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Impact of Decadal Variations of Galactic Cosmic Rays on Earth's Climate Variability

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Abstract. The existence of quasi-decadal variability in some climatic variables is well documented in scientific literature. We show evidence that this "solar signal" should be attributed to the variations of galactic cosmic rays intensity (GCR), which is modulated by the 11-year solar cycle. The GCR influence is transmitted down to the planetary surface by the lower stratospheric ozone – an additional production or destruction of which is initiated by the low energy electrons in the Regener-Pfotzer maximum (an ionisation layer produced by GCR in the lower atmosphere). Furthermore, the ozone variability impacts the upper tropospheric stability and the humidity near the tropopause. The greatest impact of the latter in the Earth's radiation balance increases or decrease regionally the strength of the greenhouse effect, and consequently – the near surface temperature.

KEY WORDS: solar cycle, galactic cosmic rays, near tropopause ozone and water vapour.

1 Introduction

The cult of the Sun – as the main source of heat for the Earth planet – dates back to ancient times. People are thankful to the God Sun for the given light, warm, food and all important in their life. The seasonal and inter annual changes of the living conditions they have related to the Sun. In 1801 a German-born British astronomer Frederic William Herschel proposed the idea for exiting relation between spots seen on the Sun's surface and regional climate, using the market price of wheat as a proxy. The establishment of the rhythmic rise and fall of sunspots number by Samuel Heinrich Schwabe in 1843 (with rough periodicity of 11 years) is followed by the assumption for corresponding variability in the brightness of our star. Accordingly, such variability could bring cooler or warmer periods on Earth and could be found in the climatic variables (temperature, rainfalls, droughts, etc.).

The idea for a *direct* solar influence on climate has intensively circulated in scientific community up to the end of 20th century, when satellite measurement reveal that variation of total solar irradiance between maximum and minimum of the solar cycle does not exceed 0.1% [1]. Obviously, such a small amplitude of variability is not able to explain the noticeable quasi-decadal variations found in the near surface temperature [2–6], precipitation [7], lower stratospheric ozone [8, 9], mean sea level [10, 11], etc.

On the other side, the cyclic variations of solar magnetic field could affect climate *indirectly* – through modulation of galactic cosmic ray (GCR) intensity, arriving at the outer heliospheric boundary from the Galaxy. The idea is firstly developed by [12], who pointed out that the ionisation created by GCR in the lower atmosphere could influence thunderstorm activity and climate variability at decadal time scales. The idea has been well appreciated by a part of the scientific community, and several hypotheses are proposed up to now, regarding the mechanism of GCR influence on climate. Their strengths and weaknesses are thoroughly discussed by [13].

According to our point of view, the solar-GCR influence on the surface temperature is mediated by the lower stratospheric ozone. Recent investigations of the energetic particles' impact on the near tropopause chemistry have revealed the existence of a secondary source of ozone above the tropopause [13], where the atmospheric humidity is strongly reduced (due the process of freeze drying near the tropopause). The ozone production is initiated by the low energy electrons in the Regener-Pfotzer maximum, which activate an autocatalytic cycle of ozone creation. Beneath the troposphere the process is ineffective due to the formation of water clusters from the ionized ozone molecule. In such a way, the uneven distribution of ionisation in the Regener-Pfotzer max [13] is projected on the lower stratospheric ozone density. Being a strong absorber of solar UV radiation, the ozone in turn creates corresponding irregularities in the near tropopause temperature, in the wet adiabatic lapse rate, and correspondingly in the static stability of the upper troposphere [14]. As a result, the regions with reduced stability are moistened by the upward movement of the wetter air masses – from the middle troposphere, while statically stable regions are continuously drying. Finally, the strongest impact of the near tropopause water in the Earth's radiation balance (which provides 90% of the impact of the whole water vapour in the atmosphere [15]) strengthens the greenhouse effect over moister regions and weakens it over drier ones.

In this article we will provide a new evidence of the existence of the decadal solar "signal" in the lower stratospheric ozone and near surface temperature and sea level pressure.

2 Data and Methods of Analysis

We have used monthly mean data for the surface pressure, air temperature at 2 m above the surface, the ozone mixing ratio at 70 hPa and specific humidity at 150 hPa – all of these have been taken from ERA-20C – the reanalysis providing a gridded data of atmospheric variables during the twentieth century, covering the period 1900–2010 (https://apps.ecmwf.int/datasets/data/era20c-daily/levtype=sfc/type=an/). The spatial-temporal synchronisation in the variations of data analysed have been estimated by the use of the cross-correlation technique. Due to the relatively lower power of this statistical method, some authors [16] have recommended replication of the calculated correlations at different time lags and for different groups of subjects. For this reason, each lagged correlation coefficient has been selected to be the maximal value among all coefficients calculated with time lags between 0 and 35 years. The correlations have been calculated from the seasonal data averaged over Dec-Apr months and smoothed by 5-point moving window. Before map drawing each correlation coefficient (statistically significant at 2σ level) has been weighted by the autocorrelation coefficient of the independent (factorial) variable, corresponding to the time lag determined in each grid point. This procedure weakens substantially the delayed correlation coefficients, thus reducing the uncertainty when comparing correlations with different time lags [16].

Winter ozone profiles for 2001 and 2009 year has been derived by ERA Interim reanalysis, calculated for period December-March (https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/).

3 Results

3.1 GCR impact on the lower stratospheric ozone variations

Analysis of time series of galactic cosmic rays (GCR) and ozone at 70 hPa shows their non-liner evolution with time (see Figure 1). For this reason the estimation of their potential covariance has been investigated by the use of the statistical method – Support Vector Machine (SVM) – an instrument of the widely known technic Machine learning. The GCR time series has been smoothed by 9 points moving window, which saves the quasi-decadal periodicity, reducing the peaks amplitude (the red curve in Figure 1). The ozone's time series have been smoothed by 5 points averaging.

We have used SVM for solving the non-linear regression problem in each point of our grid with resolution 10° in latitude and longitude. From the correlation coefficients, calculated for the model's predictions of the GCR-ozone relation, has been drawn a map, illustrating the spatial distribution of the predicted by the SVM strength of correlation between both variables. Result is shown in Figure 2.

Figure 2 illustrates that strength of the GCR-ozone covariance (at time scales up to a decade) is unevenly distributed over the globe. Compared to the covariance at multidecadal time scales [13] the correlation coefficients are much weaker.

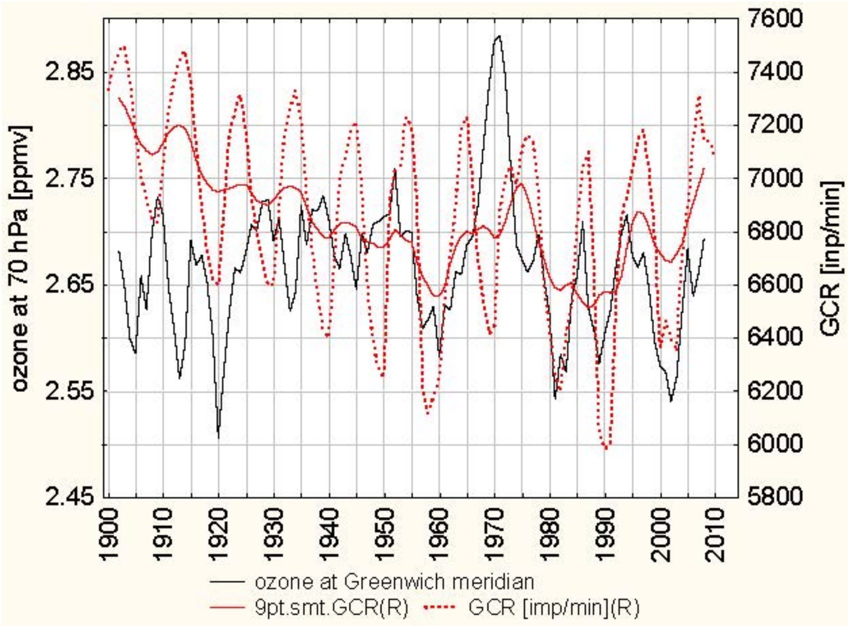

Figure 1. Time series of galactic cosmic rays (dotted curve) and ozone at 70 hPa, 50 deg. northern latitude and 0°E longitude (black curve). The 9-point smoothing of GCR is illustrated by continuous red curve.

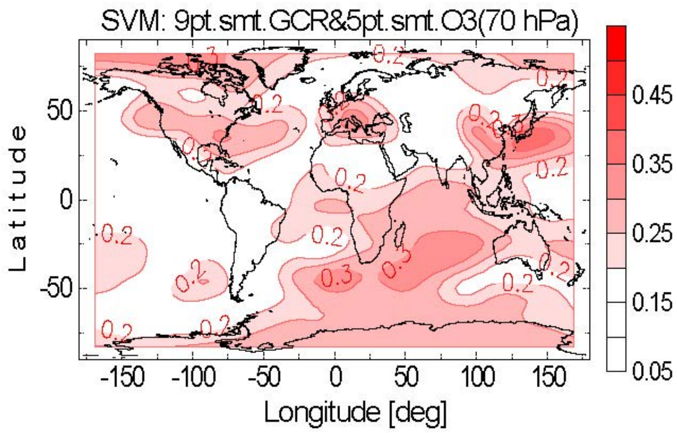

Figure 2. Prediction map of correlation between GCR and winter ozone at 70 hPa.

Nevertheless, Figure 2 shows that GCR-ozone coupling is irregularly distributed across the planet – most probably due to the geomagnetic lensing of energetic particles trapped in the Earth's radiation belts [17].

3.2 Decadal variations in the lower stratospheric O_3 density

As a validation of our concept for the mediating role of ozone in GCR-climate relation, we have compared the winter ozone profiles (December–March) in year of sunspots max (2001) and that of sunspot min (2009). The result presented in Figure 3 illustrates that the O_3 (data are taken from ERA Interim reanalysis) behaves quite unexpectedly. From the perspective of the photochemical ozone production, one should expect a higher ozone density during the solar maximum. Surprisingly, Figure 3 shows that at polar and middle latitudes, the ozone density near the peak of ozone layer is higher in solar minimum than in solar maximum.

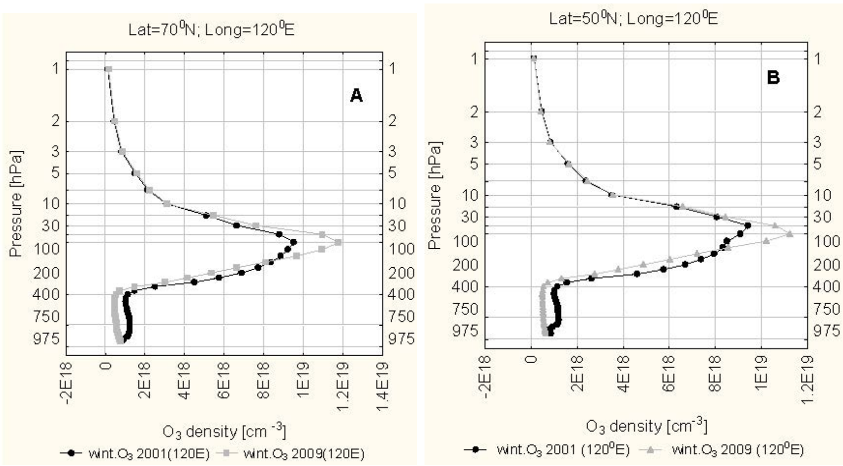

Figure 3. Vertical profiles of winter (Dec–Mar) O_3 density for 2001, year of high activity (black contours), and 2009, year of low solar activity (grey contours), at 120°E longitudes, and two latitudes: (A) 70°N; and (B) 50°N latitudes.

We have analysed also the spatial distribution of differences between solar min and solar max of the mean annual ozone values, which is presented in Figure 4. Note that in some regions, the solar minimum ozone density is higher than that in solar maximum. This result is unexplainable within the concept for UV production of atmospheric ozone, and suggests the existence of an additional ozone source in the lower stratosphere. The effect is stronger at northern middle and high latitudes, and undoubtedly could be attributed to the activation of electron-impact production of O_3 by the stronger GCR flux during solar minimum [13]. In the Southern Hemisphere, however, the cosmic ray effect is much smaller, focused mainly between the 50° and 70°S latitudes. This hemispheric asymmetry we have ascribed to the asymmetry of geomagnetic mirror of particles trapped in the Earth's magnetic field [17].

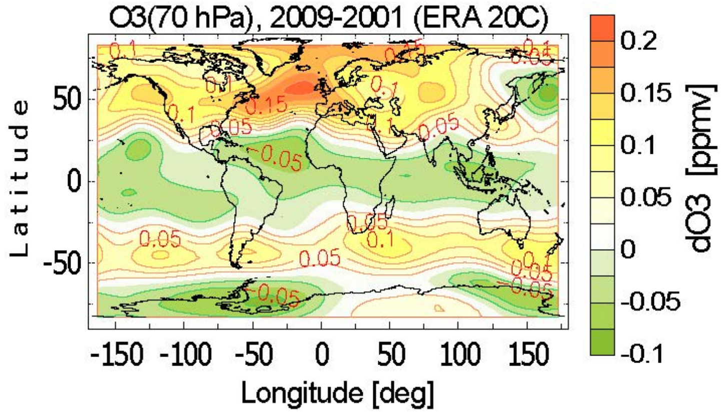

Figure 4. Spatial distribution of differences between solar minimum (2009) and solar maximum (2001) of ozone mixing ratio at 70 hPa. Data source: ERA 20 century reanalysis.

3.3 Decadal changes in temperature and sea level pressure

Spatial distribution of the decadal changes of the annual air temperature at 2m above the surface, and sea level pressure, between 2001 (an year of solar max) and 2009 (an year with deep solar min) is shown in Figure 5. Note that temperature and pressure in polar regions are higher in solar min – in contrast to the recent understanding that solar brightness increases in periods of active Sun. Actually this was the main finding of the first supporters of solar-climate relations [18–20]. At that times is was assumed that sunspots reduce the brightness of the Sun and such a result was not contradictive with the observed climate response (excluding the small amplitude of solar variations). Today, however, the warmer polar regions in a period of low solar activity inevitably has to be attributed to other factor(s) – e.g. to the redistribution of the mean planetary heat by atmospheric circulation (a hypothesis emerging yet in the beginning of the 20-th century [21,22].

Interestingly, at mid-latitudes a belt with a reduced near surface temperature is well noticed – better pronounced in the Northern Hemisphere. Comparison with the map of ozone response to the 11-yr solar periodicity (Figure 4) shows that the negative temperature anomalies fairly well correspond to the regions with increased ozone density. At tropical regions we have a slight temperature enhancement – corresponding to the reduced ozone density at 70 hPa (compare Figures 4 and 5). The pressure changes are similar to that of the temperature, but with stronger raise at polar latitudes and missing positive response at the tropics.

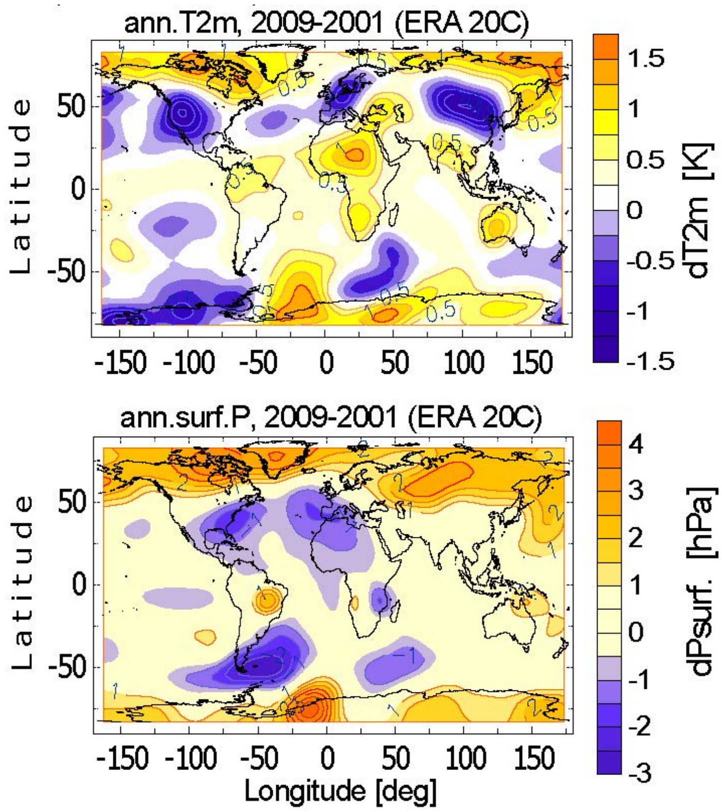

Figure 5. Spatial distribution of differences between solar minimum (2009) and solar maximum (2001) of near surface air temperature and sea level pressure. Data source: ERA 20 century reanalysis.

