Solar Variability and Climate – UTLS amplification of Solar Signal

Nataliya A. Kilifarska

Geophysical Institute, Bulgarian Academy of Sciences, Bulgaria, natalka@geophys.bas.bg

The solar signal in atmospheric interannual variability is well tracked till the stratosphere. However, it is still not clear how this signal propagates into the troposphere and does it affect Earth's climate. The mechanism suggesting downward propagation of solar effect from the stratopause levels could account for stratotropospheric teleconnections at middle to high latitudes, but is not applicable for very low latitudes, where the atmospheric angular momentum is almost constant. Some model experiments concerning tropical upwelling, point out the limitations of the concept of extratropical pump and downward control and contribution of stratospheric - tropospheric heating to the net tropical upwelling [13, 14].

Meanwhile, different sources of measurements show that at high solar activity the Upper Troposphere and Lower Stratosphere (UTLS) are warmer than at low solar activity. Based on this result and taking into account above-mentioned modelling, we propose an additional amplifying mechanism of the solar influence on climate. In brief: 1) the warmer tropical UTLS at solar maximum affects vertical propagation of equatorial waves, altering the duration of westerly QBO phase; 2) the equatorial upwelling (enhanced in solar max), on its turn is modulated by QBO. This means that westerly phase of QBO will decrease the equatorial upwelling and respectively Brewer-Dobson circulation, but easterly phase of QBO will force additionally Brewer-Dobson cell.

Introduction

Does solar variability really forces the climate – a question having many different answers. Soon W. et al. [1] estimates that about 54% of decadal and longer-scale variations can be optimally attributed to the intrinsic solar total irradiance change. Douglas & Clader [2] found out that the sensitivity to solar irradiance is about twice that expected from no-feedback Stefan-Boltzmann radiation balanced model. However, the scepticism related to the effect of solar variability on the climate, is still very high. Thus Salby et al. [3] virtually excluded any solar influence on climate.

It is generally accepted now that the response of the upper and middle stratosphere to enhanced solar radiation is manifested by higher ozone concentrations and correspondingly higher temperatures. Although models seem to be unable to produce the magnitude of the signal (especially in O_3 profile) [4], it is clear that this is largely a response to enhanced UV radiation [4, 5, 6].

The possible solar effects on the UTLS, however, are still not well established. Some aspects of the quasi-decadal signal, found in tropospheric and stratospheric geopotential heights, temperatures and total ozone, can be explained by downward propagation of wave-mean flow interactions from the upper stratosphere ([6] and references therein). With downward propagation of solar signal are associated also Northern Hemisphere sudden stratospheric warmings [7] and North Atlantic Oscillation (NAO) [8].

However, this mechanism can not explain a warmer tropical UTLS [9, 10], the QBO influence on the solar signal found in temperature (T) and geopotential height [11], the shorter duration of westerlies below 30 Mb [12], when the Sun is more active. More over some authors [13, 14] pointed out that hypothesis of the *downward control* is not applicable at very low latitudes and consequently does not explain the round year upward air motion at the equator, detected from observations.

The uncertainty found in analyses of the observational results was the basic motivation for this study. The present paper presents some observational evidence about stratospheric temperature response on the 11-year solar cycle. Some new interpretations and hypothetical explanation of the interaction between solar and QBO signal, and their complicated influence on the atmospheric thermal and dynamical regime will be presented as well.

Data and method of analysis

Free University of Berlin zonally averaged stratospheric temperature (T) for the period 1963-2001 and T profiles from the Halogen Occultation Experiment (HALOE) based on the UARS satellite, version 19, for the period 1992-2005, have been analysed. Solar radio emission in F10.7 cm is taken from http://spidr.ngdc.noaa.gov/ and the equatorial zonal wind observations from http://www.cdc.noaa.gov /ClimateIndices/.

