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IONOSPHERIC ELECTRIC POTENTIAL AS AN ALTERNATIVE INDICATOR OF SOLAR EFFECT ON THE LOWER ATMOSPHERE

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Abstract. We have explored the possibility of applying the ionospheric electric potential (EP) as a parameter describing the effects of solar activity on the troposphere. We calculated EP, using the semi-empirical model, where the potential spatial distribution is determined by solar wind, interplanetary magnetic field parameters, and the geomagnetic activity index *AL*. We have carried out a comparative analysis of EP and the commonly used geomagnetic activity indices in a high-latitude region for 1975–2019. It has been shown that EP can be used as an indicator of solar activity since it describes both short-period disturbances and long-term variations. The revealed similar trends in long-term EP and near-surface temperature variations suggest that the changes in climate system parameters are induced by slower changes in the Sun's large-scale magnetic field. The performed analysis of EP and near-surface temperature correlation maps has revealed that the atmospheric static stability conditions have an effect on spatial distribution of tropospheric response to solar impact.

Keywords: electric potential, solar activity, geomagnetic index, atmosphere, near-surface temperature.

INTRODUCTION

The climate system is affected by processes occurring on the Sun and in near-Earth space. Currently, there are various indices characterizing solar activity and its effect on Earth. Geomagnetic activity indices (*aa*, K_p, H_{po}, *AE*, *PC*, *Dst*, etc.) are widely used in current studies of solar-tropospheric relations for several reasons: 1) they characterize the solar impact reaching Earth and detected by a magnetic station; 2) the geomagnetic indices are represented by long series. However, these indices describe primarily short-period geomagnetic disturbances, partially taking into account geomagnetic variations over more than three hours [Gavrilov et al., 2016]. In addition, the globality of the geomagnetic indices is another disadvantage in studying solar-tropospheric relations since the tropospheric response to the solar effect is heterogeneous in space.

Electromagnetic coupling between components of the magnetosphere–ionosphere–troposphere system is one of the possible mechanisms of the solar effect on the lower atmosphere [Kniveton et al., 2008; Harrison, Lockwood, 2020]. Within the framework of the physical mechanism studied at ISTP SB RAS, we anticipate that solar activity variations through changes in solar wind and interplanetary magnetic field parameters affect magnetospheric convection, which, in turn, has an effect on the distribution of electric potential (EP) difference between the ionosphere and Earth's surface. An EP increase leads to a restructuring of the vertical profile of the volume electric charge, which influences the state of water vapor (the number of dimers and larger clusters increases); as a result, optical properties of water vapor change in the infrared spectrum. Thus, an increase in the greenhouse properties of the atmosphere will alter the radiation balance of the climate system [Molodykh et al., 2020]. The ionospheric electric potential is of prime importance in the above mechanism. The purpose of this work is to explore the possibility of using EP as a parameter characterizing the solar activity effect on the lower atmosphere.

1. DATA AND ANALYSIS METHOD

Empirical models can determine EP induced by the interaction between the solar wind and the magnetosphere–ionosphere system. We have calculated the spatial distribution of EP, using a semi-empirical model, in which the EP distribution is defined by variations in solar wind and interplanetary magnetic field parameters, and by the geomagnetic activity index *AL* [Weimer, 2001]. We have averaged EP for a latitude region above 60° N and have conducted a comparative analysis of EP and commonly used geomagnetic activity indices. Interplanetary medium data and geomagnetic indices with hourly resolution for the period from 1975 to 2019 have been taken from the OMNI database [https://omniweb.gsfc.nasa.gov/html/ow_data.html]. It stands to mention a new geomagnetic activity index H_{po} [Yamazaki et al., 2022]. H_{po} is an open-ended index, unlike K_p that is limited to 9o. The frequency distribution of H_{po} in the high-frequency spectrum is similar to the distribution of K_p, hence H_{po} can be employed as an alternative to K_p with a higher time resolution: 30-min (H_{p30}) and 60-mine (H_{p60}) indices [https://www.gfz-potsdam.de/en/hpo-index].

