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The Influence of Energetic Particle Precipitation on the Stratospheric Ozone

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ABSTRACT

Stratospheric ozone has suffered a substantial decrease during at least the last 20 years (1,2). The main cause of this erosion is ascribed to anthropogenic activity (3). However, it is well known that ozone abundance is also affected by natural phenomena.
Up to present the following natural causes of abundance variations have been identified: the solar cycle of ultraviolet radiation (4,5), volcanic eruptions (6), temperature inter-annual changes and the atmospheric dynamics (7), big solar proton events (8,9), galactic cosmic rays (10) and relativistic electron precipitation (11).
Maps of ozone global abundance show that the "ozone hole" manifests at latitudes of intense particle precipitation since it is geographically located within the limits of the auroral ovals. This leads to think that it is possible to find a connection between both phenomena.
In this work we present evidence of a relationship between auroral activity and the size of the ozone hole, on the basis of satellite data and on the Ap index of geomagnetic activity in the auroral ovals. Furthermore, we propose an interpretation of the influence of auroral particles on the stratospheric ozone abundance, showing that this is an additional factor to take into account in the phenomenon of the ozone hole.

1. INTRODUCTION

The influence of fast particles on the atmosphere can occur either by direct or indirect interaction depending on the particle energy. For instance, galactic cosmic rays and solar particles of very high energy have enough energy to penetrate the lower layers of the atmosphere to produce "showers" of particles in a kind of cascade effect, such that by direct collisions with the atmospheric molecules of the lower layers their abundance may be altered. Such energetic particles can reach the earth surface, as is the case of the Ground Level Events of solar particles affecting the stratospheric ozone during the event. These alterations remain during several months after the solar event. A deep study of the impact of highly energetic particles on ozone abundance can be found in (8).
On the other hand, most of auroral particles cannot penetrate deeply in the atmosphere because they have lower energies (in the order of some KeV's). In the best of cases they can reach only heights of about 60 Km, in periods of very strong geomagnetic activity. Under these conditions, particles are very numerous and precipitate basically in a continuos way, such that their influence on the earth atmosphere can be seen as a long term one.
Among the many questions that arise at this regard, we deal here with the evaluation of the importance of this effect on the atmosphere, and the physical mechanisms

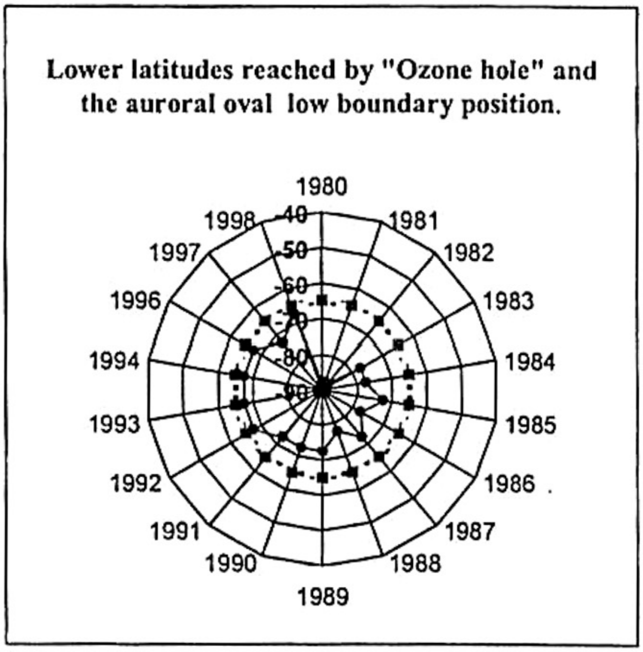

Figure 1. Maximum latitude reached by the " ozone hole" during the years 1980-1998 (the internal curve with full circles), and the position of the low frontier of the south auroral oval (the external curve with full squares). Data obtained from the Internet Web page TOMS (12).

