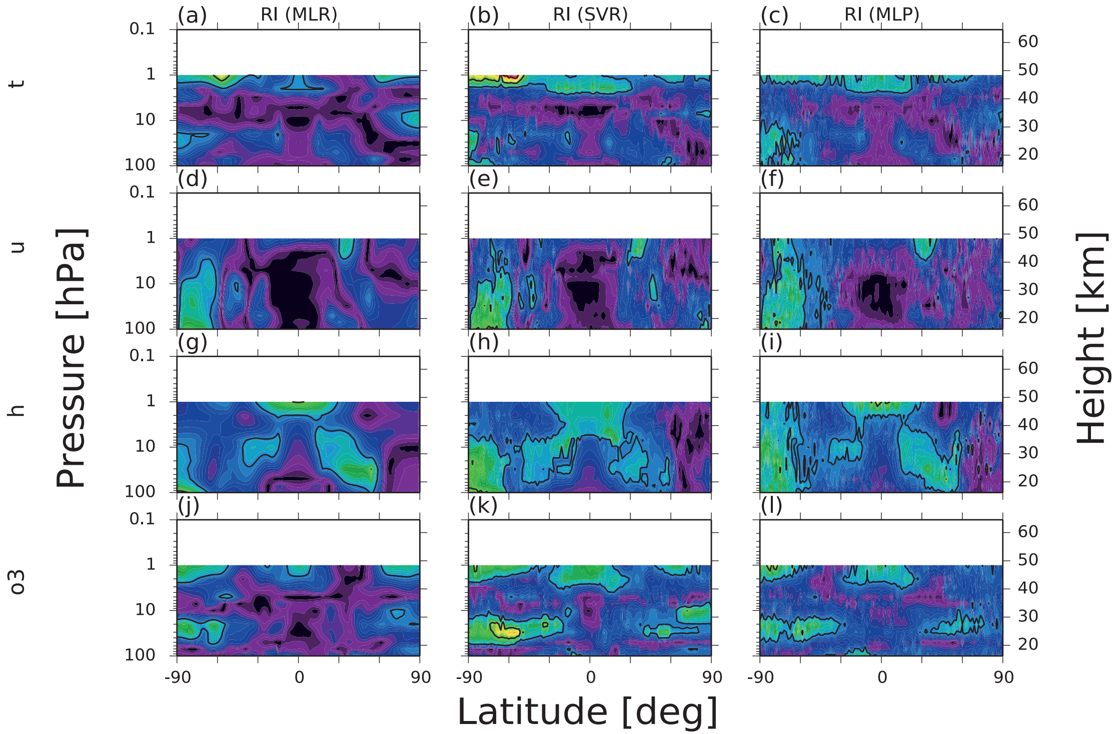


Figure 3. The annually averaged response of the solar signal in the ERA-Interim zonal-mean temperature t (a)-(c), unit: [K]; zonal wind u (d)-(f), unit: [m/s]; geopotential height h (g)-(i), unit: [gpm] ~~[m]~~ales (r4,tc5); and ozone mixing ratio $o3$ (j)-(l), unit: percentage change per annual mean. The response is expressed as a relative impact RI approach. The relative impact was modeled by MLR, SVR and MLP techniques. The black contour levels in the RI plots are 0.2, 0.4, 0.8 and 1.0.

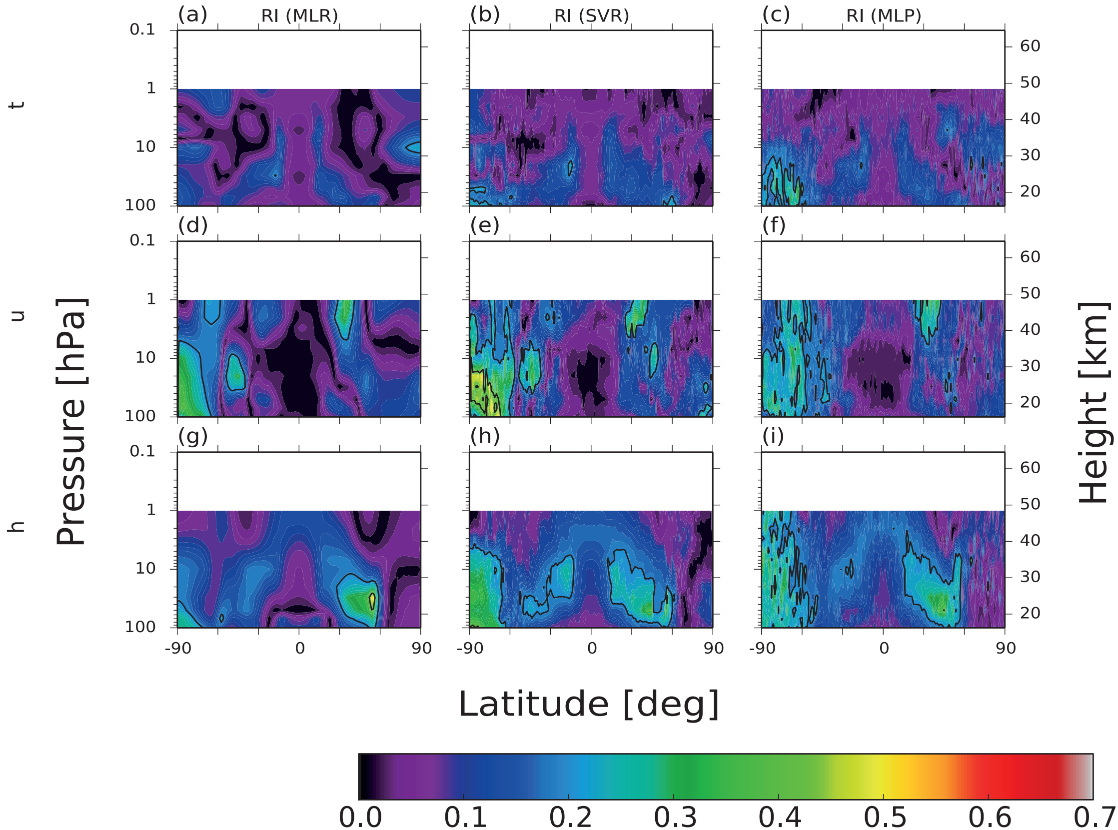
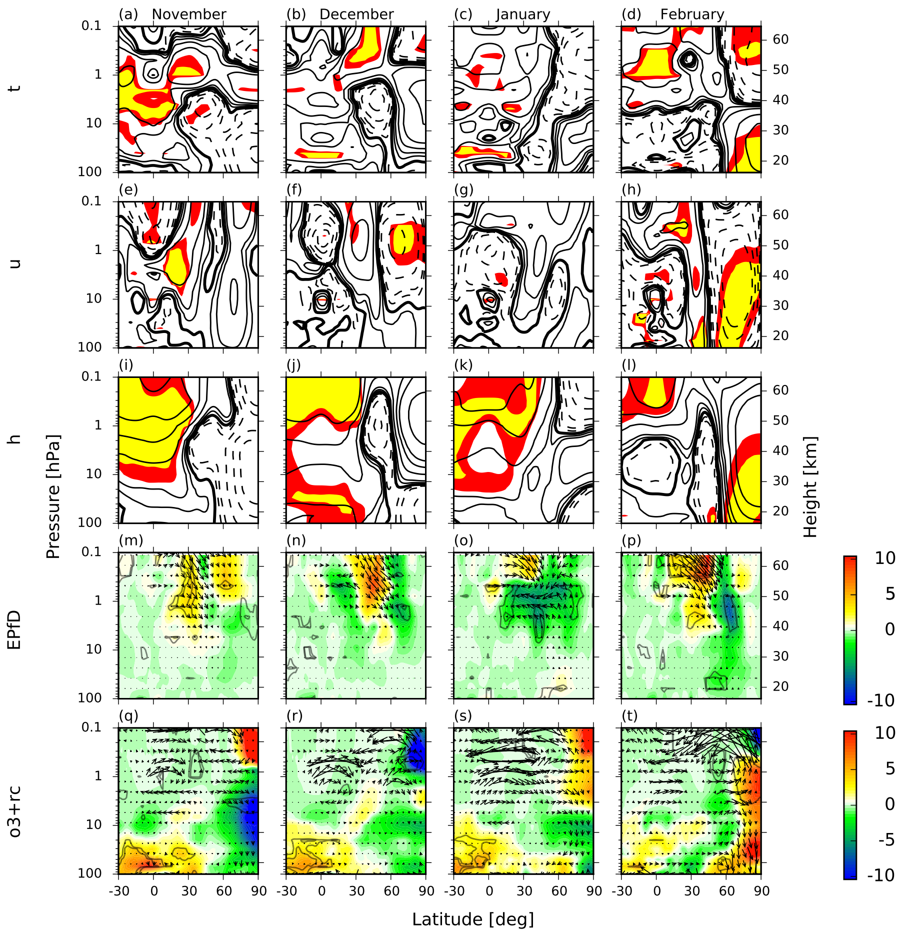


Figure 4. The annually averaged response of the solar signal in the JRA-55 zonal-mean temperature t (a)-(c), unit: [K]; zonal wind u (d)-(f), unit: [m/s]; geopotential height h (g)-(i), unit: [gpm] ~~[m]~~ ales(r4,tc5); and ozone mixing ratio $o3$ (j)-(l), unit: percentage change per annual mean. The response is expressed as a relative impact RI approach. The relative impact was modeled by MLR, SVR and MLP techniques. The black contour levels in the RI plots are 0.2, 0.4, 0.8 and 1.0.


(a) November
(b) December
(c) January
(d) February
t
u
h
EPfD
o3+rc
Pressure [hPa]
Height [km]
Latitude [deg]
(e)
(f)
(g)
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(i)
(j)
(k)
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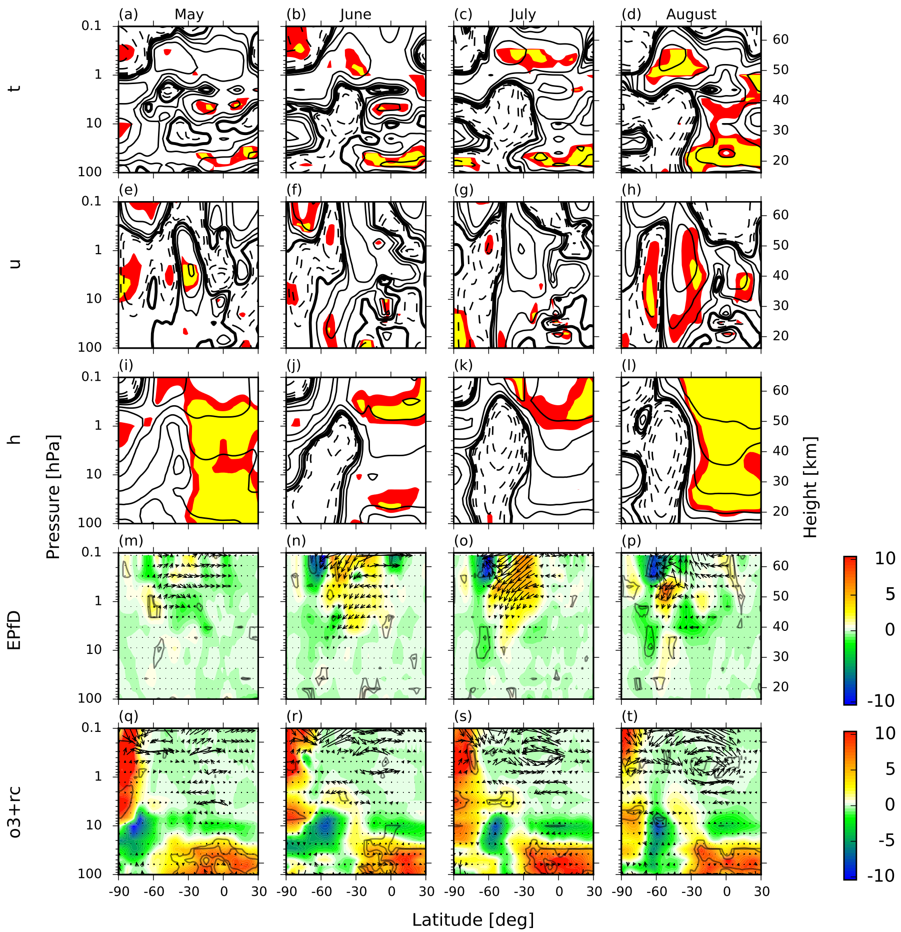
(m)
(n)
(o)
(p)
(q)
(r)
(s)
(t)

Figure 5. The monthly averaged response of the solar signal in the MERRA zonal-mean temperature t (a)-(d), unit: [K], contour levels: $\mathbf{0}, \pm 0.25, \pm 0.5, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; zonal wind u (e)-(h), unit: [m/s], contour levels: $\mathbf{0}, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; geopotential height h (j)-(l), unit: [gpm] ~~[m]~~ ales (r4,tc5), contour levels: $\mathbf{0}, \pm 10, \pm 20, \pm 50, \pm 100, \pm 150, \pm 300$; EP flux divergence $EPfD$ (m)-(p), unit: [m/s/day]; together with EP flux vectors scaled by the inverse of the pressure, unit: [kg/s^2]; and ozone mixing ratio, unit: percentage change per monthly mean; with residual circulation $o3{+}rc$ (q)-(t), units: [m/s; 10^{-3}Pa/s] during northern hemispheric winter. The response is expressed as a regression coefficient (corresponding units per S_{max} minus S_{min}). The statistical significance of the scalar fields was computed by a t-test. Red and yellow areas in Figs. (a)-(h) and grey contours in Figs. (i)-(p) indicate p-values of < 0.05 and 0.01 respectively.



(a) May
(b) June
(c) July
(d) August
t
u
h
EPfD
o3+rc
Pressure [hPa]
Height [km]
Latitude [deg]
0.1
1
10
100
-90
-60
-30
0
30
20
30
40
50
60
10
5
0
-5
-10
(e) (f) (g) (h)
(i) (j) (k) (l)
(m) (n) (o) (p)
(q) (r) (s) (t)

Figure 6. The monthly averaged response of the solar signal in the MERRA zonal-mean temperature t (a)-(d), unit: [K], contour levels: $\mathbf{0}, \pm 0.25, \pm 0.5, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; zonal wind u (e)-(h), unit: [m/s], contour levels: $\mathbf{0}, \pm 1, \pm 2, \pm 5, \pm 10, \pm 15, \pm 30$; geopotential height h (j)-(l), unit: [gpm] ~~[m]~~ ales (r4,tc5), contour levels: $\mathbf{0}, \pm 10, \pm 20, \pm 50, \pm 100, \pm 150, \pm 300$; EP flux divergence $EPfD$ (m)-(p), unit: [m/s/day]; together with EP flux vectors scaled by the inverse of the pressure, unit: [kg/s^2]; and ozone mixing ratio, unit: percentage change per monthly mean; with residual circulation $o3{+}rc$ (q)-(t), units: [m/s; 10^{-3}Pa/s] during southern hemispheric winter. The response is expressed as a regression coefficient (corresponding units per S_{max} minus S_{min}). The statistical significance of the scalar fields was computed by a t-test. Red and yellow areas in Figs. (a)-(h) and grey contours in Figs. (i)-(p) indicate p-values of $<$ 0.05 and 0.01 respectively.

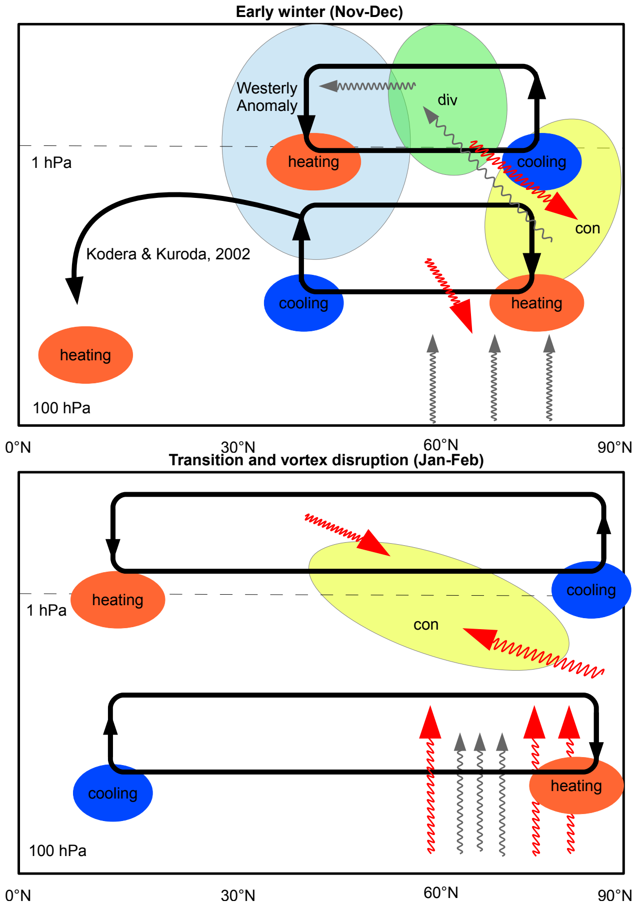

Early winter (Nov-Dec)
Westerly Anomaly
div
heating
cooling
con
1 hPa
Kodera & Kuroda, 2002
cooling
heating
heating
100 hPa
0°N
30°N
60°N
90°N
Transition and vortex disruption (Jan-Feb)
heating
cooling
1 hPa
con
cooling
heating
100 hPa
0°N
30°N
60°N
90°N

Figure 7. Solar cycle modulation of the winter circulation: schema of the related mechanisms. The upper and lower figure show early and later winter respectively. The heating and cooling anomalies are drawn with red and blue boxes. The EP flux divergence and convergence are drawn with green and yellow boxes. The wave propagation anomaly is expressed as a wavy red arrow in contrast to the climatological average drawn by a wavy grey arrow. The induced residual circulation according to the quasi-geostrophic approximation is highlighted by the bold black lines.

