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POLAR UV MEASUREMENTS—OZONE DEPLETION AND BIOLOGICAL SIGNIFICANCE

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Abstract: Man-made CFCs have been banned largely because of fears that increasing amounts of these chemicals in the atmosphere would lead to elevated levels of ultraviolet flux on the earth with resulting adverse biological effects. The link between ozone depletion and elevated levels of UV is clearly demonstrated with data from the National Science Foundation's UV Monitoring Network for Polar Regions. This network of six sites (recently expanded with a seventh, affiliated site), ranging from the South Pole to Barrow, Alaska, has routinely made high spectral resolution measurements of UV irradiance since 1988. These data allow researchers to conduct field experiments on organisms, evaluate laboratory experiments, test models, and predict the impact of ozone depletion on the environment. The network of instruments is described, and data from the 1996 "Ozone Hole," showing the impact of ozone depletion on incident spectral irradiance, is presented along with estimates of its biological impact.

1. Introduction

The Antarctic Ultraviolet Spectroradiometer Monitoring Network was established by the United States National Science Foundation (NSF) in 1988 in response to predictions of increased UV radiation in the polar regions. It is the first automated, integrated, high resolution UV-visible scanning spectroradiometer network installed anywhere in the world. The network consists of several automated spectroradiometers: five placed in strategic locations in Antarctica and the Arctic (see Table 1), one established in San Diego to collect data and serve as a training and testing facility, and one transportable system used in US and international instrument intercomparisons. The network makes essential measurements of UV spectral irradiance and has been successful in being operated in the harshest environments of Antarctica and the Arctic. It is currently returning data to researchers studying the effects of ozone depletion on terrestrial and marine biological systems, and is also being used to develop and verify models of atmospheric light transmission (see citations in Booth *et al.*, 1994). Biospherical Instruments Inc. (BSI) of San Diego, CA, under contract to Antarctica Support Associates (ASA) and directed by the National Science Foundation (NSF), is responsible for operating and maintaining the network and distributing data to the scientific community. An additional system of later design was installed in December 1996, in Valdivia, Chile, under sponsorship of the World Meteorological Organization (WMO) and is affiliated with the NSF under sponsorship of the InterAmerican Institute for Global Change Research (IAI).

Table 1. Network sites.

Site	Long.	Lat.	Estab.	Season
Antarctica:				
McMurdo	166 E	77 S	March 88	Aug.-April
Palmer	64 W	64 S	May 88	Year round
South Pole	0	90 S	Feb. 88	Sept.-March
South America:				
Ushuaia, Argentina[1]	68 W	54 S	Nov. 88	Year round
Valdivia, Chile[2]	*74 W*	*40 S*	*Dec. 96*	*Year round*
North America:				
San Diego, California	117 W	32 N	Oct. 92	Year round
Barrow, Alaska[3]	156 W	71 N	Dec. 90	Jan.-Nov.

[1] CADIC: Centro Austral de Investigaciones Cientificas.
[2] WMO sponsored, *not* officially part of the NSF network. Operational support by Dirección Meteorológica de Chile, installation at Universidad Austral de Chile.
[3] UIC/NARL: Ukpeagvik Inupiat Corp. (formerly) Naval Arctic Research.

