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The influence of solar variability and the quasi-biennial oscillation on sea level pressure

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Abstract

We investigate an apparent inconsistency between two published results concerning the temperature of the winter polar stratosphere and its dependence on the state of the Sun and the phase of the Quasi-Biennial Oscillation (QBO). We find that the differences can be explained by the use of the authors of different pressure levels to define the phase of the QBO.

We identify QBO and solar cycle signals in sea level pressure (SLP) data using a multiple linear regression approach. First we used a standard QBO time series dating back to 1953. In the SLP observations dating back to that time we find at high latitudes that individually the solar and QBO signals are weak but that a temporal index representing the combined effects of the Sun and the QBO shows a significant signal. This is such that combinations of low solar activity with westerly QBO and high solar activity with easterly QBO are both associated with a strengthening in the polar modes; while the opposite combinations coincide with a weakening. This result is true irrespective of the choice of QBO pressure level. By employing a QBO dataset reconstructed back to 1900, we extended the analysis and also find a robust signal in the surface SAM; though weaker for surface NAM.

Our results suggest that solar variability, modulated by the phase of QBO, influences zonal mean temperatures at high latitudes in the lower stratosphere and subsequently affect sea level pressure near the poles. Thus a knowledge of the state of the Sun, and the phase of the QBO might be useful in surface climate prediction.

1 Introduction

There is an established body of literature, initiated by the pioneering work of Labitzke (1987), which has identified the influence on winter temperatures in the polar lower stratosphere of the quasi-biennial oscillation (QBO) in tropical lower stratospheric winds, and of solar activity (measured by sunspot number or some other indicator such

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as 10.7 cm radio flux). What these studies found was that by segregating the meteorological data by the phase of QBO a clear signal of the 11-year solar cycle was revealed. More specifically, that the January-February temperature at 30 hPa over the North Pole tends to be warmer during the west phase of the QBO at high solar activity (HS/wQBO) and also during the east phase at low solar activity (LS/eQBO). Consistently, cold polar temperatures occur during LS/wQBO and HS/eQBO (Labitzke and van Loon, 1992; henceforth LvL92).

Camp and Tung (2007) (henceforth CT07), however, using a alternative methodology, and also a slightly altered temporal and spatial coverage for temperature, suggest a somewhat different solar/QBO relationship. They applied Linear Discriminant Analysis to north polar temperatures in the 10–50 hPa region during late winter (February–March) and found that, while their results concurred with those outlined above in that LS/wQBO emerged as distinctly cold, the temperatures of the other three (all warmer) groupings were statistically indistinguishable from each other. To inform an understanding of polar temperature variability, and to provide a test for model results, it is clearly important that the solar and QBO influences are properly characterised. Thus, there is a need to understand what produces the different conclusions, particularly regarding the HS/eQBO temperatures, found by the above authors.

Variations in strength of the winter stratospheric polar vortex are typically followed, with a lag of less than one month, by similar-signed anomalies in the tropospheric circulation that persist for up to 2 months in the Northern Hemisphere and up to 3 months in the Southern (Thompson and Wallace, 2000; Baldwin and Dunkerton, 2001). Lu et al. (2009) investigated the QBO modulation of the solar signal in polar winter temperature and wind and showed that in the Northern Hemisphere winter extratropics it is indeed QBO-phase dependent, moving poleward and downward as winter progresses, taking about 1 month to move from the upper to the lower stratosphere with a faster descent rate under wQBO than eQBO. Haigh and Roscoe (2009) showed a similar progression in the Southern Hemisphere late winter.

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These studies are consistent with the results found in surface polar modes by Haigh and Roscoe (2006) which indicated that, while no statistically significant solar signal was found in either the surface NAM or SAM, when the solar and QBO influences were combined there is a good correlation in SAM and winter NAM.

