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DO COSMIC RAYS INFLUENCE OZONE DEPLETION IN THE ANTARCTIC OZONE HOLE?

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Abstract: A linear dependence between ozone depletion on the 11 years cycle of Cosmic Rays (CR) has been often debated in the literature. At first instance, the more elemental corroboration is by means of the correlation coefficient (r). Calculations corresponding to the relevant data gives a value r = 0.5216. Since this low value is not completely conclusive, because this analysis only provides a global information about the degree of linear dependence between two time series, but does not gives information when the correlation dependence is of non-linear nature. Also, the correlation coefficient does not provides the evolution of the common synchronized periodicities, nor the evolution of the relative phase between two time series. A complementary study must be done in order to analyze local variations of power within a single non-stationary time series at multiple periodicities, such as CR and total ozone series. We apply here Wavelet Spectral Analysis, in which case the evolution of common periodicities would indicate the frequencies where both series are synchronic. Within this frame, the wavelet-squared transform coherence (WSTC) is particularly useful in highlighting the time and frequency intervals, when the phenomena have a strong interaction. Results does not show a synchronized periodicity of 11 years between ozone and cosmic rays, but only periodicities at 5.5 and 7 years with a complex non-linear relation. Concretely: there is no linear correlation between CR and total Ozone and there is no any trend with a cycle of 11 years.- CR intensity has not the principal role to explain the total ozone variations and/or the OH severity. CR are not the main control factor of ozone depletion.

Keywords: Cosmic Rays- Antarctic Ozone Hole

1 Introduction

The Antarctic region in which severe ozone depletion has taken place is known as the ozone hole. This region has two basic indicators: the area, where the ozone abundance is low, OHS (size), and the quantity of ozone mass deficit (depth). Conventionally, the OHS is calculated from the area contained by total column ozone values less than 220 Dobson Units, which is the value corresponding corresponds to the strong ozone gradient region. (1 DU=0.01 mm. thickness at standard temperature and pressure). Since the discovery of the Antarctic ozone hole (OH) [1], considerable effort has been focused on observing these ozone losses, on understanding the chemical, dynamical and radiative processes involved, and on predicting the future of polar ozone (World Meteorological Organization (WMO).). It is well known that the main cause of this stratospheric ozone reduction is anthropogenic activity, e. g. [2], but the influence of precipitating charged particles on the abundance of stratospheric ozone and other atmospheric constituents complicates the interpretation of OH trends [3]. The fast charged particles that influence the atmosphere can be roughly grouped into three types: (1) solar particles, which are mostly protons entering the polar regions and are thus often referred to as solar proton events (SPE); (2) auroral energetic electrons, precipitating in the polar zone and at high latitudes; and (3) galactic cosmic rays (GCR), also entering preferentially at high latitudes [3]. Since the early studies [4,5]. a number of papers have been published documenting the SPE-caused ozone polar changes [6], though the area in which the SPE deplete the ozone has been estimated as a minor one, in relation to the area of chlorine catalyzed depletion [5]. The GCR continually create odd nitrogen and odd hydrogen constituents in the lower stratosphere and upper troposphere that affect stratospheric ozone abundance, but nowadays it is thought that they play a small role in variations in polar ozone abundance [3]. The understanding of the influence of GCR on the OHS is relevant to the differentiation of the nature of the inducted processes in the atmosphere (natural or anthropogenic) and to the better assessment of the impact of environmental protection policies on indicators of achievement (for example, on the OH extent). It has been well known since the early 1930's that the GCR flux is maximum at polar latitudes and minimum at the equator (e.g., [7]). Depending on their primary energy GCR particles penetrate deep into the atmosphere (even reaching the Earth's surface), altering the ozone abundance probably at all latitudes: the effects above about 60 degrees are much smaller than at lower latitudes, as particles of energy below ~ 18 GeV are modulated by the Earth's magnetic field. Consequently, their influence on the ozone destruction at polar sites may reach the ceiling, at heights of 10-20 km, where the ionization and dissociation started by GCR is maximal [8]. Taking into account that the OHS and GCR time series have common periodicities in the months of September, October and November [9], it was explored in [10] whether such coincidences do or do not imply a real relationship between both phenomena: it was found that the stratospheric layer may be considered to act as a *"resonance cavity"* of the GCR variations at a wide range of frequencies, among the most prominent those of 1.3, 1.7, 3 and 5.5 years.

Using the averaged annual data of CR and OHS, in this work we evaluate their most prominent common periodicity during the period 1980-2007 and show that CR are not the main controlling factor for the severity of the ozone depletion, neither their associated periodicities can be used as a predictor of such a depletion behavior, as has been claimed in [11] on basis to a linear correlation with a 11 yrs. frequency.

2 Data and Analysis Method

Data of Galactic cosmic ray (GCR) series from 1980 to 2007, were taken from the South Pole Station in the Antarctic 90S location:
http://neutronm.bartol.udel.edu/~pyle/bri_table.html

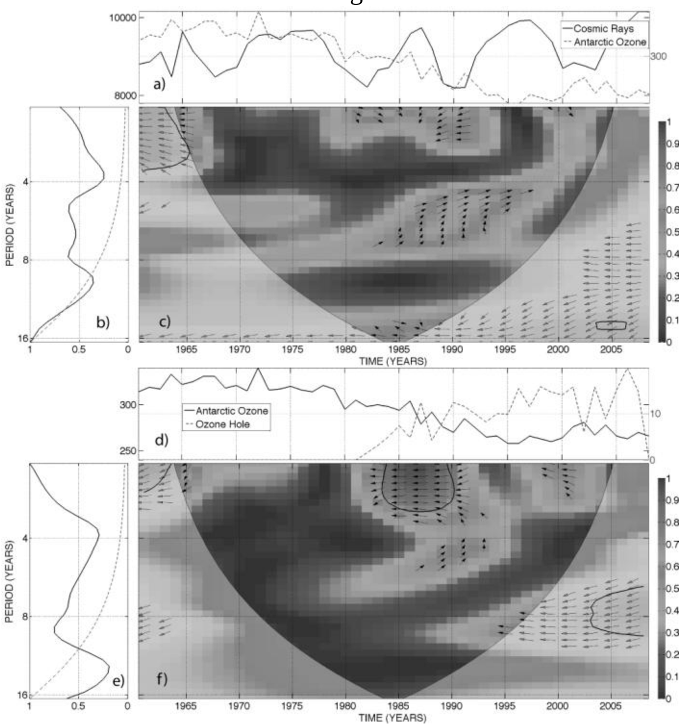
By Antarctic ozone it is mean the total ozone in Antarctic zone, and by ozone hole the conventionally definition, where the total ozone column is less than 220 Dobson Units (DU): series from 1980-2007 were taken from reports of the National Oceanic and Atmospheric Administration (NOAA) Southern Hemisphere Winter Summary 2006 :
www.cpc.ncep.noaa.gov/products/stratosphere/winter_bulletins/sh_06); http://acdb-xt.gsfc.nasa.gov/Data_service/cloud_slice/new_data.htlm;htpp://www.antarctica.ac.uk/met/jds/ozone/data/FOZ5699.DAT.

In order to analyze local variations of power within a single non-stationary time series at multiple periodicities, we apply Wavelet Spectral Analysis, in which case the evolution of common periodicities would indicate the frequencies where both series are synchronic. The wavelet-squared transform coherence (WSTC) is particularly useful in highlighting the time and frequency intervals, when the two phenomena have a strong interaction [12]. The WSTC measures the degree of similarity between the input (X) and the system output (Y), as well as the consistency of the output signal (X) due to the input (Y) for each frequency component. The WSTC spectra allows us to find linear and nonlinear relationships. If the coherence of two series is high, the arrows in the coherence spectra show the phase between the phenomena**.** Arrows at 0° (horizontal right) indicate that both phenomena are in linear phase**,** and arrows at 180° (horizontal left) indicate that they are in linear anti-phase, that is a linear correlation or anticorrelation respectively. Any other value indicate an out of phase situation, implying that the correlation among the two series is of complex nature. Significant coherence values are delimited inside the *cone of influence (COI),* where confidence is higher than *95%.* The so called Global Wavelet Spectra (GWS), is an average of the power of each periodicity in the coherence spectra. It allows us to observe at a glance the periodicities of the coherence analysis that are for above 95% confidence, appearing on or above the red noise level curve..

3 Results

In the Figure 1, panel (a) show the time series of averaged annual data of CR (continuous line) and the Antarctic Ozone (dashed line), panels (b), (e) show the normalized Global Wavelet Spectra (GWS) (in units of Power) and (c), (f) and the Local Coherence Spectra (WSTC). Panel (d) shows the time series the Antarctic Ozone (continuous line) and Antarctic Ozone Hole (dashed line).