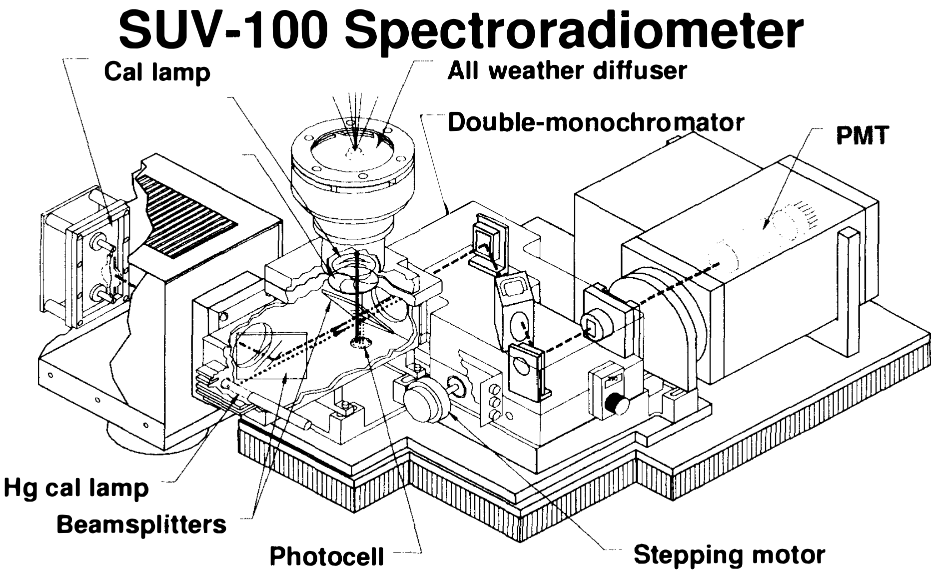

Fig. 1. SUV-100 pictorial diagram. The SUV-100D (e.g. Valdivia) is a redesigned version, with similar elements plus other enhancements.

2. Methodology

The spectroradiometers used in the network are BSI Model SUV-100, described in Booth *et al.* (1994). The network's data products include both 1 nm bandwidth (0.6 nm for Valdivia) spectral irradiance data and calculated biological dose rates. The spectroradiometer is based on a temperature stabilized, double scanning monochromator coupled to a photomultiplier tube (PMT) detector (Fig. 1). The system is optimized for operation in the UV. A vacuum formed Teflon diffuser serves as an all-weather irradiance collector and is heated by the system to minimize ice and snow buildup. The instrument has wavelength and intensity lamps for automatic calibrations at programmed intervals (typically 2–4 times per day). A data acquisition system accompanies the instrument, and a personal computer is used to control the system and log the data.

An *f*/3.50 10 cm double monochromator is the heart of the system and is configured with 167 micron input/output slits and a 250 micron intermediate slit. The holographic gratings have 1200 grooves/mm blazed at 250 nm, driven by a stepping motor with a step size of 0.05 nm. The spectral bandwidth is a nominal 1.0 nm. The photomultiplier tube (PMT) is a 28 mm diameter, 11 stage device with a bialkali cathode and a quartz window. It is housed in a cooled enclosure maintained at approximately 0° C to reduce dark current and noise. Temperature of the monochromator is carefully monitored and controlled, and is typically stable to $\pm 0.5^\circ$ C. In addition to daily

Schedule of QA/QC Activities

- **Hourly**
  - **Temperature, power checks**
  - **Monochromator position**
  - **Responsivity checks**
  - **Wavelength alignment**
- **Daily**
  - **Lamp characteristics**
  - **Operator checks**
  - **UV-B calculations**
- **Weekly**
  - **Data archive checks and data retrieval**
  - **Performance time series checks**
  - **Database updates**
  - **Web Site updates**
- **Bi-Monthly**
  - **Complete system external calibration**
  - **Examination of calibration and standards stability**
- **Yearly**
  - **Operator training at San Diego**
  - **Site visits**
    - **operation audit (testing)**
    - **standards comparison**
    - **scheduled maintenance**
  - **Reprocessing of all calibrations and data**
  - **Report generation**
- **Additionally**
  - **Intercomparisons**
  - **Model tests**
  - **Reevaluation and testing of methods**

Fig. 2. Quality control and assurance procedures. Tasks range from computer monitored activities occurring from 5 min to daily, to operator assisted activities and yearly events.

calibrations checks with the internal reference (Fig. 2), the system is periodically calibrated using an optical standard traceable to the National Institute of Standards and Technology. Further performance examinations are conducted at U.S. (THOMPSON *et al.*, 1996) and international instrument intercomparisons (SECKMEYER *et al.*, 1995).

