Long-term variations of the solar activity–lower atmosphere relationship

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Abstract. Long-term variations of the air temperature in St. Petersburg ($\varphi = 60°$N), Stockholm ($\varphi = 59°$N), English Midlands ($\varphi \sim 50°$N) and Salzburg ($\varphi = 48°$N) are considered. It is shown that in the regions under consideration the air temperature distinctly depends on the intensity of the lower atmosphere zonal circulation (North Atlantic Oscillation (NAO) index). In turn, the NAO index is shown to depend on the solar activity. However, this dependence is rather complicated and exhibits long-period variations. A possible mechanism of this phenomenon is discussed.

1. Introduction

The idea on the existence of a close relationship of solar activity with the state of the lower atmosphere, though being under discussion, is accepted by many geophysicists. During the last 30 years, numerous evidences were obtained in favor of that hypothesis [*Bauer,* 1982; *Brown and John,* 1979; *Bucha and Bucha,* 1998; *Donarummo et al.,* 2002; *Hoyt and Schatten,* 1997; *Hurrell,* 1996; *Kelley,* 1977; *Kondratyev and Nikolsky,* 1983; *Ram and Stolz,* 1999; *Schuurmans and Oort* 1969; *Svensmark and Friis-Christensen,* 1997; *Tinsley and Deen,* 1991; *Tinsley and Heelis,* 1993; *Tinsley et al.,* 1989; *Veretenenko and Pudovkin,* 1995, 1997, 1999].

Physical mechanism of this relationship was proposed by *Tinsley et al.* [1989]. According to their hypothesis, the connection between the solar activity and the state of the lower atmosphere is realized by means of cosmic rays, the flux of which is modulated by the varying magnetic field of the solar wind. In turn, variations of the cosmic ray intensity cause changes in the state of cloudiness and trigger some internal atmospheric processes associated with the release of the energy accumulated in some form, e.g., as the latent heat of water vapours.

On the other hand, the mechanism proposed by M. I. Pudovkin and colleagues supposes that variations of the cosmic ray flux and, possibly, of the solar Roentgen and UV radiation cause changes of the atmospheric transmittance and the state of cloudiness. As a result, the direct solar radiation input into the lower atmosphere also exhibits significant variations. During Forbush-decreases of Galactic Cosmic Rays (GCR) the solar energy input increases, and the lower atmosphere at high latitudes is heated, and during Solar Proton Events (SPE) the atmospheric transmittance decreases, and the lower atmosphere temperature decreases also [*Pudovkin et al.,* 1995a, 1995b].
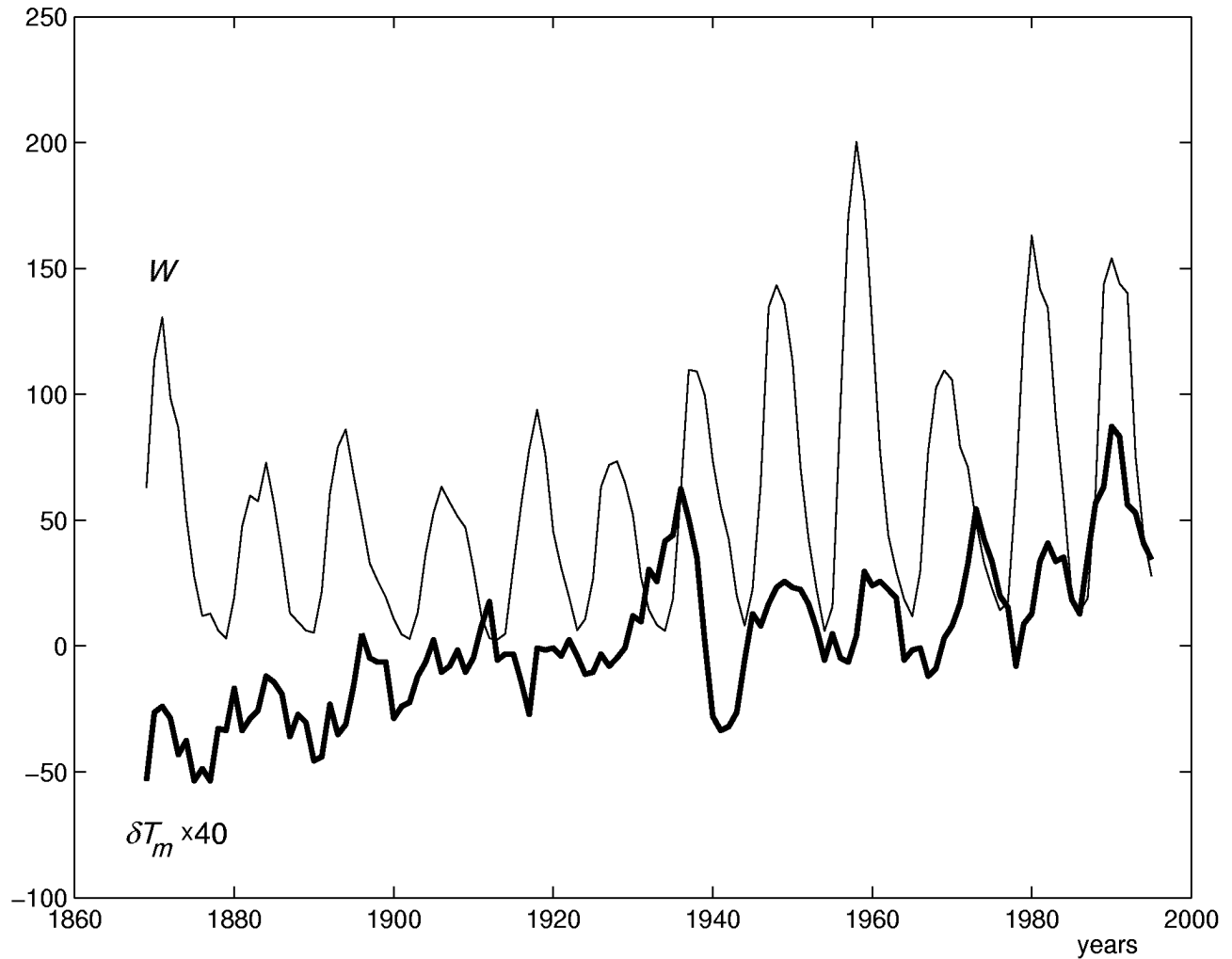
Figure 1. Variations of the annual Wolf numbers (W) and of the running mean (for 5 years) air temperatures (δT_m) in St. Petersburg for 1867–1995. The δT_m value are multiplied by factor 40.

