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ABSTRACT

An anticyclonic water movement directed away from the upwelling region along the Somali Coast has been detected with the High Resolution Infrared Radiometer aboard the meteorological satellite Nimbus II. The effect of this water movement on the distribution of organic matter is shown with a stoichiometrical model, based on elementary analyses of phytoplankton. The predicted position of the maximum of the organic material has been verified with chlorophyll measurements near the Somali Coast.

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1. INTRODUCTION

In an earlier study it was shown that the organic material can be qualitatively interpretated in terms of vertical motions in the surface layer along the Somali Coast and in the Gulf of Aden (Szekielda, 1967). Similarly, the building of isolated carbon maxima in convection cells in the same region was explained by quantitative investigations (Szekielda, 1969a). In continuing the study to explain the different concentrations of organic matter in the oceans by horizontal and vertical movements, an investigation has been undertaken to detect and analyze anticyclonic and cyclonic eddies with data obtained from the Nimbus II High Resolution Infrared Radiometer. Two anticyclonic eddies were detected, the first in the Gulf of Aden and the second near the Somali Coast at about 10° N. latitude, about 500 km east of the upwelling region.

For the discussion about the distribution of organic matter it should be remembered here that anticyclonic eddies accumulate nutrient-poor, warm water in their central part. Consequently, they should be regions with a low biological activity characterized by low concentrations of organic matter. The inverse is true for cyclonic eddies, where deeper water is transported to the surface and gives rise to a high productivity. However, the Somali Coast during the southwest monsoon is an area with strong upwelling and can be expected to contribute nutrient rich water to the anticyclonic eddy. This represents a special case; therefore, the explanation of chemical and biological factors will become more complicated. This paper will discuss some of the connections between a moving water mass and its content of organic matter.

2. METHODS

A. Temperature Measurements

Nimbus II infrared measurements have been analyzed to yield a quasi-synoptic temperature chart. These data are available from April to November 1966. The HRIR operated at 3.6 to 4.2 microns (the so-called atmospheric window) and measured the emission of the earth from an altitude of about 1,000 km, with a subsatellite ground resolution of 8 km.

Calibrations have been made on the ground in terms of effective radiance from a black body. The received energy at the radiometer has been calibrated against the black-body temperature (T_{BB}). More information about the HRIR are published in the Nimbus II Users' Guide (1966).

Although a negative deviation of the order of 2° C between HRIR temperature and the true water temperature has been observed, it seems to be that the relative accuracy will be better than the absolute, (Warnecke et al., 1969). One pre-condition for oceanographic use of satellite radiation data is a knowledge that the measurements were acquired over cloud-free regions.

B. Particulate Carbon Measurements

The carbon measurements for particulate carbon in the culture experiment (Figure 3) have been made with a CHN-analyzer, Perkin Elmer Model 240. The necessary calibration has been done with glycocoll, weighed on a Cahn electro-balance. For the determination of particulate carbon in the culture, 10 ml of the suspension were filtered over a Whatman GF/C glass fiber filter. The filter was dry frozen and analyzed after storage at -20° C. The final results were corrected for the residual carbon found on a blank filter.

C. Chlorophyll Measurements

The chlorophyll measurements resulted from the "R. V. Atlantis II," as a contribution to the International Indian Ocean Expedition. They are published by Laird, Breitvogel and Yentsch (1964) in a cruise report.

3. RESULTS AND DISCUSSION

The chart in Figure 1 explains the hydrographical features at the Somali Coast that persisted throughout the southwest monsoon season. It shows clearly the upwelling water at the Somali Coast with temperatures near 18°C. The transport of this cold water away from the coast in a northeast direction, and at 10° N, 54° E a turn to southwest, can be seen by following the 24° isoline. Probably the visible eddy is wind driven and represents an Ekman spiral. The relatively warm water in the center of the detected anticyclonic eddy reached a temperature near 26° C and showed an excellent example of the temperature distribution in an anticyclonic circulation scheme. Warren, Stommel and Swallow (1966) gave the most detailed analysis for this region with classical ship measurements, but quoting their own words, "it was obvious that rapid changes were occuring north of the ninth parallel (especially west of 53° E), with the result that repeated observations in the same area were not compatible."

