ATMOSPHERIC CHANGES AND UV-B MONITORING

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ABSTRACT. The atmospheric parameters controlling the UV-B irradiance at the Earth's surface are shortly described. The long-term changes in the stratospheric and tropospheric composition affecting the UV radiative transfer are reviewed in order to define the appropriate strategy for global UV-B monitoring. The broad-band radiometer and spectral irradiance measurements currently performed are presented and discussed.

1. INTRODUCTION

Significant ozone reductions have been observed at mid and high latitudes in both hemisphere during the last decade. Because the UV-B (280-320 nm) solar irradiance is strongly absorbed by stratospheric ozone, the global climatology of UV irradiance at the Earth's surface will be affected by ozone variabilities and trends. This wavelength interval induces also photoreactions on biological systems. Therefore it is important to quantify future UV-B changes on a global and regional scales in order to investigate the changes induced to the biosphere.

The complexity of UV-B monitoring is related to the number of factors, in addition to the stratospheric ozone, which controls the UV penetration in the troposphere. Other minor species play a non-trivial role and the scattering and extinction by aerosols, haze and clouds induce natural and/or anthropogenic variations near the surface which are more difficult to be accurately included in radiative transfer models.

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This work will briefly review the present knowledge of atmospheric changes affecting the UV-B irradiance at the Earth's surface and will give some examples of UV-B measurements currently in operation or in development.

2. THE ULTRAVIOLET IRRADIANCE AT THE EARTH'S SURFACE

The penetration of UV solar irradiance in the terrestrial atmosphere is controlled by the absorption of molecular oxygen and ozone. This process is well described by the Beer-Lambert law which corresponds to a simplified case of the general radiative transfer equation. When considering UV irradiance at the Earth's surface, additional processes should be taken into account, like the multiple scattering in the lower stratosphere and the troposphere.

The solar spectral irradiance in the UV has been measured several times from a variety of platforms, including satellite, space shuttle, balloons and airplanes. Observations were also performed from the ground (for wavelengths greater than 330 nm). The most recent measurements performed since 1983 from the space shuttle provided the most accurate values so far, with quoted accuracies between 3.5 and 5 percent between 200 and 400 nm. The UV-B range correspond to the wavelength interval between 280 and 320 nm (Figure 1). This range represents only 1.5 percent of the global solar irradiance (the solar "constant"). The Solar Mesosphere Explorer (SME) measurements from November 1981 to April 1989 do not show significant long and short-term variations in that range related to the 11-year activity cycle and the 27-day rotation period of the Sun. Consequently, the most pronounced temporal variation around 300 nm of the extraterrestrial solar irradiance is linked to the Earth's orbital parameters, inducing a change of 6.6 percent from January (maximum) to July (minimum) each year.

The factors controlling the UV radiative transfer in the atmosphere are defined by the equation of radiative transfer with the extinction cross sections expressed as the sum of the absorption and scattering cross sections. The solar zenith

