The Antarctic marine ecosystem is one of the largest ecosystems on the planet. It is bound by the Antarctic continent to the south and by the Polar Front to the north. Physical, chemical, and biological properties are distinct to this system both by their absolute value as well as by their scale of variability. For example, low and relatively constant temperatures are characteristic of surface marine waters (from −1.84° and 2.5°C) (Hofmann et al. 1996). In contrast, solar radiation presents a large seasonal variability that reaches an extreme of 24 h of light in summer and 24 h of darkness in winter, south of the Antarctic polar circle (66.5° S). Similarly, a strong seasonal variability in sea ice coverage reaches maximum values in winter (July and August) and minimum in the fall (March), sweeping approximately half the Antarctic marine ecosystem and effectively doubles the surface of the Antarctic continent. Atmospheric circulation, a driving force on air temperatures and sea ice distribution, includes several cyclonic pressure systems that surround the continent, introducing winds, cloudiness, moisture, and heat into the marine environment and coastal regions in a scale of days to weeks.

The Antarctic aquatic ecosystem has been divided into four major biogeochemical regimes: polar front, permanent open oceanic waters, areas affected by the annual advance and retreat of sea ice, and coastal waters (Tréguer and Jacques 1992). The most productive areas are concentrated in coastal regions swept by the seasonal ice edge, such as the continental shelf west of the Antarctic Peninsula (Figure 7.1). This area is characterized by highly productive waters that sustain abundant Antarctic krill, Euphausia superba. Several large-scale research projects have been carried out in this region to understand krill population dynamics and the marine food chain that supports large secondary production, the penguins and whales as major krill predators, and the linkages between environmental forcing and the marine ecosystem (El Sayed 1996). In addition, major studies on the effect of ultraviolet radiation (UVR, 280–400 nm) on marine organisms have originated in Western Antarctic Peninsula (e.g., Karentz, Cleaver and Mitchell 1991; Helbling et al. 1992; Smith et al. 1992; Malloy et al. 1997; Prézelin, Moline and Matlick 1998; Quétin et al. 1998). This is an area of particular scientific interest because of a 50-year warming trend, thus combining several aspects of global change research, mainly UV radiation and surface warming.

As an environmental factor, ultraviolet radiation is a predictable UVR to PAR (photosynthetic rate as a function of latitude and time (i.e., clouds)) can affect PAR as well (L PAR ratios remain unchanged. The PAR (Farmer, Gardiner and Shanklin 1985) 320 nm, as the ozone hole moves around (320–400 nm) or PAR, resulting in high 1992; Booth et al. 1994). This change in UVR as well as change the induction of f and long-term responses of organisms: Roy 1993).

The net effect of UVR on marine o chemical damage and biologically driven cent and Neale 2000). When considering and systems, we need to assess how envi of UVR damage (i.e., by changing expo
As an environmental factor, ultraviolet radiation (UVR) in Antarctica has a predictable UVR to PAR (photosynthetically available radiation, 400–700 nm) ratio as a function of latitude and time of the year. Variables that affect UVR (i.e., clouds) can affect PAR as well (Lubin and Frederick 1991) while UVR to PAR ratios remain unchanged. The presence of the ozone hole in Antarctica (Farmer, Gardiner and Shanklin 1985) causes an increase in UVB only (290–320 nm, as the ozone hole moves around the continent), independent of UVA (320–400 nm) or PAR, resulting in higher UVB:UVA:PAR ratios (Smith et al. 1992; Booth et al. 1994). This change in UVR ratios will increase damage by UVB as well as change the induction of repair by UVA and PAR, affecting short- and long-term responses of organisms and communities to UVR (Vincent and Roy 1993).

The net effect of UVR on marine organisms is a balance between photochemical damage and biologically driven processes of recovery and repair (Vincent and Neale 2000). When considering UVR effects on Antarctic organisms, and systems, we need to assess how environmental conditions affect both the rate of UVR damage (i.e., by changing exposure) and the rate of repair (i.e., by ac-
tivating enzymatic processes). UVB is known to affect a variety of cellular processes and molecules in the marine environment (Weiler and Penhale 1994; Hader 1997; de Mora, Demers and Vernet 2000). UVA is damaging to certain cellular process as well, such as photosynthesis (Helbling et al. 1992), but it is also involved in repair mechanisms (Mitchell and Karentz 1993). Thus, the change in the ratio of UVB:UVA, by both changes in stratospheric ozone and in the water column by differential attenuation of UVB and UVA with depth (Diaz, Morrow and Booth 2000), is key to our understanding of UV stress on aquatic ecosystems.

In this chapter we describe the major environmental factors influencing marine Antarctic organisms as they are exposed to possible effects of UVR. We review the effect of UV on Antarctic marine organisms, in particular primary production and the krill-centered food web in coastal areas. Although we address what is known of UVR effects in Antarctica, we stress the Western Antarctic Peninsula because of its interest to krill recruitment and fishery and as an area undergoing climate warming.

The Antarctic Coastal Marine Environment

Atmospheric Processes

Average winter and summer air temperatures in the Western Antarctic Peninsula are −5.5°C and 2.9°C, respectively (Smith et al. 1995). Superimposed on seasonal and interannual variability, a period of rapid warming has been observed in the Antarctic Peninsula in the last half-century. Based on records collected at Faraday (65° 15' S, 64° 15' W; see Figure 7.1) by the British Antarctic Survey, the average annual air temperature has increased by 2.4°C (Figure 7.2). Most of

![Graph showing changes in air temperature from 1945 to 1999.](image)

Figure 7.2. Faraday annual average air temperatures from 1945 to 1999 (n = 54). Lines indicate the least-squares regression line ± 1 SD. (significant at the 90% confidence level). (From Smith and Stammerjohn, in press.)

the warming is caused by an increase temperature in June (Smith, Stammerjohn, trends are comparatively smaller. The south in the data collected at Rothera (15.2°C to 14.5°C) and 15.4°C to 14.9°C; average winter temperatures observed temperature averaging trend indicates an increase in March in the region (Smith and Stammerjohn, 1995), and ice cores indicate warming periods of similar magnitude in the past. Thus, the present-day warming seems to be the same change observed in the past. In addition, a recent study has shown that we observe now is occurring at a faster rate.

Sea Ice Dynamics

Sea ice formation in Antarctica is driven by the low winter air temperature in the region. The presence of sea ice in the spring and summer is mainly due to the maximum area covered during the season and the rate of ice growth. During the winter, the sea ice retreats and melts due to a combination of factors, including solar radiation, wind, and ocean currents. Satellite passive microwave (Smith and Stammerjohn, 1995) and sea ice in spring and fall during the 1990s, result in increased winter sea ice extent. Winter sea ice extent is a result of its slower advance and faster retreat, higher winter air temperatures and faster warming to UVR in the region earlier in the year.

