# 28 Biological UV exposure in the polar oceans: Arctic–Antarctic comparisons

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**ABSTRACT**

Rising UV-B radiation in Antarctica and the potential for future ozone depletion over the Arctic have underscored the need for improved, predictive models of biological UV exposure in the polar marine environment. In this analysis we applied a `weighted transparency' model of underwater UV exposure and compared the fundamental similarities and differences between the north and south polar oceans. By way of published studies and new optical measurements in the Arctic and Antarctica we examined the effects of incident UV, albedo, attenuation by snow and ice, absorption and scattering in the water column, and biological weighting functions for UV exposure. Ozone depletion is likely to remain more severe over the Southern Ocean, however climate change over the 21 s century is predicted to be especially large in the Arctic and would be accompanied by major variations in underwater UV through the loss of sea ice and changes in the distribution of colored dissolved organic matter (CDOM). An analysis of the effects of Arctic sea ice melting shows that this process could result in order-ofmagnitude increases in biological UV exposure that greatly exceed those caused by the current extent of ozone depletion

Key Words: CDOM, global changes, ice, ocean optics, ozone depletion, UV exposure

## INTRODUCTION

The continuing increase in UVB radiation over Antarctica and the potential for stratospheric ozone depletion over the Arctic has heightened concern about the potential impacts of shifting spectral irradiance on high latitude marine ecosystems. UV radiation (UVR) causes a broad range of photobiological (Vincent & Neale 2000, Vincent & Belzile 2002) and photochemical (Whitehead *et al.* 2000) effects and there is an increasing need to understand the controls on biological UV exposure in the oceanic environment.

An index of UV exposure that has been applied to a variety of marine and freshwater questions is the parameter `weighted transparency', $T^*$ (Vincent *et al.* 1998, Pienitz & Vincent 2000, Gibson *et al.* 2000). This parameter allows the effects of stratospheric ozone depletion and changes in water column attenuation of UVR to be assessed on a common, biologically relevant scale. Comparisons with more detailed models of UV effects on photosynthesis indicate that this parameter can provide an accurate guide to the extent of UV photoinhibition (Lehmann *et al.* 2000, Neale 2001). $T^*$ is calculated by integrating the transparency of the water column to biologically weighted irradiance at each wavelength ? over the UV waveband 280-400 nm:

$$T^* = \int T^*(\lambda)\, d\lambda \qquad (1)$$

In an ice-covered ocean, $T^*(\lambda)$ may be partitioned as follows:

$$T^*(\lambda) = E_d(0^+)\, F\, (1-r)\, (1-f)\, (1/K_d)\, \varepsilon \qquad (2)$$

where the parameters at each wavelength $\lambda$ are:

$E_d(0^+)$ = the incident solar irradiance in relative energy units;
$F$ = factor modifying that flux as a function of ozone depletion in the stratosphere;
$r$ = the fraction of UV that is removed by surface reflection (albedo) from the snow, ice or water;
$f$ = the fraction of UV that is removed by attenuation by overlying snow and ice;
$K_d$ = the diffuse attenuation coefficient for UV irradiance in the water column;
$\varepsilon$ = the biological weighting factor which expresses the relative damage incurred by UV ($\varepsilon$ = 1.0 at 300 nm).

Recently it has been shown that $K_d$ can be described as a function of the inherent optical properties $a$ (absorption) and $b$ (scattering) by extending the Kirk (1984) formulation into the UV waveband (Belzile *et al.* 2002):

$$K_d = 1/\mu_o\, [a^2 + G(\mu_o)\, (a \cdot b)]^{0.5} \qquad (3)$$

where $\mu_o$ is the average cosine of the angle of the stream of photons at

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the top of the water column and $G(\mu_0)$ is an empirical function that specifies the relative contribution of scattering to attenuation. In the following paper we compare the fundamental similarities and differences in biological UV exposure between the Arctic and Antarctic Oceans, and have structured this review according to each of the terms in Eq. 2. We conclude our analyses by examining the implications of climate change for shifts in underwater UV exposure in the two polar regions.