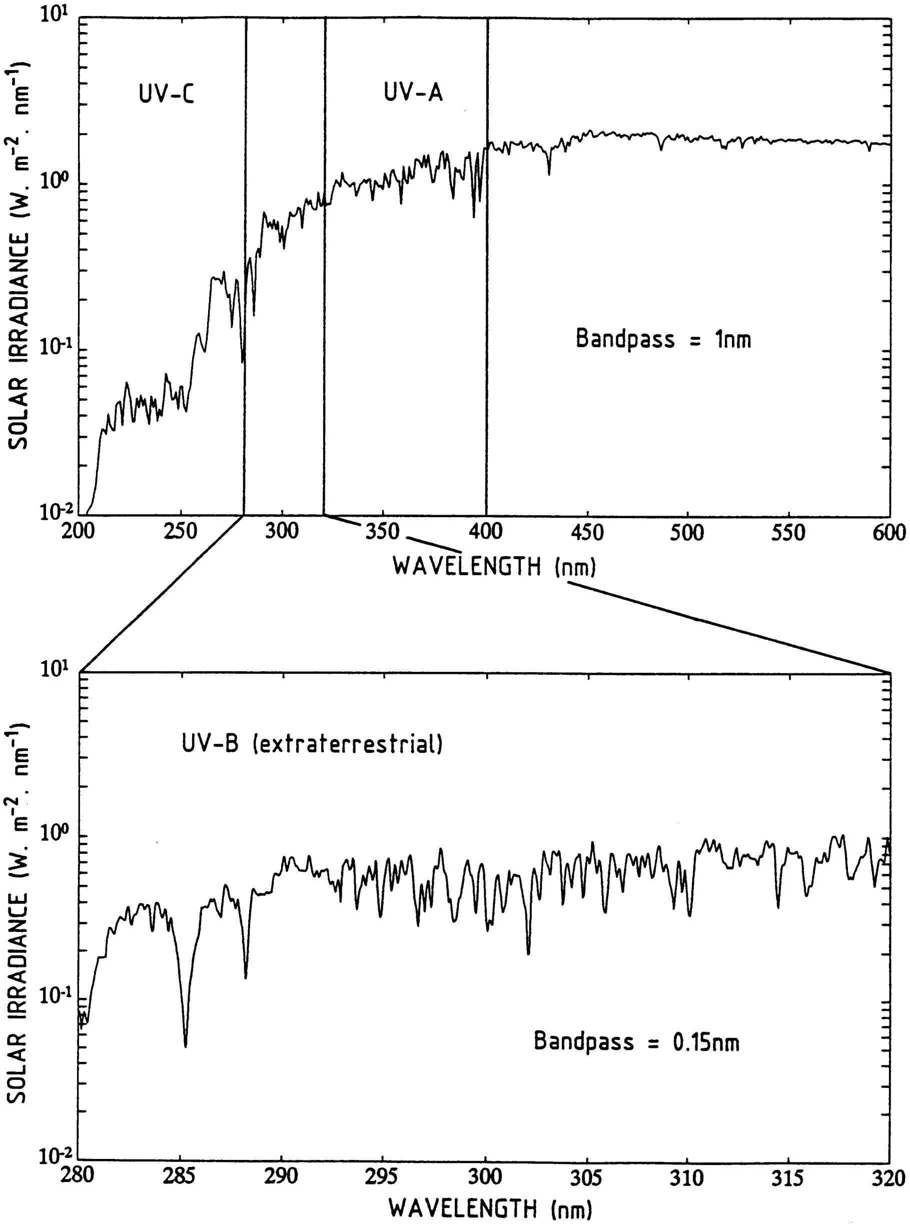

Fig. 1. The extraterrestrial solar irradiance between 200 and 600 nm (upper panel) and in the UV-B region (lower panel)

angle (SZA) is a key parameter in the definition of the atmospheric optical path. Its diurnal, monthly and latitudinal variations induce large irradiance changes in the UV-B range. For a given amount of atmospheric ozone, the SZA variations produce shifts of the atmospheric cutoff wavelength larger than 10 nm around 300 nm (Figure 2).

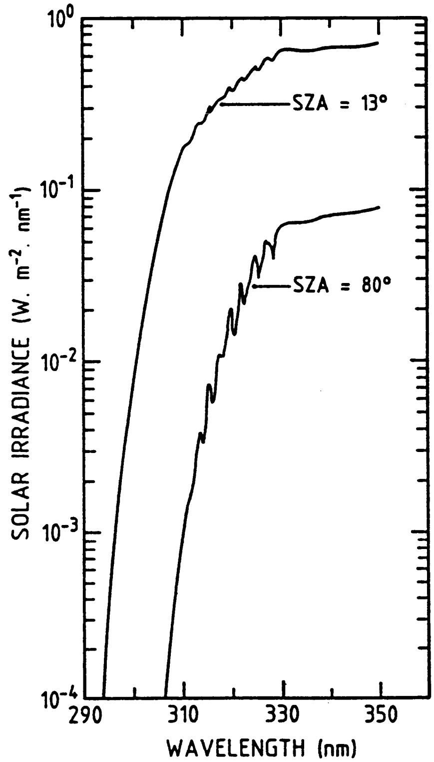

Fig. 2. Solar irradiance at the Earth's surface computed for a SZA of 13° and 80° (clear sky conditions). Adapted from WMO 1989.

2 .1. Stratospheric contributions

The ozone is the primary constituent controlling the UV penetration through the stratosphere. Its absorption cross sections in the 280-320 nm wavelength interval which overlap the Hartley and Huggins bands, are decreasing toward the longer wavelengths by more than two orders of magnitude (Figure 3) In addition their temperature dependence require the knowledge of the ozone and temperature vertical profiles to make correct calculations of the ozone optical depth.