Ultraviolet and Photosynthesis

Background information about the solar UV-B and UV-A peaks is important to understanding the effects of UVR on Antarctic marine organisms. Recent research has indicated that UV-B and UV-A peaks are absorbed strongly by phytoplankton in the Southern Ocean (Smith and Stammerjohn, 1995). The absorption of UV-B is highly dependent on temperature and chlorophyll concentration, while UV-A is more dependent on temperature and water depth. The ratio of UVB:UVA:PAR also changes with latitude, with higher UV-B:UVA ratios observed in the Southern Ocean compared to the Arctic. The net result of these changes is that the amount of UV-B absorbed by phytoplankton decreases with latitude, while the amount of UVA remains relatively constant. This has implications for the photosynthetic capacity of phytoplankton in different regions of the Southern Ocean.
the warming is caused by an increase of about 6°C in the average monthly air temperature in June (Smith, Stammerjohn and Baker 1996). Spring and summer trends are comparatively smaller. The same warming trend is observed further south in the data collected at "Ross" (67° 34' S, 68° 08' W). Enhanced meridional flows from mid- to high latitudes during winter are responsible for above-average winter temperatures observed in the past (van Loon 1967). The warming trend indicates an increase in maritime, as opposed to continental, influence in the region (Smith and Stammerjohn, in press). Palaeoecological records collected from sediments and ice cores indicate that the region has experienced other warming periods of similar magnitude in the past 7000 years (Smith et al. 1999). Thus, the present-day warming seems to be within the boundaries of climate change observed in the past. In addition to magnitude, climate variability is characterized by the rate of change. It has not been ascertained yet if the warming we observe now is occurring at a faster rate of change than previous events.

Sea Ice Dynamics

Sea ice formation in Antarctica is driven by the cooling of surface seawater by air temperature in the fall and winter months. Conversely, the ocean provides the heat to melt sea ice in the spring and summer (Figure 7.3). Sea ice extent (or maximum area covered during the season) in the Western Antarctic Peninsula is closely coupled with winter air temperature (Jacka and Budd 1991; Smith, Stammerjohn and Baker 1996). In contrast to the Southern Ocean as a whole, the warming of winter air temperature in the Western Antarctic Peninsula has resulted in decreased winter sea ice in this region, based on a 21-year record of satellite passive microwave (Smith and Stammerjohn, in press). On average, the sea ice in spring and fall during the 1990s was lower than in the 1980s as the result of its slower advance and faster retreat. A consequence of this trend is higher winter air temperatures and faster melting of sea ice is to expose plankton to UVR in this region earlier in the spring season than in previous years.

Ultraviolet and Photosynthetically Active Radiation

Background information about the solar spectrum and fundamental physical concepts related to UVR in the atmosphere and underwater have been summarized recently by Diaz, Morrow and Booth (2000). On average, only 1.5% of extraterrestrial UVB reaches the Earth's surface. Solar elevation is the most important factor governing surface UVR in the world, followed by total column ozone, which absorbs UVB strongly at 280–310 nm (Lubin, Jensen and Gies 1998). In Antarctica, irradiance is at a maximum in December and at a minimum in June (Figure 7.4). Within Antarctica, UVR variability is also driven by cloudiness. The ratio of UVB:UVA:PAR also changes seasonally because of changes in ozone concentration and differential path length through the atmosphere. As UVB is mostly absorbed in the stratosphere by ozone, the depletion of ozone (ozone hole) occurs in late winter and spring when the Antarctic vortex closes. The chlorofluorocarbons destroy the ozone on ice particle surfaces (Solomon 1988).
Changes in total column ozone, due to decreases in stratospheric ozone, noticeably increase the ratio of UVB to UVA and PAR (Booth et al. 1994). Overall, up to 60% higher UVB increases are expected in high latitudes in October due to total column ozone variability (Sabziparvar, Forster and Shine 1998). Other natural and anthropogenically induced factors can also change UVB reaching the Earth’s surface. Increased aerosols in the atmosphere are thought to decrease surface UVB up to 2% globally. Conversely, feedback effects of enhanced greenhouse gases can cool the polar stratosphere, resulting in a more stable polar vortex; this will lead to enhanced ozone depletion by chemical reactions and to reduced transport of ozone from lower latitudes (Taalas et al. 2000), resulting in increased UVB reaching Antarctica.

UVR is further modified through the air-water interface at the sea surface and after entering the water. Overall transmission in the water follows an exponential decrease with depth for both UVR and PAR (Holm-Hansen, Lubin and Helbling 1993). UVB is differentially absorbed and can reach depths of 50 m with an average effective irradiance of 20–30 m. Light transmission is inversely proportional to the diffuse attenuation coefficient, absorption of particles (i.e., phytoplankton), and water itself (Diaz, Morrow and Weisse 1989).

Through the seasons, UVR starts in the spring (Booth et al. 1994). At this time, we find that the area (see Figure 7.3) (Stammerjohn et al. 1997) through the ice varies with physical conditions like ice cover. For an average 40-cm-thick first-year ice, UVB reaches the underside of ice, with an average 40-cm-thick first-year ice, UVB can affect photosynthesis and a variety of functions (Prézelin, Moline and Mattick 1998). In the water column, affecting phytoplankton food chain (see Figure 7.4). It is not known with certainty, if a decrease in sea ice cover in the southern oceans will result in increased net UVR.
proportional to the diffuse attenuation coefficient, which is mostly controlled by the absorption of particles (i.e., phytoplankton), dissolved organic matter (i.e., Gelbstoff), and water itself (Diaz, Morrow, and Booth 2000).

Through the seasons, UVR starts in the Western Antarctic Peninsula in August (Booth et al. 1994). At this time, we can expect maximum sea ice cover in the area (see Figure 7.3) (Stammerjohn and Smith 1996). UVR transmission through the ice varies with physical conditions, in particular, ice thickness and snow cover. For an average 40-cm-thick first-year ice, only 0.5%–9% of surface UVR reaches the underside of ice, with an average of 2% (Pereovich 1993). UVR can affect photosynthesis and a variety of cellular processes in sea ice populations (Prézelin, Moline, and Matlick 1998). In ice-free areas, UVR can penetrate the water column, affecting phytoplankton and other components of the aquatic food chain (see Figure 7.4). It is not known, and probably it is difficult to measure, if a decrease in sea ice cover in the spring that increases UVR exposure of plankton will result in increased net UVR damage to the system. As the ozone
hole develops early in the season (Roscoe, Jones and Lee 1997), any biological activity during late winter and early spring will be exposed to high UVR. Possible negative feedback mechanisms are also present. The reduced melting of sea ice will have an opposite effect on UVR exposure as well. It is believed that the melting of ice increases water column stratification and favors early springtime phytoplankton development (Smith and Nelson 1986). Decreased ice melting could delay phytoplankton development in the water column and thus reduce phytoplankton UVR exposure in early spring.

