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Simulation of Ozone Depletion Using Ambient Irradiance Supplemented with UV Lamps

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ABSTRACT

In studies of the biological effects of UV radiation, ozone depletion can be mimicked by performing the study under ambient conditions and adding radiation with UV-B lamps. We evaluated this methodology at three different locations along a latitudinal gradient: Rimouski (Canada), Ubatuba (Brazil) and Ushuaia (Argentina). Experiments of the effect of potential ozone depletion on marine ecosystems were carried out in large outdoor enclosures (mesocosms). In all locations we simulated irradiances corresponding to 60% ozone depletion, which may produce a 130–1900% increase in 305 nm irradiance at noon, depending on site and season. Supplementation with a fixed percentage of ambient irradiance provides a better simulation of irradiance increase due to ozone depletion than supplementation with a fixed irradiance value, particularly near sunrise and sunset or under cloudy skies. Calculations performed for Ushuaia showed that, on very cloudy days, supplementation by the square-wave method may produce unrealistic irradiances. Differences between the spectra of the calculated supplementing irradiance and the lamp for a given site and date will be a function of the time of day and may become more or less pronounced according to the biological weighting function of the effect under study.

INTRODUCTION

In order to determine biological effects of UV-B radiation (280–315 nm), experiments can be performed in the laboratory or in the field. In experiments performed in the laboratory the samples are exposed to an artificial light source (1–4). Since biological effects are wavelength dependant, the spectral distribution of the light source is a key factor. Often, artificial sources do not adequately simulate the solar spectrum. For example, metal halide lamps and Xenon lamps that are commonly used in laboratory experiments can introduce a large source of error. If the intensity of these lamps at 305 nm is set equal to solar noon irradiance, modeled for 30°S latitude during the summer solstice, they produce an effective irradiance weighted by the Commission Internationale de L'Eclairage erythema action spectrum (5) that differs considerably from ambient values. The effective irradiance for the solar spectrum would be 24.5 μW cm^{-2}, whereas the metal halide lamp is 131.5 μW cm^{-2} and Xenon is 161.3 μW cm^{-2} (6).

Some studies performed in the field are conducted comparing samples exposed to ambient irradiance with samples screened from UV-B radiation (7–15). These conditions differ from the ambient ozone-depleted conditions affecting ultimately the estimated effect to be measured (16).

Other methodologies combine ambient irradiance with UV-B lamp supplementation in order to simulate ozone depletion (9,16–19). Samples exposed to ambient irradiance are used as controls and compared with samples exposed to ambient plus lamp irradiance. In this case, when making the design of the lamps setting some considerations have to be taken into account to provide the appropriate irradiance simulation for the selected ozone depletion. The supplementing irradiance will vary considerably with the site and season of the experiment (20,21). In order to determine the irradiance to be provided by the lamps, irradiance under normal (climatological) and depleted ozone conditions need to be modelled (9,16–19,22,23).

As part of the Enhanced Ultraviolet-B Radiation in Natural Ecosystems as an Added Perturbation Due to Ozone Depletion project, marine mesocosm experiments with lamps supplementation were carried out at three localities: Rimouski (lat 48.50°N, long 68.42°W), Canada; Ubatuba (lat 23.5°S, long 45.07°W), Brazil; and Ushuaia (lat 54.59°S, long 68°W), Argentina (the term ''mesocosm'' is defined as a large outdoor enclosure filled in with natural water). The aim of this study was to perform a comparative study of the sensitivity of ecosystems to ozone depletion, even at

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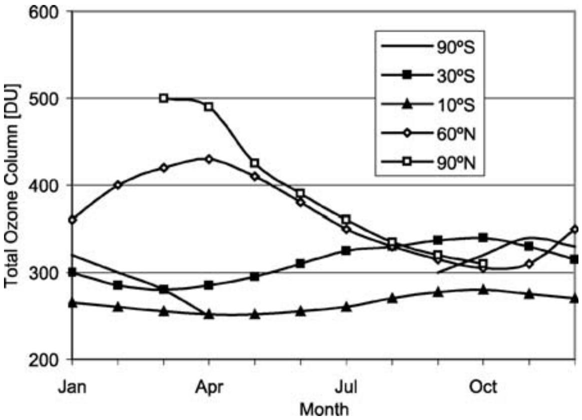

Figure 1. Total column ozone at different latitudes calculated for 1979–1982, from TOMS/Nimbus-7, version 7, provided by the North American Space Administration Goddard Space Flight Center (26).