3. Observations: Radiation Amplification Factors

Radiation Amplification Factors (RAFs) are used to describe the relationship of changes in atmospheric ozone and biological effects. Using dose weighting functions and the extensive data sets collected in this project, we can select cases where all factors other than ozone are the same and compute the difference in the biologically weighted irradiances. As an example, DNA action spectra weighted irradiances increase by 2.2 % when total column ozone decreases by 1%, all other conditions being equal as the RAF is described to be 2.2 (Figs. 3, 4) (BOOTH and MADRONICH, 1994). To examine this relationship at greater levels of ozone depletion, BOOTH and MADRONICH analyzed observations of South Pole Station spectral irradiance scans with the DNA dose weighting (SETLOW, 1974), and near-simultaneous satellite ozone measurements (supplied by R. MCPETERS of the Ozone Processing Team at NASA/GSFC, unpublished). Observations were paired when solar zenith angles matched within $\pm 0.2°$ and were equal-distant in time from the summer solstice. This pairing allows percent decrease in ozone with percent increase in UV to be calculated for conditions of similar solar angles since those observations before the solstice were likely to occur during the ozone hole. Note that in this analysis, 0% decrease does not imply any specific total

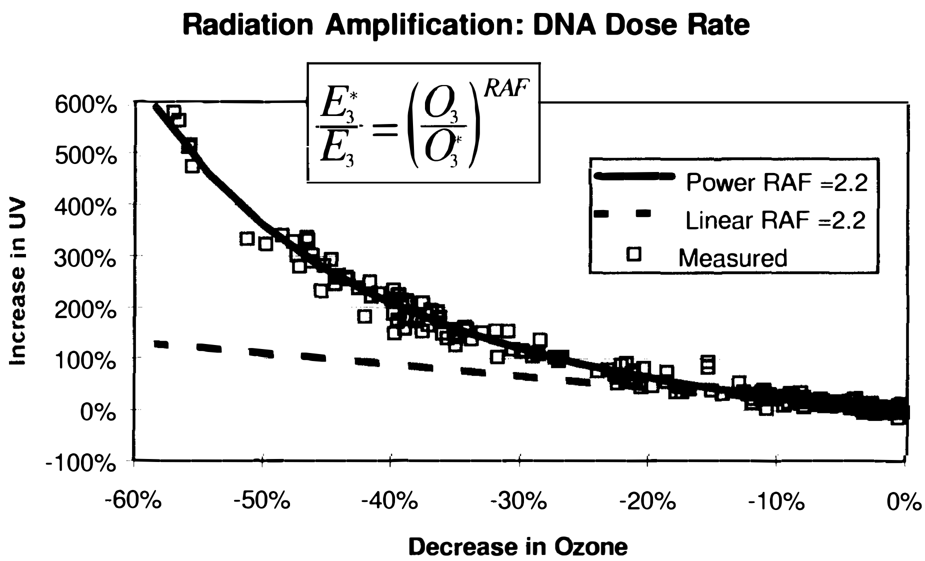

Fig. 3. Radiation Amplification: Erythema Dose Rate. As in the Fig. 5, erythema dose weighting (MCKINLAY and DIFFEY, 1987) is applied to solar irradiance to show the percent change in UV dose with decrease in ozone. The equation inset expresses the "power" form of the RAF equation where E_3 and E_3 are the irradiances, and O_3 and O_3* are the ozone amounts being compared. For details, see BOOTH and MADRONICH (1994).*