In this paper we first investigate the root of the differences between the conclusions of LvL92 and CT07 and then investigate the combined solar*QBO influence on zonal mean temperature throughout the stratosphere and troposphere. We move on to study signals of solar variability and the QBO in over a century of mean sea level pressure (SLP) data.

2 Data

2.1 Data analysed

The temperature data are taken from the NCEP-NCAR Reanalysis Project Kalnay et al. (1996) for the years 1953–2001. For the polar temperature analysis we use January–February mean values at 30 hPa. For the latitude-height sections we use monthly mean data throughout the year.

The mean sea level pressure data, obtained from http://www.hadobs.org, are globally gridded monthly mean values for 1900–2004 from the HadSLP2 dataset, an upgraded version of the Hadley Centre's monthly historical set which is based on a compilation of numerous terrestrial and marine data Allan and Ansell (2006).

2.2 Influencing factors

We assess the influence of a number of independent influences on the temperature and SLP data. These include, as well as solar variability and the phase of the QBO, "climate change", stratospheric aerosol and the phase of the El Niño-Southern Oscillation (ENSO).

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We specify a linear trend to represent long term climate change. This cover-all essentially incorporates greenhouse gases, tropospheric aerosol, stratospheric ozone and long-term changes in the Sun. Secular variation in solar irradiance is currently the subject of significant uncertainty and, furthermore, the focus of our work is on 11-year cycle variability so that the choice of long-term trend has essentially no effect on the derived solar signal.

Solar cycle variability is represented either by monthly mean sunspot number (SSN) or by the radio flux, F10.7 index, both acquired from the NOAA National Geophysical Data Center Solar and Terrestrial Physics Division http://www.ngdc.noaa.gov/stp/.

Aerosols injected into the stratosphere by explosive volcanic eruptions impact both stratospheric and tropospheric temperatures (Solomon, 2007). Here we represent the temporal variation of their effect using a measure of stratospheric aerosol optical depth (AOD) from http://data.giss.nasa.gov/modelforce/strataer/tau_line.txt for years up to 1999, extended to 2005 with near zero values.

For ENSO, we used the Niño 3.4 index, obtained from http://climexp.knmi.nl, defined as the three month running mean of sea surface temperature departures in the Niño 3.4 region (5° N–5° S, 120–170° W), calculated with respect to the 1971–2000 base period.

2.3 QBO time series

The phase of the QBO as it descends from 10 hPa to 70 hPa are available from http://www.pa.op.dlr.de/CCMVal/Forcings/qbo_data_ccmval/u_profile_195301-200412.html for years since 1953. These are derived directly from operational wind measurements by rawinsondes at equatorial meteorological observatories. Ideally these measurements are made within 2 degree latitude from the equator. The stratospheric research group at the Free University Berlin has collected and processed radio sonde measurements from 1953 onward from Canton Island, Gan (Maldives) and Singapore (Naujokat, 1986; Labitzke et al., 2002).

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Recently the QBO extending back to 1900 has been reconstructed by Brönnimann et al. (2007) (henceforth BAVJ07). The reconstructions are based on historical pilot balloon data as well as hourly sea-level pressure data from Jakarta, Indonesia. The latter were used to extract the signal of the solar semi-diurnal tide in the middle atmosphere, which is modulated by the QBO. The reconstructions are in good agreement with the QBO signal extracted from historical total ozone data extending back to 1924.

The QBO propagates downward with a speed of approximately 1 km/month with a full cycle taking about 26 months. Thus the phase ascribed to it is a function of altitude (pressure) and the results of studies which assess its influence on other meteorological variables may be sensitive to the choice of QBO pressure level. This has been recognised by a number of authors and a common solution is to extract two orthogonal time series from the QBO data by Empirical Orthogonal Function Analysis and to use both of these as indices, as first employed by Wallace et al. (1993).