However, distinct variations of the cosmic ray flux intensity are observed not only during short-term solar wind disturbances but also in the course of solar cycles. Thus, one may expect existence of corresponding long-term variations of cloudiness, atmosphere transmittance, air temperature, and, as a result, of the dynamics of the lower atmosphere [*Pudovkin and Babushkina*, 1992b; *Pudovkin and Morozova*, 1997].

In this paper, we consider long-term variations of the lower atmosphere parameters and their possible connection to the solar activity. Special attention is paid to the search of physical agents responsible for that connection.

2. Data Analysis

For the analysis, data are used on the air temperature in St. Petersburg ($\varphi = 60°$N, $\lambda = 30°$E), Stockholm ($\varphi = 59°$N, $\lambda = 18°$E), English Midlands ($\varphi = 50°$N, $\lambda = 2°$W) (ftp://ftp.cru.uea.ac.uk/people/mikehulme/outgoing/misce-

llaneous/cet.dat), and Salzburg ($\varphi = 48°$N, $\lambda = 13°$E) (Jahrbücher der ZAMG, 1867–2000) for the last two centuries, solar activity indices (Wolf numbers), and North Atlantic Oscillation indices (http://www.cgd.ucar.edu/cas/climind/nao_monthly.html).

In Figure 1, variations of the solar activity (W numbers) and of the running mean (averaged for 5 years) of the deviation δT_m of the yearly temperatures from the mean values of the latter in St. Petersburg are presented for the period 1869–1995. It is seen in Figure 1 that in spite of that the character of the temperature oscillation varies with time, the 11-year cycles are distinctly seen all over the period under consideration, and the coefficient of correlation between W and δT_m for the entire period equals $r(\delta T_m, W) = 0.3$ at the significance level 0.98 [see *Panofsky and Brier,* 1958]. At the same time, one can see that for some years the correlation between δT_m and W indices disappears or even changes sign, which agrees with earlier results by *Koppen* [1914]. This allows one to suppose that variations of δT_m are influenced by the solar activity not directly but by means of some mediatorial factors, e.g., such as circulation of the lower atmo-
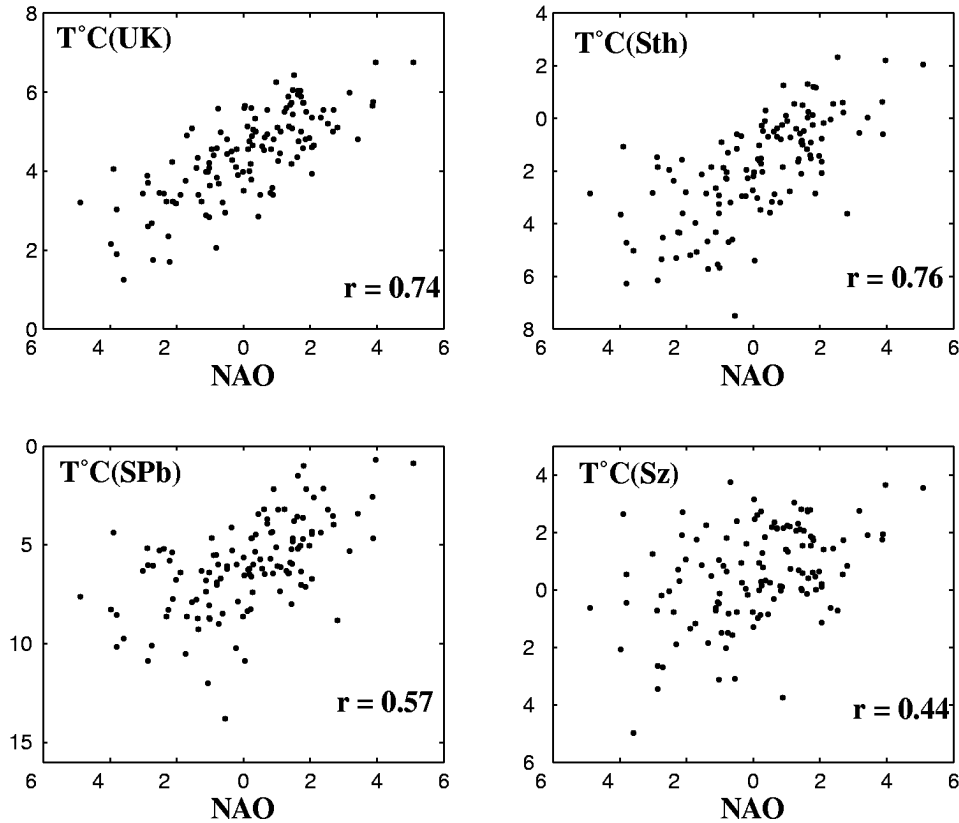
Figure 2. The wintertime temperature variations in the English Midlands (UK), Stockholm (Sth), St. Petersburg (SPb) and Salzburg (Sz) in dependence on North Atlantic Oscillation index (NAO).