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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Solar cycle in current reanalyses: (non)linear attribution study" *by* A. Kuchar et al.

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Referee #1

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We would like to thank the reviewer for his/her comments.

Author's response and changes in the manuscript are included below. In addition, you can find the revised manuscript as supplement where the particular changes are highlighted together with the comment referring to them.

(1)Similar and comprehensive work has recently made by Mitchell et al.(2014, QJRMS). They examined 9 reanalysis datasets by a multiple regression analysis. Please refer and discuss the accordance and difference between the present study and Mitchell et al (2014). They did not present dynamical analysis such as EP flux. Mitchell, D. M., et al., Signatures of naturally induced variability in the atmosphere us-

ing multiple reanalysis datasets. Q. J. R. Meteorol. Soc. (2014) DOI:10.1002/qj.2492. http://onlinelibrary.wiley.com/doi/10.1002/qj.2492/abstract

The accordance and difference between the present study and Mitchell et al (2014) are discussed in section 1 and also mentioned within the text.

(2) Description of reanalysis product on solar cycle in irradiance and ozone is needed in dataset section. See Table 2 of Mitchell et al (2014).

Since the description of reanalysis product on solar cycle in irradiance and ozone is already included in Mitchell et al (2014) we refer to this table in section 4.1.1 where the upper-stratospheric ozone anomaly is discussed.

(3) QBO3 is needed? I think regression results would not change without QBO3 term. (4) NAO is needed? The NAO is modulated by 11-year solar cycle (Kodera, 2003, GRL) and the tropospheric NAO extends to the stratosphere as AO near solar maximum. So I think the NAO term might not be needed. Without the NAO term in regression equation (1), does the result change? If the results with/without NAO are similar for solar signal, the solar signal in this manuscript is robust.

The paragraph related to the robustness of solar regression coefficient was added in section Methodology. See paragraph and documenting Fig. 1,2,3 and 4.

The robustness of solar regression coefficient has been tested in terms of including or excluding particular regressors in the regression model, e.g. NAO term was removed from the model and resulting solar regression coefficient was compared with the solar regression coefficient from original regression model. The solar regression coefficient seems to be highly robust since either the amplitude or statistical significance was not changed when NAO or QBO3 or all of them were removed. However, cross-correlation analysis reveals that the correlation between NAO and TREND, SOLAR and SAOD regressors is statistically significant.

See correlation matrix in Fig. 5.

(5) P391 line 20-21 This statistically significant response . . . From the figure, it seems to be insignificant

The upper-stratospheric ozone anomaly in ERA-Interim is definitely statistically significant. Please see the revised figures.

(6) P30897 line 15-25 Sentences and Figure 4d, h, l, indicate stronger BD circulation as summarized in the bottom figure of Figure 6. So, in February, BDC circulation is enhanced at solar maximum opposite to early winter. I think this is new and should be emphasized in the text.

Based on your comment, this was also discussed in section Conclusion. See paragraph below.

Fields of residual circulation and EP flux divergence in February are showing an opposite to what would be expected from the suppressed BDC in the SC max. There is an enhanced downwelling in polar and enhanced upwelling in eq. region under 1 hPa, suggesting the need to diagnose the influence of SC on transport at least on monthly scale because the changes in the underlying dynamics (compare upper and lower diagram in Fig. 7) would make the transport pathways more complicated. Since GCMs have not yet successfully simulated this pattern (e.g. Schmidt et al., 2010; Mitchell et al., 2015) and due to the short (35-year) time series, it is possible that this pattern is not really solar in origin but is instead a consequence of internal climate variability or aliasing from effects of the two major volcanic eruptions aligned to solar maximum periods (Chiodo et al., 2014).

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/14/C12817/2015/acpd-14-C12817-2015-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 30879, 2014.

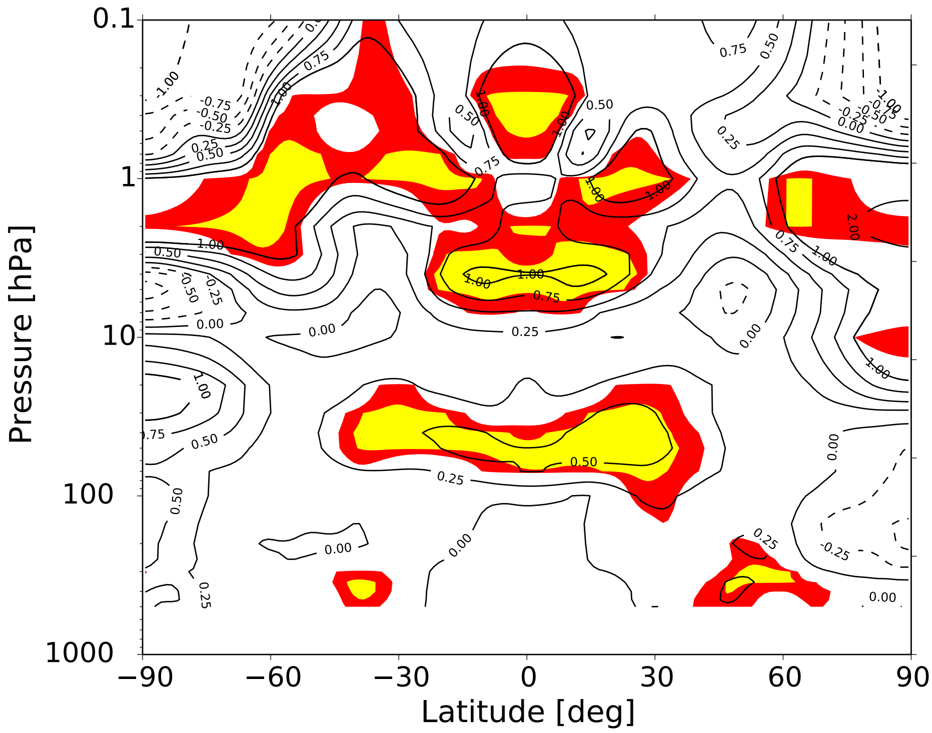

Fig. 1. Temperature response to SC for MERRA. All regressors included.

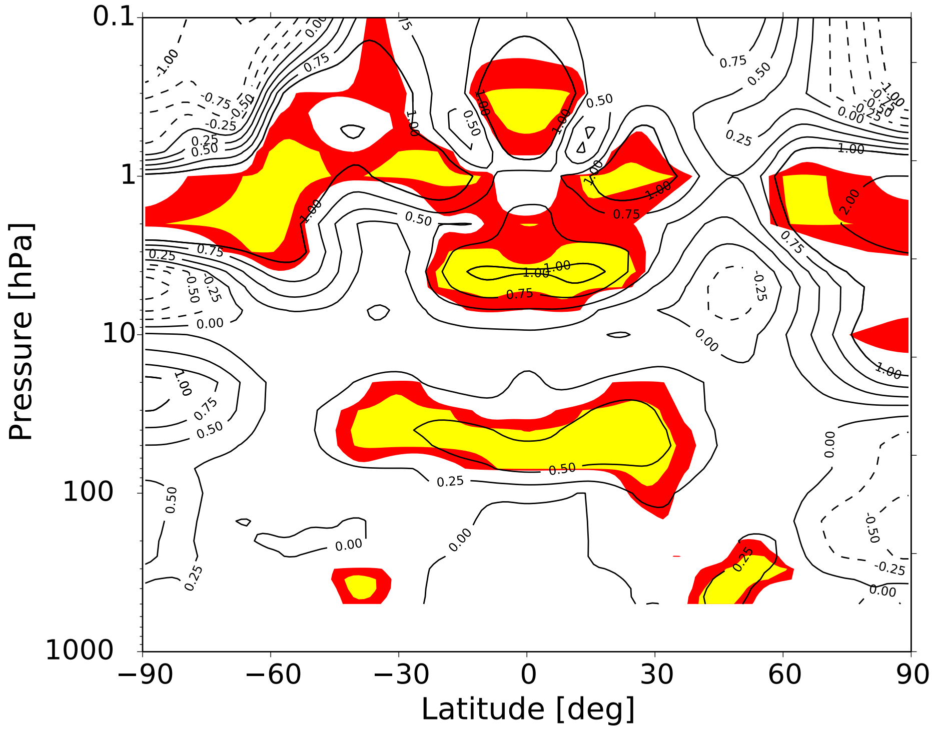

Fig. 2. Temperature response to SC for MERRA. All regressors included except NAO.

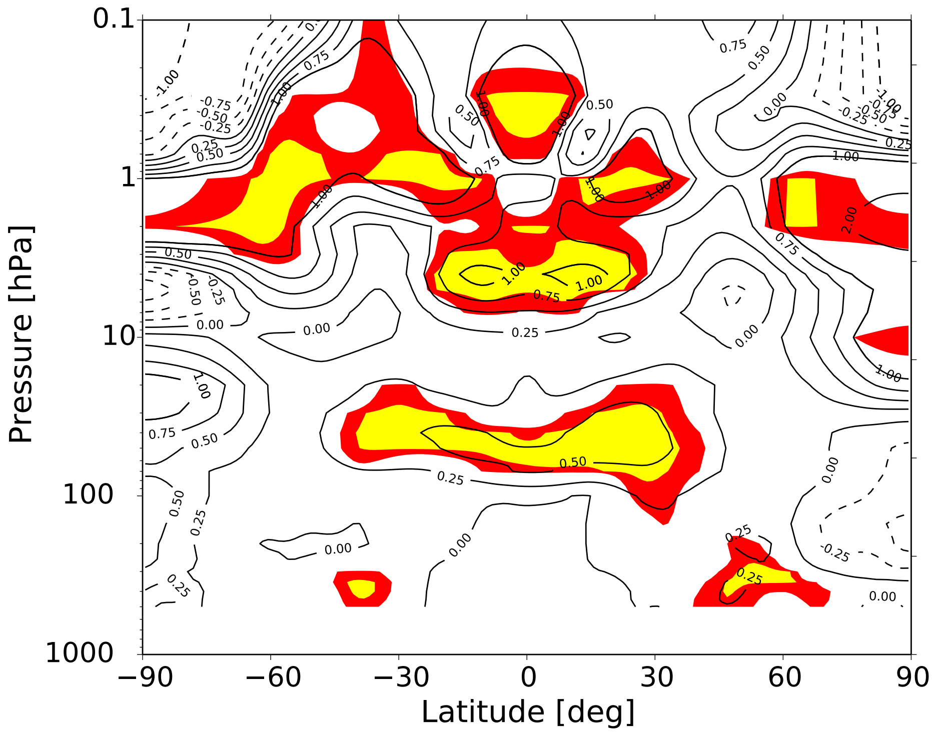

Fig. 3. Temperature response to SC for MERRA. All regressors included except QBO3.

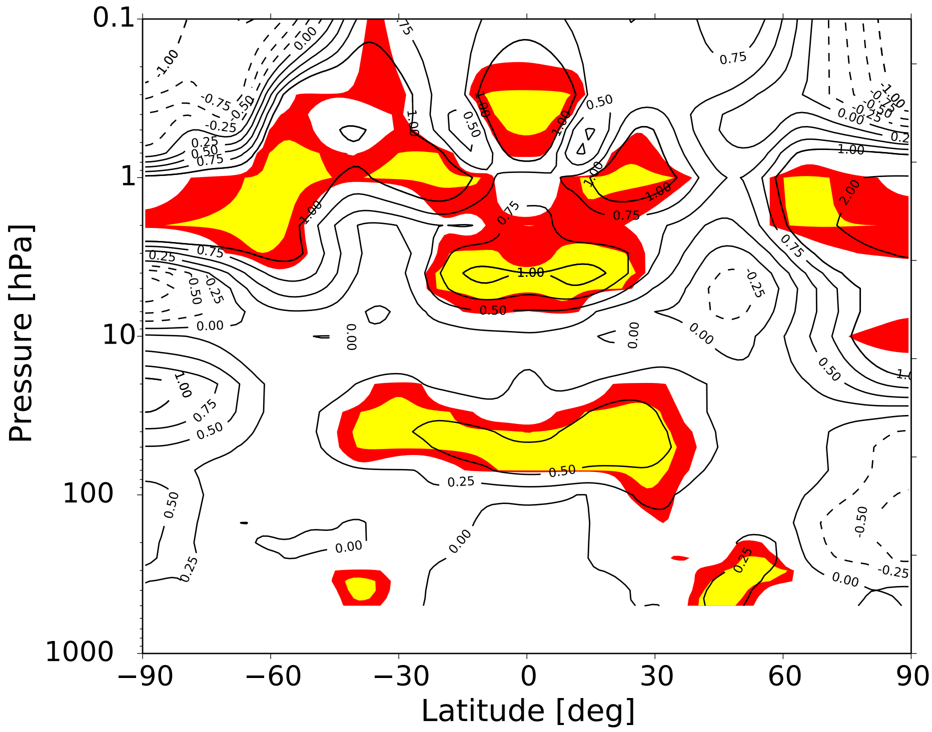

Fig. 4. Temperature response to SC for MERRA. All regressors included except NAO and QBO3.

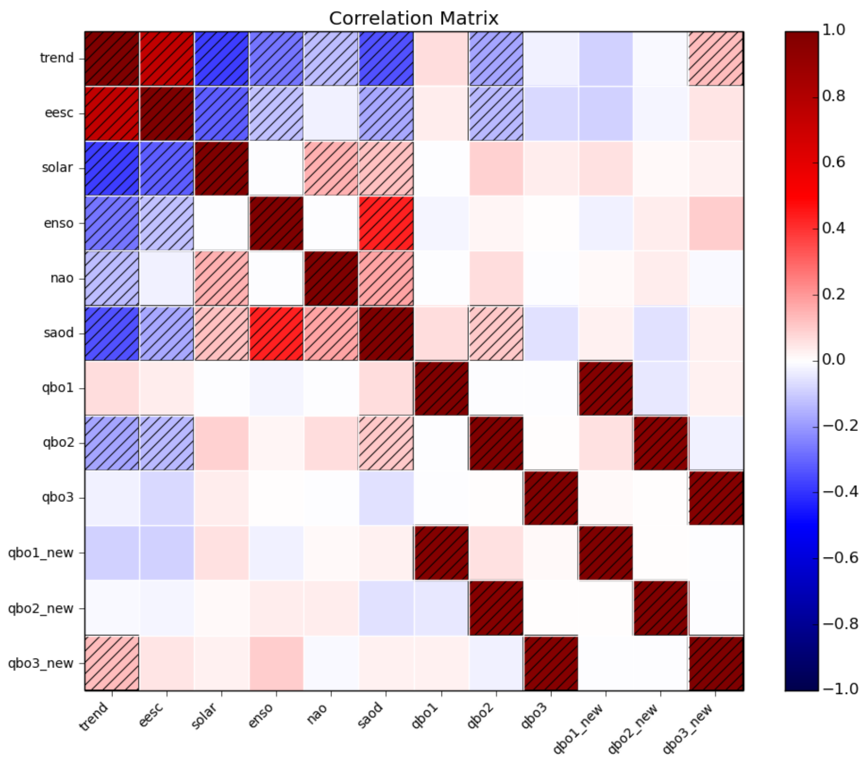

Fig. 5. Cross-correlation matrix of regressors for MERRA. QBO1_new, QBO2_new and QBO3_new were computed from a Principal Component Analysis of equatorial, deasonalized zonal mean zonal wind anomalies only.

Atmos. Chem. Phys. Discuss., 14, C12777–C12789, 2015
www.atmos-chem-phys-discuss.net/14/C12777/2015/

Interactive comment on "Solar cycle in current reanalyses: (non)linear attribution study" *by* A. Kuchar et al.

A. Kuchar et al.

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Received and published: 25 March 2015

Referee #2

We would like to thank the reviewer for his/her comments.

Author's response and changes in the manuscript are included below. In addition, you can find the revised manuscript as supplement where the particular changes are highlighted together with the comment referring to them.

Specific comments

1. The title does not really make sense. Consider changing to "The solar cycle in current reanalyses: linear verses non-linear attribution approaches" or something similar.

The title was change to "The 11-year solar cycle in current reanalyses: A (non)linear at-

tribution study of the middle atmosphere" based on the technical comment 3 of referee #4.

2. L41: insert 'most of' between 'where' and 'the ozone'.

"most of " was inserted between 'where' and 'the ozone'.

3. L66 missing citation, perhaps include Austin et al, 2008 here.

It was already corrected.