2. RESULTS AND DISCUSSION

2.1. Short-period EP variations

Magnetic storms are caused by the constant influence of solar wind and interplanetary magnetic field variations on Earth's magnetosphere. Geomagnetic storms are traditionally divided into storms with sudden and gradual commencements. According to [Obridko et al., 2013], the difference between magnetic storms is dictated by different sources on the Sun: storms with sudden commencement are caused by coronal mass ejections; storms with gradual commencement, by high-speed solar wind streams from coronal holes. We have therefore analyzed the relationship of EP variations with geomagnetic indices for magnetic storms of these types occurring in solar activity cycles 21–24 (see Table). Information on the geomagnetic storms has been obtained from the magnetic storm catalog presented on the IZMIRAN website [https://www.izmiran.ru/magnetism/magobs/MagneticStormCatalog.html].

Correlation coefficients between EP variations and geomagnetic indices during geomagnetic storms. Magnetic storm intensity — 4

Date	$R_{EP/Dst}$	$R_{EP/Hp60(Kp)}$	$R_{EP/AE}$	$R_{EP/PC}$
Geomagnetic storms with sudden commencement				
April 11, 1981	–0.32±0.07	0.28±0.07	0.27±0.07	0.54±0.05
April 06, 2000	–0.30±0.07	0.52(0.51)±0.06	0.53±0.06	0.81±0.03
November 20, 2003	–0.74±0.03	0.67(0.68)±0.04	0.59±0.05	0.70±0.04
November 07, 2004	–0.41±0.06	0.48(0.47)±0.06	0.38±0.07	0.58±0.05
March 17, 2015	–0.55±0.05	0.46(0.45)±0.06	0.46±0.06	0.60±0.05
Geomagnetic storms with gradual commencement				
July 13, 1982	–0.08±0.08	–0.01±0.08	0.15±0.08	0.03±0.08
April 07, 1995	–0.21±0.07	0.27(0.23)±0.07	0.31±0.07	0.40±0.06
July 15, 2000	–0.05±0.08	0.30(0.24)±0.07	0.43±0.06	0.32±0.07
August 24, 2005	0.17±0.07	0.05(0.01)±0.08	0.08±0.08	0.01±0.08

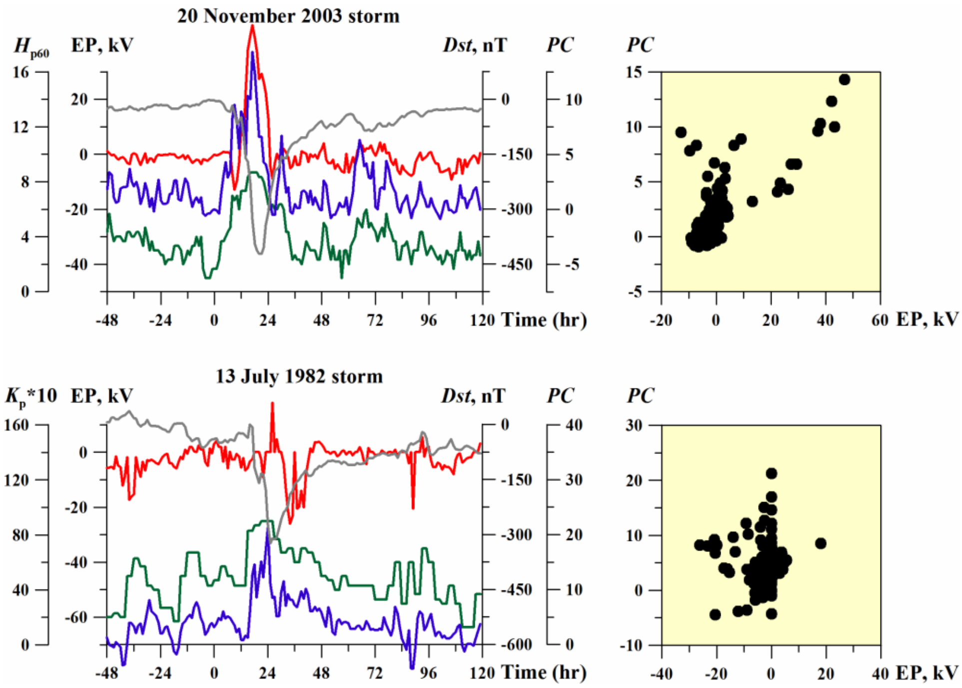

Figure 1. Variations in EP (red line) and geomagnetic indices for a 7-day interval during strong geomagnetic storms: gray line — *Dst*; green line — H_{p60}, K_p×10; blue line — *PC*. Zero on the horizontal axis is the onset of a geomagnetic storm (left); scatter plots of hourly EP and *PC* (right)

