Reports

Ultraviolet Radiation Levels During the Antarctic Spring

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The decrease in atmospheric ozone over Antarctica during spring implies enhanced levels of ultraviolet (UV) radiation received at the earth's surface. Model calculations show that UV irradiances encountered during the occurrence of an Antarctic "ozone hole" remain less than those typical of a summer solstice at low to middle latitudes. However, the low ozone amounts observed in October 1987 imply biologically effective irradiances for McMurdo Station, Antarctica, that are comparable to or greater than those for the same location at December solstice. Life indigenous to Antarctica thereby experiences a greatly extended period of summerlike UV radiation levels.

MUCH OF THE CONCERN OVER changes in the ozone layer centers on the biological importance of UV radiation (*1*). The spectral regions of primary interest for biological damage are the UV-B at wavelengths from 280 to 320 nm and, to a lesser extent, the UV-A from 320 to 400 nm. The reduction in total column ozone observed over Antarctica (or "ozone hole"), which develops in September and dissipates during November of each year (*2*), implies an increase in biologically effective UV radiation at the earth's surface. The large solar zenith angles characteristic of the polar regions usually imply small UV irradiances as compared with those at lower latitudes. However, when accompanied by a dramatic decrease in column ozone, it is not obvious how the springtime irradiances compare with middle latitude values or to radiation levels typical of an unperturbed Antarctic summer solstice.

One concern involves possible eye damage to researchers who visit Antarctica for extended periods of time. A relevant comparison for this case is between Antarctic UV levels and the maximum irradiances that humans encounter at low to middle latitudes. A second, and potentially more significant, concern centers on the response of indigenous Antarctic life to enhanced UV irradiances. Many organisms appear to develop only the minimum defenses necessary to tolerate the UV radiation levels in which they have evolved (*3*). Adverse responses may occur, depending on the dose-response relation, if the irradiance exceeds natural levels for a prolonged time. A relevant comparison here is between UV irradiances encountered during an "ozone hole" and those typical of an Antarctic summer solstice with an unperturbed ozone amount.

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We report calculations of UV irradiance at the earth's surface for McMurdo Station, Antarctica (McMurdo, 78°S), during depleted ozone and normal ozone conditions. We compare these irradiances with calculations for the latitude of Miami, Florida (26°N), on 21 June and McMurdo on 21 December. Results for 26°N should be viewed as representative of low to middle latitude sites in general, rather than being specific to Miami. The radiative transfer equations to be solved have been discussed in detail elsewhere (*4*). The only significant change from our earlier model involves a correction to account for the sphericity of the atmosphere, which is essential for application to the large solar zenith angles encountered at high latitudes. The radiative transfer model includes all orders of scattering, absorption by ozone, and reflection from a lower boundary. We assume clear skies and a surface albedo of 0.95, which is appropriate to clean Antarctic snow and ice cover. The irradiance calculations encompass wavelengths from 295 to 400 nm and use recommended values of the extraterrestrial solar irradiance, ozone absorption cross sections, and Rayleigh scattering cross sections (*5*).

The downward irradiances at the earth's surface for local noon as functions of wavelength for Miami on 21 June and McMurdo on 21 December are shown in Fig. 1A. The column ozone values adopted here are 280 and 350 Dobson units (DU), respectively (*6*). We selected these ozone amounts based on measurements from the Nimbus 7 Solar Backscatter Ultraviolet radiometer for the year 1979. The solar zenith angles are 2.3° at Miami and 54.2° at McMurdo. At wavelengths greater than 330 nm, the irradiance

