Climate Change Research: Evaluation and Policy Implications
S. Zwerver, R.S.A.R. van Rompaey, M.T.J. Kok and M.M. Berk, (Eds.)

Evaluating the role of the biological pump in the Northeast Atlantic through paleo primary productivity reconstruction

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Abstract

The general objective of the project *calcareous plankton as a monitor of a natural CO_2 experiment during the last glacial-interglacial cycle* (Geological subprogram of "Calcareous plankton and the oceanic carbon cycle: *Emiliania huxleyi* as a model system") is to quantify natural changes in plankton production and its role in the global carbon cycle. More specifically the research concentrates on 1) the reconstruction of long-term carbonate production during the last glacial cycle (150,000 years) at 48°N and 25°W, and 2) the determination of regional trends in carbonate production in the Northeast Atlantic during times of rapid climatic change.

To estimate past primary productivity using biogenic carbonate accumulation on the seafloor, one needs to quantify the amount of detrital and biogenic carbonate as well as the loss of calcium carbonate by dissolution. We developed a new method to quantify dissolution using recent sediments from a range of oceanic water depths which represent different degrees of dissolution. This can be applied to deep water piston cores to determine temporal variation in carbonate dissolution.

Our time series of reconstructed surface ocean productivity of the last 150,000 years, based on biogenic carbonate accumulation at 48°N, 25°W, indicates that during interglacials (warm periods) primary productivity is generally high, whereas during glacials (cold periods) it is low. This corresponds to times of high and low atmospheric CO_2 respectively, as suggested by the VOSTOK ice core record.

The regional reconstruction of oceanic primary productivity shows that the contrast in productivity values between warm and cold periods decreases going from 60°N to 45°N. Published reconstruction's at low latitudes (i.e. upwelling off NW Africa) indicate a continuation of this trend, ending in the tropics with high productivity during glacials and low productivity during interglacial periods which is the opposite of the higher latitude situation. This will be of importance when modelling global oceanic carbon flux.

1. INTRODUCTION

The atmospheric stock of carbon dioxide continues to increase and with it, the potential for greenhouse induced global warming. However, the rate of carbon dioxide increase is less than the amount of CO_2 released to the atmosphere since a portion is taken up by the ocean (1). Biological productivity is one of the mechanisms responsible for partitioning carbon within the ocean by drawing down both the atmospheric and surface water pCO_2 (2). This biological pump depends on photosynthesis for carbon fixation, therefore on primary producers (i.e. coccolithophorids and diatoms) and on the amount of the primary production which escapes recycling in the mixed layer. The efficiency of this pump is further enhanced by the amount of carbon stored in deep-sea sediments either as particulate organic carbon (POC) or as carbonate (particulate inorganic carbon, PIC). In the present ocean calcifying pelagic organisms such as coccolithophorids and foraminifera are primarily responsible for the long term storage in deep

sea sediments. Some coccolithophorids, particularly *Emiliania huxleyi*, are important contributors of carbonate since they are capable of forming gigantic blooms at mid-latitudes (3).

Since biological productivity plays an important role in the atmospheric CO_2 uptake, we want to quantify the temporal and spatial variation in primary productivity for the Northeast Atlantic during the last glacial-interglacial cycle. By doing so we expect to gain a better understanding of the role of this part of the open ocean and to provide input for numeric models of the carbon cycle.

In three piston cores from above the lysocline we determined temporal and regional variations in primary productivity during the past 150 ka (ka=1000 years) for the high to mid latitude (60-45° N) Northeast Atlantic. Paleo primary productivity was derived from biogenic carbonate accumulation rates according to the method developed by Brummer and Van Eijden (4). We did not use organic carbon burial flux, since the little that is randomly preserved in deep water sediments of an open-ocean environment, does not represent the original production. Yet, these sediments cover orders of magnitudes large basin areas (5) and form a major link in the dynamics of the global carbon cycle.

When using biogenic carbonate in deep-sea sediments as a primary productivity proxy two problems have to be addressed. Firstly, because carbonate dissolves increasingly below the lysocline, the use of its accumulation rate as a proxy for productivity may result in too low an estimate. We therefore developed a method for quantifying carbonate loss due to dissolution, using recent deep-sea sediments recovered from a range of water depths representing different degrees of dissolution (6). Secondly, carbonate in North Atlantic sediments can originate from both, calcifying organisms in the surface water and from ice rafting (7,8). The biogenic and detrital components must be separately quantified before biogenic carbonate can be used as a primary productivity proxy (9).