sphere and associated transport of air masses and clouds. In the further analysis, we investigate the relationship of the temperature variations with the lower atmosphere dynamics characterized by the North Atlantic Oscillations (NAO) indices, which are known to effectively influence the weather in Europe [*Bucha and Bucha,* 1998; *Hurrel,* 1995].

Pudovkin and Lyubchich [1989] showed that influence of heliospheric factors on the state of the lower atmosphere is more pronounced in winter months. In this connection in Figure 2 the values of the winter air temperature in all the regions under consideration for 125 years are presented dependent on the NAO indices. One can see that there exists a strong relationship of NAO with the temperature in England and Stockholm ($r = 0.75$). In St. Petersburg, the coefficient of correlation of NAO indices and air temperature values is smaller ($r = 0.57$). This allows one to suppose that in spite of St. Petersburg being rather close to Stockholm, the nearby Arctic Ocean influences the weather in St. Petersburg more noticeably than the weather of Stockholm.

The connection between NAO indices and the ground level air temperature in Salzburg (Austria) is less clear ($r = 0.44$), though it still exists.

Thus, the air temperature, at least in northwestern Europe, really is closely associated with variations of NAO indices. However, what is the cause of the NAO indice variations?

To clear up this question, Figure 3 presents variations of

NAO indices (yearly ones and averaged for 5 year intervals) for winter months of 1867–1997 years along with variations of Wolf numbers. As is seen in Figure 3, the relationship between the NAO and solar activity variations is rather complicated or may be absent on the whole. Actually, the coefficient of correlation between NAO and W indices for the entire period under investigation equals 0.06 and is statistically insignificant.