(a) (b)

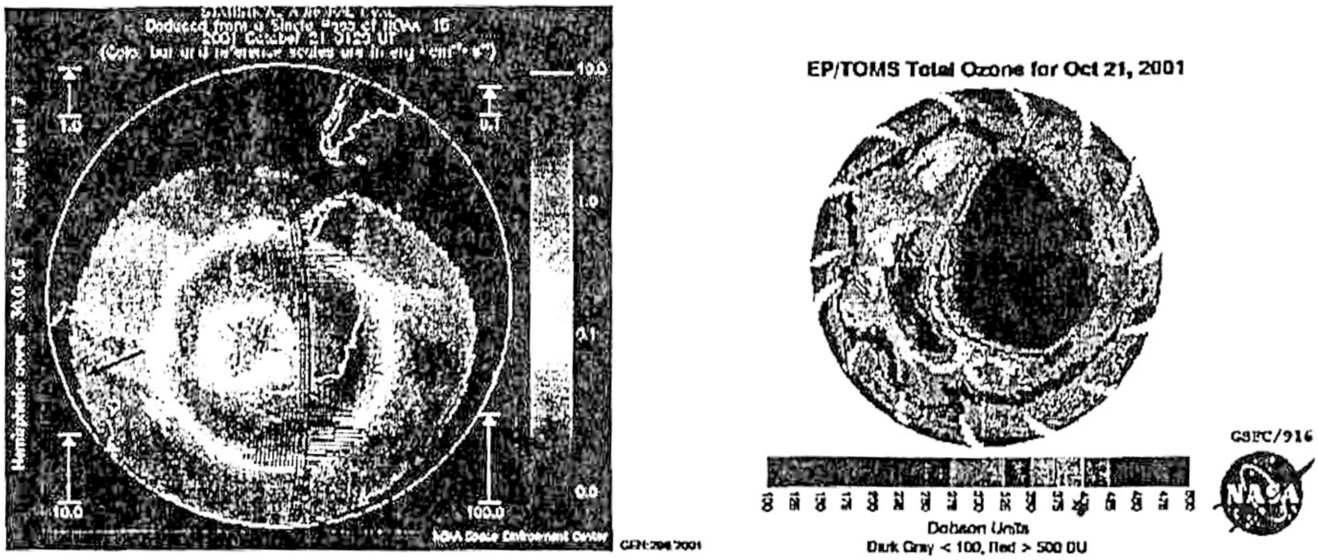

Figure 2. At left (a) it is shown particle precipitation in the auroral south zone during October 21, 2001; at right (b), the position of the ozone hole in the south hemisphere for the same date. It can be appreciated that the precipitation of auroral particles takes place just above the ozone hole. Photographs and map were obtained from Internet in the pages of TOMS (12) and POES Energetic Particles (13) respectively.

of interaction at such atmospheric heights.

In this paper we propose a connection between the precipitation of auroral particles and the erosion of the stratospheric Antarctic ozone as a consequence of the following mechanisms: injection of electric charges to the global circuit by means of auroral electrons., emission of UV radiation in the auroras and heating of the neutral atmosphere by the auroral particles. On basis to ozone satellite data (12), we show evidences to support the hypothesis of a physical connection between the auroral precipitation and the increase of the Antarctic ozone hole size. Additionally, we show that the variation pattern of the ozone hole area is consistent with the amplitude and behavior of the auroral variation cycle of 11 years.

Conventionally it is considered that there is an " ozone hole" when the ozone abundance is lower or equal to 220 DU in an specific geographic locality. The main reason to propose a connection between auroral activity and the "ozone hole" is that both phenomena occurs in similar geographic areas (fig. 1) ; they coincide, in general, in longitude and latitude (fig. 2) but manifest themselves at different heights. While the "ozone hole" is located in the stratosphere between 20 –30 Km of height, auroras occur at the high atmosphere, which particles are able to penetrate only to 90 – 95 km of height. This can be seen in a typical electron density profile during an auroral event (fig 3).

2. THE INTERACTION MODEL

The general scenario proposed in this work is the following: auroral particles precipitate within a zone where the magnetic field topology is favorable for their propagation toward the low atmosphere, since magnetic field lines are roughly in a perpendicular orientation with respect to the earth surface. These particles interacting with the local atoms and molecules in the upper atmospheric layers produce ionization, dissociation, excitation and so, secondary ions and electrons that penetrate even to lower heights.

This favors the entrance of positive and negative charges at atmospheric heights lower than about 100 Km. most of which become assimilated in the low ionosphere, producing an alteration of the global circuit, and therefore, which entails a corresponding modification of the electric field and the circulating currents in the stratosphere. There is also a heating of the neutral atmosphere, below the aurora, which produce ascending winds (14). Additionally, due to the interaction of the auroral electrons with the atmosphere, some times occur high emissions of UV radiation that may reach the earth surface.

