# Mechanism of Solar influence on the winter time Polar Atmosphere

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**Abstract.** The purpose of this paper is to isolate the main factors standing behind the polar night jet variability. We find out that stratospheric thermo-dynamical conditions prior to the onset of the two different types of major stratospheric (MSWs) are substantially different. We discover that the splitting of the polar vortex is critically dependent on the deceleration of the core of the westerly jet. Examination of the stratospheric thermal regime shows that such a deceleration is observed prior to the onset of the split vortex events and is obviously related to the broad heating of the whole middle stratosphere – from the pole to the mid-latitudes. Multiple factorial analyses of the potential triggers of this pre-conditional warming reveal that about 50—60% of the total T and U variability can be attributed to a sudden decrease of the galactic cosmic rays. We hypothesize that its relation to the abrupt increase of the stratospheric temperature is through the corresponding enhancement of the ozone concentration. The later is a result from the reduction of the ozone depleting compounds, i.e. NOx and NOx families. The displacement type of MSWs appears when the pre-conditional warming of the stratosphere is confined to the Pole (below 10 hPa). In this case the vortex is highly baroclinic, and even highly distorted dos not split. Statistical analysis shows that the impact of all examined factors is much less, compared to the split vortex MSWs, what supposes that some other mechanisms, or their combination, are responsible for the appearance of this type of MSWs.



**Keywords:** polar vortex, stratospheric warming, cosmic rays

## 1. Introduction

Stratospheric sudden warmings and the mechanism of their occurrence have exited scientist for more than 40 years. One of the most exploited concepts is that of wave-mean flow interactions according to what the stratospheric warmings result from saturation and breaking of vertically propagating planetary waves. The usefulness of this paradigm has been successfully demonstrated in the pioneering mechanistic modelling work of Matsuno (1971) and Holton (1976). Less popular, but supposed very promising, is a concept based on interactions of coherent structures of potential vorticity due to the fact that the dynamics of the winter stratosphere often takes on a more local character than those described by global waves. This synoptic view was advocated by O'Neill and Pope (1988) and developed further by Dritschel (1995), Scott and Dritschel (2005), etc.

Despite the success of the wave–mean flow description, some of stratospheric warmings like Canadian warmings appear in years with modest wave activity and are not preceded by extreme wave breaking (Baldwin and Holton, 1988) and this fact put a question about the existence of alternative mechanisms. Still unanswered is the question why splitting type warmings are "preconditioned" (McIntyre, 1982) while "displacement" type are not? This work is an attempt to find answers on this questions looking for the physical processes responsible for this variety in specific manifestation of stratospheric warmings.

## 2. Data and method of analysis

We used ERA-40 data set for temperature (T) and zonal wind (U), which consist of 6-hourly analyses through the period 1957-2002 (available at http://www.ecmwf.int/research/era). The figures shown in this paper are for 12:00 local time and standard pressure levels from 1000 to 1 hPa, taken at the Greenwich meridian. Daily values of solar radio emission at 10.7 cm ($F_{10.7}$) and cosmic rays intensity measured at the ground from station Climax are taken from http://spidr.ngdc.noaa.gov/.

In order to isolate the effects of different factors, influencing spatial-time distribution of atmospheric parameters, we have created several composites separating data according the following criteria:

1. "composite T(60N)" – contains U or dT data for days with *positive temperature* anomalies at *$60^0$N latitude* and 10 hPa;
2. "composite T(pole)" – contains U or dT data for days with *positive temperature* anomalies at *North Pole* and 10 hPa;
3. "composite U(60N)" - contains U or dT data for days with *negative wind* anomalies at *$60^0$ latitude* and 10 hPa;

Here and further dT denotes deviation of daily T from its daily average calculated over 45 years time series of temperature. We will call these composites "causal". The latitude $60^0$N and the height of 10 hPa have been chosen for analyses, because according the criteria of the WMO a sudden stratospheric warming is classified as a major if a reversal of the zonal wind and latitudinal temperature gradient at this latitude and altitude is observed.

Data in each composite were stratified additionally according to the sign of the equatorial stratospheric winds at 30 hPa (QBO – quasi-biennial oscillations) and for each phase they were separated on three bands depending on the amplitude of T or/and U anomalies (i.e. anomalies<1σ, 1σ<anomalies<2σ and anomalies>2σ); σ - denotes a standard deviation. Our decision to separate all composites according to the phase of QBO is motivated by the QBO signal found in many of the polar atmosphere parameters (Labitzke and van Loon, 1988; Salby and Callaghan, 2000; Balachandran and Rind, 1995, Gray et al., 2001, etc.) as well as by the widely accepted opinion that east QBO conditions favour occurrence of stratospheric warmings (Holton and Tan, 1980).

We created also 2 composites for each type of major warmings (as determined by Charlton and Polvani, 2007) defined as follow;

4. "composite split(prior)" - contains U or dT data from 10 days interval prior to each major warming of *splitting type*
5. "composite split(post)" - contains U or dT data from 10 days interval after each major warming of *splitting type*
6. "composite displ(prior)" - contains U or dT data from 10 days interval prior to each major warming of *displacement type*
7. "composite displ(post)" - contains U or dT data from 10 days interval after each major warming of *displacement type*

Statistical analysis of the composites **split(prior)** and **displ(prior)** is performed in order to isolate the most important factors affecting altitude-latitude distribution of the temperature and zonal wind in the preparation stage of two types major warmings. We have used different statistical approaches, but as well as our main purpose is to estimate the percentage impact of each of the examined factor in a total variability of T and U, here we will present results from multivariate general regression models analysis.

