IMPACT OF SOLAR VARIABILITY ON THE TERRESTRIAL ATMOSPHERE

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ABSTRACT
Evidence in atmospheric responses to solar variations have been reported from satellite observations like Nimbus 7 and Solar Mesosphere Explorer, for minor constituents like ozone and nitric oxide. Model calculations generally support the observed changes. They are based on our current knowledge of aeronomical processes and on the solar variations observed during the last solar cycle. This paper briefly reviews these different topics. The impact of solar variability on stratospheric ozone is also compared to man-made perturbations. Possible feedbacks between stratospheric perturbations and tropospheric chemistry are also presented.

I. INTRODUCTION
The solar electromagnetic radiation is the primary source of energy for the terrestrial environment. The largest fraction of energy associated with the solar spectrum is situated in the visible. The ultraviolet domain for wavelengths shorter than 320 nm represents only a small fraction (2 percent) of the total incident flux. This spectral range is of fundamental importance for aeronomical processes from the troposphere to the thermosphere. It also plays an important role for photobiological processes in the biosphere because of its ability to destroy living cells and its role in initiating photosynthesis, the primary basis for life on Earth. Most of the solar radiation of wavelength larger than 320 nm is reaching the Earth's surface and channelled into heat. About 70 percent of the incident flux is so absorbed. The Earth's radiative budget depends upon the balance between the outgoing infrared radiation and the total solar input.

Because of the complexity of the atmospheric processes and the strong interplay and feedback between chemical composition and radiative budget, climate studies should include observations of visible and ultraviolet solar radiation and its variability, in close relation with the atmospheric constituents which control the penetration of solar radiation and the transfer of the outgoing thermal radiation. The ozone molecule is a key minor constituent for the stratosphere and the mesosphere. It provides the main heat source through the absorption of solar ultraviolet radiation and thus determines in large part the temperature profile in the stratosphere and the general circulation. Ozone therefore couples the stratosphere and the tropospheric climate through complex processes involving radiative, chemical and dynamic effects. The study of solar variability with respect to anthropogenic perturbations is of crucial importance to distinguish between the various perturbation expected to affect the terrestrial environment in the future.
These problems are of major concern for the International Geosphere Biosphere Program (IGBP). This work will briefly review the current knowledge on variations in solar ultraviolet input into the terrestrial atmosphere and their impacts on mesospheric, stratospheric and tropospheric oxidation processes. The impact of solar variability on stratospheric ozone will also be compared to man-made perturbations.

II. AERONOMIC PROCESSES

Absorption of solar extreme ultraviolet radiation (EUV) determines the structure of the upper thermosphere and leads to ionization of the major species, namely O₂, N₂ and O. Consequent reactions involving recombination of ions and electrons produce minor species like NO. Details on nitric oxide photochemistry are given in a recent model developed by Cleary (1986). In the lower thermosphere (altitudes below 120 km) absorption by molecular oxygen in the Schumann-Runge continuum is responsible for heating and production of atomic oxygen which is transported to the upper mesosphere, together with nitric oxide. The thermal balance in this region is also controlled by infrared radiative losses from CO₂ and NO. More informations on thermospheric aeronomy have been reported, for instance, by Banks and Kockarts (1973) and Roble (1977).

Solar Lyman α and ultraviolet radiation of wavelengths larger than 180 nm are absorbed in the mesosphere and in the stratosphere. The Lyman α solar chromospheric line initiates photoionization processes in the D-region, and the photodissociation, for instance, of water vapor in the mesosphere, controlling the ozone budget in the mesosphere through the production of OH radicals as explained later.

Ozone, which protects the biosphere from harmful solar ultraviolet radiation, is produced in the upper stratosphere by photodissociation of molecular oxygen by radiation of wavelengths shorter than 242 nm, through the following reaction:

\[ \text{O}_2 + h\nu (\lambda < 242 \text{ nm}) \rightarrow 0 + 0 \]

\[ \text{O}_2 + 0 + M \rightarrow \text{O}_3 + M \]

The ozone itself is photodissociated to form atomic oxygen:

\[ \text{O}_3 + h\nu \rightarrow \text{O}_2 + 0 \]

Chemical loss of odd oxygen was first attributed by Chapman in 1930 only to the reaction:

\[ 0 + \text{O}_3 \rightarrow 2\text{O}_2 \]

Later on, it was realized that this reaction is catalyzed by various radicals according to mainly the following scheme:

\[ \text{...} \]
\[
\begin{align*}
X + O_3 & \rightarrow XO + O_2 \\
XO + O & \rightarrow X + O_2
\end{align*}
\]

net \[O_3 + O \rightarrow 2O_2\]

the catalyst X being H, OH, NO, Cl or Br.