4. L72 include Matthes et al, 2004 and Matthes et al, 2010 here.

These citations were included.

5. L72-84 some discussion of the Kren et al, 2014 paper should be made here, as there look at this relationship in models and conclude that it could be chance.

The Kren et al, 2014 paper is discussed in that place. See in the text or sentence below.

However, fully coupled WACCM-4 model simulations by Kren et al, 2014 raised the possibility of occurrence of the observed solar-QBO response in the polar region.

6. L97 Next to (or instead of) Gray et al, please include Kuroda and Kodera, 2001.

Kuroda and Kodera, 2001 was included instead of Gray et al., 2010.

7. L108-109 Please include Gerber et al, 2009 in this list. Also, Mitchell et al, 2013 should be cited in place of (or as well as) the Baldwin and Dunkerton paper, as this was an update that dealt with timescales explicitly.

The paragraph included these citations were deleted according to the specific comment 2 of referee #4.

8. L122-135. Here reference should be made to the recent Chiodo papers (Chiodo et al, 2012; 2014).

Chiodo et al., 2012 was included instead of Gray et al., 2010. Chiodo et al., 2014 was then discussed several times.

9. L129: Include Scaife et al, 2013 here.

Scaife et al, 2013 was included in that place.

10. L136-152 I think more needs to be made of the different types of MLR (see overall comment 1).

The paragraph related to the different types of MLR in terms of NAO and QBO3 terms was made in section Methodology. See paragraph and documenting figures 1,2,3 and 4.

The robustness of solar regression coefficient has been tested in terms of including or excluding particular regressors in the regression model, e.g. NAO term was removed from the model and resulting solar regression coefficient was compared with the solar regression coefficient from original regression model. The solar regression coefficient seems to be highly robust since either the amplitude or statistical significance was not changed when NAO or QBO3 or all of them were removed. However, cross-correlation analysis reveals that the correlation between NAO and TREND, SOLAR and SAOD regressors is statistically significant.

11. L175 My overall comment 1 is linked the Fujiwara et al, 2012.

The accordance and difference between the present study and Mitchell et al (2014) was discussed in section 1 and also mentioned further within the text. See added paragraph below.

Under this framework the paper by Mitchell et al. (2014a) has been published where 9 reanalysis datasets were examined in terms of 11-year SC, volcanic, ENSO and QBO variability. Complementing their study, we provide comparison with nonlinear regression techniques here, assessing robustness of the results obtained by Multiple Linear Regression 10 (MLR). Furthermore, EP-flux diagnostics are used to examine

solar-induced response during winter season in both hemispheres, and solar-related variations of assimilated ozone are investigated.

12. L178 (and elsewhere) Consider changing 'on the last generation' to 'to the most recent generation at the time of writing'

" last generation" was only changed to "the most recent generation" within the text since it is kind of obvious that " the most recent" is related to the time of writing.

13. L202-215 See my overall point 2 here. But you should discuss papers that have calculated TEM diagnostics in reanalysis, as well as explaining any issues you may have had in doing so. For instance, Seviour et al, 2013 show how to do it for ERA-I, as well as issues that are faced. Mitchell et al, 2014b do the same for MERRA.

According to this specific comment and overall point 2 we have added these two paragraphs. Although the Eliassen–Palm (EP) flux diagnostics (described below) was computed on a 3-hourly basis the regression results have not changed significantly.

The Eliassen–Palm (EP) flux diagnostics (described below) was computed on a 3-hourly basis from MERRA reanalysis and subsequently monthly means of EP flux diagnostic variables were produced. Similar approach has been already used by Seviour et al, 2013 and Mitchell et al, 2014b. The former study proposed that even 6-hourly data are not only necessary but should also be sufficient to diagnose tropical upwelling in the lower stratosphere.

For this purpose the quasi-geostrophic approximation of Transformed Eulerian Mean (TEM) equations were used in the form employed by Edmon Jr et al. (1980), i.e. using their formula (3.1) for EP flux vectors, (3.2) for EP flux divergence and (3.4) for residual circulation. These variables were then interpolated to a regular vertical grid. For the visualization purposes the EP flux arrows were also scaled via the formula (3.13) in (Edmon Jr et al., 1980). The script was publicly released (Kuchar, 2015).

14. L232-235 This is not very clear until later in the analysis section. Rewrite so it is

clear right away.

This part was rewritten to be clearer.

15. L296-299 Many studies just use AR1 for this, do the authors think that AR2 is better for some reason? Could they explain this.

Although the solar regression coefficient seems to be unchanged when using AR1 instead of AR2 we concluded the AR2 is more convenient because the autocorrelation of residuals is better removed according to the Durbin-Watson is mostly equal to 2 (i.e. indiciates no autocorrelation) throughout the whole zonal mean. See figures below documenting the D-W test based on the regression model with AR2 (Fig. 5) and AR1 (Fig. 6).

This part "{we have used an iterative algorithm to model the residuals as a second-order autoregressive process. The Durbin-Watson statistic has been used to detect the autocorrelation of the error terms from the regression model." was replaced by "we have used an iterative algorithm to model the residuals as a second-order autoregressive process (AR2). Durbin-Watson test confirmed that this setup was sufficient to model most of the residual autocorrelations in the data."

16. Section 4.1 see overall comment 1.

The results from the Mitchell et al. 2014 paper were discussed in section 4.1.1.

17. L410-415: Expand on what is meant by 'using the model with EESC. . .' (see comment 14. Also, use 'regression model' rather than 'model' otherwise readers may get confused with GCM models.

Those sentences were clarified in the way suggested above.

18. L476-578: I do not really follow this argument, and it is rather important because all your figures use it. Could you expand on this. Also, explain clearly how columns 2-4 should be interpreted from now on (e.g. on figures 1-3).

This part was revised according to this comment.

19. Figure 3: I do not see the O3 response.

The structure of figures was revised – regression coefficient results through reanalyses are situated in one figure and relative impact results are situated in one figure for each reanalysis.

20. L525 I think the PJO needs to be discussed here. Please also cite the Kuroda and Kodera, 2001 paper.

The Kuroda and Kodera, 2001 paper was cited in this place.

21. L556-562 Again, not the PJO here.

The Kuroda and Kodera, 2001 paper was added here.

22. L628 This paragraph is a little confusing. What the authors say is only true in November, not really true for all of early winter. For instance, in December the vortex is weaker, and more easterly (between 80-90N).

"early Northern hemispheric (NH) winter (including November)" was replaced by "November"

23. L669 – Insert 'probably' between 'This' and 'results'.

"probably" was inserted between "This" and "results".

24. L752 Missing reference, I would add Austin et al, 2008 here.

This reference was already completed in the ACP discussion paper.

25. L788-802 To me this is the key conclusion of the paper. I think it should be right at the front of the conclusions.

This paragraph was moved at the front of the conclusions, i.e. on the second position.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/14/C12777/2015/acpd-14-C12777-2015-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 14, 30879, 2014.

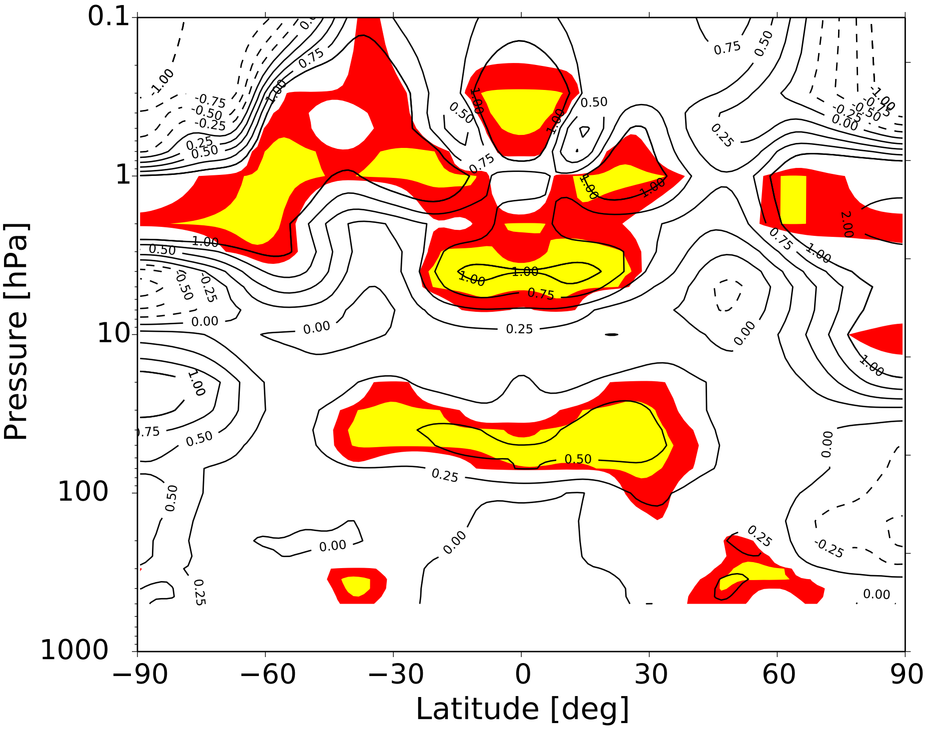

Fig. 1. Temperature response to SC for MERRA. All regressors included.

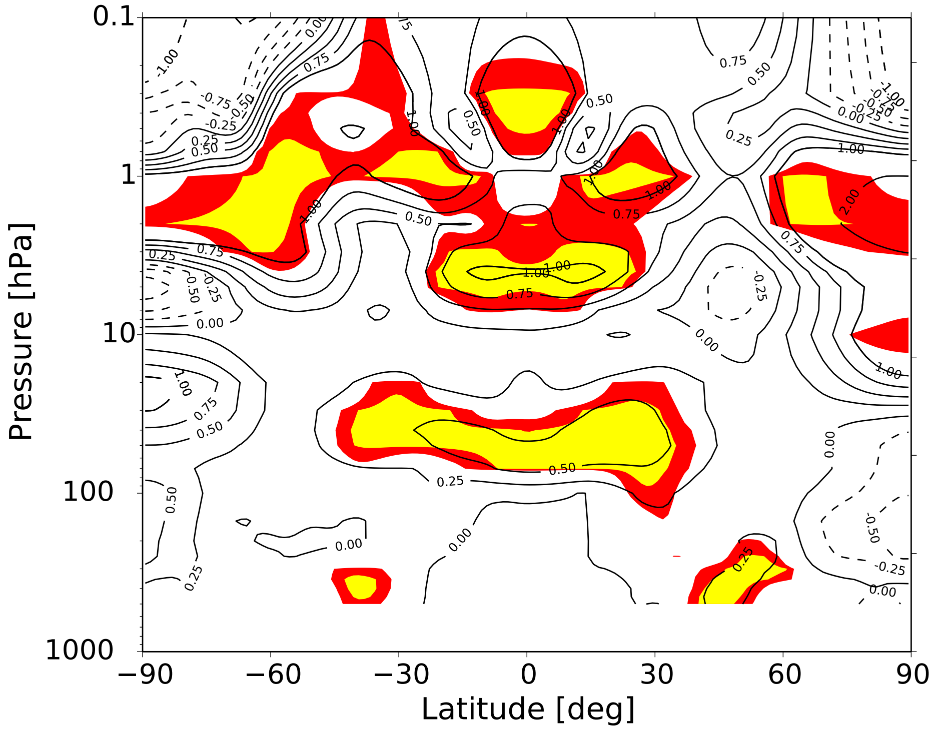

Fig. 2. Temperature response to SC for MERRA. All regressors included except NAO.

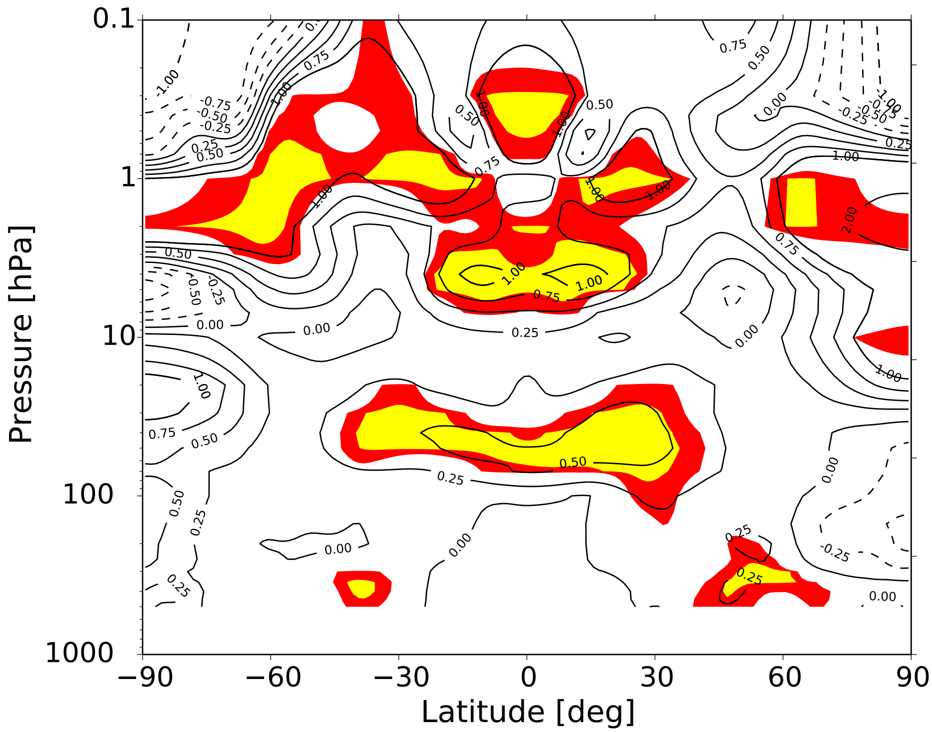

Fig. 3. Temperature response to SC for MERRA. All regressors included except QBO3.

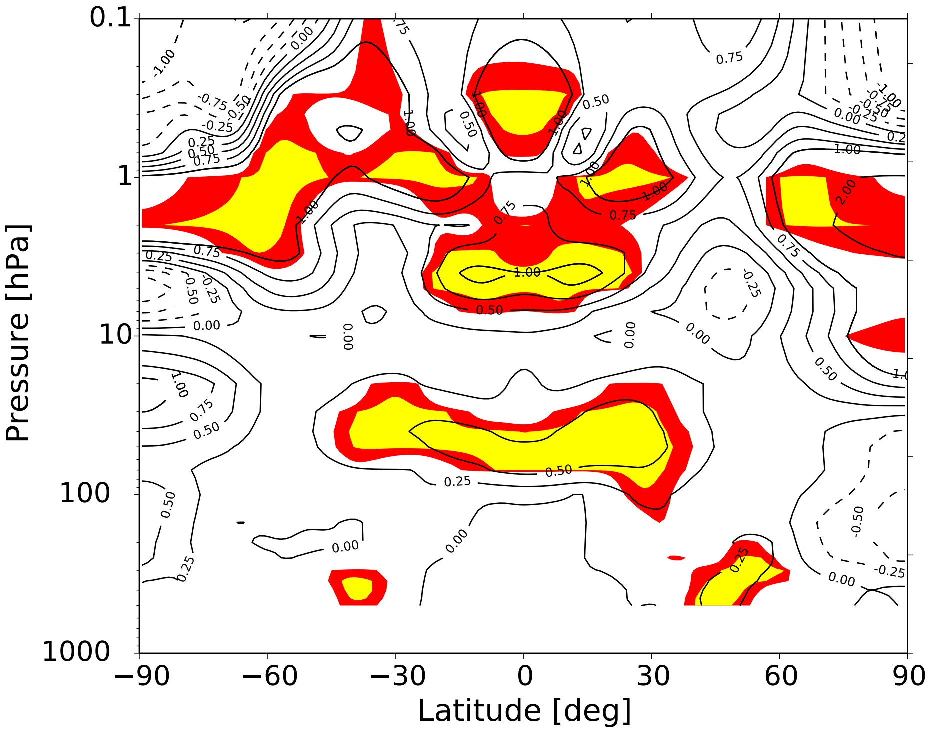

Fig. 4. Temperature response to SC for MERRA. All regressors included except NAO and QBO3.