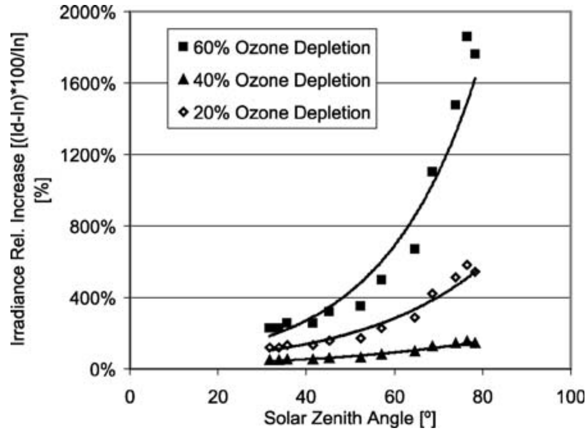

Figure 2. Relative increase in 305 nm irradiance at Ushuaia (lat 54.59°S, long 68°W) as a function of solar zenith angle under clear skies for different ozone depletion percentages.

places where there is no statistically significant ozone depletion and where day-to-day ozone variability is very small. The following three treatments were applied: 60% ozone depletion was selected to simulate the ‘‘ozone hole’’ or ‘‘high UV radiation’’ treatment, a moderate depletion of 30% was selected as ‘‘low UV radiation’’ treatment and control mesocosms were not exposed to higher UV-B radiation but ‘‘dummies’’ with the shape of the lamps holders were added to provide similar conditions (22). We discuss the calculation of the supplementing irradiance at these three sites. There were marked differences in ozone and irradiance patterns between these sites as the result of their geographic location. Ubatuba is in a tropical region in the southern hemisphere, where irradiance levels are high and there is no statistically significant ozone depletion (24). Rimouski and Ushuaia are mid-latitude sites, located at the northern and southern hemispheres, respectively, with lower irradiance levels and moderate to substantial degrees of ozone depletion (24). During spring Ushuaia is also affected by the presence of the Antarctic ozone hole (25).

In this article we discuss in detail the parameters to be taken into account in the calculation of the supplementing irradiance at different latitudes, specifically the discrepancies between the calculated supplementing irradiance and the irradiance supplied by the lamps system.

MATERIALS AND METHODS

Total column ozone exhibits pronounced geographical and temporal variations (Fig. 1). To simulate ozone depletion the climatological ozone distribution for the selected site and season needs to be determined. To perform this calculation historical total column ozone is used. The period 1980–1986 can, for example, be selected. This period involves the earliest satellite measurements available and comprises half a solar cycle (from a maximum to a minimum), diminishing the influence of this parameter in the obtained climatological data. Another option would be to select the period 1979–1982, if one is interested in minimizing the effect of ozone depletion.

Ozone climatologies for the three studied sites were determined using total ozone mapping spectrometer total column ozones from 1979 to 1982 (26). Since NASA does not provide overpass values for Ubatuba (lat 23.5°S, long 45.07°W) and Rimouski (lat 48.50°N, long 68.42°W), the calculations for these locations were based on total column ozone levels obtained from the following nearby locations: Cachoeira Paulista (lat 22.75°S, long 45°W) and Caribou (lat 46.87N, long 68.02W), respectively. Daily total column ozone from satellite Nimbus-7, version 7, provided by National Aeronautic and Space Administration Goddard Space Flight Center (26) were used. Monthly mean values were calculated for each site. Climatological characteristics were determined by third-degree curves fitting the monthly means.

Given the total column ozone level, the resulting irradiance will depend on many other factors (*i.e.* the distance between the earth and sun, levels of atmospheric gases other than ozone, levels of aerosols, solar zenith angle, cloud cover, altitude and surface albedo). Some of these factors are well established, whereas only an approximate value can be used for others. Solar zenith angle and the distance between the earth and the sun are very important in determining the irradiance at the earth’s surface. Variations with time of the day, latitude and season are the result of changes in the solar zenith angle. For a given level of ozone depletion the irradiance increase will vary with solar zenith angle. Figure 2 shows the relative increase of irradiance at 305 nm for different ozone depletions and as function of solar zenith angle at Ushuaia.