We have also followed this approach: Fig. 1a shows the first two spatial patterns (EOFs) and Fig. 1b the associated principle component time series (PCs) which together account for 95% of the variability in the whole dataset. The first EOF peaks broadly around the 25 hPa level and the second around 48 hPa so using the raw time series of the QBO data near these two levels will similarly account for most of the variability.

3 North pole winter lower stratosphere temperature

In order to disentangle the apparently contradictory findings of LvL92 and CT07 with regard to the comined solar and QBO effects on polar temperature, as outlined above, we have carried out a number of tests. We use the polar temperature at 30 hPa averaged over January and February, as LvL92. We also carried out the analysis (not shown) using the wider range of altitudes and months used by CT07 but that did not manifestly change the results. Based on the observation by Salby and Callaghan (2004) that the QBO wind changes sign during the winter of some solar max years, CT07 used the average value of the QBO (at a given pressure level) during DJFM (December-January-February-March) to reduce monthly fluctuations. Here we used the DJFM average value for both the QBO and solar F10.7 index.

We sort the temperature data into the four groupings by whether at the date in question the F10.7 cm index is less than/greater than 155 units and the QBO index less than/greater than zero. We calculate the average value of all the data points which fall within the respective quadrant. In these calculations, we omitted those years adversely affected by volcanic eruptions (1964, 1983, 1992). The resulting averages are presented in Fig. 2 which shows the values estimated using two different pressure levels to define the QBO time series.

The left-hand panel of Fig. 2 shows the sorting carried out using as the QBO index the value at 40 hPa, as used by LvL92. The LS/wQBO quadrant is the coldest at 200.2 K, the HS/eQBO quadrant is 4.0 K warmer (not statistically significant at the 90% level) while the LS/eQBO and HS/wQBO quadrants both significantly (about 8 K) warmer. These results coincide with those of LvL92.

The right-hand panel of Fig. 2 shows the sorting carried out using as the QBO index the value at 30 hPa, as used by CT07. The LS/wQBO quadrant is still the coldest but now the warmest quadrant is that of HS/eQBO. The difference between these two, at 5.4 K is significant at the 90% level; the three warmer quadrants are not statistically separable. These results coincide with those of CT07.

We conclude that the main source of discrepancy between the results of LvL92 and CT07, and the reason for their different conclusions, is their use of different pressure levels to define the phase of the QBO. In an updated version of their work Labitzke et al. (2006) used 45hPa, rather than 40 hPa but this did not affect their earlier conclusions. It is interesting to note that as the QBO-W signal propagates down through the stratosphere it often stalls for several months between 30 and 50 hPa so that the regions above and below are out of phase for longish periods. The EOF analysis in the previous section also found that the signals near 20–30 and 40–50 hPa were, on average, out of phase. Thus sorting the temperature data according to the dates of

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these signals is likely to give different results. If the physical mechanisms which link tropical winds with polar temperatures are to be identified then the precise dating of the signals is essential.

4 Zonal mean temperatures

We have analysed monthly mean zonal mean temperatures from 1958–2004 from the NCEP Reanalysis dataset (Kalnay et al., 1996) using the same multiple linear regression technique as Haigh (2003). This estimates amplitudes of variability due to various climate factors incorporating an autoregressive noise model. In this methodology, noise coefficients are calculated iteratively with the components of variability so that the residual is consistent with a red noise model of order one (AR(1)). We find by experiment with the monthly mean data that using a noise model of higher order does not significantly affect the results. A Student's t-test is used to estimate the level of confidence in the derived regression coefficients.

In the regression we include indices for: a linear trend, representing climate change; stratospheric aerosol optical depth, representing the influence of volcanic eruptions and ENSO. We adopt two different approaches to the solar and QBO influences: first including separate indices for each and secondly using a compound index for which the LS/eQBO and HS/wQBO have positive values, while LS/wQBO and HS/eQBO have negative, with the QBO value defined at 40 hPa, as suggested by the LvL92 polar temperature analysis discussed above (see Haigh and Roscoe, 2006, for further details).