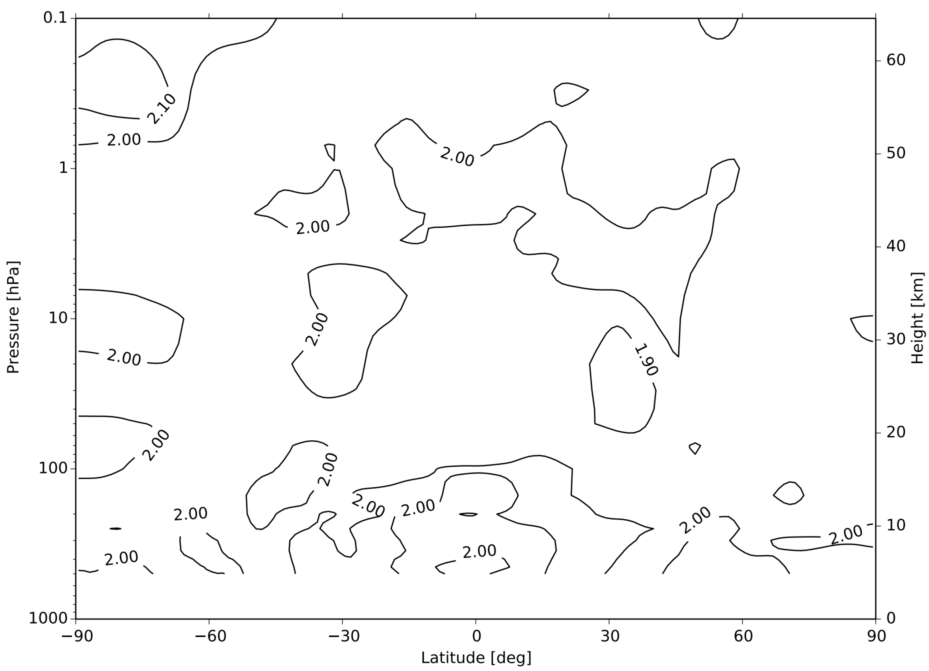

Fig. 5. D-W test of temperature regression coefficient for MERRA. AR2

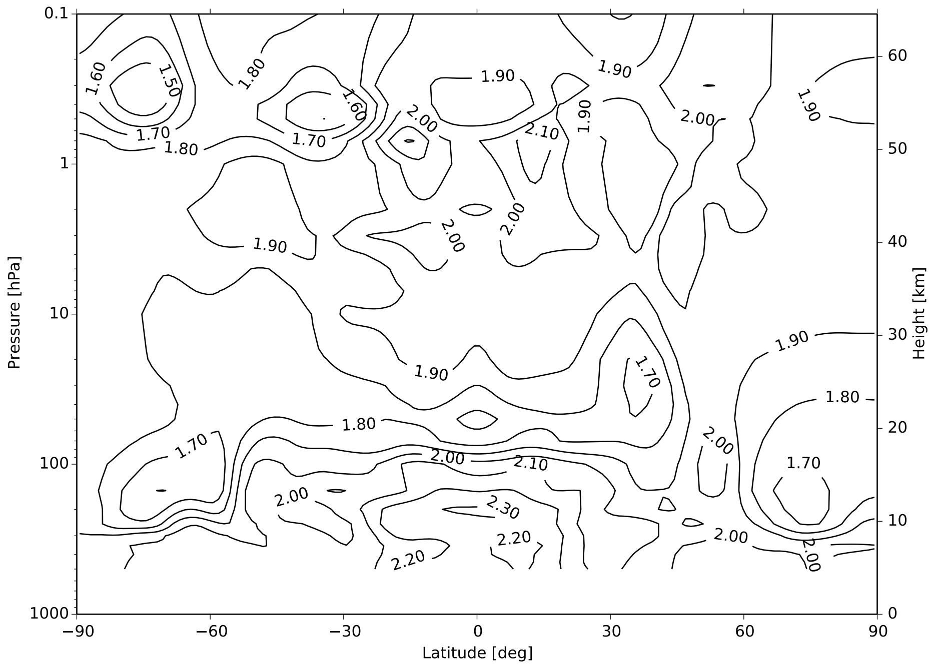

Fig. 6. D-W test of temperature regression coefficient for MERRA. AR1

Atmos. Chem. Phys. Discuss., 14, C12756–C12776, 2015
www.atmos-chem-phys-discuss.net/14/C12756/2015/

Atmospheric Chemistry and Physics Discussions

Interactive comment on "Solar cycle in current reanalyses: (non)linear attribution study" *by* A. Kuchar et al.

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Received and published: 25 March 2015

Referee #3

We would like to thank the reviewer for his/her comments.

Author's response and changes in the manuscript are included below. In addition, you can find the revised manuscript as supplement where the particular changes are highlighted together with the comment referring to them.

(1) It is found that the 11-year ozone response in the tropical upper stratosphere differs greatly between the MERRA and ERA-Interim datasets (Figures 1m and 2m) and that neither response resembles that derived from observations, i.e., there is no double-peaked response. The annual mean upper stratospheric ozone response is decidedly negative for ERA and is slightly negative for MERRA, which is inconsistent with the ef-

fects of 11-year solar UV forcing. For ERA, the negative response is most pronounced (up to 5%) at polar latitudes. In contrast, analyses of merged SBUV ozone data yield a positive response in the upper stratosphere with more pronounced positive maxima at polar latitudes. Analysis of the seasonal dependence of the polar maxima show that they occur mainly in the summer season in each hemisphere (see, e.g., Figure 1 of Tourpali et al., JGR, v. 112, D12306, doi:10.1029/2006JD007760, 2007). Obviously, therefore, there is an issue with the assimilation of ozone in the reanalysis datasets. In the text (p. 30891), the pronounced negative polar ozone response is interpreted as "connected with a higher destruction of ozone during the solar maximum period and consequent heating of the region." This is possible since increases in temperature lead to increased ozone losses because of the temperature dependence of the reaction rates that control the ozone balance. Would this interpretation require that the assimilation model had interactive ozone chemistry? Please expand the discussion of this interpretation. In the case of MERRA, SBUV ozone profiles are assimilated while, in the case of ERA, no solar cycle variation of ozone is passed to the forecast model. There is also no solar cycle in irradiances passed to the radiative part of the forecast model for any of the three reanalysis datasets considered here. So, no direct solar-induced increase in ozone production would be expected even if the assimilation model has interactive chemistry. The SBUV ozone profiles have very low vertical resolution and may yield an 11-year ozone response that is biased toward higher altitudes compared to SAGE observations, which have much better (1 km) vertical resolution. So, assimilation of the SBUV profiles in the MERRA system may not have produced a realistic 11-year ozone variation in that reanalysis dataset. How does the lack of a realistic upper stratospheric ozone variation affect the value of the reanalysis datasets for investigating 11-year dynamical responses? This should also be discussed somewhere in the manuscript. The paragraph below was added to clarify this in the manuscript.

The negative response could be interpreted as a consequence of temperature rise leading to increased ozone losses because of the temperature dependence of the reaction rates that control the ozone balance in the upper stratosphere. This interpretation does not require that the assimilation model had included interactive ozone chemistry since in the model used for ERA-Interim the ozone as a prognostic variable is relaxed towards a photochemical equilibrium for the local value of the ozone mixing ratio, the temperature, and the overhead ozone column (Dee et al., 2011). An additional term is used to parameterize the heterogeneous chemistry. This fact together with the finding that the temperature and ozone are highly negatively correlated in the upper stratosphere, e.g. -0.93 for zonal mean between 15°S and 15°N in 1 hPa, provide reasonable explanation of the negative ozone response to the SC which is driven by temperature variability in the upper stratosphere. In the case of MERRA, while SBUV ozone profiles are assimilated with solar cycle passed to forecast model (as ozone analysis tendency contribution), no solar cycle was passed to the radiative part of the model. The same is 5 also true for ERA-Interim and JRA-55 (see descriptive table of reanalysis product on SC in irradiance and ozone in Mitchell et al. (2014a). Among other tendencies the dynamics and chemistry components also contribute to total tendency of ozone. These two tendencies prevent any variations in ozone analysis tendency though. Thus periods longer than 1 year are filtered out in the upper stratosphere. Only annual and semi-annual cycles are 10 included. The SC-like periods seem to be diminishing approximately from 5 hPa except in the polar regions fro both hemispheres. The negative correlation -0.93 between the tendency of dynamics and chemistry and tendency from analysis for zonal mean in the tropical upper stratosphere confirms this statement as well. This negative correlation roots from anti-phase relationship between the tendency from dynamics and chemistry. Therefore de15 spite the fact that the analyzed ozone should contain a solar signal, the signal is very weak and is compensated by internal model variability in terms of dynamics and chemistry. Since the SBUV ozone profiles have very low vertical resolution this may also affect the ozone response to the SC in the reanalysis. These facts should be also taken into account in case of monthly response discussion of particular variables in the section 4.2.

(2) The derived upper stratospheric temperature response in all three reanalysis

datasets (Figures 1a, 2a, and 3a) is less than accurate due to the existence of large offset errors occurring at times when the input satellite radiance data and/or the assimilation scheme changed (McLandress et al., 2014). This problem is briefly noted on p. 30884, line 9, but it is not considered to be a major issue. Also, no attempt is made to correct or adjust the reanalysis temperature data prior to the analysis. Such retrospective adjustments are probably next-to-impossible for MERRA and JRA but could have been attempted for ERA using the procedures developed by McLandress et al. However, the McLandress et al. study only considered discontinuities occurring in 1985 and 1998. As noted by them, another discontinuity occurred during 1979 that would also need an adjustment if the time series begins in that year. But, at a minimum, the offsets in 1985 and 1998 could have been corrected. In the revised paper, please (a) apply the necessary adjustments and repeat the analysis for the ERA data; and (b) add statements to the discussion and conclusion sections pointing out the likely errors in the temperature results resulting from these unphysical temperature discontinuities.

The regression analysis has been repeated with the adjustments in 1985 and 1998. For simplicity the fundamental regressors were involved: trend, solar, saod, qbo1(2), enso. The differences between particular regression coefficient without adjustment and with adjustment are illustrated in the Fig. 1.

First of all, the adjustment dataset by McLandress et al. 2013 were downloaded and applied for the 1, 2, 3, and 5 hPa temperature field of the ERA-Interim dataset. As regards solar regressors the most pronounced differences are apparent in higher latitudes and especially in 1 hPa. However, the regression coefficients decreased by about 50 % when using adjusted dataset instead of unadjusted dataset these differences are not statistically significant in terms of 95% confidence interval. The difference in tropical latitudes is about 0.2 K/(Smax-Smin). Trend regressor reveals large turnaround from positive trend to negative trend in these levels. Another regressors do not reveal any remarkable difference.

In the revised paper the statements about the results of repeated analysis with adjustments were added, see below. However, we keep the results from original analysis in order to refer and discuss the accordance and difference between our results and results from Mitchell et al., 2014, where no adjustment has been considered as well.

This paragraph was added: However, upper-stratospheric temperature response could be less than accurate due to the existence of discontinuities in 1979, 1985 and 1998 (Mclandress et al. 2013) coinciding with solar maxima. Therefore, the temperature response to solar variation may be influenced by these discontinuities in the upper stratosphere. The revised analysis with the adjustments from Mclandress et al. (2013) showed in comparison with the original analysis without any adjustment that the most pronounced differences are apparent in higher latitudes and especially in 1 hPa. However, the regression coefficients decreased by about 50% when using adjusted dataset and the differences are not statistically significant in terms of 95% confidence interval. The difference in tropical latitudes is about 0.2 K/(Smax-Smin). The trend regressor t from Eq. (1) reveals large turnaround from positive trend to negative in the adjusted levels, i.e. 1, 2, 3 and 5 hPa. Other regressors do not reveal any remarkable difference. The results in Figs. 1(b,e,h,k) and 2 from raw dataset ware kept in order to refer and discuss the accordance and difference between our results and results from Frame and Gray (2010); Mitchell et al. (2014a), where no adjustment has not considered as well.

(3) There is no mention in the manuscript of the possibility that the calculated linear solar regression coefficients are affected by aliasing from the effects of strong volcanic aerosol injection events (El Chichon and Pinatubo) occurring following the cycle 21 and 22 maxima, respectively. The record is short (35 years) and these two fortuitously placed injection events are unique to this time period. They could have produced decadal-scale variations in the stratosphere that would not be entirely orthogonal to the solar forcing variable (the 10.7 cm radio flux). So, there could be some mixing of the volcanic and the solar regression coefficients. The most well-known possibility is that part or all of the 11-year lower stratospheric response of ozone and temperature de-

rived from observations is a consequence of such aliasing (Solomon et al., JGR, 1996; Lee and Smith, JGR, 2003). Austin et al. (2008) concluded that this was not likely to be true for the chemistry climate models considered by them because the solar regression coefficients over the 1960-2005 period did not change much if an aerosol term was included or not in the regression model. However, Chiodo et al. (ACP, v. 14, p. 5251, 2014) have recently tested in more detail one such chemistry-climate model (WACCM 3.5) by carrying out simulations with and without volcanic aerosol forcing. They find that, at least for this specific model, the apparent solar-induced ozone and temperature responses in the lower stratosphere largely disappear in the simulation with no volcanic aerosol forcing. Thus, at least for WACCM 3.5, the solar-induced lower stratospheric response appears to be due almost entirely to the aliasing effects of the two eruptions. On the other hand, it is known that some CCMs overestimate ozone losses during high aerosol loading periods, causing a larger aliasing effect on the solar response than would occur when analyzing observations (Dhomse et al., ACP, 2011). At least some coupled climate models (e.g., MIROC-ESM-CHEM; Watanabe et al., Geoscientific Model Development, v. 4, p. 845, 2011) produce solar-induced lower stratospheric responses that are not strongly affected by aliasing from the El Chichon and Pinatubo eruptions. So, the answer to the question of whether or not the observationally estimated lower stratospheric response is strongly affected by volcanic aerosol aliasing unfortunately appears to depend on the model that is employed to simulate the climate system. Even the upper stratospheric solar response could be affected by such aliasing since the dynamical evolution of the entire stratosphere in winter was affected by these major eruptions. Further work is needed to resolve this issue. In the meantime, one should be careful to note the possibility that the lower stratospheric solar response derived from observational datasets could be affected by such aliasing. This should be done at appropriate places in the paper with appropriate added references.

The paragraph below was added regarding this comment.

However, the results presented by Chiodo et al. (2014) suggest the contribution of solar cycle variability could be smaller since two major volcanic eruptions are aligned with solar maximum periods and also given the shortness of analysed time series (in our case 35 years). These concerns related to the lower stratospheric response of ozone and temperature derived from observations has already been raised (e.g. Solomon et al., 1996;Lee and Smith, 2003). However, another issue is whether or not the lower stratospheric response could depend on the model employed in the simulations Mitchell et al. (2015).

(4) In the monthly analyses shown in Figures 4 and 5, by far the largest apparent solar response occurs in February at high northern latitudes in the form of a lower stratospheric warming, a mesospheric cooling, and an associated weakening of the zonal wind (polar vortex). This apparent response has been found in previous analyses of the ERA data (e.g., Frame and Gray, 2010). It is possible that this response is indeed solar-induced. For example, Gray et al. (J. Atmos. Sci., v. 61, p. 2777, 2004) suggests that the negative zonal wind response in late northern winter may be caused by an increased likelihood of major stratospheric warmings later in the winter under solar maximum conditions when the polar vortex in early winter is stronger, on average, and therefore less susceptible to disruption. In this manuscript (p. 30894), the February negative zonal wind response is regarded as real on statistical grounds alone: "In February, the intensive stratospheric warming and mesospheric cooling is associated with a more pronounced transition from winter to summer circulation attributed to the solar cycle (in relative impact methodology up to 30%)". However, one problem with this conclusion is that general circulation models have not yet successfully simulated the strong final warming in February under solar maximum conditions (e.g., Schmidt et al., JGR, v. 115, doi:10.1029/2009JD012542, 2010). Also, there is no similar observed response in late winter in the southern hemisphere. Given the short (35-year) record, it is possible that this response is not really solar but is instead a consequence of internal climate variability or aliasing from effects of the two major volcanic eruptions. Please revise the discussion to note this possibility.

This was discussed in the paragraph below within the revised manuscript.

However, GCMs have not yet successfully simulated this pattern (e.g. Schmidt et al., 2010; Mitchell et al., 2015). Due to the short (35-year) time series, it is possible that this pattern is not really solar in origin but is instead a consequence of internal climate variability or aliasing from effects of the two major volcanic eruptions aligned to solar maximum periods Chiodo et al. (2014).

(5) The Introduction does not really explain what will be done in this manuscript and why it is necessary. It consists of a general and rather lengthy review of the topical area of solar cycle forcing of the stratosphere, including observational and model results. This review includes some material that could be left out and is not written in a way that explains what the outstanding questions / issues are. It never says what the objectives of the present work are and why they need to be addressed. Why is it necessary to consider non-linear methods in addition to linear multiple regression? Why is it necessary to investigate whether solar responses derived from assimilated reanalysis datasets are consistent with previous analyses of observations alone (e.g., whether a double-peaked response can be extracted from the reanalyses)? What will be done in this manuscript that is different from previous work? Please revise.

The Introduction was revised regarding to this comment. See added paragraph below.

Under this framework the paper by Mitchell et al. (2014a) has been published where 9 reanalysis datasets were examined in terms of 11-year SC, volcanic, ENSO and QBO variability. Complementing their study, we provide comparison with nonlinear regression techniques here, assessing robustness of the results obtained by Multiple Linear Regression (MLR). Furthermore, EP-flux diagnostics are used to examine solar-induced response during winter season in both hemispheres, and solar-related variations of assimilated ozone are investigated.

(6) Abstract, lines 17-20: "Furthermore, the seasonal dependence of the solar response was also discussed mainly as a source of dynamical causalities in the wave

propagation characteristics in the zonal wind and the induced meridional circulation in the winter hemispheres." This sentence is not clear. Please re-write or leave out. Also, in the next sentence, please insert "at solar maximum" after "Brewer-Dobson circulation".

The abstract was rewritten in this way.