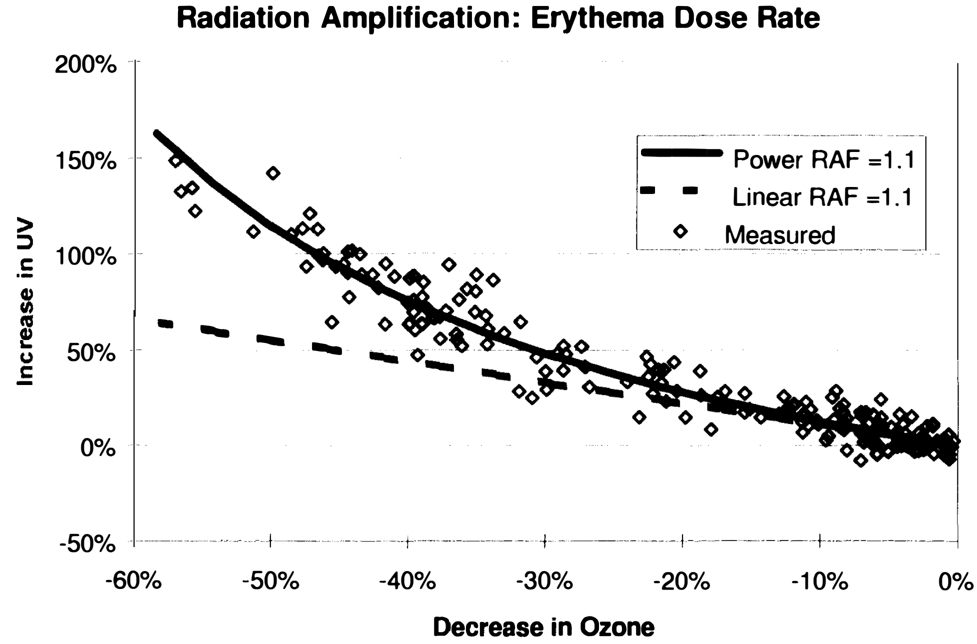

Fig. 4. As in Fig. 3, but using the CIE erythema action spectra described by McKinlay *and* Diffey *(1987).*

ozone concentration, just the highest concentration found in the data set.

4. Comparative Measurements of UV at the NSF Monitoring Sites

As a means of obtaining an overview of the UV exposure at the monitoring sites, we compared biological doses for each site over various periods of time (see Table 2). Doses were calculated by first applying the CIE sanctioned action spectra for human erythema (McKinlay and Diffey, 1987) to SUV spectral irradiance data to obtain an instantaneous dose rate, and then computing the integrated dose for each time period. The objective was to contrast UV exposure over different time periods and to show how the relative ranking of exposures at different sites varies depending upon the time period considered.

Hourly exposures were calculated by converting instantaneous exposure rate data, recorded in hourly SUV spectral irradiance scans, to hourly exposures based on the assumption that each rate was constant for one hour. All hourly data points having a solar zenith angle less than 90° were included; those having solar zenith angles greater than 90° (*i.e.*, sun below the horizon) were considered to be 0. Missing data points were filled by using data recorded at the same time on the previous or following two days or at the same time and day of the previous or following year, in that order of preference. Daily exposures were calculated by summing the hourly exposures over 24 hours. Palmer Station recorded both the highest hourly and the highest daily (24 hour) exposures. However, the highest weekly exposure occurred at the South Pole. This is partially due to the fact that the South Pole experiences fewer clouds than the Palmer and McMurdo sites. Also, we argue that polar exposures cited here may underestimate

Table 2. Maximum erythemal doses (in kJ/m²) for each site over different time periods. The maximum dose for each time period is underlined.

Erythemal dose	Barrow	McMurdo	Palmer	San Diego	S. Pole	Ushuaia
Max yearly	307.0	425.2	506.4	<u>1115.6</u>	463.2	536.4
Max monthly	79.1	127.2	112.7	<u>151.8</u>	141.5	107.3
Max weekly	21.8	30.8	36.2	39.3	<u>44.1</u>	27.5
Max daily	3.44	5.11	<u>7.15</u>	6.10	6.41	5.64
Max hourly	0.406	0.539	<u>1.018</u>	0.984	0.282	0.845
Start date	Feb. 91	Dec. 89	Mar. 90	Oct. 92	Jan. 91	Sep. 90
End date	July 95	Apr. 95	July 95	June 95	Mar. 95	July 95

the total human exposure because these measurements consider only the downwelling incident irradiance and ignore the reflected component from snow. Conversely, weekly doses are based on a 24 hour integrated exposure of a human effect, but few humans actually receive a 24-hour exposure.

