THE POLAR VORTEX EVOLUTION AS A POSSIBLE REASON FOR THE TEMPORAL VARIABILITY OF SOLAR ACTIVITY EFFECTS ON THE LOWER ATMOSPHERE CIRCULATION

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Abstract. In this work we continue studying possible reasons for the temporal variability of long-term effects of solar activity (SA) and galactic cosmic ray (GCR) variations on the lower atmosphere circulation. It was revealed that the detected earlier ~60-year oscillations of the amplitude and sign of SA/GCR effects on the troposphere pressure at high and middle latitudes are closely related to the state of a cyclonic vortex forming in the polar stratosphere. A roughly 60-year periodicity was found in the vortex strength affecting the evolution of the large-scale atmospheric circulation and the character of SA/GCR effects. It was shown that the sign reversals of the correlations between tropospheric pressure and SA/GCR variations coincide well with the transitions between the different states of the vortex. Most pronounced SA/GCR influence on the development of extratropical baric systems is observed when the vortex is strong. The results obtained suggest that the evolution of the stratospheric polar vortex plays an important part in the mechanism of solar-atmospheric links.

1. Introduction

Our previous study showed that the response of tropospheric pressure to variations of solar activity (SA) and galactic cosmic ray (GCR) fluxes reveals a regional structure determined by the positions of the main climatic atmospheric fronts, as well as it strongly depends on the epochs of the large-scale circulation [Veretenenko and Ogurtsov, 2012]. In the epochs of increasing intensity of the meridional circulation (the form C according to Vangengeim-Girs classification [Vangengeim, 1952; Girs, 1974]) an increase of GCR fluxes at minima of the 11-year cycle is accompanied by an intensification both of extratropical cyclones at Polar fronts of middle latitudes and Arctic anticyclones at high latitudes of the Northern hemisphere, as well as by a weakening of the equatorial trough at low latitudes. In the epochs of decreasing meridional circulation the troposphere response to SA/GCR variations reveals a similar regional structure, i.e., the regions of most pronounced effects are closely related to the climatic atmospheric fronts, but the sign of SA/GCR effects in these regions is opposite.

It was also detected [Veretenenko and Ogurtsov, 2012] that the evolution of the meridional circulation is characterized by a roughly 60-year periodicity which, in turn, influences the sign of SA/GCR effects on troposphere pressure. Indeed, the reversals of the correlations between sea-level pressure at high latitudes and sunspot numbers occurred in the 1890s, the early 1920s, 1950s and the early 1980s and coincided well with the changes in the evolution of the C-type meridional circulation. Hence, the aim of this work is to study what processes may influence the evolution of the large-scale circulation and, then, the character of SA/GCR effects on troposphere pressure.

2. The polar vortex location and the distribution of SA/GCR effects

It is known that the main elements of the large-scale circulation at middle and high latitudes are the polar vortex, planetary frontal zones and extratropical cyclones and anticyclones, all these elements are closely interconnected. The stratospheric polar vortex is a large-scale cyclonic circulation forming in a cold air mass and extending from the middle troposphere to the stratosphere over the polar region. A planetary frontal zone is a system of individual frontal zones (regions of high temperature contrasts that arise in the troposphere due to the difference of thermal characteristics of air masses forming over different kinds of surface). Cyclonic activity at middle latitudes is closely related to frontal zones which supply energy for the development of extratropical baric systems (cyclones and anticyclones).

The polar vortex formation is due to air inflow to the Arctic region and its cooling over ice surface under the conditions of negative radiation balance. Air cooling and descent contribute to the growth of surface pressure. Simultaneously with the surface pressure increase a lowering of isobaric levels takes place resulting in the formation of low pressure area at the level 500 hPa and above. Thus, cyclonic circulation (the western zonal flow) arises around the pole. Circular air motion in the vortex isolates cold air inside it from warmer air at middle latitudes; it causes an appreciable increase of temperature gradients at the vortex edges. The typical location of the vortex as the low temperature area, with temperature gradients enhancing at its edges, is shown in Fig.1a, the data were calculated using NCEP/NCAR reanalysis data [Kalnay et al, 1996].

The vortex is known to play an important part in a variety of atmospheric processes. In particular, air cooling to low temperatures (–80°C) in the vortex area contributes to the formation of polar stratospheric clouds (PSC), with chemical processes on PSC particles catalyzing ozone destruction. The vortex state influences the evolution of large-scale dynamic processes in the atmosphere, e.g., the North Atlantic Oscillation polarity [Baldwin and Dunkerton, 2001]. The rotation of cold and warm epochs in the Arctic seems to be related also to the vortex state [Gudkovich et al., 2009].