Clouds are responsible for large changes in irradiance. In general, they produce attenuation, although increases for short periods may be observed because of redirection of the radiation at clouds edges. Albedo and aerosols also have considerable effects on ground UV radiation, and many efforts are being carried out to improve the characterization of their effect. All of these factors have been studied separately and jointly by different authors (27–33).

In order to determine the climatological irradiance for each site, climatological ozone values were introduced in an 8-stream model, which was based on a disort model (34), and irradiance was calculated for the fifteenth day of each month under clear sky conditions. The ozone-depleted irradiance was modelled in accordance with the same procedure. The lamp supplementing irradiance was calculated as the difference between both irradiances (ozone depleted irradiance − ozone climatological radiance).

The supplementing irradiance for a given level of ozone depletion will also vary with time of the day. Nevertheless, in order to simplify the lamp setting two common methodologies are used. One of them consists of supplementing a fixed irradiance during the whole day or during 4–5 h around solar noon (square wave). A more sophisticated methodology consists of supplementing a fixed percentage of the ambient irradiance. In his case it is necessary to include a feedback control system to check the ambient irradiance and manage the lamp intensity accordingly (9,16–19,22).

The spectral distribution of the supplementing irradiance exhibits differences with respect to site and season. We used fluorescent light tubes Philips TL40W-12RS, which have been shown to provide light with spectra that constitute a good approximation to simulated irradiance increases due to depletion in ozone levels.

RESULTS AND DISCUSSION

Estimation of local total column ozone levels

Ozone climatological data for the selected sites are shown in Fig. 3a,c,e. Lower total column ozone and smaller annual-cycle amplitude were observed for Ubatuba, as expected; with extreme values of the climatology between 287 and 261 DU. For Rimouski

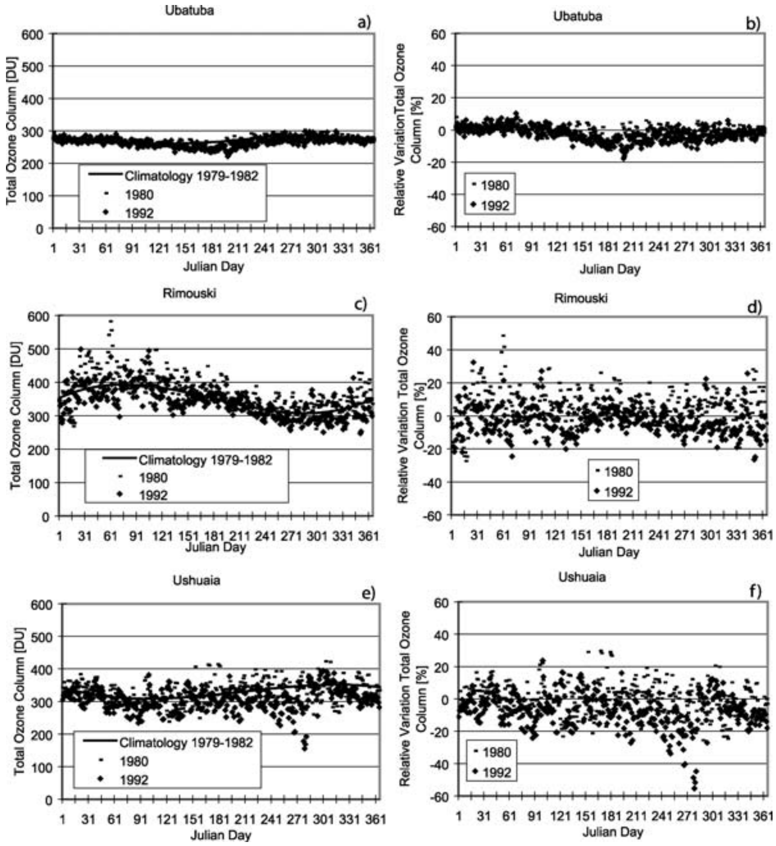

Figure 3. Total column ozone level, climatologic data (for 1979–1982) and time series data for 1980 and 1992 for Ubatuba (a), Rimouski (c) and Ushuaia (e). Daily percentage variations in the total column ozone level, relative to climatology data, for 1980 and 1992 for Ubatuba (b), Rimouski (d) and Ushuaia (f).

the annual cycle showed the largest amplitude, varying from 393 to 307 DU. For Ushuaia, the annual cycle ranged from 352 to 309 DU. Known ozone climatological differences between the northern and southern hemispheres are reflected in the climatological data of these two sites (35).