The relationship between variations of NAO and W indices is presented in Figure 4 in a more detail in which there is given the running coefficient of correlation $r(NAO, W)$ between annual values of NAO (data for only winter months are used) and W, calculated for moving 11-year interval. Being calculated for a relatively small amount of correlated pairs, the obtained values of the correlation coefficient are statistically insignificant and may be consider rather as an indicator of NAO and W variations proceeding in phase or in antiphase. In this connection, there is presented in Figure 4 the running coefficient of correlation between daily values of NAO and W indices for 1948–2002 years (when the corresponding data are available) calculated for the moving interval of 1001 points (also for winter months). In this case the probability of null hypothesis is less than 0.01 when the correlation coefficient is greater than 0.08 [*Panofsky and Brier,* 1958]. Thus, the obtained coefficient of correlation $r(1001)$, though being small, is statistically significant. At the same time, the shape of the $r(1001)$ curve is rather close to that of
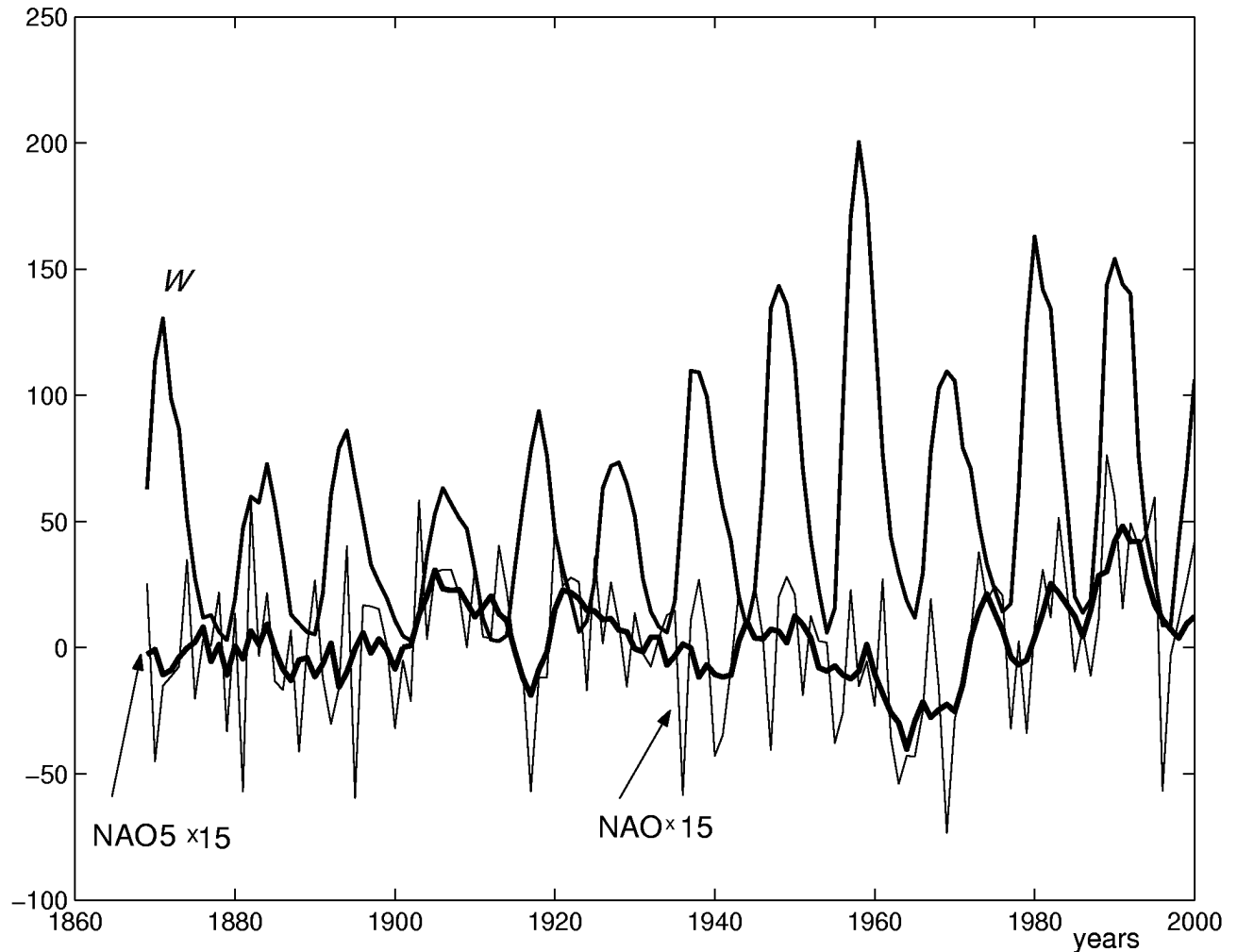
Figure 3. Variations of the Wolf numbers (W), yearly NAO indices (NAO) multiplied by factor 15, and of the running mean (for 5 points) values of NAO (NAO(5)), also multiplied by 15.

$r(11)$, which allows one to consider the latter as sufficiently representative.

Returning to Figure 4, a relatively regular change of the sign of the correlation coefficient $r(\text{NAO}, W)$ for the period 1870–1940 attracts our attention: it is positive during even solar cycles and negative during odd cycles; in the period 1940–2000 this regularity disappears. This allows one to suppose that the observed relationship between variations of the dynamics of the lower atmosphere and the solar activity is occasional and has no physical ground, while the change of the sign of r is explained by the gradually increasing shift of phase between independent NAO and W oscillations. To clear up, at least partially, this question, we consider short-time variations of solar activity and NAO indices with the purpose to find out whether the regularity peculiar for the long-term variations is preserved during individual events. In this connection, Figure 5a (bottom) presents the NAO variation (obtained by the superposed epoch method) around a local maximum of daily W numbers on 1972–1974 years (Figure 5a, top) when the NAO–W

correlation for long-term variations is negative; the key day corresponds to the day of local (in time) maxima of daily Wolf numbers (see Figure 5a, top). One can see that in this case the short-term increase of the solar activity is followed as in the case of long-term variations by the decrease of NAO indices.

Figure 5b (bottom) shows variation of NAO indices for winter months of 1955–1957 years when the correlation between long-term variations of NAO and W is positive (see Figure 4). As is seen in Figure 5b, short-term increases of the solar activity on the years under consideration are associated, as in the case of long-term variations, with the increase of NAO indices.