Let us compare the typical location of the vortex and the distribution of SA/GCR effects at high latitudes in the periods of enhancing and weakening meridional circulation of the type C. This circulation

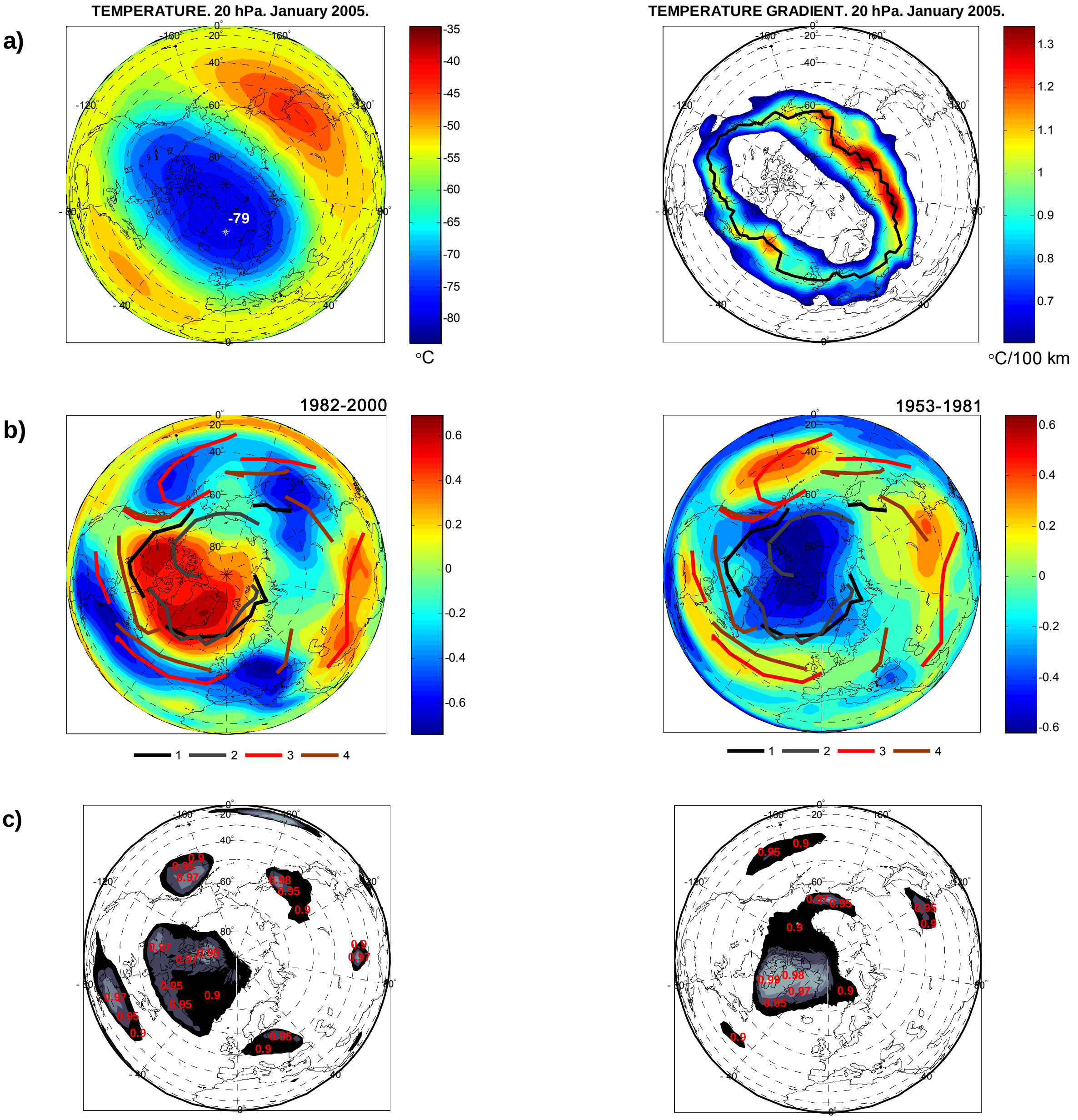

Fig.1. a) Distribution of mean monthly values of temperature (left) and magnitude of temperature gradients (right) at the level 20 hPa in the stratosphere for January 2005. b) Distribution of the correlation coefficients *R(GPH700, NM)* between tropospheric pressure and GCR intensity for the periods of enhancing (left) and weakening (right) meridional circulation of the C type. The positions of climatic fronts are shown by curves 1 and 2 (Arctic fronts in January and July, respectively) and 3 and 4 (Polar fronts in January and July, respectively). c) Distribution of the levels of statistical significance for the correlation coefficients.