## INCIDENT UVR ($E_d(0+)$, F)

There are major differences between the two polar regions in terms of atmospheric circulation and stratospheric ozone (Staehelin *et al. 2001).* Cyclonically spinning, near-cylindrical masses of air form over both poles during winter and these polar vortices maintain the extreme low temperatures that are required for stratospheric ice clouds and the chemical breakdown of ozone. However, the Antarctic vortex is much more stable because of weaker forcing from lower latitudes in the Southern Hemisphere. The Antarctic vortex is therefore colder and persists for *2-3* months longer than in the Arctic, resulting in increased ozone depletion. Even in the 1950s, prior to the effects of CFCs and other ozone-depleting substances, total ozone over the Antarctic in winter and spring was about 30 % lower than over the Arctic (absolute difference of 160 Dobson Units, DU). Given the weaker polar vortex, ozone depletion over the Arctic is weaker, more episodic and subject to much larger interannual variations.

Spring ozone (October mean values) at Halley Station (Lat. 75°S) in Antarctica has shown evidence of decline from the 1970s onwards (Staehelin *et al.* 2001). Values were about 300 DU in the early 1970s, dropping to 200 DU by the early 1980s and 125 DU in the 1990s, and biological UV doses have increased by a factor of two over the period 1979-1999 at Halley Bay. 75.5 °S (Fig. 1.11 in Dahlback 2002). Fortuitously, the most severe ozone depletion occurs well before the seasonal bloom in the marginal ice edge zone, however there may be photobiological effects on the sea ice biota during spring given the enhanced UV-transparency of Antarctic sea ice at that time (Trohdahl & Buckley 1990). Significant ozone depletion, and the concomitant rise in incident UVB, was observed in the Arctic in the 1990s. Spring ozone (March values) dropped from around 500 DU during the period 1957-1990 to values less than 450 DU in the 1990s, with extreme depletion to 270-320 DU through most of March 1997. However, the 1990s were also a period of large interannual variations in ozone Levels over the Arctic and these have obscured long term trends at some sites; e.g., annual UV dosages at Ny-Alesund. latitude 79 °N, increased significantly by 21% from 1979 to 1993, but the increase over the full period 1979-99 is not statistically significant (Dahlback 2002). Although it is hoped that the downward ozone trends may reverse in the near future as a consequence of reduced anthropogenic emissions of CFCs and related compounds, some of the longer-lived ozone-depleting substances are still accumulating in the stratosphere (Staehelin *et al.* 2001) and climate change may prolong the effects of depletion (see below). The minimum winter temperatures of the Arctic stratosphere are very close to the threshold for the chlorine reactions that lead to ozone loss, and the Arctic remains vulnerable to large-scale ozone depletion (Dahlback 2002).

Superimposed on these long term trends are short term variations in the amount and spectral shape of UVR reaching the Earth' s surface caused by seasonal and latitudinal changes in solar zenith angle (SZA), cloud cover and surface albedo, as well as the circulation dynamics of the stratosphere. When the ground is covered by snow, incident erythemal UV may increase by up to 25% due to multiple reflections between the surface and the atmosphere; this relative increase can reach 80% on overcast days (Renaud *et al.* 2000).

## ALBEDO (1-r)

Albedo, the ratio of upwelling ($E_u$) to downwelling ($E_d$) irradiance, is the combined result of the surface (specular) reflectance and volume reflectance. Given the highly diffuse nature of UVR, the albedo of a water body is relatively insensitive to SZA and waves and varies between 5-8% (Jerome & Bukata 1998). In both polar regions, snow and sea-ice cover exert a major effect on albedo and near-surface transmission, and thus the amount of downwelling UV entering the water column. Snow UV albedo is generally > 80%. Cold sea ice albedo is also high but decreases to 50-60% for bare melting ice. Melt ponds are a common feature over Arctic sea ice during late spring and summer and have albedo values as low as 30%. Contrary to the pronounced decrease of UV albedo observed in the Arctic as melting progresses (Perovich *et al.* 1998, Belzile *et al.* 2000 and refs therein), the dry climate of Antarctica often induces the formation of a scattering surface layer with high albedo (Trodahl & Buckley 1990). Ice albedo is therefore likely to be consistently higher in summer in Antarctica than at equivalent latitudes in the Arctic.

Our snow-clearing experiments in Hudson Bay at the edge of the Arctic Ocean underscore the large albedo effect on UV transmittance through sea ice. These measurements were made near local solar noon using a Biospherical PUV500 UV profiling radiometer that was positioned via a retractable arm flush against the lower ice surface and 1 m away from the entry hole, the latter fitted with a light-tight cover during observations. Surface incident irradiance ($E_d$) was measured simultaneously with a Biospherical PUV510 radiometer. The removal of surface snow caused a 3 to 16 fold increase (depending on site) in under-ice UVR, thus a similar increase in T». Even a layer of snow only 2-cm thick reduced UVR by a factor of 3, with slightly greater effects at the shorter wavelengths (Fig. 1). Given the higher levels of precipitation in the north polar region, this influence of snow cover is likely to be more pronounced in the Arctic.