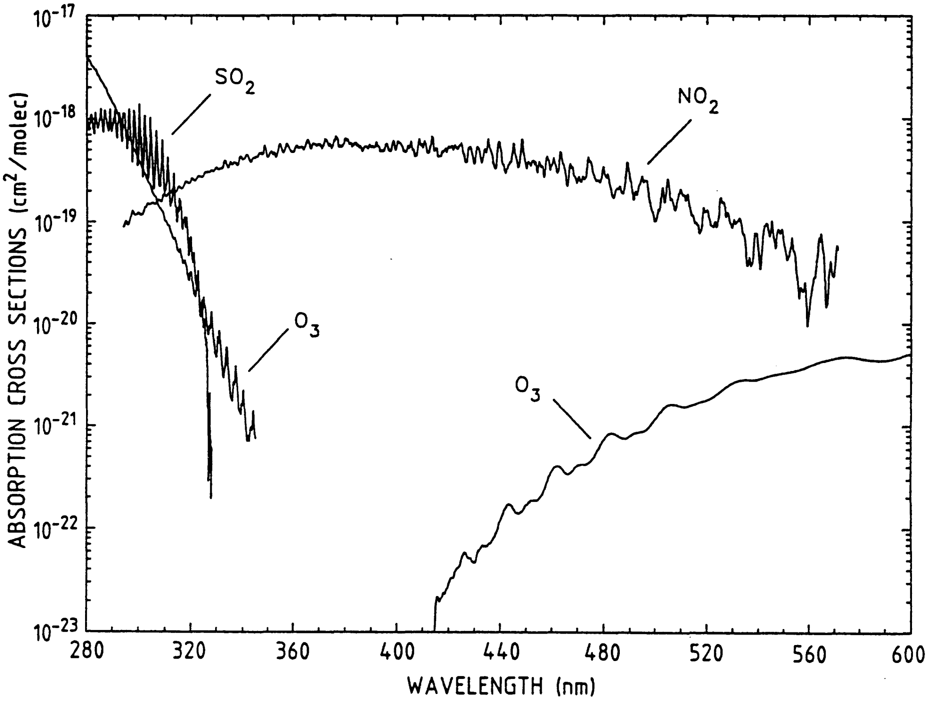

Fig. 3. Absorption cross sections of ozone, nitrogen and sulfur dioxide between 280 and 600nm.

The Rayleigh scattering is controlling in a lesser extent the atmospheric extinction in the UV, mainly in the lower stratosphere. The stratospheric aerosol extinction has also to be taken into account after major volcanic eruption like the Mt. Pinatubo in June 1991. The optical depth of the other trace constituents, like for example the nitrogen dioxide, is negligible because of their lower column densities by comparison with ozone.

The climatology of ozone has been systematically studied since the International Geophysical Year (IGY) in 1957-1958 and shows large seasonal and latitudinal variations both in total abundances and in vertical distribution of concentration, producing large gradient in solar UV-B.

2.2 Tropospheric contributions

The structure and composition of the troposphere contribute significantly to the radiative transfer of UV solar irradiance. In addition, the Rayleigh scattering becomes an important process controlling the UV penetration, reaching its maximum efficiency near the surface. The presence of gaseous pollutants like nitrogen and sulfur dioxide having absorption bands in the UV-B range (Figure 3) should also affect the tropospheric transmission of UV solar irradiance with large hemispheric, latitudinal, seasonal and altitude variations in relation with the anthropogenic sources of pollution. In addition, the recent changes in tropospheric ozone are related to increased emissions of hydrocarbons, carbon monoxide and nitrogen monoxide. Consequently, trends of tropospheric pollutants are difficult to be evaluated and predicted on a global scale. Ozone sondings in Europe have shown ozone increases up to 10 km altitude.

The light scattering by haze, particulates and aerosols is another important factor for tropospheric radiative transfer of solar irradiation. The role of clouds is one of the most varying parameter because of their high spatial and temporal variabilities and their different structures. Cloud extinction could reduce UV irradiance by a factor up to 5.

The role of the Earth's albedo as to be carefully taken into account when measuring and modelling the UV irradiance at the surface. This parameter is responsible for enhancement of tropospheric radiation (Figure 4) due to the combination of albedo and scattering effects, for particular atmospheric conditions. An global amplification ratio can be defined which depends upon the relative importance of albedo and Rayleigh scattering with respect to altitude.