type is characterized by stationary or slowly moving large-amplitude waves in the pressure field, the air and heat exchange between latitudes being enhanced. The specific feature of the C form of meridional circulation is a formation of a height crest over the eastern North Atlantic and a trough over the European part of Russia [Girs, 1974]. Fig.1b shows the correlation coefficients between tropospheric pressure characterized by mean yearly values of geopotential (gp) heights of the 700 hPa level (*GPH700*) according NCEP/NCAR reanalysis data [Kalnay et al., 1996] and GCR intensity characterized by mean yearly values of the neutron monitor counting rate in Climax *NM* (ftp://ftp.ngdc.noaa.gov/STP). The statistical significance levels of the correlation coefficients evaluated with the random-phase test are presented in Fig.1c.

Comparing the data in Fig.1 we can see that the polar region bounded in the lower troposphere by climatic Arctic fronts is a region of most statistically significant correlation independently of the time period and the evolution of the meridional circulation. At middle latitudes statistically significant correlations are observed only in the period of enhancing meridional circulation. The highest significance of the correlation coefficients is observed at climatic Polar fronts near the eastern coasts of North America (the North Atlantic zone of extratropical cyclogenesis), near the eastern coasts of Eurasia (the North Pacific zone of extratropical cyclogenesis) and over the Gulf of Alaska. The area of appreciable correlation is also observed over the Central and Southern Europe; it seems to be associated with Mediterranean region of intensive cyclogenesis. Thus, during the period of enhancing meridional circulation an increase of GCR fluxes is accompanied by noticeable changes in the evolution of extratropical baric systems: we can see a simultaneous intensification of mid-latitudinal cyclones at Polar fronts and near-surface anticyclones in the Arctic. In the period of weakening meridional circulation the statistically significant response of the atmosphere to GCR variations is observed only at polar latitudes. So, the region of the polar vortex formation seems to be a particular region for SA/GCR effects on the lower atmosphere circulation. This suggests also an important part of processes at high latitudes for the mechanism of solar-climatic links.

3. Time evolution of SA/GCR effects on troposphere pressure and the polar vortex intensity

Let us consider the time evolution of SA/GCR effects in the lower atmosphere circulation on a longer time scale. According to the data by Veretenenko and Ogurtsov [2012], the correlation coefficients between tropospheric pressure at high latitudes and sunspot numbers reveal a pronounced ~60-year periodicity, with the reversals of the correlation sign taking place in the end of the 19th century, the early 1920s, 1950s and the early 1980s. These reversals coincide well with the climatic regime shifts associated with a roughly 60-year variability over the North Pacific and North America [Minobe, 1997]. Gudkovich et al. [2009] detected a similar periodicity in anomalies of mean yearly sea-level temperatures at polar latitudes. According to these data, the ~60-year cycle in the Arctic manifests itself as the rotation of warm and cold epochs closely related to the polar vortex state. A warm epoch is associated with a strong vortex and a cold epoch with a weak one, and the transitions between these epochs were found in the same years as mentioned above. Thus, the reversals of the sign of SA/GCR effects coincide well with the transitions between cold and warm periods in the Arctic corresponding to the different states of the vortex.

In Fig.2 the time variations of SA/GCR effects on tropospheric pressure are compared with the vortex evolution. The pressure data were taken from MSLP archive (ftp://ftp.cru.uea.ac.uk). To calculate the characteristics of the vortex NCEP/NCAR reanalysis data were used [Kalnay et al, 1996]. Fig.2a shows the correlation coefficients $R(SLP,\ R_Z)$ between mean yearly values of sea-level pressure (*SLP)* and sunspot numbers (R_Z) for sliding 15-year intervals in the regions of formation of the vortex center over Canada-Greenland (60-85°N, 220-350°E) and the Polar frontal zone near the eastern coasts of North America (25-40°N, 280-300°E). The latest region is the North Atlantic zone of intensive cyclogenesis. The long-term variations of frequency of occurrence of the C form of meridional circulation are presented in Fig.2b. In Fig.2c we can see anomalies of the vortex strength which is characterized by the difference of zonal values of geopotential heights ΔH between the latitudes 40 and 65°N for the 500 hPa level. Anomalies of stratospheric temperatures at the level 50 hPa averaged over the region 60-90°N are shown in Fig.2d.