Thus, the correlation between the long-term variations of NAO and W indices has the same sign as that for short-term variations of them on the same years. Correspondingly, the change of that sign cannot be explained by the phase shift of long-term variation and rather has some physical reasons, such as the state of the background lower atmosphere, or the characteristics of the solar radiation. In this connection, it is
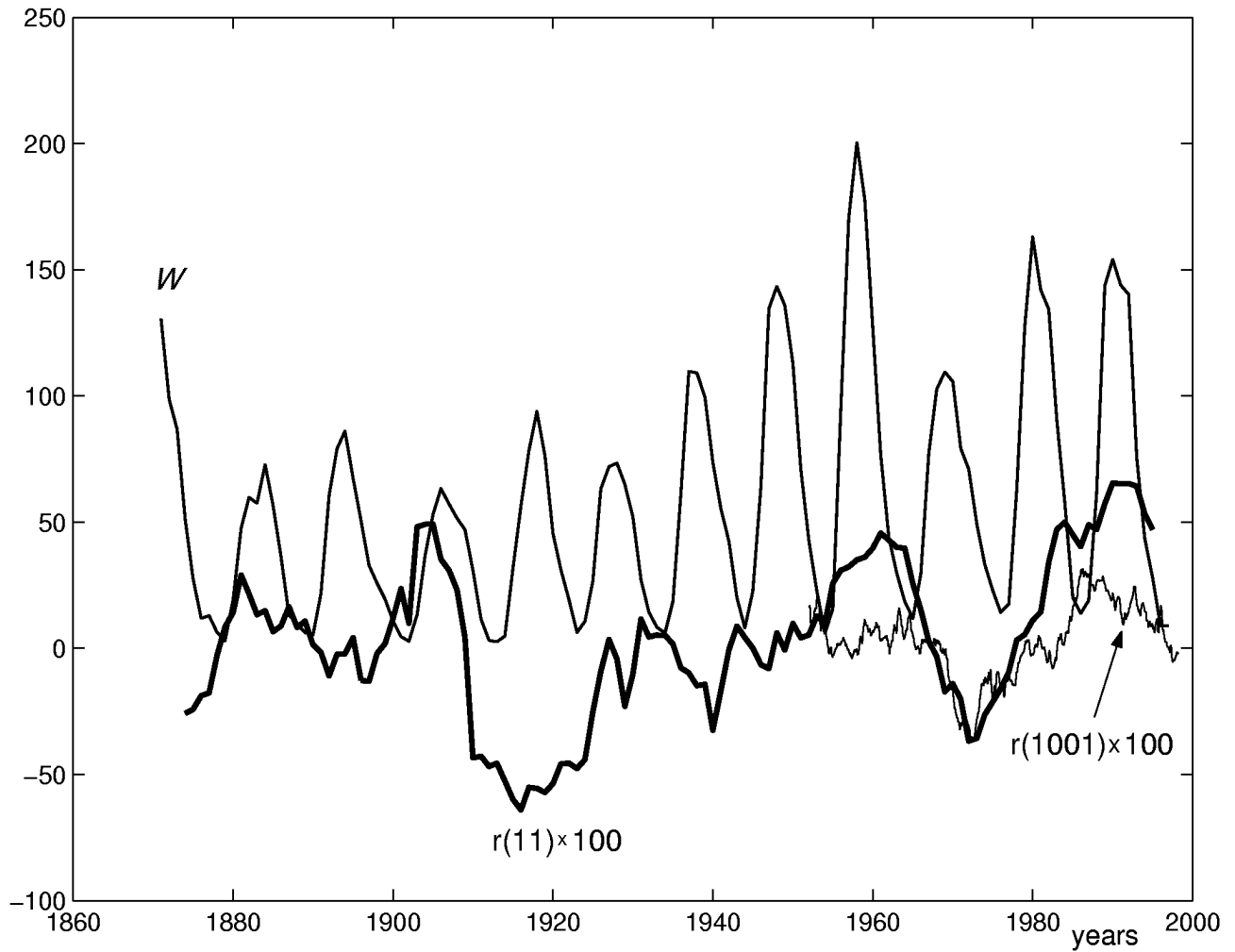
Figure 4. The Wolf numbers and the running mean values (for 11 year interval) of the coefficient of correlation between NAO and Wolf numbers. The thin solid line shows the running coefficient of correlations between daily values of NAO and W indices calculated for moving interval for 1001 points.

worth remembering that the value of NAO is defined as the difference of normalized sea level pressure between Azores ($\varphi = 40°$N) and Iceland ($\varphi = 65°$) and hence is determined by the state of the lower atmosphere in two significantly spaced Earth regions which may be influenced by different components of the solar radiation.

Pudovkin and Babushkina [1992a] and *Veretenenko and Pudovkin* [1995] show that short-term variations of cosmic rays (such as Forbush decreases (FD) and solar proton events (SPE)) are associated with characteristic changes of the cloudiness state and atmosphere transmittance. Then one may expect the cyclic variations of the cosmic ray flux intensity to be also associated with corresponding variations of the atmosphere transmittance in the regions under consideration. In this connection, Figure 6a [after *Pudovkin and Veretenenko*, 1999] gives variations of normalized half-year

(October–March) values of the total solar radiation δQ (including both the direct and scattered radiation) in the latitudinal belts $\varphi = 65° - 68°$ and $\varphi = 50°$ for 1962–1983 years with the linear trends being subtracted, and the half-year data are smoothed by two points. As is seen in Figure 6a, the values of δQ really exhibit distinct long-term variations in the both latitudinal belts. Returning to Figure 4, one can see that the period under investigation (1960–1985) corresponds to the interval of a greatly complicated behavior of the coefficient of correlation between NAO and W indices with twofold change of the sign of $r(\text{NAO}, W)$. It is more interesting to see whether the variations of the solar energy input at the two latitudinal belts really may explain the observed variation of NAO indices.

