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EXTERNAL FORCING AND INTERNAL VARIABILITY OF THE UPPER TROPOSPHERE-LOWER STRATOSPHERIC TEMPERATURE

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Abstract. The temperature regime of the upper troposphere/lower stratosphere (UTLS) is analysed using 56 year data record of NCEP/NCAR re-analysis. The impact of a four factor affecting altitude-latitude distribution of UTLS temperature anomalies (QBO, solar variability, ENSO and NOI) was analysed by a multiple regression analysis. It was found that the external (solar) forcing is modulated by the internal QBO (quasi biennial oscillations) of the stratospheric equatorial winds - i.e. the "net effect" of enhanced solar irradiation at solar max is a warmer UTLS when westerly winds are placed over the equator and cooler UTLS during the east QBO phase. A possible mechanism for interplay between QBO wind phase and solar signal is discussed.

Key words: troposphere-stratosphere, variability, thermal regime, solar forcing, QBO modulation

Introduction

The recently increased scientific interest to the Upper Troposphere-Lower Stratosphere region (UTLS) is determined by its great sensitivity to climate changes and the possibility for its backward influence on the climate through different feedbacks. The interannual variability (i.e. deviation from the climatological annual cycle) of troposphere-stratosphere system can be generated by variations of an external forcing, or can be generated internally within the system. One of the specific characteristic of this variability is the dominated role of the internal processes and the very small impact of the external forcing (Yoden et al., 2002). However, the strong non-linear character of the troposphere-stratosphere system (defined by some authors as stochastic - i.e. Weisenfeld and Moss, 1995) could amplify the small amplitude periodicity of the external forcing (Palmer, 1998; Yoden et al., 2002).

This paper presents an analysis of the solar variability impact - an external forcing for the atmosphere, and three of the factors determining its internal variability - i.e. quasi-biennial oscillations (QBO) of the stratospheric equatorial winds, El Nino/Southern Oscillation and North Atlantic Oscillation (NOI), using the long record of NCEP/NCAR temperature data for the period 1948-2003.

Many authors pointed out the existing relation between solar and QBO signals found in the atmospheric parameters (Labitzke and van Loon, 1999; Salby and Callaghan, 2000; Soukharev and Hood, 2001; Mayr et al. 2003, Kilifarska, 2005). In our point of view the main arena for the interplay between QBO and solar radiative heating is UTLS region, thus some explanations about the mechanism of this interaction is presented in this paper too.

Data and method of analysis

The monthly temperatures (T) from NCEP/NCAR (National Centre for Atmospheric Research) reanalysis for the period 1948-2003 are studied with a main purpose to estimate the relative impact of external (solar) forcing in the UTLS thermal regime and three of the factors determining its internal variability - QBO, El Nino/Southern Oscillation and North Atlantic Oscillation (NOI). The model used in NCEP reanalysis has 28 levels extending from the surface to ~ 40 km., with space resolution of 2.5° x 2.5° in latitude and longitude respectively. The data was first averaged longitudinally and then the latitude-altitude deviations (anomalies) from the climatological monthly averages over the whole period have been calculated.

We analysed the T anomalies by a multiple linear regression model (1).
All the "a" coefficients are determined by least squares fit and represent the amplitudes of the mean value, trend, solar, QBO, El Nino/Southern Oscillation (ENSO) and NAO

$$Y(t) = a_0 + a_T t + a_S X_S(t) + a_Q X_Q(t) + a_{ENSO} X_{ENSO}(t) + a_{NAO} X_{NAO}(t) + N(t) \qquad (1)$$