First of all, we can see that the correlation coefficients $R(SLP,\ R_Z)$ reveal a pronounced~60-year periodicity both in the region of the polar vortex formation and the North Atlantic zone of cyclogenesis, the correlations in these regions being always in the opposite phase. This suggests that SA/GCR effects in these regions are closely interconnected. At the same time the character of SA/GCR effects seems to be influenced by the evolution of the meridional circulation and the vortex state. It is seen that in ~1950-1980 the polar vortex was weak. It was manifested as a decrease of pressure gradients between high and middle latitudes. A weakening of the vortex resulted in the increase of heat exchange in the stratosphere and, hence, to the increase of stratospheric temperature in the vortex area. In the troposphere the intensity of the C-type meridional circulation was decreasing, and a cold epoch was observed in the Arctic [Gudkovich et al., 2009]. We can see that in the period of a weak vortex there was a positive correlation of pressure and sunspot numbers at high latitudes and a negative one in the North Atlantic zone of cyclogenesis. As GCR intensity is inversely correlated with sunspot numbers, it means that at the stage of a weak vortex both extratropical cyclones and polar anticyclones weakened with the increase of GCR fluxes at the minima of the 11-year cycles. In ~1980-2010 the vortex was strong, the pressure gradients between high and middle latitudes were enhanced and stratospheric temperatures were low. In this period the meridional circulation of the C type was intensifying, and a warm epoch in the Arctic was observed. During this period there was a negative correlation of sea-level pressure with sunspot numbers at polar latitudes (a positive one with GCR intensity) and a positive correlation in the North Atlantic cyclogenetic zone (a negative one with GCR intensity).

Thus, the data in Fig.2 suggest a ~60-year periodicity in SA/GCR effects on tropospheric pressure, as well as in the vortex development, the transitions between its different states occurring in the 1950s, 1980s and apparently near the 2010s. These transitions coincide with those between cold and warm epochs in the Arctic detected in surface temperatures [Gudkovich et al., 2009]. As Fig.2 shows, the sign reversals of SA/GCR effects coincide well with the transitions between the different states of the vortex. When the vortex is strong (~1980-2010) meridional processes in the troposphere intensify and GCR increase is accompanied by an enhancement both of cyclonic activity at middle latitudes and anticyclone formation at polar ones. When the vortex is weak (~1950-1980) the meridional circulation weakens and GCR effects change the sign. Thus, the ~60-year variation of the amplitude and sign of SA/GCR effects on troposphere pressure seem to be closely related to the vortex state and the corresponding changes in the evolution of the large-scale atmospheric circulation. It should also be stressed that at the present time the vortex seems to change its state (see Fig.2c, d), so we could expect a reversal of those correlations which were observed between dynamic processes in the lower atmosphere and SA/GCR characteristics during the last thirty years.

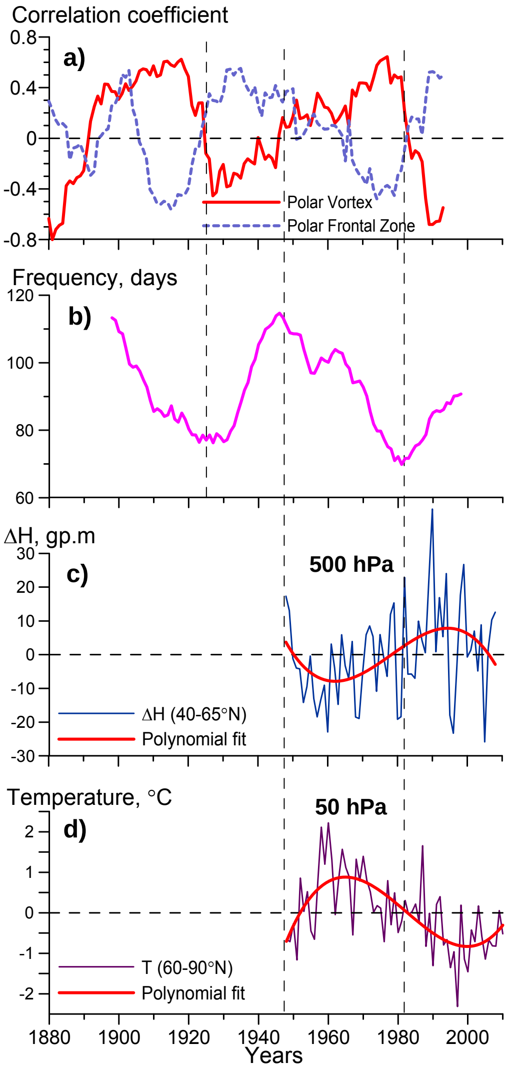

Fig.2. a) Time variations of the correlation coefficients between yearly values of troposphere pressure in the regions of the polar vortex (red line) and the North Atlantic Polar zone (blue line) and sunspot numbers for 15-year sliding intervals.