Figure 6b shows variations of observed values of NAO by a thin solid line (smoothed by 3 points with the linear trend
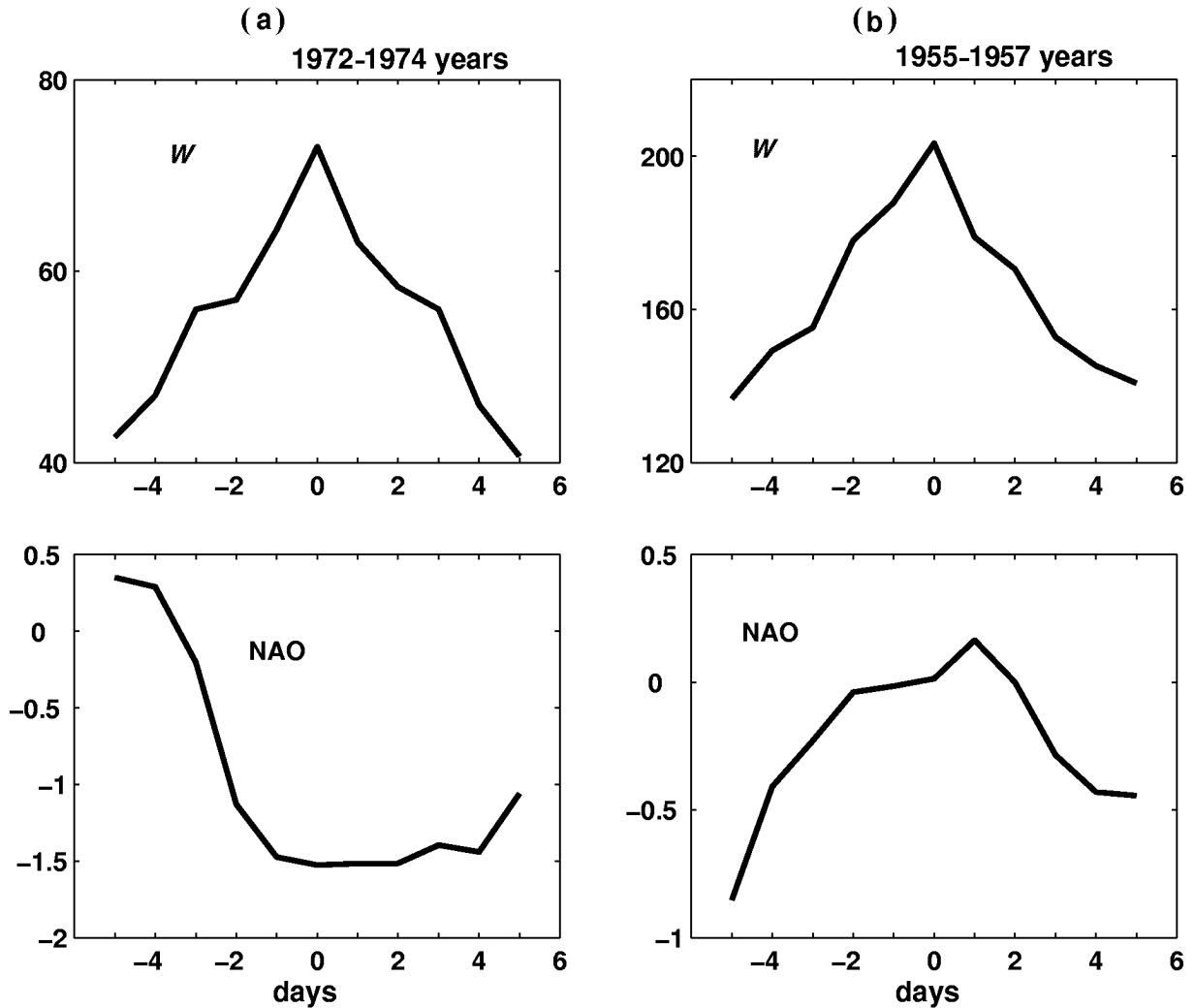
(a)
1972-1974 years

(b)
1955-1957 years

Figure 5. Variations of daily NAO and W indices around local maxima of the Wolf numbers obtained by the superposed epoch method for (a) 1972–1974 and (b) 1955–1957 years.

being excluded) and those calculated with the use of the empirical formula

$$\text{NAO}_{\text{cal}} = -2.6 - 0.2 \times \delta Q_{65} - 0.4 \times \delta Q_{50}$$

obtained from the multiple regression of data presented in Figures 3 and 6a. The curves given in Figure 6b illustrate a rather close agreement between the observed and calculated values of NAO: the coefficient of calculation between them equals 0.57 at the significance level 0.95. Thus, the variations of the NAO indices really are influenced by the variation

of the solar energy input to the lower atmosphere at the boundaries of the latitudinal belt under study.

Naturally, there arises a question on the cause of the observed variations of the atmosphere's transmittance. To answer this question, in Table 1 we represent a fragment of a related table from *Pudovkin and Veretenenko* [1999].