It is expected in this general scenario the appearance of a vertical density profile of positive charges and another one of negative charges, with their maximum shifted in height because their difference in motility (electrons move faster) and different interaction cross-sections with the atmospheric constituents. A typical vertical density profile of electrons in auroral regions is schematically illustrated in Fig. 3, where it can be appreciated that it reaches its maximum at a height of 90 – 95 Km, with densities in the order of 10^5 particles/cm^3 (14). Since auroral particles precipitate into the atmosphere under the impulsion of some acceleration mechanism of magnetospheric origin, it is expected that both profiles

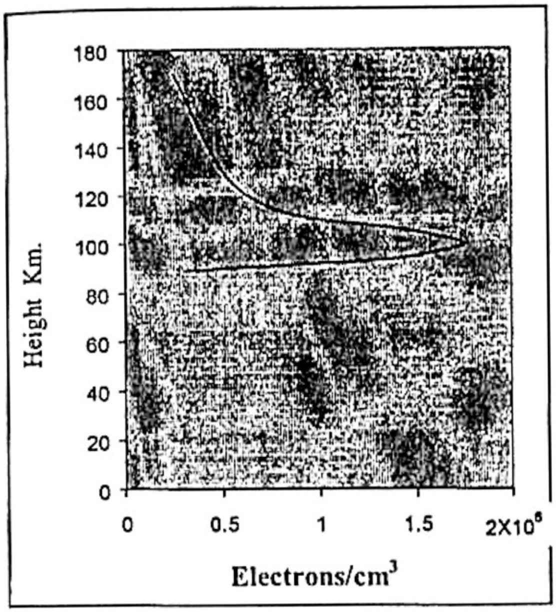

Figure 3. General shape of vertical profiles of the electronic concentrations in auroras, e.g. (14).

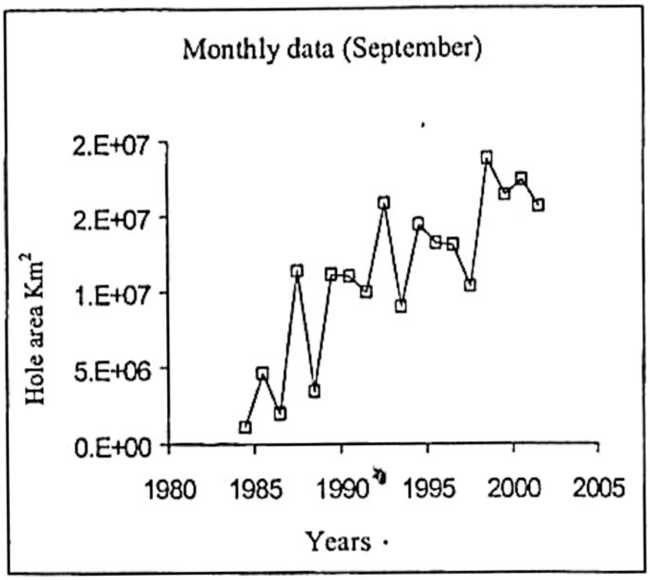

Figure 4. Area of the ozone hole (Km^2) on basis to the average monthly data for the month of September (12). Data for 2000 and 2001 are approximated values taken from the graphic reports given in (12), and data for 1993-1995 were taken from the reported graphics in (19).

(of negative and positive charges) be similar in a same event to maintain the quasi-neutrality of the ionosphere, however, during the event three different situations may occur before reaching the quasi-neutrality equilibrium: first, overabundance of positive (or negative) charges with respect to negative (or positive) charges, 2^{nd}. that both charge distributions be similar but not identical (for instance, as previously mentioned, they may reach their maximum at different heights, because their different motility) and third, that both distributions (electrons and ions) be identical.

Under the first two options an effective electric field will be produced that will penetrate into the low atmospheric layers, which does not take place under the third option.

The intensity of such electric field will depend in the first case on the electronic density and in the 2^{nd} case on the shape of the density distributions of ions and electrons. Several efforts are being done at present to establish the magnitude and duration of the induced electric fields during auroral events, with emphasis at high latitudes where a significant local influence may take place in the low atmosphere [see for instance ref. (15)]

Present measurements has not yet provided a definite picture of the cause-effect relation, since the phenomenon involves complex relationships with the local conditions where measurements can be done, what makes difficult to determine in univocal way the origin of the measured electric field variations that at the level of the earth surface in the Antarctic reach almost 3000 V/m but is not necessarily of auroral origin (16). However, it is reported in (16) variations of the "fair-weather" electric field that can be associated with geomagnetic activity, indicating that the field increases from its normal value (~ 100 V/m) up to ~ 260 V/m which is twice or more than the expected value at the earth surface (17).