HALOE temperature profiles from 0.01 to near 10 hPa are retrieved from its CO_2 channel transmittances and from NCEP (National Centre for Environmental Prediction) analyses below 5 hPa level. Trough most of the UARS mission the NCEP analysis is obtained from SSU sensor on NOAA 11 satellite. HALOE sunrise and sunset T(h) values were separately interpolated in latitude-height grid: 80^0S - 80^0N latitudes and 5 - 85 km, in steps of 5^0 in latitude and 2 km in altitude). Each latitude bin is normally composed of several days of profiles. Hence the exact date of each time series point is obtained by averaging the times of the individual profiles. The seasonal component from the both data sets was removed by subtracting the mean of each month taken over the whole period from the monthly values. The differences have been then selected according the phase of the quasi-biennial oscillations of the equatorial stratospheric winds (QBO) and the level of solar activity.

Results and discussion

Fig. 1 and Fig.2 present the latitude-height distribution of Northern Hemisphere (NH) temperature deviations – for January and February and for the whole year correspondingly, calculated from FUB data series. A glance at the Fig.1 shows one of the well-documented features of the northern polar stratosphere – it is warmer when easterly winds are placed at 30 hPa, but this warming is better pronounced at solar minimum (left column).

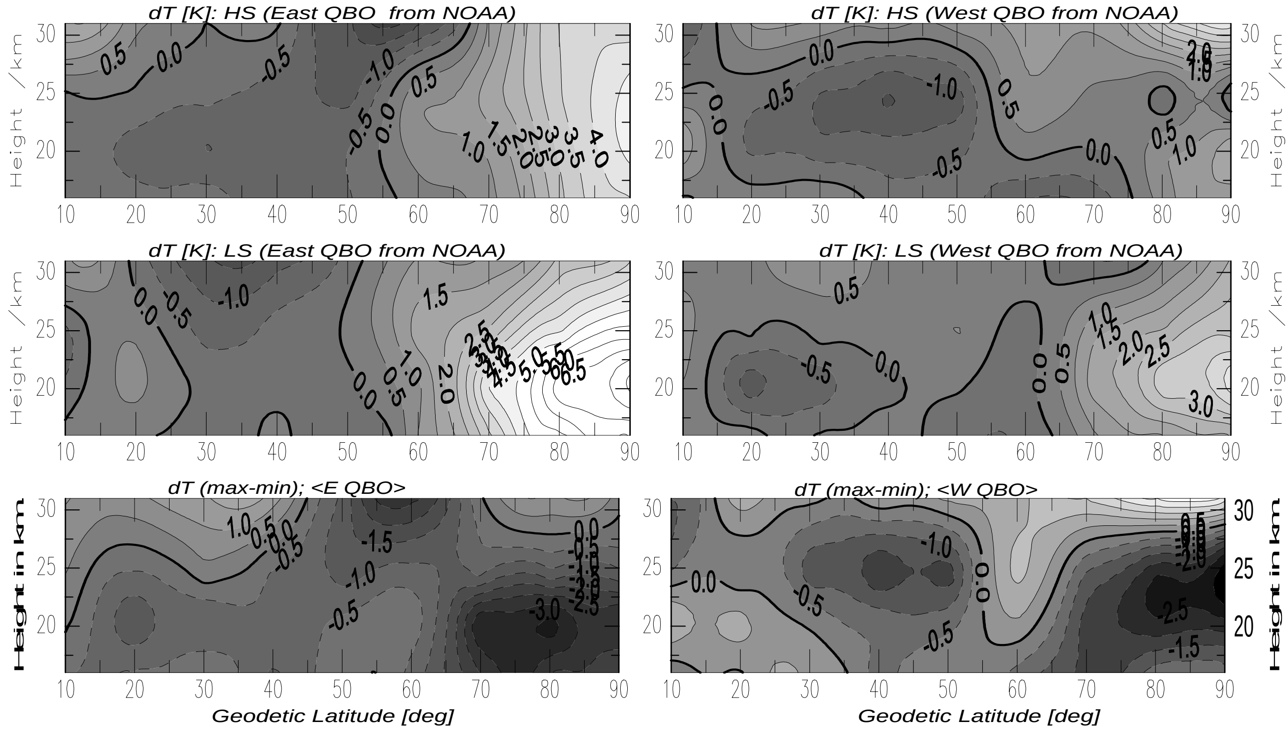

Fig.1 Latitudinal-height distribution of the Northern Hemisphere winter temperature differences between monthly values and the monthly mean averaged over the whole time series (first and second row) and between solar maximum and solar minimum conditions (last row) derived from Berlin stratospheric data set. Dashed contours represent the negative anomalies.