## ATTENUATION BY SNOW AND ICE (1-*f*)

Attenuation coefficients of UV for snow and ice are difficult to quantify experimentally due to the solid state of these media, the strong

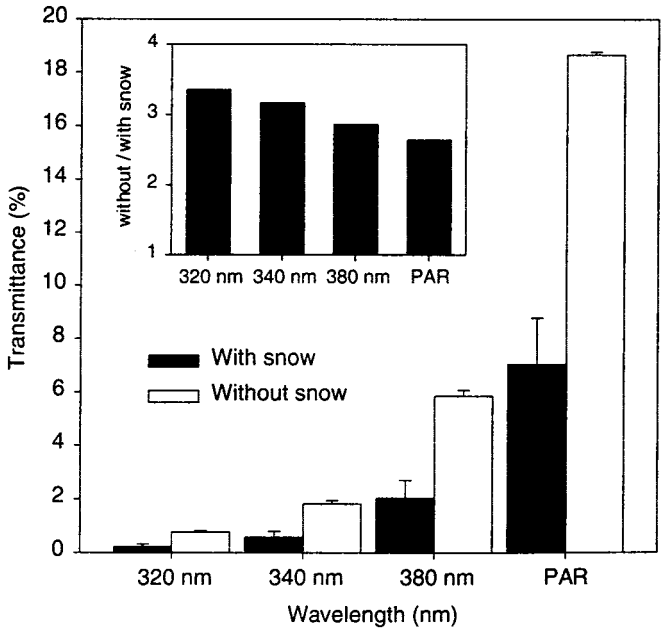


*Fig. 1.* Transmittance through 0.7 m-thick sea ice with and without the natural 2 cm-deep snow cover, Hudson Bay 16 April 1999.

horizontal variations of the optical properties that are often observed, and the difficulties associated with the determination of $E_d(0^-)$. No values for $K_d$(UV) of snow have been published although in the visible $K_d$ is high with reported values of-2O-4O $m^{-1}$(Grenfell & Maykut 1977). In early spring, about 1 % of incident UVB is transmitted through ~1.6 m of sea ice (Arctic, Perovich et al. 1998; Antarctic, Trodahl & Buckley 1990). However, the development of ice algae can decrease UV transmittance by an order of magnitude (Perovich et al. 1998). Autochthonous CDOM derived from ice algae has a significant impact on UV attenuation in sea ice (Belzile et al. 2000). In the Arctic in late spring, the melting of the snow cover, ponding of meltwater over the ice surface and the flushing of ice algae all tend to increase UV-B transmittance by up to about 10% (Belzile et al. 2000). In Antarctica, the highly scattering ice surface forms as the melt progresses, resulting in an order of magnitude decrease in UV-B transmission relative to early spring values (Trodahl & Buckley 1990).

## WATER COLUMN TRANSPARENCY (1/$K_d$)

Colored dissolved organic matter (CDOM) derived from terrestrial soils and vegetation or from microbial autochthonous production plays a major role in biological UV exposure because of its strong UVabsorbing properties (Gibson et al. 2000). An example of the variability in CDOM concentrations between and within the polar oceans is given in Figure 2. For these measurements, CDOM absorption coefficients, $a_{CDOM}$ (m-1), were measured on surface water samples. Samples were filtered through 0.22 µm Sartorius cellulose acetate filters and stored at 4°C in amber glass bottles until analysis (within 1 month). We then measured $a_{CDOM}$ every 2 nm over the wavelength range 250-820 nm using a 1 cm, acid-cleaned. quartz cuvette in a Hewlett Packard 8452A spectrophotometer. The high concentrations of organic material entering the Arctic Ocean are illustrated by the Great Whale River which discharges into Hudson Bay, and which had an $a_{CDOM}$ value on the mid-summer date of sampling that was two orders of magnitude higher than the same measurements in the Southern Ocean and parts of the Arctic Ocean.

