

important factor in its cycling. However, neither stable cesium in a montane lake which undergoes reduced oxygen concentrations (14) nor ^{137}Cs and stable cesium in a hypereutrophic lake which undergoes intensely anoxic, hypolimnetic conditions (15) show indications of a seasonal cycle. Cycling of ^{137}Cs coincident with thermal stratification has been reported in Lake Michigan (16). However, this cycling is apparently controlled by particulate transport and resolution in the water column well above the sediments. Hypolimnetic water in Lake Michigan does not become anaerobic over the vast bulk of the lake area, and ^{137}Cs concentrations are constant throughout the year in the deeper waters. This cycling observed in Lake Michigan and the mechanism controlling it are quite different from the case of intense anaerobiosis encountered during thermal stratification in Par Pond. Moreover, the cesium source terms in all the examples except Par Pond were either tracer material or fallout and weathering products rather than a nuclear fuel element. Because of the apparent anomalous behavior of ^{137}Cs in Par Pond and its relevance to the nuclear fuel cycle, further studies are required to define the cause of the ^{137}Cs cycling and the availability of this material to the biota of the system.

JAMES J. ALBERTS

Savannah River Ecology Laboratory,
Drawer E, Aiken, South Carolina 29801

LAURENCE J. TILLY

TORGNY J. VIGERSTAD

Savannah River Laboratory,
Savannah River Plant, Aiken

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9. The total water samples were fumed with

HNO_3 , and the ^{137}Cs was precipitated with KF. The ^{137}Cs concentration was then determined on a gas-flow proportional counter.

10. Water samples (25 to 50 liters each) were collected by means of a 10-liter polyvinyl chloride Van Dorn sampler bottle fastened to the hydrographic sampling wire horizontally so that the sample would represent a narrow lens of water at the sampling depth. The water samples were centrifuged through an eight tube, KSB continuous-flow centrifuge (Sorvall, SS-3) at 200 ml/min and 27,000g. Known volumes of the centrifugate were passed through ion-exchange columns. To determine ^{137}Cs , the radioactivity of the resins was counted with a NaI well crystal (22.9 by 22.9 cm).
11. The 50-liter samples were collected by means of the specially adapted Van Dorn sampler, filtered through 0.45- μm membrane filters (Millipore), and spiked with HCl (final pH ~ 2) and 5 mg of stable cesium to retard adsorption losses on container walls. The sample was evaporated in glass to a final volume of 500 ml; the ^{137}Cs concentration was determined by gamma-counting of the entire sample on a low-background NaI detector (7.6 by 7.6 cm).
12. Par Pond is a surface discharge reservoir with an average thermocline depth of ~ 6 m. The minimum replacement time of the reservoir calculated from rainfall discharge data and Savannah River makeup water volume is 8 to 10 months. Since this time period is long compared to the time of stratification, it would be expected that most of the ^{137}Cs in the reservoir would remain in the system rather than be flushed over the dam.
13. Further evidence of the retention of ^{137}Cs in the

sediments may be found in the specific activities of the sediments. Although a ^{137}Cs sediment burden cannot be determined from existing data, the mean ^{137}Cs activity of the upper 2 inches of 45 cores taken in 1962 through 1963 was 181 pCi per gram of dry weight (range, 1 to 3559 pCi/g). The mean ^{137}Cs activity for three cores taken in 1976 was 224 pCi/g (range, 150 to 278 pCi/g). These data indicate that the ^{137}Cs activities of the sediments have not changed significantly during the intervening years.

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13 April 1978; revised 6 November 1978

Biological Control of Dissolved Aluminum in Seawater: Experimental Evidence

Abstract. *Experimental evidence supports the hypothesis that the concentration and distribution of dissolved aluminum in ocean water are controlled by biological activity in the surface waters. The growth of the diatom *Skeletonema costatum* in artificial seawater media spiked with aluminum reduced the aluminum concentration to that actually found in surface open ocean waters (about 0.5 micrograms per liter). Furthermore, aluminum had a catalytic and limiting effect on the growth of the diatoms.*

The concentration of dissolved Al in surface open ocean waters is less than 1 $\mu\text{g/liter}$ (1). The mechanisms that maintain this low concentration are poorly known. In the past it has been assumed that the seawater Al concentration was the result of thermodynamic equilibria between the water and various aluminosilicate minerals (2). Several investigators attempted to reproduce these observed seawater Al concentrations either by the dissolution or precipitation of aluminosilicate minerals in aqueous solutions or by the adsorption of dissolved Al onto various types of suspended particles (3). However, in these experiments equilibrium concentrations of dissolved Al below 1 $\mu\text{g/liter}$ were not obtained.

Recently, it was suggested that the dissolved Al concentration in the oceans is controlled by biological activity. Mackenzie et al. (4) observed a depletion of dissolved Al in the photic zone of the Mediterranean Sea parallel to an observed depletion in dissolved silica. This covariance was thought to be due to biological uptake of Al and Si by siliceous

organisms. They concluded that "the silicon and aluminum cycles in the oceans are linked through the activity of diatoms" (4, p. 680). Van Bennekom and van der Gaast (5) identified authigenic smectites regularly distributed in the frustules of diatoms collected at sea. Lewin (6) suggested that Al and Fe are necessary to the formation of diatom frustules because the adsorption of these cations onto the silica frustules renders them resistant to dissolution.

To verify the hypothesis that dissolved Al concentrations in surface open ocean waters can be related to the activity of diatoms, I carried out culture experiments using the diatom *Skeletonema costatum*, a common neritic species, grown in an artificial seawater culture medium spiked with dissolved Al. The Al concentration in the medium was monitored during the development of the culture; even in a medium to which 25 $\mu\text{g/liter}$ had been added, the dissolved Al concentration was reduced to less than 1 $\mu\text{g/liter}$ during the growth of the diatoms.

The basic culture medium used in the

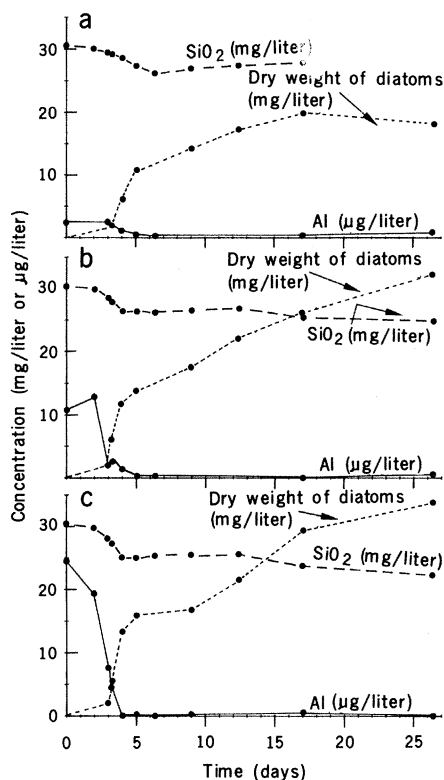


Fig. 1. Plots of the dissolved SiO_2 concentration, dissolved Al concentration, and dry weight of diatoms as a function of time during the growth of the diatom *Skeletonema costatum* in culture media with initial Al concentrations of (a) 2.5, (b) 12, and (c) 25 $\mu\text{g/liter}$.

experiments was the ASP-2 artificial medium of Provasoli *et al.* (7). The diatom *Skeletonema costatum* was obtained, in bacteria-free condition, from the Food Chain Research Group (FCRG) algal culture collection at the Institute of Marine Resources, University of California, San Diego. The experimental cultures were grown in large polystyrene vats into which 7 liters of culture medium were placed after filtration through 0.22- μm Millipore filters and sterilization by passage through an ultraviolet light sterilizer (Hanovia). Each vat was initially inoculated with 10 ml of a culture that had been growing in the same medium in a 1-liter Pyrex Erlenmeyer flask, previously inoculated with the culture as received from the FCRG. The vats were kept at $21^\circ \pm 2^\circ\text{C}$, approximately 40 cm from four 40-W fluorescent daylight lamps, and were illuminated continuously. The cultures were vigorously shaken twice each day.

Three diatom cultures were grown in three media that were identical except for their initial concentrations of dissolved Al: 2.5, 12, and 25 $\mu\text{g/liter}$. Two vats were filled with 7 liters of the medium of each initial Al concentration. One was inoculated with a diatom culture as

described above. The other was not inoculated and served as a control to evaluate the possibility of Al precipitation in the medium or adsorption on the polystyrene vats during the experiment. The controls showed no significant variations in Al or silica (SiO_2) concentration throughout the experiment.

I monitored the development of the cultures by periodically removing a 50-ml sample from each vat, including the controls, and filtering it through a 0.45- μm Millipore filter. The filtrate was then rinsed with distilled water, dried at 60°C , and weighed. This procedure gave a quantitative measure of the growth of the cultures expressed as milligrams per liter (dry weight) of diatoms. The filtrate was then analyzed for dissolved Al and SiO_2 . For the SiO_2 analyses, I used the colorimetric method of Mullin and Riley (8); I analyzed for Al by using a fluorometric method, with salicylidene-*O*-amino-phenol as the complexing agent (9). Although less sensitive than other fluorometric methods, this method is free of any interference caused by dissolved Fe, inherent in other fluorometric methods, because of a preliminary extraction step. The Al analyses have a precision of $\pm 0.5 \mu\text{g/liter}$.

The experimental results are depicted in Fig. 1. In all three media, the concentration of Al was reduced to less than $0.5 \pm 0.5 \mu\text{g/liter}$ during the growth of the cultures. This observation suggests that the concentration of dissolved Al observed in surface open ocean waters ($< 1 \mu\text{g/liter}$) could be the result of the biological activity of diatoms, and perhaps of other plankton, in these waters. Furthermore, these experimental results substantiate the geochemical cycle of dissolved Al in the oceans proposed by Stoffyn (10) and Mackenzie *et al.* (4), in which the biological uptake of Al by diatoms and their subsequent sedimentation are assumed to be an important mechanism for the removal of dissolved Al from the oceans.

The cultures developed more slowly in the medium with a low initial Al concentration than in the media with high initial concentrations [the slower development of the initially low Al culture is evident from the slower removal of SiO_2 and the slower increase in the dry weight of diatoms in this culture (Fig. 1a) as compared with the other two cultures with higher initial Al (Fig. 1, b and c)]. Furthermore, the maximum amount of SiO_2 removed in each culture was proportional to the initial Al concentration (Fig. 2), and the final dry weight of diatoms was larger in the cultures with larger initial Al

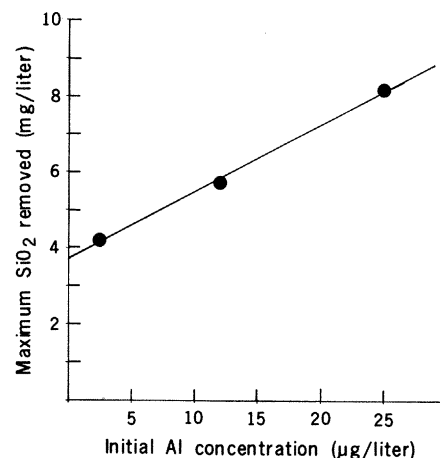


Fig. 2. Plot of the maximum amount of SiO_2 removed from the culture media owing to the growth of the diatoms as a function of the initial Al concentration.

(Fig. 1). These observations suggest that Al had a catalytic effect on the development of the diatom cultures and, more surprisingly, that it limited the growth of the diatom cultures. These results corroborate those of Menzel *et al.* (11) who observed that the addition of Al to Sargasso Sea water has a catalytic effect on the productivity of the organisms in the water, and particularly that of the diatoms. If sufficient dissolved SiO_2 was present. They did not observe, however, a larger final cell density in cultures with initial high concentrations of Al as compared to those with initial low concentrations of Al. A linear extrapolation (Fig. 2) to an initial Al concentration of 0 $\mu\text{g/liter}$ implies a removal of SiO_2 , and therefore a growth of the diatoms at an initial Al concentration of 0 $\mu\text{g/liter}$. This observation suggests that, although Al has a catalytic effect on the growth of diatom cultures and even limits their growth, Al is not indispensable to the growth of diatoms.

MARC STOFFYN*

Department of Geological Sciences,
Northwestern University
Evanston, Illinois 60201

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- * Present address: Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4A2, Canada.

4 August 1978; revised 2 October 1978

Heat Storage in the Oceanic Upper Mixed Layer Inferred from Landsat Data

Abstract. *From the spacing of internal wave packets generated by tidal flow over topography, one can determine their propagation speed. The propagation speed depends upon the density anomaly and depth of the upper mixed layer. Attributing the density anomaly to temperature only, one can calculate the heat storage in the upper oceanic layer. On the basis of Landsat images of the New England continental shelf, the heat storage calculated from satellite data has been compared with available in situ observations. The data show that the method may have merit and is deserving of further refinement.*

The amount of heat stored in the upper ocean during the warm season is governed by the balance between incoming solar radiation and exchanges of heat with the atmosphere and the water layers below the upper heated layer. Horizontal advection in both the atmosphere and the ocean also affects the state of the upper warm layer in the ocean at a geographical location. The amount of heat stored in the upper warm layer and the depth of the layer affect biological productivity, and the heat available for direct participation in the formation of atmospheric disturbances affects weather development. In addition, the heat stored in the upper ocean during the warm season may be a useful climatological variable. The continuous observation of the upper warm layer over a large area is an expensive and difficult effort, since observations are affected by the internal tides, which must then be observed.

We have found a method for estimating the heat stored in the seasonal upper warm layer, using information available in Landsat images. Tidal flow over topography produces internal wave packets (1, 2). These internal waves cause horizontal convergences and divergences in the velocity field of the sea surface, which, in the presence of capillary waves or short gravity waves, will stretch and compress these surface waves, creating bands of variation of surface roughness above the internal waves (3). Internal waves in the upper layers of the ocean can therefore generate surface signs that are discernible in satellite images (4).

Figure 1 shows a contrast-enhanced Landsat image from the region of the northeastern American continental shelf. Two wave packets are visible, apparently being emitted from the same location at successive tidal periods. The spacing between successive wave packets is the distance traveled per tidal period. Dividing the distance by the period of the

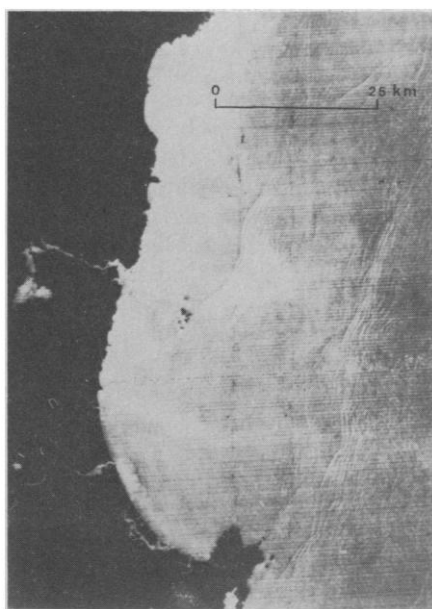


Fig. 1 (left). Enlargement of Landsat image 1364-14550 taken on 23 July 1973. We can see two wave packets north of Cape Ann; the waves propagate shoreward.

Fig. 2 (top right). Frequency distribution of distance between the wave packets corrected by the multiples of a fundamental minimum distance (78 observations).

semi-diurnal lunar tide (M_2), which is approximately 12.4 hours, yields the propagation speed of the wave.

For an idealized stratification where the ocean is composed of two homogeneous layers, the boundary between them being a sharp pycnocline, the wave propagation speed of an interfacial internal wave is

$$c^2 = g \Delta \rho h / \rho_2 \quad (1)$$

where c is the propagation speed, g is the acceleration of gravity, $\Delta \rho$ is the density difference between the upper and the lower homogeneous layers, ρ_2 is the density of the lower layer, and h is the depth of the upper layer. Equation 1 is based on the assumption that the wavelength is much longer than h and that the lower layer is much deeper than the upper layer. Typically, the wavelengths seen in satellite images range from 400 m to 2 km, h is typically 10 m, and the total depth varies from 20 to 200 m.

The density anomaly, $\Delta \rho = \rho_2 - \rho_1$, is due to temperature and salinity differences (ΔT and ΔS) in the two layers, according to the approximate relation

$$\Delta \rho = \rho_2 (\alpha \Delta T - \beta \Delta S) \quad (2)$$

where α is the coefficient of thermal expansion and β is the fractional increase in density per unit increase in S at con-

