Bakhmutov V., Kilifarska N., Melnyk G., Shenderovs'ka O.:
Interpretation of space-time temperature variations in Antarctica
in connection with changes in the geomagnetic field and
low stratospheric ozone, Ukrainian Antarctic Journal, 1, 3—14, 2020.
doi:10.33275/1727-7485.1.2020.372

V. Bakhmutov[1, 2], **N. Kilifarska**[3], **G. Melnyk**[1, *], **O. Shenderovs'ka**[1]

[1] S.I. Subbotin Institute of Geophysics, National Academy of Sciences of Ukraine, Kyiv, 03142, Ukraine
[2] State Institution National Antarctic Scientific Center, Ministry of Education and Science of Ukraine, Kyiv, 01601, Ukraine
[3] National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Sofia, 1113, Bulgaria

*** Corresponding author:** melnykgv@gmail.com

Interpretation of space-time temperature variations in Antarctica in connection with changes in the geomagnetic field and low stratospheric ozone

Abstract. In this work we review space-time temperature variations in Antarctica and possible ways the various geophysical factors caused by fluctuations of the main geomagnetic field could influence it. We analyzed data of direct ground observations of temperature and the geomagnetic field, and data of ERA-20CM and ERA Interim on air temperature variation, ozone concentration and specific humidity at the upper troposphere—lower stratosphere level. The values of module of total intensity of the magnetic field vector were calculated according to the IGRF model. Time series of galactic cosmic rays (annual data since 1700) were provided by the World Data Center for Paleoclimatology. Solar proton fluxes with energies ≥10 MeV were taken from several sources: (1) historical reconstructions of large solar proton events before 1950, (2) published data on solar proton fluxes and (3) satellite data on solar proton events. Time series were analyzed using Statistica and Microsoft Excel software. The fastest decrease in geomagnetic field's intensity occurs in West Antarctica where there is also seen the largest increase in surface temperature in the region during the XXth century. Besides that, in Central and East Antarctica there are trends towards decreasing of air temperature and strengthening of geomagnetic field. The concomitance might indicate a link between the geomagnetic field and regional climatic change. We explain it thusly: (i) the geomagnetic field controls the charged particles flux entering the Earth's atmosphere; (ii) the charged particles influence the ozone concentration near tropopause and through this, the temperature and humidity in the upper troposphere—lower stratosphere, (iii) the induced changes in humidity near tropopause have an effect on surface temperature by strengthening or weakening the greenhouse effect. Changes in the geomagnetic field intensity can be one of the factors which shape the temporal and regional variability of surface temperature. Low intensity of the geomagnetic field and the highest speed of its changes in the West Antarctica correspond to the systematically low ozone concentration and increased air humidity near tropopause. The factors cause retention of Earth's longwave radiation in the troposphere due to the greenhouse effect which results in regional warming in the region.

Keywords: geomagnetic field, climate, Antarctica, upper troposphere—lower stratosphere, ozone, cosmic rays

1 Introduction

One of the scientific problems requiring interdisciplinary research is the probability of the relationship between long-term climatic changes with changes in the geomagnetic field. It has been discussed in the scientific community for the last fifty years, as the global temperature kept increasing and the intensity of geomagnetic field kept decreasing.

The geomagnetic field has an effect on a multitude of processes in different layers of the planet. It is one of the determining components of the whole complex integral system which protects life from cosmic radiation. Since this geophysical factor is ubiquitous and probably linked to different processes (or directly influencing them) it draws significant attention of specialists from various sciences.

The probable multilayered connection between the geomagnetic field and climate has been studied since 1970-s, with the hypothetical connection sought at different timescales, from millions and thousands of years (Vasiliev et al., 2012; Kitaba et al., 2013; Rossi et al., 2014; Valet et al., 2014; Vares, Persinger, 2015; Kitaba et al., 2017) regarding changes in the dipole magnetic (paleomagnetic) field, to months or days regarding the geomagnetic activity arising from outer sources in the magnetosphere and ionosphere (Mufti, Shah, 2011; Seppälä et al., 2013). Some studies also evaluate the changes in the main magnetic field of the Earth whose sources lie in the core and at the core-mantle boundary at the timescale of the first hundreds-dozens of years. One such paper (Campuzano et al., 2018) used an example of analyzing changes in the area of the South Atlantic magnetic anomaly and in the global sea level in the last three hundred years after the long-term trend was discarded, and confirmed a hypothesis on which we had based our previous research (Bakhmutov et al., 2014; Kilifarska et al., 2015, 2016; Kilifarska et al., 2020), namely that the geomagnetic field can have an effect on climatic changes but not the other way round.

In this work we continue our lasting search for the connection between the changes in the geomagnetic field and climate (Bakhmutov et al., 2014; Kilifarska et al., 2015, 2016; Kilifarska et al., 2020) since the start of the last century and until today, but the object of study here is the Antarctic region. Our aim is to provide an explanation for the empirical material on the problem of the geomagnetic field — climate connection, including, as part of our hypothesis, the regional specifics of change in surface temperature in the Antarctica: the fast growth it shows in the west concurrently with a slower growth and even decrease in the center and in the east.

2 Data and methods

To analyze space-time changes in the geomagnetic field we used the calculated mean annual values of the module of total intensity of the geomagnetic field vector F (nT) and its secular variation dF (nT/year) according to International Geomagnetic Reference Field (IGRF) (http://www.ngdc.noaa.gov/geomag-web/#igrfwmm) model with 10° increments in latitude and longitude over the period of 1900–2020; the values of F observed by geomagnetic observatories (Table) are taken from the database of the British Geological Survey (http://www.geomag.bgs.ac.uk/data_service/data/annual_means.shtml).

Annual fluxes of galactic cosmic rays (GCR) were obtained from the World Data Center for Paleoclimatology, Boulder (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/solar_variability/usoskin-cosmic-ray.txt). The data on solar protons fluxes (SPF) with energies equal or over 10 MeV were taken from several sources: (1) historical reconstructions of large proton events, 1561–1950 (McCracken et al., 2001), (2) published SPF data for 1955–1986 (Shea, Smart, 1990) and (3) satellite data on SPF which have an effect on the Earth's environment, starting at 1976 (National Oceanic and Atmospheric Administration (NOAA), Space Environment Service Centre (ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt).