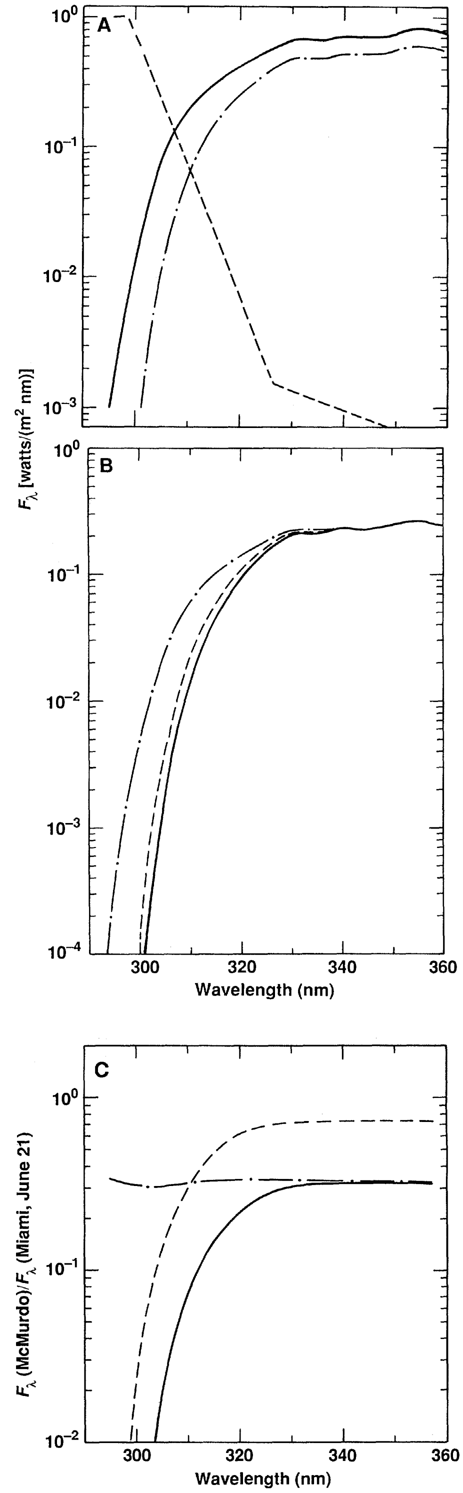

Fig. 1. Downward solar irradiance (F_λ) reaching the earth's surface at local noon as a function of wavelength. (**A**) Results for the latitude of Miami, Florida, on 21 June (solid line) and for McMurdo on 21 December (dot-dash line). Dashed line is the erythema action spectrum in relative units. (**B**) Results for McMurdo on 5 October with a solar zenith angle of 71.6°. Curves appear for ozone column abundances of 315 (solid line), 250 (dashed line), and 110 DU (dot-dash line). (**C**) Ratio of F_λ values at the earth's surface for McMurdo for various dates and ozone amounts to those for Miami on 21 June: solid line, 5 October, 315 DU; dot-dash line, 5 October, 110 DU; and dashed line, 21 December, 350 DU.

ratio (McMurdo to Miami) is 0.70 to 0.75. The ratio decreases rapidly toward shorter wavelengths as absorption by ozone becomes significant. The spectra of Fig. 1A serve as baselines against which to measure Antarctic radiation levels during periods of reduced ozone.

Irradiances computed for McMurdo with a solar zenith angle of 71.6°, appropriate to noon on 5 October, are shown in Fig. 1B. An ozone amount of 315 DU is typical of observations during October at Halley Bay, Antarctica, in years prior to 1968 (*7*). A column ozone of 250 DU existed over McMurdo in early September of 1987, whereas the lowest value observed anywhere over Antarctica was slightly below 110 DU on 5 October 1987 (*8*). At wavelengths greater than 340 nm, an ozone reduction has no impact on surface irradiances. However, at a wavelength of 315 nm, a decrease in ozone from 315 to 110 DU is accompanied by a factor of 2.2 increase in irradiance. At 305 nm the corresponding enhancement is a factor of 14.

Downward irradiances computed for McMurdo and normalized to results for Miami at summer solstice are shown in Fig. 1C. This comparison pertains to an assessment of human health during extended visits to Antarctica. Results appear for McMurdo on 5 October with ozone amounts of 110 and 315 DU and 21 December with 350 DU. All of the ratios in Fig. 1C are less than unity. However, the total radiation field includes both downward and upward components. The upward component over a snow-covered Antarctic surface makes a greater contribution to the total irradiance than is the case for Miami at summer solstice. Even with such adjustments, life forms accustomed to summer radiation levels at low to middle latitudes would not have experienced abnormally large UV-B exposure under conditions encountered in Antarctica through 1987.