General regression model (GRM) differs from the multiple regression one in terms of the number of dependent variables that can be analyzed. A single dependent variable in the multiple regression analysis is replaced by many, not certainly independent variables. This means that the ***Y*** vector of *n* observations of a single *Y* variable in GRM is replaced by a ***Y*** matrix of *n* observations of *m* different *Y* variables. Similarly, the $\boldsymbol{b_i}$ vector of regression coefficients for a single ***Y*** variable is replaced by a $\boldsymbol{b_i}$ matrix of regression coefficients, with one vector of $\boldsymbol{b_i}$ coefficients for each of the *m* dependent variables, i.e.

$$Y = b_0 + b_1X_1 + b_2X_2 + ... + b_kX_k,$$

where **Y** is *m* x *n* matrix of the dependent variables and $b_0, b_1, ..., b_k$ are *m x n* matrixes of regression coefficients.

The GRM goes a step beyond the multiple and multivariate regression models by allowing for linear transformations or linear combinations of multiple dependent variables. As well as to separate univariate tests of significance for correlated dependent variables are not independent and may not be appropriate, GRM provides multivariate tests of significance when responses on multiple dependent variables are correlated. As a measure of significance of multivariate associations GRM uses Wilks' Lambda criterion defined as follows:

$$Wilks'\,Lambda = \prod \left(1/\left(1+\lambda_i\right)\right),$$

where $\lambda_i$ are the ordered eigen values of the product matrix $\mathbf{E^{-1}H}$. Here **E** stands for the *error matrix* (i.e. the matrix of sums of squares and cross-products for the dependent variables that are **not accounted** for by the predictor, and **H** stands for the *hypothesis matrix* (i.e. the matrix of sums of squares and cross-products for the dependent variables that are accounted for by **all** the predictors). Wilks' lambda is a direct measure of the proportion of variance in the combination of dependent variables that is unaccounted for by the independent variables. Another advantage of GRM is that it provides a solution for the normal equations when the *X* variables are not linearly independent and the inverse of ***X'X*** does not exist.

## 3. Results from analysis of temperature and zonal wind anomalies

### *a) results from "causal" composites*

The first column in Fig.1 presents meridional cross-sections of the zonal wind distribution when the temperature at $60^0$N latitude and 10 hPa gradually increases. The first row corresponds to a weak T enhancements - less than σ, while the last row reflects the zonal wind distribution during periods of very strong warming of the upper stratosphere at $60^0$N, i.e. dT> 2σ. The second column in Fig.1 shows the average zonal wind distributions when the upper polar stratosphere at 10 hPa is gradually warmed – from weak disturbances (dT<σ) to very significant warming (i.e. dT>2σ). And the last column of Fig. 1 illustrates the typical meridional distribution of the zonal wind when a gradual deceleration of the upper stratospheric westerlies is encountered. The top of Fig.1 shows results from the east QBO and the bottom - from the west QBO composites. Note that the phase of QBO has very little influence on the shape of the polar vortex.

It is worthwhile to point out that warming of the middle stratosphere near $60^0$N latitude shifts the stratospheric part of the polar vortex poleward. For T anomalies greater than 2σ the vortex becomes purely barotropic. In the opposite case - when the Polar upper atmosphere is heated - the vortex becomes more baroclinic and tilted toward the equator. The most interesting, however, is the vortex response to a sudden deceleration of zonal wind near its core. The $3^{-rd}$ column in Fig 3 shows a splitting of the polar jet in two parts, even for a medium range of the zonal wind deceleration. This process is observed for both phases of QBO.

Analysis of polar jet sensitivity to the latitude position of the wind deceleration shows that vortex splitting depends not only on the latitude but also on the strength of the forcing. Thus for medium range of deceleration (i.e. greater than σ and less than 2σ) the vortex splits only when the forcing is applied in a small area near $55^0$-$60^0$N latitude. For a strong level of forcing (greater than 2σ) – a weakening of westerlies in a wider range of latitudes equatorward of $60^0$N may lead to vortex splitting (not shown).

***b) analysis of thermal and dynamical forcing of polar jet and their relation to the type of stratospheric warmings***

Examination of the meridional structure of the zonal wind and Eliassen-Palm (EP) flux anomalies for two periods - 10 days prior to and 10 days after the onset of a ***displacement type*** of warmings - shows that stronger westerlies southward of $60^0$N in the middle and upper stratosphere do not favour upward propagation of planetary waves prior to the onset of these events for both QBO phases (see Fig. 2a). Moreover, the stratospheric part of the vortex is displaced equatorward and the reference to Fig. 1 shows that this usually is related to the ***warming of the polar stratosphere***. This possibly explains the negative wind anomaly shown in Charlton and Polvani (2007) for period (-20, -5) days prior to the displacement type warmings. In the next 10 days following the zero day the planetary waves are well focused in the upper polar stratosphere (in east QBO phase) and due to the easterly momentum deposition of breaking waves the vortex is displaced further equatorward. In west QBO, however, the waves are refracted downward from the stratopause levels of the vortex and perhaps this is the reason for its smaller change.