To analyze the changes in surface temperature we used the observations of the READER project stations (Table, http://www.antarctica.ac.uk/met/READER/surface/stationpt.html).

We also employed data of ERA-20CM (Hersbach et al., 2015; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20cm-model-integrations) and ERA Interim (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) on the temperature values two meters above the planetary surface (T2m), specific air humidity SpH at the150 hPa level and ozone O_3 concentration at the 70 hPa level for 1900—2019 to construct a time diagram of T2m and 1900—2010 to calculate other parameters. In our previous works (for example, Kilifarska et al., 2016) we used data of the ERA-40 and ERA Interim ECMWF reanalyses, based on observations of the second half of the XXth century. ERA-20CM is a unification of 10 atmospheric models for 1899—2010. Of course, ERA-20 CM cannot aspire to the same precision, especially in the first half of the XXth century, yet according to (Hersbach et al., 2015), the data can be used to statistically evaluate climatic parameters, so we tried to incorporate them as an accessible information source.

To establish space-time synchronicity in the studied parameters' variation we used a non-linear Machine Learning method, the Support Vector Machine (SVM) (cf. Shawe-Taylor, Sun, 2014), which is an algorithm based on a Gaussian radial basis function. The method was applied to original (not smoothed) data. However, it is unable to determine the direction of the causal link. In view of this, we also applied the well-known method of cross-correlation analysis. Coefficients of cross-correlation are calculated as usual by normalizing the cross-correlation by the standard deviations of both time series. Notably, before we built correlation maps we assigned weight coefficients for the correlation coefficients — coefficients of the influencing factor's autocorrelation corresponding to the time delay of the response (for more detail cf. Kenny, 1979). The procedure allows direct comparison of the degree of connection between both variables.

Time series analysis and plotting was done in standard software packages, Statistica and Microsoft Excel. To draw the maps we used a standard SURFER packet.

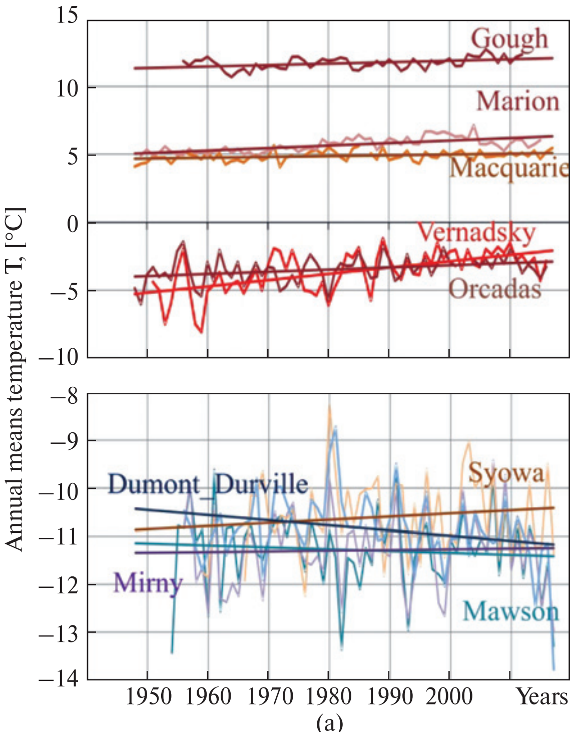
3 Results and discussion

Surface temperature. According to many observations (see for instance Turner et al., 2005; Steig et al., 2009 and references therein), during the last 50 years the surface temperature has been growing faster in the West Antarctica while in the center and in the east this increase was much slower or altogether absent so the region has even been said to cool down. The highest positive trends of mean annual temperature are seen at stations in the west of Antarctica (Faraday/Akademik Vernadsky station, Gough, Orcadas), a slower growth is recorded at Macquarie, Marion, Syowa (east), and Dumont d'Urville, Mawson, Mirny (center and east) report altogether negative trends. However, one should also note that during the last decade Faraday/Akademik Vernadsky station and Orcadas in the west have documented a trend to lower mean annual temperature. It is hard to predict how the process will develop given the general positive trend from the middle of the last century (Fig. 1a).

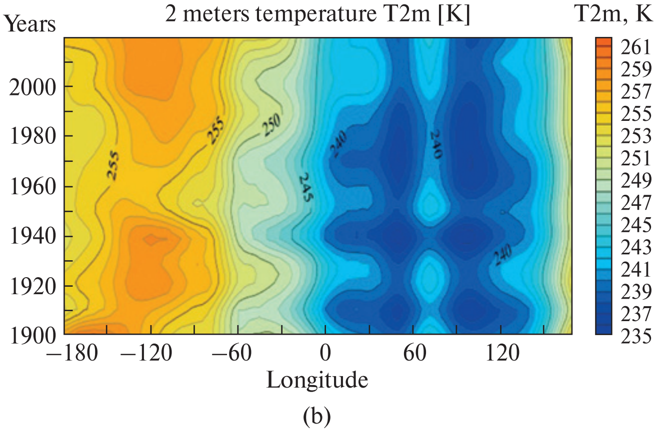
Analysis of the spatial distribution of temperature changes since 1900 according to the ERA-20CM data places the minimal temperatures over the continent's center. The time diagram T2m (Fig. 1b) has two areas, the "warm" in the west and "cold" in the center and in the east. There is also seen a general trend to higher temperature and especially intense warming in the west beginning in 1970-s to 2010. In the West Antarctica, a period of increasing temperature (early XXth century to 1940) was succeeded by three relatively cooler decades (1940-s—1970-s) and finally a new warming which is still going on. Since the data were averaged for every decade there is no clear trend to lower mean annual temperature as seen from the meteorological stations's records. A span that does stand out is the so-called plateau, where the temperature does not increase. In the "cold" part there are two longitude zones of 0°—60° E and 90°—120° E growing stronger in the first, third to fifth and sixth to ninth decades of the XXth century. Since 1990-s these areas are somewhat weaker, especially 0°—60° E, yet there is also a tendency to reintensification of cooling in late 2010-s.

Therefore both according to direct observations and to the ERA-20CM and ERA Interim data, Antarctica's west and east have different dynamics of temperature changes in the XXth—XXIth centuries.