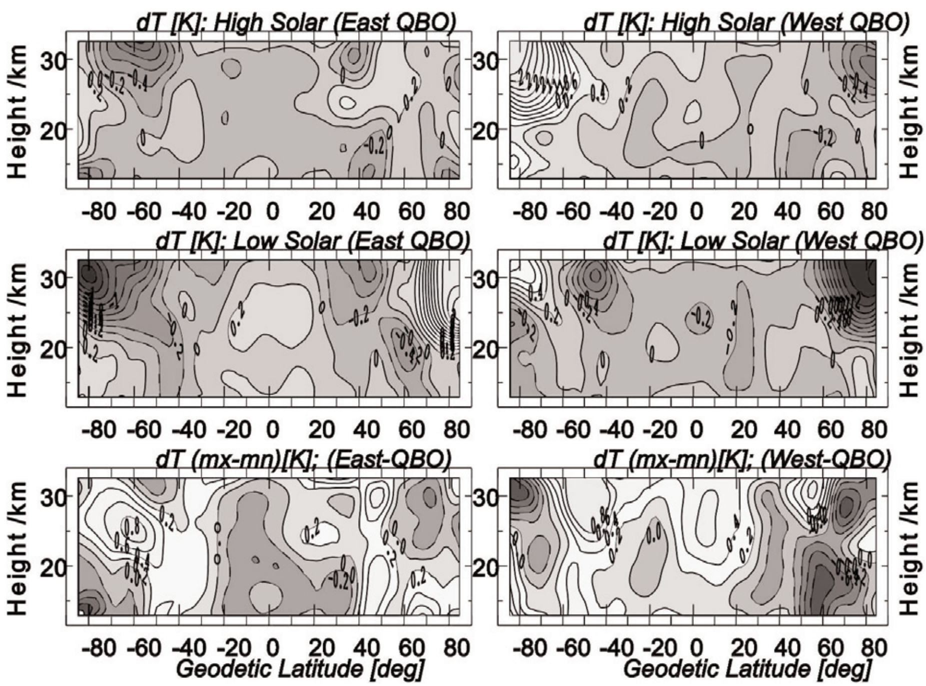
components of interannual variability. Time series $X(t)$ represent monthly median values of solar radio emission at 10.7 cm, Singapore 30 mbar zonal wind, SOI (Southern Oscillation Index) and NAO indexes correspondingly, for the period examined. $N(t)$ is treated as a "noise"- i.e. the impact of the processes not included in the (1) into the temperature anomalies -$Y(t)$.

Statistical results

A first inside for the latitude-altitude distribution of UTLS temperature deviations from its monthly averages, calculated over the whole interval 1948-2003, is presented in Fig. 1. As in Labitzke - 2005, data was separated according the QBO wind phase and solar activity. The most prominent feature of the tropical T anomalies is a warmer lower stratosphere (compared to monthly averages over all 56 years) during the periods of active sun and westerly zonal wind placed at 30 hPa (1-th row, right column). The picture is reversed for a low solar activity (i.e. positive T anomalies are found during the QBO east phase - first column, second row in Fig.1). This inconsistency in the UTLS temperature response on QBO forcing can e related to the increased tropical *up-welling* (down-welling) for *east* (west) QBO phase, when the sun is more active, followed by enhanced adiabatic *cooling* (warming) of the tropical UTLS. This means that the initial T response is redistributed by the atmospheric circulation.

Looking at the T differences between solar max and solar min (3-rd row in Fig. 1) one can see that solar influence on UTLS temperature regime is modulated by the QBO phase - i.e. in the periods of westerly zonal winds at 30 hPa the slightly increased solar irradiance (at solar max) warms upper troposphere-lower stratosphere by more than 0.6 K (3-rd row, second column), while during east QBO phase the net effect is "cooling" of UTLS. This comes to show that without some statistical analysis this interrelation between QBO and solar signals can not be resolved.

Fig. 1. Latitudinal-height distribution of NCEP/NCAR temperature differences between monthly values and the monthly averages calculated over the whole period 1948-2003 (first and second row)



and between solar maximum and solar minimum conditions (last row). Dashed contours represent the negative anomalies, the zero line is ticker.

In order to separate the effect of the main factors determining latitude-altitude distribution of T anomalies (QBO, 11 year solar cycle, ENSO and NOI) and to detect quantitatively their impact, a multiple regression analysis was applied and the results are presented in Fig. 2. The effectiveness of the different process' influences on the thermal regime of UTLES is estimated by the formula:

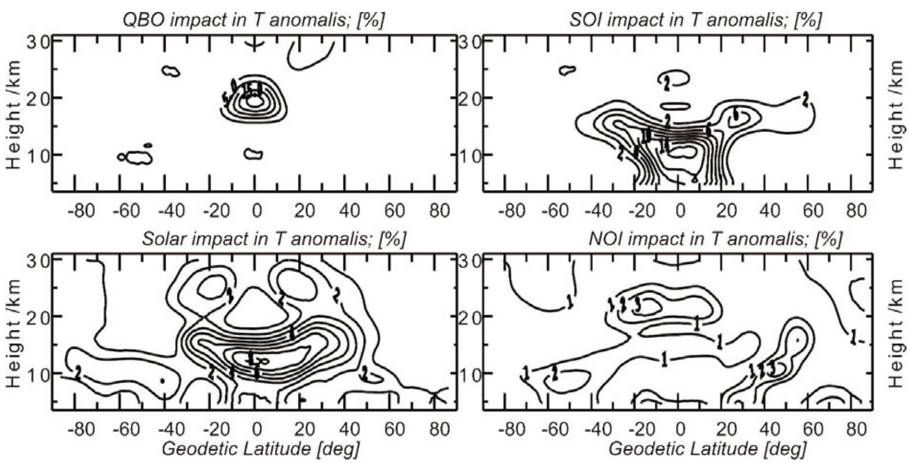
where a_i are the regression coefficients, σ_i - dispersion for each of the processes included

$$\sum_{i=1}^{m}\frac{a_i^2\sigma_i^2}{\sigma_y^2}+\frac{\sigma_N^2}{\sigma_y^2}=1 \qquad (2)$$

into the regression equation; σ_y - dispersion of T data record.