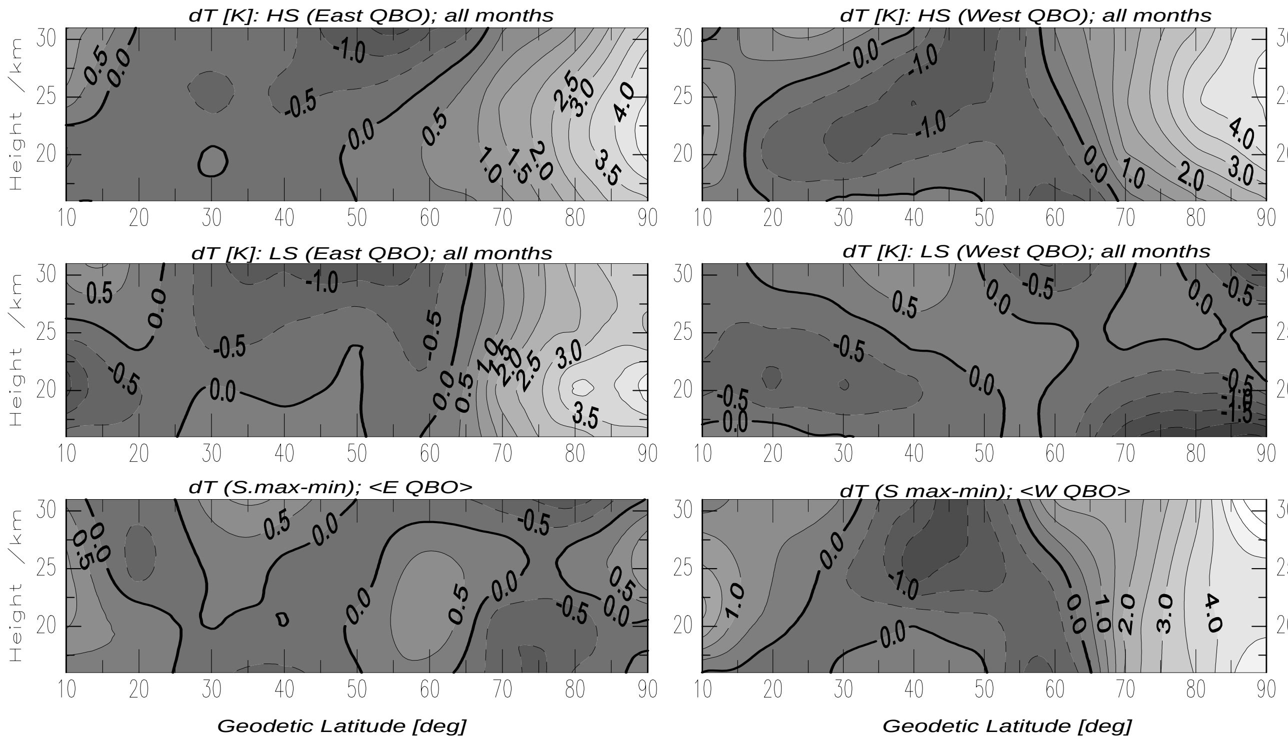

Fig.2 The same as Fig.1, but calculated from entire FUB data set.