The situation is completely different for the ***split vortex*** warmings (see Fig. 2b). Prior to the initial day the vortex is highly weakened (especially in east QBO phase) and barotropic. It serves as a duct for the vertical propagation of the planetary waves and no evidence for their breaking is found. Even after the establishment of the major warming the waves continue their free propagation upward. Consequently, the wave breaking can hardly be attributed for the vortex deceleration. A reference to Fig. 1 shows that this is a typical zonal wind structure when ***middle atmosphere at $60^0$ N is warmed***.

In summary, we find that the *displacement type* of the major warming events result as a consequence of a preliminary heating of the polar stratosphere, while most crucial for the polar vortex *splitting* appears to be deceleration of the zonal wind near the core of the jet (compare Figs. 1 and 2). The meridional structure of T anomalies of **split(prior)** and **displ(prior)** composites, presented in Fig. 3, confirm this conclusion. It is well seen that in the preparation phase of the displaced vortex warmings, the greatest positive T anomalies are placed over the pole (below 10 hPa). The preconditioning of splitting type warmings oppositely is marked by broad warming of the whole middle stratosphere - from the Pole to about $40^0$N latitudes. Due to the Coriolis' effect this heating obviously forces the zonal wind deceleration near the core of the vortex.

## 4. Factors triggering stratospheric warmings

In this section we try to understand which factors (internal and external) are accountable for the thermal forcing of the night polar jet and correspondingly for eventual occurrence of displacement or splitting type major warmings.

To answer this question four general regression models were built with dependent variables - temperature and zonal wind profiles in latitudinal band 30-$80^0$N. As independent variables we have considered solar UV radiation, CRs, two modes of internal atmospheric variability, namely QBO (quasi-biennial oscillation of the equatorial stratospheric wind) and ENSO (El Ninõ Southern Oscillation), and Eliassen-Palm (EP) flux. Since the QBO index is provided on monthly basis only, we used the daily values of equatorial zonal wind at 30 hPa as a proxy of "daily QBO" index.

Our preliminary estimations have shown that the impact of ENSO in the total variability of T and U is relatively small and not independent on QBO, so we excluded them from our regression models. We have analysed the impact of EPz at different levels and due to the high colinearity and great cancellation effect between them we choose to include in our statistical model the EPz passing trough 150 hPa. Thus multiple regression coefficients of temperature and zonal wind in our statistical modes are defined as a function of four independent parameters, i.e.

$$R(T,U) = f\left(F_{10.7}, daily\ QBO, CRs, EP_z\left(150\ \mathrm{hPa}\right)\right)$$

We have analysed the composites of zonal wind and temperature in the preparatory phase (i.e. 10 days prior to the initial day) of each type of major warmings, separated according to the QBO phase. The calculated semi-partial regression coefficients multiplied by 100 are presented in Figs. 4a and b. They indicate the amount of variability of the dependent variable described by the corresponding predictor. Analysis of stratospheric thermal conditions prior to the major warmings of *splitting type* shows that both weakening of the amplitude of QBO and decreased intensity of the galactic CRs are related to the warming of the lower-middle stratosphere. They describe up to 50% of the stratospheric T variability prior to the split vortex events (see Fig. 4a, left column). The maximal influence of the QBO is found at mid-latitudes, while the CRs effect is focused mainly around the auroral oval (i.e. $50^0 \div 70^0$N latitudes). The influence of these two factors on the zonal wind is also quite similar. Thus the decrease of the equatorial easterlies and the CRs intensity are related to the weakening of the zonal wind at the equatorial edge of the polar jet (see right column of Fig.4a).

For the split vortex warmings, appearing in west QBO phase, the impact of the equatorial stratospheric winds is highly reduced (middle row of Fig. 4b). The maximum influence of CRs on the stratospheric T is shifted equatorward and slightly upward, while their effect on the zonal wind (consisting of a weakening of the polar atmosphere westerlies or strengthening of the easterlies) is focused mainly at high latitudes. However, another factor seems to have a significant role in the preparation of the westerly split vortex events – solar UV radiation. Enhancement of solar UV is accompanied with a warming of the polar lower/middle stratosphere and correspondingly with deceleration of the equatorial edge of the polar vortex (see first row of Fig. 4b).