**UVR Effects on Primary Production in the Western Antarctic Peninsula**

**Phytoplankton Development**

In the vicinity of Palmer Station (64° 46.7’ S, 64° 04.0’ W), midway through the Antarctic Peninsula (see Figure 7.1), phytoplankton growth starts in October and measurable accumulation (>1 mg chlorophyll a m^{-2}) is seen in October or November (see Figure 7.4). Phytoplankton concentration, measured as chlorophyll a (chl a), is low through the winter (0.001–0.04 mg m^{-3}; Vernet, unpublished data) and early spring (0.04–0.12 mg chl a m^{-3}; Kelley et al. 1999). Phytoplankton develops through the summer (December to February) and lasts until March or April (Smith, Baker and Vernet 1998). The area is swept by several biomass peaks centered at the month of January. In years of high production, chl a can reach concentrations of 40 mg m^{-3} in the mixed layer while in years of low production the accumulation does not surpass 3–4 mg m^{-3}. On the continental shelf, a large gradient is observed from high values near the shore to low values on the continental slope, about 200 km offshore. Thus, phytoplankton can reach high accumulations in this region through spring and summer, under high UVR and PAR.

Large interannual variability in phytoplankton accumulations and corresponding primary productivity are characteristic of this region. During the 1990s (1991–2000), estimated annual primary production in the vicinity of Palmer Station varied by a factor of 8 (54–380 g C m^{-2} year^{-1}). This variability is associated also with changes in phytoplankton composition. The main microphytoplankton groups (>2 m) dominating in the region, in order of importance, are diatoms, cryptomonads, and prymnesiophytes. The northern coastal areas in the Peninsula are characterized by high diatom concentrations and sometimes cryptomonads (Vernet et al. 1994; Moliné and Prézelin 1996; Ross et al. 2000) whereas further south, in the region of Marguerite Bay, summer populations are dominated by prymnesiophytes (e.g., *Phaeocystis* sp.).

**UVR Effect on Primary Production**

The overall effect of UVR on phytoplankton is to decrease rates of primary production (Smith 1989; Holm-Hansen, Helbling and Lubin 1993; Cullen and Neale 1994; Prézelin, Boucher and Schofield 1994; Weiler and Penhale 1994; Smith and Cullen 1995; Cullen and Neale 1996) and light-saturated carbon uptake rate (Cullen, Neale and Lesser 1992; Ekblom and Helle 1996). UVR inhibits carbon incorporation rates (Holm-Hansen, Villafane and Helbling 1996) observed in UVR inhibition from the surface to the bottom of the water column (Helmin-Hansen, Mitchell and Smith et al. 1992), as expected from UVR photoinhibition studies.

The effect of UVR on the inhibition of photosynthesis (280–390 nm) (Neale 2000) is more than twice the inhibitory effect on UVR (Holm-Hansen, Villafane and Helbling 1996), whereas other populations are more sensitive to UVR photoinhibition (Neale 1996a). This difference is of importance for the stratospheric ozone, affecting only UVR (290–320 nm) and linear across UVR irradiance levels; the inhibition of Antarctic coastal phytoplankton has an optimal range of 10–40 W m^{-2} for UVR and 10 W m^{-2} for UVB (Booth et al. 1996). The UVB has a higher sensitivity and a threshold for inhibition above 10 W m^{-2} has been attributed to differences in phytoplankton adaptation to in situ conditions.

**Variability in UV Inhibition of Phytoplankton**

To date, the effect of UVR on Antarctic phytoplankton has been measured in specific cultures and in a variety of fields, but not in situ. The effect of UVR on Antarctic phytoplankton has been carried out in late winter and spring, when there is a period of ozone depletion. This makes it difficult to extrapolate to other time or space scales.

To assess the effect of UVR on primary production, recent experiments were carried out at the Palmer Station (1997–2000). Samples were taken randomly within the mixed layer at Palmer Station and Rothera. Each experiment was performed every 2, 4, 8, and 24 h. UVB and UVR incubations with a GUV-511 from Biolog were conducted by integrating 305-nm irradiance. Ambient temperature was maintained in the incubation tank. The experiments showed inhibition of primary production correlated by a negative ratio of PP_{UV} + PP_{UV} + of incubation, there was a negative linear correlation of the 305-nm dose, showing higher inhibition...

The effect of UVR on the inhibition of carbon uptake is not constant across the spectrum (280–300 nm) (Neale 2000). In some populations, UVA can have twice the inhibitory effect as UVB (Holm-Hansen, Villafañe, and Helbling 1997) whereas other populations are more sensitive to UVB (Boucher and Prézelin 1996a). This difference is of importance to assess possible effects of decreased stratospheric ozone, affecting only UVB. The response of phytoplankton is not linear across UVR irradiance levels; the threshold for photosynthetic inhibition of Antarctic coastal phytoplankton has been determined to be 0.5 W m⁻² for UVB and 10 W m⁻² for UVA (Booth et al. 1997). In contrast, an order of magnitude higher sensitivity and no threshold was observed for Arctic phytoplankton sampled from a deep mixed layer (Helbling et al. 1996). The variability has been attributed to differences in phytoplankton composition and to the degree of adaptation to in situ conditions.

**Variability in UV Inhibition of Primary Production**

To date, the effect of UVR on Antarctic phytoplankton has been studied in monospecific cultures and in a variety of field assemblages. Most of the projects have been carried out in late winter and spring (September to December), coinciding with the period of ozone depletion. These experiments are short term and difficult to extrapolate to other time or space scales.

To assess the effect of UVR on primary production at longer term and space scales, recent experiments were carried out in four consecutive summers (January to mid-February), from 1997 to 2000, in the Western Antarctic Peninsula. Samples were taken randomly within the grid shown in Figure 7.1, between Palmer Station and Rothea. Each experiment was incubated for 24 h and sampled every 2, 4, 8, and 24 h. UVB and PAR irradiance were measured during the incubations with a GUV-511 from Biospherical Instruments Inc. Dose was calculated by integrating 305-nm irradiance (μJ cm⁻²) over the time of the incubations. Ambient temperature was maintained with running seawater from the ship's seawater intake sampled at 3-m depth. Inhibition of primary production is expressed as the ratio of primary production exposed to UVR and PAR to primary production when UVR was blocked (PP_{UVR+PAR}/PP_{PAR}).