Ozone exhibits day-to-day fluctuations, which also present geographical characteristics. In Fig. 3a,c,e time-series data from 1980 and 1992 (26) were included. Relative variations of the total column ozone level were calculated as percentages for those time series (Fig. 3b,d,f). Smaller day-to-day variation was observed at Ubatuba, with values ranging from 303 to 221 DU; relative variation fluctuated from 10 to–18%. Fluctuations were more pronounced at Rimouski (from 582 to 247 DU) and Ushuaia (from 424 to 156 DU). Relative variations oscillated from 49 to –27% (at Rimouski) and from 30 to –55% (at Ushuaia). Lower ozone levels observed at Ushuaia during spring correspond to the Antarctic ozone hole passing overhead. The supplementing irradiance to simulate the ozone depletion is calculated on the basis of ozone climatological values and, as observed, large day-to-day variation may occur in the total column ozone. As a result of this short-frequency variation a difference between the calculated irradiance, which is based on climatological ozone characteristics, and the irradiance corresponding to the real ozone value present during the experiment may occur. This difference should be evaluated after the experiment (22).

Estimating increased UV-B irradiance under ozone depletion

The irradiance increase produced by ozone depletion will vary with season, mainly as a result of solar zenith angle variation, and with wavelength, mainly as a consequence of ozone cross-section. Figure 4 shows the irradiance increase at noon, for 30% and 60% ozone depletion and at wavelengths 305, 313 and 320 nm at the three sites for all seasons. Larger differences were observed between summer and winter at higher latitudes and shorter wavelengths. Seasonal variation in the pattern of irradiance increase is the same for both ozone depletions (30% and 60%), although as expected the magnitude increased with the level of ozone depletion. Depending on the site and the season 60% depletion in the ozone level may produce a relative increase of 130–1900% in the irradiance at 305 nm. As expected the largest increase was observed at Ushuaia in winter, but it should be noted that the absolute value of the irradiance is very small during that season at that site.

As mentioned above, when performing lamp-supplemented experiments the supplementing irradiance may be a fixed value or a fixed percentage of the ambient irradiance. In both cases the calculation is usually performed to obtain the irradiance necessary to simulate the desired ozone depletion at noon and under clear skies. Thus, both approaches are equivalent under those specified conditions. A difference in irradiance will occur for the rest of the day or under cloudy skies. To analyze discrepancies as function of time of the day hourly irradiances were considered. For this purpose a single day for each site was selected.

We based the selection of the day on a simulation of the ozone hole. This phenomenon affects Antarctic and sub-Antarctic regions during spring. Usually, the lowest total column ozone level occurs in October, with near 60% depletion with respect to climatological values, but, in general, as a consequence of the solar zenith angle the irradiance has larger values in November, even in the presence