The Great Whale River has DOC concentrations around 4 g C $m^{-3}$, however even higher concentrations may occur in the large Siberian rivers. The North Dvina River contains 20 g C $m^{-3}$ DOC (Gordeev et al., 1996), and the Lena River 7-8 g C $m^{-3}$ DOC, increasing to 12 g C $m^{-3}$ when in flood (Cauwet & Sidorov, 1996). Strong underwater attenuation of short visible wavelengths has been measured in the estuaries of the Ob and Yenisey Rivers, implying that UV wavelengths are also strongly attenuated in these terrestrially influenced regions (Aas et al. 2002). High CDOM conditions can also persist well offshore. In Hudson Bay, 3.5 km beyond the river mouth where salinities were 24 ppt we observed an $a_{CDOM}$ that was more than 50% of the riverine value (Fig. 2). The influence of the DOC-rich freshwater plume of the Lena River has been observed up to 400 km offshore (>5 g C $m^{-3}$ at 4 m; Cauwet & Sidorov 1996), and much of the Siberian Shelf is likely to be characterized by high $a_{CDOM}$ conditions.

Low $a_{CDOM}$ values were a characteristic of all of the samples we obtained from the Antarctic and Subantarctic Ocean, as expected (Fig 2). However, there was a threefold variation between sites, possibly reflecting differences in the extent of CDOM production from autochthonous sources, i.e., synthesis by algal and bacterial processes. Yocis et al. (2000) reported a similar range of aCDOM values at stations nearby the Antarctic Peninsula and in the confluence of the Weddell and Scotia Seas. Values of aCDOM in the North Water (NOW) polynya of the Arctic Ocean, a region well away from coastal influences, were very low and similar to mean values in our Antarctic Peninsula samples. These observations indicate that the spatial variability in UV exposure is much greater in the Arctic Ocean relative to the Southern Ocean. The NOW polynya values varied by a factor of two, which Scully & Miller (2000) attribute to variations in autochthonous organic carbon. The relatively high $a_{CDOM}$ that we observed at Resolute (Fig. 2) is also likely to be due to autochthonous processes since there is minimal riverine input from the terrestrial environments of this region, and the overlying sea ice had a rich basal layer of ice algae at this time of year (May).

The large site-to-site variability in underwater UV attenuation in both polar regions is illustrated in Figure 3a compiled from our own measurements at four wavelengths and from literature data at 340 nm. In the Arctic this variability is extreme, caused by major variations in local CDOM and seston concentrations. In Hudson Bay, spectral absorption by CDOM is orders of magnitude greater than the other light absorbing components (Fig. 3b) and contrasts markedly with the equivalent curves from Antarctica where particles play an important role given the low aCDOM (Fig. 3c). However, parts of the Arctic Ocean, illustrated by sta. C54 in the NOW polynya, have relatively low CDOM absorption coefficients and Kd values fall within the upper part of the range for Antarctic waters (Fig. 3a).

