A.4 Effects of increased ultraviolet irradiance on the marine environment: controversial results, and perspectives

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A.4.1 The aquatic environment: distinct characteristics.

The solar radiance spectrum ranges from 100 nm to 1 mm, which includes infrared radiation, visible light and ultraviolet radiation. The latter can be subdivided into UV-A (400–315 nm), UV-B (315–280 nm) and UV-C (280–100 nm) (10). Organisms that are directly exposed to UV-C and UV-B radiation suffer a wide range of damages, affecting molecular and organismal functions and structures. Fortunately atmospheric gases, especially ozone and oxygen, absorb all UV-C and part of the UV-B (figure 1). This protects the biosphere from the most dangerous types of UV radiation (10, 7).

![Solar spectrum reaching the outside layer of the atmosphere and the earth’s surface, on a sunny day with a sun position at 28 degrees (ref. 7)](image)

Since the beginning of the industrial period, increasing amounts of chemical compounds have been emitted into the atmosphere. Chemical compounds such as chlorofluorocarbons (CFCs) have proven to deregulate the natural ozone balance. These gases are very inert and accumulate in the atmosphere. Long-lived chlorine reservoir species (HCl, CINO₂) are converted into the reactive form as soon as the temperatures high up in the atmosphere drop below 195K: the threshold to the formation of polar stratospheric clouds (PSC’s). The long-lived chlorine reservoirs are then photolysed into species involved in stratospheric ozone destruction (Cl, ClO, ClO₂, Cl₂O₂, NO, HO, Br...) (11). The first observations made of decreasing ozone concentrations in the stratosphere were made in the 1950’s. Concentrations above the Antarctic had dropped to 320 DU, whereas values above the Arctic still averaged 400 to 450 DU (33). Since then, ozone concentrations have dropped further, and recent modelling studies have predicted that ozone would reach a minimum around 2020 (11). The ozone decrease is correlated to an increasing amount of short-wavelength UV-R reaching the earth’s surface; these short UV-B wavelengths are known to interfere with biological systems, both on the level of cells and of whole organisms and parts thereof, both algae, plants, and animals (1, 10, 13, 18).

The increasing UV-B radiation reaching the earth surface has proven to affect many biological processes and is by and large detrimental to individual organisms (34). The increase of skin cancers, eye damage and other health effects on humans and animals has lead
to much political and scientific concern. This resulted in the decision to stop ozone breakdown process. Agreements have been made at several world climate conferences such as in Montreal in 1987 to forbid emissions of chlorinated fluorocarbons (CFCs).
Unfortunately, ongoing emissions of greenhouse gases such as methane and carbon dioxide are responsible for cooling down the stratosphere, which consequently triggers the conversion of long-lived chlorinated compounds into the reactive species. Cooling of the stratosphere is expected to cause more ozone breakdown than was originally expected, especially on the northern hemisphere (9). As a consequence more damaging UV-R will be able to reach northern latitudes.

The damaging effects of UV-R on terrestrial organisms have been studied extensively, but effects on aquatic organisms are less well known. It was long believed that UV-R did not penetrate in water, and would therefore not have any effects on freshwater or marine organisms. Recently, measurements of penetration of UV-R into the water column have demonstrated that UV-R penetrates to significant depths of the upper part, in which most primary production takes place (8). Primary production, the basis of the food chain in lakes, rivers, seas and oceans in the ocean, is mainly performed by microalgae. Marine microalgae are responsible for 40% of CO₂ fixation of the Earth, and much of this carbon, fixed in organic matter, is transported to the deep ocean, through a process referred to as the “biological pump” (9). Thus, detrimental effects of UV-R on microalgae might trigger a reduced CO₂ uptake capacity of the ocean, which would eventually have consequences for the CO₂ concentration in the atmosphere. Other trophic levels of the marine ecosystem are also affected by UV-R: bacterioplankton, viruses, zooplankton and even fishes (8). The impact of UV-R on the various levels of the marine ecosystem will be reviewed in this report. New modelling results will be integrated in the report in order to estimate the effects of ongoing ozone decreases on the primary production and its impact on the ocean’s CO₂ uptake capacity. Effects of UV-R on nutrients will not be reviewed, e.g., UV’s influence on iron speciation or on dissolved organic matter breakdown to components available to heterotrophs; both effects enhance food chain efficiency (6, 8, 9, 13).