The main difference with Fig. 2 (presenting the average T differences for all months) is that polar cap is much less warm during solar min and east QBO conditions, while for west QBO the warming of the polar stratosphere actually disappears. The strongest warming of the winter polar cap at solar minimum conditions may be interpreted as indirect confirmation of Holton-Tan mechanism [15] and the impact of the planetary waves in sudden stratospheric warmings - effective mainly in easterly winters. However, it is difficult to explain its less efficiency at solar maximum when the polar cap is warmer independently on QBO phase.

The third row at both figures shows the latitude-height distribution of differences between solar maximum and solar minimum for east (left column) and west phase of QBO (right column). The data suggests that the annually averaged solar signal (i.e. the impact of increased solar radiation in the stratospheric temperature enhancement) in the tropical stratosphere is better pronounced during westerly years (Fig.2, last row, right column). These findings do not confirm Labitzke's results [11, 16] based on NCEP/NCAR re-analyses for the period 1968-2002. She reports about stronger solar signal found during the west phase of QBO. This was our main motivation to look at another data set.

HALOE data time series (14 years) are relatively short for any statistical significance of the results. However, this is an original and independent data source - not manipulated by any analytical or empirical equations. Due to the shortness of HALOE time series only the round year temperature anomalies has been analysed with seasonal variability excluded from data set (see section 2 for details).

Fig.3 presents the latitude-height temperature deviation from its main state derived from HALOE data. To eliminate any influences from Pinatubo volcanic eruption, the first 2.5 years of data time series were ignored.