The monthly exposures in Table 2 show that a mid-latitude site such as San Diego experiences peak monthly exposures greater than those of the South Pole, although not by much. It is more significant that the monthly exposure at San Diego in summer substantially exceeds that of any of the polar sites except for the South Pole. We attribute this to the frequent cloudiness found at the other Antarctic sites and to the dynamics of the polar vortex, which causes the "ozone hole" to "wobble" over the continental margins. The maximum yearly dose occurred in San Diego. This dose was essentially twice the magnitude of the Antarctic and Argentine yearly doses.

5. Dynamic Features in UV Exposure

The thickness of the ozone layer over a given place is not constant, but rather shows a seasonal dependence. Due to the "ozone hole," regions around Antarctica can experience large swings in total column ozone, and consequently, experience large swings in UV irradiance. Using the DNA dose weighting, we present the time series of noontime DNA weighted irradiances at McMurdo Base in Antarctica since 1988 (Fig. 5). 1996's recent data is shown as a solid line, and corresponds closely to the rotation of the ozone hole as seen in TOMS images. Visible irradiance (shown in the inset plot), is predominantly governed by sun angle and cloud cover and shows relatively little variability other than that associated with higher sun angles as summertime approaches.

In late November 1996, Ushuaia experienced record-level elevated irradiances due to the "ozone hole." It is common in the Antarctic region to see strong swings of irradiance due to rotation of the normally aspheric polar vortex (the "ozone hole"). This can be seen in recent satellite data from Ushuaia, at the southern tip of Argentina (Fig. 6). When these swings of ozone-depleted air pass over during a time of clear skies, the UV levels are elevated for periods of one to a few days (Figs. 7, 8).

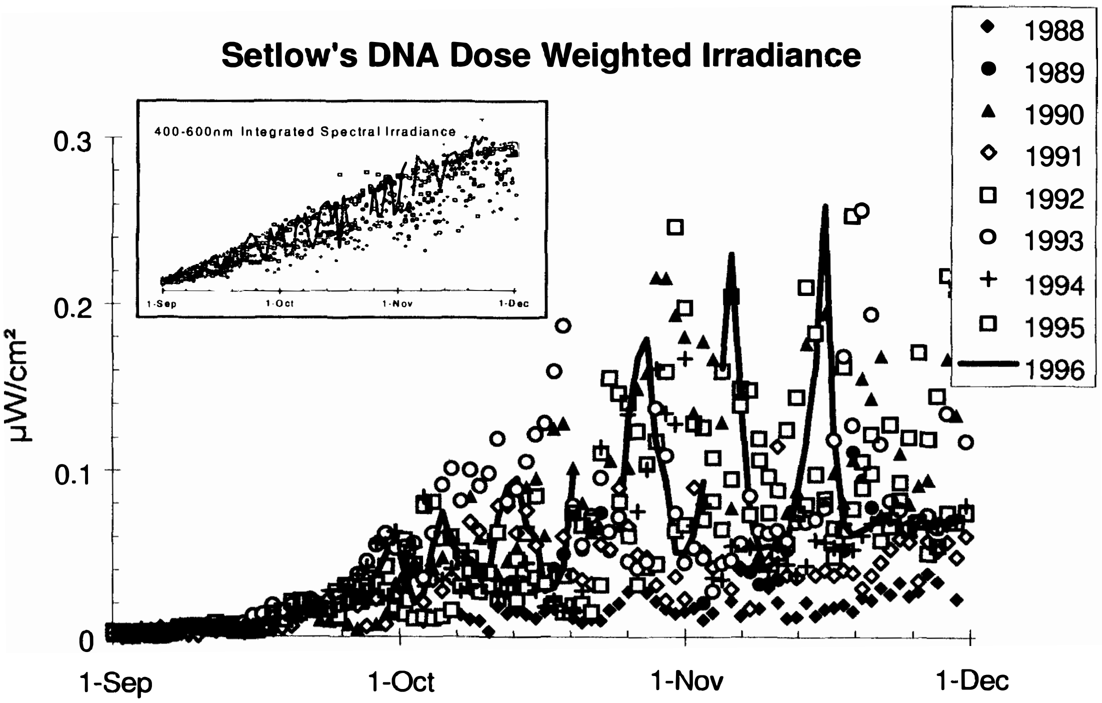

Fig. 5. Setlow's DNA dose Weighted Irradiance at McMurdo, Antarctica. The large variations in UV are caused by the unique characteristics of each year's ozone hole, ranging from the relatively small one of 1988 to 1996 when the edge of the region of highest depletion made weekly appearances over McMurdo.

