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THE MYSTERY OF ANTARCTIC CLIMATE CHANGE AND ITS RELATION TO GEOMAGNETIC FIELD

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Abstract. The regional characteristics of changing climate are serious challenge for the current understanding regarding the driving factors of climate variability. Here we present a plausible explanation for the diversity of regional response of Antarctic climate to uniform enhancement of greenhouse gases, i.e. the simultaneous warming of the Western and cooling of the Eastern Antarctica. The explanation is related to the heterogeneously distributed geomagnetic field, controlling the intensity and depth of particles penetration in the Earth's atmosphere. We discover that at seasonal basis the solar proton activity initiates enhancement of the ozone density in the lower stratosphere over East Antarctica. This starts up the mechanism for drying of the upper troposphere and lower stratosphere − through O_3 influence on temperature and static stability of air masses. Thus warming of the tropopause region reduces static stability, blocking upward propagation of the water vapour from the wetter middle troposphere. As a result the Earth's longwave radiation freely escapes in the space − a process accompanied with persistent cooling of the surface air in the eastern part of the continent. During the passed half a century the ozone density in the Western Antarctica is substantially lower, that diminished severely the ozone-water vapour cooling effect.

Key words: geomagnetic field intensity, energetic particles, lower stratospheric ozone and water vapour, climate variability.

Загадка зміни клімату Антарктики та її зв'язок з геомагнітним полем.
Н.А. Кіліфарська, В.Г. Бахмутов, Г.В. Мельник
Реферат. Регіональні характеристики зміни клімату є серйозним викликом для нинішнього розуміння рушійних факторів мінливості клімату. Ми пропонуємо вірогідне пояснення різноманітності регіональної реакції клімату Антарктики на рівномірне підвищення парникових газів, тобто одночасного потепління Західної та охолодження Східної Антарктиди. Пояснення пов'язане з неоднорідним розподілом геомагнітного поля, яке контролює інтенсивність і глибину проникнення часток в атмосфері Землі. Ми доводимо, що на сезонній основі сонячної протонної активності ініціюється підвищення щільності озону в нижній стратосфері над Східною Антарктидою. Це запускає механізм «висушування» верхньої тропосфери і нижньої стратосфери – через O_3 вплив на температуру і статичну стабільність повітряних мас. Таким чином, потепління області тропопаузи знижує статичну стабільність, блокуючи поширення водяної пари вгору з вологої середньої тропосфери. В результаті довгохвильове випромінювання Землі вільно виходить у простір, цей процес супроводжується стійким охолодженням приземного шару повітря у східній частині континенту. В минулому півстолітті щільність озону в Західній Антарктиді істотно знизилася, що значно зменшує породжений озоно-водяною парою ефект охолодження.

Загадка изменения климата Антарктики и её связь с геомагнитным полем.
Н.А. Килифарска, В.Г. Бахмутов, Г.В. Мельник
Реферат. Региональные характеристики изменения климата являются серьезным вызовом для сегодняшнего понимания природы движущих факторов изменчивости климата. Мы предлагаем правдоподобное объяснение разнообразия региональной реакции климата Антарктики на равномерное повышение парниковых газов, то есть одновременного потепления Западной и охлаждения Восточной

Антарктиды. Объяснение связано с неоднородно распределенным геомагнитным полем, которое контролирует интенсивность и глубину проникновения частиц в атмосферу Земли. Мы предполагаем, что на сезонной основе солнечной протонной активности инициируется повышение плотности озона в нижней стратосфере над Восточной Антарктидой. Это запускает механизм «осушения» верхней тропосферы и нижней стратосферы – посредством O_3 влияния на температуру и статическую устойчивость воздушных масс. Таким образом, потепление области тропопаузы снижает статическую устойчивость, блокируя распространение вверх водяного пара из влажной средней тропосферы. В результате длинноволновое излучение Земли свободно выходит в пространство, процесс сопровождается устойчивым похолоданием в приземном слое воздуха в восточной части континента. В ходе прошедшего полувека плотность озона в Западной Антарктиде существенно снизилась, что значительно уменьшило порождённый озоново-водяным паром эффект охлаждения.