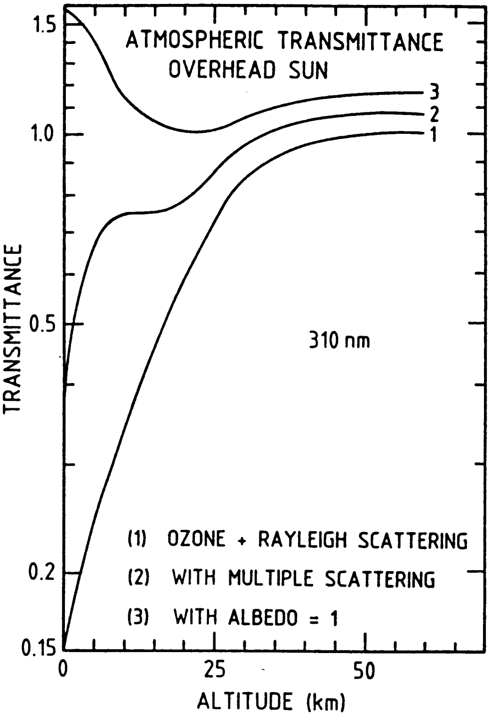

Fig. 4. Atmospheric transmittance at 310nm for an overhead Sun, from 0 to 60km altitude in a standard atmosphere, for ozone and Rayleigh extinction only (1), with the addition of multiple scattering (2) and with the additional effect of an albedo of 1 (3). From Nicolet (1992).

3. BIOLOGICAL WEIGHTED IRRADIANCE

The UV irradiation induces biological photoreactions which are characterized by action spectra, specific to each process (Figure 5). They generally have a maximum at wavelengths shorter than 300 nm, even below 280 nm (UV-C domain), and decrease sharply by several orders of magnitude in the UV-B region. Some of them exhibit a non negligible response in the UV-A range represented by a tail in the action spectrum, having a smooth decrease in efficiency toward the visible range. Consequently, the UV-A, not affected by atmospheric ozone change, need to be quantified for effect studies on biota.

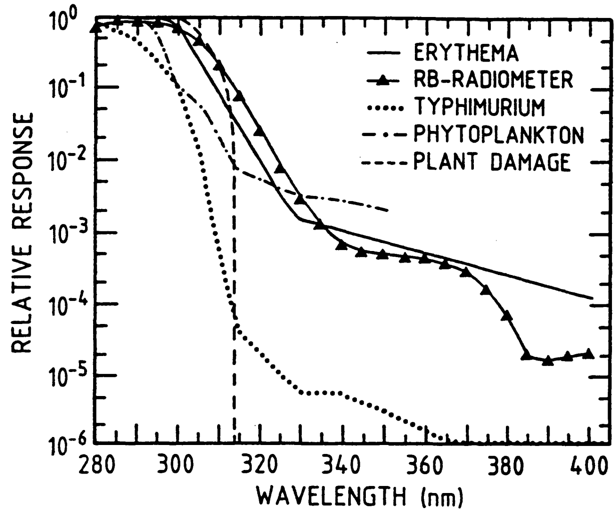

Fig. 5. Selected biological action spectra with the relative response of the Robertson and Berger radiometer.

The convolution of the action spectrum (or the spectral weighting function) with the UV solar irradiance at the Earth's surface gives the biological weighted irradiance or the instantaneous biological dose rate defined, for a specific biological photoreaction, by :

$$R(\tau) = \int_{\lambda} A(\lambda) \, . \, F(\lambda,\tau) \; d \qquad (1)$$

where $A(\lambda)$ is the action spectrum and $F(\lambda,\tau)$ the solar irradiance (direct + diffuse) at a given wavelength (λ) and an optical depth (τ), as illustrated in figure 6.

The UV-dose is the integration over the exposure time :

$$D(A) = \int_{t} R(\tau) \; dt \qquad (2)$$

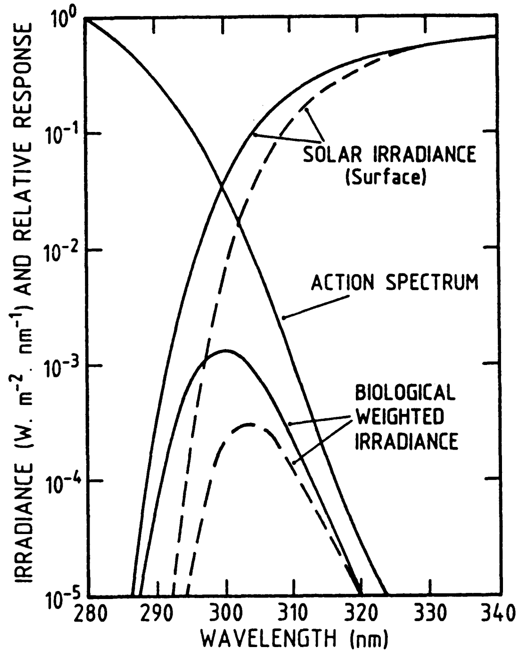

Fig. 6. Definition of the biological weighted irradiance (see text).