(7) P. 30881, lines 10-12. "Gray et al. (2009) have shown, with the fixed dynamical heating model, that the response of temperature in the photochemically controlled region of the upper stratosphere is approximately given 60% by direct solar heating and 40% due to indirect effect by the ozone changes." This statement is a simplification of what is shown in Figure 2 of Gray et al. (2009). In fact, the contribution from the indirect effect of the ozone changes varies from nearly zero in the equatorial middle stratosphere to 60% near the equatorial stratopause. It is a strong function of position, depending on what the solar-induced ozone change is, which can vary strongly with season.

The statement was revised and the area with this proportion limited to the upper tropical stratosphere.

(8) P. 30881, lines 20-22. This sentence refers to the confirmation of the double-peaked vertical structure in the simulations analyzed by Austin et al. (2008). Please revise based on Comment 3 above.

This sentence was revised according to this comment. See below.

The observed double-peaked ozone anomaly in the vertical profile around the equator was reproduced, nevertheless the concerns about physical mechanism of the lower stratospheric response was expressed Austin et al. (2008).

(9) P. 30882-83, lines 27-. This brief summary mentions the work of Ineson et al. 2009 and Harder et al. 2009. However, a more recent detailed review of solar spectral irradiance variability has been given by Ermolli et al. (Atmos. Chem. Phys., v. 13, p.

3945, 2013). They discuss, for example, that the Harder et al. measurements from the SORCE satellite may have been affected by instrument degradation with time and so may be too large in the UV. They conclude that the SORCE measurements, which are currently being re-calibrated by the SORCE team, probably represent a liberal upper limit on the true SSI variation while proxy-based SSI models such as the NRL model represent a lower limit. Please revise to bring this up to date.

The paragraph below was added according to this comment.

However, the measurements by Harder et al. (2009) from SORCE satellite may have been affected by instrument degradation with time and so may be overestimated in the UV (Ermolli et al., 2013). They have also concluded that the SORCE measurements probably represent the upper limit in the magnitude of the SSI variation. Consequent results of GCMs, forced with the SSI from the SORCE measurements, have shown larger stratospheric response than for NRLSSI dataset. Thus, coordinated work is needed to have reliable SSI input data for GCM simulations (Ermolli et al., 2013), and also to propose robust conclusions concerning solar cycle (SC) influence on climate (Ball et al., 2014).

(10) P. 30883, lines 10-13. These two sentences should be combined into one.

These two sentences were combined into one.

(11) P. 30884, line 20. Please change to: ... were analyzed on a daily ... P. 30885, first line: Please insert "For example," before "the Brewer-Dobson ...". P. 30885, line 6: Please change "Except for" to "In addition to".

All suggested changes were realized.

(12) P. 30885, lines 6-14. This whole paragraph seems out of place in a section on Datasets. Please move it to either the Introduction or to section 4.2. In our opinion this paragraph forms a bridge between Introduction and Methodology sections. Based on that this paragraph would not be moved.

(13) P. 30885, Eq. 1. This seems to be a standard regression model except for the NAO term. Is the NAO really independent of the other terms? Or, does it depend partly on ENSO and on the solar cycle? If the latter, then this may introduce errors in the results since there will be mixing of coefficients. Please either remove this term from the model or discuss the issue of independence and whether an NAO term is needed.

The paragraph related to the robustness of solar regression coefficient was added in section Methodology. See paragraph and documenting figures 2,3,4 and 5.

The robustness of solar regression coefficient has been tested in terms of including or excluding particular regressors in the regression model, e.g. NAO term was removed from the model and resulting solar regression coefficient was compared with the solar regression coefficient from original regression model. The solar regression coefficient seems to be highly robust since either the amplitude or statistical significance was not changed when NAO or QBO3 or all of them were removed. However, cross-correlation analysis reveals that the correlation between NAO and TREND, SOLAR and SAOD regressors is statistically significant.

See correlation matrix Fig. 6.

(14) P. 30886. Use of the 10.7 cm flux is acceptable for the solar proxy. However, the results are presented as solar max minus min values in the figures. What is the corresponding difference in the 10.7 cm flux? Is it 100 flux units? Please state this or, otherwise, it is not possible to convert the coefficients in the figures to actual numbers per change in the solar flux. It should also be stated in this paragraph that the 10.7 cm flux is a proxy for solar ultraviolet variations at wavelengths (200-300 nm) that are important for ozone production and radiative heating in the stratosphere.

The information about normalization was added. The statement “for solar ultraviolet variations at wavelengths 200-300 nm that are important for ozone production and radiative heating in the stratosphere” was added as well.

(15) P. 30887, line 13. Please define NWS, either here or in the reference list. Line 25: Perception. NWS was replaced by NOAA since the NAO was downloaded from their website included in the references.

(16) P. 30888, line 2. feedforward should be feed-forward and backpropagation should be back-propagation.

These words were changed in this way.

(17) P. 30889, first line. change to: ... from purely practical . . .

“pure” was changed to “purely”.

(18) P. 30889. Here, the figures are discussed for the first time. Looking at the figures, the small size makes them difficult to read. Also, the hatching to indicate statistical significance makes it difficult to determine exactly what the underlying color is. I am not sure what to do about this but the authors should consider a different presentation method. Would it be possible to enlarge by a factor of 2-3 the regression coefficient plots while leaving the RI plots (which are less illuminating) at a small size?

The paper figures were completely revised. Regression coefficient figures were put together for all reanalyses and relative impact figures were drawn for each reanalysis. Monthly response figures were also revised – temperature, zonal wind geopotential height response is expressed by contours and results are shown from 30° at the summer hemisphere to 90° in the winter hemisphere as was suggested above.

(19) P. 30891, lines 7-9. “The largest discrepancies can be seen in the upper stratosphere and especially in the temperature field ...”. It should be noted here that this could be at least partly because the discontinuities in the reanalysis temperature data are most pronounced in the upper stratosphere. It will be interesting to see how the ERA-Interim results change after the discontinuities are minimized using the McLandress procedure.

See your comment 3.

(20) P. 30895, lines 3-7. This sentence should be divided into two sentences. The second sentence should begin with: While, in the MERRA . . .

These two sentences were divided.

(21) P. 30895-30898 - Dynamical effects discussion. Overall, this is a valuable and detailed description of the dynamical processes that are implied by the monthly linear regression results. In particular, as stated at the bottom of p. 30895, the coupled solar-induced anomalies of ozone, temperature, geopotential, and E-P flux divergence support the hypothesis of a weaker BDC near solar maxima, consistent with the previous interpretations of Kodera and Kuroda (2002) and Matthes et al. (2006). However, it is also stated on p. 30895, lines 7-9, that an effort is made in this section to "deduce the possible processes leading to the observed" solar-induced anomalies. I am not sure that this section really achieves this goal. It is more a description of what is happening dynamically rather than why. You are right it is more a description. Thus "deduce" was replaced by "describe".

(22) At the end of section 5 (p. 30898), it is noted that the weakening of the BDC is apparently not as well established in the SH winter as in the NH winter. It is then stated that this could help explain why the temperature response in the equatorial lower stratosphere is larger in August during SH winter (about 1 C) than it is in December for NH winter (about 0.5 C). First of all, although the lower stratospheric temperature response in SH winter (Figure 5d) does appear to be larger than during NH winter (Figure 4d), it is quite impossible to read the amplitudes of the response from these figures (see comment 18 above). More importantly, if the slowing of the BDC is less in the SH winter, then why is the lower stratospheric temperature anomaly larger at that time?? Again, the discussion in this section is useful for describing what is happening but does not really address the why question. To address the why question, diagnostic analyses of model data are probably required.

This part was completely revised since the statements about BDC and temperature

anomalies were inconsistent.

(23) Conclusions section (p. 30898). Please add a caution to the reader who may otherwise think that the reanalysis datasets are free of errors and that it is straightforward to evaluate the 11-year solar response using these datasets. In particular, please note again the existence of large discontinuities in the temperature record occurring in 1979, 1985, and 1998 that will translate into errors in the derived solar coefficients.

The caution was made in this paragraph, which was added into the Conclusion.

The reanalyses have proven to be extremely valuable scientific tools (Rienecker et al., 2011). On the other hand, they have to be used with a caution for example, due the existence of large discontinuities occurring in 1979, 1985 and 1998 (McLandress et al., 2013) that translated into errors in the derived solar coefficients. For instance the revised anal15 ysis with the adjustments from McLandress et al. (2013) resulted to 0.2 K/(Smax-Smin) difference between regression coefficients in tropical latitudes of the upper stratosphere.

(24) P. 30899, lines 8-9. Again, the statement that the Austin et al. (2008) results confirmed the double-peaked structure is a bit of an exaggeration. Please revise (see comment 3).

"even confirmed by the coupled chemistry climate model simulations (e.g. Austin et al., 2008)" was replaced by "in spite of that the concerns about physical mechanism of the lower stratospheric response was expressed (e.g. Austin et al., 2008)".

(25) P. 30900, some English corrections: Line 2: ... which investigated the solar ...; Line 15: ... show an ability to simulate the ...; Line 19: ... on northern winter conditions; nevertheless, southern winter ...

First two issues were changed. However, the sentence "The main part deals with the solar influence on northern winter conditions nevertheless, southern winter anomalies were also discussed." were deleted based on the comment 30 of ref. #4.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/14/C12756/2015/acpd-14-C12756-2015-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 14, 30879, 2014.

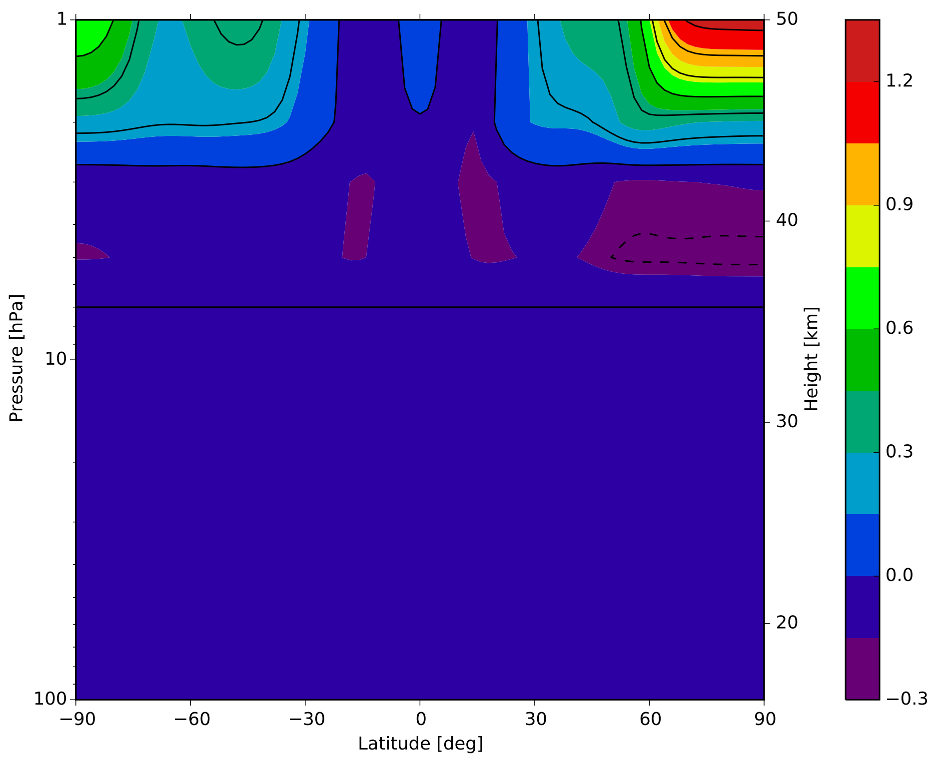

Fig. 1. Difference between solar regression coefficient of non-adjusted and adjusted ERA-INTERIM dataset. Contour lines are drawn with step 0.2.

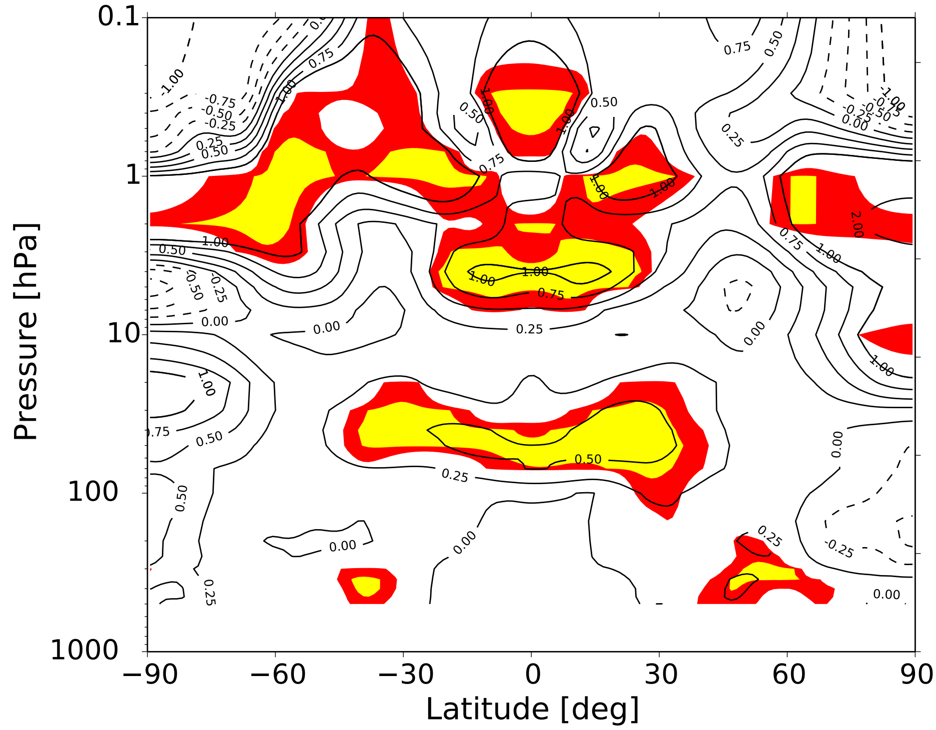

Fig. 2. Temperature response to SC for MERRA. All regressors included.

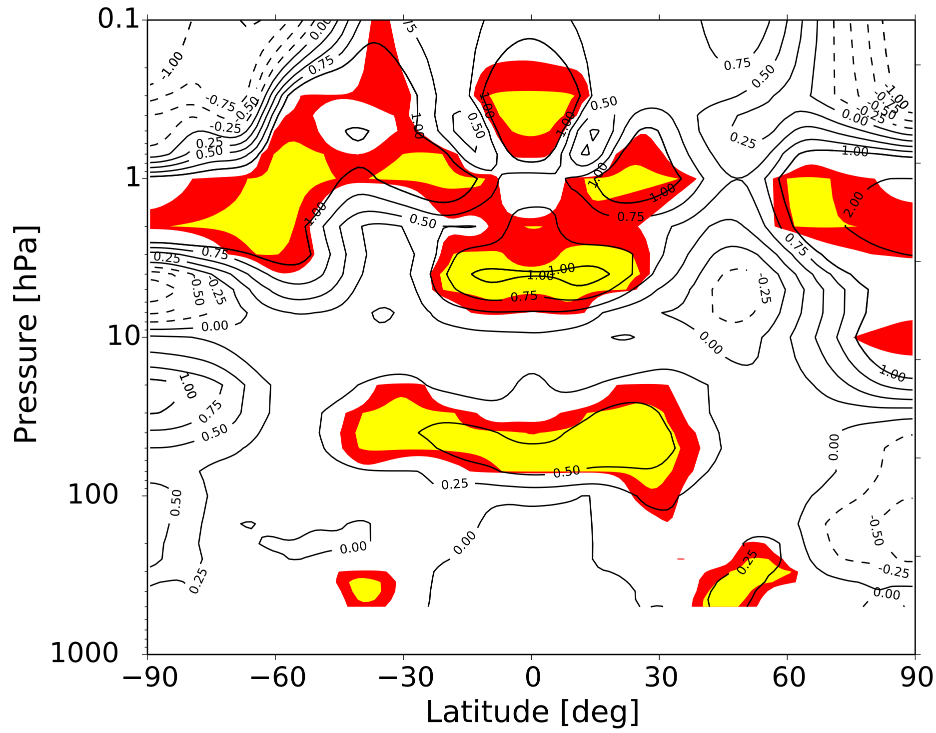

Fig. 3. Temperature response to SC for MERRA. All regressors included except NAO.