1. Introduction

Evolution of the Antarctic temperature during the last 1.5 centuries (Schneider et al., 2006) is one of the paradoxes of the contemporary climate. The simultaneous warming of the Western and cooling of the Central-Eastern Antarctica excite the minds of many scientists-climatologists, atmospheric physicists, geophysicists etc. Some of the existing explanations relate this phenomenon to the strengthening of the positive phase of the Southern Annular Mod (SAM) and an associated increase in the circumpolar westerlies over recent decades (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Shindell and Schmidt, 2004; Keeley et al., 2007). Other authors suggest that local circulation pattern, i.e. amplification of the wavenumber-3 pattern (inherent to circumpolar circulation and associated with regional sea-ice changes) have a larger role in the West Antarctica warming (Steig et al., 2009). There are also hypothesized links relating the Antarctic climate with ENSO events (Turner, 2004), semiannual oscillation of circumpolar vortex (van den Broeke, 2005), etc. All of them are based, however, on internal climate variability with unknown origin.

On the other hand many authors have suggested a relation between cooling climate and stronger geomagnetic filed (Elsasser et al., 1956; Harrison and Funnell, 1964; Bucha et al., 1970; Wollin et al., 1971; King, 1974; Courtillot et al., 1982; 2007; Gallet et al., 2005; Bakhmutov et al., 2011). As far as the area with negative temperature trends (Central-Eastern Antarctica) is very close to the geomagnetic pole, such a possible relation inevitably comes in mind. The mechanism of geomagnetic influence on climate is usually associated with galactic cosmic ray influence on the processes of aerosol formation and clouds' nucleation. However, it seems not supported neither by the satellite and ground-based measurements of clouds' microphysical parameters and aerosols (Kristjansson et al., 2008; Sloan and Wolfendale, 2008; Calogovic et al., 2010; Kulmala et al., 2010, etc.), nor by the some controversial results of the CERN pilot CLOUD experiment (Duplissy et al., 2010; Kirkby et al., 2011). Consequently, at present time there is no mechanism capable of explaining the geomagnetic influence on climate.

The aim of this paper is to offer a new mechanism capable of explaining the statistical relation found between geomagnetic field and Earth's climate, as well as to show evidence supporting its validity in the Southern Hemisphere. In the following sections we will describe consequently all links in the chain of causal relations between geomagnetic field and climate variability.

2. Geomagnetic control of energetic particles precipitation

As proposed from many authors, the most probable way for geomagnetic influence on climate is through its control on intensity and spatial distribution of energetic particles − continuously or sporadically bombarding Earth's atmosphere. Heterogeneous geomagnetic filed reasonably suggest non-even distribution of precipitating energetic particles over the globe. To determine the areas with stronger and weaker particle precipitation, we have provided a lagged cross-correlation analysis between geomagnetic filed intensity, GCR and the less energetic solar protons, in each node of our grid (with 10° steps in latitude and longitude). We have used annual values of geomagnetic field and solar proton fluxes with energy higher than 10 Mev (SPF) and 22 running average of GCR (as a measure of their long-term variability). The latter has been chosen, because of the previously found increased climate and lower stratospheric O_3 sensitivity to the long-term variations of GCR (Kilifarska, 2012). From the maximal (statistically significant at 95%) coefficients we have created maps illustrating the geomagnetic field effect on the GCR and solar protons intensity. Results for the Southern Hemisphere (SH) are presented in Fig.1. The particles response to geomagnetic forcing is instantaneous, so the maps of time lags are not shown.

Analysis of Fig.1 reveals that intensity of energetic particles entering Earth's atmosphere depends not only on the strength but also on the variability of geomagnetic field. The Fig.1 implies the following conclusions: (i) coherence in temporal variability of geomagnetic field and GCR is found only in regions with unchanged or gradually increasing geomagnetic field (panel A), but not in regions of its weakening; (ii) solar proton precipitation in the areas with growing geomagnetic field are less tolerated than that of GCR (compare panels A-B); (iii) unlike the GCR, the intensity of solar protons in regions with decreasing magnetic field is moderately related to its variability (panel B); (iv) maximum negative correlation between geomagnetic field and GCR is placed near the South Pole, suggesting that stronger geomagnetic field in this region is a barrier for GCR penetration deeper in the atmosphere (Fig. 1-6 see the color paste between pages 48&49).