b) Annual frequencies of occurrence (a number of days during a year) of the C form of meridional circulation (15-year running averages).

c) Anomalies (deviations from the climatic mean) of yearly values of the difference of zonal gp heights ΔH between the latitudes 40 and 65°N for the 500 hPa level.

d) Anomalies (deviations from the climatic mean) of yearly values of stratospheric temperature at the 50 hPa level in the high-latitudinal region 60-90°N.

The vertical dashed lines show the moments of the correlation reversals. The thick red lines at the panels c) and d) show the 3rd order polynomial fits of the data.

A possible reason for the sign reversals of SA/GCR effects may be changes in the troposphere-stratosphere coupling caused by different conditions for propagation of planetary waves during the periods of a strong or weak vortex [Perlwitz and Graf, 2001]. As a result, the stratosphere influences the troposphere only when the vortex is strong and planetary waves are reflected back to the troposphere. When the vortex is weak only the troposphere influences the stratosphere. Thus, if GCR variations produce any effect in the stratosphere in the period of a strong vortex, this effect may be transferred to the troposphere and intensify dynamic processes in it. Intensification of the vortex seems to contribute to the increase of temperature contrasts in tropospheric frontal zones and, then, enhance extratropical cyclogenesis. So we can see noticeable changes in the development of extratropical cyclones and polar anticyclones in this period. When the vortex is weak the stratosphere does not influence the troposphere, SA/GCR effects on extratropical cyclogenesis weaken; this seems, in turn, to influence the formation of Arctic anticyclones. As the vortex strength reveals a ~60-year variation, this may explain the detected temporal variability of SA/GCR effects on tropospheric pressure.

4. Specific features of the vortex location and a possible mechanism of solar-climate links

The data presented above suggest that the polar vortex plays an important part in the mechanism of solar-atmospheric links. Indeed, its location seems to be rather favourable for different mechanisms of solar activity influence on the lower atmosphere circulation. In particular, the data in Fig.3a shows that the area of the vortex formation is characterized by low values of geomagnetic cutoff rigidity. So GCR particles with a broad energy range may precipitate in this area including the low energy component strongly modulated by solar activity and ion production rate is higher than at middle and low latitudes.

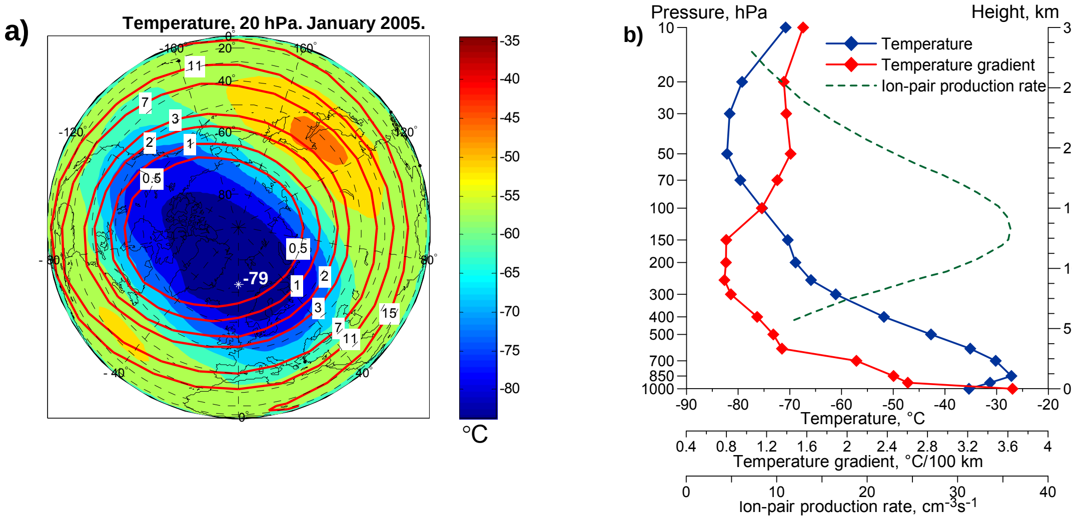

Fig.3. a) Distribution of mean monthly temperature (°C) in the stratosphere in January 2005. Red lines show vertical geomagnetic cutoff rigidities (in GV). b) Height dependences of minimum temperatures in the Arctic air mass and maximum magnitudes of temperature gradients at its edges in January 2005. The dashed line shows ion-pair production rate in free ambient air at polar latitudes [Bazilevskaya et al., 2008].