Geomagnetic field. The most steady trait of the magnetic field of the Earth is the variability of its space-time structure. Long-term changes in the mag-

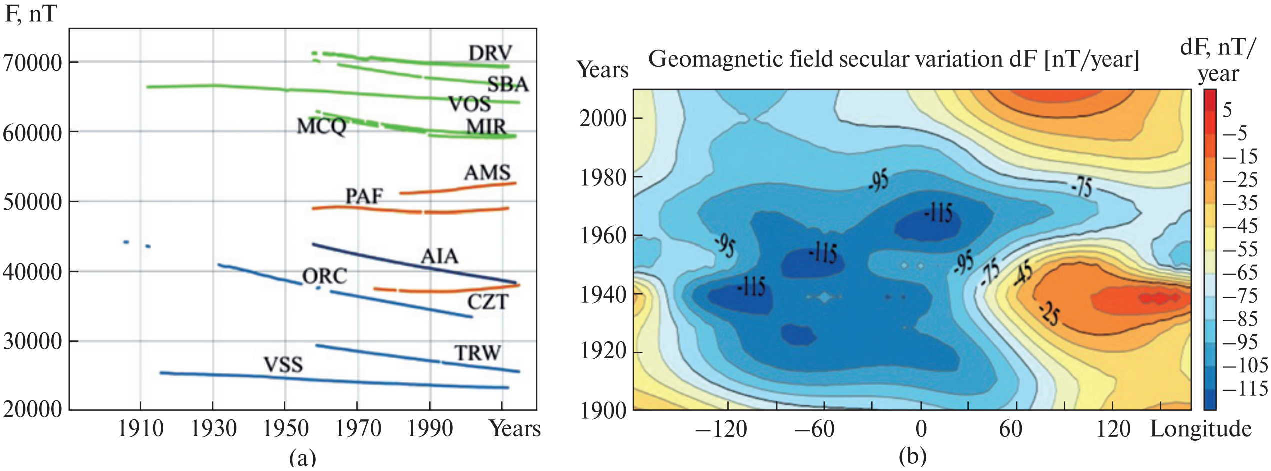


(a)



(b)

Figure 1. Surface air temperature changes (a) according to Antarctic READER stations data – annual means; (b) T2m time diagram by ERA data average in 60°–80° S latitude band for period 1900–2019 for winter (July). Fig. 1a has been created by READER data (http://www.antarctica.ac.uk/met/READER/surface/stationpt.html). Fig. 1b has been created by ERA-20CM (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20cm-model-integrations) and ERA Interim data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim)



(a) (b)

Figure 2. Geomagnetic field changes (a) according to the geomagnetic observatories data; (b) time diagram of the secular variation according to the IGRF model for latitudes 60°–80° S. Fig. 2a has been created by British Geological Survey data (http://www.geomag.bgs.ac.uk/data_service/data/annual_means.shtml). Fig. 2b has been created by IGRF calculated data (http://www.ngdc.noaa.gov/geomag-web/#igrfwmm)

nitude and direction of the geomagnetic field in the time range of first years to first hundreds–thousands years are known as secular variation (or secular variations). The source of these variations is the convection of the outer core substance, and the magnetic field it produces makes up on average 95% of all observed magnetic field on the planet surface and is the Earth's main magnetic field. Both by calculation and by measurement, its magnitude has been decreasing for the whole Earth in the XXth–early XXIth century.

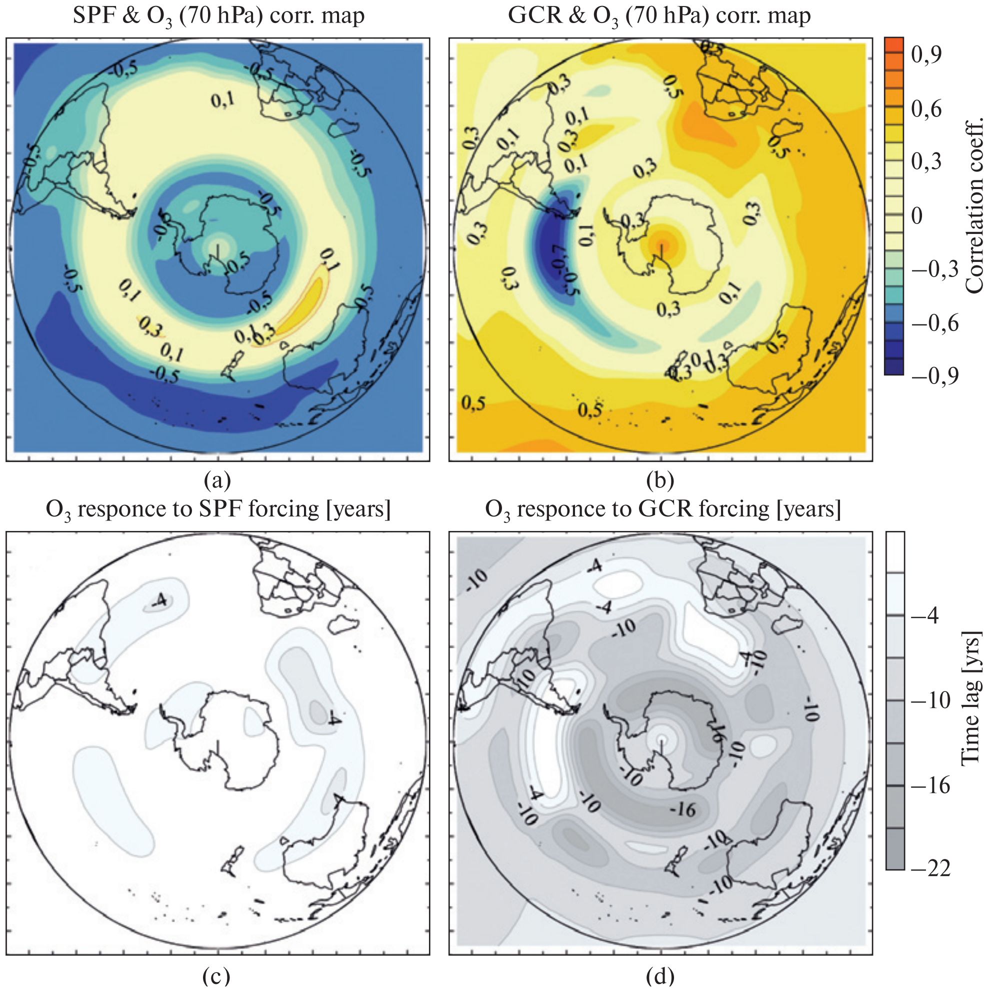
Observations of the geomagnetic field in Antarctica were initiated in 1950-s. Data on the secular variation in Antarctica may be obtained from the local observatories' records (Fig. 2a, Table).