The radiation amplification factor (RAF) is the relative increase in the biological weighted irradiance for unit-relative reduction of ozone :

$$\mathrm{RAF} = - \frac{\Delta R}{R} \Big/ \frac{\Delta O_3}{O_3} \qquad (3)$$

The RAFs indicate how the biological weighted irradiance for each biological photoreactions will change with increase of UV-B irradiation due to ozone reduction. They do not include the absolute sensitivity of a biological processes. Because of possible effects of UV-A irradiance which are not dependent on ozone change, this range should be include in the calculation of RAFs which can be significantly reduced. The RAFs calculations presented in the UNEP 1991 report shows a large range of values, between 0.1 and 4. If the atmospheric parameters are not varying during ozone changes, they do not affect the RAF values (WMO, 1989). The relative changes in stratospheric and tropospheric ozone slightly modify RAF values (Brühl and Crutzen, 1989).

4. LONG-TERM CHANGES IN ATMOSPHERIC COMPOSITION

A large majority of atmospheric factors controlling the UV irradiation at the Earth's surface is experiencing, since decades, long-term changes due to anthropogenic activities, on global and regional scales.

4.1. Stratospheric Changes

Significant ozone reduction has been reported from the recent re-analysis of the Total Ozone Mapping Spectrometer (TOMS) observations with a new retrieval method based on internally self-consistent calibration (Herman et al, 1991). Measurements made by the Stratospheric Aerosol and Gas Experiment (SAGE) have shown that the most important decreases are occurring in the lower stratosphere (Mc Cormick et al, 1992).

The TOMS total ozone data from Nov. 1978 to Mar. 1991 indicate a seasonally averaged decrease of 4 percent per decade in the Southern Hemisphere around 40° S, the reduction becoming larger when moving southward. In the Northern Hemisphere, the 4 percent contour line is varying from 30° N in winter to 60° N in summer (for details, see Stolarski et al, 1992). The largest decrease is occurring in October during the Austral spring in Antarctica (the ozone "hole"), reaching more than a factor of 2 in 1992 with respect to the value observed in the 1960's. In the Northern Hemisphere, the maximum reduction is taking place during winter and spring, at high latitudes. Heterogeneous processes similar to that occurring on Polar Stratospheric Clouds (PSCs) are currently the most likely mechanisms proposed to explain the reduction at mid and high latitudes (Hofmann and Solomon, 1989) which cannot be reproduced so far by modelling. Ground-based measurements of total ozone and its vertical distribution are supporting the satellites findings (Stolarski et al, 1992).

Trends in stratospheric aerosol concentrations are directly affected by important volcanic eruptions such as El Chichon in 1982 and Mt. Pinatubo in 1991. Results obtained from satellite and ground-based observations since more than 10 years give a time decay for stratospheric aerosols between 0.5 to 1.5 years (Yue et al, 1991). The impact of stratospheric aerosols on the radiative transfer of UV irradiance has been recently studied by Michelangeli et al (1991). The net effect is a decrease in the biological weighted irradiance. Nevertheless, as sulfuric acid aerosols could contribute to ozone reduction, they indirectly affect the stratospheric UV radiative transfer by increasing the UV-B irradiance at the surface.

4.2 Tropospheric changes

Tropospheric ozone accounts of 10 percent of the total atmospheric abundance. Due to its photochemical production in polluted areas, its concentration is highly variable with geographical location, season and time. If the tropospheric ozone has increased in summertime by a factor of 3 since the end of the 19th century, the current trend according to the time series analysis from balloon sondings from Payerne, Switzerland (Staehelin and Schmid, 1991) shows an increase between 1 and 1.6 percent per year through the whole troposphere. Similar figures have been obtained in Hohenpeissenberg, Germany (London and Liu, 1992).

In the Southern Hemisphere, negative trends have reported from various observations sites with a maximum of 17 percent decrease in summer at the South Pole (Schnell et al, 1991).

The effect of positive trends in tropospheric ozone is to reduce the level of UV-B irradiance at the surface. Brühl and Crutzen (1989) have studied the relative impact of troposphere and stratosphere trends in the UV-B penetration. They concluded that tropospheric ozone is more effective in UV absorption than stratosphere ozone for SZA less than 60°. It means that the relative impact of these two atmospheric layers will introduce a seasonal and latitudinal dependence in the biological weighted irradiance.