3. Particles effects on the lower stratospheric O_3

The second step in the chain of causal relations, initiated by geomagnetic filed, is particles' influence on the atmospheric chemistry. Our previous investigations show that lower stratospheric O_3 variations are tightly related to energetic particles precipitating in the atmosphere (Kilifarska et al., 2013 a, b). This was the motivation for the next step in our research − to identify the areas with highest particles' impact on the columnar ozone density. Applying again the lagged cross-correlation analysis between winter total ozone (TOZ) and both types of energetic particles, we have obtained maps of statistically significant correlations. Fig. 2 presents results separately for galactic cosmic rays and solar protons. Note that besides over the Antarctica, the correlation coefficients between GCR and winter ozone are negative (Fig. 2, panel A). Their maximal values correspond well to areas with strong magnetic field and those with anomalously weak field over Brasilia and South Atlantic Ocean. This implies that intensification of GCR flux has a negative impact in the columnar O_3 balance – especially well pronounced at mid-latitudes.

Despite numerous studies reporting for destruction of mesospheric O_3 during solar proton events, their effect on seasonal basis appears to be an enhancement of the total ozone density (Fig. 2, panel B). Only over the Antarctica there is a small area, where winter TOZ weakly decreases with enhancement of solar proton flux intensity. Note also the almost instantaneous total O_3 response to variations of solar proton flux intensity, and its delayed response (by 2-4 years) to GCR forcing.

Examination of the 55-year average of ozone mixing ratio during the period of ozone hole formation (September-October), and its anomalous deviations from dynamically evolving decadal means, shows that at 30 hPa and below the O_3 anomalies at tropics and extratropics become positive (see Fig. 3). Comparison with Fig. 2 indicates that the area of positive correlation between solar protons and TOZ fairly well corresponds to the positive anomalies of O_3 mixing ratio at 30 and 70 hPa. Consequently, the climatological impact of solar protons in the middle-lower stratospheric ozone balance is positive indeed.

4. Mechanism for solar protons' influence on ozone

In the Northern Hemisphere, GCR release the maximum of their energy near the tropopause, where they activate an autocatalytic cycle for O_3 production (Kilifarska, 2013). The negative correlation between GCR and ozone in the Southern Hemisphere suggests, however, that conditions favouring appearance of the autocatalytic cycle are most probably not fulfilled. The reason for this most likely lies in geomagnetic field intensity, which controls the depth of particles penetration into the atmosphere. Being stronger in the Southern Hemisphere polar region, it stops GCR at upper atmospheric levels, where the higher value of H_2O mixing ratio impedes activation of the ozone producing cycle. This could be the reason for the negative GCR−TOZ correlation found in the Southern Hemisphere.

The positive impact of solar protons in the SH total O_3 budget, however, suggests another mechanism for ozone formation initiated by the solar protons. It is well established that solar particles reduce ozone density at mesospheric and upper stratospheric levels − through the activation of HO_x and NO_x ozone destructive cycles. Consequently, the most probable explanation for the positive correlation between solar protons and TOZ is the ozone's self-restoration at lower levels, when its optical depth is reduced – a consequence of the O_3 depletion aloft (Sonnemann and Hartogh, 2009). The process of O_3 self-restoration is not easily understandable, because solar UV radiation capable of reaching the middle stratosphere could not dissociate molecular oxygen O_2 at these levels (Banks and Kockarts, 1972). Therefore, it is reasonable to conclude, that it could not produce ozone. However, the large UV continuum, known as Hartley band (200-350 nm), is able to dissociate ozone − creating vibrationally excited molecular oxygen O_2^*. The latter is easily dissociated by the longer UV radiation (freely penetrating at these levels), which creates atomic oxygen and consequently ozone, i.e.:

$$O_3 + h\nu(248\text{ nm}) \rightarrow O_2^* + O$$
$$O_2^* + h\nu(>300\text{ nm}) \rightarrow 2\,O$$

$$\underline{\qquad\qquad\qquad\qquad}$$
$$\textit{Net: } 1\,O_3 \rightarrow 3\,O_3$$