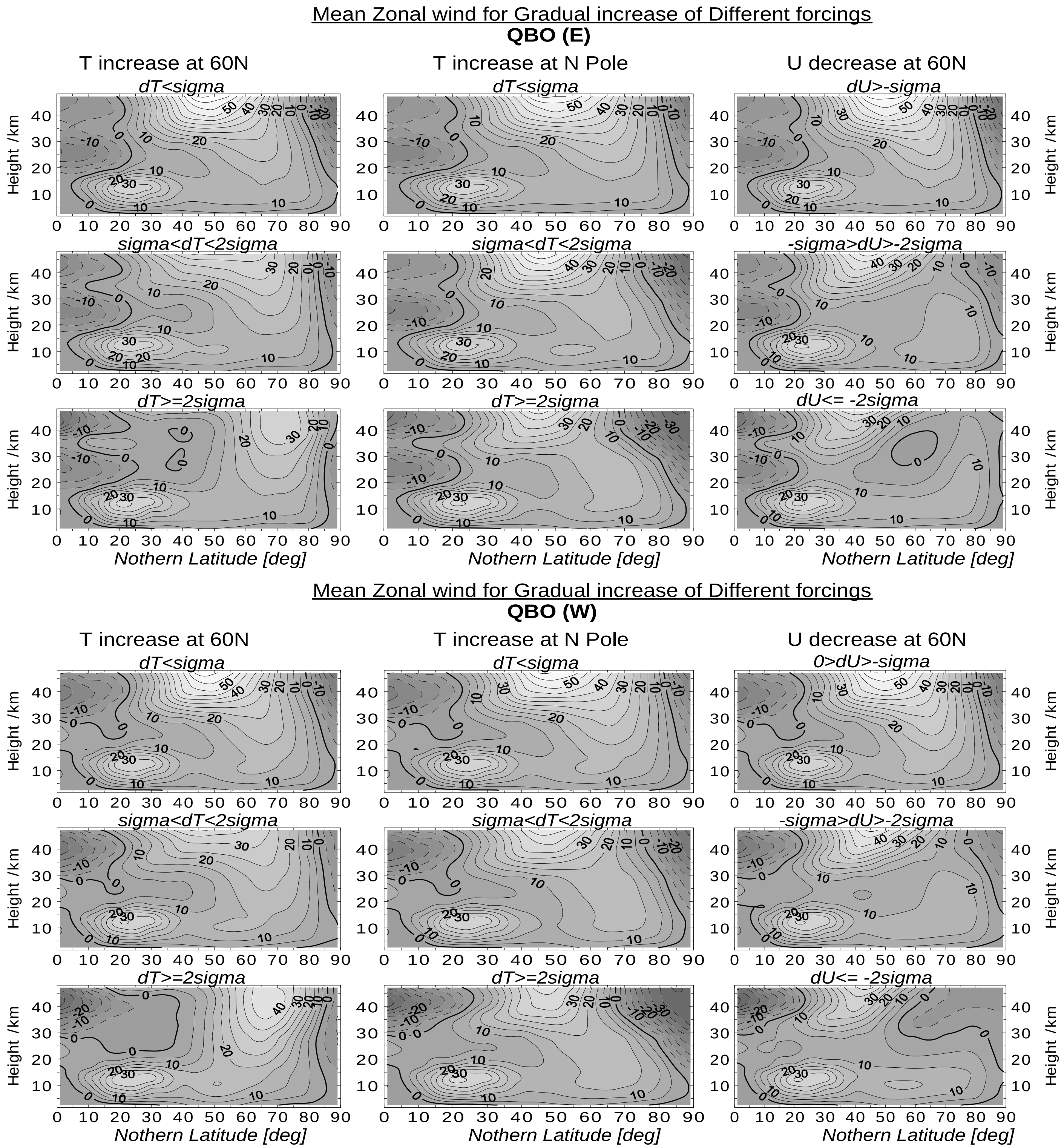


*Fig.1 Meridional cross-section of zonal wind response on three different type of forcing: 1-st column- gradual warming of middle stratosphere (10hPa) at 600N latitude; 2-nd column - gradual warming of North Pole and 3-rd column - gradual decrease of zonal wind at 600N latitude. The first row in the upper and bottom part of the figure presents weak levels of forcing factors, i.e. less than 1σ; the second row corresponds to medium forcing, i.e. greater than 1σ and less than 2σ; the third row shows the zonal wind response on strong forcing, i.e. greater than 2σ. Dashed lines mark the easterlies, while continuous lines - westerlies.*