The tropospheric ozone should have a beneficial effect in reducing the surface UV irradiance. Liu et al (1991) have calculated that the DNA weighted irradiance has been reduced since the last century by 6 to 18 percent in summer, at 40° N, based upon the large diminution in the visual range observed over that period of time. Such an effect should have masked UV increase related to ozone reduction deduced from the TOMS observations.

The tropospheric aerosol distribution in space and time is also highly variable and poorly documented. Global climatology has been deduced from satellite observations (SAGE) and reported by Kent et al (1991). Its temporal variations need to be monitored carefully in order to distinguish between ozone-related and aerosol-related surface UV irradiance changes.

Another constituents affecting the surface UV-B irradiance are pollutants like NO_2 and SO_2. Their effects will be strongly space-related to their anthropogenic sources, mainly enhanced in industrialized regions of the Northern Hemisphere, at mid-latitudes. Biogenic emissions in tropical latitudes in the Southern Hemisphere (e.g. Africa) have also to be considered (Müller, 1992).

NO_2 and SO_2 tropospheric concentrations can be modelled or current emissions rates and for pre-industrial conditions. But there is no trend on a global scale reported for the last decade. Frederick and Weatherhead (1992) have studied the effect on the erythermal weighted irradiance of gaseous pollutant trends in four monitoring sites for which decreases of O_3, NO_2 and SO_2 concentrations in the boundary layer have been measured. They found an increase in mean trends based on TOMS ozone data only, for this biological weighted irradiance, varying from 4 to 50 percent between polluted and unpolluted atmosphere, from May to July, from 1980 to 1990. It means that UV-B trends will be differently affected according to pollution conditions and the pollutant emissions regulation enforced in some cities and/or countries. For example, SO_2 emissions are decreasing in many industrialized countries in the Northern Hemisphere but still increasing in developing countries.

The major source of solar irradiance variability at the Earth's surface is certainly the cloud cover. The attenuation of UV irradiance should depend on the type and distribution of clouds. Data on global average cloudiness are available from ground-based observations since the 1950's. Since the mid 1960s, different satellite observations were used to infer overall global cloud patterns. At the end of the 1970's, the International Satellite Cloud Climatology Project (ISCCP) was implemented.

The analysis of the 30-year trend (1952-1981) of amounts of different cloud types has been published by London et al (1991) from ship observation in the tropical oceans. The trend is positive for cirrus and cumulonimbus between 10° N and 20° C. The other cloud types remained steady or decreased during the same period. On the other hand, significant differences of cloudiness between the two hemisphere and between land and ocean have been reported by London et al (1989).

These studies show the complexity introduced by the spatial and temporal variability of clouds for an adequate interpretation of UV irradiance measurements at the Earth's surface. Radiative transfer model developments including the effect of cloudiness are also required for correct calculations of its impact on surface UV climatology.

Some studies on cloud effects have been reported by Frederick and Snell (1990), Tsay and Stamnes (1992) and Frederick and Weatherhead (1992).

5. UV-B MEASUREMENTS AND MONITORING

Currently, there is no global suitable UV-B measurement network. Only networks for limited geographical coverage are implemented, like the National Science Foundation (NSF, USA) Polar programs. The lack of measurements do not allow correct description of a global UV-B irradiance climatology and related trends.

The objectives of UV-B networks should be to provide this climatology at the surface and to detect trends. Additional measurements are needed to measure the different factors controlling the surface UV-B irradiance such as stratospheric and tropospheric ozone, aerosols, SO_2, NO_2, cloud cover, optical depth and albedo. The irradiance measurements should be expanded to the UV-A range and the visible. These requirements imply a strategy for the definition of the various sites with a minimum of co-located ancillary measurements.

Because of the limited number of stations in current and future networks, the global distribution of UV irradiance will rely upon modelling, combining ground-based and satellite observations of the various parameters needed in radiative transfer models.

If the observed stratospheric ozone depletion should imply increases in UV-B irradiance at the Earth's surface, there is no direct experimental confirmation of the predicted UV-B increased, as reported by Madronich (1992). The only exception concerns very large ozone reduction prevailing during the Austral spring, during the ozone "hole" conditions. Some other observations become now available at relatively high latitudes in the Southern Hemisphere in Australia and New Zealand. In the Northern Hemisphere no UV-B decrease has been reported so far on a global scale.