Fig. 2 shows that the most effective is the QBO influence, maintaining up to 30 % of T anomalies, but it is strongly restricted within ±20° and centred near 20 km. The impact of NOI in the same altitude/latitudinal interval is only 2-3-%. The average solar impact is up to 10%, placed near the tropopause in latitudinal interval 40S:45N. Approximately, in the same altitude/latitude interval is the ENSO impact into the tropical T anomalies - up to 14%, which may explain the difficulties to detect the 11 year solar signal in this altitude range.

Fig.2. Altitude-latitude distribution of QBO, 11 year solar cycle, ENSO and NOI impact in UTLS



temperature anomalies.

Comparison between maximum impact of the different factors affecting T distribution and real T anomalies (Fig.1 - 1st and 2nd row) show that the initially created anomalies are redistributed by the atmospheric dynamics. Labitzke, 2003 pointed out that the solar modulation of tropical T regime could affect the tropospheric Hadley and stratospheric Brewer-Dobson circulation systems. In our point of view there are two channels for an interaction between solar variability and QBO - having a potential to affect the global circulation system and the details of this interplay are described briefly in the next paragraph.

Interplay between 11-year solar cycle and QBO wind phase

1. QBO modulation of the solar impact into the thermo-dynamical regime of the troposphere -stratosphere system

As has been pointed by Salby and Callaghan, 2004 "…the 11 year modulation of stratospheric interannual variability enters through systematic changes of the residual circulation". Our imagination about the possible way of interplay between QBO and solar signal is presented schematically in Fig.3.

The additional heating of the stratosphere in the periods of enhanced solar irradiance (not only in the upper but also in the lower stratosphere, as revealed by the multiple regression analysis presented above) increases the meridional heat transport from tropics towards the polar regions. The secondary meridional circulation, associated with QBO, modulates this heat transport. Especially sensitive to its influence is vertical up-welling and down-welling of the air masses, presented schematically in Fig. 3. It can be seen that the easterlies (Fig. 3-left) should increase the up-welling over the equator, reducing the tropospheric Hadley and increasing the stratospheric Brewer-Dobson circulations. The adiabatic cooling related to this uplifting of the air could explain the negative T anomalies during the east QBO phase (Fig.1-1st row, left). The air subsidence in the tropics, when the westerly zonal winds are placed at 30 hPa, should increase the solar heating effect near tropopause, reducing Brewer-Dobson and enhancing Hadley circulation.

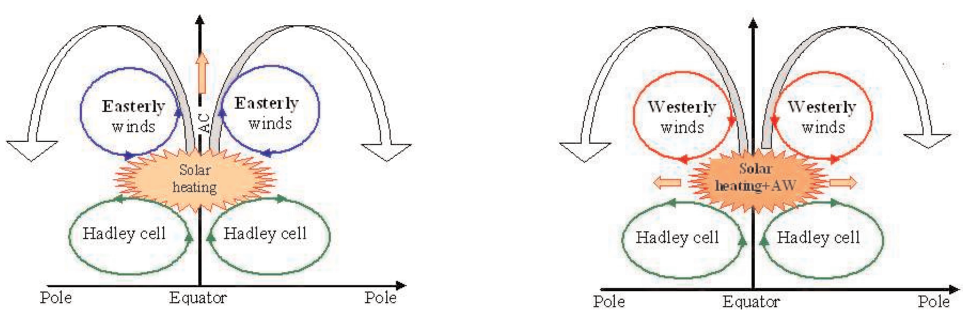


Fig.3. Schematic illustration of the role of secondary meridional circulation induced by Easterly (left) and Westerly (right) equatorial winds for re-distribution of the heat in the stratosphere.

Some authors (Kodera and Kuroda-2002; Labitzke-2003) hypothesises about the decreasing of the Brewer-Dobson circulation in the periods of active sun, as a result of the reduced wave forcing. However, Plumb and Eluszkiewicz-1999 and Scott-2002 pointed out that the round year upward air motion at very low latitudes can not be explained by downward control hypothesis, because it is not applicable there. They note that the impact of the thermal forcing can not be ignored in supporting the upward air motion over the equator and that QBO phase can modulate this process (Semeniuk and Shepherd, 2001).

In resume, the "net effect" of enhanced solar irradiance during high solar activity depends on QBO wind phase and this fact should be taken into account when the impact of solar variability in interannual variations is estimated.