Those radicals are primarily of tropospheric origin except for NO which, in addition to production processes in the stratosphere from \(N_2O\) oxidation, can also be supplied by downward transport from the lower thermosphere in the polar night.

More details on chemical processes in the middle atmosphere are given in Brasseur and Solomon (1986). Figure 1 illustrates the complexity of processes determining the structure of the stratosphere.

In the troposphere, the central role is played by OH radicals which oxidize various hydrocarbons like, for instance, methane and chlorocarbons and, consequently, control their tropospheric lifetime and their fluxes into the stratosphere.

This radical is of photochemical origin and depends upon the level of UV-B radiation (280-320 nm) in the troposphere and, consequently, upon the amount of ozone in the stratosphere. It is produced by the following reactions:

\[
\begin{align*}
O_3 + h\nu (\lambda < 310 \text{ nm}) & \rightarrow O_2 + O^1(D) \\
H_2O + O^1(D) & \rightarrow 2OH.
\end{align*}
\]

A more comprehensive scheme of tropospheric chemistry is presented in figure 2. The oxidation processes are actually initiated by a small wavelength range limited on one side by the ozone cutoff of solar radiation and on the other side by the quantum yield values of \(O^1(D)\) production (figure 3). Changes of damaging ultraviolet radiation in the troposphere related to total ozone variations are illustrated by figure 4. Links between solar radiation, stratospheric and tropospheric chemistry and climate are illustrated in figure 5.

This brief survey is intended to demonstrate that the solar ultraviolet radiation is the critical driving force in aeronomic processes; it illustrates the complexity of the solar-terrestrial interactions, the ozone molecules being involved in coupling phenomena between chemical, radiative and dynamic processes needed to understand our atmospheric environment.

III. THE ULTRAVIOLET SOLAR RADIATION

The Sun is the primary driver for terrestrial aeronomic processes. More specifically, solar ultraviolet radiation plays the fundamental role in determining the structure and the composition of the atmosphere. For the stratosphere, the wavelength range between 175 nm and 240 nm is responsible for the production of ozone. For the troposphere and the biosphere, the wavelengths larger than 290 nm are the most important in controlling the photobiological processes.
Our knowledge of solar ultraviolet irradiance made an important step forward since 1982 with the rocket measurements reported by Mount and Rottman (1983a, 1983b, 1985) and the Spacelab 1 and 2 observations reported by Labs et al. (1987) and VanHoosier and Brueckner (1987). This progress is mainly due to improvements in calibration procedures used in the laboratory but also in orbit, when properly using the space shuttle advantages (Simon and Hilsenrath, 1988).

The ultraviolet range of the solar electromagnetic spectrum is characterized by its temporal variations which directly affect the atmosphere. Two time scales are generally considered in relation with atmospheric studies: the 11-year activity cycle and the 27-day rotation period of the Sun. Despite of considerable effort during the last solar cycle, the amplitude of solar variation associated with its 11-year activity cycle is still uncertain. The Solar Backscatter Ultraviolet (SBUV) spectrometer data were analyzed by Heath and Schlesinger (1986); they deduced long-term variation from an empirical relation based on temporal variation of ratios between core and wings irradiances of the Mg II lines at 280 nm. Their variations are not confirmed by the Solar Mesospheric Explorer (SME) results obtained during the declining phase of solar cycle 21 (since 1982) which lead to lower values in the overlapping wavelength range (160 - 300 nm). In addition, long-term variations between 115 and 180 nm deduced by comparison between rocket observations during maximum solar activity, namely 1979 and 1980 (Mount et al., 1980; Mount and Rottman, 1981) and those performed at solar minimum (Rottman, 1981), are of about a factor 2 at Lyman α and around 150 nm. These values are now totally contradicted by recent analysis of SME data, leading to variations of the order of 15 percent around 150 nm and of 5 percent between 180 and 210 nm (figure 6).

The 27-day solar rotation variations have been well documented with the SBUV satellite and the SME data base. This short-term variation has been more extensively studied because it is much less affected by sensitivity drifts of the SBUV spectrometer. If the agreement between the two satellites during the overlapping period of time is very good for the major rotation variation on August 1982, the average during the declining phase of the solar cycle shows some appreciable differences beyond 240 nm where SBUV data are less noisy than those of SME and below 190 nm where SME data are of better quality and give higher 27-day variations than SBUV, especially at the Si II line lying in the 180-182 nm interval. Figures 7 and 8 present a FFT analysis of 27-day variations on both time series between 160 and 300 nm. A more complete picture is presented by the 3-D plot on figure 9 illustrating the 27-day variations deduced from SME data, from Lyman α to 300 nm.