2. MATERIAL AND METHODS

The studied sediments (box and piston cores) were recovered from the Northeast Atlantic (Fig. 1) during APNAP (Actuomicropaleontology Paleoceanography North Atlantic Project, 1988) and JGOFS (Joint Global Ocean Flux Studies, 1990) cruises with the Dutch R/V Tyro.

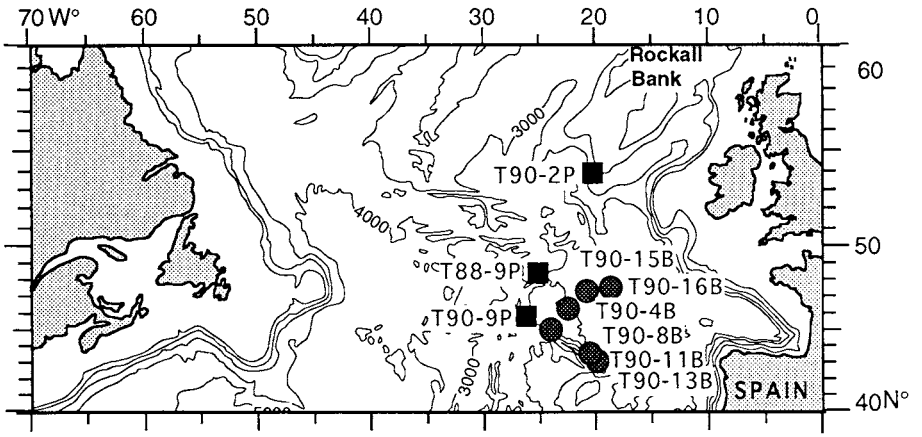

Fig. 1 Physiographic map of the Northeast Atlantic Ocean showing the position of the studied box and piston cores.

For quantifying carbonate dissolution we used six box cores recovered between 44 to 47°N latitude and 20 to 24°W longitude and ranging from 3208-4375 m water depths, thereby representing different degrees of carbonate dissolution. To calculate the carbonate accumulation rates, we took a sample from the top and from a deeper interval in each box core and determined its carbonate weight percent and age. Dry bulk density was analysed on corresponding samples. Carbonate weight percent of the bulk sample, of the coarse (>32μm) and of the fine fraction (<32 μm) were determined by a gasonometric technique, with a precision of ± 2%. Dry bulk density was determined by weighing 5 cm^3 of sediment after drying at 50°C. Accelerator mass spectrometry (AMS) ^{14}C measurements dated twelve samples consisting of hand-picked, >250 μm sized, excellently preserved, mixed planktic foraminifera.

To reconstruct regional variations in primary productivity during the last 150 ka we used three piston cores, which were recovered from above the lysocline between 53 to 45°N. Samples were taken at about 10 cm intervals for floral, faunal, carbonate, dry bulk density, terrigenous component and stable isotope analyses.Weight percent carbonate and dry bulk density for these samples were measured according to the method given above.

Samples were dry-sieved through 125 μm mesh screens and then repeatedly split until about 500 grains remained. The biogenic carbonate component of the coarse (>125 μm) fraction is composed mostly of foraminifera and pteropods while that of the <32 μm fraction mainly consists of coccoliths. The detrital carbonate content of the coarse fraction was counted. The amount of detrital grains in the <32 μm fraction was visually estimated on smear slides of the fine fraction/bulk sample using a polarising microscope. Since these counts compare well with visual estimates, we used them both to approximate the relative frequencies of the bulk fraction. The relative frequencies were converted into absolute weights for the calculation of accumulation rates by assuming that detrital and biogenic carbonate grains have the same densities.

For the build-up of a solid time frame, radiocarbon measurements using accelerator mass spectrometry (AMS) were used to date a selection of samples consisting of >250 μm sized mixed planktic foraminifera of an age of <50ka. Moreover stable isotope stratigraphy and two major North Atlantic ash falls were used in combination with the ^{14}C dating to complete the stratigraphic framework for the studied sediments.

3. BIOGENIC CARBONATE ACCUMULATION AS A PRIMARY PRODUCTIVITY PROXY

Biogenic carbonate accumulation rates can be used as a primary productivity proxy based on the observation, that the organic carbon flux and the carbonate fluxes in present day oceans are highly correlated when normalised to a 3200 m water depth (4,5,9,10,11,12; fig. 2a). When we assume a temporally constant carbon/carbonate rain ratio at a given depth, we can translate the carbonate flux in organic carbon flux (at 3200 m; fig. 2b)) and then reconvert this to surface ocean primary productivity using Suess' (13) formula, which corrects for organic carbon consumption with depth in the water column. The assumption of a constant rain ratio is supported by various other studies (14, 15, 16) and for different oceanic productivity regimes varying over an order of magnitude, which makes biogenic carbonate accumulation a viable proxy for primary productivity in open ocean environments.

When carbonate dissolution can be quantified this primary productivity proxy can be applied on sediments recovered from greater water depths. We quantified carbonate loss by taking the difference in the carbonate mass accumulation rate of deeper cores from the shallowest one (6). It is assumed, that sediments in the shallowest core are undissolved, and represent the initial carbonate rain rate. We also assume that the initial carbonate rain rate is the same for all cores. These assumptions are viable since the studied box cores were recovered from a small geographic area governed by the same water masses and ecological regimes. Also, the shallowest core contains pteropods and juvenile foraminifera indicating that it lies above the

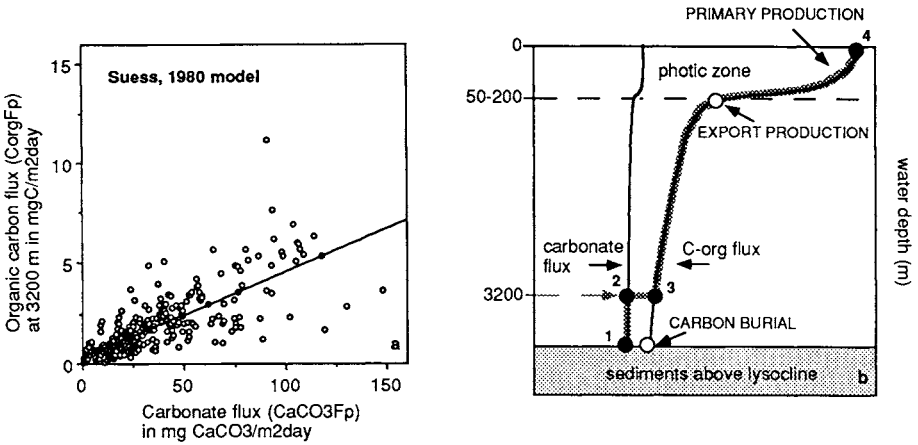

Fig. 2a Plots of organic carbon normalized to 3200 m according to Suess (13) versus carbonate export production, as intercepted in deep moored sediment traps in mid- and high latitude North Atlantic. We used the data set illustrated in (4) and added sediment trap data from the North Atlantic (17), including Lofoten Basin, Greenland Sea and Fram Strait (18), and equatorial Pacific (19). The linear regression is expressed as: organic carbon flux (3200 m) = 0.043*carbonate flux + 0.353 (r^2=0.60). b. Explanation of how primary productivity can be reconstructed from biogenic carbonate accumulation rates (step 1 to 4) using the above described correlation between organic carbon flux and carbonate flux at 3200 m and the equation of Suess (13) to relate export production at depth with primary production.

aragonite compensation depth and has undergone little if any carbonate dissolution. Thus, its carbonate accumulation rate (fig. 3) can be taken as the original carbonate rain rate. The carbonate dissolution rate increases with increasing water depth. A remarkable increase in carbonate loss is observed at 4,000 m which mark the lysocline (Fig. 3). It is not possible to define which fraction is most sensitive to dissolution since with increasing dissolution the fine fraction (<32 μm) becomes enriched with fragments from the coarse fraction (>32 μm).

4. RESULTS

Primary productivity estimates based on biogenic carbonate mass accumulation rates are generally high during interglacials (warm periods), moderate during ambient glacials (cold periods) and low during Heinrich events (Fig. 4A). In our time series of surface ocean productivity of the last 150,000 years, based on biogenic carbonate accumulation at 48°N, 25°W, interglacials have an average productivity of 80 gC/m2/a, whereas glacials reach their maximum average at 49 gC/m2/a. Short intervals of reduced productivity during cold as well as warm periods correspond to "Heinrich events", which are short periods of massive iceberg discharge in the North Atlantic.

This primary productivity reconstruction shows a positive correlation with atmospheric CO_2 recorded in the Vostok ice core, with high primary productivity and atmospheric CO_2 during interglacial periods and vice versa during glacial periods (Fig. 4B).

The regional reconstruction of oceanic primary productivity based on biogenic carbonate accumulation at three sites (53°, 48° and 45°N) gives similar results namely high productivity during interglacials and low productivity during glacials. At 53°N primary productivity during interglacials reaches averaged values of 120 gC/m2/a, whereas at 45°N only 25-30 gC/m/a is produced therewith creating a strong gradient in productivity. Furthermore, the contrast between "warm" and "cold" productivity decreases significantly from 60 gC/m2/a at 53°N to 5-10 gC/m2/a at 45°N.

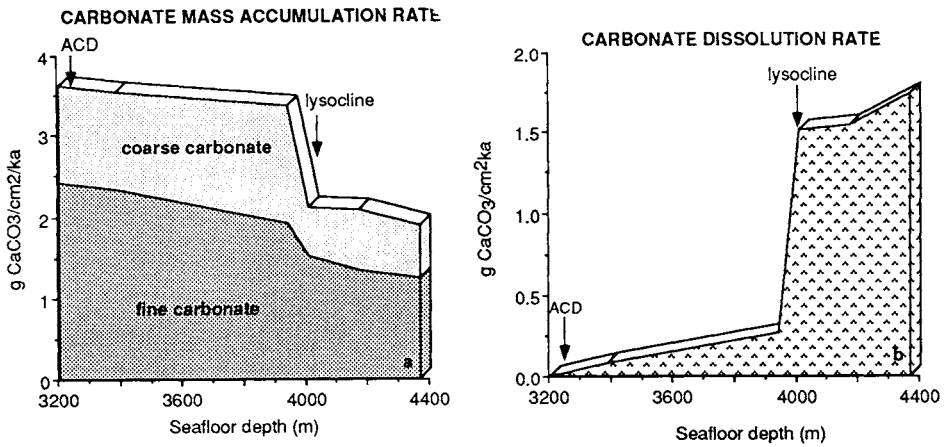

Fig. 3a Carbonate mass accumulation rate in g/cm^{2}ka of the coarse (>32 μm) and fine (<32 μm) carbonate fractions. We used two age-models to determine carbonate accumulation rate, one based on calendar-calibrated radiocarbon ages (20) and the other on reservoir-corrected (-400 a) radiocarbon ages (21, 22), for calculating carbonate mass accumulation rates. Accumulation rates based on calendar-calibrated ages are 14 to 20% lower than those based on reservoir-corrected radiocarbon age. b. Carbonate dissolution rate given in g/cm^{2}ka as a function of water depth. Modified from (6).

5. CONCLUSIONS & DISCUSSION

Although the North Atlantic mid latitudes are not assumed to be a prime region for "biological pumping" (drawing down of CO_2 by increased primary productivity), a preliminary comparison of our reconstructed surface water productivity with the Vostok ice core atmospheric CO_2 record shows that during times of high atmospheric CO_2 ocean surface waters were blooming and vice versa. This is in agreement with the suggestion that phytoplankton growth at high- to mid latitude oceans is stimulated by increased CO_2 concentrations when light and nutrient conditions are optimal (23). However, they do not necesarily indicate that huge amounts of CO_2 were drawn down, since we did not calculate actual amounts with respect to the covered area.

During Heinrich events, which generally correlate to times of low or decreasing atmospheric CO_2, extensive iceberg shedding made surface waters unfavourable for primary producers. During these periods reconstructed primary productivity of the two northernmost cores (53° and 48°N) is lower than in the ambient periods. Exceptions to this pattern are the periods around Termination I and II (12 and 125 ka), during which a dramatic increase in CO_2 concentration and Heinrich events occurred.

Regional productivity reconstructions reveal a decreasing contrast in primary productivity between warm and cold periods going from 60°N to 45°N. Published reconstruction's at low latitudes (15, 24) confirm a continuation of this trend ending in the tropics with high productivity during glacials and low productivity during interglacial periods.

More detailed age-models are needed for both ice cores as well as deep sea cores to determine lead and lag times and answer the question whether variation in primary productivity is one of the causes or an effect of changes in atmospheric CO_2 concentration. Furthermore, the strong geographical and temporal variation in primary productivity demonstrates the need for a higher coverage of deep sea cores with similar paleoproductivity estimates to arrive at a detailed picture of the global pattern necessary for Global Circulation Models.

To further improve the quantitative paleoproductivity estimates, research is required to validate primary productivity proxies world wide, and to update existing recent primary productivity maps. Our results suggest that during interglacials spring blooms at mid- to high latitudes act as one of the major biological pumps, whereas during glacials maximum productivity is restricted to low latitude upwelling areas.

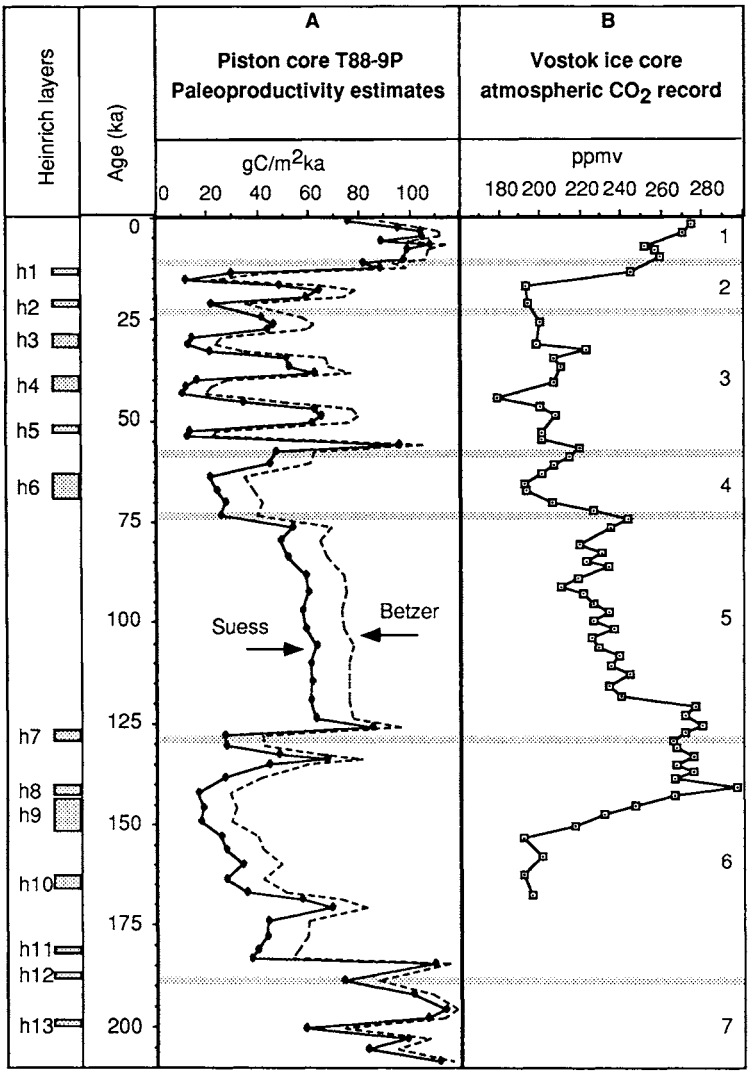

Fig. 4

(A) Primary productivity estimates for piston core T88-9P based on biogenic carbonate mass accumulation rates given in gC/m^2a using Suess (13) and Betzer (25) models to convert the carbonate flux in primary productivity. (B) The 160 ka atmospheric CO_2 record of Vostok ice core (26). After Kreveld et al. (9). Numbers (1 to 7) refer to isotopic stages.