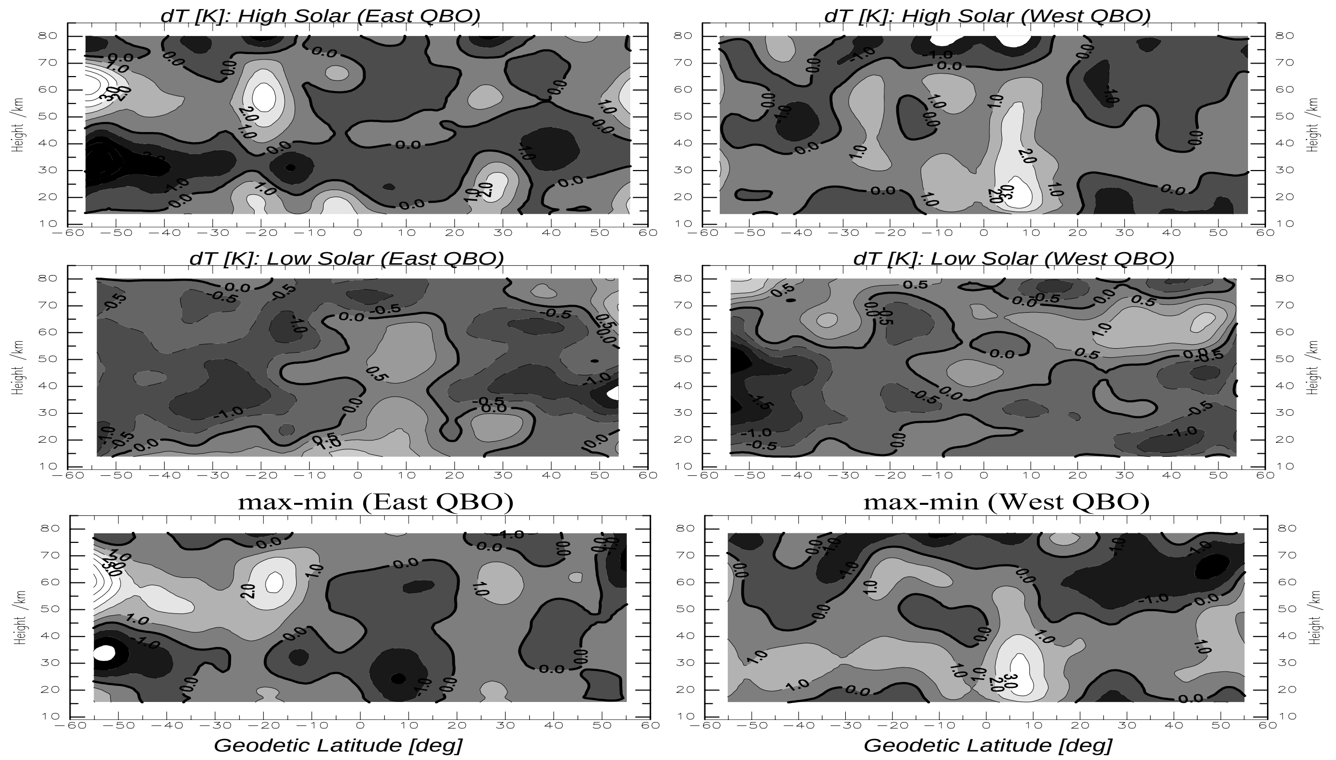

Fig.3 Latitudinal-height distribution of T differences between monthly values and the mean averaged over the whole time series –first and second row and solar maximum and solar minimum conditions (last row) derived from HALOE data.

It can be seen that for solar min and east QBO the whole tropical stratosphere is slightly warmer (0.5-1^{0}K) than average, while for west QBO phase the main warming is placed at the upper stratosphere and lower mesosphere. During active sun conditions (Fi.g3, 1^{-st} row) and easterlies at 30 hPa the upper stratospheric subtropics are 1-2^{0}K warmer than its main state. However, when westerlies are placed at 30 hPa whole tropical stratosphere is 1-2^{0}K warmer, with the "hottest" spot in the lower stratosphere. A glance at the 3^{-rd} row of Fig.3 show that the maximum solar signal in the lower stratosphere is observed during the west QBO phase, in disagreement with [11, 16].

These results require an explanation of the mechanisms of interaction between solar signal and QBO and their combined effect on the atmospheric thermodynamics. About this relation we will hypothesis in the next section.

Interplay between 11-year solar cycle and QBO

In our point of view there are two channels for these interactions between solar variability and QBO and their complicated effect on of stratosphere-troposphere system.

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

As has been pointed by Salby and Callaghan, 2004 [17] "…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.4.

The additional heating of the stratosphere - not only in the upper but in the lower stratosphere as well - obviously 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 upwelling and downwelling of the air masses, presented schematically in Fig.4 (a, b). It can be seen that in boreal winter the westerly winds at 30 hPa strengthens the Southern Hemisphere (SH) branch of QBO meridional circulation. This may be the reason for the positive solar signal in the lower equatorial stratosphere (Fig 2 and 3, right column) and the warmer summer Antarctic [19], when westerlies are placed over the equator. The NH QBO cell diminishes the downwelling at mid and high latitudes and it can be seen very well at the wintertime T differences, presented in Fig.1 (right column) – for high and for low solar activity. However, on the annually average basis its effect is negligible at solar max (Fig.2, right column, first row) due to the more effective heating of the upper stratosphere (through O_3 absorption of solar UV) and stronger poleward heat transport and anomalous downwelling over the Arctic.

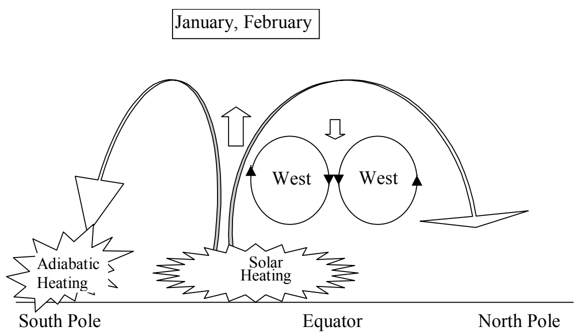

Fig. 4(a). Schematic illustration of the role of secondary meridional circulation (induced by Westerly equatorial winds) for re-distribution of the heat in the stratosphere.

