POSSIBLE EFFECTS OF OZONE DEPLETION ON THE GLOBAL CARBON CYCLE

TSUNG-HUNG PENG

Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831 USA

ABSTRACT. The increase of UV-B radiation resulting from ozone depletion is considered to have damaging effects on marine ecosystems. A cutback of marine productivity would tend to reduce the oceanic uptake of atmospheric CO_2. Box models of the global oceans based on the distribution of bomb-produced ^{14}C are used to evaluate the possible effects of ozone depletion on the atmospheric CO_2 concentration. The maximum effect presumably takes place if the ozone hole reduces the marine productivity to zero in the Antarctic Ocean. In a business-as-usual scenario of future CO_2 emissions, the atmospheric CO_2 partial pressure (pCO_2) would increase by an additional 37 μatm over the course of the next century. This increase corresponds to 4.6% of the projected atmospheric pCO_2 in the year 2090. However, if the damaging effect caused by the destruction of the stratospheric ozone layer is assumed to lower the productivity over the Antarctic Ocean by 10%, the atmospheric pCO_2 would rise by less than 3 μatm over the expected atmospheric level in the next century.

INTRODUCTION

The ozone layer in the stratosphere serves as a shield protecting the Earth's surface from solar ultraviolet radiation. Heath (1988) reported changes in total column ozone from 1970 to 1986, based on satellite observations. For example, the stratospheric ozone between 65°N and 65°S decreased about 5% between 1978 and 1986. Farman, Gardiner and Shanklin (1985) observed large losses of total ozone in Antarctica during the austral spring (ozone hole, a loss of total ozone reached 50% within the hole in October 1987), and linked them with the increase in concentrations of chlorofluorocarbons (CFCs) in the atmosphere. These chemicals are released into the atmosphere through their use in foam production, refrigerants, aerosol sprays and halons in fire extinguishers. The inorganic chlorine derived from these human pollutants photochemically catalyzes the reaction that changes ozone into oxygen, and leads to destruction of ozone in the stratosphere.

The 31-nation Montreal Protocol calls for a 50% reduction from 1986 production levels by 1998 and predicted that, if these nations adhere to the Protocol, the ozone loss at most latitudes would be only a few percentage points. However, the discovery of the Antarctic ozone hole and its significance regarding the enhanced potency of CFCs and stratospheric ice particles to ozone destruction lead to the realization that the Protocol's proposed CFC control measures may not be sufficient. In response, the Protocol was revised recently to phase out CFC production by the year 2000. Ozone scientists who study the problem fear that even this measure may not be enough to hold ozone depletion to tolerable levels (Kerr 1991). Further, the residence time of CFCs in the atmosphere is on the order of a few hundred years, so the destruction of ozone in the stratosphere is expected to continue in the next century, even if control policies to curb the further release of CFCs into the atmosphere are successfully implemented. Hardy and Gucinski (1989) predicted that the total decline from 1969 to 2060 might reach more than 16% in the southern latitudes and at least 14% at northern latitudes in the winter.

The direct consequence of a decreasing ozone layer is the increase in ultraviolet radiation reaching the Earth's surface. In general, shorter wave lengths of ultraviolet radiation are more damaging to biological processes than longer wave lengths (Jagger 1985). The short wave length UV-B radiation (280–320 nm) thus becomes the focus for estimating effects of ozone depletion on marine eco-systems. Much research has focused on the effects of increasing UV-B radiation on phytoplankton (Worrest 1986; Smith & Baker 1989), zooplankton, benthos and fish (Hardy & Gucinski 1989). Although some degree of damage is expected, these estimates contain considerable uncertainty. It

is not possible, for example, to relate a quantitative reduction of primary productivity to a given extra dose of UV-B radiation. Worrest (1986) concludes that an enhanced UV-B exposure is more likely to change species composition of the marine plant communities than to decrease the net production. In the case of UV-B effects on fish, however, Worrest (1986) reports that about a 9% decrease in the atmospheric ozone column would induce a 20% increase in biologically damaging UV-B radiation, which would kill about 8% of the annual anchovy larval population throughout the water column.