Results using the first approach are shown in Fig. 3a for the solar signal and b for the QBO. These are similar to those found previously by Haigh (2003) and Frame and Gray (2010). The solar signal is positive everywhere except in the polar lower stratosphere, statistically significant at the 5% level in mid-latitudes at all levels from the surface to >25 km and largest (>0.75 K) in the lower stratosphere sub-tropics with lobes of about 0.5 K extending into tropospheric mid-latitudes. The QBO signal has its characteristic,

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and strong, butterfly pattern in the low latitude stratosphere with a cooling in the polar stratosphere and little impact on the troposphere.

The second approach, using the combined index, is shown in Fig. 3c. The Northern Hemisphere polar lower stratosphere signal is positive, as would be expected from the LvL92 results, but does not appear in the Southern Hemisphere. The positive signal extends to the surface in mid-latitudes but is smaller than the solar impact alone in the troposphere. The warmer southern high latitude troposphere is consistent with the Haigh and Roscoe (2009) results for SAM. Thus using the compound index suggests a weak relationship between the polar lower stratosphere and mid-latitude troposphere in the Northern Hemisphere and a stronger one between the extra-tropical lower stratosphere and lower troposphere high latitude temperatures in the Southern Hemisphere.

5 Sea level pressure

Previous studies (Baldwin and Dunkerton, 1999, 2001, 2005; Thompson et al., 2005) have shown that large-amplitude variations in the strength of the stratospheric polar vortex are typically followed, with a lag of less than one month, by similar signed anomalies in the tropospheric circulation. These can persist for up to 2–3 months and suggest a route whereby changes in stratospheric circulation may influence surface climate and Baldwin and Dunkerton (2005) suggested that solar and QBO influences may be felt at the surface via the polar modes. We now investigate solar and QBO signals in sea level pressure to see if these are consistent with this idea and our results above.

5.1 1953–2004

A multiple regression analysis of the SLP data are has been carried out, similar to that of Roy and Haigh (2010) except that it incorporates an assessment of the QBO signal. Because direct measurements of QBO phase are only available back to 1953 our first

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analysis uses data only since that date. The independent parameters used are: a linear trend, AOD, SSN, ENSO, QBO at 30 hPa and QBO at 50 hPa. Some of the results are shown in Fig. 4. The solar signal (Fig. 4a) does not show any large areas of significance but the pattern shows positive values on the poleward sides of the sub-tropical high pressure regions, suggesting an expansion of the tropical Hadley cells; first found as a solar signal in a GCM experiment by Haigh (1996). Overwhelmingly the largest signal is associated, unsurprisingly, with ENSO (Fig. 4b), showing the longitudinal gradients in the Pacific Ocean characteristic of that phenomenon. QBO-50 (Fig. 4c) shows a small, but significant increase in pressure across much of the tropics. The QBO-30 pattern (not shown) shows a pattern with greatest impact in mid- to high latitudes, but very little of significance.

5.2 Combined solar*QBO results

The results for polar temperatures in Sect. 3, for zonal mean temperatures in Sect. 4 and for SAM by Haigh and Roscoe (2009), all showed some stronger signals in response to a combined solar*QBO index than to either separately. We now carry out the regression analysis of the SLP data using this compound index (incorporating the QBO-50 series). Other indices used in the regression were the linear trend, AOD and ENSO. The resulting solar*QBO signal is shown in Fig. 4d. It indicates a weakening of the polar modes in the northern and the Southern Hemispheres, thus it appears that the LS/eQBO and HS/wQBO combinations produce negative signals in surface SAM and NAM while the LS/wQBO and HS/eQBO combinations are associated with strengthening modes. A negative signal is seen over most of the tropics in both panels. The same analysis using the QBO-30 series in place of the QBO-50 (not shown) produces a similar pattern, although of smaller amplitude. We assume that the distinction between the responses to different QBO levels seen in the stratosphere is washed out as the signal propagates further downwards due to the variability in time it takes for the anomaly to reach the surface (Baldwin and Dunkerton, 1999).