The easterlies (Fig.4b) will reduce the impact of the lower stratosphere in the meridional heat transport but will increase the downwelling at high latitudes. This may explain the positive temperature anomalies of polar stratosphere for both - minimum and maximum solar activity, when easterlies are placed over the equator (Fig.1 and Fig.2, left column). The above described picture is additionally modulated by the season (i.e. for equinoctial periods the maximum solar warming is placed over the equator and westerlies keep it in the lower stratosphere, while easterlies spread it al the upper levels).

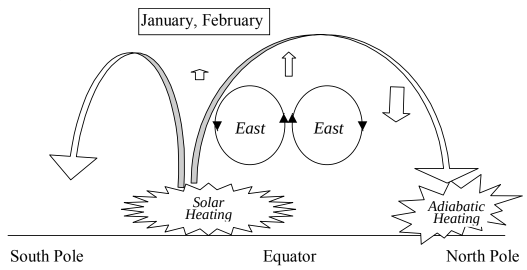

Fig.4(b) Schematic illustration of the role of easterlies in the meridional heat transport in the stratosphere.

Some authors [11, 16, 18] 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 & Eluszkiewicz [13] and Scott [14] point 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. This means that more warming of the lower stratosphere at solar max 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.5.

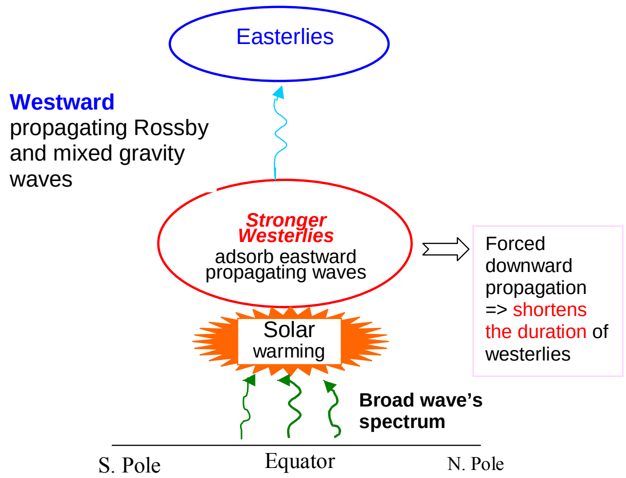

Fig.5 Schematic illustration of solar modulation the duration of westerly winds in the equatorial stratosphere.

It can 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 (UTLS), 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 [20]). Easterlies at 30 hPa decrease the UTLS westerlies (at the top of Hadley cells) which allows the eastward propagating (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.

Conclusions

The 11 year solar and QBO signals, found in interannual variability of many stratospheric and tropospheric parameters and events, 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. Base of this fact and taking into account the resent result related to the modelling of stratosphere-troposphere dynamics, the author presents a new mechanism explaining the interplay between 11 year solar and QBO signal 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 solar warming in the lower stratosphere is stronger and kept at UTLS when westerly winds are placed over the equator. The QBO meridional circulation also affects the processes of redistribution of the heat fluxes. This means that easterlies over the equator favour the extreme downwelling over the winter polar cap, while the westerlies diminish these processes; 2) The warming of the lower stratosphere 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 winds that deposit their energy and momentum into the westerly shear. This process forced downward propagation of the westerlies shortening their duration. Easterlies are practically not affected by this process because they simply diminish UTLS westerlies (at the top of the Hadley circulation) allowing the eastward propagating waves to penetrate the upper stratosphere, where to deposit their energy and momentum.

Acknowledgements

Author is thankful to Stratospheric Research Group at the Institute of Meteorology of the Free University Berlin and HALOE data team for the data provided. NSF of Bulgaria, contract No H3 1518/05, founded this work.

REFERENCES

[1] W.Soon, E. Posmentier, S.Baliunas, “Climate Hypersensitivity to solar forcing”, *Ann.Geophys.*, Vol. 18, 2000, pp. 583-588.

[2] D.Douglas, B.Cader, “Climate sensitivity of the Earth to solar irradiance”, *Geophys. Res. Lett.*, Vol. 29, No 16, 2002, pp. (33)1-(33)4, doi: 10.1029/2002GL015345.