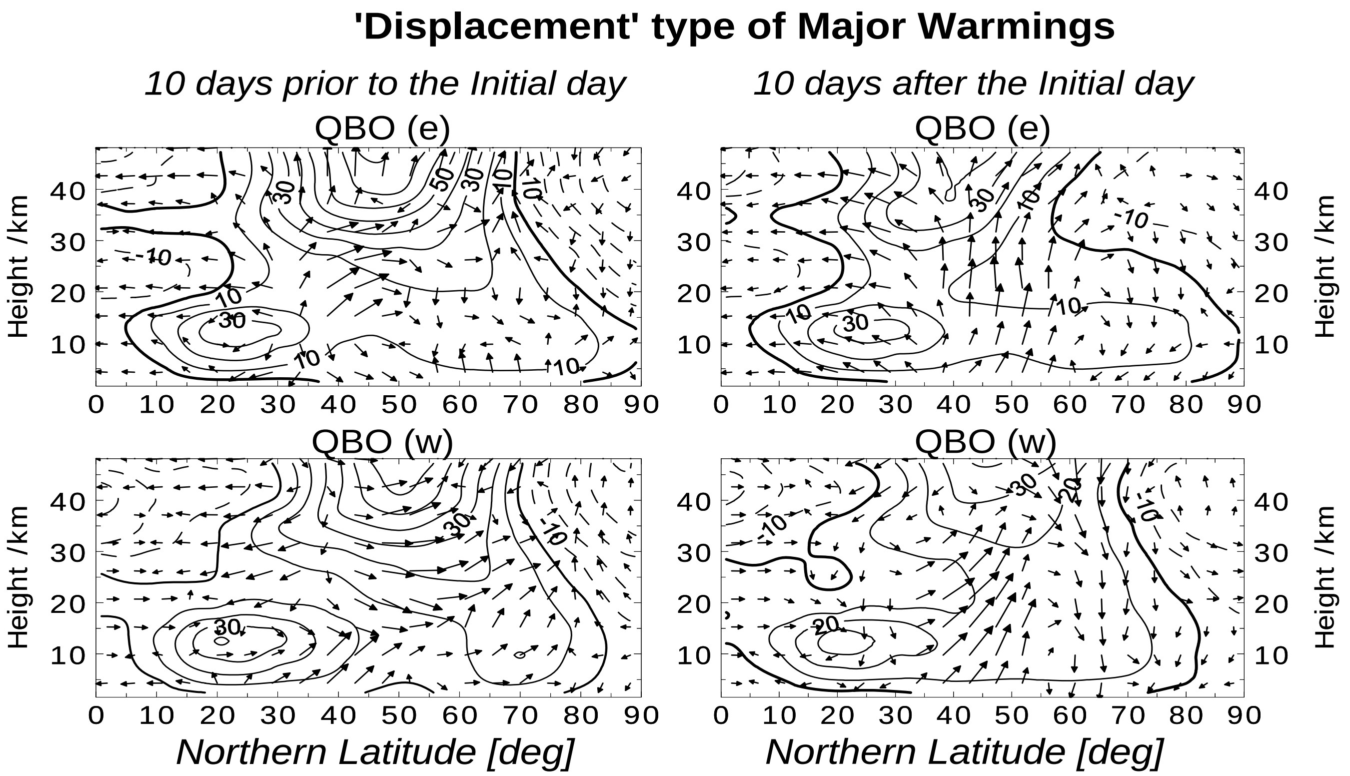


*Fig. 2a. Meridional cross-section of mean zonal wind and EP flux for 10 days prior to (left column) and 10 days after (right column) the initial day of displacement type major warmings.*

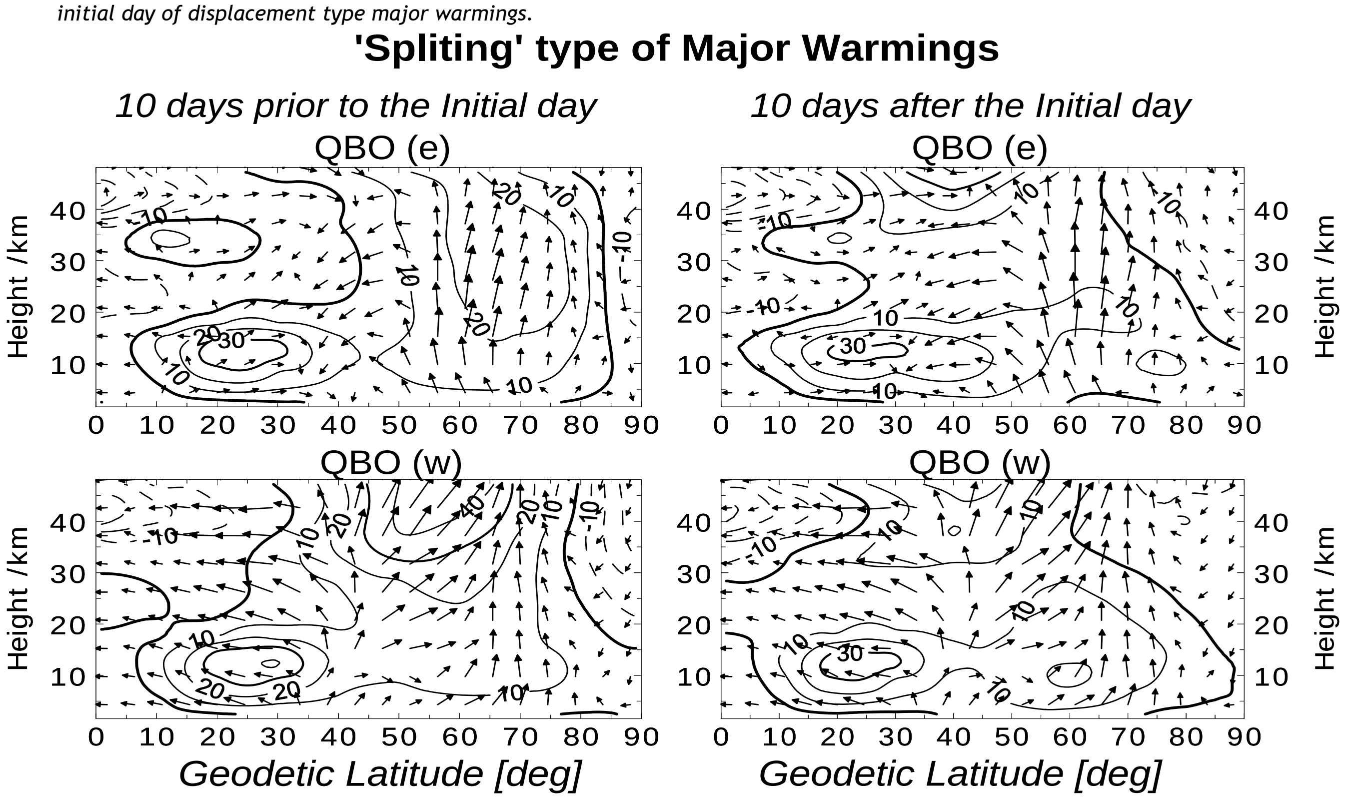


*Fig. 2b. Meridional cross-section of mean zonal wind and EP flux for 10 days prior to (left column) and 10 days after (right column) the initial day of splitting type major warmings.*