This mechanism is known also as Slanger's mechanism for ozone formation (Slanger et al., 1988). The modelling estimation of the O_3 self-restoration effect shows that its amplitude increases with downward propagation of the upper levels ozone depletion (Kilifarska et al., 2013b). The deeper the O_3 anomaly penetrates, the stronger the self-restoration effect is. The O_3 self-restoration mechanism is less productive, compared to the autocatalytic ozone production cycle, because it depends on the sporadic precipitation of solar particles, on the depth of their precipitation and on the smaller number of O_3 molecules produced. Therefore we hypothesize that this may be considered a reason for substantially lower ozone density in the Southern Hemisphere.

5. Ozone mechanism for influence on climate

It has long been known that variations of the lower stratospheric ozone density influence Earth's climate (Ramanatan et al., 1976; Wang et al., 1993; Forster and Shine, 1997; Stuber et al. 2001, etc.). However, due to the fact that the mechanism of such an influence is unclear and the factor(s) controlling ozone variability at these levels is unknown − the importance of the lower stratospheric O_3 as a potential driver of climate variations was simply ignored. In the sections 3 and 4 above, we have through some more light on the particles' impact in the lower stratosphere ozone variability. Here we will describe the most probable way for the ozone influence on climate.

Our understanding for the obtained relation between lower stratospheric O_3 and climate variability consists of three main links: (i) ozone influence on the near tropopause temperature; (ii) alteration of UTLS humidity by the temperature variations; (iii) greenhouse warming or cooling of the surface temperature, due to the exerted water vapour forcing (Kilifarska, 2012b). Below we will describe briefly each of these links.

5.1.Lower stratospheric O_3 and near tropopause T

Being one of the strongest radiatively active atmospheric gases, the lower stratospheric O_3 is known to influence substantially the temperature near the tropopause (Wirth, 1993; de Forster and

Tourpali, 2001; Seidel and Randel, 2006; IPCC/TEAP, 2005). This influence is easily understandable with the ozone's affinity to adsorb not only incoming solar, but also emitted by the Earth long-wave radiation. The close relation between lower stratospheric ozone and temperature near the tropopause has been noticed by several authors (de Forster and Tourpali, 2001; Seidel and Randel, 2006; Randel et al., 2009; etc.) reporting for cooling of the tropopause and lower stratosphere during the period of the strongest O_3 depletion in 1990s.

5.2. Tropopause T and atmospheric static stability

It is now well understood that temperature of the tropopause controls static stability of the upper tropospheric air masses (e.g., North and Eruhimova, 2009) in such a way that warmer tropopause increases stability of air parcels, while the colder one – reduces it. Static stability or the "gravitational resistance of the atmosphere to vertical displacements" (Young, 2003) is usually determined by the adiabatic lapse rate of air masses. The lower boundary of conditional instability (allowing uplifting of the water vapour) is defined by the moist adiabatic lapse rate, while its upper limit – by the dry adiabatic lapse rate (e.g., Young, 2003; North and Eruhimova, 2009). While the dry adiabatic lapse rate $\mathbf{\Gamma_d}$ is constant (~9.8°C per km), the moist (known also as a *wet* or *saturated*) lapse rate $\mathbf{\Gamma_w}$ depends on the temperature and humidity at a given altitude (see the American Meteorological Society definition of $\mathbf{\Gamma_w}$, described by eq. 1).