The instruments used for current and future observations fall into two categories : the broad-band radiometer like the Robertson Berger (RB) meters, and the spectroradiometers giving spectral distribution of UV irradiance, like the instrument developed by Biospherical Instruments for the NSF network. A third type might be considered, namely the narrow band radiometers at fixed wavelength.

5.1 The Broad-band Radiometer

The most widely deployed instrument during the last 20 years is the RB meter, which correspond to the broad-band instrument category, having a weighted irradiance sensitivity close to the sunburn weighted irradiance (see Figure 5). A network of 25 RB meters have been deployed in USA and 11 in other countries between 1974 and 1980. Part of them are in operation and are presently reporting data. In 1991 and 1992, 47 new versions of RB meters have been deployed in several countries, including 26 instruments for the Canadian network.

The main limitations of the broad-band radiometers are their low sensitivity to ozone changes and the fact that they do not represent the diversity of action spectra and their related radiation amplification factors.

Three time series of RB meter observations have been reported. Garadazha and Nesval (1987) reported from their observations made in Moscow between 1968 and 1983 a decrease of 0.8 percent per year in the instrument count number. For the same period they also observed 13 percent of increase in cloudiness and 15 percent in turbidity. Consequently, it is very difficult to relate these observations to any changes in stratospheric ozone.

The results from 8 RB meters in USA have been analyzed by Scotto et al (1988), reporting a signal decrease between 0.5 and 1.1 percent per year from 1974 to 1985. An explanation for this apparent contradiction has been proposed by Grant (1988) arguing that local pollution may have accounted for the observed weighted irradiance decrease. Indeed, most of the RB meters used in this study are located in urban and near urban sites. This argument is now superceded by a recent analysis of the calibration stability of the RB meters in USA which could have suffered from a decrease in the instrument calibration during that period due to change in the calibration procedure (DeLuisi, private communication). This problem emphasizes the importance of the long term calibration traceability for any kind of instruments.

Blumthaler and Ambach (1990) have performed continuous observations since 1981 at the Jungfraujoch (Swiss Alps) at 3600 m altitude. They reported an increase of 0.7 ± 0.2 percent per year over the full period of observations.

Frederick and Weatherhead (1992) have conducted a careful analysis of RB meter and Dobson data at 2 sites, namely Bismarck and Tallahassee (USA) between 1974 and 1985. They concluded that the RB meter data are only consistent with the calculated ozone total content based upon the Dobson data for the months of high UV-B irradiances (Figure 7). There is no explanation for such discrepancy between the observed and calculated trends for months of low RB meter signal levels.

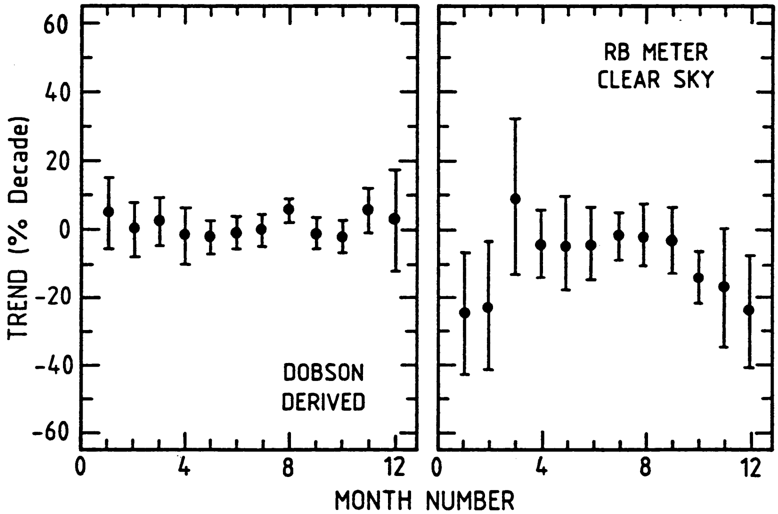

Fig. 7. Trends by month of the year between 1974 and 1985 in the RB meter data for Bismarck (USA). The left panel gives the results derived from the Dobson data. The right panel gives the RB meter data for clear sky conditions. Adapted from Frederick and Weatherhead (1992).

The radiation amplification factor associated with the RB meter is smaller than majority of calculated RAFs and therefore makes more difficult the interpretation of UV-B trends. If these trends are only due to ozone changes, corrections could be applied for other biological action spectra and, consequently, different weighted irradiance. If these trends are partly due to aerosol and/or cloudiness changes, this scaling becomes inappropriate. Finally, the main limitation is also due to the inconclusive results for long-term detection for reason not always fully understood.