The experiments showed inhibition of primary production by UV, as indicated by a negative ratio of PP_{UVR+PAR}/PP_{PAR} (Figure 7.5). For any given time of incubation, there was a negative linear correlation between inhibition and 305-nm dose, showing higher inhibition at higher dose. The inhibition decreased...
with time, as seen by a decrease in the slope at time intervals of 4, 8, and 24 h. After 24 h, some samples showed slightly higher production under UVR + PAR than under PAR alone.

Large variability in daily 305-nm doses was observed for all 4 years (Table 7.1). Changes in dose are related to variability in irradiance as all incubations were integrated by the same time interval (2, 4, 8, and 24 h). For low daily 305-nm doses (≤3.136 μJ cm⁻²), as observed in January 1997, there was acclimation by phytoplankton carbon uptake to UVR. We observed a decrease in sustainable inhibition with time, with maximum inhibition and a final inhibition of 0.93 ± 0.74 and 1.12 ± 0.71. With intermediate 305-nm UV dose, respectively, there was acclimation in 1998. In 2000, with maximum 24-h 305-nm PAR accumulation was observed. As all experiments were conducted in mid-February of each year, changes by variability in sun angle or different weather patterns affecting UVR availability in UVR are attributed mainly to temperature.

To understand the factors controlling phytoplankton acclimation, we calculated a regression equation of primary production (primary production + PAR) and 24 h for each of the 4 years (Table 7.2). We also observed an increase in inhibition with time (see Table 7.2). Higher inhibition after 24 h or an average 305-nm dose per year explains 79% of the inhibition in UVR (Figure 7.6a) and temperature (Figure 7.6b).

Similarly to our results in the previous studies, observed in the cyanobacterium Phor, as growth increased from day 1 to day 24, acclimation within 24 h of exposure to UVR in the Antarctic Peninsula in 1997, is comparable to the algal species Chlorella or coastal phytoplankton from the vicinities of the mid-latitudes in maximum photosynthetic rates. UVR exposure (Lesser, Neale, and Curry).

How representative are the experiments used to overall primary production in the Antarctic and PAR decrease exponentially with distance with respect to UVA and PAR. We estimated:

<table>
<thead>
<tr>
<th>Year</th>
<th>Slope</th>
<th>Intercept</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>0.186</td>
<td>0.14</td>
<td>0.94</td>
</tr>
<tr>
<td>1998</td>
<td>0.035</td>
<td>0.60</td>
<td>0.69</td>
</tr>
<tr>
<td>1999</td>
<td>-0.038</td>
<td>0.83</td>
<td>0.97</td>
</tr>
<tr>
<td>2000</td>
<td>-0.047</td>
<td>0.90</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Primary production (UVR + PAR)/primary production (PAR) 24 h in the Western Antarctic Peninsula experiment.
face inhibition with time, with maximum inhibition of 0.27 ± 0.32 after 2 h incubation and a final inhibition of 0.95 ± 0.23 after 24 h (Figure 7.5 and Table 7.1). With intermediate 305-nm UV doses (≤9617 μJ cm⁻² and ≤9,697 μJ cm⁻², respectively) there was acclimation in 1998 and a lack of acclimation in 1999. In 2000, with maximum 24-h 305-nm UV doses ≥27,067 μJ cm⁻², no acclimation was observed. As all experiments were carried out from mid-January to mid-February of 1997 to 2000, changes in 305-nm UV doses were not caused by variability in sun angle or difference in total ozone column but by changes in weather patterns affecting UVR reaching the ocean surface. The observed variability in UVR is attributed mainly to variability in cloud cover.

To understand the factors controlling inhibition of carbon uptake and the ability of phytoplankton to acclimate, a linear least-squares regression was calculated to the average inhibition of primary production (primary production_{UV + PAR}/primary production_{PAR}) as a function of incubation time (2, 4, 8, and 24 h) for each of the 4 years (Table 7.2). A positive slope indicates a decrease in inhibition with time (see Table 7.1) whereas a negative slope indicates higher inhibition after 24 h or an absence of acclimation. The total average 305-nm dose per year explains 79% of the variance in acclimation observed interannually (Figure 7.6a) and temperature can explain 34% of the variance (Figure 7.6b).

Similar to our results in Antarctic phytoplankton, acclimation to UVR was also observed in the cyanobacterium Phormidium maruyai (Roos and Vincent 1998) as growth increased from day 1 to day 5 in cells incubated under UVR and PAR. Acclimation within 24 h of exposure to ambient UVR, as seen in the Western Antarctic Peninsula in 1997, is comparable to responses by the subtropical diatom Chaetoceros gracilis Schutt (Hazzard, Lesser and Kinzie 1997). Antarctic coastal phytoplankton from the vicinity of McMurdo Station showed a 22% decrease in maximum photosynthetic rate (ng C (mg chl a)⁻¹ h⁻¹) after 9 days of UVR exposure (Lesser, Neale and Cullen 1996).

How representative are the experiments performed with surface phytoplankton to overall primary production in the water column? As discussed earlier, UVR and PAR decrease exponentially with depth, and UVR is differentially absorbed with respect to UVA and PAR. We can expect UVB to decrease to 1% of sur-

<table>
<thead>
<tr>
<th>Year</th>
<th>Slope</th>
<th>Intercept</th>
<th>r²</th>
<th>Average 24 h 305-nm dose (μl cm⁻²)</th>
<th>Average temperature (°C)</th>
<th>Acclimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
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<td>0.94</td>
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<tr>
<td>1998</td>
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<td>0.69</td>
<td>5838 ± 2776</td>
<td>1.62 ± 0.56</td>
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</tr>
<tr>
<td>1999</td>
<td>-0.038</td>
<td>0.83</td>
<td>0.97</td>
<td>7957 ± 1595</td>
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</tr>
<tr>
<td>2000</td>
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<td>0.60</td>
<td>0.60</td>
<td>23908 ± 3100</td>
<td>0.17 ± 1.33</td>
<td>No</td>
</tr>
</tbody>
</table>

Primary production_{UV + PAR}/primary production_{PAR} as a function of incubation time (2, 4, 8, and 24 h) in the Western Antarctic Peninsula experiment for each of the four years (data in Table 7.1).
face irradiance at 36-m depth in low productive Antarctic waters where chl a concentration is approximately 0.25 mg m\(^{-3}\) (Holm-Hansen, Helbling and Lubin 1993). The results presented in Figure 7.5 and Tables 7.1 and 7.2 would be representative of UVB at 30% of surface irradiance or about 5-m depth and thus representative of irradiance encountered in the mixed layer. For more productive, less clear waters, this represents shallower depth (2–3 m).