Fig.3b shows the height dependences of the characteristics of the Arctic air mass where the vortex is formed calculated for January 2005 on the base of NCEP/NCAR reanalysis data, as well as that of ion production rate caused by GCR in free air at polar latitudes. We can see that the temperature in the vortex center decreases with the increase of height and reaches its minimum at the levels 30-50 hPa (20-25 km). The temperature gradients at the vortex edges increase with height in the stratosphere starting from the level 150 hPa, their maximum being observed at the levels 50-10 hPa (20-30 km). In the troposphere temperature gradients are maximal near surface corresponding to Arctic fronts separating the Arctic air from warmer air of middle latitudes. Thus, the vortex is most pronounced at the 50-30 hPa levels where the minimum of stratospheric temperatures and the maximum of temperature gradients at its edges are observed. We can see that the highest values of ion production rate due to GCR are observed in the lower part of the vortex (10-15 km) where temperature gradients start increasing. On the other hand, the 11-year modulation of GCR fluxes is strongest at the heights 20-25 km [Bazilevskaya et al., 2008] where the vortex is most pronounced. Hence, the vortex location seems to be favorable for the mechanisms of solar activity influence on the atmosphere circulation involving GCR variations. It is also favorable for the mechanisms involving solar UV variations, as at these heights (15-25 km) in the polar stratosphere the maximum ozone content is observed.

The evolution of the vortex is known to be determined by dynamic coupling between the troposphere and stratosphere via planetary wave propagation, as well as by radiation processes in the stratosphere. So, we can suggest that the mechanism of SA/GCR influence on the troposphere circulation involves changes of the vortex strength associated with changes of the heat-radiation balance in the stratosphere. These changes may be caused by variations of atmosphere transparency in visible and infrared range associated with the effects of ionization and atmospheric electricity variations on cloudy and aerosol particle characteristics [Tinsley, 2008]. Indeed, a considerable increase of aerosol concentration at high latitudes which was most pronounced at the heights 10-12 km and accompanied by the temperature decrease in overlying stratospheric layers was detected during a series of powerful solar proton events on January 15-20, 2005 [Veretenenko et al., 2008]. In turn, the increase of the vortex strength intensifies temperature gradients at its edges (see Fig.4). At the stages of a strong vortex this increase of temperature gradients may be transferred to the troposphere via planetary waves and contribute to the increase of temperature contrasts in tropospheric frontal zones and the intensification of extratropical cyclogenesis.

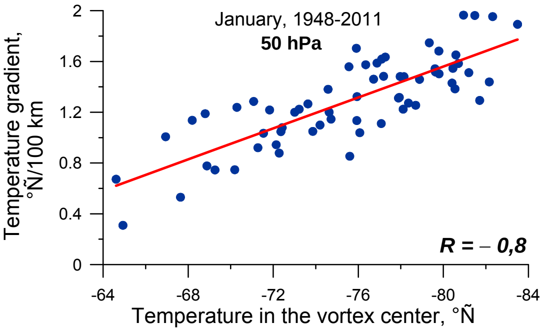

Fig.4. Maximum values of temperature gradient magnitude at the vortex edges versus minimum temperatures in the vortex center at the level 50 hPa (mean monthly values for January, 1948-2011).

5. Conclusions

The results of this study showed that the evolution of the stratospheric polar vortex plays an important part in the mechanism of solar-climatic links. The vortex strength reveals a roughly 60-year periodicity influencing the large-scale atmospheric circulation and the sign of SA/GCR effects on the development of baric systems at middle and high latitudes. The vortex location is favorable for the mechanisms of solar activity influence on the troposphere circulation involving variations of different agents (GCR intensity, UV fluxes). In the periods of a strong vortex changes of the vortex intensity associated with solar activity phenomena seem to affect temperature contrasts in tropospheric frontal zones and the development of extratropical cyclogenesis.

Acknowledgments

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