Table 1 presents the coefficients of partial correlation of values of δQ_{65} and δQ_{50} with the variation of the cosmic ray flux (Climax neutron monitor data), of the geomagnetic AE index and of the Kleczek flare index I_{fl} (*Solar Geophysical*

Table 1. Partial Correlation Coefficients Between δQ and Various Cosmophysical Factors

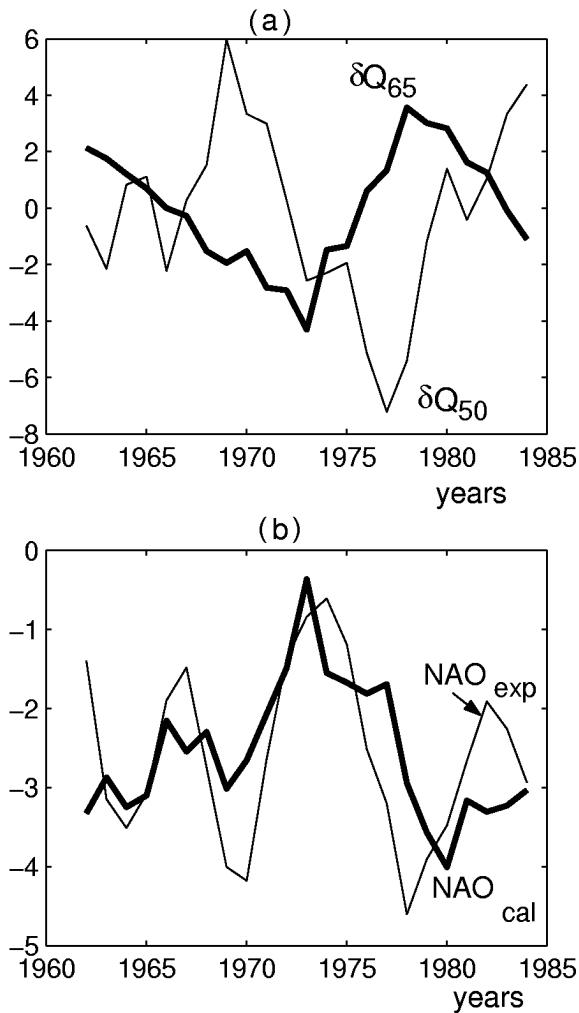| Latitude	Cosmic Rays	AE	I_{fl}	Multiple Correlation Coefficient
$65°$–$68°$	-0.62 (99%)	$-0.27(-)$	-0.5 (95%)	$0.62(95\%)$
$50°$	$0.37(-)$	$-0.33(-)$	0.62 (99%)	$0.67(98\%)$

Figure 6. (a) Variations of the declination of the solar energy input from the long-term trends at high (δQ_{65}) and low (δQ_{50}) latitudes and (b) those of the observed (NAOexp) and calculated (NAO$_{cal}$) values of NAO indices.

Data, 1997); the values in parentheses show the significance level of the obtained coefficients of correlation.

Data presented in Table 1 show that variations of the solar energy input into the lower atmosphere at the both latitudinal belts are determined mainly by variations of two cosmophysical factors: of the cosmic ray intensity and of the solar flare index. However, influence of those factors is different at different latitudes: at high latitudes, the atmosphere transmittance is determined mainly by the cosmic ray flux intensity variations, while at lower latitudes, by solar flares. The latters may characterize intensity of the solar Roentgen and UV radiation responsible for the ozone content variation and hence for the atmosphere transparency at low latitudes [*Haigh,* 1996]. Thus, the observed apparently irregular variations of NAO indices really may be explained by non synchronous variations of the cosmic ray flux intensity, solar wave and corpuscular radiation.

3. Conclusions

Data presented above and their analysis allow us to arrive at the following conclusions.

1. The ground level air temperature in northwestern Europe in winter months is closely associated with North Atlantic Oscillations (NAO) index. In central Europe (Austria) the influence of the NAO index variations on the state of the lower atmosphere is less pronounced.

2. Variations of the NAO indices are determined by the variations of the solar energy input into the lower atmosphere at the edges of the latitudinal belt under consideration: the coefficient of the multiple regression between values of NAO, δQ_{65} and δQ_{50} equals $r = 0.57$ at the significance level 0.95.

3. In turn, the solar energy input into the lower atmosphere is determined by the combined effect of variations of the cosmic ray flux intensity and of the solar flare index. These two cosmophysical agents influence the transmittance of the atmosphere at different latitudes in a different way, which may explain the observed behavior of NAO indices (and, consequently, of the air temperature) in the course of solar cycles.

This allows us to suppose that the observed relationship of the air temperature and NAO indices with the solar activity is not occasional and has some physical grounds.

References

Bauer, S. J., Zum Problem Sonnenaktivität — Wetter und Klima, *Wetter Leben, 34,* 221, 1982.

Brown, G. M., and J. I. John, Solar cycle influences in tropospheric circulation, *J. Atmos. Terr. Phys., 41,* 43, 1979.