The two curves in Fig. 1C for unperturbed ozone levels, 5 October with 315 DU and 21 December with 350 DU, show the expected decrease in irradiance toward short wavelengths relative to Miami. However, the curve for 110 DU on 5 October is nearly horizontal and illustrates the large irradiance increases that can occur at wavelengths where absorption by ozone is important. The noontime UV-B irradiance on 5 October with 110 DU of ozone exceeds that for Antarctic summer solstice at wavelengths shorter than 310 nm. Random fluctuations in ozone from day to day are small compared with the absolute changes that occur as the ozone hole develops and dissipates from September through November (*7*). The differences between curves in Fig. 1, B and C, arise from the elevation of the sun at local noon and the ozone amount. Systematic changes in irradiance over a time scale of 1 month exceed any random variations related to the daily behavior of ozone within the polar vortex.

Biological responses to UV radiation depend on the convolution over wavelength of solar radiation with an action spectrum, in which the action spectrum measures the relative sensitivity of an organism to damage by sunlight of varying wavelengths. We refer to this convolution as the biologically effective irradiance. The action spectrum for erythema (*9*), a reddening of the skin and the likely initial step in the development of some types of skin cancer, is shown in Fig. 1A. This action spectrum decreases by three orders of magnitude as wavelength increases from 295 to 340 nm.

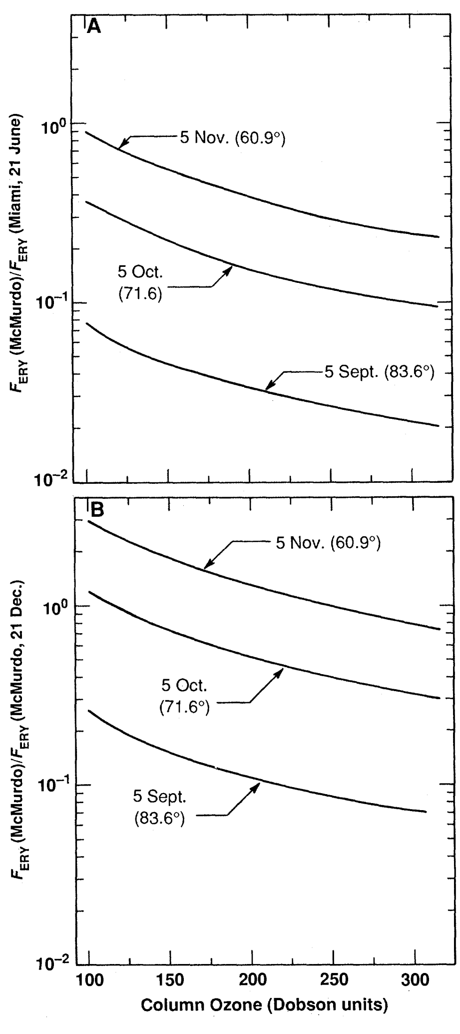

Fig. 2. Ratio of biologically effective downward irradiance (F_{ERY}) computed for a range of ozone values at McMurdo (**A**) to that for Miami on 21 June and (**B**) to that for McMurdo on 21 December. All values refer to local noon. The solar zenith angles for McMurdo appear in parentheses. The ozone amount at Miami is 280 DU and at McMurdo on 21 December is 350 DU.

The biologically effective downward irradiance computed for McMurdo, normalized to that for Miami on 21 June, is shown in Fig. 2A for a range of ozone values from 100 to 315 DU and solar zenith angles for local noon on 5 September, 5 October, and 5 November. As expected from Fig. 1C, all of the ratios remain less than unity for ozone values encountered through 1987. However, if the curves of Fig. 2A were adjusted to refer to total irradiance, the sum of downward and upward components, all of the ratios would be increased by a factor of 1.7. Based on this measure, a column ozone value of 140 to 145 DU over Antarctica on 5 November would imply a total biologically effective irradiance at noon equal to that at summer solstice at the latitude of Miami. An ozone column of 65 to 70 DU would provide the same noontime irradiance on 5 October. The latter values are less than any observed through 1987. In Fig. 2B the biologically effective irradiance for McMurdo is normalized to the 21 December value with an ozone column of 350 DU. During October and at least early November 1987, it is likely that the biologically effective irradiance at the earth's surface was near or exceeded values typical of an unperturbed Antarctic summer solstice.