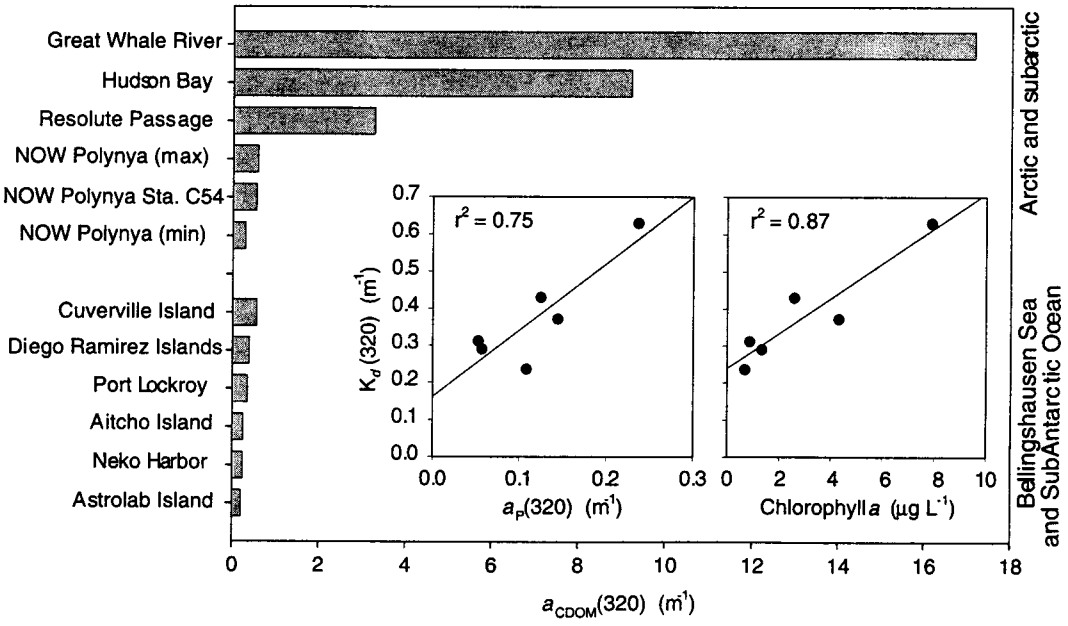


*Fig. 2.* Compilation of $a_{CDOM}$ for sites in the Arctic and Antarctic. Values for the NOW Polynya are from Belzile *et al.* (2000) and Scully and Miller (2000). Insert: Statistical relationships between $K_d(320)$ and bio-optical variables measured in the SubAntarctic Ocean and Antarctic Ocean (Bellingshausen Sea) in January 2001. The $K_d$ values were obtained from log-linear regressions of $E_d(320)$ versus depth, measured with a Biospherical Instruments PUV500 profiling radiometer. Values of $a_p$ were measured by spectrophotometry and chlorophyll *a* was determined fluorometrically.

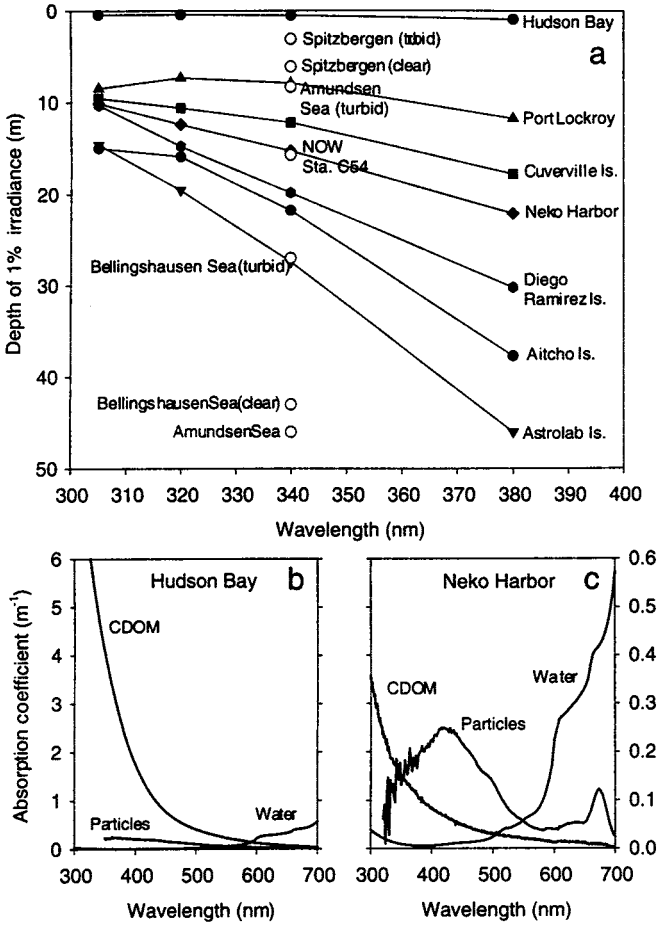


*Fig. 3.* a) Depth of 1% UV at four wavelengths in Hudson Bay (from Laurion *et al.* 1997) and the SubAntarctic and Antarctic Oceans (obtained with a PUV500 profiling radiometer). Also shown are the values at 340 nm for the Arctic NOW polynya (from Belzile *et al.* 2000); a fjord in Spitzbergen with and without the influence of turbid inflows (from Hanelt *et al.* 2001); sites in the Bellingshausen and Amundsen Seas, Antarctica (from Stambler *et al.* 1997) and from the Bellingshausen Sea near Elephant Island (Helbling *et al.* 1994, cited in Stambler *et al.* 1997). b) and c) Spectral absorption of water, particles and CDOM for Hudson Bay, 14 August 1999, and for Neko Harbor, Antarctic Peninsula, 3 January 2001; note the tenfold difference in absorption scales between the two panels.