$$\Gamma_w = g \cdot \frac{1 + \dfrac{H_v \cdot r_v}{R_{sd} \cdot T}}{c_{pd} + \dfrac{H_v^2 \cdot \varepsilon \cdot r_v}{R_{sd} \cdot T^2}} \qquad (1)$$

where: $\mathbf{\Gamma_w}$ is the wet adiabatic lapse rate, [K.m^{-1}]; $\boldsymbol{g}$ – Earth's gravitational acceleration (9.8076, [m.s^{-2}]); $\boldsymbol{H_v}$ – heat of vaporization of water (2.501*10^6 [J.kg^{-1}]); $\boldsymbol{r_v}$ is the ratio of the mass of water vapor to the mass of dry air, known also as a mixing ratio, [kg.kg^{-1}]; $\boldsymbol{R_{sd}}$ – specific gas constant of dry air (287 [J.kg^{-1}.K^{-1}]); $\boldsymbol{\varepsilon}$ =0.622; **T** – temperature of the saturated air, [K]; $\boldsymbol{c_{pd}}$ – the specific heat capacity of dry air at constant pressure, [J.kg^{-1}.K^{-1}].

Equation (1) shows that warming of the air near the tropopause leads to an enhancement of the $\mathbf{\Gamma_w}$, which reduces the range of conditional instability of air or with other words – increase its stability. Thermodynamically stable conditions prevent uplifting of H_2O vapour across the tropopause. Oppositely, cooling of the tropopause region increases air masses' instability leading to upward propagation of the water vapour. Consequently, ozone variability near the tropopause affects simultaneously temperature and humidity variations at the most sensitive for the outgoing long-wave radiation altitudes near the tropopause.

5.3. Water vapour greenhouse effect

It is broadly accepted that the water vapour in the free atmosphere has the strongest impact into the greenhouse warming of the Earth planet (IPCC, 2007; Schmidt et al. 2010). According to the IPCC, however, the greenhouse warming of H_2O vapour is not a driver, but simply a response of the climate system to the warmer Earth climate, initiated by the increased concentration of anthropogenic greenhouse gases like carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, halocarbons, etc. On the other hand, it is well established that the lower tropospheric H_2O vapour has a little influence on the Earth's radiations balance (IPCC, 2007). The actual impact in the greenhouse effect belongs to the humidity near the tropopause (Spencer and Braswell, 1997; Smith et al., 2001; Inamdar, 2004), due to its extremely low temperature. Recall that the colder water vapour has less ability to emit back into the space absorbed long-wave radiation (emanated by the Earth), trapping it into the troposphere.

6. Evidence confirming geomagnetic influence on climate

In order to check the validity of the proposed mechanism for geomagnetic field influence on climate we have analysed time series of merged ERA 40 and ERA Interim reanalyses. Thus the available data records exceed 50 years, offering gridded data of all parameters we are interested in.

6.1.Synchronous temporal variations of UTLS ozone and humidity

The ozone mechanism for influence on climate predicts that depletion of the lower stratospheric $O_{3,}$ and correspondingly cooling of the tropopause, should be accompanied by an increased humidity, while O_3 abundance – by a reduced humidity (see sub-sections 5.1 and 5.2). Analysis of the winter time series of ozone at 70 hPa and SpH at 150 hPa, shows a well pronounced tendency for dephasing of their maxima and minima (see Figs. 4). Due to the irregularly distributed ozone over the globe, and its leading role in modulation of the upper troposphere − lower stratosphere (UTLS) temperature and humidity, it is worth to examine the spatial distribution of the connectivity between ozone and humidity. Results from such an analysis will be shown in the next sub-section.

6.2.UTLS ozone-water vapour forcing of surface T

To examine the spatial distribution of the coherence between UTLS ozone and water vapour variability we have calculated in each node of our grid (step in altitude and longitude is 10°) the lagged correlation coefficients between SpH at 150 hPa and O_3 at 70 hPa. Then we have selected the maximal, statistically significant at 95%, correlation coefficients and mapped them. The contours of the correlation map, overdrawn on the SH surface air temperature ‘dynamical’ anomalies is shown in Fig. 5. The correlation coefficients are much lower that that in the Northern Hemisphere, i.e 0.4-0.6. Their highest values are obtained at tropical latitudes, where the humidity response to O_3 forcing is delayed by more than 10 years (Fig. 5, panel B). For this reason, and for the sake of clarity, contours higher than 0.5 (corresponding to the heavily delayed tropical humidity response to O_3 forcing) are omitted in the Fig. 5 (panel A).