[3] M.Salby, P.Callaghan, D.Shea, “Interdependence of the tropical and extratropical QBO: Relationship to the solar cycle versus a biennial oscillation in the stratosphere”, *J. Geophys. Res.*, Vol. 102, 1997, pp. 29789-29798.

[4] D.Shindell, D.Rind, N.Balachandran, J.Lean, P.Lonergan, “Solar Cycle Variability, Ozone and Climate”, *Science*, Vol.289, 1999, pp.305-308.

[5] J.Haigh, “The role of stratospheric ozone in modulating the solar relative forcing of climate”, Nature, 1994, pp. 544-546.

[6] L.Hood, “Solar variability and its effect on the Earth’s atmospheric and climate system, effects of solar UV variability on the stratosphere”, *AGU Monograph Series*, AGU, Washington, D.C., 2003.

[7] L.Gray, S.Phipps, T.Dunkerton, M.Baldwin, E.Drysdale, M. Allen, “A data study of the influence of the equatorial upper stratosphere on northern-hemisphere stratospheric sudden warmings”, *Q.J.R. Meteorol. Soc.*, Vol.127, 2001, pp. 1985-2003.

[8] K.Kodera, “Solar influence on the spatial structure of the NAO during the winter”, *Geophys. Res. Lett.*, Vol. 30, 2003, pp. (24) 1- 4.

[9] C.Zerefos, K.Tourpali, I.Isaksen, C.Schuurmans, “Long term solar induced variations in total O3, stratospheric T and tropopause”, *Adv. Space Res.*, Vol. 27, 2001, pp. 1943-1948.

[10] N.Kilifarska, J.Haigh, “Climate sensitivity to solar modulation of H2O vapour derived from HALOE data”, *Proceedings of ISCS’03*, ESA Publication Division, *ESA SP-535*, 2003, pp. 339-344.

[11] K.Labitzke, “On the solar cycle-QBO relationship: a summary”, *J. Atmos. Sol. Terr. Phys.*, Vol. 67, 2005, pp. 45-54.

[12] M.Salby, P.Callaghan, “Connection between the Solar Cycle and the QBO: The missing link”, *J. Climate*, Vol. 13, 2000, pp. 2652-2662.

[13] R.Plumb, J.Eluszkiewicz, “The Brewer-Dobson circulation: dynamics of the tropical upwelling”, *J. Atmos. Sci.*, Vol. 56, 1999, pp. 868-890.

[14] R.Scott, “Wave-driven mean tropical upwelling in the lower stratosphere”, *J. Atmos. Sci.*, Vol. 59, 2002, pp. 2745-2759.

[15] J.Holton, H.Tan, “The influence of the equatorial quasi-biennial oscilation on the global circulation at 50 mb”, *J. Atmos. Sci.*, Vol. 37, No 10, 1980, pp. 2200-2208.

[16] K.Labitzke, “The global signal of the 11-year sunspot cycle in the atmosphere: When do we need the QBO”, *Meteorolog. Zeitschrift*, Vol. 12(4), 2003, pp. 209-216.

[17] M.Salby, P.Callaghan, “Evidence for solar cycle in the general circulation of the stratosphere”, *J. Climate*, Vol. 17, No 1, 2004, pp. 34-46.

[18] K.Kodera, Y. Kuroda, “Dynamical response to solar cicle”, *J. Geophys. Res.*, Vol. 107, No D24, 2002, doi:10.1029/2002JD002224.

[19] N.Kilifarska, P.Mukhtarov, “Is the wave forcing the only explanation of stratospheric warmings?”, *Proceedings of 11th International conference on solar-terrestrial influences*, Sofia, November, 2005.

[20] R.Plumb, “The interaction of two inertial waves with the mean flow; implication for the theory of QBO”, *J. Atmos. Sci.*, Vol. 34, 1977, pp. 1847-1858.