Fig. 6. Images of the ozone hole from satellite in late November, 1996. ADEOS/TOMS data on left, NASA Earth Probe TOMS data on right.

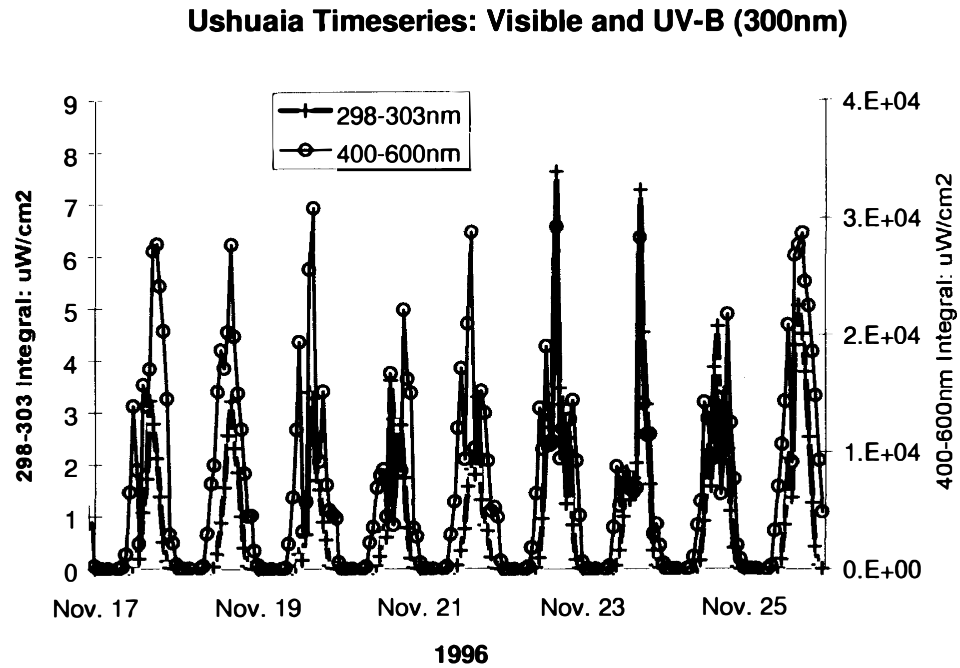

Fig. 7. 1996 time series from Ushuaia showing both visible and UV-B irradiance for the period of time shown in the TOMS imaged in the previous figure. The visible portion of the spectrum shows the effects of changes in cloud cover, but average visible irradiance changes relatively little during this period. Conversely, in the spectral region around 300 nm, a sharp rise in irradiance is noted on November 22 and 23, when we see that the elongated area of strong ozone depletion passed overhead.

6. Conclusions

In summary, the NSF network measured short term (hourly and daily) UV doses, in the Antarctic Peninsula (Palmer) that exceeded those of San Diego, while long term (yearly) doses in San Diego were substantially greater than those of other sites. Intermediate term doses (weekly) were highest at the South Pole. It is important to note that these doses only include downwelling irradiance measurements and do not account for the increase in human exposure that occurs over ice or snow due to the high reflectivity of such surfaces.

The level of biological impact of ozone depletion is dependent upon many factors including level of depletion, time of year, cloud cover, organisms considered, duration of exposure, and other environmental factors. The 1996 ozone hole was slightly smaller than the record, presumably due to meteorological conditions. However, we recently have seen evidence that its persistence is longer than most holes.

The NSF UV Monitoring Network continues to provide evidence that ozone depletion and the increased levels of ultraviolet light are linked, and using high-resolution spectral data, various spectral dose rate models can be applied to estimate the biological impact of this aspect of global change.