Because of the expected damage to primary productivity in the ocean under a continuing depletion of ozone layer, concerns about indirect effects of ozone depletion on the global carbon cycle have been suggested (H. Lee II, personal communication 1991). The reduced marine productivity would weaken the biological CO_2 pump, and hence, would cause atmospheric CO_2 to rise above the expected level. Such an increase in atmospheric CO_2 would further enhance the probability of climate change induced by Greenhouse warming. For this reason, we need to examine the sensitivity of oceanic CO_2 uptake to possible reductions in biological productivity caused by the increasing UV-B radiation resulting from stratospheric ozone depletion. Although a quantitative effect of ozone depletion on primary productivity in the ocean is not available, limits of the possible effects on the atmospheric CO_2 level could be estimated using box models of the ocean, properly calibrated with the distribution of ^{14}C in the ocean. I estimate here these possible effects of ozone depletion on atmospheric CO_2.

OCEAN MODEL BASED ON RADIOCARBON DISTRIBUTION

Marine biological activity plays an important role in the global carbon cycle. Today, oceanic plants growing in temperate and tropical regions use nutrients (*e.g.*, phosphate and nitrate) so efficiently that the partial pressure of CO_2 (pCO_2) in surface water is reduced to the minimum. This is because the plant growth reduces the total CO_2 content of the surface water. By contrast, oceanic nutrients are not efficiently used in the polar regions. Martin, Fitzwater and Gordon (1990) and Martin, Gordon and Fitzwater (1990) proposed to add iron to these regions, which would enhance the biological productivity, and thus, would take up extra CO_2 from the atmosphere. Peng and Broecker (1991a) devised a box model of the ocean to test how effectively the iron fertilization in the Antarctic Ocean would lower the atmospheric pCO_2 in the next century. In this case, the biological productivity is enhanced to take up more CO_2 for the purpose of reducing the potential of Greenhouse warming. The ozone depletion, however, would have the opposite effect on biological productivity and cause the atmospheric CO_2 to rise. The ozone hole discovered in Antarctica presents a greater possibility for damaging phytoplankton in the Antarctic Ocean than in the other parts of the global oceans. Thus, we can use the same ocean model developed by Peng and Broecker (1991a) to simulate the effects of the damaged marine ecosystems in the Antarctic Ocean on raising the atmospheric CO_2 level in the next century.

Peng and Broecker (1991a) described the model in detail. Figure 1 shows a brief summary of the model. The world ocean is represented by five boxes: surface mixed layers of Antarctic and non-Antarctic (0–75 m), diffusive layers of Antarctic and non-Antarctic (75–2000 m) and a well-mixed deep sea (2000–4000 m). A well-mixed atmosphere over the ocean surface mixed layer is added to complete a closed ocean-atmosphere carbon system. The exchange rate of CO_2 across the sea-air interface is taken to be 20 mol m^{-2} yr^{-1} for a pCO_2 of 330 μatm (Peng *et al.* 1979). The sea surface area over the Antarctic Ocean is assumed to be 10% of the global ocean surface area. The remaining 90% surface area is assigned to non-Antarctic oceans. Based on measurements made during the Geochemical Ocean Sections Study (GEOSECS) program, the inventory of bomb-produced ^{14}C in the Antarctic Ocean shows a consistent deficiency compared with the amount expected
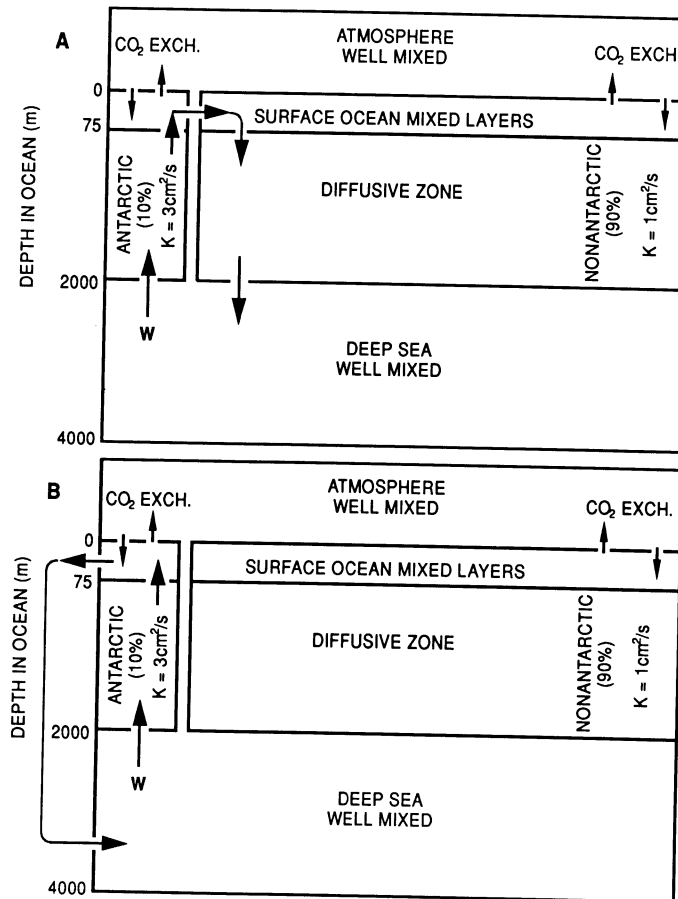
Fig. 1. Linked vertical advection-diffusion model used to evaluate the response to increased UV-B radiation over Antarctic surface waters. The upwelling and vertical eddy diffusion parameters are derived from the distribution of bomb-produced ^{14}C obtained during the GEOSECS program. A shows the lateral transfer of water upwelled in the Antarctic to the non-Antarctic surface ocean. B shows this upwelled water converted to deep water and transferred directly to the model's deep reservoir. The upper 2000 m of the ocean column is essentially the box-diffusion model of Oeschger *et al.* (1975).