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5.3 1900–2004

The availability of the BAVJ07 reconstruction of the QBO dating back to 1900, discussed in Sect. 2.3, enables us to analyse the role of QBO over a longer term climate record. First, as a consistency check, we carried out an analysis with these data for the period 1953–2004. The results (not shown) are similar to those derived using the DLR QBO data (and shown in Fig. 4) providing confidence in an extension to the analysis back through the earlier period.

Results from the analysis of the whole, more than a century, period are shown in Fig. 5. Comparison with the corresponding panels of Fig. 4 show very similar patterns and magnitudes indicating that these responses are robust for over a century.

6 Summary and conclusions

Our initial aim was to understand the reason(s) for an apparent inconsistency between two published results concerning the temperature of the winter polar stratosphere and its dependence on the states of the Sun and the QBO. We show that the apparent difference can be explained by use in the two papers of different pressure levels to define the phase of the QBO. EOF analysis reveals that the QBO around 40–50 hPa is, on average, temporally out of phase with that at 20–30 hPa so that the use of these two levels by Labitzke and van Loon (1992) and Camp and Tung (2007), respectively, means that they are not seeing the same aspect of any physical signal.

We have also analysed zonal mean temperatures throughout the lower stratosphere and troposphere to investigate the existence more widely of any coupled solar and QBO influence. We find, while it exhibits strongly in the lower stratosphere, that in the troposphere any influence of the QBO, either on its own or coupled to solar effects is much smaller than the pure solar signal. A possible exception is manifest at very high latitudes with warmer temperatures corresponding to the LS/eQBO and HS/wQBO states (and colder to LS/wQBO and HS/eQBO).

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Seeking to investigate further the solar and QBO influences at the surface we also carried out a multiple regression analysis of SLP data. First we accomplished this, using established QBO time series 1953–2004. By themselves the solar and QBO signals were rather weak, although the solar pattern is consistent with previous studies suggesting a slight expansion of the Hadley cells when the Sun is more active. The compound solar*QBO signal shows significant increase in SLP at very high latitudes, consistent with LS/wQBO and HS/eQBO produce a strengthening (and LS/eQBO and HS/wQBO a weakening) in the polar modes.

By employing a QBO dataset reconstructed back to 1900 we were able to extend our SLP analysis back to that date. We find a robust signal in the Southern Hemisphere, which shows a response in surface SAM as described above, independently in both the first and second half of the century. This result is found almost irrespective of details of the choice of QBO index pressure. The Northern Hemisphere result is qualitatively similar but smaller and less statistically robust.

We conclude that a signal of solar variability, modulated by the phase of the QBO, is detectable in sea level pressure at high latitudes and thus that a knowledge of the state of the Sun and of the QBO might be useful in predicting tendencies in polar surface climate on timescales of a few years.

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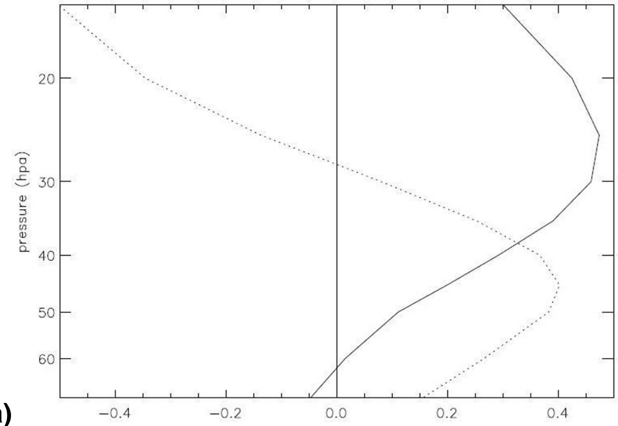
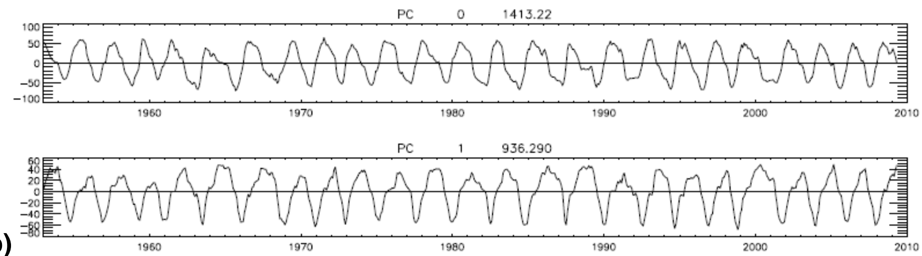