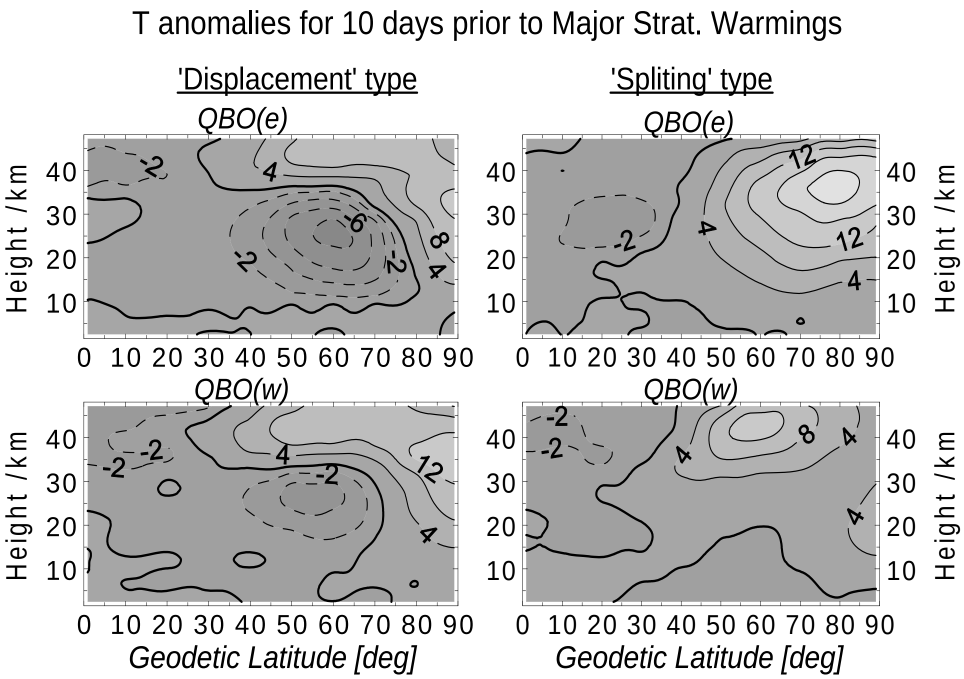


*Fig. 3. Mean meridional distribution of temperature anomalies typical for displacement (left column) and splitting type (right column) observed 10 days prior to stratospheric major warmings. Upper row corresponds to warmings occurred in east QBO phase and the bottom – for west QBO events.*

What concerns the effect of the planetary waves, the GRM analysis shows that their influence on T and U during the preparatory phase of the major warmings of splitting type is very weak and generally non-significant at 95% level. This means that the wind reversal, observed during the major warmings is at most only weakly related to the planetary wave activity.

This result raises the reasonable question about the mechanisms of stratospheric heating during the preconditioning of the major warmings. The possible mechanism for the temperature enhancement will be analysed in the Discussion and Conclusions section.

Regarding the displacement type of warmings, analysis of the results shows that temperature and zonal wind in the phase of preparation are less influenced by the factors examined (not shown). For both QBO phases the heating related to the reduction of the galactic CRs intensity is placed at much lower latitudes what is followed by some increase of westerly jet (see Fig. 2a). The impact of all factors is much smaller, compared to the split vortex warmings, and highly dispersed what reflect in a small performance of the statistical models created(not shown) .

## 5. Discussion and conclusions

In this study we try to answer two main questions:

1. Does the different types of major stratospheric warmings (MSWs) are forced in a different way?
2. What are the physical mechanisms standing behind these forcing?

Analysis of the Northern Hemisphere winter-time zonal wind response, to a gradually increasing thermal and dynamical forcing, shows that the crucial for the polar vortex splitting is a medium to strong deceleration of the zonal winds. And what is more important – this deceleration has to be applied near the core of the jet.

On the other hand, analysis of the thermo-dynamical conditions in the stratosphere reveals that the whole middle stratosphere – from the pole to mid-latitudes – is heavily warmed for 10 days prior to the appearance of the MSWs of splitting type. This supposes a significant weakening of the polar vortex only because of the action of the Coriolis force. In cases when pre-conditional warming is confined to the high latitudes (particularly below 10 hPa), the vortex is more baroclinic and tilted toward the equator. Although heavily distorted, the vortex keeps its integrity and its centre is usually shits away from the Pole.

Consequently, we conclude that the occurrence of the **split vortex** major stratospheric warmings is prepared by the global heating of the middle stratosphere, switching on a deceleration of the core of the vortex. The **displaced vortex** MSWs are rather related to a local heating of the Polar Stratosphere.