if ^{14}C enters the ocean through the gas exchange process (Broecker *et al.* 1985). This deficiency traditionally implies that deep ocean water upwells in this region. A portion of this upwelled water moves beneath the sea-ice fringe, where its density increases by brine release, causing it to sink back into the deep sea. The remainder moves to the north. Some becomes intermediate water, which penetrates northward into the Atlantic, Pacific and Indian Oceans, and some is mixed into the temperate surface water. Because little is known about what portion of upwelled water forms deep water, and what portion forms temperate surface and intermediate water, two separate models represent both cases. One, the lateral transport model, depicts the lateral transport of the upwelled water to form temperate surface and intermediate water (Fig. 1A). The other, the deep transport model, depicts the deep transport of the upwelled water to form deep water (Fig. 1B). The real world should lie between these two extreme cases.

The upwelling rate required to generate the observed ^{14}C deficiency in the Antarctic Ocean is 15 m yr^{-1} (Broecker *et al.* 1985). Because the Antarctic surface area is taken to be 10% of the total ocean area, this upwelling rate corresponds to a water flux of 17.4 Sv (17.4×10^6 m^3 s^{-1}). The

mean penetration depth of bomb-produced ^{14}C for 15 GEOSECS profiles for latitudes south of 49° S is 260 m (Broecker *et al.* 1985). This extent of penetration into the upwelling plume can be obtained by using a vertical eddy diffusivity of 3 cm^2 s^{-1}. These values are adopted in the model parameters for the Antarctic boxes. In addition, we set the vertical eddy diffusivity in the non-Antarctic region at 1 cm^2 s^{-1}, which also derives from the GEOSECS bomb-^{14}C distribution.

The biological productivity in the surface mixed layer depends on the availability of nutrients, which are, in general, represented by the PO_4 content in seawater. A strong biological productivity quickly reduces PO_4 content in the surface mixed layer. Thus, the biological removal of carbon and nutrients from the surface euphotic layer can be simulated by the residence times of PO_4 in the mixed layer and the Redfield C:P ratio. The simulation starts with steady-state distribution of PO_4 in the ocean with residence time of 3.5 years in the Antarctic to yield 1.6 μmol kg^{-1} of PO_4 in the surface water over the Antarctic column, and with residence time of 0.5 years in the non-Antarctic region to yield near zero PO_4 over the non-Antarctic column. The remineralization function for sinking organic matter was set to yield PO_4 profiles similar to those observed. The Redfield ratio of carbon atom to phosphorus atom in the falling organic debris is 130. A steady-state global carbon cycle is then calculated by adjusting the total CO_2 and alkalinity in the model ocean to yield a preindustrial atmospheric pCO_2 of 280 μatm.