Note that the area of highest coherence between O_3 and water vapour corresponds to the positive surface temperature anomalies over the West Antarctica and their negative values at the eastern coast of the continent (background map in Fig. 5, panel A). Reference to Fig. 3 reveals that during the passed half a century the average lower stratospheric ozone anomalies over the Eastern Antarctica are positive. According to our mechanism for ozone influence on climate (see section 5) this suggests cooling of the surface T, what actually has been observed for the period 1957–2012 (Fig. 5, panel A).

Significance of correlation coefficients is usually estimated by the Student t-test. However, due to the indication for violation of some of the basic assumptions required for application of Student t-test, we have carried out an additional test for spuriousness of the calculated correlations, as suggested by Kenny (1979). Details of the test are described in Data and Methods section, while the results are shown in Fig.6. Comparison of Fig. 6 with Fig. 5 shows that after correction for non-stationarity of the ozone-water vapour causal structure, the ozone cooling of the Eastern Antarctica is much better captured.

7. Data and Methods

7.1.Data used

We have used ERA 40 and ERA Interim reanalyses data for the ozone mixing ratio, the total ozone, the specific humidity and the air temperature at 2 meters above the surface, covering the period 1957–2012. To avoid data inconsistency between the two reanalyses, we have equalized their means (calculated over the entire periods with data available for each) in every grid point. For the total ozone, the specific humidity (SpH) and the temperature at 2 meters above the surface

(T2m) we have used the monthly means. Monthly values of the ozone mixing ratio have been calculated from the 6-hours reanalyses data, taken at 12:00, because of an encountered problem in the spatial distribution of ERA Interim monthly ozone records.

Climax neutron monitor data record has been used as a measure of GCR intensity, because of its longer length. It has been additionally expanded backward and forward (Kilifarska, 2012a), to extend the length of the calculated 22 running averages used as a measure of the long-term GCR variability. The record of annually averaged solar proton fluxes with energies E>10 MeV (starting in 1970) is adopted by data taken from (Kurt et al., 2004) and NOAA Space Environment Service Centre (http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt).

Taking into account possible non-stationarity of the data means, we have calculated monthly average deviations from their dynamically evolving decadal means for all examined atmospheric parameters. We call them 'dynamical anomalies' and they do not possess any trend or long-term variations. The advantage of this procedure consists in the easier deconvolution of variability shorter than a decade from the climatic scale variations.

7.2. Methods

The spatial distribution of coherent variations between examined parameters has been analyzed by the use of lagged cross-correlation analysis, which is easily programmable. Moreover, due to the relatively lower power of this method to derive a meaningful conclusion about causality, it is recommended by Kenny (1979) to replicate calculated correlations at different time lags and different groups of subjects. This strategy was strictly followed in our analysis. For example, each lagged correlation coefficient has been selected as a maximal value among all coefficients calculated with time lags of 1 to 20 years. For every two parameters we have applied this technique in each grid point, i.e. 684 pairs of time series have been analyzed in order to determine each correlation map. The cross-covariance coefficients at lag *m* have been calculated by moving the axis of the independent variable (i.e. the cause, or the forcing parameter) backward, i.e.

$$c_{xy}(k)=\frac{1}{N-1}\sum_{m}\left(Y_t-\overline{Y}\right)\left(X_{t+m}-\overline{X}\right) \qquad for\ t=1\ to\ N; \quad m=-1\ to\ -k$$

where N is the number of observations in time series. For this reason the time delay is given in our maps as a negative value. The cross-correlation coefficients are calculated through normalization of the cross-covariance on the standard deviations of both time series.