On average, daily depth-integrated primary production decreases by 6%–12% in the presence of UVB (Holm-Hansen, Mitchell and Vernet 1989; Smith et al. 1992; Helbling et al. 1992) during springtime ozone depletion over Antarctic coastal waters, although higher water column inhibition has been measured also (i.e., 25%; Boucher and Prézelin 1996b). UVR inhibition of annual primary production was calculated as 2% for the Southern Ocean (Smith et al. 1992). Helbling, Villafañe and Holm-Hansen (1987) and methodology, calculated the decrease in the entire icefree waters south of the antarctic convergence. These measurements increased with water depth and are based on discrete hourly or daily measurements of primary production over a period of time (i.e., month-long cruise) in kilometers as opposed to the whole South Pole region.

### Temperature

Low ambient temperatures are characteristic of Antarctic. Lowest, freezing temperatures in the Western Antarctic Peninsula and the Weddell Sea are −1.6°C and warmer waters in the Ross Sea. Furthermore, the influence of temperature on primary production is complex, the higher temperature should promote higher primary production.

Temperature influences also the efficiency of carbon uptake (a factor of 2) in polar mat-forming psychrophilic diatoms, growing slowly (0.23 ± 0.02 GFD) at 19.9°C (Tang, Trincadi and Vincent 1993). Polar cyanobacteria Phormidium minus show a significant increase in quantum yield (P versus I) curves for higher temperature (a factor of 2) and a number of temperature measurements (a factor of 2) were combined higher temperature of 2°C to 4°C for incubations under PAR only, were combined, Pmax was increased by 12%.

The combined effect of temperature and light on the productivity of multiple stressors (Falk et al. 2011) showed that the dominant limiting factor will be...
bligning, Villafane and Holm-Hansen (1994), on the basis of different assumptions and methodology, calculated the decrease in primary production to be 0.15% for the entire ice-free waters south of the Polar Front. The degree of uncertainty of these measurements increases with area- and time-integrated calculations, as they are based on discrete hourly or daily measurements (i.e., depths) taken in a short period of time (i.e., month-long cruise) and space (i.e., several hundred square kilometers as opposed to the whole Southern Ocean).

**Temperature**

Low ambient temperatures are characteristic of the marine environment in the Antarctic. Lowest, freezing temperature is \(-1.84^\circ\text{C}\). In late spring and summer, low temperatures in the Western Antarctic Peninsula are associated with melting ice \((-1.61^\circ\text{C})\) and warmer waters are offshore, \(2.5^\circ\text{C}\). For any given location, the melting and formation of ice drive the distribution of low surface temperature. Furthermore, melting of continental ice decreases temperature and salinity in nearshore areas.

Overall response of the UVR inhibition of primary production was also influenced by the ambient (incubation) temperature during the 1997–2000 experiments. Average temperature for all the experiments was \(1.29^\circ \pm 0.72^\circ\text{C}\), varying from \(-1.5^\circ\) to \(2.5^\circ\text{C}\). The ability of the phytoplankton to acclimate carbon uptake to ambient UVR was enhanced at higher temperatures (Figure 7.6b and Table 7.2). The influence of temperature on acclimation could result from the influence of temperature on repair mechanisms (Vincent and Neale 2000) because the higher temperature should promote higher enzymatic activity.

Temperature influences also the effect of UVR on primary production (as measured by carbon uptake) in polar mat-forming cyanobacteria. Cyanobacteria are psychrophils, growing slowly \((0.23 \pm 0.069 \text{ day}^{-1})\) at the optimum temperature of \(19.9^\circ\text{C}\) (Tang, Tremblay and Vincent 1997). Experiments carried out on the polar cyanobacterium *Phormidiun marayi* West and West showed a synergistic effect of temperature and UVR inhibition (Roos and Vincent 1998). Cyanobacteria were grown at 5°, 10°, 15°, 20°, and 25°C. Photosynthesis versus irradiance \((P \text{ versus } I)\) curves showed that maximum photosynthetic rate \((P_{\text{max}})\) was a function of temperature (a factor of 2.7 higher at 35°C than at 5°C), but no effect of temperature was observed on the light-limited response. After several days of acclimation under UVR, \(P_{\text{max}}\) was reduced by 30% but there was no effect by temperature on \(P_{\text{max}}\) or \(\alpha\). From Table 7.1 of Roos and Vincent, we can calculate that temperature reduced \(P_{\text{max}}\) by 78% (0.22 of optimal photosynthesis) from 20°C to 5°C for incubations under PAR only. Cultures grown at 20°C under UVR showed decreased photosynthesis by 21% or 0.79 of optimal. When both factors were combined, \(P_{\text{max}}\) was 0.146 of optimal photosynthesis or resulted in a 85% reduction.

The combined effect of temperature and UVR inhibition can be compared to models of multiple stressors (Folt et al. 1999). The comparative model implies that the dominant limiting factor will be expressed when more than two stress-
sors are present. The additive model predicts that the combined effect of two stressors will be equal to the sum of the effect of each factor separately. The multiplicative model predicts that the final result in the presence of both factors will be equal to the multiplication of the effect of the two independent factors. Synergism occurs when the observed effect of both factors is larger than that predicted by a model, and antagonism among multiple stressors is present when the combined effect is less than predicted by a model.

In the example of the cyanobacteria, comparing temperature effect (from 20°C to 5°C) and UVR effect at optimal photosynthesis (at 20°C), the additive model predicts a 78% + 21% = 99% reduction in P_{max} (78% + 21% reduction). The multiplicative model predicts P_{max} to be 0.17 (0.22 * 0.79) of optimal values, and the multiplicative model predicts that the dominant stress factor, in this case temperature, will predominate and that the combined effect of both stressors would be 0.22 of optimal photosynthesis. In the experiment, the observed P_{max} for both factors (temperature and UVR) combined was 0.146 of optimal photosynthesis (85% reduction), better than the 98% reduction predicted by the additive model and worse than the 0.17 (83% reduction) predicted by the multiplicative model. Thus, for this case, there was a multiplicative synergistic effect of both stressors. The authors interpreted their result as a decrease in repair mechanisms at low temperatures.

Similar multiplicative effect for temperature and UVR combined was also observed in Nostoc sp. (Ardoz, Lebert and Häder 1998) grown at 18°C and exposed to temperatures up to 47°C and to UVB of 0-150 kJ m^{-2}. Cells could survive high temperature (84% survival or 16% reduction at 42°C and 20% survival at 47°C) but were more sensitive to UVR at 18°C (40% survival at 30 kJ m^{-2} or 60% reduction). When both factors were combined at 42°C and 30 kJ m^{-2}, they observed a 12% survival or 88% reduction. The comparative model predicts a 60% reduction in survival, the multiplicative model predicts a 67% reduction, and the additive model predicts a 76% reduction. Thus, high temperature and UVR have a synergistic effect on Nostoc sp., as concluded by the authors. In the case of Nostoc sp., this is an additive synergistic effect, with a higher reduction than for the multiplicative synergistic model.