Bucha, V., and V. Bucha, Geomagnetic forcing of changes in climate and in the atmospheric circulation, *J. Atmos. Sol. Terr. Phys., 60,* 145, 1998.

Donarummo, J., M. Ram, and M. R. Stolz, Sun/dust correlations and volcanic interference, *Geophys. Res. Lett., 29*(9) 1361, 2002.

Haigh, J. D., The impact of solar variability on climate, *Science, 272,* 981, 1996.

Hoyt, D. V., and K. H. Schatten, *The Role of the Sun in Climate Change,* 279 pp., Oxford Univ. Press, New York, 1997.

Hurrell, J. W., Decadal trends in the North Atlantic Oscillations — Regional temperatures and precipitations, *Science, 269,* 676, 1995.

Hurrell, J. W., Influence of variations in extratropical wintertime teleconnections on northern hemisphere temperature, *Geophys. Res. Lett., 23,* 665, 1996.

Kelley, P. M., Solar influence on North Atlantic mean sea level pressure, *Nature, 269*, 320, 1977.

Kondratyev, K. Ya., and G. A. Nikolsky, The solar constant and climate, *Sol. Phys., 89*, 215, 1983.

Koppen, W., Lufttemperaturen, Sonnerflecke and Vulkanausbruche, *Meteorol. Zeitung, 31*, 305, 1914.

Panofsky, H. A., and G. W. Brier, *Some Applications of Statistics to Meteorology*, The Pennsilvania State University, University Park, P., 1958.

Pudovkin, M. I., and S. V. Babushkina, Atmospheric transparency variations associated with geomagnetic disturbances, *J. Atmos. Terr. Phys., 54* (9), 1135, 1992a.

Pudovkin, M. I., and S. V. Babushkina, Influence of solar flares and disturbances of the interplanetary medium on the atmospheric circulation *J. Atm. Terr. Phys., 54*, 841, 1992b.

Pudovkin, M. I., and A. A. Lyubchich, Manifestation of solar and magnetic activity cycles in air temperature variations in Leningrad, *Geomagn. Aeron. (in Russian), 29*, 359, 1989.

Pudovkin, M. I., and A. L. Morozova, Time evolution of the temperature altitudinal profile in the lower atmosphere during solar proton events, *J. Atmos. Sol. Terr. Phys., 59*, 2159, 1997.

Pudovkin, M. I., and S. V. Veretenenko, Helio-magnetospheric disturbances and the state of the lower atmosphere, in *Problems of Geospace 2 (Proceeding of 2nd International Workshop, St. Petersburg, Russia, June 29–July 3, 1998)*, edited by V. S. Semenov et al., pp. 21–37, Verlag der Osterreichischen Akad. der Wiss., Wien, 1999.

Pudovkin, M. I., S. V. Veretenenko, R. Pellinen, and E. Kyro, Cosmic ray variation effects in the temperature of the high-latitudinal atmosphere, *Adv. Space Res., 17*, 165, 1995a.

Pudovkin, M. I., S. V. Veretenenko, R. Pellinen, and E. Kyro, Influence of solar cosmic ray bursts on the temperature of the high-latitudinal atmosphere, *J. Tech. Phys., 36*, 433, 1995b.

Ram, M., and M. R. Stolz, Possible solar influences on the dust profile of the GISP2 ice corn from Central Greenland, *Geophys. Res. Lett., 26*, 1043, 1999.

Schuurmans, C. J. E., and A. H. Oort, A statistical study of pressure changes in the troposphere and lower stratosphere after strong solar flares, *Pure Appl. Geophys., 75*, 233, 1969.

Svensmark, H., and E. Friis-Christensen, Variation of cosmic ray flux and global cloud coverage—a missing link in solar-climate relationships, *J. Atmos. Sol. Terr. Phys., 59*, 1225, 1997.

Tinsley, B. A., and C. W. Deen, Apparent tropospheric response to MeV–GeV particle flux variations: a connection via electrofreezing of supercooled water, *J. Geophys. Res., 96*, 22,283, 1991.

Tinsley, B. A., and R. A. Heelis, Correlations of atmospheric dynamics with solar activity: evidence for a connection via the solar wind, atmospheric electricity, and cloud microphysics, *J. Geophys. Res., 98*, 10,375, 1993.

Tinsley, B. A., G. M. Brown, and P. H. Scherrer, Solar variability influences on weather and climate: possible connection through cosmic ray fluxes and storm intensification, *J. Geophys. Res., 94*, 14,783, 1989.

Veretenenko, S. V., and M. I. Pudovkin, Effects of the galactic cosmic ray variations on the cloudiness state, *J. Techn. Phys., 36*, 363, 1995.

Veretenenko, S. V., and M. I. Pudovkin, Effects of the galactic cosmic ray variations on the solar radiation input in the lower atmosphere, *J. Atmos. Sol. Terr. Phys., 59*, 1739, 1997.

Veretenenko S. V., and M. I. Pudovkin, Variations of solar radiation input to the lower atmosphere associated with different helio/geophysical factors, *J. Atmos. Sol. Terr. Phys., 61*, 521, 1999.

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