(a)



(b)

Fig. 1. Results of Empirical Orthogonal Function Analysis of zonal mean zonal wind data from the equatorial lower stratosphere, representing the phase and magnitude of the QBO. **(a)** First two EOFs and **(b)** the PC time series of these.

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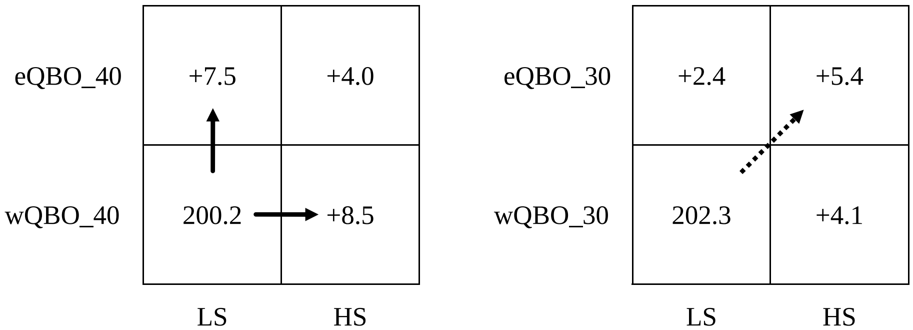

Fig. 2. Average JF temperature at 30 hPa over the North Pole as a function of the phase of the QBO and state of the Sun. The QBO phase is defined by the sign of the zonal wind over the equator at (in the left hand panel) 40 hPa as used by LvL92 and (in the right hand panel) 30 hPa as used by CT07. Separation of solar activity into low/high by F10.7 value of less than/greater than 155 units. The lower left box gives the mean temperature (K) for the LS/wQBO combination and the other 3 boxes give differences in temperature (K) from that state. The number of datapoints in each box ranges between 6 and 16 and the standard error on the mean ranges between 1.3 and 2.6 K; a solid[dotted] arrow indicates a difference which is statistically significant at the 99[90]% level.

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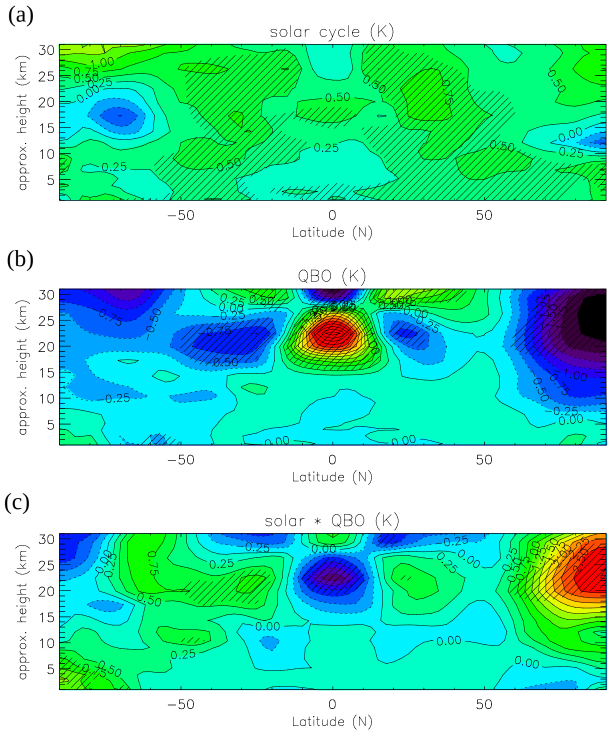