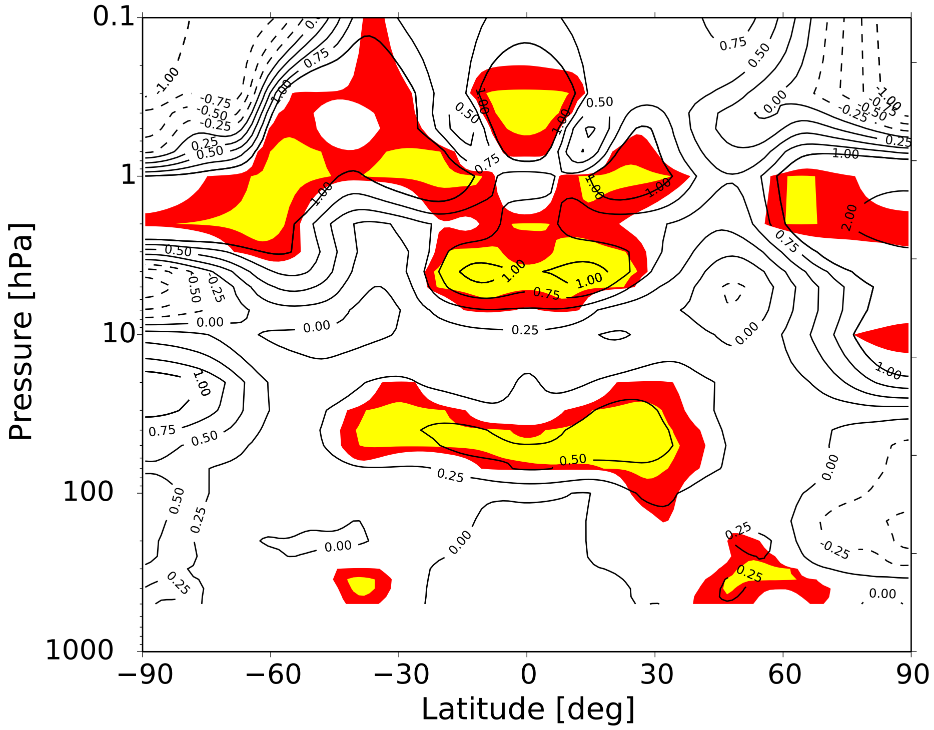

Fig. 4. Temperature response to SC for MERRA. All regressors included except QBO3.

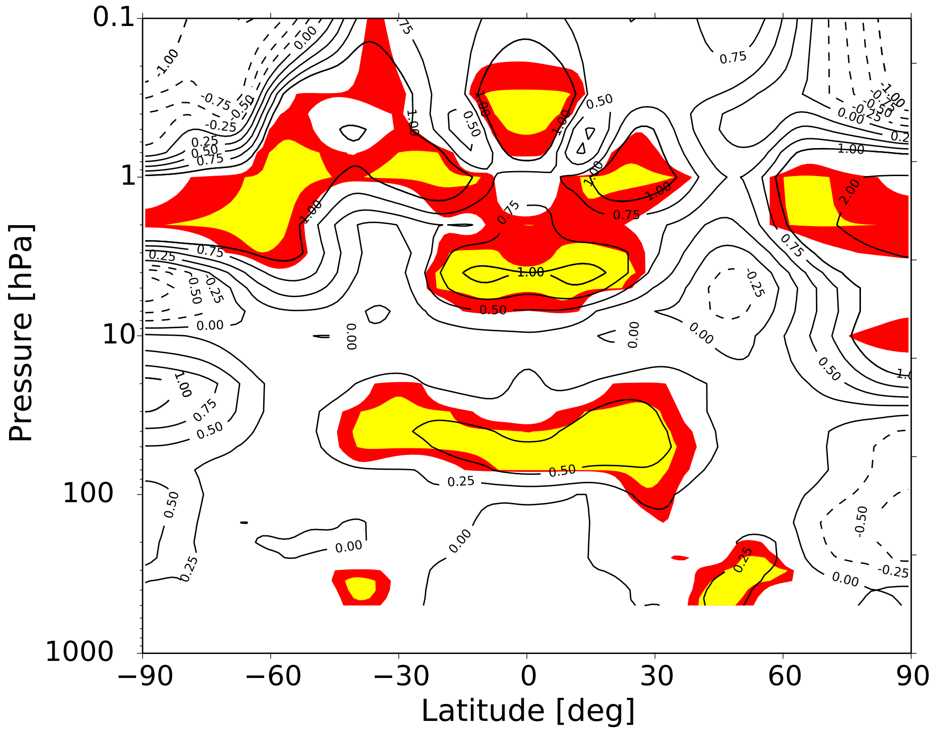

Fig. 5. Temperature response to SC for MERRA. All regressors included except NAO and QBO3.

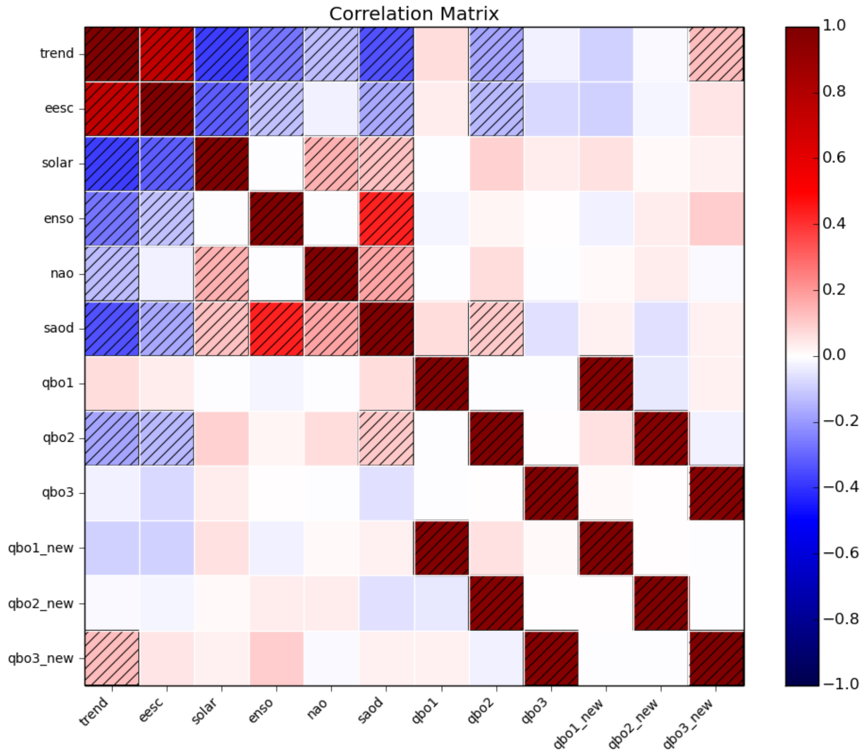

Fig. 6. Cross-correlation matrix of regressors for MERRA. QBO1_new, QBO2_new and QBO3_new computed from a Principal Component Analysis of equatorial, deasonalized zonal mean zonal wind anomalies only.

Atmos. Chem. Phys. Discuss., 14, C12790–C12816, 2015
www.atmos-chem-phys-discuss.net/14/C12790/2015/

Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Solar cycle in current reanalyses: (non)linear attribution study" *by* A. Kuchar et al.

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Referee #4

We would like to thank the reviewer for his/her comments.

Author's response and changes in manuscript are included below. In addition, you can find the revised manuscript as supplement where the particular changes are highlighted together with the comment referring to them.

General comments

There are a lot of different techniques being used simultaneously in this paper. Overall I feel like there needs to be more in depth explanation of what is precisely done. Also, more intermediate results in the methodology chapter should be presented. It is, e.g.,

not surprising to see that all three statistical methods lead to similar results given only monthly data were used. The true power of nonlinear methods only comes into play when having lots of events available. Daily data would be a good starting point. In my opinion, there should be a few time series figures demonstrating the hind-casting abilities of the different methods. Also, the authors should consider combining all three methods and averaging them in a weighted fashion based on their forecast abilities.

We have considered this general comment as a relevant and corresponding experiments were done. However, these suggestions seem to be out of range of our paper. Thus no relevant changes in the paper were considered according to this comment.

The hindcasting abilities of the different methods was demonstrated daily and monthly zonal means of ERA-Interim temperature time-series between 25°N a 25°S in 1 and 50 hPa. All statistical models were trained with data from training period 1979-2006 to set up the tunning parameters. The tunning was done by 5-fold crossvalidation. The model configuration with the highest correlation calculated for the crossvalidated subsets was used for testing period 2007-2013.

The results in form of coefficient of determination are presented in the Fig. 1. From these table it is quite obvious that the referee's statement about power of nonlinear methods when having lots of events, i.e. using daily data is valid only for SVR. The neural networks in our case are not so powerful as was expected. This could be affected by the fact that we use only one layer of hidden neurons and therefore the training was not conducted so properly as in the SVR training.

Using two layer neural networks we achieved even better performance. However, coefficient of determination based on daily data is still lower. The comparably worse performance of MLPs may be a result of their increased vulnerability to inhomogeneities and breaks in the data, due to high complexity of the respective transfer function combined with its nature as global mapping in the space of predictors

Specific comments

(1)P30881,L23 to P30882,L5 This paragraph is in my opinion too early, it should be placed behind the general explanation of the mechanism (currently L6 to L18).

Your comment was considered as relevant and moved behind the paragraph “The ozone and temperature perturbations associated....”.

(2)P 30882, L19 to L25 This paragraph seems to have nothing to do with the rest of the analysis and should be omitted.

This part of the paragraph was omitted: “Observational and modeling studies over the past two decades have fundamentally changed our understanding of wave processes and the coupling between the middle atmosphere and tropospheric conditions (Gerber et al., 2012). It has been shown that the stratosphere plays a significant and active role in tropospheric circulation on various time scales (Baldwin and Dunkerton, 1999; Lu et al., 2013; Solomon et al., 2010). A deeper understanding of the mechanisms of communication between the middle atmosphere and troposphere contributes to better climate change predictions. However, a number of questions about the coupling processes with regard to solar signal perturbation have to be answered.”

(3)P30883,L2 The TIM/SIM data (Harder et al., 2009) mentioned here are currently checked and corrected for possible instrument degradation. These data should be considered as the upper boundary of possible solar spectral irradiance variations, whereas the NRLSSI data by Lean (2005) which are widely used in chemistry climate models give a kind of a lower limit. An appropriate statement should be made in the text. There is a review on this issue by Ermolli et al. (2013) which should be cited here.

The paragraph below was added according to this comment.

However, the measurements by Harder et al. (2009) from SORCE satellite may have been affected by instrument degradation with time and so may be overestimated in the UV (Ermolli et al., 2013). They have also concluded that the SORCE measurements

probably represent the upper limit in the magnitude of the SSI variation. Consequent results of GCMs, forced with the SSI from the SORCE measurements, have shown larger stratospheric response than for NRLSSI dataset. Thus, coordinated work is needed to have reliable SSI input data for GCM simulations (Ermolli et al., 2013), and also to propose robust conclusions concerning solar cycle (SC) influence on climate (Ball et al., 2014).

(4)P30884,L13 The introduction ends somewhat abrupt without a statement on the intention nor the focus of the present paper. This should be added here. Furthermore, a short outline of the paper should be given, e.g. "In section 2 the datasets are presented, in section 3 the analysis methods are described ...“

The paragraph with a short outline was added. See below.

The paper is arranged as follows. In section 2 the used datasets are described. In section 3 the analysis methods are presented along with regressor terms employed in the regression model. Section 4 is dedicated to the description of the annual response results. In subsection 4.1.1 solar response in MERRA reanalysis is presented. Next, in subsection 4.1.2 other reanalyses are compared in terms of SC. Comparison of linear and nonlinear approaches is presented in subsection 4.1.3. Section 4.3. describes monthly evolution of SC response in the state variables. Section 5 is aimed at dynamical consequences of the SC analysed using the EP-flux diagnostics.

(5)P30885,L20ff I am missing explanations of the various parameters used in equation (1) such as z, phi, and lambda.

The explanation of these parameters was added.

(6)P30886,L10ff The QBO factors should be calculated from the data of each reanalysis and then used together with the respective data set. Computing them just from MERRA seems inconsistent. Why are the QBO factors computed using the regression model itself? Statistical features that serve as input to a supervised method should be independent. I would recommend to compute the QBO factors from a Principal Component Analysis of equatorial, deasonalized zonal mean zonal wind anomalies. The QBO factors were calculated from the data of each reanalysis and this fact was also mentioned within the manuscript. However, the results haven't changed significantly. See Figs. 2 and 3 for ERA-Interim and Figs. 4 and 5 for JRA-55.

As was already pointed out in the text this approach follows the paper by Frame a Gray (2010) to avoid contamination of the QBO regressors e.g. by the solar signal as well as the other regressors. However, the contamination needs not to be just linear and stationary as is considered in linear regression approach. The regression analysis has been repeated with the QBO regressors computed from a PCA of equatorial, deseasonalized zonal mean zonal wind anomalies. For this purpose the MERRA reanalysis was used. The differences between solar regression coefficient results from revised and original analysis are presented in Figs. 6 and 7. It is obvious that the amplitude of the solar signal changes according to the changes in QBO regressors, but the pattern is still the same. These changes can be considered as statistically significant.

In addition, the correlation analysis between the regressors did not reveal any remarkable changes, only the correlation changes either between QBO2 and TREND, EESC and SAOD or QBO3_new and TREND are worthy of notice since these correlations are statistically significant for p value < Âă0.05. See correlation-matrix in Fig. 8.

(7)P30887,L10 Why was the NAO included as a regressor variable? It could be that the NAO is not independent from other regressors, such as the solar cycle or ENSO, so you introduce possible errors in the regression model. Did you test whether the solar regression coefficient changes markedly when you include or leave out the NAO regressor? Please, discuss this in the text. What does the reference NWS,2013 mean?

NWS was replaced by NOAA since the NAO was downloaded from their website included in the references.

The paragraph related to the robustness of solar regression coefficient was added in

section Methodology. See paragraph and documenting Fig. 6,9,10 and 11.

The robustness of solar regression coefficient has been tested in terms of including or excluding particular regressors in the regression model, e.g. NAO term was removed from the model and resulting solar regression coefficient was compared with the solar regression coefficient from original regression model. The solar regression coefficient seems to be highly robust since either the amplitude or statistical significance was not changed when NAO or QBO3 or all of them were removed. However, cross-correlation analysis reveals that the correlation between NAO and TREND, SOLAR and SAOD regressors is statistically significant.

See correlation matrix figure 8.

(8)P30887,L27 What does the author mean by "highly complex"? The MLP is in fact a fairly simple mathematical construct.

This collocation was omitted in the manuscript.

(9)P30888,L9 There are no words about the hyperparameters of MLP and SVR. Which values do they have and how were they determined? Also, which algorithm is used to optimize the MLP? Which SVR is used, epsilon or nu SVR? It would also be interesting to know which software libraries were used in this study.

All information suggested above was added to the manuscript. Software libraries were mentioned in the acknowledgement section.

(10)P30888,L15 Lack of explanatory power? What is meant here?

The sentenced was revised. See below.

The earlier mentioned lack of explanatory power of the nonlinear techniques in terms of complicated interpretation of statistical models (Olden, 2002).

(11)P30888,L21 Using the relative impact based on the median is ok for this study. However, an even better approach would be to average across relative impacts based on quantile variations. The author should consider looking at the featureimpact Python package which implements this approach.

We considered relative impact based on quantile variations via the feature impact Python package, which implements this approach. The results of relative impact for monthly zonal mean of ERA-Interim temperature between 25°N a 25°S in 1 and 50 hPa are presented in Figs. 12 and 13. Linear regression, Neural networks and SVR have been used in the left, middle and right figure respectively. Blue line corresponds to original approach based on the median and red line correspond to quantile-variation approach. The relative impact values of solar regressors are almost the same through all methods. However, the relative impact of other regressors may differ. The relative impact of solar regressor based on the median seems to be robust in all cases. Therefore, we conclude it is convenient to use this approach, although the approach based on quantile variations would appear even better, especially in case of other regressors.

Based on the statements above no revisions was not considered in this point since we have already discussed quartile variation approach in our paper.

(12)P30888,L23 y-y_k is the difference and not the variance of it.

This sentenced was revised. “variance of” was added in front of difference.

(13)P30889, L11 to L13 What is the average difference between the solar maxima and minima in the period 1979-2013 in terms of F10.7 solar radio flux units? Please state clearly the value in the text and in the figure captions. In the literature the commonly used value is 100, sometimes 130 units.

The signal is expressed as the average difference between the solar maxima and minima in the period 1979-2013, i.e. normalized by 126.6 solar radio flux units. And this part was also included in the manuscript.

(14)P30891, L20 The negative ozone response in the ERA-Interim dataset needs some further explanation. Higher destruction of ozone at solar maximum as stated in the text

should become the dominant process higher up in the mesosphere (due to enhanced water vapor photolysis generating OH which in turn depletes ozone). And what is meant by "consequent heating“? Should it be cooling? Please clarify this in the text.

The paragraph below was added to clarify this in the manuscript.