Figure 1 exemplifies variations in EP and geomagnetic indices for geomagnetic storms with sudden (November 20, 2003) and gradual (July 13, 1982) commencements. Analysis of individual geomagnetic disturbances has shown that EP variations correlate well with geomagnetic indices during magnetic storms with sudden commencement. The correlation between EP variations and geomagnetic indices lowers during magnetic storms with gradual commencement,possibly because variations in the solar wind, interplanetary magnetic field, and hence in EP reflect both sporadic processes on the Sun and variations in large-scale solar magnetic fields. Thus, EP describes short-period disturbances associated with both coronal mass ejections and high-speed solar wind streams from coronal holes, unlike geomagnetic indices, which describe the degree of geomagnetic disturbance.

2.2. Long-term EP variations

Climate conditions in recent decades are characterized by an increase in the rate of near-surface warming, especially in the Arctic and Subarctic regions. To assess future climate changes, it is necessary to adequately model processes in different atmospheric layers, including the upper layers and taking into account their interaction with processes in the lower atmospheric layers [Mokhov, 2020]. Developing an algorithm for the parametric effect of solar activity on the troposphere requires determining the optimal characteristic of the solar effect on the lower atmosphere.

The behavior of long-term variations in EP and geomagnetic activity indices is illustrated in Figure 2, which shows variations in EP, K_p, *PC* over the period from 1975 to 2019. The trend in increasing EP has been observed for the last three solar cycles. The opposite trend is typical of the geomagnetic indices. The detected asynchrony of the characteristics under study may be related to peculiarities of the development of solar activity cycles (22–24), which indicate a change in the magnetic field generation mode in the solar convection zone [Ishkov, 2010]. The annual average temperature, averaged for a latitudinal region above 60° N, at σ=0.995 hPa from the NCEP/NCAR reanalysis is given as a characteristic of the climate system [Kalnay et al., 1996; https://www.esrl.noaa.gov/psd].

Comparative analysis of Figure 2 shows the trend of synchronous variations in EP and near-surface temperature. We can therefore assume that the Sun's large-scale magnetic field has a greater impact on long-term temperature variations than the small-scale one.

2.3. Spatial distribution of EP

The tropospheric response to the solar effect is known to have a nonuniform space-time structure [Veretenenko, Ogurtsov, 2012]. We therefore assume that the presence of spatial distribution of EP — the solar effect characteristic — provides an unambiguous tropospheric response. Due to the fact that the EP model used in the work can calculate its spatial distribution, we have drawn maps of the correlation between EP and near-surface temperature variations for the period from 1975 to 2019 (Figure 3, *a*). As expected, a positive relationship prevails between them, i.e. we have obtained an unambiguous temperature response to the solar effect. The differences observed in the Arctic sector (negative correlation) might be determined by peculiarities of the troposphere in the region. Vertical temperature stratification of the atmosphere characterizes the static stability of the troposphere whose variations are associated with the conditions of occurrence and development of convection, cloud formation, and vortex activity. Spatial distribution of sensitivity of the vertical temperature gradient γ to near-surface temperature variations is illustrated in Figure 3, *b*. The parameter $d\gamma/dT$, characterizing the sensitivity of γ to the near-surface temperature, was calculated from the annual average data for the period from 1975 to 2019. The obtained positive correlation of γ with the near-surface temperature indicates a positive climatic feedback in the interannual variability. This feature agrees with the results received by Akperov et al. [2019], which suggest that the static stability of the troposphere of the Arctic latitudes in the Northern Hemisphere generally decreases with global warming. The greatest increase in the sensitivity of γ to near-surface temperature variations occurs in the Arctic region in which a negative correlation between EP and near-surface temperature variations is observed.

CONCLUSIONS

Analysis of the possibility of using the ionospheric electric potential (EP) as a characteristic of the solar effect on the lower atmosphere allowed us to draw the following conclusions:

1. EP can be used as an indicator of solar activity since it describes both short-period disturbances with a characteristic time of less than three hours, and long-term variations.

2. The synchronicity of long-term EP and near-surface temperature variations confirms that changes in climate system parameters may be associated with slower changes in the large-scale magnetic field of the Sun.