One should also consider the biologically effective irradiance integrated over 24 hours. We computed integrated values appropriate to McMurdo for 5 October with 110 DU of ozone and 5 November assuming 150 DU, and took the ratio of these to the integrated irradiance for 21 December with 350 DU of ozone. These ratios are 0.75 to 0.80 for 5 October and 1.5 to 1.6 for 5 November. Note that the time of minimum ozone amount is not the time of maximum irradiance. From October through December, the solar zenith angle at a fixed local time decreases. This effect leads to an increase in surface irradiance even though ozone amounts are recovering toward unperturbed values after an October minimum. The magnitude of the radiation dose, integrated over an Antarctic spring, depends on details of the ozone depletion's temporal decay combined with the rising of the sun toward summer solstice. Any change in the recovery time of the ozone layer would be especially significant here. From the standpoint of Antarctic life, the ozone hole provides a greatly extended period of summerlike UV radiation levels, beginning in October. This phenomenon merits detailed study from the standpoint of photobiology and ecology.

REFERENCES AND NOTES

1. J. Calkins, *The Role of Solar Ultraviolet Radiation in Marine Ecosystems* (Plenum, New York, 1982); R. Worrest and M. Caldwell, *Stratospheric Ozone Reduc-*

tion, Solar Ultraviolet Radiation and Plant Life (Springer-Verlag, Berlin, 1986).
2. R. Stolarski et al., Nature 322, 808 (1986).
3. J. Calkins and T. Thordardottir, ibid. 283, 563 (1980).
4. J. Frederick and D. Lubin, J. Geophys. Res. 93, 3825 (1988).
5. Atmospheric Ozone 1985, Assessment of Our Understanding of the Processes Controlling its Present Distribution and Change (National Aeronautics and Space Administration, Washington, DC, 1986).
6. One Dobson unit is equal to an ozone column content of 2.69×10^{20} molecules per square meter of horizontal area extending from the ground to the top of the atmosphere.
7. J. Farman et al., Nature 315, 207 (1985).
8. A. J. Krueger, personal communication (1987); Science 239, 146 (1988).
9. B. Diffey, Photochem. Photobiol. 46, 55 (1987).
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The Position of the Gulf Stream During Quaternary Glaciations

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Ocean general circulation theories predict that the position of the boundary between subtropical and subpolar gyres (and therefore the position of the Gulf Stream–North Atlantic Current system and the subpolar-subtropical front) is set by the line of zero "Ekman pumping," where there is no convergence or divergence of water in the directly wind-forced surface layer of the ocean. In the present-day North Atlantic Ocean this line runs southwest to northeast, from off the Carolinas to off Ireland. However, during the last ice age (18,000 years ago) the subpolar-subtropical boundary ran more zonally, directly toward Gibraltar. A numerical atmospheric general circulation model indicates that the field of Ekman pumping 18,000 years ago was modified by the presence of a continental ice cap more than 3 kilometers thick such that the line of zero Ekman pumping overlaid the paleogyre boundary. These results demonstrate that the presence of a thick continental ice sheet could have caused changes in sea surface temperatures in the North Atlantic during Quaternary glaciations by altering wind patterns.

IN THE PRESENT-DAY NORTH ATLANTIC Ocean, the boundary between subtropical and subpolar gyres runs southwest to northeast, from Hatteras to the Norwegian Sea. The warm Gulf Stream and its extension, the North Atlantic Current system, coincide with this boundary. Together, these currents supply between 50 and 100 W m^{-2} of heat to the high latitude North Atlantic (*1*), and, once cooled, their waters sink to become a major source of bottom water to the world ocean. In contrast, during the last glacial maximum approximately 18,000 years ago, the gyre boundary and associated currents were more zonal and located farther to the south (*2, 3*), resembling the present-day North Pacific.