No experiments are yet available to calculate synergism or antagonism by temperature and UVR on primary production in Antarctic phytoplankton. The results presented here (Figures 7.5, 7.6 and Tables 7.1, 7.2) suggest that temperature might have an effect on acclimation to UVR. Thus, there is a suggestion that ambient low temperatures decrease the rate of repair and that a similar synergistic effect of temperature and UVR can be expected, as for polar and temperate cyanobacteria.

**Nutrient Metabolism**

UVR affects nutrient uptake and nitrogen metabolism in marine phytoplankton (see Vernet 2000). Furthermore, recent studies show that nutrient limitation might affect UVR inhibition on population growth. In an experiment carried out with natural phytoplankton for 7 days, onset of UVB effect on phytoplankton at 5-m depth or greater was observed on day 3 (as precisely as possible). (Figures 7.7 (Mosaij et al., 1981) temperature and UVR, nutrient limitation. Cullen and Lesser (1991) found that C. nana was 8.6 times more sensitive to UVR.

In contrast, other long-term experiments using marine diatom Phaeodactylum tricornutum showed inhibition due to nutrient limitation. The freshwater green alga Selenastrum capricornutum showed stronger inhibition of photosynthesis for short-term exposure (hours) but is resistant to nutrient limitation (Yeend, Reaers and Rončak 1981).

**Community Composition**

Damage to organisms exposed to UVR (Ekelund 1990; Karentz, Cleaver and Josse 1989) suggests a change in species composition, with species that are more resistant to UVB, followed by the more sensitive algal species. Green algae and cyanobacteria, such as diatoms, show sensitivity to UVR.

**Figure 7.7:** Phytoplankton (5-30 μm) exposed to UVR for 7 days in a mesocosm experiment. (Drawn from Mostajir et al., 2000)
depth or greater was observed on day 3, once nitrate concentration decreased appreciably (Figure 7.7) (Mostajir et al. 1999). Similar to the combined effects of temperature and UVR, nutrient limitation and UVR might have a synergistic effect. Cullen and Lesser (1991) found that nitrate-limited "Thalassiosira pseudonana" was 8.6 times more sensitive to UVB than nitrate-replete cells.

In contrast, other long-term exposure experiments showed mixed results. The marine diatom "Phaeodactylum tricornutum" exposed to UVR showed a lack of growth inhibition due to nitrogen limitation (Behrenfeld, Hardy and Lee 1992). The freshwater green alga "Selenastrum capricornutum" grown under UVB and phosphate limitation showed higher inhibition of photosynthesis and growth than for short-term exposure (hours) but a relaxation in the inhibition of nutrient limitation (Veen, Reuvers and Ronçak 1997).

**Community Composition**

Damage to organisms exposed to UVB varies by 100 fold between species (Ekuland 1990; Karentz, Cleaver and Mitchell 1991). The differential sensitivity to UVB suggests a change in species composition caused by long-term UVB exposure, with species that are more UV tolerant ultimately dominating (Worrall et al. 1981). In general, based on culture studies, diatoms are the most resistant to UVR, followed by prymnesiophytes and other flagellates, such as cryptomonads. Green algae and cyanobacteria are usually considered as resistant as diatoms. This differential sensitivity among phyla has been established based on

![Figure 7.7. Phytoplankton (5- to 30-μm cells) abundance and nitrate concentration during a 7-day experiment in a 1500-L mesocosm with St. Lawrence River water under four UVB treatments. (Drawn from Mostajir et al. 1999.)](image-url)
several cellular processes, such as nitrogen assimilation (Döhler 1997), radiocarbon uptake (Davidson and Marchant 1994; Helbling, Villafañe and Holm-Hansen 1994; Vernet et al. 1994; Villafañe et al. 1995a), specific growth rate (Karentz 1994; Davidson et al. 1994; Villafañe et al. 1995b), and cell abundance in natural populations (Karentz and Spener 1995).

Experiments with mixed populations can be used to test predictions on phytoplankton succession based on differential UVR sensitivity established in the laboratory and from short-term field experiments. Davidson, Marchant and de la Mare (1996) found that 2-day UVB exposures of exponentially growing mixed cultures at 0°C favored *Phaeocystis antarctica* over diatoms. They rejected a hypothesis based on previous experiments in which they found diatoms were three to five times more resistant than *P. antarctica* (Davidson et al. 1994). Part of the discrepancy can be attributed to differences in experimental design; this latter experiment used 91.5 J m⁻² day⁻¹ UVB exposure whereas previous cultures had been exposed to 20%–65% of average springtime UVB radiation in the area.

**Cell Size**

A differential effect of UVR on cell size has been observed for diatom cultures (Karentz, Cleaver and Mitchell 1991), with greater damage being associated with smaller cells. Small cells have a shorter light path length with reduced absorption and refraction by cytoplasmic components between the cell membrane and nuclear DNA, which results in increased UVB reaching the DNA (Raven 1991; García-Pichel 1994; Booth et al. 1997).

Increases in cell size have been observed in cultures under UV exposure (Döhler 1985; Behrenfeld, Hardy and Lee 1992; Veen, Reuvers and Ronçak 1997) and are a consequence of the reduction in specific growth rates. Buma, Engelen and Gieskes (1997) attributed the increased cell size to an arrested cell cycle caused by residual DNA damage, as measured by concentration of thymidine dimer cellular content. The increase in cell size results from carbon uptake in the absence of cell division. Coastal waters have, on average, a higher proportion of larger cells than open waters (Malone 1980). For example, more than 80% of the nearshore phytoplankton biomass was associated with cells larger than 10 μm in Terre Adélie, Antarctica, during summer whereas 70 km offshore, cells larger than 10 μm represented only 30% of the total biomass and 59% of the cells were between 1 and 10 μm (Fiala and Delille 1992). Within Antarctic coastal waters, high chl a accumulations are dominated by large cells (e.g., >20 μm) while low chl a concentrations are dominated by smaller cells (Holm-Hansen and Mitchell 1991; Bügge et al. 1996). Based on increased inhibition found in smaller cells, presumably due to their smaller light path length, we might hypothesize that oceanic Antarctic phytoplankton may have a higher sensitivity to UVB.