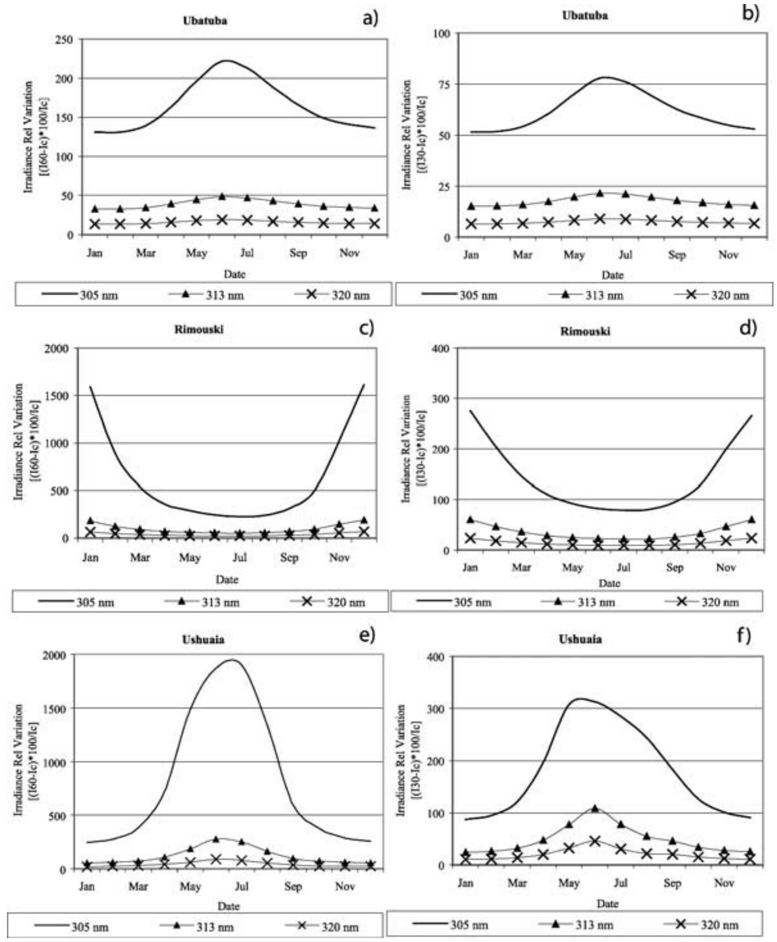

Figure 4. Year round irradiance increment in percentage relative to climatologic data, at 305 nm (—), 313 nm (Δ) and 320 nm (×), for 60% (a, c and e, respectively) and 30% (b, d and f, respectively) ozone depletion at Ubatuba (a,b), Rimouski (c,d) and Ushuaia (e,f). I_{60} = irradiance under 60% ozone depletion; I_c = climatological irradiance; I_{30} = irradiance under 30% ozone depletion.

of milder ozone depletions (36). In addition, the number of daylight hours is larger in November, which also may result in larger daily integrated levels of irradiance. Thus, for Ushuaia we chose November to perform biological studies and determine the effects of ozone depletion. In order to compare the three sites in similar situations, we analyzed irradiances in mid-November for Ushuaia and Ubatuba and in mid-June for Rimouski.

Evaluation of the supplementing methods

Figure 5a,c,e shows the value of the supplementing irradiance during daylight at different UV-B wavelengths for 60% ozone depletion at the three localitions. Figure 5b,d,f shows the irradiance increase, as a percentage of the climatological irradiance, for the same ozone depletion. Although supplementing a fixed percentage of ambient irradiance provides a better simulation of irradiance increase due to ozone depletion (9,16–19,22), it may be observed that neither the absolute value nor the percentage of irradiance is constant with time of the day. Table 1 shows the difference with respect to the modelled values under conditions of ozone-depleted irradiance at 305 nm during supplementation at a fixed value (irradiance) or a fixed percentage. The ratio of the calculated supplementing irradiance at time *h* from noon and at noon is included in the table in order to contribute to the evaluation of the differences in daily integrated irradiance levels. Table 1 shows also the difference between modelled daily integrated irradiance levels for 60% ozone depletion and the daily integrated irradiance levels obtained by means of the fixed-irradiance method during 5 h period centered around noon and by means of the fixed-percentage method performed during daylight hours. Despite of the similarity in the integrated irradiances, much larger differences are observed with the fixed-value approach than with the fixed-percentage method when considering hourly irradiances. These results correspond to clear skies. When clouds are present the methodology that involves a fixed percentage of the instantaneous ambient irradiance will reflect this change in the supplementing irradiance. On the other hand, in the case of applying a fixed irradiance value, the variation in the instantaneous ambient irradiance will not be reflected and large discrepancies are expected.

A comparative analysis of both methods shows measured and modelled 305 nm irradiance as function of local time during 1–6 November 2001 for Ushuaia (Fig. 6). Modelled irradiance was calculated under clear sky conditions and climatological ozone, as well as from real-time ozone present during the period under consideration. As a consequence of this difference in ozone, the calculated percentage or fixed value of irradiance to be supplemented (depending on the method) is expected to differ from the necessary supplementation, even under clear skies. Cloud cover will contribute further to increase the discrepancies. When applying the calculated percentage or the calculated fixed irradiance, the discrepancy in the accumulated irradiance during 6–10 November would be 2.5% for the fixed-percentage method and 28% for the fixed-value method. It should be noted that the presence of ozone values lower than the climatological values tend to compensate for the discrepancies produced by clouds in the fixed-value method.