In order to evaluate the possible effects of increasing UV-B radiation resulting from continuous depletion of the stratospheric ozone layer in the next century on increasing atmospheric pCO_2 level caused by uncontrolled release of anthropogenic CO_2, we need to know the relationship between UV-B radiation increase and marine productivity reduction. Because a quantitative destruction of marine productivity by excess UV-B radiation is not known, we assume a hypothetical case of maximum effect in which the plant productivity in the Antarctic Ocean is completely eliminated by a persistent ozone hole for the next century. However, the destruction over the non-Antarctic region is assumed negligible because of less serious ozone depletion. The elimination of marine productivity in the Antarctic Ocean is simulated by setting an infinite PO_4 residence time in the surface water of this region.

The fossil-fuel CO_2 emission (Fig. 2) for the next century (1990–2090) is taken from an Intergovernmental Panel on Climate Change (IPCC) business-as-usual scenario (Houghton, Jenkins & Ephraums 1990). The input of man-made CO_2 into the atmosphere started in 1800 and continued through 1990. During that period, the fossil-fuel production is based on Marland's (1990) estimates. The release of CO_2 from the terrestrial ecosystem is obtained by deconvolution (Peng 1991) of time history of atmospheric pCO_2 based on pCO_2 measurements of air bubbles in ice cores (Neftel *et al.* 1985) and of air samples (Keeling *et al.* 1989). The amount of terrestrial CO_2 release after 1990 is assumed to remain constant at the 1990 level.

RESULTS AND DISCUSSIONS

The effect of the ozone hole on Antarctic productivity was assumed to start in 1991 after a steady-state global carbon cycle was perturbed with man-made CO_2 beginning in 1800. The elimination of marine productivity in the Antarctic Ocean releases oceanic CO_2 back to the atmosphere. As a result, the atmospheric pCO_2 elevates above the level expected if the ozone hole does not disturb the marine biological activity. The increase in atmospheric pCO_2 (ΔpCO_2) is defined as the difference in atmospheric pCO_2 with and without ozone effects. As shown in Figure 3A for the deep transport model, the ΔpCO_2 increases with time and reaches 37 μatm by the year 2090, which is about 4.6% of the projected pCO_2 level (*i.e.*, ~800 μatm) at that time in a normal atmosphere with no ozone hole. The percentage of ΔpCO_2 changes only very sightly with time after
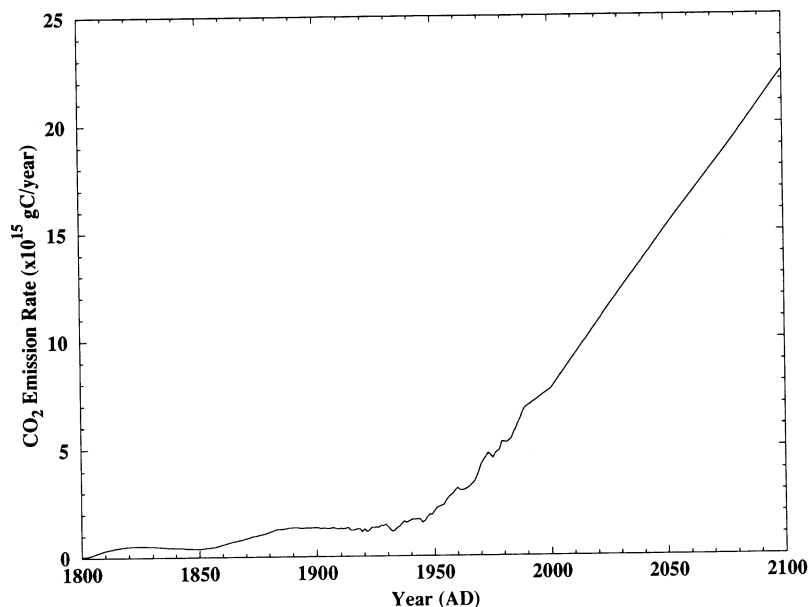
Fig. 2. Scenario of fossil fuel CO_2 emissions based on an IPCC business-as-usual case for the next century. The time history of CO_2 release between 1800 and 1990 is based on Marland's (1990) estimates for fossil-fuel production and deconvolution results (Peng 1991) for terrestrial CO_2 release based on the atmospheric CO_2 record.