A decrease in the magnitude of the module of the geomagnetic the geomagnetic total field vector F is seen across the whole Antarctic region, with varying speed, yet it has somewhat "slowed down" since middle 1990-s (Fig. 2a); the slope of the graph changes at this point. It is notable for observatories of the Central and East Antarctica and the adjacent territories (observatories MIR, MCQ, VOS, SBA, DRV; all observatory codes are given according to the IAGA-code). The geomagnetic field changes more rapidly in the west (observatories VSS, TRW, ORC, especially at the AIA observatory (Melnyk et al., 2014); for the 1957–2010 the overall decrease in F is over 5200 nT). At the stations in the center of the South Atlantic Anomaly (VSS) and on the geomagnetic pole (DRV), F has been decreasing more slowly during these years. Positive trends in F have been seen in the Indian Ocean (PAF, CZT, AMS) since 1990-s.

According to the IGRF model (Thébault et al., 2015) the geomagnetic field in the Southern Hemisphere has currently less intensity than the in Northern Hemisphere and decreases faster (Melnyk et al.,

Table. Geomagnetic observatories and meteorological stations in Antarctica and nearby

№	IAGA code	Name	Geographical coordinates	
			latitude φ°	longitude λ°
		Geomagnetic observatories		
1	VSS	Vassouras	–22.400	316.350
2	TRW	Trelew	–43.268	294.620
3	ORC	Orcadas	–60.733	315.220
4	AIA	Argentine Islands	–65.250	295.733
5	MIR	Mirny	–66.550	93.016
6	MCQ	Macquarie Island	–54.500	158.950
7	VOS	Vostok	–78.450	106.866
8	SBA	Scott Base	–77.850	166.783
9	DRV	Dumont d'Urville	–66.670	140.020
10	PAF	Port–aux–Francais	–49.350	70.200
11	CZT	Port Alfred (Crozet)	–46.430	51.870
12	AMS	Amsterdam Island (Martin de Vivies)	–37.800	77.570
		Meteorological stations		
1	—	Faraday/Vernadsky	–65.400	295.600
2	—	Gough	–40.400	350.100
3	—	Orcadas	–60.700	315.300
4	—	Macquarie	–54.500	158.900
5	—	Marion	–46.800	37.800
6	—	Dumont D'urville	–66.700	140.000
7	—	Mawson	–67.600	62.900
8	—	Syowa	–69.000	39.600
9	—	Mirny	–66.500	93.000



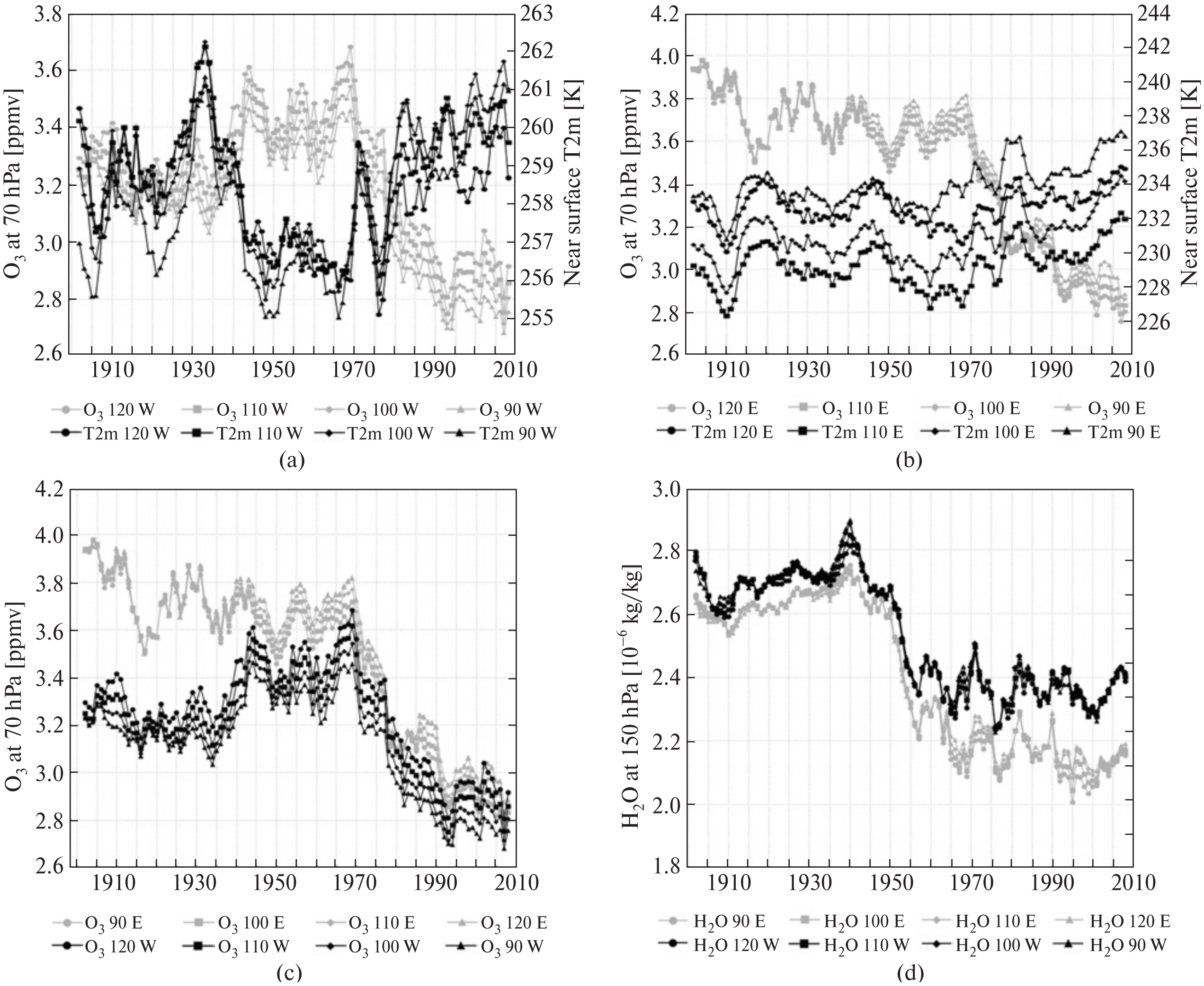
(a) (b)