5.2 Spectral measurements

The main advantage of the spectral measurements with a full width at half maximum (FWHM) smaller than 2 nm is that they can be convoluted with the large variety of action spectra. These data could also be used to calculate biological weighted irradiance for effects which are yet sufficiently studied or known. This kind of measurements also allows the identification for reasons of UV-B changes. Unfortunately, the available time series are too short and sparse to deduce any statistically significant UV climatology and trends.

Several programs are currently in operation or in development in various countries. Two of them will be shortly described.

5.2.1. The NSF UV Radiation Monitoring Network

The ultraviolet radiation monitoring network was established by the NSF (USA) in 1988 to measure the impact of the large stratospheric ozone depletion experienced in Antarctica. Five automated spectroradiometers located in Antarctica and the Arctic (see Table 1) provide UV irradiance measurements for biological effect studies.

Table 1 : NSF UV radiation monitoring network

Location	Date of installation	Long.	Lat.
South Pole	Feb. 1988	0°	90.00°S
Mc Murdo	Mar. 1988	166.40°E	77.51°S
Palmer	May 1988	64.03°W	64.46°S
Ushuaia (Arg)	Nov. 1988	68°W	54.59°S
Pt.Barrow (Alaska)	Dec. 1990	156.78°W	71.3°N

The instruments used in these 5 stations is based on a 10 cm double monochromator. Internal calibration is performed with tungsten and mercury lamps. The spectral bandwidth is 0.7 nm. The temperature of the instrument is carefully stabilized within ± 0.5°C. The input optics is a teflon diffuser.

Several publication have already reported and analyzed UV radiation data from the stations in Antarctica (see Lubin et al, 1992 and references therein). The observations confirm the theory for the large observed ozone changes. Increase of UV-B irradiance by a factor of 2 has been observed for several days during the Austral spring of 1990 at Palmer Station with respect to irradiance values calculated with ozone amounts typical for years before 1980 (Frederick and Alberts, 1991). The analysis of data obtained in Ushuaia (Argentina) in December 1990 give a noontime irradiance 45 percent larger than prediction based on TOMS ozone climatology over ten years, for a wavelength of 305.5 nm (Frederick et al., 1993).

5.2.2.The European Community project

The European Community project is aimed at establishing the criteria for a network of instruments to monitor the UV spectral irradiance throughout Europe. It is based upon existing instruments. Because of their diversity, they need to be fully intercompared in order to investigate their compatibility before being used in an European network. Two intercomparison campaigns took place near Thessaloniki (40°5N, 23.1°E, Greece) in Summer 1991 and 1992, with 10 instruments based on spectrometers from Jobin Yvon (models DH 10, HR 320 and 320), Bentham (models DM150 and 300), Brewer MK II and III, Optronics 742, EG & G 1453A and Kratos GM200-2 for the 2nd campaign, with bandwidth between 0.37 and 2.6 nm. Some instruments are already competent for UV spectral irradiance measurements while others need only little modifications to become so. The participants included 8 European institutions, 1 Canadian and 1 company from New Zealand.

In addition to this instrumental effort, a traveling calibration lamp unit has been design to monitor the calibration stability of each instrument at their home sites. The prototype has been tested during the 2nd campaign. This portable lamp unit will undergo further small improvements before being used to check the consistency of each instrument responsivity over large period of time. The results of the 1st campaign have been in reported by Gardiner et al (1992). The report for the 2nd campaign is in preparation.

6. CONCLUSIONS

Global scale reductions in stratospheric ozone have been observed during the last decade. As a consequence, UV-B irradiance at the Earth's surface should have been increased, according to the radiative transfer theory. This is only confirmed for large ozone reductions like in Antarctica, during the Austral spring. Tropospheric changes with ozone and aerosol increases observed in the Northern Hemisphere could have masked the UV-B trends. Because of relatively more important stratospheric ozone reduction and less tropospheric pollution, significant increases of UV-B are most likely to appear first in the Southern Hemisphere.

There is no adequate global network for UV-B trend measurements currently in operations. A monitoring strategy should be defined, taking into account the changes in the atmospheric parameters affecting the UV radiation field at the surface. This requires, in addition of high quality spectral irradiance measurement, co-located ancillary measurements in order to discriminate the relative impacts of tropospheric and stratospheric trends on the UV-B climatology. Model developments for realistic atmosphere need also to be pursued. Several programs in various countries are now addressing these different aspects related to UV-B monitoring.

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