50 years of ozone effects. The maximum ozone effect causes the PO_4 concentration in the Antarctic surface water to change from 1.6 to 2.3 μmol kg^{-1}. For comparison, Figure 3 illustrates the decrease in atmospheric pCO_2 if a completely successful iron fertilization in the Antarctic Ocean is implemented (Peng & Broecker 1991b). The decrease caused by the iron-enhanced use of high nutrient concentration in the Antarctic surface water reaches 64 μatm by the year 2090, which is about 8% of the expected normal atmospheric pCO_2 at that time. The maximum iron fertilization effect causes the PO_4 concentration in the Antarctic surface water to change, however, from 1.6 to near 0.0 μmol kg^{-1}. These results, under the assumption of highly exaggerated effects on marine productivity, show that both the ozone hole and iron fertilization would not make a significant difference to the atmospheric pCO_2 if fossil fuel CO_2 emissions follow a business-as-usual scenario for the next century. However, results of box-model simulations for iron fertilization by Joos, Sarmiento and Siegenthaler (1991) and Joos, Siegenthaler and Sarmiento (1991) indicate that the reduction of atmospheric pCO_2 could reach as high as 107 μatm. These authors expressed such reduction by the percentage of net increase in atmospheric pCO_2 in the next 100 years. Thus, a 107-μatm reduction represents 24% of the predicted net increase in atmospheric pCO_2 from 1991 to 2090 (*i.e.*, 107/(800–355) × 100). Using a more sophisticated 3-D ocean general circulation model, Sarmiento and Orr (1991) obtained a mean reduction of 72 μatm in their iron fertilization simulations. Based on such a wide range of pCO_2 reduction using various ocean models, we see that these model simulations contain a considerable amount of uncertainty.

In the case of the lateral transport model (Fig. 3B), the effects of both the ozone hole and iron fertilization on atmospheric pCO_2 are smaller than those of the deep transport mechanism. For the ozone hole effect, atmospheric pCO_2 increases 17 μatm by the year 2090. The iron fertilization, on the other hand, causes a 25 μatm decrease in atmospheric pCO_2. The main reason for a less effective influence on atmospheric pCO_2 under the lateral transport mechanism is that the upwelled
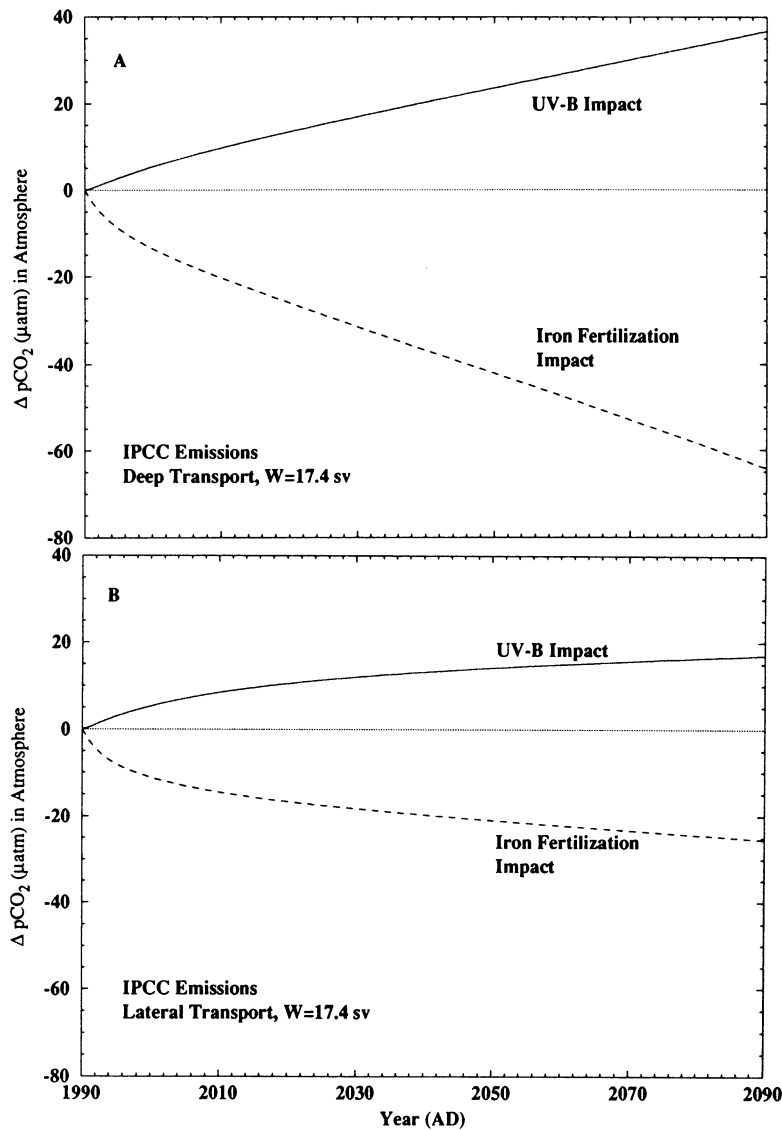
Fig. 3. Changes in atmospheric pCO_2 resulting from ozone hole effect or iron fertilization in the Antarctic Ocean. —— = atmospheric ΔpCO_2 resulting from damages to marine production caused by the ozone hole. --- = atmospheric ΔpCO_2 resulting from enhanced marine production by iron fertilization. A is for deep transport; B, lateral transport.