The position of the gyre boundary can have important consequences on both surface water properties and deep and bottom water production. The present-day warm-water influx to high latitudes significantly enhances the evaporation (and cooling) over that of resident cooler waters, resulting in density changes sufficient to produce bottom water (*4*). The zonal orientation of the gyre boundary 18,000 years ago suggests that the excursion of warm water to high latitudes had ceased. This implies that subpolar surface waters were cool and that deep-water production was reduced. Geological and microfossil evidence supports the first of these implications (*3*) and geochemical data support the later (*5*).

Previous studies have suggested that the reason for this realignment is related to atmospheric forcing (*6*), but the exact mechanism has remained unclear. We suggest that the presence of continental ice may have been responsible for modifying the wind field in such a manner as to cause the line of zero "Ekman pumping"—a dynamically critical parameter to the gyre geometry—to

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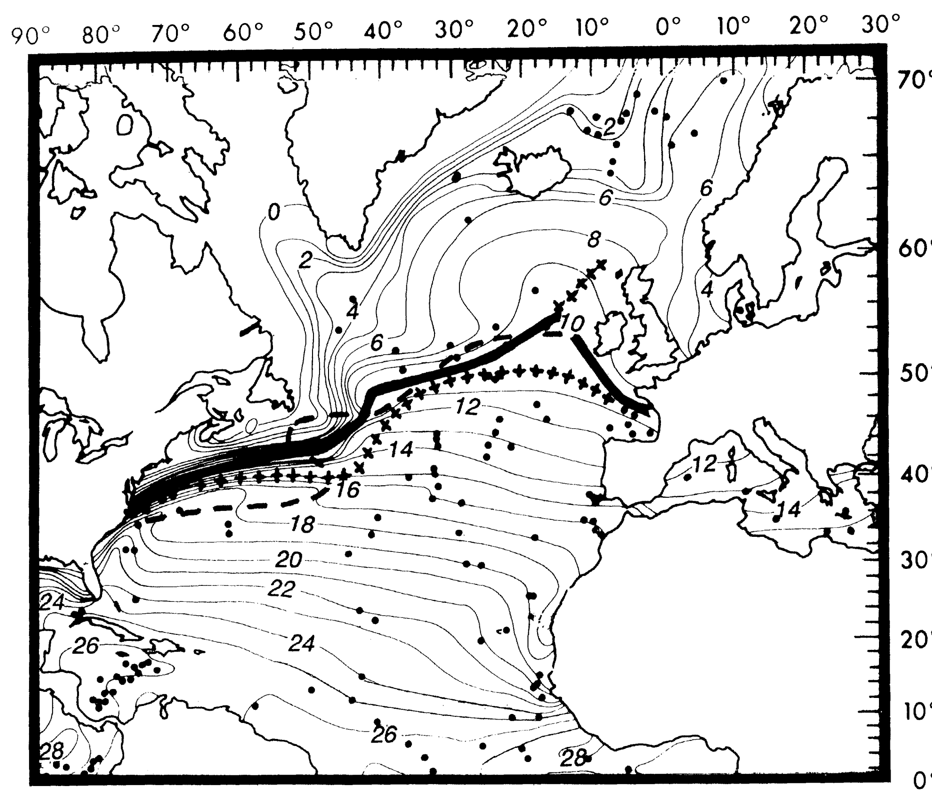

Fig. 1. Present-day January SST compiled by the CLIMAP group (*2*). The dots are positions of the data points used to make this reconstruction. The heavy solid line is the 10°C isotherm, which was chosen to represent the position of the subpolar-subtropical gyre boundary (*10*). The heavy dashed line is the present-day position of the line w_e = curl(τ) = 0 (*13*). The crossed line represents the circulation pattern of the Gulf Stream–North Atlantic Current system as determined by Sverdrup et al. (*14*). The 10°C isotherm, maximal thermal gradient, and Gulf Stream–North Atlantic Current system all coincide. Note that the line w_e = curl(τ) = 0 essentially determines the position of these features.