Fig. 3. Results from multiple linear regression analysis of NCEP reanalysis zonal mean monthly mean temperatures (1958–2004). **(a)** and **(b)** show the signals associated with solar variability and the QBO, respectively, when these are included as independent indices in a multiple regression. **(c)** shows the results of another analysis in which the compound index is used in place of the two individually. The contour interval is 0.25 K; positive values have solid lines and green-red colouring, negative values dashed lines and blue-black; hatching indicates a signal ascertained to be statistically significant at the 5% level.

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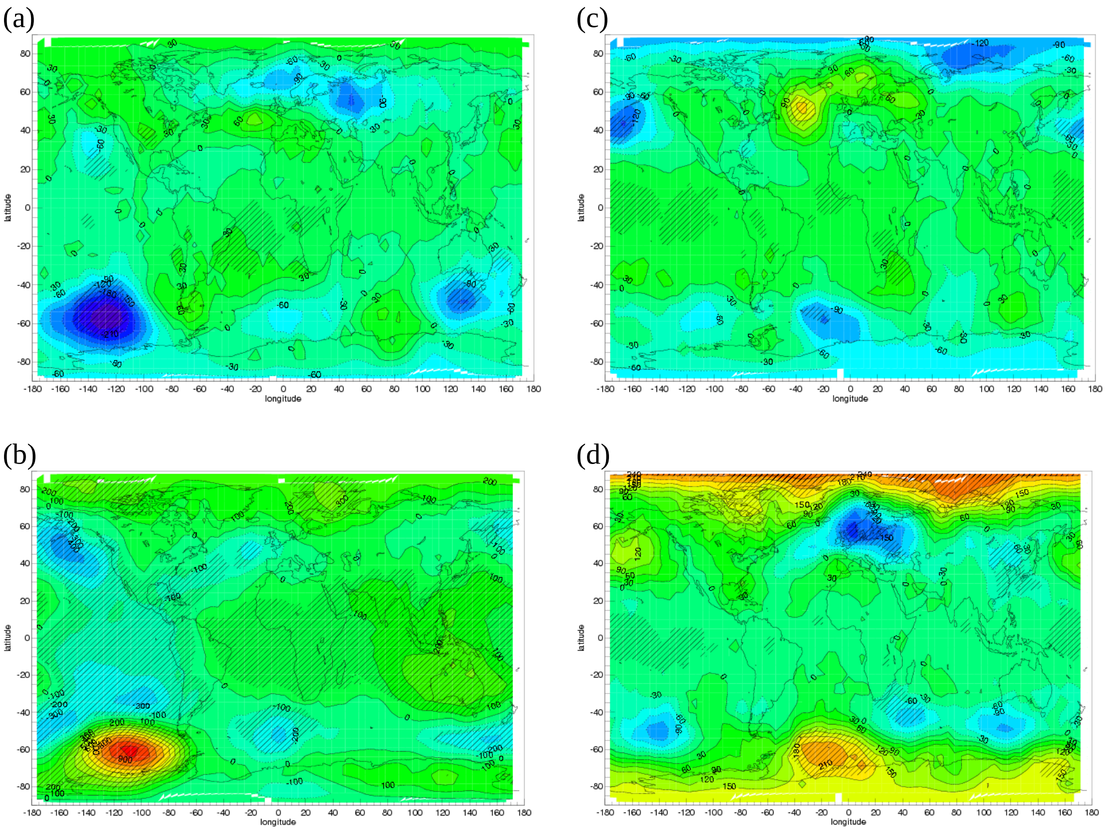