The answer of the second question requires an explanation of the mechanism(s) of the abrupt increase of the stratospheric temperature. Our analysis of the EP flux shows that it can hardly be attributed to the planetary wave forcing, because there is either no evidence of the wave breaking or only a weak focusing of the planetary waves is observed. Multiple factorial statistical analyses (GRM) confirm this conclusion, revealing that the impact of EP flux in the temperature and zonal wind variability is very weak (no more than 10-20%) and is generally non-significant.

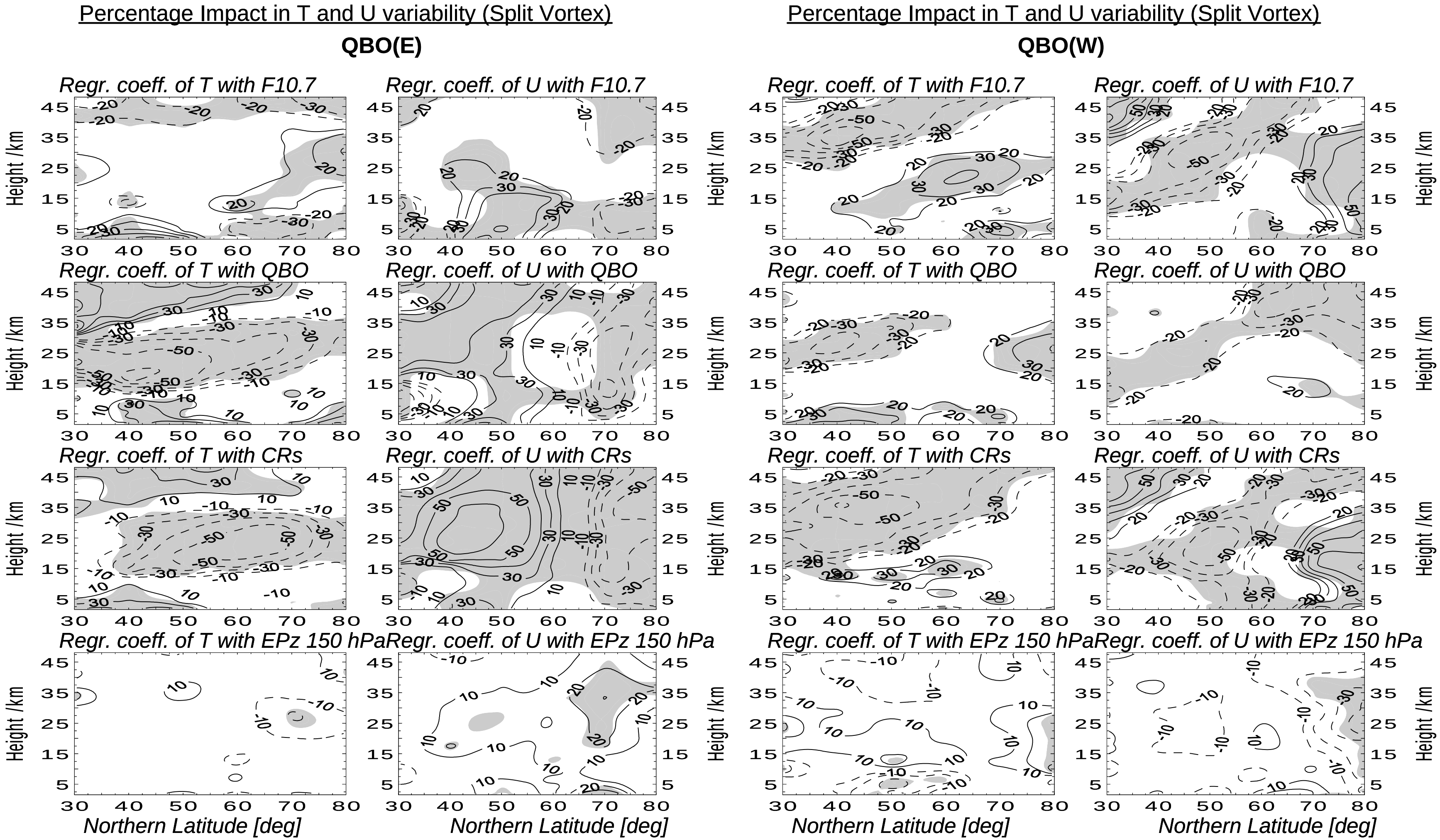


*Fig. 4a. (left panel) Percentage of total variability of temperature (left column) and zonal wind (right column) explained by each component of general regression model in the case of splitting type major stratospheric warmings and east QBO. First row shows solar impact, second - QBO, third - effect of solar proton fluxes on stratosphere, bottom row - total variability described by the whole model. Shaded areas are statistically significant at 2σ level. (right panel) Same as the left panel but for west QBO phase.*