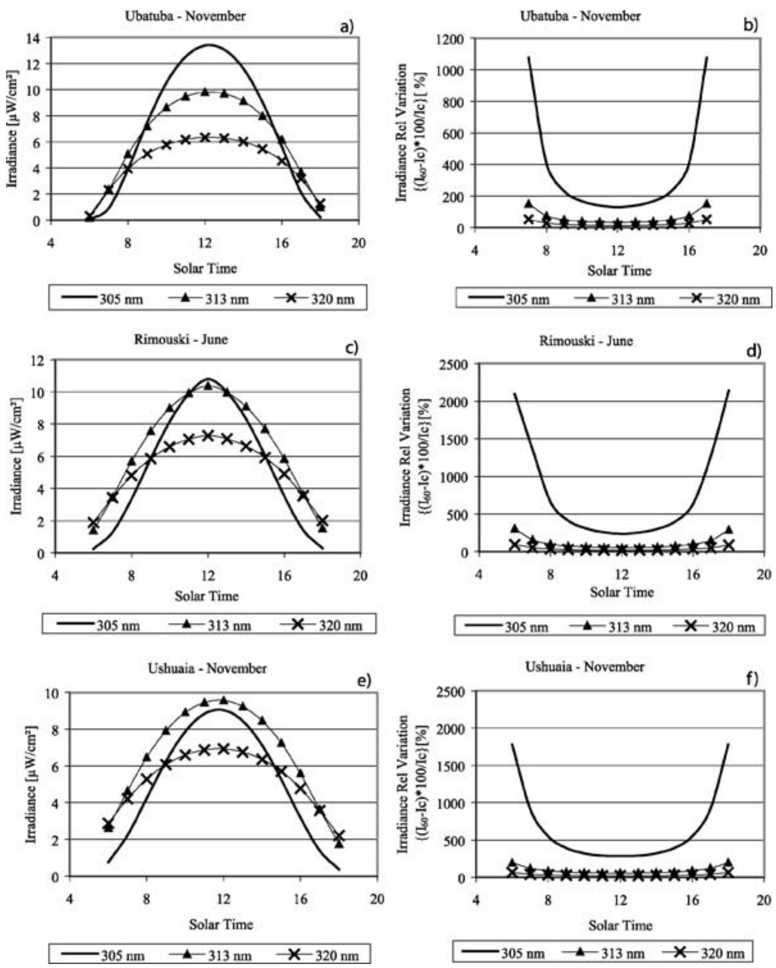

Figure 5. Supplementing irradiance levels (given as absolute values for the fifteenth day of the month) for 60% of ozone depletion by time of day Ubatuba in November (a), Rimouski in June (c) and Ushuaia in November (e). Supplementing irradiance levels (given as percentages of climatological ozone levels) by time of day for Ubatuba in November (b); Rimouski in June (d) and Ushuaia in November (f). Measurements were made at the wavelengths 305 nm (—), 313 nm (▲) and 320 nm (×).

Because the largest discrepancies are seen on 6 November (Fig. 6), we performed a more detailed analysis for that day. The difference between daily integrated modelled irradiance based on 60% ozone depletion from climatological norms and the actual needed daily integrated irradiance, given the actual ozone level and the presence of clouds, would have been 33% in the fixed-percentage method and 220% for the fixed-value method. The equivalent ozone depletion simulated at that day corresponds to 75% with the fixed-percentage method. For the fixed-value method the simulated ozone depletion would exceed 100% (which is equivalent to 0 ozone column). In summary, in very cloudy days supplementation by the square method may produce unrealistic irradiances. This occurs because this supplementing method is not sensitive to ambient changes. Table 2 shows the differences between both irradiances at different times of the day.

The purpose of the example presented in Table 2 was to describe the maximum discrepancy between real-time 305 nm irradiance and supplemented irradiance. The divergences for both methods tend to diminish when several days are considered (*i.e.* 6–10 November). Furthermore, the observed differences with climatological ozone in Ushuaia are a consequence of the effect of the ozone hole. At the other sites the discrepancies should be much lower. For example, during the experiment at Ubatuba the mean total column ozone level for the 7 days of the experiment was 267.8 DU, which is very closed to the normal climatological level for that month (266 DU) (22).

Evaluation of the lamp spectrum

Regardless of the selected supplementing method, the spectra of the supplementing irradiance and the lamp will present some additional differences. The spectral distribution of the supplementing irradiance for a given ozone depletion is a function of the location, date and time of day. Figure 7 shows the spectra of the supplementing irradiance at noon and 4 h from noon at the three

Table 1. Difference between supplementing irradiance and modelled irradiance, calculated for 60% ozone depletion, for different time lags referred to noon and daily integrated irradiance, at 305 nm.*

	Ubatuba			Rimouski			Ushuaia		
Time from solar noon (h)	FP (%)	FV (%)	I_h/I_n	FP (%)	FV (%)	I_h/I_n	FP (%)	FV (%)	I_h/I_n
4	−54	197	0.26	−34	69	0.33	−41	96	0.35
3	−30	55	0.52	−17	25	0.57	−22	35	0.58
2	−14	17	0.75	−6	7	0.79	−9	11	0.80
1	−4	4	0.94	0	0	0.95	−1	2	0.95
Daily integrated irradiance	−14	−16		−16	−24		−17	−24	

*FP = supplementing irradiance calculated as a fixed percentage of ambient irradiance; FV = supplementing irradiance fixed value (square wave); I_h = irradiance at time h; I_n = irradiance at solar noon.