Our results from the Antarctic Peninsula region show a close correlation between UV attenuation and seston concentrations measured as either chlorophyll a or absorption due to particulate matter (a) (Fig. 2). This is consistent with the observations by Stambler *et al.* (1997) who found a similar relationship between $K_d$(UV) at 340 and 380 nm and chlorophyll a concentrations in the Bellingshausen and Amundsen Seas. This seston effect is likely to be small relative to attenuation by CDOM in the extensive river-influenced shelf regions of the Arctic Ocean. To evaluate the relative importance of UV attenuating materials in the Southern Ocean we applied Eq. 3 to our absorption and profiling data for UV at 320 nm. The absorption coefficients of particulate matter and CDOM were measured by spectrophotometry. The scattering coefficient, b(λ) was estimated from c(660) measured using a Seatech transmissometer. Measured a(660) and pure grater values for c(660) were subtracted from c(660) to obtain *b(660); b* was extrapolated to 320 nm using a $\lambda^{-1}$ spectral dependence (Morel 1988). For all stations, $a_{CDOM}$ contributed the dominant fraction of the $K_d$(320). For example, at the station shown in Fig. 3c (Neko Harbor), $a_{CDOM}$ accounted for 49.9 % of modeled $K_d$(320) while $a_P$ (seston) contributed 25.6 %, $a_{WATER}$ 4.6 %, and scattering the remaining 19.9 %.

Interestingly, Arrigo *et al.* (1998a) found very high particulate absorption in the UV-B region for phytoplankton blooms in the southwestern Ross Sea ($a_p$(320) up to 6 times higher than $a_p$(435)). This strong UV absorption was likely due to mycosporine-like amino acids and was probably higher than $a_{CDOM}$.

In both polar regions, scattering is likely to play a greater role in near-shore waters that are influenced by turbid glacial inflows. For example, UV attenuation varied greatly in Arctic Kongsfjord at Spitzbergen during the period of turbid freshwater discharge from melting snow and glacial ice (Hanelt *et* al. 2001). Strong attenuation due to inorganic particles originating from glacial erosion of adjacent islands was also observed in the Southern Ocean (Mitchell & Holm-Hansen 1991, Helbling *et al.* 1994, cited in Stambler *et al.* 1997).

## BIOLOGICAL WEIGHTING FACTORS (ε)

The biological impact of UV exposure is highly dependent upon the spectral composition of the underwater radiation field. The biological weighting factors (BWF) express the relationship between biological damage and UV wavelength and typically show a sharp increase with decreasing wavelength. However, the exact form of this relationship differs greatly among different types of biological effects as well as with duration of exposure, the pre-acclimation characteristics of the biological community, species composition and a variety of other factors that are currently subject to discussion and ongoing research. For example, Neale *et al.* (1998) found that the UV-tolerance of phytoplankton in the Weddell-Scotia Confluence was highest in assemblages from shallow mixed layers, suggesting acclimation and-or selection for tolerant genotypes.

The spectral weighting effect was examined in the modelling study by Gibson *et al.* (2000) for the Arctic Ocean. Their results draw attention to the combined effect of ozone depletion and changes in CDOM in controlling the extent of DNA damage, and the much greater influence of CDOM in controlling the variations in UV-inhibition of photosynthesis. This is because the latter process is strongly influenced by UV-A as well as UV-B, whereas the BWF for DNA damage rises much more steeply with decreasingly wavelength and UV-A thus plays a lesser role. Changes in ozone concentration affect primarily UV -B wavelengths and therefore have greater impact on DNA damage.

## POTENTIAL IMPACTS OF CLIMATE CHANGE

Climate change is likely to exert a strong effect on underwater UV exposure in the polar regions through several mechanisms. Firstly, the warming of the troposphere will be accompanied by a cooling of the lower stratosphere, and there is already some evidence of this effect in the polar regions. This would result in a strengthening of the polar vortex which in turn could lead to longer-lasting conditions for ozone loss (Staehelin *et al.* 2001). The Arctic stratosphere would appear to be especially sensitive to a small amount of additional cooling (Dahlback 2002). It is also possible that greenhouse warming could lead to increased zonal flow in mid-latitudes causing the polar vortex to be more stable, again favoring ozone loss and a delay in the eventual recovery from CFC emissions (Shindell *et al.* 1998).