A.4.2 Previous research

Measurements of UV-R penetration have been made at several oceanic and coastal locations. UV-R proved to reach different depths depending on particulate matter suspended in the water and on the amount of DOC (Dissolved Organic Carbon) and DOM (Dissolved Organic Material), all strongly absorbing UV-R (8, 9, 27). In the productive waters of Chesapeake Bay (Western North Atlantic Ocean) UV-R did not penetrate more than 0.5m from the surface (3). In the St. Lawrence Gulf, on the other hand, 10% UV-R reaches 50% of the summer mixing layer, which comprises the upper 3 - 4m of the water body (25, 27). Ocean waters usually allow much more UV-R to penetrate than more productive coastal waters, which contain more plankton, detritus, DOC and DOM (13, 16). The attenuation of the downwelling ultraviolet irradiance is wavelength dependent: the shorter wavelengths are more rapidly absorbed, which means that little damaging UV-B penetrates to significant depths of the water column (16, 20). The biological damage potential, which can be estimated from the DNA damage action spectrum, proved to have an even faster attenuation with depth than UVB-R. However, damaged DNA can be found to depths up to 50m: photoproducts developed near the surface are mixed downwards where winds and tides result in vertical mixing (2).
The upper water layer, the mixing layer, is the most productive (8). It contains the microalgae that require visible light to perform photosynthesis. The microalgae are not only exposed to visible light (PAR, Photosynthetically Active Radiation) but to UV-R as well. Phytoplankton exposed to UV-R suffer a wide range of damage at different levels: molecular, cellular, population and community (1, 8, 9, 13). Solar UV-R has proven to affect growth, reproduction, photosynthetic enzymes, pigments and other cellular proteins (1, 8, 19, 24). Especially irradiation by short UV wavelengths triggers structural changes in DNA mainly in the form of cyclobutane dimers (CPDs) and pyrimidine (6-4) pyrimidone dimers (1, 8, 24). Setlow’s DNA action spectrum demonstrates the potential for UV-R damage to DNA, which increases exponentially with decreasing wavelengths (figure 2) (8).

![Figure 2](image.png)

**Figure 2.** Biologically active UV-R under full column atmospheric ozone values of 348 and 250 DU. Spectral irradiance $F(\lambda)$, erythemal action spectrum $B(\lambda)$, and the spectrum of biologically active radiation $F(\lambda)B(\lambda)$. (ref. 10)

Microalgae generally dispose of repair mechanisms that enable them to cope with these UV induced structural hiatus. The repair mechanisms consist of a photoenzymatic (“light”) repair mechanism, and a nucleotide excision (“dark”) repair mechanism (2). Diel patterns of DNA damage and repair have been observed in microalgae exposed to natural UV-radiation in the marine environment (2). The amount of CPDs accumulated during the day and decreased overnight, but some residual DNA damage was still present at the end of the night, which indicated that dark repair processes could not remove all CPDs (2). The UV induced damage reduces the microalgae’s photosynthetic and growth rate and inorganic carbon uptake (4, 9, 15, 24). The latter is important for carbon dioxide sequestration by the ocean, as mentioned already. Production measurements indicated that CO$_2$ uptake decreases by 50% under UV-R stress (5). In Antarctic and temperate phytoplankton UVB irradiation reduced the inorganic uptake by 25 to 50%, compared to phytoplankton shielded from UVB (8). Microalgae are the driving motor of marine food webs on which zooplankton and all other components of the ecosystem depend (9, 13). A reduced primary production is likely to be
reflected in the production of the higher trophic levels of the food chain, first affecting the grazers, zooplankton such as ciliates and flagellates, and eventually secondary consumers and fishes (8, 15, 18, 31). Modelling studies have resulted in estimates of the effect of reduced primary production on fish production: a 5% primary production reduction would translate to a 6 to 9% reduction in fishery catches (13). A 7% loss of fish yield represents 10 million tonnes of fish and shellfish per year, which equals the total amount of yearly aquaculture production (13).

A few studies have assessed the direct effects of UV irradiation on zooplankton and fishes (8). Zooplankton is often present in the mixing water layer and is consequently also exposed to UV-R. Adult zooplankton generally dispose of UV absorbing compounds such MAAs (Mycosporine-like Amino Acids) and blue pigments that prevent or at least limit the amount of UV irradiating the DNA (3, 8, 21). Adult fishes can avoid exposure to damaging solar UV-R by active migration and also dispose of a protective layer: the skin and its silver scales, which reflect UV-R. Fish and zooplankton larvae and eggs on the other hand are often located in the uppermost water layer or float passively at the very surface (1, 26, 31). As a consequence the eggs and larvae may become exposed to intense UV radiation. Several studies on commercial fish species such as Northern Anchovy (Engraulis mordax) and Atlantic Cod (Gadus morhua) have demonstrated that eggs, which had been irradiated by UV-B, suffered DNA damage (13, 18, 25, 32). They often developed into misformed fish larvae and had a higher mortality rate (8, 13, 25, 29). Larvae also may be affected by deleterious effects of UV-R, especially young larvae which haven’t developed any UV protection mechanisms (s.a. UV absorbing compounds) (13). Young fishes (fingerlings) exposed to high UV-R underwent epidermis damage (sunburn), which was often associated to opportunistic fungal infection (8, 13). The latter suggests a damaged immune system. Several fish species inhabiting shallow waters proved to suffer of eye lens damage (8). These observations clearly demonstrate that the higher trophic levels of the marine ecosystem also undergo the direct effects of UV radiation. UV-B impact on Northern Anchovy (Engraulis mordax) lead to a 13% decrease in its annual production (25). Such UVB induced production reduction is not negligible and has large implications in fish species of commercial importance.