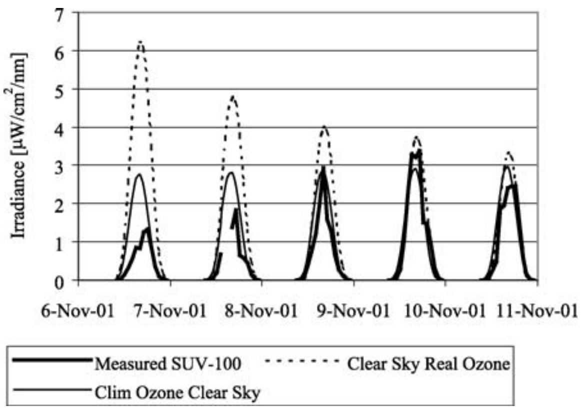

Figure 6. Irradiance at 305 nm as function of local time for Julian Days 310–314 in 2001 measured at Ushuaia with the spectroradiometer SUV-100 of the US National Science Foundation UV Radiation Monitoring Network (37) (thick-filled line); modelled for clear sky and ozone climatology (thin-filled line); and modelled from clear sky and real-time ozone column (dotted line).

Table 2. Difference between supplementing irradiance for the fixed percentage and fixed value methods and calculated for 60% ozone depletion, for different time lags referred to noon and daily integrated irradiance, at 305 nm, for Julian Day 310 in 2001.*

Time from solar noon (h)	FP (%)	FV (%)
−4	−12	1340
−3	15	793
−2	35	509
−1	47	347
0	52	374
1	50	224
2	42	187
3	27	287
4	4	642
Daily integrated irradiance	33	220

*FP = supplementing irradiance calculated as a fixed percentage of ambient irradiance; FV = supplementing irradiance fixed value (square wave).

sites on the dates noted above (November for Ubatuba and Ushuaia and June for Rimouski), combined with the spectrum of fluorescent light tubes Philips TL40W-12RS. Since the lamp and the supplementing irradiance spectra exhibit differences, a criterium needs to be adopted in order to determine the lamp intensity. In this Fig. 7 the lamp intensity was adjusted to produce an integrated UV-B irradiance (280–315 nm) equal to the modelled supplementing irradiance needed to simulate 60% ozone depletion. For Ubatuba at noon both spectra adjust very well for lower wavelengths whereas the values differ more for larger wavelengths. At the other two sites the lamp provides irradiances that are slightly larger than those calculated for lower wavelengths but larger wavelengths show smaller differences. At 4 h from noon, different results were observed as a consequence of the change in the spectral distribution of the supplementing irradiance. For all the sites the difference between the supplementing irradiance and the lamp was larger for wavelengths <320 nm; a good agreement was observed for larger wavelengths.

The differences between lamps and calculated supplemented irradiances may become more or less pronounced when considering the action spectrum of a given biological effect (38). Lamp intensity may be adjusted to accomplish conditions other than agreement in the integrated UV-B (*e.g.* agreement at 305 nm or at irradiance weighted for a given action spectrum), depending on the lamp spectrum and the effect to be analyzed. The shape of the weighting function of the effect under study needs to be taken into account when making this decision. For action spectra with much larger weight at lower wavelengths (*e.g.* DNA damage) the difference between the spectra of the lamp and the supplementing irradiance should be minimized for lower wavelengths. For action spectra that exhibit less pronounced differences between the weight of lower and larger wavelengths (*e.g.* CIE erythema) the difference between the lamp and the supplementing irradiance spectra should be more balanced.