Fig. 4. Results of multiple linear regression analysis of sea level pressure data 1953–2004. Components (Pa) due to **(a)** solar (SSN); **(b)** ENSO; **(c)** QBO (at 50 hPa) Results of a separate analysis in **(d)** show the compound Solar*QBO (at 50 hPa) signal. Dashed lines indicate negative values; hatching indicates areas assessed statistically significant at the 5% level. Contour interval in **(a)**, **(c)** and **(d)** is 30 Pa and for **(b)** 100 Pa. The same colours are used each side of the zero contour in all panels.

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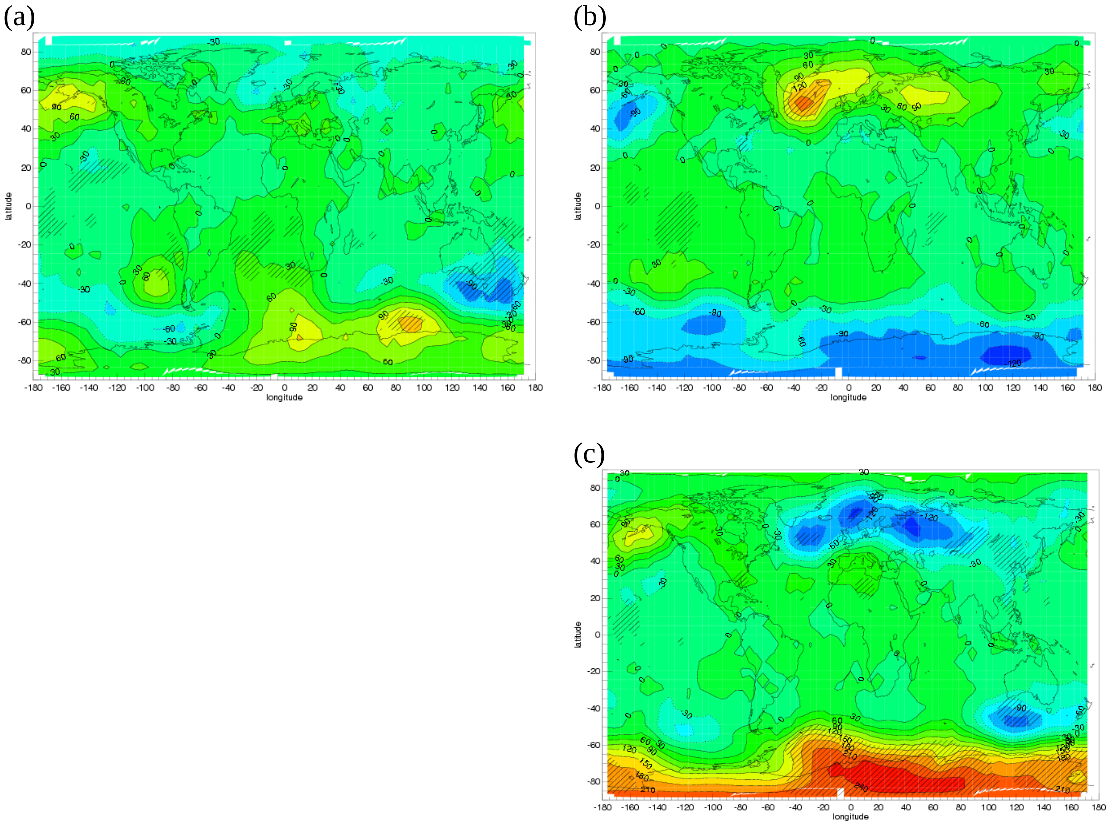

Fig. 5. (a), **(b)**, **(c)** as Fig. 4a, c and d, respectively, but over the period 1900–2004, using the Brönnimann et al. (2007) QBO time series. The contour interval is 30 Pa and colours around the zero contour are same as Fig. 4.

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