Antarctic water, after reaching the surface layer and being subjected to biological effects, is transported to the surface mixed layer of the non-Antarctic ocean, where CO_2 is exposed to the atmosphere again and can exchange with atmospheric CO_2. By contrast, the deep transport mode sends the Antarctic surface water into the deep ocean and effectively isolates CO_2 from the atmosphere.

The Antarctic ozone hole is most apparent in the austral spring season. During the other seasons of the year, the ozone layer recovers mostly, and hence, offers some shielding function over the

Antarctic Ocean. The model simulation of a year-round ozone hole effect of complete destruction over the Antarctic surface water is obviously inconsistent with current observations. Model simulations of ozone holes that are less destructive to marine ecosystems are made to show how atmospheric pCO_2 would respond. Shown in Figure 4 are curves of increase in atmospheric pCO_2 caused by 100%, 50% and 10% ozone hole effects using the deep-transport model. At 50% effective, the ΔpCO_2 in year 2090 drops from 37 to 15 μatm, and at 10% effective, it drops to less than 3 μatm. It is generally believed that the most likely overall damaging effect of ozone depletion would be below 10%. If so, the model predicts a negligible effect on carbon cycle. Thus, the maximum effect of ozone depletion on atmospheric pCO_2 in the next century would most likely be lower than 3 μatm.
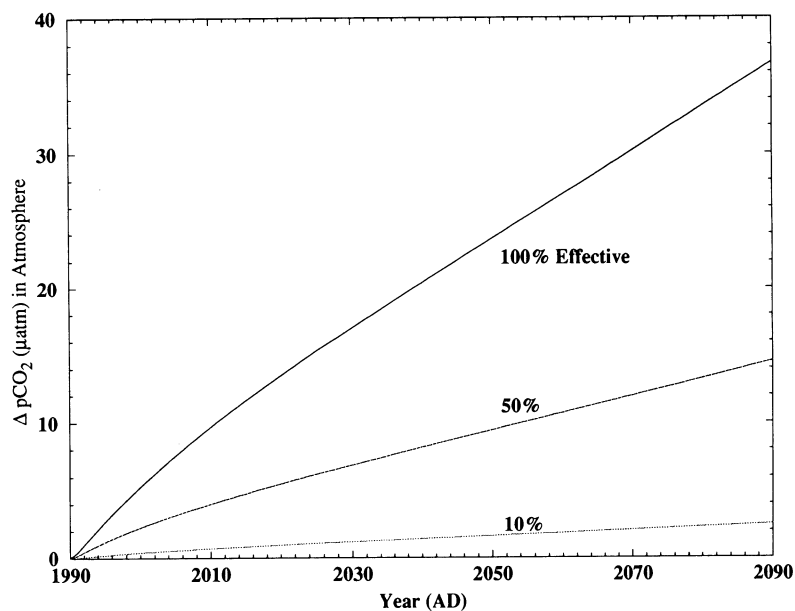

Fig. 4. Atmospheric ΔpCO_2 resulting from 100%, 50% and 10% effective damages to marine productivity caused by the Antarctic ozone hole. The deep-transport model and upwelling flux of 17.4 Sv are used.

CONCLUSION

The model simulations considering the real potential damaging effects of increased UV-B radiation on marine ecosystems reveal that the global carbon cycle would not be affected by ozone depletion in a significant way over the next century. A more detailed analysis would require a better understanding of the relationship between changes of UV-B radiation and phytoplankton productivity. In the present situation, the increase in atmospheric pCO_2 would not be significantly enhanced by the stratospheric ozone depletion.

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