Over the past eight years, the NSF's UV Monitoring Network of instruments has provided data for the support of several research programs, details of which may be

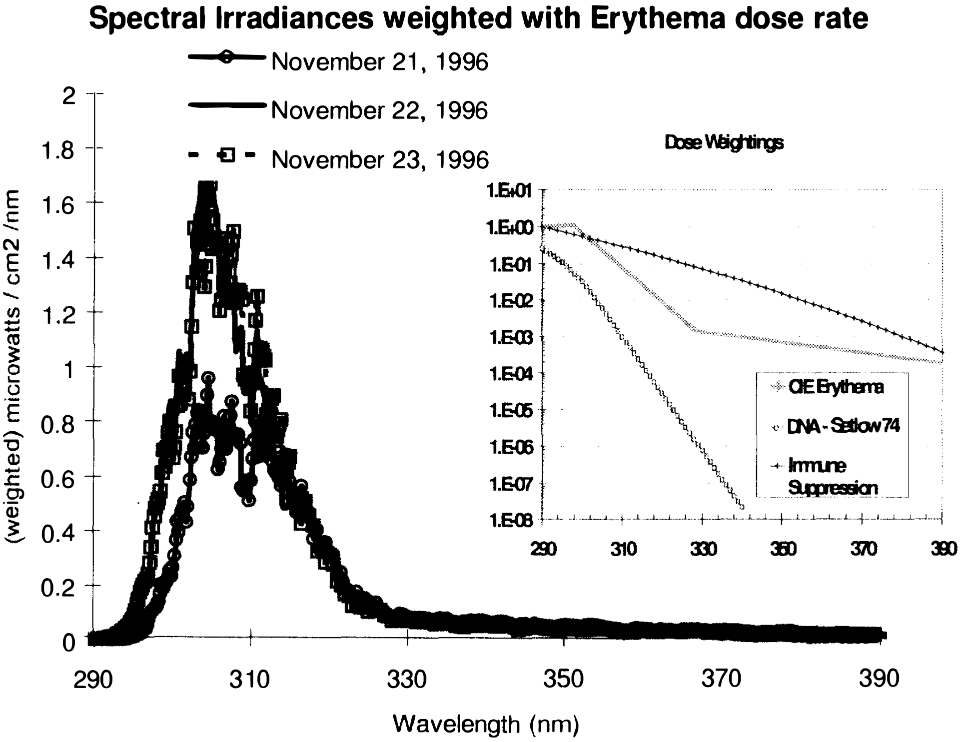

Fig. 8. Spectral Irradiances weighted with Erythema dose rate. Determination of the biological impact of increased UV is usually estimated with use of a dose weighting function such as shown in the inset plot above. In this example, we use the erythemal dose weighting function and compute the product with the spectral irradiance for the same three days (noontime) at Ushuaia. Although these three spectra were taken at the same time of day and the irradiances above 312 nm are similar, great differences are seen as the data approach shorter wavelengths.

found in the following references: BENAVIDES *et al.* (1994), BOOTH and MADRONICH (1994), BOOTH *et al.* (1994), CULLEN *et al.* (1992), DIAZ *et al.* (1990, 1994a, b), FREDERICK and ALBERTS (1991), FREDERICK *et al.* (1993), HOLM-HANSEN *et al.* (1993a, b), LUBIN and FREDERICK (1990, 1991), LUBIN *et al.* (1989, 1992), MADRONICH (1993, 1994), MCKENZIE *et al.* (1994), SECKMEYER *et al.* (1995), SMITH and BAKER (1989), SMITH *et al.* (1992a, b), STAMNES (1993), STAMNES *et al.* (1990, 1991, 1992), and THOMPSON *et al.* (1996).

Data Availability

Subsets of these data are available over the World Wide Web (www.biospherical.com), and full annual data sets are distributed at no charge on CD-ROMs. For more information, please contact: C.R. BOOTH at Biospherical Instruments Inc., 5340 Riley St., San Diego, CA 92110 (Fax: (619) 686-1887, or Internet: uvgroup@biospehrical.com). These data may also be requested through our www address.

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