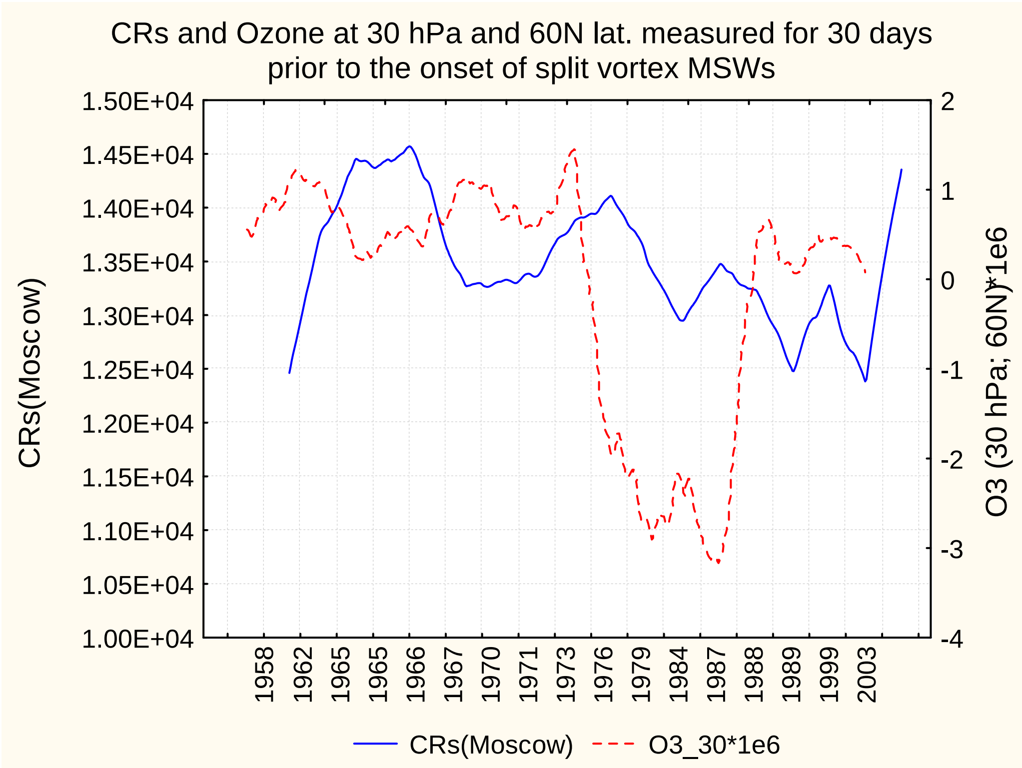


*Fig. 5. Smoothed composites of Cosmic Rays from Moscow neutron monitor and ozone anomalies at 10 hPa and 600N latitude, measured for 30 days prior to the onset of the split vortex major stratospheric warmings for the period 1957-2009. The ozone curve is shifted backward by 30 points (~ 1 year).*

At the same time GRM shows that the decrease of the galactic CRs intensity explains more than 50-60% of T and U variations during the preparatory phase of the split vortex major warmings, for both QBO phases. The question is how the CRs' reduction can be related to the enhancement of the stratospheric T?

It is well known that the stratospheric ozone is the most effective heater of the stratosphere. So, if we could expound how the decrease of CRs intensity will increase the ozone concentration, this will explain the significant negative correlation found between T and CRs. Our preliminary analysis shows that the ozone response to the energetic particles' forcing depends strongly on their energy (paper submitted to J. Atmos. Sol. Terr. Phys, 2010). The highly energetic protons reduce the ozone *in* situ trough activation of the O3 destructive cycles of the NOx and NOx families – a fact which is broadly accepted by the scientific community (i.e. Jackman and McPeters, 2001; Krivolutsky, 1999; Seppälä et al., 2008, etc.). Consequently, the reduction of the intensity of the most energetic particles, entering the Earth atmosphere, should increase the amount of the lower/middle stratospheric ozone, due to the reduction of the O3 destructive species. As an indirect conformation of this argument, it should be stressed that the dominant part of the split vortex MSWs occur during low/middle solar activity, i.e. in periods of generally high level of CRs and lower ozone concentrations (see Fig. 5). In these circumstances, a sudden decrease of the CRs intensity could produce a significant positive $O_3$ anomaly and correspondingly sudden increase of the stratospheric temperature.

What concerns to the mechanisms of the polar stratosphere warming (typical for the preparatory phase of the displaced vortex MSWs) it may be attributed to the adiabatic warming of the downward transported air masses from the mesosphere and upper stratosphere.

In resume, this research reveals the existence of differences in the stratospheric thermo-dynamical conditions prior to the onset of the two different types of the major stratospheric warmings. We find out that the splitting of the polar vortex is critically dependent on the deceleration of the core of the westerly jet. Examination of the stratospheric thermal regime shows that such a deceleration is observed prior to the onset of the split vortex events and is obviously related to the broad heating of the whole middle stratosphere – from the pole to the mid-latitudes. Multiple factorial analyses of the possible factors, which can be potential triggers of this pre-conditional warming, reveal that about 50-60% of the total T and U variability can be attributed to sudden decrease of the galactic cosmic ray flux. We hypothesise that its relation with the abrupt increase of the stratospheric temperature is through the corresponding enhancement of the ozone concentration. The later is a result from the reduction of the ozone depleting compounds, i.e. $NO_x$ and $NO_x$ families.

The displacement type of major MWs appears when the pre-conditional warming of the stratosphere is confined to the Pole (below 10 hPa). In this case the vortex is highly baroclinic, due to the equatorward shifting of its upper stratospheric part, but dos not split. Statistical analysis shows that the impact of all examined factors is much less, compared to the split vortex MSWs, what supposes that some other mechanisms are responsible for the appearance of this type of MSWs (e.g. an adiabatic heating due to an increased downwelling within the polar region).

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