All correlation coefficients presented in this paper are calculated from the mean winter values. Cross-correlations of external factors (i.e. long-term variations of galactic cosmic rays and solar proton fluxes) were calculated without any smoothing, while relations between atmospheric parameters themselves − with 3 point running average smoothing. Maps of connectivity between examined parameters have been created from only statistically significant coefficients. The Student's t-test of significance, however, is based on the assumptions that: (i) relation between the examined variables is linear; (ii) each pair (X_i,Y_i) of analyzed variables is independent from the others; (iii) both variables X and Y are normally distributed. Because there are indications for violations of some of them (e.g. first and second), we have carried out an additional test for spuriousness of the calculated correlations, following (Kenny, 1979).

The key assumptions used in the cross-lagged correlation analysis are: (i) *stationarity*, meaning that variables' causal structure does not change over time and (ii) *synchronicity* ensuring that both variables are measured at the same moment in time (Kenny, 1979), and in our case − at the same geographical place. If we apply the path analysis, as described in (Kenny, 1979), and assume that our variables X and Y are influenced by a third variable F, the structural equations of X and Y − in two moments in time − could be written in the form:

$$X_1=a_1.F_1+c_1.U_1$$
$$X_2=a_2.F_2+c_2.U_2 \qquad (2)$$
$$Y_1=b_1.F_1+d_1.V_1$$
$$Y_2=b_2.F_2+d_2.V_2$$

Where a_1, a_2, b_1, b_2 are paths or causal parameters from external forcing F to variables X and Y, in the moments 1 and 2. Variables U, V include all factors influencing X and Y besides F. We will treat them as a noise. Moreover, variables U, V and F are uncorrelated to each other but autocorrelated.

For the two-wave, two-variable case stationarity implies $\mathbf{a_1=a_2}$ and $\mathbf{b_1=b_2}$. In case of stationarity there are two over-identifying restrictions: equality of the *synchronous* correlations $\boldsymbol{\rho_{x1,\,y1}=\rho_{x2,\,y2}}$, and equality of the *cross-lagged* correlations $\boldsymbol{\rho_{x1,\,y2}=\rho_{x2,\,y1}}$. The strategy of cross-lagged analysis consists of examining the *synchronous* correlations in order to test for *stationarity*, and if stationarity is satisfied, the *cross-lagged* correlations can be used to test for *spuriousness*. Thus null hypothesis in our analysis is that equality of cross-lagged correlations indicates spuriousness of the possible relations between X and Y.

For the special case in which there are two waves in the distribution of lagged coefficients at times 1 and 2, the synchronous correlations take the form (Kenny, 1979):

$$\rho_{x1,\,y1}=a_1.b_1.A_{F1,F1} \qquad (3)$$
$$\rho_{x2,\,y2}=a_2.b_2.A_{F2,F2}$$

while the cross-lags are as follows:

$$\rho_{x1,\,y2}=a_1.b_2.A_{F1,F2} \qquad (4)$$
$$\rho_{x2,\,y1}=a_2.b_1.A_{F2,F1}$$

where $A_{F1,F1}$, $A_{F2,F2}$, $A_{F1,F2}$ and $A_{F2,F1}$ are autocorrelation functions of the forcing factor F in moments 1 and 2. Moments 1 and 2 (of maximization of the lagged cross-correlation coefficients) is defined by the backward shifting of Y or by the forward shifting of X. For this reason, due to the asymmetry of cross-correlation coefficients, both autocorrelation functions $A_{F1,F2}$ and $A_{F2,F1}$ are nonequivalent.

Now, if we introduce the ratios:

$$K_x^2=\left(\frac{a_2}{a_1}\right)^2 \text{ and } K_y^2=\left(\frac{b_2}{b_1}\right)^2$$

as a measure of stationarity of the causal structure of variables X and Y (if the stationarity assumption is fulfilled, $K_x=K_y=1$), then (3) could be written in the form:

$$\rho_{x1,\,y1}=a_1.b_1$$
$$\rho_{x2,\,y2}=a_1.b_1.K_x.K_y$$

The product $(K_x.K_y)^{1/2}$ we call *correction factor for stationarity*. Consequently, if the causal structure of X and Y is quasi-stationary, the multiplication of the first synchronous correlation $\rho_{x1,y1}$ and the division of the second synchronous correlation $\rho_{x2,y2}$ by the correction factor $(K_x.K_y)^{1/2}$ will equalize the values of synchronous correlations.