3.4 Synchronisation between the lower stratospheric O_3, near tropopause humidity and the air surface temperature variations

According to our mechanism, the ozone variability above the tropopause is transmitted downward by the corresponding changes in the near tropopause humidity. As an additional evidence of such a relation, we have examined maps of ozone lagged cross-correlation with water vapour at 150 hPa and with air temperature at 2 m above the surface. The correlation maps are shown in Figure 6.

It is easily seen that similarly to the GCR-ozone relation (shown in Figure 2) the ozone "projection" on the near tropopause humidity and air surface temperature (T_{2m}) is also irregularly distributed. Note also that regions with maximal strength of ozone-humidity relation fairly well coincide with that of ozone-temperature covariance – i.e. Caribbean and Indian-western Pacific regions, as

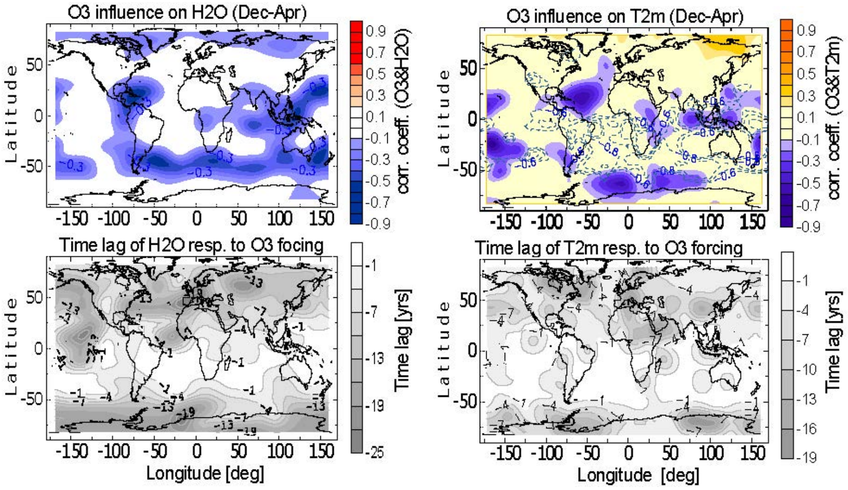

Figure 6. *Upper panels:* Maps of ozone lagged correlation with water vapour at 150 hPa (left) and air surface air temperature (right); Dashed lines denote the instantaneous correlation (with zero time lag) between ozone and water vapour. *Bottom panels:* Time lags of H_2O (left) and T_{2m} (right) response to ozone forcing.

well as the broad region in the Southern Ocean. The time lag of both variables – water vapour at 150 hPa and surface air temperature – is 2-3 years, which is a reasonable delay. It is worth to remind that analysed data are preliminary smoothed by 5-year moving window, what means that the observed coherence between ozone, water vapour and temperature variability operates at time scales longer than 5 years.

4 Conclusions

Comparative and statistical analysis of the lower stratospheric ozone, near tropopause humidity and air surface temperature, during the period 1900-2010, reveals the existence of a moderate covariance with the 11-year cycle of galactic cosmic rays. This is an indication that the temporal variations of these climatic variables are synchronized at time scales between 5 and 10 years – in addition to their multidecadal coherent variability [13]. The relation to the GCR flux we ascribed to the activation of ion molecular reactions producing ozone in the lower stratosphere – where the atmospheric humidity is severely reduced [23]. Thus, quasi-decadal variations of GCR are imprinted onto the ozone. Through alteration of atmospheric static stability, this "signal" is furthermore transmitted to the near tropopause humidity, and consequently to the near surface temperature, due to the strongest impact of the water vapour in the greenhouse effect.

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