2. Solar modulation of the duration of QBO westerlies

The second channel of solar cycle - QBO interaction alters the duration of westerly winds over the equator. The sketch of this mechanism is shown in Fig.4, which could be described briefly as follow. The warmer lower stratosphere at solar max is additionally warmed by westerly QBO meridional cell. This warming forces the poleward heat transport in the upper troposphere - lower stratosphere, enhancing the westerlies there. Stronger westerly shear on its turn absorbs energy and momentum from a broader spectrum eastward propagating waves (Kelvin and mixed gravity). This forces a downward propagation of stratospheric westerlies, shortening their duration. Note that QBO period is strongly sensitive to the vertical flux of horizontal momentum $\overline{u'w'}$ (increase of momentum flux decreases the period of QBO - Plumb, 1977). Easterlies at 30 hPa decrease the UTLS westerlies (at the top of Hadley cells) which allows the eastward travelling (Kelvin and mixed gravity) waves to propagate upward into the upper stratosphere (due to the reduction of the UTLS westerly shear). There they form the westerly counterpart of the east QBO at 30 hPa by deposition of energy and momentum.

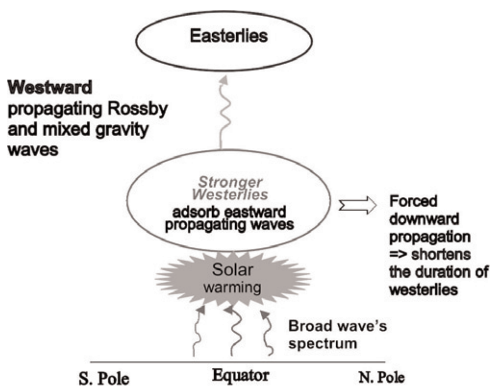


Fig.4. Schematic illustration of solar modulation the duration of westerly winds in the equatorial stratosphere.

Conclusions

The 11 year solar and QBO signals, found in interannual variability of many stratospheric and tropospheric parameters, arises a challenging question about the mechanism of their interrelation. QBO variations have been found even in some solar parameters like UV radiation and F10.7 radio emission. On the other hand quasi-decadal variability was found in the quasi-biennial oscillations (QBO) of the equatorial stratospheric winds. This paper presents some observational evidences that the upper troposphere and lower stratosphere are warmer in the periods of active sun and westerly zonal winds placed at 30 hPa over the Equator. Based on this fact and taking into account the resent result related to the modelling of stratosphere-troposphere dynamics, the authors present a new mechanism explaining the interplay between 11 year solar and QBO signals found in many data sets.

In brief there are two channels for materialisation of this interrelation: 1.) QBO in the equatorial stratospheric winds modulates the solar signal in the upper troposphere-lower stratosphere (UTLS) through the secondary meridional circulation associated with QBO. Thus the "net effect" of enhanced solar irradiation at solar max is a warmer UTLS when westerly winds are placed over the equator and cooler (compared to the climatological mean calculated over 56 years) upper troposphere/lower stratosphere during the east QBO phase. 2.) The warming of the UTLS alters the vertical propagation of the equatorial waves. Combined with westerly winds it leads to stronger absorption of the eastward propagating Kelvin and mixed gravity waves that deposit their energy and momentum into the westerly shear. This process forces downward propagation of the westerlies shortening their duration. Easterlies are practically not affected by the solar signal because they simply diminish UTLS westerlies (at the top of the Hadley circulation) allowing the eastward propagating waves to penetrate the upper stratosphere, where they deposit their energy and momentum.

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Външни въздействия и вътрешно-атмосферна изменчивост на високата тропосфера-ниската стратосфера

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Резюме:Температурния режим на високата тропосфера-ниската стратосфера е анализиран въз основа на 56 годишен ред от данни за температурата (NCEP/NCAR re-analysis). Приноса на четири от факторите влияещи върху широчинно-височинното разпределение на температурните аномалии (отклоненията от средното за 56 години) е анализиран с помощта на многофакторен регресионен анализ. Резултатите показват, че влиянието на 11 годишния слънчевата активност е модулирано от направлението на зоналния вятър в екваториалната стратосфера на ниво 30 hPaл С други думи в периоди на висока слънчева активност повишената слънчева радиация води до повишаване температурата на високата тропосфера-ниската стратосфера, когато на 30 hPa в екваториалната стратосфера духат западни ветрове (от запад на изток). При смяна в посоката на вятъра обаче, се наблюдава обратния ефект - понижение на температурата. В статията се обсъжда и един възможен механизъм обясняващ взаимовръзката между квази-двугодишните колебания (QBO) в стратосферния вятър над екватора и влиянието на слънчевата активност.