Similarly, the cross-lagged correlations (4) could be written in the form:

$$\rho_{x1,\,y2}=a_1.b_1.K_y.A_{F1,F2}$$
$$\rho_{x2,\,y1}=a_1.b_1.K_x.A_{F2,F1}$$

The *correction factor for cross-lagged correlations* could be defined as $(K_y/K_x)^{1/2}$. Consequently, division of $\rho_{x1,y2}$ and multiplication of $\rho_{x2,y1}$ by the correction factor $(K_y/K_x)^{1/2}$ should equalize the cross-lagged correlation coefficients. If there is a difference between corrected $\rho_{x1,y2}$ and $\rho_{x2,y1}$ this would be an indication that any possible relation between variables X and Y is non-spurious.

8. Theory application

We assumed that the external third variable influencing both ozone and humidity in the lower stratosphere is galactic cosmic rays (GCR). From the *synchronous* correlation of GCR with each of them we have calculated correction factors for non-stationarity. With these factors we have corrected synchronous as well as cross-lagged correlation coefficients between ozone and humidity. After correction, *synchronous* correlations of O_3 and humidity with GCR have been equalized in each grid point, which is an indication that causal relation between them does not change much with time. Then we have calculated the differences between *cross-lagged correlations* of O_3 and water vapor and the results are plotted in Fig. 6. The Fisher z-transformation is used to estimate the significance of the differences between corrected cross-lagged correlation coefficients. We found that for differences higher than 0.38, the power of the test (giving the probability of rejecting the false null hypothesis) is greater than 0.8. Consequently, the existence of statistically significant causal relation between ozone and humidity could be suggest for differences higher than 0.38. The positive differences indicate that the O_3 influence on humidity is greater then the opposite – the humidity influence on O_3.

9. Conclusions

Applying lagged cross-correlation analysis, we found that intensity of energetic particles reaching the Earth's surface is influenced by both: (i) relatively stable and (ii) dynamically varying components of geomagnetic field. We found that galactic cosmic rays are attracted in regions with growing magnetic field intensity, but show no connectivity to geomagnetic filed in areas of its weakening. Solar protons with energies more that 10 MeV are less sensitive to geomagnetic filed variations. They show smaller affinity to the growing magnetic filed (although it is still well pronounced) and precipitate even in regions with declining magnetic filed. On the other side, GCR intensity is severely depleted in the region with strong and stable geomagnetic field over Australia (Fig. 1 A). Similarly, solar protons are more attracted in the Atlantic region having weak and stable magnetic filed (Fig. 1 B).

These results give some pre-requisites where the stronger particles' influence on climate could be expected. Our analyses show that lower stratospheric O_3 could be a mediator of particles influence on climate variability. Examination of connectivity between total ozone density (TOZ) and energetic particles shows that solar protons have a positive impact in the TOZ balance near the eastern coast of Antarctica. The positive O_3 anomalies are detected near the tropopause, which according to the ozone mechanism for influence on climate leads to some cooling of the East Antarctica (for more details see section 5).

We have examined the spatial distribution of connectivity between lower stratospheric O_3 and H_2O vapour in order to estimate validity of the newly proposed mechanism for ozone influence on climate. It was found that the highest coherence in ozone-humidity variations fairly well resembles the negative T anomalies in the East Antarctica (Fig. 6). Consequently, the weaker or negative trends found in the Eastern Antarctica could be easily explained by the higher ozone density, providing drying of the near tropopause layer in the region. The reduced water vapour at these levels allows escaping of the long-wave Earth's radiation into the space, followed by cooling of the surface air.

This simple explanation of the 'mysterious' variety of Antarctic climate during passed half a century is going beyond the common interpretations of climate variability related to the internal atmospheric modes − like Southern Annular Mode, ENSO etc., − intensification or weakening of which is also unexplainable. Involvement of the geomagnetic field intensity, as one of the main players determining variability of climate system, makes clear that Earth's climate could have significant temporal and regional variability, even if the external impact remains constant − only as a consequence of geomagnetic field variations.

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