IV. ATMOSPHERIC RESPONSE TO SOLAR ULTRAVIOLET VARIATIONS

Responses of the middle atmosphere to solar ultraviolet variations are summarized in figure 10.

At present, effects of long-term variation of solar ultraviolet irradiance are not conclusive because observations of changes on that time scale in both the ultraviolet solar flux and the sensitive trace species are not reliable at the level of natural changes. This situation has pushed forward theoretical investigation made by means of one- and two-dimensional photochemical models. The first two-dimensional (altitude and latitude) study based upon reasonable but empirical solar ultraviolet variation related to the 11-year activity cycle has been published by
Brasseur and Simon (1981), followed by other studies considering new inputs improving our knowledge of solar variabilities (Garcia et al., 1984; Brasseur et al., 1988).

Actually, the long-term response of atmospheric ozone to solar variations needs to be much better understood and well supported by dedicated observations because natural changes in ozone have to be removed from time series obtained during the two last consecutive solar cycle in order to detect the ozone trend resulting from human activities. The model simulation of ozone perturbation recently reported by Brasseur et al. (1988) shows that the solar cycle effect during the declining phase of solar cycle 21 (from 1979 to 1986) is of the same order of magnitude that anthropogenic perturbations (figure 11). Predictions in total ozone trend during the current solar cycle (its maximum of activity being expected in 1991) give an increase of ozone toward a maximum at that time. This means that the solar cycle variation in ultraviolet irradiance will counterbalance the predicted decrease due to anthropogenic chlorine compound emissions. After 1991 the total ozone column is predicted to decrease again with a rate still enhanced by the decline in solar ultraviolet irradiance.

Consequently, reliable observations of solar variation are urgently needed to be able to quantitatively discriminate between natural changes and anthropogenic perturbations.

The only unambiguous evidence of trace species response to solar cycle in the atmosphere is, until now, the nitric oxide measurements performed by SME and reported by Barth et al. (1988). SME Lyman α observations have been used as an index for EUV and X-ray irradiance, showing a positive correlation with nitric oxide concentration in the lower thermosphere during the declining phase of solar cycle 21 (figure 12 and 13).

Because of the difficulty in detecting changes in the atmosphere related to the solar activity cycle, the impact of the 27-day variation associated with the rotation period of the Sun was in the meantime analyzed in detail. Indeed, observations over short time scale periods are by far more accurate by avoiding the aging problem of observing instrumentation. These studies have been very useful in the validation of photochemical processes.

Observational evidence of ozone responses to short-term solar ultraviolet variation have been reported by Gille et al. (1984), Hood (1984, 1986, 1987), Keating et al. (1985, 1987), Eckman (1986a) on the basis of available satellite data, namely the Nimbus 4 Backscattered Ultraviolet (BUV), the Nimbus 7 Limb Infrared Monitor of the Stratosphere (LIMS), SBUV and the Nimbus 7 Stratospheric and Mesospheric Sounder (SAMS). Examples of ozone response in the stratosphere and in the mesosphere are respectively given in figure 14 and 15. In addition, variations of nitric acid and nitric dioxide related to the 27-day variability have been reported by Keating et al. (1986).

These studies have been supported by theoretical analysis like those of Eckman (1986b) and Brasseur et al. (1987). They showed the strong anticorrelation between ozone and temperature in the upper stratosphere. When the temperature feedback on ozone variation is removed, correlation of ozone changes with the 27-day solar variabilities at 205 nm is clearly demonstrated, especially at 2 mb (~43 km altitude).
V. CONCLUSION

One purpose of IGBP is to move from multidisciplinary toward interdisciplinary approach of scientific questions and to apply this concept to the geosphere and the biosphere. Among the multiple disciplines involved, for instance, geophysics, biology, ..., the Sun-Earth relationship are of fundamental importance for global changes. This topic is very broad and cannot be limited to a single aspect such as climatology, but should expand beyond current limits between disciplines in geophysics. This approach requires the study of the mutual interactions between different atmospheric and biological processes at all altitudes ranges.