Secondly, changes in the amount and distribution of CDOM entering coastal waters will have a major influence on underwater UVR. For some areas of the Arctic, climate change will be accompanied by increased vegetation, a concomitant increase in CDOM loading (Freeman *et al.* 2001) and reduced exposure to underwater UV, although these positive effects may be offset by reduced availability of PAR for photosynthesis (Arrigo & Brown 1996, Pienitz & Vincent 2000, Neale 2001). Major shifts in current patterns across the Arctic Ocean are likely to accompany any substantial change in climate. As shown above, there are large spatial variations in CDOM concentration across the

*Table 1.* The effect of ice cover and 100 DU ozone depletion on biological UV exposure. The index $T^*$ was calculated for an inshore ice-free site (station K7) in Hudson Bay and for an offshore site in the Arctic NOW polynya (station C54, 0.6 m ice and 2 cm of snow) with and without ice cover . The calculations used either BWFs for UV-photoinhibition of photosynthesis ($T^*_{PI}$) or UV damage of DNA ($T^*_{DNA}$), with incident UV values for the Arctic and $F$ values as in Gibson *et al.* (2000): $K_d$ for Hudson Bay from Laurion *et al.* (1997): and $K_d$, $r$ and $f$ for NOW from Belzile *et al.* (2000).

| Site | $T^*_{PI}$ | | $T^*_{DNA}$ | |
|---|---|---|---|---|
| | 330 DU ozone | 230 DU ozone | 330 DU ozone | 230 DU ozone |
| Hudson Bay | 0.24 | 0.25 | 3.3 | 7.7 |
| NOW polynya | | | | |
| ice-covered | 0.56 | 0.57 | 4.1 | 7.9 |
| no ice | 7.0 | 7.3 | 89.0 | 201.1 |

Arctic Ocean; changing circulation will therefore lead to a redistribution of these materials and large regional increases or decreases in underwater UV exposure. Large-scale shifts in the distribution of water masses have already been observed in the Arctic Ocean (Dickson 1999). To examine the potential magnitude of CDOM effects we calculated the index T* for an inshore water column at Hudson Bay and for an offshore water column in the Arctic NOW polynya. both under icefree conditions (Table 1). Moderate ozone depletion (decrease of 100 DU) caused only a 5% increase in biological exposure weighted for UV inhibition of photosynthesis ($T^*_{pI}$), whereas the difference in CDOM accounted for a 29-fold difference in underwater UV exposure between sites. For T* weighted for DNA damage ($T^*_{DNA}$), moderate ozone depletion increased UV exposure by a factor of 2.3, but this was small relative to the 27-fold increase caused by differences in CDOM between sites.

Thirdly, the melting of snow and ice cover caused by rising temperatures would lead to a substantial increase in underwater UV exposure. To place this effect in context we calculated T* for the NOW site with and without its cover of sea ice. The removal of ice increased $T^*_{pl}$ by a factor of 12 and $T^*_{DNA}$ by a factor of 22 (Table 1). Again the Arctic is likely to be more prone to this effect than the Antarctic in the immediate future. General circulation models (GCMs) predict that global warming will occur first and most intensely at high northern latitudes (Houghton et al. 2001). The north polar ice cap has experienced some thinning and contraction over the last three decades and GCMs predict a complete loss of sea ice across the Arctic Ocean basin by the end of this century (Vincent et al. 2001 and refs therein). This effect may be partially offset by increased cloud cover and precipitation that is likely to accompany any warming trend (Houghton et al. 2001).

Finally, changes in mixed layer depth in the polar oceans will affect the average UV dose experienced by plankton communities circulating through the water column, as well as the duration of exposure to strong UV fluxes in the near surface waters. The Arctic Ocean has a much shallower mixed layer than the open waters of the Southern Ocean because of the strong freshwater influence, and any change in precipitation and runoff into the Arctic Basin could exacerbate this effect. Similarly, Southern Ocean waters near the continent are often stratified by meltwater input (e.g.. Antarctic Peninsula. Mitchell & Holm-Hansen 1991; Terra Nova Bay. Arrigo et al. 2000) and changes in glacier and/or sea ice dynamics would also affect planktonic exposure to UVR in these productive coastal regions.

In summary, the Arctic and Antarctic Oceans are both experiencing increased biological UV exposure associated with stratospheric ozone depletion. The strength of the Antarctic Vortex is such that the magnitude of effect on incident UVR is much greater in the south polar relative to north polar region. However, the impacts of climate change are likely to be felt more strongly and more rapidly in the Arctic region. The results presented here show that climate-related effects such as sea ice melting in the Arctic could potentially result in greater change in underwater UV exposure than the factor of two increase caused by recent ozone depletion in Antarctica.

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