More recently research has also been directed to the impact of UV-B on bacterioplankton that occupy the central role in the microbial food web and are essential for the carbon cycle (1, 8, 28). Bacterioplankton is responsible for breaking down dead organic material and recycle organic carbon and essential nutrients (phosphate, silica, nitrate, etc), making them available for microalgae and consequently for higher trophic levels (8, 28). Bacterioplankton located in the upper mixed layer proved to suffer of UV-R induced damage, including DNA damage and reduced triated amino acid uptake, which translates into reduced bacterial production (8, 12, 18, 28).

In the marine ecosystem bacteria, viruses and phytoplankton are closely linked to one another (8). As a consequence the effects of UV-R on one group affect the other groups. Viruses are also subject to UV induced damage which translates to a reduced infective capacity, therewith reducing the effect of viruses on phytoplankton, which plays a central role in phytoplankton mortality (8, 18). Reduced microalgal primary production has been suggested to make more inorganic carbon available for the microbial food web, enhancing its production and its importance in the carbon cycle (8, 30). Since both bacterioplankton and phytoplankton are sensitive to UV-R, the overall reduced productivity might have implications for the ocean’s CO2 uptake capacity (13). Next to a possible reduction in the “biological pump”, UV directly photolyses DOM into CO and CO2 which means that UV-R might be responsible for the reduced ocean’s CO2 uptake capacity and an increased CO2
emission from the ocean (8, 12, 13). An overview of the UV-R induced effects on the marine ecosystem is illustrated in figure 3.

![Figure 3. Overview of the UV-R induced effects on the marine ecosystem](image)

One important aspect is studied since very recently. This is the influence of UV radiation on OH radicals (6, 8). These hydroxyl radicals are a major sink of gases in the atmosphere, and affect biocell structures and inorganic matter under water (8). OH radical formation is hard to quantify because of their ephemeral nature.

**A.4.3 Modelling**

It is clear that UV-R affects the marine ecosystem at different trophic levels in direct and indirect ways. In a model developed by Van Oijen (1998; ref. 9) the direct UV-R effect on global primary production is estimated for recent (1998) and past (1978) ozone layer conditions. The ocean’s reduced carbon fixation capacity due to ozone depletion proves to be an ocean wide phenomenon. As expected, the primary production reduction is highest in the polar regions and especially in the Antarctic Ocean during the appearance of the ozone hole. The strongest reduction is detected for the month October: carbon fixation is reduced by max. 2.2%. Between 30° N and 30°S there are hardly any changes in primary production. In the Arctic a decrease of max. 0.6 percent is estimated for the period March-May, during the appearance of the ‘northern ozone hole’. However, the absolute decrease in primary production in an ocean province depends not only on the increase in UV-R, but also on the amount of biomass it affects. In absolute numbers, the decrease in primary production in the Atlantic Ocean contributes as much to the total decrease in carbon fixation as the decrease in
the Antarctic. According to the model, the global decrease in primary production due to enhanced UV-R is only tenths of percents over the past decades (see table 1).

Table 1. Primary production reduction in percents for the different oceans from 1978 to 1998.

<table>
<thead>
<tr>
<th>Ocean province</th>
<th>Total primary production reduction 1978-1998 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific</td>
<td>0.15</td>
</tr>
<tr>
<td>Atlantic</td>
<td>0.18</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>0.21</td>
</tr>
<tr>
<td>Indian</td>
<td>0.14</td>
</tr>
<tr>
<td>Antarctic</td>
<td>0.26</td>
</tr>
<tr>
<td>Arctic</td>
<td>0.14</td>
</tr>
</tbody>
</table>

In this study, the model of Van Oijen (1998) is used to calculate the expected decrease in primary production (CO2 fixation) from 1998 to 2018. It is assumed that the trend in ozone concentrations over the past decades will remain the same for the coming 20 years. The modelling results indicate that increased UV-R will reduce the world-wide microalgal primary production from 1978 to 2018 (figures 4a, 4b and 4c). Over this period, the percentage decrease in primary production due to ozone depletion is highest for the Antarctic Ocean, max. 5.3%. Due to some problems with processing of the maps, this cannot be viewed on figures 4a, b and c.