The differential effects of UVR on phytoplankton populations, resulting from their composition or size, are relevant to the spatial, seasonal, and interannual variability in phytoplankton (Ross et al. 2000) and also result from the consequences of global change that could affect the composition. It has been suggested that continental glacial melt in the region (as a consequence, decreasing surface salinity) and dominant phytoplankton groups in the toponads) seem to favor shallower mixed water column. These algae are smaller in length. They are not selected by krill in small size (Häblerman 1988). In addition, UVR (Vernet et al. 1994). Such a shift in phytoplankton may be relevant for climate warming, could affect the food chain but also increase the overall UVB.
quences of global change that could influence a shift in coastal phytoplankton composition. It has been suggested that increased air temperature is increasing continental glacial melt in the region of the Western Antarctic Peninsula and, as a consequence, decreasing surface salinity and increasing stratification. From the dominant phytoplankton groups in the area, Cryptophyceae (also known as cryptomonads) seem to favor shallow mixed layers, with lower salinity and a stratified water column. These algae are unicellular, flagellate cells, 13–20 μm in length. They are not selected by krill in a mixed assemblage, probably due to the small size (Haberman 1998). In addition, they are known to be more sensitive to UVR (Vernet et al. 1994). Such a shift in phytoplankton composition, an indirect effect of climate warming, could not only affect the efficiency of the food chain but also increase the overall inhibition of primary production in the area.

Effect of UVR on the Antarctic Food Chain in the Western Antarctic Peninsula

The phytoplankton growth that supports krill populations in the Western Antarctic Peninsula is composed of large cells (>20 μm) that prefer calm conditions and shallow mixed layers. Phytoplankton under these conditions are usually less sensitive to UVR (Karentz et al. 1991) or have a faster recovery rate (shallow mixed layers). Once the phytoplankton accumulation reaches high particle concentration, there is a shielding of UVR for cells at depth due to increased UVR absorption by surface populations. Thus, it seems phytoplankton can grow under high UVR but that once the populations are established they can acclimate to, or avoid, damaging UVR.

Before experiments in mesocosms, prediction of UVR effects on ecosystems had assumed a linear addition of UV effects on different trophic levels. More recent experiments suggest that UVE might change carbon and energy flows in an ecosystem, thus favoring some pathways at the expense of others. For example, differential UVR sensitivity between algae and herbivores can increase algal populations by decreased grazing pressure (Bothwell et al. 1993). Similarly, increase in substrate due to photosynthesis of dissolved organic matter has been reported as enhancing bacterial populations exposed to low levels of UVB (Hermel, Müller-Niklaus and Frick 1993). Thus, changing the interaction between biotic and abiotic components or between different components of the food web can sometimes decrease or reverse the deleterious effect of UBV on a known organism (Vernet and Smith 1997).

Research on the effect of UVR at the ecosystem level is a demanding task. Mostajer et al. (1999) cite five criteria necessary to extend results from laboratory and mesocosms into whole ecosystems. First, the experiment must have organisms representative of natural environments. Second, it is the relative sensitivity of the different elements of the community that determines the net effect of UV on the ecosystem, not the absolute response. Thus, experiments need to be carried out with all the elements of the system under study present. Third, en-
enhanced UVB irradiances and doses must be plausible, i.e., not too high, but repre-
sentative of ozone-depleted conditions at that location. Fourth, the effect of
UVB must be carried out under environmentally representative conditions, e.g.,
nutrient depletion for surface summer populations. Fifth, natural mixing rates
should be included in the experiment.

Mesocosm experiments have not been carried out for Antarctic systems but
in temperate, subarctic, and arctic environments. Subarctic experiments lasting 7
days in St. Lawrence Estuary surface water (screened by a 240-nm mesh) main-
tained between 8.5° and 11.4°C in summer (July) at four UVB treatments (no
UVB, natural UVB, low UVB, and high UVB) showed a shift from herbivory
to microbial food web. Ciliates and large (5–20 μm) phytoplankton were differen-
tially sensitive to UVB. Ciliates showed decreased abundance at all UVB levels
while large phytoplankton did not show inhibition at natural UVB but de-
creased in number at both levels of enhanced UVB (low UVB and high UVB,
which enhanced by a factor of 1.23 and 1.79, respectively, the natural UVB
levels). As a consequence of decreased predation, ciliate prey increased: bacte-
ria, heterotrophic flagellates, and small (<5 μm) phytoplankton showed higher abun-
dance under UVR. These results suggest that enhanced UVB levels at realistic
doses expected under severe ozone depletion can change the food web structure.

Ciliates are particularly sensitive to UVB. Experiments in freshwater systems
in the Arctic, at 3.8° to 5.2°C, showed species-specific ciliate and rotifer inhibi-
tion of growth by UVB (Wickman and Carstens 1998). Not all species were in-
hibited; some showed no UVB effect whereas others were enhanced under UVB.
Heterotrophic flagellates and bacteria were not sensitive to UVB, similar to the
results from the St. Lawrence Estuary (see also Rae and Vincent 1998). In tem-
perate areas, experiments show either no effect of UVB (Hill et al. 1997, Lange
et al. 1999) or show that some predators or some grazers are more sensitive than
their prey to UVB exposure (Bothwell et al. 1993; Williamson et al. 1999; Zag-
garese and Williamson 2000).

In the Western Antarctic Peninsula, krill, salps, and copepods are the main
components of the macrozooplankton assemblages (see Figure 7.4). Years of
abundant krill seem to alternate with years of salp dominance, and the two groups
do not overlap geographically (Ross et al. 1996). This alternation correlates with
years of higher and lower ice coverage in the previous winter, with krill domi-
nating after winters with high ice (Loeb et al. 1997). Natural UVB fluxes in ice-
free areas during springtime are high enough to cause DNA damage in krill, al-
though no quantitative relationship was found between DNA damage and UVB
flux in the field (Maller et al. 1997). Krill and Antarctic fish that reproduce in
spring and summer showed, on average, higher rates of DNA repair than species
that reproduce in the winter.

Under experimental conditions, PAR radiation, three to five times lower than
noon surface irradiance caused captive juvenile krill to die within 1 week (New-
man et al. 1999). The addition of UVB radiation, similar to exposure at 0- to
15-m depth, increased krill mortality and decreased overall activity. Krill exposed
to sublethal UVA doses also showed decreased activity. As these organisms had
been kept in darkness for several months before the experiments, it is not known
if they were more susceptible than usual and were needed to ascertain overall UVR
damage in deep ice. They might be highly susceptible but, the age is unknown.

It is not known and probably is difficult to show in the spring that increases UVR
damage to the coastal Antarctic food web (krill) less than 1 year) with the under-ice
vegetation from UVR in early spring and prolongs ice retreats. As the ice melts, the
young krill sporophylls and new ones are known to begin to grow in the
summer plankton accumulation is also plankton DNA repair rates, as in the case
of phytoplankton DNA repair rates, as in the case

Years of early ice retreat, as in 1995, offer the possibility of developing an ice-edge
plankton community, and also expose young krill to high UVR. Ice protects krill larvae feeding under
UV exposure in a vulnerable time with postsporophyll levels until the bloom develops.