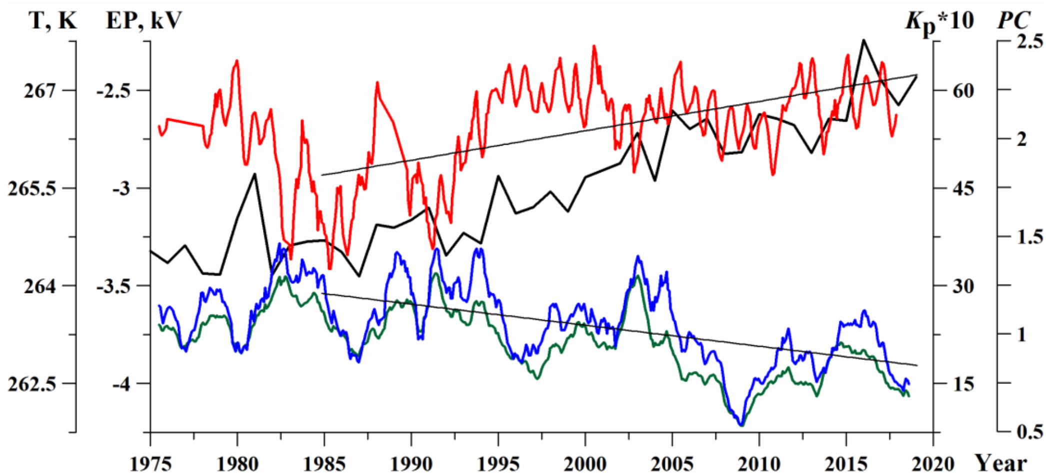

Figure 2. Monthly average values of EP (red line) and geomagnetic indices: $K_p\times10$ (green line); *PC* (blue line), smoothed by 12 points, and annual average near-surface temperature (black line) from 1975 to 2019

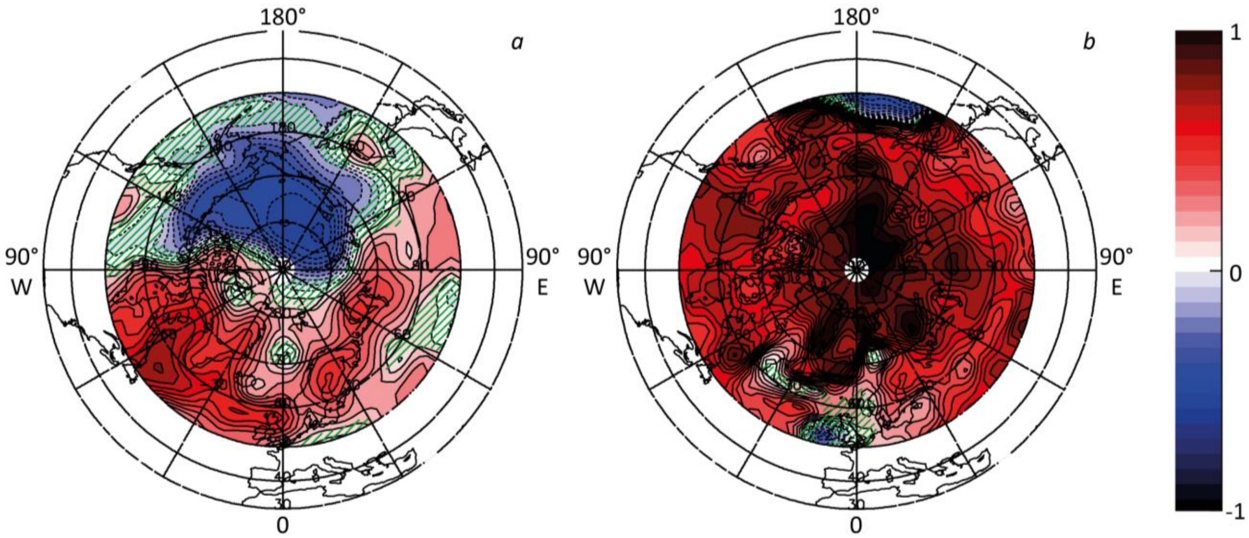

Figure 3. Spatial distribution of correlation coefficients between EP and near-surface temperature (*a*); $d\gamma/dT\times10$ (*b*); the regions with values below the standard deviation are hatched in green

3. The calculated maps of correlation between EP and near-surface temperature allow us to assume that the spatial distribution of the tropospheric response to the solar effect is altered by natural atmospheric conditions associated with changes in vertical temperature stratification in the troposphere.

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