(c) (d)

Figure 3. Correlation maps of ozone concentration at 70 hPa with solar proton (a) and galactic cosmic rays (b) fluxes for the period 1900–2010, the lagged correlation coefficients have been weighted by the autocorrelation function of forcing factor, corresponding to a particular time lag of calculated correlation coefficient; the delay time of the reaction O_3 to the corresponding effect (c, d). Correlation coefficients have been calculated for GCR by World Data Centre for Paleoclimatology, Boulder, and the NOAA Paleoclimatology Program data (a) for the solar proton with energy ≥10 MeV fluxes by McCracken et al., 2001; Shea, Smart, 1990 and NOAA, Space Environment Service Centre data (b) O_3 at 70 hPa by ERA-20CM data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20cm-model-integrations)

2014). Main magnetic structures here are the Southern Atlantic Anomaly (lowest F magnitude) and the anomaly connected to the geomagnetic pole where the F magnitude reaches maximum values. The field's intensity decreases faster in the West Antarctica. The negative focus of the secular variation (area of the strongest changes) near the Antarctic Peninsula appears in the first decade of the XXth century, strengthened until 1960-s, than began to weaken. In the last decade (2010–2020) the geomagnetic field changes in the Southern Hemisphere are overall slower, yet the above-mentioned negative focus remains (Fig. 2b).

Therefore, the intensity of the geomagnetic field F in Antarctica decreases faster in the west, slower — in the center and the east of the region (Fig. 2b). The fastest decrease is seen at the magnetic observatory AIA (Akademik Vernadsky station).



(a) (b) (c) (d)

Figure 4. Time series of winter (May-Sep) ozone O_3 at 70 hPa and temperature T2m in West (*a*) and East (*b*) Antarctica, ozone O_3 at 70 hPa and humidity H_2O at 150 hPa at 70° S on longitudes 90° W, 100° W, 110° W, 120° W and 90° E,100° E, 110° E, 120° E. Data are smoothed by 5-point filter. Plots have been created by ERA-20CM data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20cm-model-integrations)

Correlations between the geomagnetic field, ozone and surface temperature. Currently there are several hypotheses attempting to explain the revealed correlations between the geomagnetic field and climate (e.g., Bochniček et al., 2012; Veretenenko, Ogurtsov, 2012). Almost all of them center around the high-energy charged particles (mostly protons and electrons) which constantly or sporadically permeate the Earth's atmosphere.

Most studies in this direction have been done for the Northern Hemisphere since the observation network here is more developed.

The hypothesis we propose regarding the link between the geomagnetic field and the surface air temperature through a chain of causal relationships includes a mechanism (Kilifarska et al., 2015), based on the effect of the charged particles on the ozone balance near tropopause. Unlike the known mechanisms of O_3 destruction in the mesosphere and upper stratosphere (through solar protons activating the NOx and HOx ozone-destroying cycles), we look at another mechanism of the cosmic rays influencing the ozone near tropopause. The mechanism considers

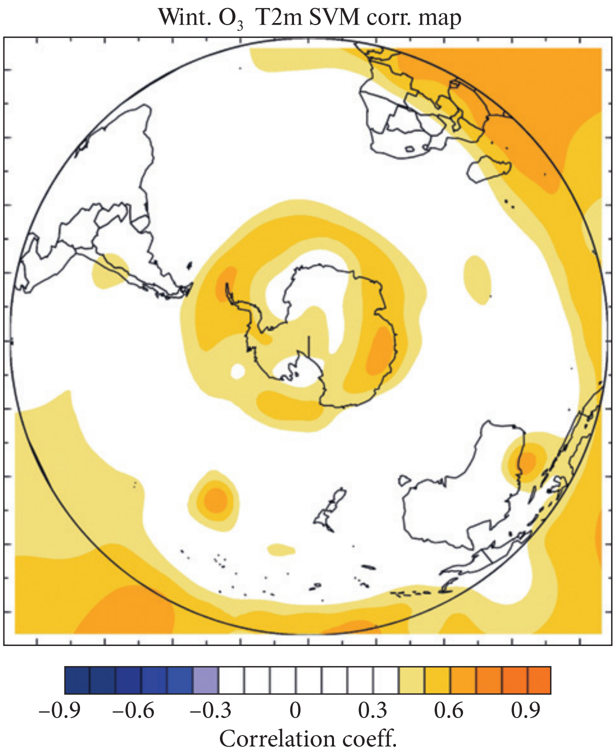


Figure 5. Correlation map of the winter ozone at 70 hPa and near surface temperature, calculated during the period 1900–2010, by the Support Vector Machine technique. The plot has been created by ERA-20CM data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20cm-model-integrations)

not only ozone destruction but also its production in the lower stratosphere through two pathways: (I) ionic-molecular autocatalytic cycle of ozone production initiated by GCR, for the Northern Hemisphere (Kilifarska, 2012, 2013); (II) ozone "self-restoration" effect initiated by high-energy solar particles which dominates in the Southern Hemisphere (Kilifarska et al., 2013). These different mechanisms of the effect on the atmospheric ozone are closely related to the depth of the cosmic rays' and solar protons' penetration into the atmosphere. The depth depends not only on the particles' energy but also on the intensity and configuration of the geomagnetic field. The spatial distribution of various particles' effect on ozone for temperate to high latitudes of the Southern Hemisphere at the 70 hPa level is shown in Fig. 3.

Fig. 3a demonstrates the solar protons' flux variations correlate with decreasing ozone concentration without time lag. The exception is the region between East Antarctica and Australia (relatively close to the geomagnetic pole) where increase in SP flux leads to higher ozone content.

The GCR effect is seen non-uniformly; thus, in the regions of the geographic pole, West Antarctica, and over the Ross Sea and Victoria Land ozone changed synchronously with changes in the GCR during the XXth century. During the time the GCR flux kept decreasing and the ozone concentration in the lower stratosphere in these regions decreased, too (Kilifarska, 2017).

On the other hand, analysis of time series of T2m and ozone at the 70 hPa during the XXth century shows that in West Antarctica they changed synchronously, out of phase (Fig. 4a). Both series have a fairly high variation amplitude. East Antarctica (Fig. 4b) shows a negative trend in secular variation of ozone which until early 1970-s was not at all reflected in variations of temperature. Only after 1970-s temperature began to slowly grow, perhaps due to the significantly lower ozone content in the lower stratosphere.