Because the relationship between ozone depletion and reduction of primary production is not linear, changes in the global patterns in reduction can be observed. Compared to the period 1978-1998 (figure 4a), there is a stronger decrease in carbon fixation in the North Atlantic over the period 1998-2018 (figure 4b). As already pointed out above, between 1978 and 1998 the effect of ozone depletion on the northern hemisphere affects global
Figure 4. Expected UV-R induced primary production for the period:

a) 1978 to 1998;
b) 1998-2018;
c) 1978 to 2018.
primary production as much as the appearance of the Antarctic ozone hole. The new modelling results suggest that in the near future, ozone depletion on the northern hemisphere might even play a more important role in reducing global primary production than the Antarctic ozone hole.

Between 30°S and 60°S, there is a lower in carbon fixation over the period 1998-2018 compared to 1978-1998. This observation can be explained by a slightly positive effect of ozone depletion because not only UV-R but also PAR (photosynthetically active radiation) increases. In some situations, this positive effect of ozone depletion is larger than the negative effect.

A.4.4 Future research

The increasing UV irradiation levels following stratospheric ozone depletion have a wide range of deleterious effects on the marine ecosystem. Especially concerning is the impact on the “biological pump”. Nevertheless some interpretations and calculations of UV-R impacts on organisms and food webs should be put in perspective.

First of all, the effects of UV-R on marine microorganisms are often evaluated for a continuous exposure to a fixed amount of UV irradiation. In reality, microalgae are subject to vertical mixing in the water column, which implies that the amount of UV irradiation and the spectral composition of UV-R to which they are exposed changes all the time (4, 8). In order to get a realistic evaluation of the impact of UV-R the vertical mixing component should be included in the evaluation of UV impact. Another important aspect is determining the actual biological impact of UV-R on the target organism (microalgae, zooplankton, fishes, bacterioplankton, and viruses). As mentioned before, short wavelength UV is much more damaging than the longer wavelengths (23), but is also more quickly absorbed in the water column. In order to be able to make accurate estimations of UV-R effects, one needs to measure the actual penetration of the different UV wavelengths into the water column and then calculate the action spectrum (with biological weighting functions) for the studied organism (5, 8, 13, 14, 22, 28). The action spectrum is calculated for each wavelength in the UV range and can be mapped onto the irradiance levels of the area and depth of interest (23). This alone would allow an accurate estimation of the deleterious effects of UV-R in the aquatic environment. At the same time, the repair capacity of organisms and their protective mechanisms, should be taken into account (17, 19, 22, 32).

Another aspect is often overlooked in the interpretation of the negative effects of UV on the marine ecosystem. The decreased primary production does not only affect the CO₂ uptake capacity but as mentioned before, it also affects other parts of the food chain, including fish production. The most productive waters are also the more turbid waters in which UV-R penetration is strongly limited. This implies that the effects of UV-R on the marine environment might be less than what has been thought in the past. In other words, estimations of the negative impact of UV on the marine ecosystem can easily be overestimated. However, experimental studies on the deleterious effects of UV-R on eggs and larvae of commercial fishes have demonstrated that there is a considerable reduction in production and that even a small decrease in primary production directly affects higher trophic levels. The expected further increase in UV-R for the coming years and the extension of ozone losses to lower latitudes are likely to have a serious impact on fish production.

Finally, as a consequence of global warming by increased atmospheric CO₂ concentration, more cooling is hypothesized in the stratosphere, which will be responsible for triggering
more ozone breakdown. This suggests that UV induced CO₂ uptake reduction might be at the basis of a vicious circle that will lead to more damaging UV-R reaching the earth surface. It is clear that the impact of a reduced carbon uptake capacity will have a positive feedback on the greenhouse gas CO₂ and the greenhouse effect.

A.4.5 Perspective

So far, studies performed on the effects of UV-R on the marine environment clearly indicate that UV has strong deleterious effects at all trophic levels. The most concerning impacts of UV are on the ocean’s CO₂ uptake capacity mediated by microalgal primary production and the direct or indirect effects on fisheries production. Missing is an evaluation of UV-mediated radical formation. Radicals affect structures and essential components inside cells, and influence the cycling of elements. Especially the hydroxyl radical (OH) is highly reactive, but hard to quantify because of its rapid turnover.

Future studies need to assess the impact of UV-R on target organisms by using action spectra and accurate measurements of UV spectral irradiance in the water at different depths. A complicating factor here is vertical mixing so organisms tend to be exposed to a variable spectral irradiance climate. New action spectra have to be calculated for each studied organism in changing environments.

Obviously the effect of UVR on the ocean’s CO₂ uptake capacity is concerning. Any decreased CO₂ fixation capacity will add up to the increased anthropogenic CO₂ emissions. The modelling effort presented here suggests a decreased efficiency of the “biological pump” of CO₂ if ozone depletion goes on in the next decades.
References

3. Neale, P.J., Accomplishments and Directions.