An increase of the global electric field of this magnitude implies according to the Ohm law (Eq. 1) that the global current at the stratospheric level may also duplicate (assuming that the conductivity remains unchanged),

$$J = \sigma E, \qquad (1)$$

where J is the density of the vertical electric current, E is the electric field and σ is the atmospheric conductivity. However, experiments have shown that not always exists an increase of the current associated with the auroral events, since in occasions J remains unchanged, which leads to infer that σ is modified in some events, e.g. (18). What is relevant within the context of this work is that in some cases J can duplicate its normal value. In such a case, assuming that σ remains quasi constant, the increase of the electric current at the stratospheric level can reach approximately the double of its normal value. An increase in the current density J implies an increase of the number of moving charges or an increase of their velocity

$$J = \Sigma_i N_i q_i v_i \qquad (2)$$

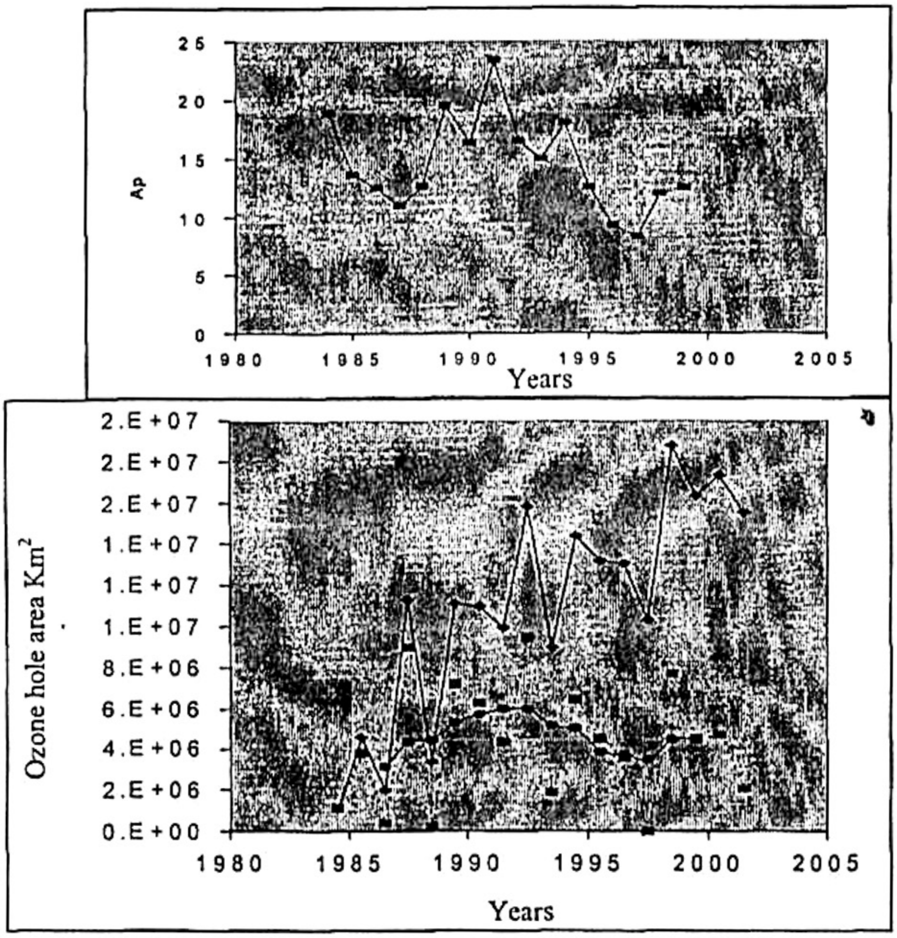

Figure 5. (a) Annual indexes of geomagnetic activity Ap, (b) evolution of the area of the ozone hole: the upper solid curve is total area, the dashed curve is the cyclic contribution and the doted line is the smoothed curve of the cyclic contribution.