Naganoba et al. (1999) showed a potential difference in sensitivity between UVB
and ozone depletion when years of high UVB irradiance coincided with years of
high ozone depletion, and indirectly, UVB may affect krill reproduction by direct or by direct net damage on krill
permits krill larvae feeding under UVR exposure in a vulnerable time with postsporophyll levels until the bloom develops.

Further research is needed to understand how UVB affects the planktonic food web.

The effect of UVR on Antarctic marine plankton has been studied in the summers follow
Figure 7.4. They are abundant in ice with small phytoplankton cells charac-
terized by small cells (Krant et al. 1995a,b), thus indirectly affecting
locations, have deeper mixed layers of plankton and zooplankton could be a decreased ability to repair (Neale, D.

In summary, recent studies have shown that plankton to UVR. The knowledge of how the web has not yet been
been used to detect possible changes. Studies on abiotic factors (Mopper and Wilhelm 2000), phytoplankton, and i
if they were more susceptible than wild krill to UVR. Thus, field experiments are needed to ascertain overall UVR effect on krill. To date, indications are that they might be highly susceptible but, as their repair rate is also high, net damage is unknown.

It is not known and probably is difficult to measure if a decrease in sea ice cover in the spring that increases UVR exposure will result in increased net UVR damage to the coastal Antarctic food web. The obligate association of young krill (less than 1 year) with the under-ice surface during winter protects these larvae from UVR in early spring and provides protection from exposure until the ice retreats. As the ice melts, the young larvae are in an environment that promotes phytoplankton growth and provides food for the young krill (Ross et al. 2000). It is not known if the shallow mixed layer associated with the ice edge phytoplankton accumulation is also an environment conducive to high zooplankton DNA repair rates, as in the case of phytoplankton.

Years of early ice retreat, as in 1998 (see figure 7.3), not only decrease the chances of developing an ice-edge phytoplankton bloom because of low PAR but also expose young krill to high UVR-PAR during periods of low ozone. If ice protects krill larvae feeding underneath the ice, then earlier melting increases UVR exposure in a vulnerable time when larvae might be subject to low food levels until the bloom develops.

Naganobu et al. (1999) showed a positive correlation between krill recruitment and ozone depletion when years of high ozone depletion and expected higher UVR irradiance coincided with years of lower year 1 class. Thus, directly or indirectly, UVB may affect krill recruitment, either through decreased primary production or by direct net damage on krill larvae. Data interpretation is further limited by the fact that years of low recruitment coincided with years of low winter sea ice cover. These results, based on correlations between UVB variability resulting from stratospheric ozone depletion and krill recruitment, do not show causal effect by UVB. Further research on the physiological and environmental factors influencing UVB damage in krill is needed to ascertain if UVB affects krill recruitment.

The effect of UVR on Antarctic salps and copepods is unknown. Salps become abundant in the summers following a low ice winter (Loeb et al. 1997; see figure 7.4). They are abundant in oceanic Antarctic waters and are associated with small phytoplankton cells characteristic of offshore assemblages. UVR can be more damaging to small cells (Karentz, Cleaver and Mitchell 1991; Villafañe et al. 1995a,b), thus indirectly affecting salp food source. In addition, offshore locations have deeper mixed layers than coastal environments where phytoplankton and zooplankton could be more susceptible to UVR because of their decreased ability to repair (Neale, Davis and Cullen 1998).

In summary, recent studies have shown the susceptibility of Antarctic zooplankton to UVR. The knowledge of the effect of UVR on the Antarctic food web has not yet been approached systematically nor has the experimental design been done to detect possible changes in the energy flow within the ecosystem. Studies on abiotic factors (Mopper and Kiefer 2000), bacteria (Jeffrey, Kase and Wilhelm 2000), phytoplankton, and krill are starting to emerge. However, we
need a more comprehensive approach such as those obtained from microcosms experiments in other areas.

Conclusions

In conclusion, the damage caused by UVR to the marine ecosystem in coastal environments (seasonally swept by the advance and retreat of sea ice) in Antarctica is tightly coupled to the meteorology (i.e., clouds) and sea ice dynamics of the area. Large interannual variability from January 1997 to January 2000 on the effect of UVR on primary production is caused by a factor of 5 on UVR exposure resulting from cloud cover. Because of the rapid absorption of UVB by ice, maximum UVB exposure will occur under icefree conditions. Those conditions will be subject to large interannual variability on total area covered by sea ice and by the specific of sea ice formation and retreat, which can vary as much as several months for any given location. Melting of sea ice in spring exposes krill larvae to higher UVB and higher predation but also provides the conditions for phytoplankton development necessary for production of food. Higher sea ice in winter is related to higher krill abundance in the following growing season, either by direct effect on UVR protection or indirectly by higher food availability.

The balance between repair and damage in phytoplankton in this area is primarily controlled by UVR radiation and also by water temperature. As radiation affects damage and because temperature might be related to repair processes, we can speculate that changes in UVR, caused either by anthropogenically induced changes or by natural variability, might control net damage. Finally, although large strides have been accomplished in Antarctica with respect to understanding the overall effect of abiotic and biotic components of the ecosystem, a more systematic approach is needed to characterize the relative effect of UVR on the interacting elements.

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In comparison to the Earth, extraterrestrial UV radiation regimes, both in terms of intensity and quality (Horneck et al. 1984; Horneck et al. 1988) and in terms of atmospheric and thus its UV regime (Armstrong et al. 2007).火星，另一方面，环境总大气压力类似于地球的大气组成部分，但其大气压力可能由于其他星体的光辐射而被影响。

There are a number of reasons why life on Earth is so resilient to the environmental conditions. First, we are interested in the fact that Earth has been colonized by microbial ecosystems (Shapiro and Packer 1997) and possibly for 3.8 billion years (Stettler et al. 2001). The nature of microorganisms spatially and temporally may exist on Mars, as well as their presence on Earth about 4.5 Ga ago, that leads us to potentially new surfaces.

Mars is of particular interest. We have evidence of extraterrestrial life, which ranges in age from at least 3.5 Ga ago, promising to find liquid water (Carr 1987). Furthermore, the impact flux is very high today, and so there is a high possibility of contamination of the terrestrial planets (Gladman et al. 1997). The media may be encouraged by the media for the likelihood of finding life on Mars, which was considered a dead planet.

Another more practical reason for studying extraterrestrial UV radiation is to understand the impact of such conditions on terrestrial ecosystems. UV radiation has been shown to have significant effects on plant and animal species, and understanding these effects is crucial for conservation efforts and the management of ecosystems. Additionally, understanding the effects of extraterrestrial UV radiation on biological systems can provide insights into the potential for life on other planets and the implications for extraterrestrial UV radiation on biological systems.

References:


