Light-saturated primary production in antarctic coastal waters

MARK A. MOLINE, *Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey 08903-0231*
BARBARA B. PRÉZELIN, *Marine Primary Productivity Group, Department of Biological Sciences, University of California, Santa Barbara, California 93106*
HERVÉ CLAUSTRE, *Laboratoire de Physique et Chimie Marines, Villefranche-sur-mer, France*

During the austral spring and summer seasons from 1991 to 1994, 756 discrete water samples were collected at the Palmer Long-Term Ecological Research (LTER) program stations B and E (Moline and Prézelin 1997a). For each discrete sample, photosynthesis-irradiance (P-I) relationships (n=25) were determined. Photosynthetic parameters P_{max} (the light saturated photosynthetic potential), α (the light-limited photosynthetic efficiency), I_k (=P_{max}/α; an estimate of the minimum irradiance required for the onset of light-saturated photosynthesis), β (the efficiency of photoinhibition), and I_t (the irradiance threshold for the onset of photoinhibition) were derived from the P-I relationships and then used to calculate primary production for each discrete sample. The diel patterns of each parameter were also measured weekly and incorporated into the production calculations to produce daily rates of primary production throughout the water column over the 3-year sampling period. Q_{par} [400–700 nanometers (nm)] irradiance values for the productivity calculations were obtained by integrating surface/in-water irradiance measurements taken while sampling and incident irradiance recorded continuously every 5 minutes at Palmer Station over the three sampling seasons. Primary production estimates were also calculated using theoretical clear-sky Q_{par} irradiance, calculated from Morel (1991) and Antoine (personal communication) using an atmospheric correction (350 dobson units for ozone content and 2 centimeters precipitable water content). Light-saturated primary production was quantified as the fraction of production operating at P_{max} at an irradiance greater than the measured value of I_k. Further details of sample collection and analyses are described elsewhere (Claustre, Moline, and Prézelin in press; Moline and Prézelin 1997a,b).

Primary production for the nearshore LTER stations showed significant variability with each season and between years (figure 1*A*). Much of the seasonal variability was the result of fluctuations in biomass as a result of advective processes and vertical mixing within the water column (Moline and Prézelin 1997b). The temporal changes in the taxonomic structure of the water column also significantly affected the measured rates of carbon uptake (Claustre et al. in press). High interannual variability resulted from differences in the stability and durations of low wind speeds between years. Significantly higher production was measured during a large diatom bloom in December 1991 (figure 1*A*). The percentage of primary production that was light-saturated over the three spring and summer periods averaged 47±17 (figure 1*B*). A seasonal trend was evident; peak saturation occurred during the peak solar irradiance and a generally lower percentage of saturation occurred earlier and later in the year. During the 1991–1992 bloom, light-saturated production was lower and may have been a result of light limitation by self-shading (Moline et al. 1997, pp. 67–72; Moline and Prézelin 1997a).

Cloud cover significantly decreased the incident surface irradiance by an average of 37±24 percent from clear sky conditions and was consistent between years (figure 2*A*). On occasions, measured irradiance was higher than modeled clear-sky irradiance, probably resulting from light reflectance off surrounding snow cover and glaciers in this coastal envi-

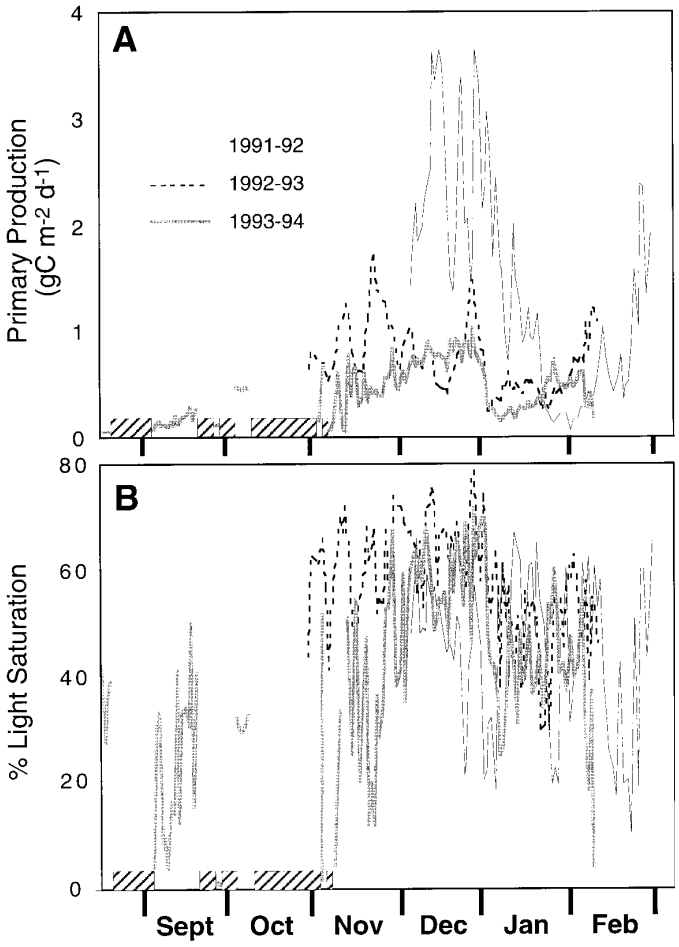

Figure 1. (*A*) Average daily depth-integrated primary production measured at stations B and E and (*B*) the percent of light-saturated primary production for three austral springs and summers between 1991 and 1994. Hatched bars indicate the presence of sea ice during the 1993–1994 season. (gC m^{-2} d^{-1} denotes grams of carbon per square meter per day.)

ronment. The decrease in surface irradiance from cloud cover was estimated to decrease water column primary production by as much as 73 percent (November 1994) with an average of 20±17 percent for all three seasons (figure 2*B*).

Light-saturated primary production was also calculated using modeled clear-sky irradiance. When the effect of cloud cover was removed, the percent light saturation increased by 8.4±9.8 percent (figure 2*C*). No seasonal trends were evident; however, the percentage of change in the light-saturated primary production during the 1991–1992 season was not as great as the following two seasons. This smaller change may have been a result of the high *in situ* light attenuation due to high biomass during the bloom (December 1991 to January 1992) and toward the end of the sampling season in February 1992 (figure 1*A*).

The relatively small increase in the light-saturated production compared to the increase in irradiance when cloud cover was removed shows that the majority of production in these coastal waters was light-saturated over the season and also that light saturation was at a maximum. This finding is further illustrated by comparing the percentage of light saturation (calculated using the measured irradiance values) to the measured daily irradiance for all sampling days over the 3-year period (figure 3). For samples collected in open water, the maximum percentage of light-saturated production increased with increasing light. The percent saturation itself, however, saturated (at approximately 70–75 percent) at irradiances greater than 20–25 einsteins per square meter per second (E m^{-2} s^{-1}). These irradiance levels indicate that these phytoplankton have the potential of being light-saturated from the end of September to the middle of March, nearly the full growing season in these polar waters. This long growing season may result from both the value of I_k (and depth within the water column where the irradiance is equal to I_k) and the fact that for a portion of the day, light is not saturating. Therefore, approximately 25–30 percent of water column primary production occurs below the depth where $I_k=Q_{par}$ and/or in the early and late hours of the daily solar cycle. Samples taken when the region was ice covered did not begin to show light saturation until daily irradiance values were above approximately 50 E m^{-2} s^{-1}.

Results from this highly resolved temporal study quantify light-saturated primary production in this coastal region and show that these phytoplankton are generally light-saturated during most of the growing season from September to March. These results also argue against light-limitation being a major factor limiting primary production in the southern oceans.

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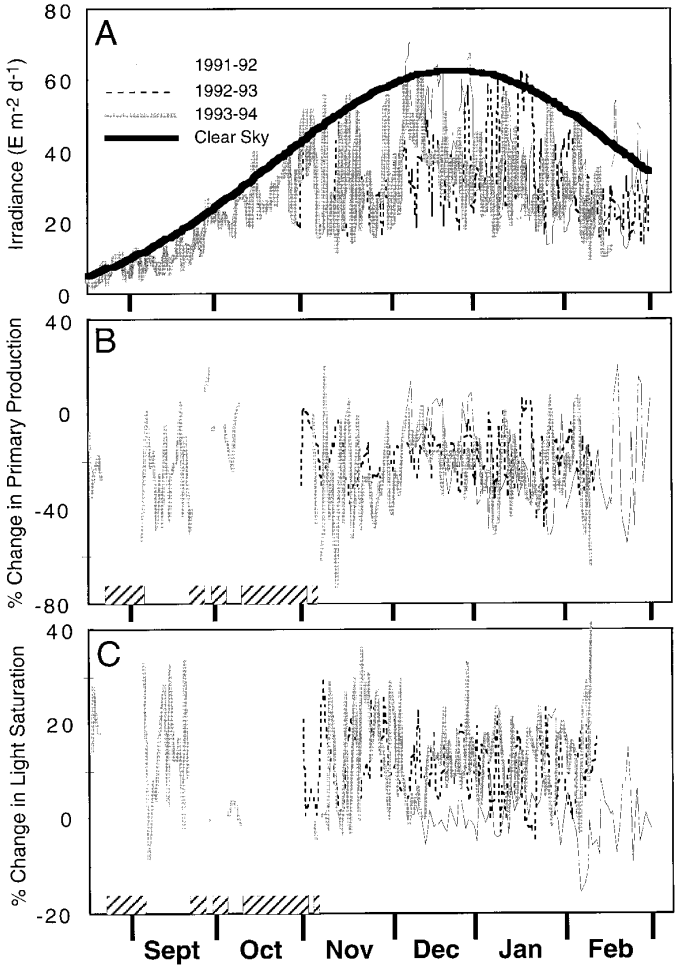

Figure 2. (*A*) Daily surface Q_{par} irradiance measured at Palmer Station during the austral springs and summers of 1991–1994. Also included is the modeled daily surface Q_{par} irradiance calculated for clear-sky conditions (thick solid line). (*B*) The percentage of change in primary production resulting from the presence of cloud cover over the 3 years. (*C*) The percentage of change in light-saturated production when the effect of cloud cover on surface irradiance is removed. Hatched bars indicate the presence of sea ice during the 1993–1994 season. (E m^{-2} d^{-1} denotes einsteins per square meter per day.)

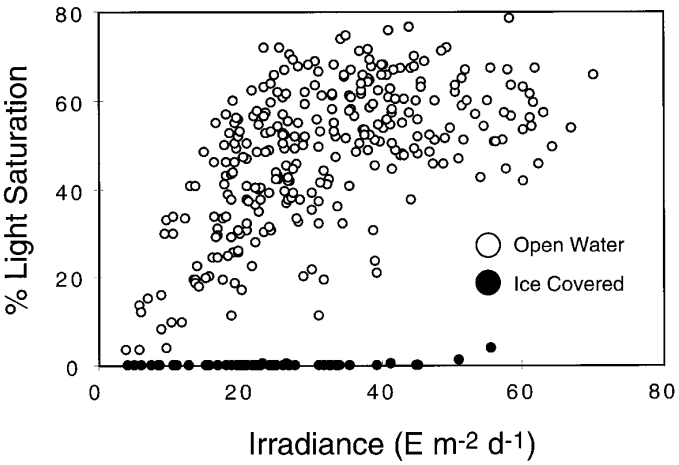

Figure 3. The percentage of light-saturation as a function of daily surface Q_{par} irradiance for all sampling days during the austral springs and summers of 1991–1994. (E m^{-2} d^{-1} denotes einsteins per square meter per day.)

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Radium-226/barium ratios for dating biogenic carbonates in the southern oceans: Preliminary evidence from coastal mollusk shells

PAUL ARTHUR BERKMAN, *Byrd Polar Research Center, Ohio State University, Columbus, Ohio 43210-1002*

TEH-LUNG KU, *Department of Geological Sciences, University of Southern California, Los Angeles, California 90089-0740*

The purpose of this preliminary study was to assess the viability of radium-226/barium (^{226}Ra/Ba) as an alternative to carbon-14/carbon-12 (^{14}C/^{12}C) for dating marine fossils that have circumpolar distributions in raised beaches and reflect environmental events around Antarctica during the Holocene (Berkman 1992). The similarity in the water column marine geochemistry between ^{226}Ra and Ba is such that barium can be treated as a stable "isotope" of ^{226}Ra for dating materials in the same manner as ^{14}C/^{12}C ratios (Broecker and Peng 1982). The stimulus for this study was the uncertainty, which may be hundreds of years, in correcting the radiocarbon reservoir for dating biogenic materials in the southern oceans (Berkman and Forman 1996).

Radium-226 (half-life, 1,620 years) enters the ocean mostly via diffusion across the sediment-water interface where a large concentration gradient of ^{226}Ra exists because of the deposition of its radioactive precursor, the particle-borne ^{230}Th (Ku and Luo 1994). Because of the relatively intense vertical mixing in the circumantarctic region, surface-water ^{226}Ra concentrations are within 30 percent of the deep-water values (Ku et al. 1970; Ku and Lin 1976). This contrasts with situations in the low-latitude oligotrophic oceans, where the surface and deep concentrations may differ by a factor as large as six. Radium/calcium (Ra/Ca) ratios for marine mollusk shells can vary directly with sea-water Ra/Ca ratios but are strongly influenced by the species and their carbonate mineralogy (Blanchard and Oakes 1965). Around Antarctica, the scallop (*Adamussium colbecki*) is among the most common coastal marine mollusks having extant assemblages that can serve as experimental analogs for interpreting the geochemistry of adjacent fossils in raised beaches.

Calcitic shells of living *Adamussium* have unit-cell dimensions that are larger than those in pure calcite crystals (Berkman et al. 1992). These unit-cell data reflect isomorphic substitutions in the carbonate matrix by divalent cations that have larger ionic radii than calcium: namely, barium, strontium, or radium. Primarily for this reason, preliminary ^{226}Ra/Ba analyses were conducted with *Adamussium* shells that were collected alive using scuba gear in Explorers Cove (77°35'S 163°40'E), Antarctica, during the 1986–1987 austral summer.

Similar size *Adamussium* shells (79.7±4.8 millimeters in height) were analyzed for ^{226}Ra to eliminate any geochemical variations that may be associated with their ontogeny. Because the *Adamussium* shells are wafer thin [3–4 grams (g) each], several shells were combined to obtain the 25–35-g batches of carbonate for the ^{226}Ra measurements by alpha-scintillation counting with the Rn-emanation method at the University of Southern California (Ku et al. 1970). The shells were either cleaned with distilled water or dilute acid before being roasted at 500°C. Complementary analyses of calcium and barium were conducted by inductively coupled plasma spectrometry at the University of Michigan on 12 acid-cleaned shells from Berkman (1994, pp. 11–33). The results are listed in the table.

The concentration of ^{226}Ra can be predicted in the *Adamussium* shells in relation to calcium, which has a sea-water concentration of approximately 400 milligrams per kilogram (mg kg^{-1}). The ^{226}Ra concentration in antarctic surface (0–100 meters) sea water is 0.18 disintegrations per minute per kilogram (dpm kg^{-1}; GEOSECS station 287 at 69°18'S 173°30'W; Ostlund et al. 1987). If ^{226}Ra and Ca were incorporated from sea water into the *Adamussium* shells without fractionation, then 1 g of shell (400 mg calcium + 120 mg car-