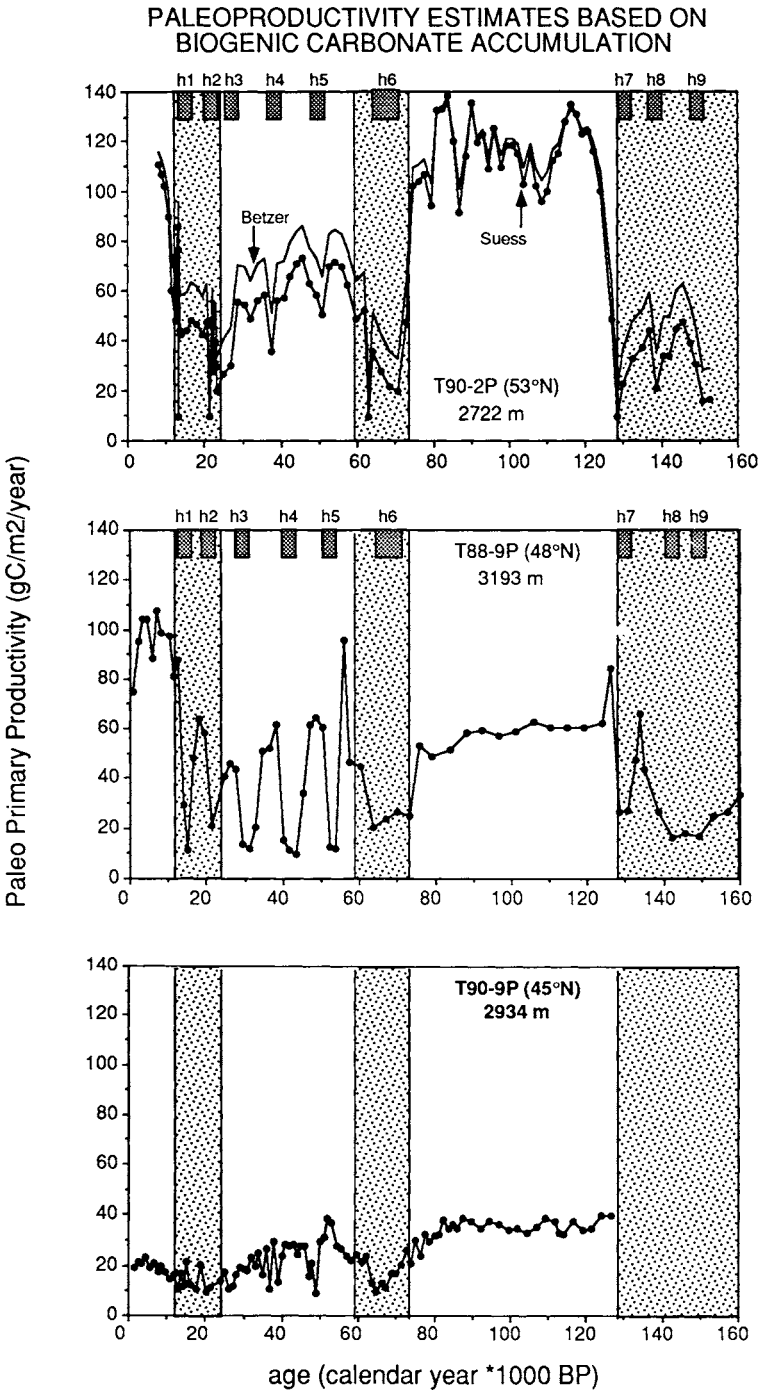

Fig. 5

Paleoproductivity estimates based on biogenic carbonate accumulation rates (4, 9, 13, 15) for three Northeast Atlantic cores, which were all recovered well above the lysocline. Note a decrease in productivity going form 53°N to 45°N as well as in the contrast between warm and cold productivity. Lines represent oxygen stable isotope stage boundaries; dotted areas represent cool periods.Rectangles h1-h9 mark intervals interpreted as Heinrich layers.

6. ACKNOWLEDGEMENTS

This research has largely been funded by the Dutch Research Program Global Air Pollution and Gobal Change. The studied material was collected during Dutch APNAP and JGOFS cruises and were financed by the Foundation for Oceanic Research (SOZ). The radiocarbon dating was executed at the Van der Graaff Laboratory, State University, Utrecht. Michael Knappertsbusch is gratefully acknowledged for his supply of sediment trap data. Jakko van Waarden and Ron Kaandorp are thanked for their work on core T90-9P.

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