Moreover, SVP analysis of the coherence of both variables' space-time variations showed the existence of a region of tight correlation around the Antarctic (Fig. 5). This raises a reasonable question of how ozone can influence near surface temperature.

By our hypothesis of ozone's impact on climate (Kilifarska, 2012; Kilifarska et al., 2015) the amount of water on the level of upper troposphere–lower stratosphere is largely controlled by the interaction of the moist adiabatic lapse rate, temperature and humidity. An increase in the O_3 and consequently air temperature near tropopause leads to increasing moist adiabatic lapse rate and through this to more stable air mass. Thermodynamically stable conditions prevent the H_2O steam rising up through the tropopause. Conversely, lesser ozone quantities and therefore cooler tropopause translate into decreased moist adiabatic lapse rate and less stable air masses. This allows the moister air to penetrate through the tropopause into the lower stratosphere, increasing the specific humidity near tropopause. Thus, ozone variability near tropopause at once influences changes in both temperature and humidity at the most sensitive to the ascendant long-wave radiation heights near tropopause. It is easily observable in the West Antarctica where the secular variations of near surface temperature and of ozone at the 70 hPa level synchronize (Fig. 4a). On the other hand, ozone concentration in the West Antarctica was invariably lower than in the East up until the 1970-s (Fig. 4c). According to the hypothesized mechanism (Kilifarska et al., 2015) this entails increased humidity in the higher troposphere and lower stratosphere; Fig. 4d reflects exactly that. This might mean that most of the long-wave radiation in the sector was "trapped" in the troposphere which could cause uninterrupted long-term warming in the region. Meanwhile the air masses over the East Antarctica (at the 150 hPa level) remained more "transparent" for long-wave radiation, which even facilitated an insignificant cooling in the area.

In the context of the link to the main geomagnetic field it should be noted that lower ozone concentration over the West Antarctica and its great temporal variability could be explained by a weaker magnetic field here which allows more charged particles to enter the Earth's atmosphere. Considering that tropopause here lies significantly higher (Evtushevsky et al., 2008), it is possible that ionic-molecular reactions activated by secondary electrons in the lower atmosphere cause ozone destruction in the region (Kilifarska, 2017).

Currently there is no consensus in the scientific community as to the causes of the warming in West Antarctica. It is explained by the effect of warming in the Pacific Ocean tropics (Ding et al., 2011), decrease in ice cover in the Amundsen Sea and Bellingshausen Sea (Schneider et al., 2012), regional changes in atmospheric circulation such as the growing power of El Niño's positive phase — Southern oscillation and consequently the growing circumpolar western waves during the last decades (Thompson, Solomon, 2002; Keeley et al., 2007; Turner, 2004). All these hypotheses are based on climate's internal variability which itself requires explanation. We offer another explanation of the phenomenon without necessarily discarding the other factors' influence.

Some authors state that growing temperatures in the Antarctic Peninsula region have not been seen since the end of 1990-s (Turner et al., 2016; Oliva et al., 2017). According to ground observations in the READER project framework, Akademik Vernadsky and Orcadas stations have been registering decreasing temperatures since 2010 (Fig. 1a). A "plateau" in the variation of temperature two meters above planetary surface in the region is seen in the ERA-20CM data massive. Meanwhile, since the start of the XXIth century O_3 concentration at the 70 hPa level has begun to somewhat increase (Fig. 4c), in line with our hypothesis of the effect ozone exerts on the near surface temperature. Another piece of evidence supporting it is the general deceleration of the decrease in the geomagnetic field both according to observations and to IGRF calculations.

4 Conclusions

Analysis of space-time distribution of the geomagnetic field's magnitude and near surface temperature allowed us to trace the field's specific features. In the West Antarctica there is seen the fastest decrease in the geomagnetic field's intensity and increase in near surface temperature. Meanwhile in the East Antarctica the trend is towards growing intensity of the geomagnetic field's intensity and decreasing near surface temperature.

We offer an explanation of these trends through a mechanism which unites into a single chain the links between the geomagnetic field, atmosphere ionization by charged particles in the Regener-Pfotzer Maximum, lower stratospheric ozone, temperature and humidity near tropopause and as a result, the near surface temperature. Additional supporting evidence includes the revealed correlations of the GCR and SP with ozone concentration (Fig. 3), and the found higher ozone concentration and lower humidity at the level of upper troposphere–lower stratosphere over the East Antarctica compared to the West during the whole of the studied period, 1900 to 2010, and not just in the last 50 years, as we have previously shown (Kilifarska et al., 2016). The proposed mechanism allows to explain the observed asymmetry in the

Antarctic temperatures which is clearer in the second half of the XXth century. This might be caused by our using reanalysis data and not directly observed values for its first half. Lower ozone content over the West Antarctica leads to increased humidity near tropopause. Such conditions cause a decreased thermodynamical stability of air in the tropopause region, leading to the larger part of long-wave radiation in the sector being retained in the troposphere and therefore uninterrupted warming. Meanwhile over the East Antarctica the dry upper troposphere layers are transparent for long-wave radiation leading to its cooling.

At the first glance, the no longer increasing and even decreasing temperature in the West Antarctica over the last decade could also be explained by the proposed mechanism. However, it is yet unclear whether it is a short-term fluke or a stable trend, so it is still too early to draw conclusions about this phenomenon.

Therefore, our proposed hypothesis of the connection between the geomagnetic field and climate provides a possible explanation for the observed simultaneous warming in the west and "cooling" in the east and center of the Antarctic continent, employing secular variation of the magnetic field as one of the geophysical causes.

The presented results could help specialists in different disciplines to broaden the current understanding of environmental factors able to influence the atmospheric ozone variation and climate variability. Further analyses of empirical material and model experiments to clarify the finer details of every link of the proposed causal chain between the geomagnetic field, ozone layer and climate is necessary. Perhaps it should be considered to compute future climatic models.

Author contribution. VB: conceptualization. NK, GM, OS: investigation, formal analysis. VB, NK, GM: methodology, writing – original draft. VB, NK, GM: writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

References

Bakhmutov, V.G., Martazinova, V.F., Kilifarska, N.A., Melnyk, G.V., Ivanova, E.K.: Geomagnetic field and climate variability. Part I: Spatial-temporal distribution of geomagnetic field and climatic parameters during XX century, Geophysical Journal, 36 (1), 81–104, doi:10.24028/gzh.0203-3100.v36i1.2014.116153, 2014.

Bochniček, J., Davidkovová, H., Hejda, P., Huth, R.: Circulation changes in the winter lower atmosphere and long-lasting solar/geomagnetic activity, Annales Geophysicae, 30 (12), 1719–1726, doi:10.5194/angeo-30-1719-2012, 2012.

Campuzano, S.A., De Santis, A., Pavón-Carrasco, F. J., Osete, M.L., Qamili, E.: New perspectives in the study of the Earth's magnetic field and climate connection: The use of transfer entropy, PLoS ONE, 13 (11), e0207270, doi:10.1371/journal.pone.0207270, 2018.

Ding, Q., Steig, E. J., Battisti, D. S., Küttel, M.: Winter warming in West Antarctica caused by central tropical Pacific warming, Nature Geoscience, 4, 398–403, doi:10.1038/ngeo1129, 2011.

Evtushevsky, O.M., Grytsai, A.V., Klekociuk, A.R., Milinevsky, G.P.: Total ozone and tropopause zonal asymmetry during the Antarctic spring, Journal of Geophysical Research: Atmospheres, 113 (D7), doi: 10.1029/2008jd009881, 2008.

Hersbach, H., Peubey, C., Simmons, A., Berrisford, P., Poli, P., Dee, D.: ERA-20CM: a twentieth-century atmospheric model ensemble, Quarterly Journal of the Royal Meteorological Society, 141 (691), 2350–2375, doi:10.1002/qj.2528, 2015.

Keeley, S.P.E., Gillett, N.P., Thompson, D.W.J., Solomon, S., Forster, P. M.: Is Antarctic climate most sensitive to ozone depletion in the middle or lower stratosphere? Geophysical Research Letters, 34 (22), doi:10.1029/2007GL031238, 2007.

Kenny, D.A.: Correlation and causality, Wiley, New York, 277 pp., 1979.

Kilifarska, N.: Climate sensitivity to the lower stratospheric ozone variations, Journal of Atmospheric and Solar-Terrestrial Physics, 90–91, 9–14, doi 10.1016/j.jastp.2012.03.002, 2012.

Kilifarska, N.A.: An autocatalytic cycle for ozone production in the lower stratosphere initiated by Galactic Cosmic rays, Comptes Rendus de l'Académie Bulgare des Sciences, 66 (2), 243–252, 2013.

Kilifarska, N.A.: Hemispherical asymmetry of the lower stratospheric O_3 response to galactic cosmic rays forcing. ACS Earth and Space Chemistry, 1, 80–88, doi:10.1021/acsearthspacechem.6b00009, 2017.

Kilifarska, N.A., Bakhmutov, V.G., Melnyk, G.V.: Energetic particles influence on the Southern Hemisphere ozone variability, Comptes Rendus de l'Académie Bulgare des Sciences, 66 (11), 1613–1622, 2013.

Kilifarska, N.A., Bakhmutov, V.G., Melnyk, G.V.: Geomagnetic field and climate variability. 2. Probable mechanism, Geophysical Journal, 5, 66–92, doi: 10.24028/gzh.0203-3100.v37i5.2015.111146, 2015.

Kilifarska, N.A., Bakhmutov, V.G., Melnyk, G.V.: Relationships of climate changes with geomagnetic field. P.3. Northern and Southern hemispheres, Geophysical Journal, 38 (3), 52–71, doi:10.24028/gzh.0203-3100.v38i3.2016.107779, 2016.

Kilifarska, N.A., Bakhmutov, V.G., Melnyk, G.V.: Geomagnetic field's imprint on the 20-th century climate variability, Geological Society, London, Special Publication, 497, doi:10.1144/sp497-2019-38, 2020.

Kitaba, I., Hyodo, M., Katoh, S., Dettman, D.L., Sato, H.: Midlatitude cooling caused by geomagnetic field minimum during polarity reversal, Proceedings of the National Academy of Sciences of the United States of America, 110 (4), 1215–1220, doi:10.1073/pnas.1213389110, 2013.

Kitaba, I., Hyodo, M., Nakagawa, T., Katoh. Sh., Dettman, D.L., Sato, H.: Geological support for the Umbrella Effect as a link between geomagnetic field and climate, Scientific Reports, 7, 40682, doi:10.1038/srep40682, 2017.

McCracken, K.G., Dreschhoff, G.A.M., Zeller, E.J., Smart, D.F., Shea, M.A.: Solar cosmic ray events for the period 1561–1994: 1. Identification in polar ice, 1561–1950, Journal of Geophysical Research: Space Physics, 106 (A10), 21585–21598, doi:10.1029/2000JA000237, 2001.

Melnyk, G., Bakhmutov, V., Shenderovs'ka, O.: Antarctic geomagnetic field changes in the last century, Ukrainian Antarctic Journal, 13, 75–80, doi: 10.33275/1727-7485.13.2014. 214, 2014.

Mufti, S., Shah, G.N.: Solar-geomagnetic activity influence on Earth's climate, Journal of Atmospheric and Solar-Terrestrial Physics, 73 (13), 1607–1615, doi:10.1016/j.jastp.2010.12.012, 2011.

Oliva, M., Navarro, F., Hrbáček, F., Hernández, A., Nývlt, D., Pereira, P., Ruiz-Fernández, J., Trigo, R.: Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere, Science of the Total Environment, 580, 210–223, doi:10.1016/j.scitotenv.2016.12.030, 2017.

Rossi, C., Mertz-Kraus, R., Osete, M.-L.: Paleoclimate variability during the Blake geomagnetic excursion (MIS 5d) deduced from a speleothem record, Quaternary Science Reviews, 102, 166–180, doi: 10.1016/j.quascirev.2014.08.007, 2014.

Schneider, D.P., Deser, C., Okumura, Y.: An assessment and interpretation of the observed warming of West Antarctica in the austral spring, Climate Dynamics, 38, 323–347, doi: 10.1007/s00382-010-0985-x, 2012.

Seppälä, A., Lu, H., Clilverd, M.A., Rodger, C.J.: Geomagnetic activity signatures in wintertime stratosphere wind, temperature, and wave response, Journal of Geophysical Research: Atmospheres, 118 (5), 2169–2183, doi:10.1002/jgrd.50236, 2013.

Shawe-Taylor, J., Sun, Sh.: Chapter 16 — Kernel methods and support vector machines, in Academic Press Library in Signal Processing, 1, 857–881, doi:10.1016/B978-0-12-396502-8.00016-4, 2014.

Shea, M.A., Smart, D.F.: A summary of major solar proton events, Solar Physics, 127, 297–320, doi:10.1007/BF00152170, 1990.

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C., Shindell, D.T.: Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year, Nature, 457,459–462, doi:10.1038/nature07669, 2009.

Thébault, E., Finlay, C.C., Beggan, C.D., Alken, P., Aubert, J., Barrois, O., Bertrand,F., Bondar, T., Boness, A., Brocco, L., Zvereva, T.: International Geomagnetic Reference Field: the 12-th generation, Earth, Planets and Space, 67, 79, doi: 10.1186/s40623-015-0228-9, 2015.

Thompson, D.W.J., Solomon, S.: Interpretation of recent Southern Hemisphere climate change, Science, 296, 895–899, doi: 10.1126/science.1069270, 2002.

Turner, J.: The El Niño-Southern Oscillation and Antarctica, International Journal of Climatology, 24 (1), 1–31, doi: 10.1002/joc.965, 2004.

Turner, J., Colwell, S.R., Marshall, G., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A., Iagovkina, S.: Antarctic climate change during the last 50 years, International Journal of Climatology, 25, 279–294, doi: 10.1002/joc.1130, 2005.

Turner, J., Lu, H., White, I., King, J.C., Phillips, T., Hosking, J.S., Bracegirdle, T.J., Marshall, G.J., Mulvaney, R., Deb, P.: Absence of 21st century warming on Antarctic Peninsula consistent with natural variability, Nature, 535, 411–415, doi: 10.1038/nature18645, 2016.

Valet, J.-P., Bassinot, F., Bouilloux, A., Bourlès, D., Nomade, S., Guillou, V., Lopes, F., Thouveny, N., Dewilde, F.: Geomagnetic, cosmogenic and climatic changes across the last geomagnetic reversal from Equatorial Indian Ocean sediments, Earth and Planetary Science Letters, 397, 67–79, doi: 10.1016/j.epsl.2014.03.053, 2014.

Vares, D.A.E., Persinger, M.A.: Earth's Diminishing Magnetic Dipole Moment Is Driving Global Carbon Dioxide Levels and Global Warming, International Journal of Geosciences, 6 (8), 846–852, doi: 10.4236/ijg.2015.68068, 2015.

Vasiliev, S.S., Dergachev, V.A., Raspopov, O.M., Jungner, H.: Long-term variations in the flux of cosmogenic isotope ^{10}Be over the last 10000 years: Variations in the geomagnetic field and climate, Geomagnetism and Aeronomy, 52, 121–128, doi: 10.1134/S001679321201015X, 2012.

Veretenenko, S., Ogurtsov, M.: Regional and temporal variability of solar activity and galactic cosmic ray effects on the lower atmosphere circulation, Advances in Space Research, 49 (4), 770–783, doi: 10.1016/j.asr.2011.11.020, 2012.

Received: 17 March 2020
Accepted: 2 June 2020

В. Бахмутов [1, 2], Н. Кіліфарска [3], Г. Мельник [1, *], О. Шендеровська [1]

[1] Інститут геофізики ім. С. І. Субботіна НАН України, м. Київ, 03142, Україна
[2] Державна установа Національний антарктичний науковий центр
МОН України, м. Київ, 01601, Україна
[3] Національний інститут геофізики, геодезії та географії Болгарської академії наук,
м. Софія, 1113, Болгарія

*** Автор для кореспонденції:** melnykgv@gmail.com

Інтерпретація просторово-часових варіацій температури в Антарктиці у зв'язку зі змінами геомагнітного поля та нижньостратосферного озону

Реферат. В роботі розглянуто просторово-часові зміни температури в Антарктиці та можливі фактори впливу на них різних геофізичних чинників, обумовлених змінами головного геомагнітного поля. Проаналізовано дані прямих наземних спостережень температури та геомагнітного поля, а також дані ERA-20CM та ERA Interim про варіації температури повітря, концентрації озону та питомої вологості на рівні верхньої тропосфери—нижньої стратосфери. Значення повного вектора напруженості геомагнітного поля розраховані за моделлю IGRF. Часові ряди галактичних космічних променів — річні значення (з 1700 р.) — надані Всесвітнім центром даних палеокліматології. Потоки сонячних протонів з енергіями ≥10 МеВ взяті з кількох джерел: (1) історичні реконструкції потужних сонячних протонних подій до 1950 року, (2) опубліковані дані про потоки сонячних протонів та (3) супутникові дані про сонячні протонні події. Для аналізу часових рядів були залучені програми Statistica та Excel. Найшвидше зменшення напруженості геомагнітного поля відбувається на заході Антарктики, де спостерігається найбільше зростання приземної температури у цій області протягом XX століття. Крім того, в центрі та на сході Антарктики спостерігаються тенденції до зниження температури повітря та до посилення геомагнітного поля. Цей збіг може вказувати на зв'язок між геомагнітним полем та регіональними кліматичними змінами. Його ми пояснюємо наступним механізмом: (i) геомагнітне поле контролює потік заряджених частинок, що проникають в атмосферу Землі; (ii) заряджені частинки впливають на концентрацію озону поблизу тропопаузи, що, в свою чергу, впливає на температуру та вологість у верхній тропосфері—нижній стратосфері, (iii) викликані зміни вологості поблизу тропопаузи впливають на приземну температуру повітря через посилення або послаблення парникового ефекту. Зміни напруженості геомагнітного поля можуть бути одним із факторів, що впливають на часову та регіональну мінливість приземної температури. Низька інтенсивність геомагнітного поля та найвища швидкість його змін у західній частині Антарктики відповідають систематично низькій концентрації озону та підвищеній вологості повітря поблизу тропопаузи. Ці фактори спричиняють утримання довгохвильового випромінювання Землі у тропосфері завдяки парниковому ефекту, що забезпечує регіональне потепління у цьому регіоні.

Ключові слова: геомагнітне поле, клімат, Антарктика, верхня тропосфера—нижня стратосфера, озон, космічні промені