Ozone depletion affects irradiance at wavelengths in the UV-B, whereas the UV-A irradiance remains unchanged. Nevertheless, when applying lamp supplementation, a small amount of UV-A radiation is added (Fig. 7). Some authors recommend that undesirable UV-A provided by the lamps should be compensated for (9) by also using lamps on the control samples, applying only the UV-A by filtering the UV-B with mylar. Other authors consider that the amount of integrated UV-A provided by the lamps is negligible, compared with ambient UV-A (18). We have determined that the level of UV-A provided by the lamp is *ca* 10% of the ambient level. We consider that the decision to add UV-A to the control samples should be evaluated by taking into account the action spectrum of the effect under study. If the weighting function of the effect shows relatively large values in the UV-A, then compensating for the applied UV-A radiation in the control sample will be more critical (38).

Finally, in some studies changes in lamp height are used to produce different UV supplementation values. This method would produce a variation in the shadow on the experimental container (38). We recommend the use of a balaster (*i.e.* voltage regulator) to modulate the feeding voltage of the lamps as a means to produce the desired UV irradiance (22). Furthermore, selecting smaller holders will minimize the effect of shadows (22).

CONCLUSIONS

Comparison of fixed-percentage and fixed-irradiance supplementation methods showed that supplementing a fixed percentage of ambient irradiance provides a better simulation of irradiance increase due to ozone depletion, particularly under cloudy conditions. On very cloudy days supplementation by the square method may produce unrealistic irradiances.

Depending on the action spectrum of the biological effect under study, differences between applied lamps supplementation and calculated supplemented irradiances may become more or less pronounced. We recommend minimizing the difference between the lamp and the irradiance where the weighting function shows larger susceptibility.

In order to modulate the irradiance in the fixed percentage method, it is recommended to use a balaster to graduate the feeding voltage of the lamps instead of changing lamp height.

The decision to add UV-A to the control samples should be evaluated by taking into account the action spectrum of the effect under study.

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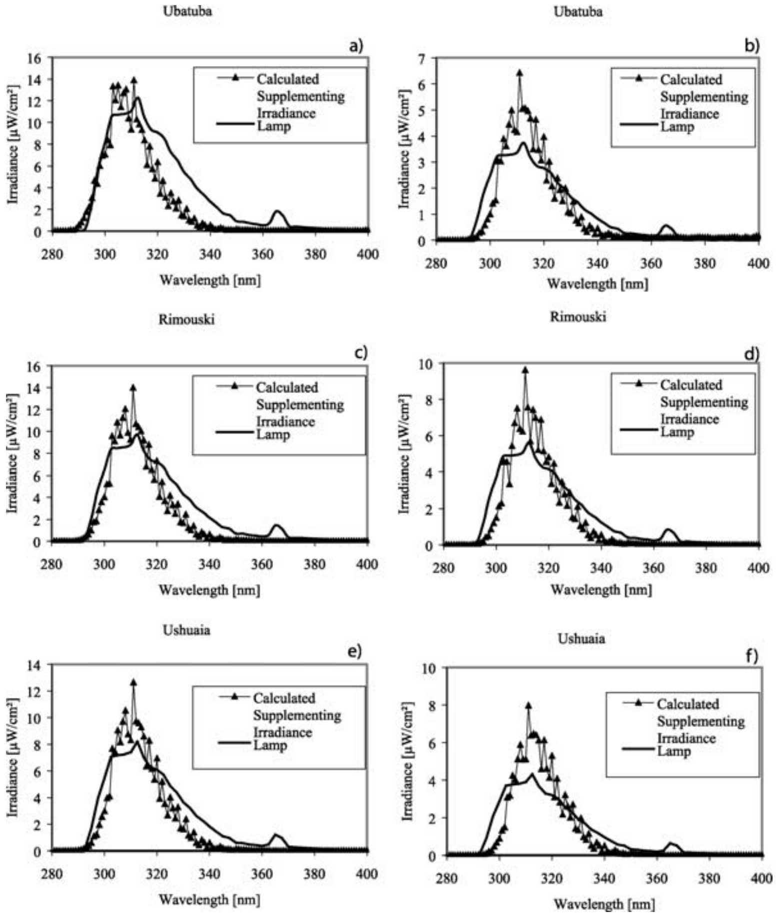

Figure 7. Spectra of calculated supplementing irradiance during November at Ubatuba and Ushuaia and during June at Rimouski, created using fluorescent Philips TL40W-12RS light tubes covered with cellulose acetate film, at noon (a,c,e) and 4 h from noon (b,d,f). The lamp intensity was adjusted to provide the same UV-B integrated irradiance (280–315 nm) as the supplementing irradiance calculated for 60% ozone depletion.

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