The negative response could be interpreted as a consequence of temperature rise leading to increased ozone losses because of the temperature dependence of the reaction rates that control the ozone balance in the upper stratosphere. This interpretation does not require that the assimilation model had included interactive ozone chemistry since in the model used for ERA-Interim the ozone as a prognostic variable is relaxed towards a photochemical equilibrium for the local value of the ozone mixing ratio, the temperature, and the overhead ozone column (Dee et al., 2011). An additional term is used to parameterize the heterogeneous chemistry. This fact together with the finding that the temperature and ozone are highly negatively correlated in the upper stratosphere, e.g. -0.93 for zonal mean between 15°S and 15°N in 1 hPa, provide reasonable explanation of the negative ozone response to the SC which is driven by temperature variability in the upper stratosphere. In the case of MERRA, while SBUV ozone profiles are assimilated with solar cycle passed to forecast model (as ozone analysis tendency contribution), no solar cycle was passed to the radiative part of the model. The same is also true for ERA-Interim and JRA-55 (see descriptive table of reanalysis product on SC in irradiance and ozone in Mitchell et al. (2014a). Among other tendencies the dynamics and chemistry components also contribute to total tendency of ozone. These two tendencies prevent any variations in ozone analysis tendency though. Thus periods longer than 1 year are filtered out in the upper stratosphere. Only annual and semi-annual cycles are included. The SC-like periods seem to be diminishing approximately from 5 hPa except in the polar regions fro both hemispheres. The negative correlation -0.93 between the tendency of dynamics and chemistry and tendency from analysis for zonal mean in the tropical upper stratosphere confirms this statement as well. This negative correlation roots from anti-phase relationship between the tendency from dynamics and chemistry. Therefore de15 spite the fact that the analyzed ozone should contain a solar signal, the signal is very weak and is compensated by internal model variability in terms of dynamics and chemistry. Since the SBUV ozone profiles have very low vertical resolution this may also affect the ozone response to the SC in the reanalysis. These facts should be also taken into account in case of monthly response discussion of particular variables in the section 4.2.

(15)P30891, L27 It is not entirely clear which dataset the authors are talking about in this paragraph.

"solar signal" was replaced by "ozone response".,

(16)P30892, L22 Do you mean southern hemisphere? From the figures I cannot detect any relative impact signal in temperature exceeding say 30% in the northern hemisphere.

You are right. "southern"was replaced by "northern".

(17)P30892,L25 This is the first mention of volcanic signals being important in the lower stratosphere. In my opinion, this needs some further discussion. Given the shortness of the examined time series (1979-2013, i.e. 35 years) and the fact that two major volcanic eruptions happened with about 10 years difference and, thus, were aligned to maxima in the 11-year solar cycle it is possible that there are some problems with the attribution. This is e.g. discussed in a recent paper by Chiodo et al., ACP, 2014 also in view of the length of the considered time series, using a chemistry climate model. However, the possibility of aliasing must be mentioned in the text and some appropriate citations should be included.

The paragraph below was added regarding this comment.

However, the results presented by Chiodo et al. (2014) suggest the contribution of solar cycle variability could be smaller since two major volcanic eruptions are aligned with so-

lar maximum periods and also given the shortness of analysed time series (in our case 35 years). These concerns related to the lower stratospheric response of ozone and temperature derived from observations has already been raised (e.g. Solomon et al., 1996;Lee and Smith, 2003). However, another issue is whether or not the lower stratospheric response could depend on the model employed in the simulations Mitchell et al. (2015).

(18)P30893,first paragraph This paragraph explains what has not been done in a lengthy way. I would suggest to substantially shorten this or to omit it.

First sentence was omitted.

(19)P30893,L9ff From the above explanations I cannot follow this conclusion. Please, clarify this in the text.

This paragraph of the manuscript was revised to be more clear than before.

(20)P30894, L8 From Figure 4d I cannot see any downward propagation of a temperature anomaly. I can only see a positive temperature anomaly that extends further down into the stratosphere compared to the January situation, at least at low latitudes. Do you mean this? Or do you mean something that happens from February to March? Please clarify this in the text.

"propagates downward" caused a misunderstanding and was replaced by "extends further down".

(21)P30894, L14 I can guess from the Figure 4d and 4h that the anomalies reach tropospheric levels. But strictly spoken this is not shown in your figure.

The citation of Mitchell at al., 2014 paper was placed here since they included also tropospheric levels in the regression analysis.

(22)P30894, L28 Geopotential height anomalies are not shown in Figures 4 and 5. Please state this in the text.

The additional figures of geopotential height anomalies were included.

(23)P30895, L3ff This is a whole paragraph about something that is not shown (no October panels in Fig 4) and it reappears in the conlusions section. I suggest omitting these sentences.

“only November shown” statement was included in this place. Although the figures of monthly response does not include October we believe these differences in the lower mesosphere should be pointed out since the model top could play a role in this case.

(24)P30896, L24 Again, geopotential height anomalies are not shown in Figure 4. The authors discuss the shape of the vortex in this section without showing geopotential height results, this is somewhat strange. I suggest either inclusion of additional figure panels or a restriction of the discussion to the shown variables.

The additional figures of geopotential height anomalies were included.

(25)P30897, L12 to L14 At this point Sudden StratosphericWarmings are mentioned for the first and only time. This is done in a way that the reader can gain the impression these warmings happen only in February which is not true. Did you check the occurrence rates and the seasonal distribution of SSWs in the MERRA dataset? If not, please omit this sentence. This applies also to the last half sentence in the abstract.

The sentence was omitted. The last sentence in the abstract was changed to: “The hypothetical mechanism of a weaker Brewer Dobson circulation at solar maxima was reviewed together with discussion of polar vortex behaviour.”

(26)P30898, L2 What do you mean by "latitudinal coordinates“? Please, reformulate and clarify.

“coordinates” was changed to “component”.

(27)P30898, L19 and P30899, L3 It is sufficient to state once that you used the last generation of reanalysis datasets.

“last generation of reanalysed data” was changed to “three reanalysed datasets: MERRA, ERA-Interim and JRA-55” in the conclusion section.

(28)P30899, L1 Given the short analysis period (35 years), I would not write "robust“, also in view of a possible aliasing issue with the volcanic eruptions.

“can be considered sufficiently robust and they” was deleted from this sentence.

(29)P30899, L2 Frame and Gray used ERA data, right? So please do not call it an observational study since it is a reanalysis study. This does also apply to the same sentence in the abstract.

“observational” was changed to “attribution”.

(30)P30900, L18 to L20 The sentence starting with "The main part ...“ can in my opinon be deleted. Otherwise you should add in a concise way the essence of the dynamics discussion.

“The main part deals with the solar influence on northern winter conditions nevertheless, southern winter anomalies were also discussed.” was deleted.

(31)P30901,L2 Please reformulate "So it would be desirable ...“ into "Hence, it would be interesting to ...“ Otherwise the question arises why you didn’t do it, immediately.

“So it would be desirable” was reformulated to “Hence, it would be interesting”.

Technical comments:

(1)The figures are very difficult to read due to their smallness and their design and should, therefore, be substantially enlarged or even re-designed in a different way, e.g., with contours on top of the color fields. Maybe statistical significance can be included in a different way (e.g. as bold white contour) as it is really difficult to see the color behind the hatching and then to get an impression on the magnitude of the significant signal. This is especially a problem in Figures 4 and 5. Another suggestions for Figures 4 and 5: Why not concentrate on the respective winter hemisphere and show results from the equator to the winter pole or possibly from 30° at the summer hemisphere to 90° in the winter hemisphere? And a question concerning the scaling of the EP-Flux arrows: The arrows show predominantly horizontal anomalies, did you apply the scaling only to the horizontal component?

The paper figures was completely revised. Regression coefficient figures were put together for all reanalyses and relative impact figures were drawn for each reanalysis. Monthly response figures were also revised – temperature, zonal wind geopotential height response is expressed by contours and results are shown from 30° at the summer hemisphere to 90° in the winter hemisphere as was suggested above. The scaling was applied for both components. However, the vertical component of residual circulation was multiplied by 1000, thus the units are in 10ˆ{-3} Pa/s.

(2)A native English speaker needs to proofread this paper.

The manuscript was proofread before ACP discussion. In this phase the authors paid more attention to correct way of writing. Before prospective publishing the paper could be proofread again.

(3)Maybe the paper title should be formulated more precisely, e.g. "The 11-year solar cycle in current reanalyses: A (non)linear attribution study of the middle atmosphere“

The paper title was changed to “The 11-year solar cycle in current reanalyses: A (non)linear attribution study of the middle atmosphere”.

(4)Please rename in the abstract (P30880,L5) the "traditional linear approach“ as "multiple linear regresion approach“.

“traditional linear” was replaced by “multiple linear regression” in the abstract.

(5)Temperature differences are given in Kelvin, not in #C as temperature itself. Please change this in the text and in the figure captions.

The unit of geopotential height is given as meters [m]. Isn't it geopotential meters

[gpm]?

The units were revised in these cases.

(6)Please consider reformulating the section headlines to remove the parentheses, e.g. 4.1.1 Annual response – Comparison with JRA-55 and ERA-Interim.

This section headline without parenthesis was considered as more convenient.

(7)P30887, L25f there is twice "in our case“ in this sentence.

“in our case” was deleted once.

(8)P30894, L1 Do you really mean "alternation“ in the sense of reversal or "alteration“ in the sense of change?

“alternation” was changed to “alteration” because it was supposed to mean in the sense of change since regression coefficients express relative change between Smax and Smin.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/14/C12790/2015/acpd-14-C12790-2015-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 30879, 2014.

1hPa:

	Monthly		**Daily**	
	Train	Test	Train	Test
LREG	0.135902128359	0.188644744567	0.0999010739788	0.119092463972
SVR	0.139631982558	0.123990201857	0.731505412416	0.671168700694
NNET	0.697032804235	0.561393545156	0.299611435909	0.289565371261

50 hPa:

	Monthly		**Daily**	
	Train	Test	Train	Test
LREG	0.0389747054139	0.151568481135	0.02337480342	0.0305293568918
SVR	0.0604949228305	0.0825654167504	0.734330755984	0.657803351645
NNET	0.789019942167	0.51132516853	0.346617586523	0.369187889736

NNET 2HL	0.967575411623	0.461844164912	0.742810213875	0.708926970146

Fig. 1. Coefficient of determination of particular hindcast experiments for 2 pressure levels.

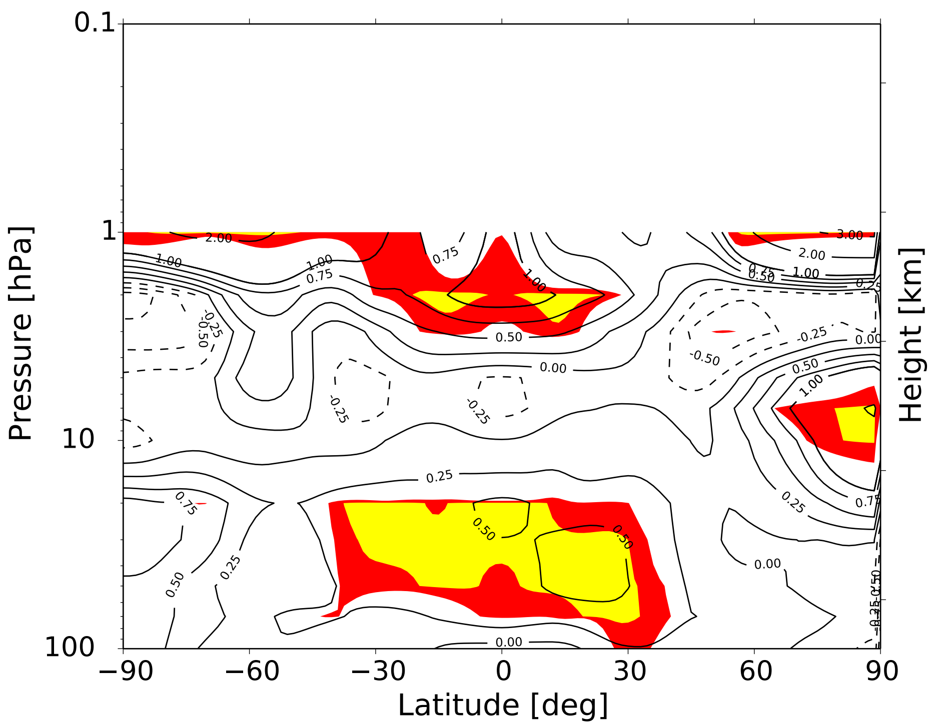

Fig. 2. Temperature regression coefficient for ERA-Interim. The QBO factors were calculated from the MERRA.

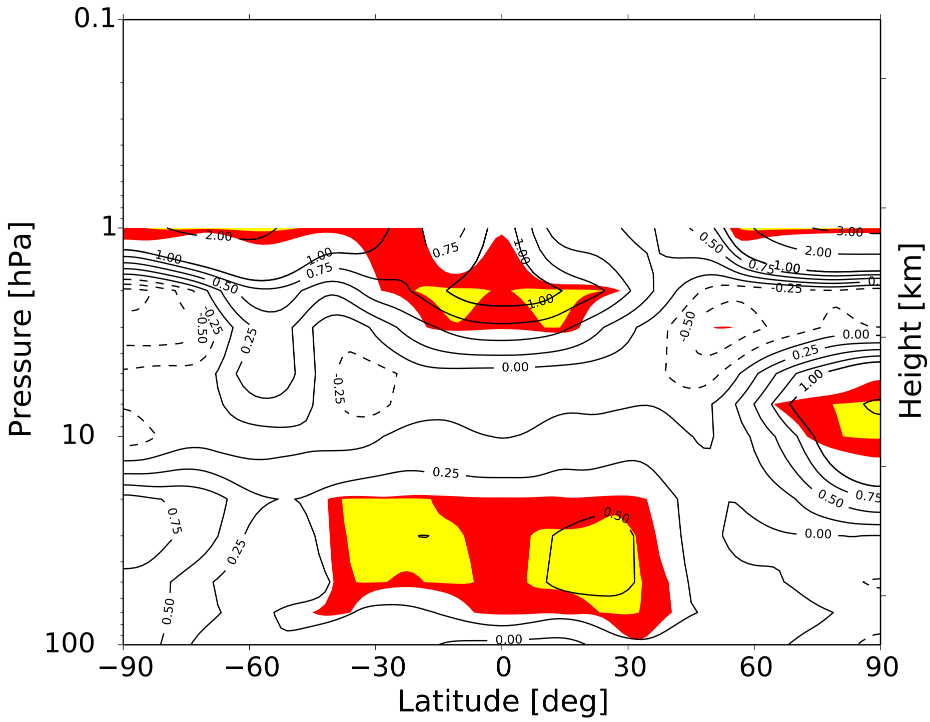

Fig. 3. Temperature regression coefficient for ERA-Interim. The QBO factors were calculated from the ERA-Interim.

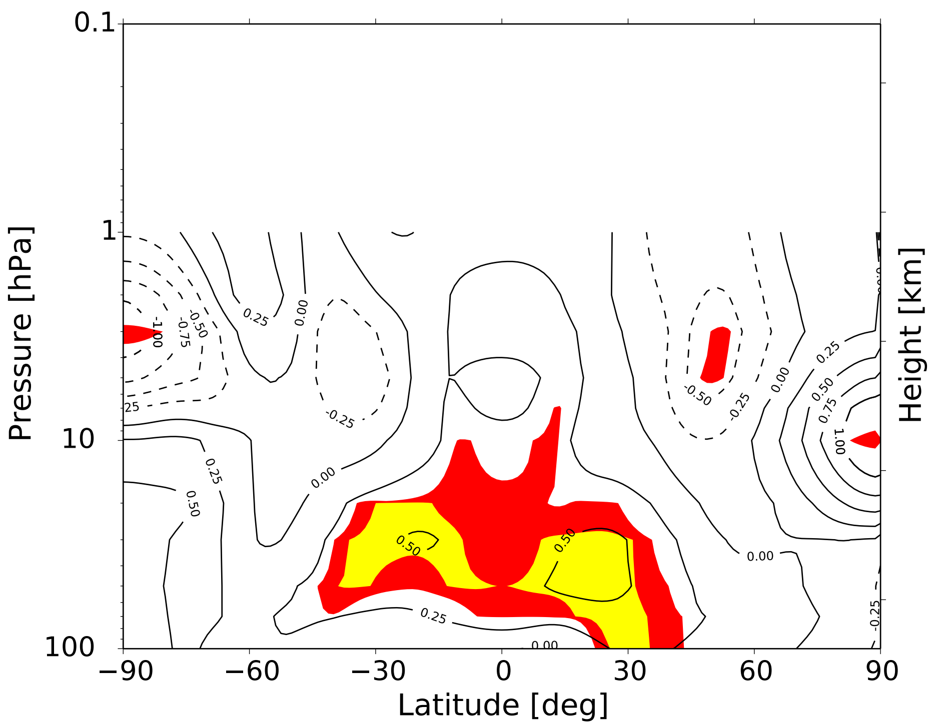

Fig. 4. Temperature regression coefficient for JRA-55. The QBO factors were calculated from the MERRA.