Figure 1



According to [11] there is *convincing evidence of the linear time anticorrelation between CR intensity and global O_3 depletion, and since the 11-yr cycle variation of the CR intensity is predictable, the CR-driven electron reaction mechanism leads to direct predictions of one of the severest O_3 losses (due to the CR peak) in 2008–2009, and of probably another maximum in OHS around 2019–2020.* This would imply a direct positive correlation among total ozone and OHS. However, the Global Wavelet (average of the power of each periodicity), panel (b), does not show a synchronized periodicity of 11 years between total ozone and cosmic rays, but only periodicities at 5.5 and 7 years in the interval 1985-1995, with a coherence of 0.6 and a quasi-complex relation (non-linear). The WSTC, Panel (b), shows additional periodicities in the range 1.3-1.7 yrs. in reverse phase, during the limited interval 1988-1992. The GWS and WSTC between the Total Antarctic Ozone (continuous line) and the Antarctic Ozone Hole (dashed line), panels (e) and (f) show periodicities in the range 1.3-3 yrs. in anticorrelatoion, but these are not continuous in time, rather limited to the interval 1982-1991. Multiannual periodicities (7-9 years) can be seen totally out of the COI, that even if one would like to associate them to a periodicity of 11 years, this is discontinuous in time, covering rather 2003-2007, what avoids any prediction for the next years.

In Panel (b) just on the dashed curve of 95% confidence there are multiannual periodicity (> 15 yrs.), but again completely out of the Cone of Influence (COI) throughout all the time interval. Therefore, the wavelet analysis show that the CR cycle of 11 years cannot be used to predict the behavior of the total ozone because that would imply the need of a high coherence value and continuous through all the time interval, which is not observed in Panels (b) and (c). Besides, panels (e) and (f) show that any time behavior of the global ozone is scarcely translated on the OHS, because their main interaction is in the lower frequencies, in anticorrelated phase and during a very short time interval.

4 Discussion

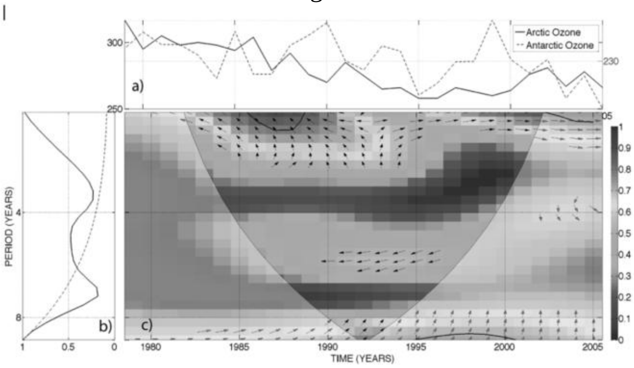
In contrast with the results in [11] we have shown in section 3 that there is no a reverse linear dependence between Antarctic ozone and CR at the 11 yrs. periodicity, but rather a positive weak correlation at lower frequencies and in a limited time interval (1982-1996).. It should be emphasized that results in [11] are based on the best-fit linear line between CR and total ozone variation, however, his best-fitted linear line in his Fig. 4 shows that data dispersion is such that could also be described by any polynomial (n higher 2). No even measures of the linearity degree, as the correlation coefficient (r) are reported. Such kind of measures are fundamental in order to justify the use of CR intensity to predict the total ozone variations and/or the OH severity, The statement *''a strong correlation''* is used in [11] to describe the observed relationship; but, usually this statement implies that (r) is close to 1 and that the independent variable explains most of the variation of the dependent variable. Recently, calculations of (r) were done in [13], using the same data corresponding to that shown in Fig. 4 of [11],, finding a value as low as - 0.5216, and concluding the CR intensity is not the principal variable to explain the total ozone variations and/or the OH severit. At the best it explains, in a linear relationship, only about 27% (r^2) of the total ozone variation, so that other causes should be used to predict most of the variation of the Antarctic ozone. In [14] it is exhaustively shown some of the deficiencies in [11] including the very low value of (r). Nevertheless, this low value is not completely conclusive, because it may happen that the kind of correlation between two phenomena is of non-linear nature, and with a different phase among them, or there is a time delay between one series time (input) and the system reaction (output), and however, do exist a real physical connection, which is not reflected by the low (r) value. Though a Correlational analysis is usually the necessary first step to be done for determining whether or not there is connection between two time series, characterizing two different physical processes, however, such analysis only provides a global information about the degree of linear dependence between the two series, but does not give any information when the correlation dependence is of non-linear nature, and does not provides the evolution of the common synchronized periodicities, nor the evolution of the relative phase among them. It may occur that the global Correlation Coefficient is low, but in some periods of the studied time interval the coherence could be, however, relatively high, indicating the possibility of a non-linear correlation (a complex one) in those periods. Therefore, a complementary study must be done in order to analyze local variations of power within non-stationary time series at multiple periodicities, as CR and O_3 time series. To do so, we obtain from Wavelet-Coherence analysis not only global but also local information in time, and per frequency band [15]: it provides the coherence between both series, by means of the evolution of common synchronized periodicities in time-frequency space and the evolution of the relative phase between two series, determining whether their correlation is linear or not in different band widths, for instance:

- we learn from the coherence between CR and O_3, panel (c) in the figure 1 that there is a multiannual common periodicity (1-3 yrs), with a coherence 0.65 in the period 1980-1993, in an complex relation, turning to an anti-phase relation at the last years. The coherence degrades to 0.3 - 0 in the precedent and proceeding years. However, there is a high value (0.7-1) in the period 1960-1966.
- We also learn that during the period 1985-1995 there is another multiannual common periodicity (5.5-7 years) with a coherence of 0.7 degrading to 0.4 in the surrounding years, with a rather complex (non-linear) relation. Additionally, it can be seen a multiannual periodicity (lower than 3 years) with a high coherence (~ 1) in the period 1983-1990, in anticorrelation, which gradually degrades in the surrounding years to a non linear (complex situation). It has been previously mentioned the presence of a multiannual periodicity (~ 8-16-years) in anti-phase behavior , which is out of the cone of influence (COI), that is less of 95% confidence; here is included the 11 years periodicity, after the year 2000, with a coherence of 0.6. Similar result can be seen in panel (f) where an anticorrelated situation is found during 1995-2007 with a coherence of 0-6-0.7, but again out of the COI. Such detailed information cannot be obtained from a Correlational analysis that as we said before is only of global nature.

Another issue contributing to distortions in the analysis in [12] is the use the incorrect CR time series: the CR data were averaged from 3 station measurements , but two of them are in the north hemisphere, out of the studied latitudes 0°–60° S and 60°–90° S. It is well known that the entrance of CR to earth is highly depen-

dent on latitude and longitude, carried out in a complex way through the so called *acceptance cones* . According to [16] the entrance of cosmic rays , controlled by the following aspects: - The sensitivity (absolute counting rate) varies from one station to the next so that normalization must be used to permit inter-comparison between stations. - the asymptotic cone of acceptance does not have the same shape for all stations, implying that each station respond differently to complex cosmic ray anisotropies – the mean asymptotic directions of the various stations are such that they do not all scan the same circle of the celestial sphere. A correction must be done to eliminate incompatibilities. – the mean asymptotic directions of the stations are not equally spaced in longitude . Thus the counting rate does not lie on a regular grid iin the time-direction plane, so that interpolation schemes must be used – all stations records contain intrinsic fluctuations, so that corrections must be applied. Tables for mean asymptotic coordinates of several stations and contour maps of acceptance cones are given in many works (e.g. [16]). Therefore, work [11] should be based only on data of South hemisphere stations of close mean asymptotic longitude and latitude.
Another source of distortion in [11] is the mixing of ozone data of very different latitudes. Here below we show how data differs very much according latitudes.

Figure 2



We present the wavelet of two time series of ozone from a north and a south hemisphere. It can be appreciated that there is no any kind of relation. This implies that data of the north hemisphere could be only approximated to data of the south hemisphere if as explained in section 3, inside the COI we would have found the coherence near a value 1 (according the scale in Fig. 1) and arrows pointing to the right.

5 Conclusions

Concretely , using Wavelet Analysis we have found that:
(i) cosmic rays have certainly some interaction with the OHS and O_3, translated at several pulsating periodicities, among the most important those in the range 5-7years
(ii) in spite that O_3 fluctuations have not yet been linked with CR fluctuations at midlatitude and tropical regions [17, however, the existence of fluctuations (as those found in this work) in the total ozone variations at Antarctic latitudes, with frequencies similar to those of CR intensity, may perhaps help to explain the discrepancy between the observed and the expected ozone mass depletion [11]. (iii) the 11 yrs. periodicity has not any important role in such interaction , and so there is no any trend for a huge ozone hole in 2019-2020 if such an assumption is only based on a 11- years cycle. (iv) there is no a linear correlation between CR and O_3, what implies that the correlation coefficient is too low, so that CR intensity has not the principal role to explain the ozone variations and/or the OH severity, but rather a minor one, no higher than 27%. Other causes should be evoked to predict most of the ozone variation, regardless of the level of CR intensity.

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