Where i denotes the type of charge carriers, N_i is the number of carriers of the type i per volume unit, q_i is the charge of each type of carrier and v_i is the average displacement velocity of the charge carrier of type i. Therefore, in occasions when a change of geomagnetic activity does not produce a change of the charge density N_i in the stratosphere (and conductivity σ remains constant in consequence), it is inferred that the charge velocity is duplicated and their kinetic energy will increases by a factor of four, such that the circulating charges increase their feasibility to dissociate ozone and oxygen through collisions with the traversed medium, and consequently to create and destroy the stratospheric ozone.

3. RESULTS AND ANALYSIS

According to the present interaction model a relation between auroral activity and ozone erosion must exist. Based on the fact that an increase of the stratospheric current implies an increase of the number of collisions of ions and electrons with the medium that may dissociate the local ozone and oxygen, and hence, affecting the photochemical processes of creation and destruction of ozone, even in the absence of the solar light. Besides, other auroral effects must be considered: auroras emit UV radiation (which can interact with the stratospheric ozone), and there is a heating of the neutral atmosphere below the auroral zone. These heating effect produce the appearance of ascendant winds just below the auroral zone (14) that may favor the PSC (Polar Stratospheric Clouds) to reach higher heights (below the aurora) and participate in the process of ozone erosion by the normal way.

On basis to the previous discussion, we can infer that during the obscurity of the Antarctic winter (not solar illumination) the conditions for ozone erosion are present, mainly in periods of high auroral activity.

Though, in principle seems easy to corroborate this hypothesis, however, satellites monitoring the total ozone make use of the backscattered Earth radiance, so that cannot obtain data under conditions of obscurity.

Nevertheless, it is expected that during the first days of solar illumination (early September) the effect of auroral activity may be perceptible before the chemistry and atmospheric dynamics becomes completely dominated by solar illumination.

Looking for this possible connection we analyzed the areas of the Antarctic ozone hole, on basis to the average monthly data reported in Internet (12), (19) for the month of September from 1979 –2000. The behavior of the size of the ozone hole is illustrated in Fig. 4. Here it can be appreciated at least two patterns, one with a monotonic growing tendency, which is very consistent with the expectance of the anthropogenic contamination (20), and a cyclic (oscillatory) pattern with a similar periodicity of that of the auroral activity cycle of 11 years.

When this cyclic pattern is compared with a graphic of the Ap index (which is characteristic index of geomagnetic activity in the auroral oval) it is found that they behave qualitatively similar, as can be seen in Fig. 5. The kind of the relationship is not linear, as we suspected, since not all events affect in the same way the stratosphere because the interaction aurora-stratosphere may occur at least by one of the three different auroral associated effects discussed before, that is, direct particle interactions or indirectly particle effects through UV radiation and ascendant winds.

It can be appreciated on Fig. 5 that the relative importance of the cyclic variation of the area of the ozone hole (dotted line) vary in time, because the size of the hole (solid line) is increasing with time. According to the smoothed curve of the cyclic component (overlaying the cyclic curve), before 1991 the expected contribution from the auroral activity in defining the size of the hole was of the same order or bigger than the growing linear tendency attributed to contaminants of the anthropogenic type. After 1991 the later is more important that the cyclic component. By the year 1999 the contribution of this cyclic component is only about 30% which is not negligible, at least during the month of September.

Consequently, we can affirm that given the magnitude of the auroral effect on the size of the hole, this is another natural factor to take into account among the processes of variation at long term. Probably this effect has been permanently present, but it remained unprovided because the ozone hole was discovered only the 1980's (when the effects of the anthropogenic contaminants manifest in a more drastic form) and we have a few years of data, less than two 11-years periods. Perhaps the ozone hole was present before those years but the absence of high quality data and global coverage did not allow evidencing it. We claim here that ozone erosion of the cyclic type (that may not be considered as a hole) has been present due to natural phenomena. What is important to emphasize is that nowadays the dominant effect in the continuos increase of the hole during the periods of solar illumination is the anthropogenic contamination.

4. CONCLUSIONES

On basis of data of the size of the ozone hole and auroral activity we have present here a model that predicts a cyclic erosion of the stratospheric Antarctic ozone. As a consequence, even under conditions of obscurity with no solar illumination during the Antarctic winter there is ozone erosion, and a kind of hole (or depression) of cyclic character may develop in periods of high auroral activity. This prediction could be confirmed with observational experiments based in a different method than the used in TOMS, which satellite data (12) has been considered in this work. Data during obscurity periods is required in order to test our predictions.

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