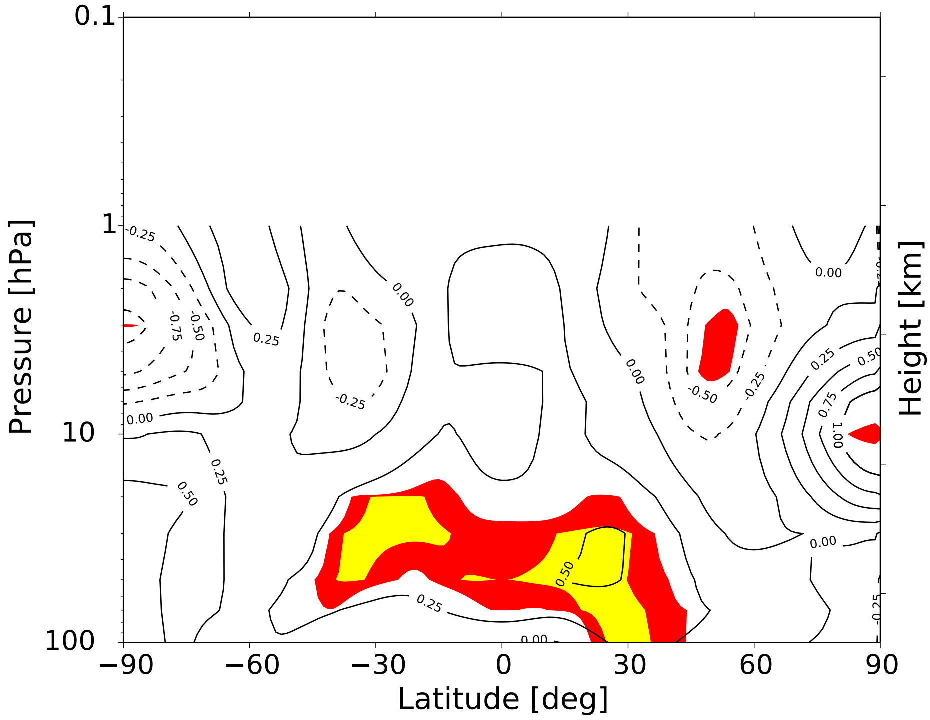

Fig. 5. Temperature regression coefficient for ERA-Interim. The QBO factors were calculated from the JRA-55.

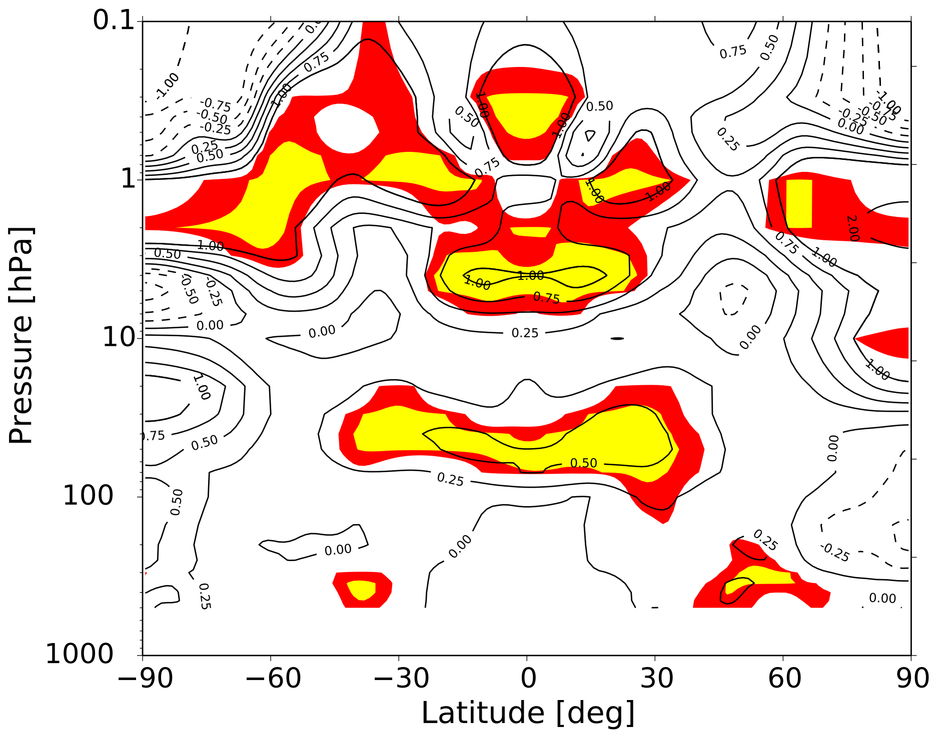

Fig. 6. Temperature response to SC for MERRA. The QBO factors were computed by the approach following the paper by Frame and Gray (2010).

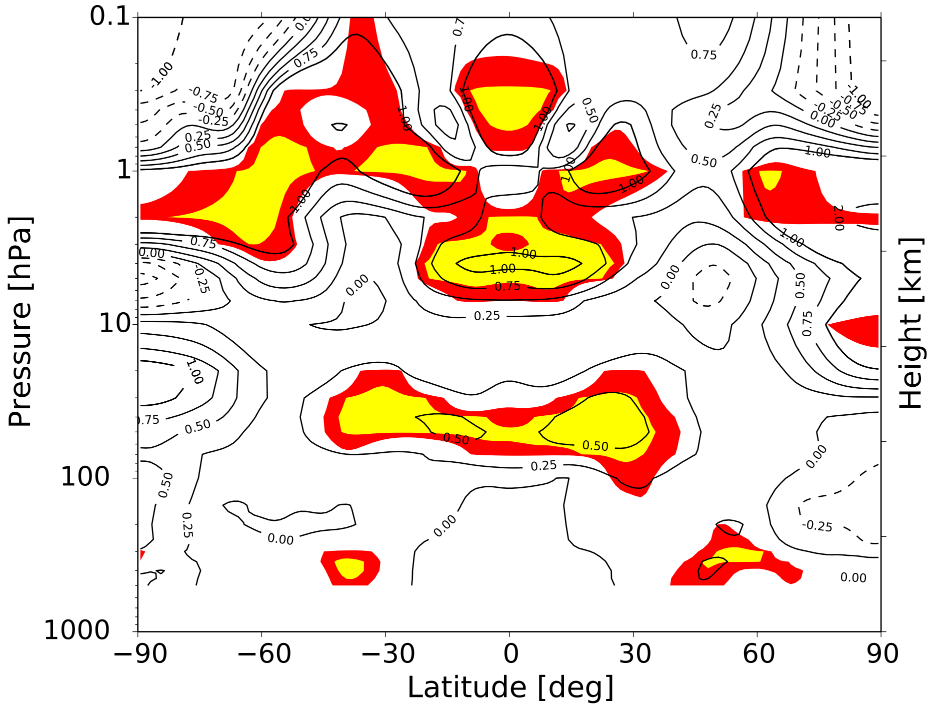

Fig. 7. Temperature response to SC for MERRA. The QBO factors were computed from a PCA of equatorial, deseasonalized zonal mean zonal wind anomalies.

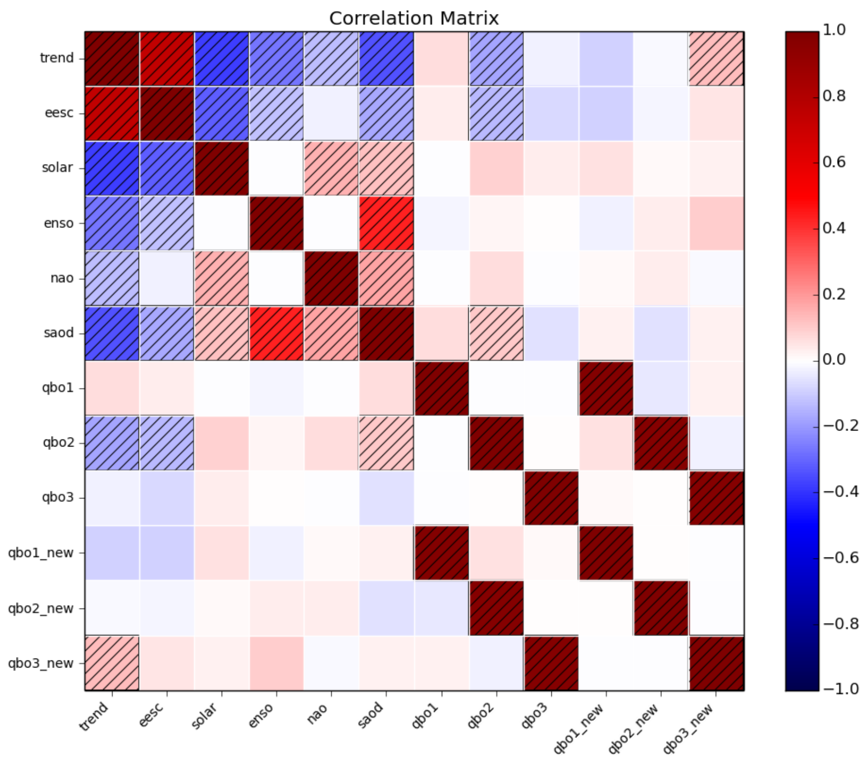

Fig. 8. Cross-correlation matrix of regressors for MERRA. QBO1_new, QBO2_new and QBO3_new computed from a Principal Component Analysis of equatorial, deasonalized zonal mean zonal wind anomalies only.

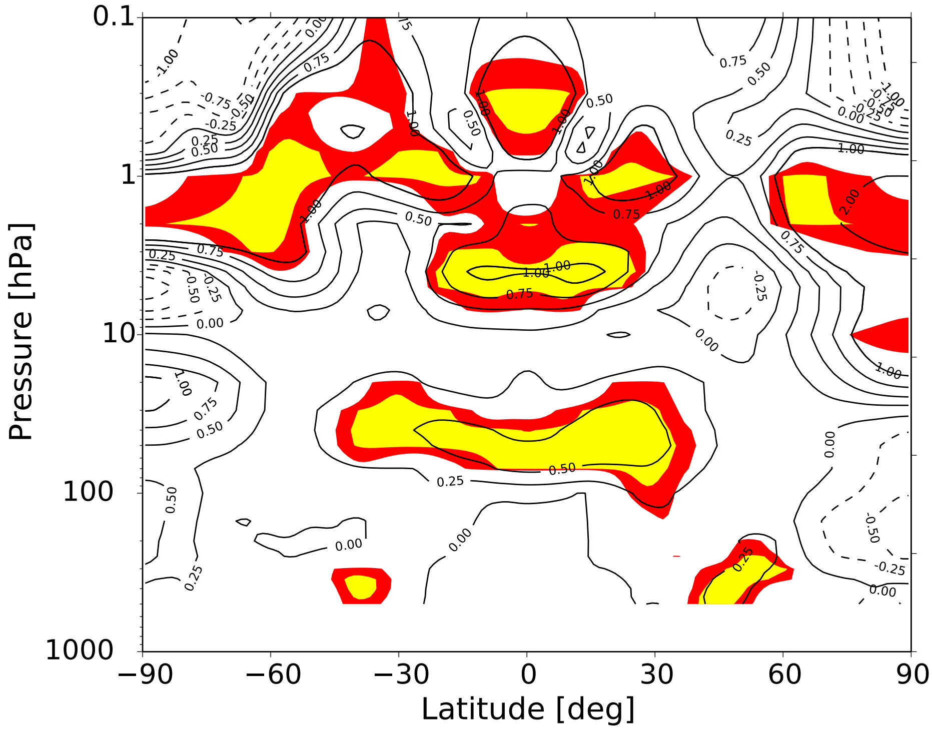

Fig. 9. Temperature response to SC for MERRA. All regressors included except NAO.

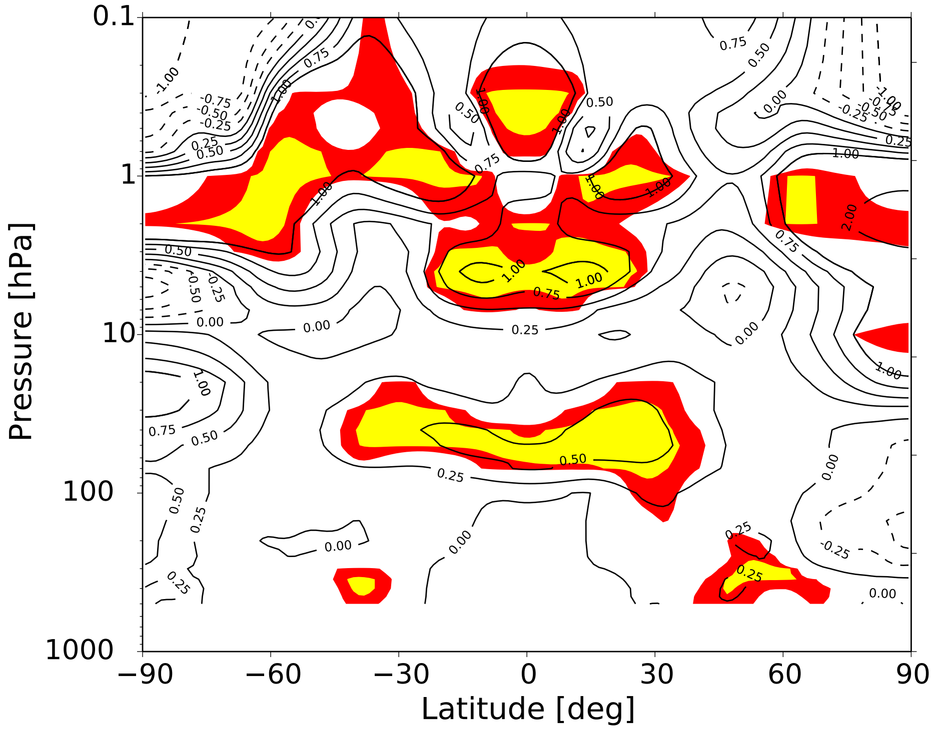

Fig. 10. Temperature response to SC for MERRA. All regressors included except QBO3.

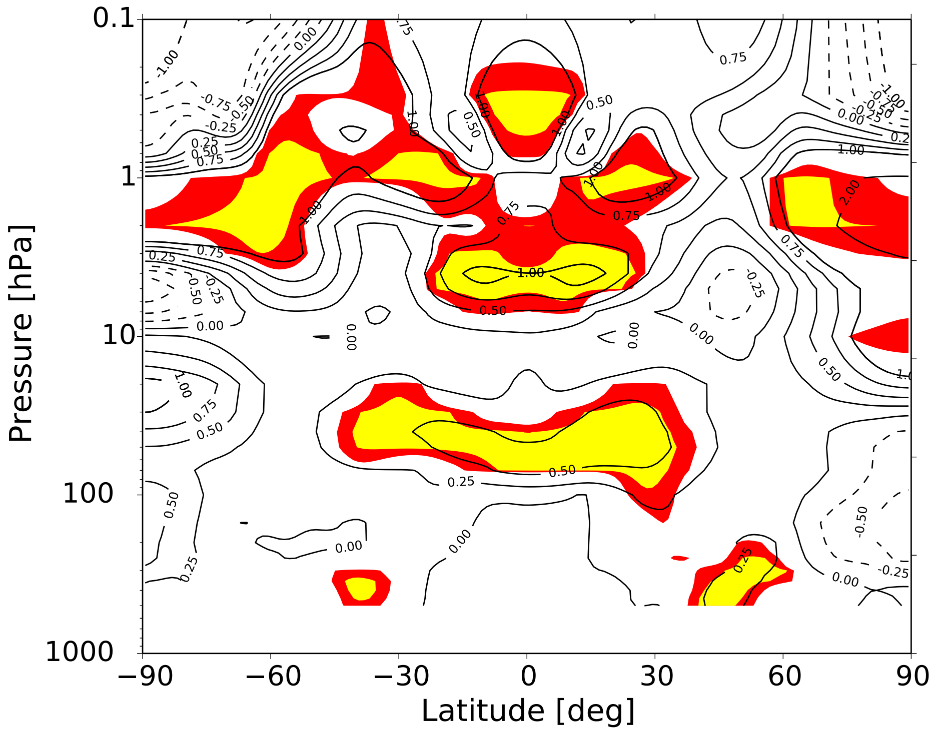

Fig. 11. Temperature response to SC for MERRA. All regressors included except QBO3 and NAO.

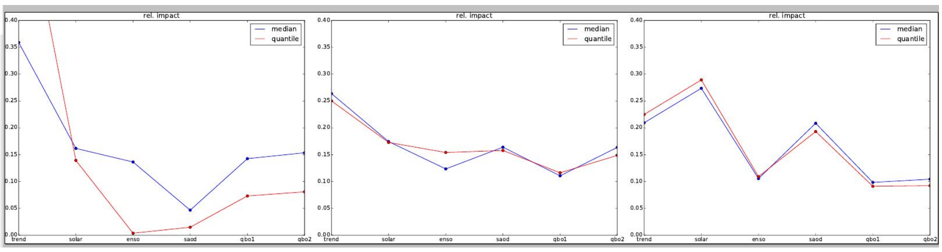

Fig. 12. The results of relative impact for monthly zonal mean of ERA-Interim temperature between 25°N a 25°S in 1 hPa.

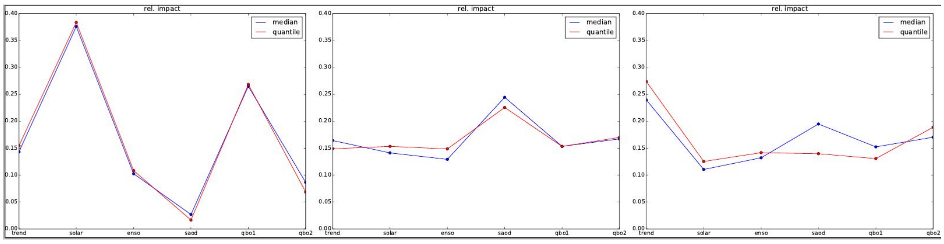

Fig. 13. The results of relative impact for monthly zonal mean of ERA-Interim temperature between 25°N a 25°S in 50 hPa.