A high level of skill has been reached in geophysics by the Belgian scientific community since many years. This know-how is recognized by the international community. Theoretical and experimental works have been successfully conducted in all aspects involved in solar-terrestrial interaction studies (modelling, satellite observations, laboratory studies, ...). The IGBP would give the opportunity, in the 1990’s to fully develop the Belgian potentialities in geoscience.
REFERENCES


Figure Captions

Figure 1.- Schematic depiction of principal coupled processes relevant to the stratosphere (after "Earth System Science", NASA, 1988).

Figure 2.- Schematic depiction of principal interactions relevant to the tropospheric biochemical cycles (after "Earth System Science", NASA, 1988).

Figure 3.- Solar ultraviolet radiation at the Earth's surface and O(1D) quantum yield as a function of wavelength.

Figure 4.- Relative change (in percent) in farmful ultraviolet radiation as a function of relative ozone change (in percent) in the atmosphere.

Figure 5.- Links between solar radiation, stratospheric and tropospheric chemistry and climate.

Figure 6.- Solar cycle variation between 140 and 200 nm deduced from rocket and satellite observations during solar cycle 21.

Figure 7.- Comparison of 27-day variation deduced from SME and SBUV observations as a function of wavelength, for a major variation on August 11, 1982.

Figure 8.- Comparison of 27-day variation averaged on 1982, 1983 and 1984 deduced from SME and SBUV observations, as a function of wavelength.

Figure 9.- Amplitude (in percent) of 27-day variation, averaged over 5 nm intervals, as a function of wavelength and time, deduced from SME time series between January 1, 1982 and December 31, 1984, by means of a FFT analysis.

Figure 10.- Schematic depiction of the middle atmosphere responses to solar variations.

Figure 11.- Relative ozone change between 1979 and 1986 (expressed in percent) averaged over all latitudes and seasons. The contributions of the trace gases and solar effects are shown together with the combined results. The largest decrease (7.2%) is found at 42 km (after Brasseur et al., 1988).

Figure 12.- Solar Lyman alpha irradiance. The time period is January 6, 1982 - April 19, 1985 (after Barth et al., 1988).

Figure 13.- Variation of low-latitude nitric oxide in the E-region. The time period is January 6, 1982 - April 19, 1985 (after Barth et al., 1988).
Figure 14.- Ozone response corrected for temperature effects to change in 205 nm solar radiation derived from Nimbus 7 (November 1978 to May 1979), Nimbus 7 SBUV over the same data interval as LIMS, and Nimbus 7 SBUV over the longer period from December 1978 to October 1982. The SBUV ozone data is corrected for temperature effects, using Nimbus 7 SAMS temperatures. The sensitivities are all obtained at 10, 5, 2, 1 and 0.5 mbar and are displaced on the figure for clarity. The "ratios" for ozone and 205 nm solar flux are defined as (X - \bar{X})/\bar{X}, where \bar{X} is the 5-day running mean of the parameter and \bar{X} is the 27-day running mean of X. The theoretical response without temperature effects for 27-day solar variations is taken from Brasseur et al., 1987 (after Keating et al., 1987).

Figure 15.- Mesospheric ozone response to change in 121.6 nm (solar Lyman \alpha) radiation, as a function of pressure and approximate altitude. The terms are defined as in Figure 14. The sensitivities are determined from SME 1.27 μm ozone data averaged between + 40° latitude and SME solar Lyman \alpha data (December 1981 - September 1983) (after Keating et al, 1987).
Figure 1.

Figure 2.
Figure 3.

Flux (W m⁻² nm⁻¹)

- Extraterrestrial flux
- Flux at ground
- Ozone cutoff
- O(¹D) quantum yield

Wavelength (nm)

280 300 320 340 360 380 400

Ozone cutoff:

UV-B

UV-A
Figure 4.
- 63 -

Figure 5.
Figure 6.
Figure 7.

Figure 8.
Figure 9.

Aug. 11, 1982

30% —

31 Dec. 1984

122.5

Si II Al edge

λ (nm) 297.5

1 Jan. 1982

Time
RESPONSES OF THE MIDDLE ATMOSPHERE TO THE SOLAR VARIATIONS

Figure 10.
Figure 11.
Figure 12.

SOLAR ULTRAVIOLET FLUX

Ly α

Figure 13.

LOW LATITUDE NITRIC OXIDE

NO
Figure 14. 

Figure 15. 

\[ \frac{(O_3 - \overline{O}_3)}{\overline{O}_3}/\left(\frac{l_{205} - \overline{l}_{205}}{l_{205}}\right) \]

\[ \frac{(O_3 - \overline{O}_3)}{\overline{O}_3}/\left(\frac{l_{122} - \overline{l}_{122}}{l_{122}}\right) \]