This changing in the temperature distribution was based on the variable intensity of the upwelling water. The Nimbus II satellite made it possible to follow such a development of the cold water along the Somali Coast. Although a comparison of Figure 2 with Figure 1 shows a rapidly changing pattern during a period of only three days, it was possible, using satellite data, to follow the development over a period of several weeks.

A comparison of chlorophyll and temperature data obtained during the southwest monsoon period for the area near the Somali Coast reveals that no simple relationship between both parameters exists. However, for an explanation of organic material in a current system, the lag between the time when the phytoplankton starts to grow and the time when the maximum phytoplankton occurs, has to be considered. This means that the highest chlorophyll concentrations can be found far from the place where vertical motions enrich the euphotic zone with nutrients. Therefore, the distance of the chlorophyll maximum from the upwelling zone depends upon the horizontal velocity of the currents. In the following model the organic carbon has been calculated for two different conditions. An upwelling region has been assumed and the building of carbon has been calculated during the transport of the upwelled water away from the coast on a spiral. The current velocity has been varied, so that in the first case the maximum for carbon value has been reached before arriving at the central part of the gyre. In the second example, a horizontal transport has been assumed so that the maximum carbon concentration occurs in the center of the gyre. The model to calculate the organic carbon [C] has the following form:

$$[C] = C_0 + f\int_0^{20} \frac{dp}{dt}\, dt \tag{1}$$

where $\frac{dp}{dt}$ is the reacted phosphate per liter per day, C_0 the fraction of organic carbon present in the water before starting the photosynthesis, and f the factor to convert the reacted phosphate into organic carbon. This stoichiometrical factor is based on elementary analyses of phytoplankton:

$$\begin{gathered} 224\, CO_2 + 253\, H_2O + 29\, HNO_3 + 2H_3PO_4 = \\ (CH_2O)_{224}\, (NH_3)_{29}\, (H_3PO_4)_2 + 282\, O_2 \end{gathered} \tag{2}$$

Equation (1) is valid only from the 1st to the 20th day of the growth of the algae. After the 20th day a decomposition factor of 14.56μg - atom $C \cdot l^{-1} \cdot day^{-1}$ has been used (Szekielda 1969b). The final equation will then be:

$$[C] = C_0 + \left(112\int_0^{20} \frac{dp}{dt}\, dt\right) - 14.56\,(t - 20)\, x \tag{3}$$

$$\text{where } x = \begin{cases} 0 & \text{for } t < 20 \\ 1 & \text{for } t \geq 20 \end{cases}$$

and t gives the time in days. The decomposition has been calculated to 40μg - atoms $C \cdot l^{-1}$. This value corresponds approximately to the concentrations of organic carbon found in waters without photosynthesis. The nature of the decomposition of the organic material after reaching the highest cell concentration in an algae culture has been determined in a laboratory experiment. The results are given in Figure 3. Although the maximum of carbon concentration could not be found on the 20th day (as assumed in the model) the rapid decrease of the particulate carbon concentration is evident after reaching the highest cell concentration in the culture.

The results in Figure 4 show the distribution of organic material in a simulated circulation scheme with upwelling. When horizontal velocities are slow, the maximum concentration of organic carbon is found near the upwelling region and builds a ring with high concentrations around the inner part of the eddy (Figure 4A). When high horizontal transport of the water masses appears, the maximum concentration of organic carbon is found in the middle of the anticyclonic gyre. Assuming a current speed of 300 $cm \cdot sec^{-1}$ within the anticyclonic movement at the Somali Coast as measured by Swallow and Bruce (1966), the distribution of organic material would be as shown in Figure 4B. Chlorophyll concentrations determined during the southwest monsoon in 1963 have been used to support the model. In Figure 5, it is obvious that the highest chlorophyll concentrations are not in the region of upwelling itself. Rather, they are found in the region where the temperature from satellite observations indicates the location of the central part of the anticyclonic gyre. A neighboring isolated maximum of chlorophyll occurs to the east of the anticyclonic gyre.

Duing's (1969) calculation using the dynamic height relative to the 800 decibar level also shows the anticyclonic eddy. Further, he found a cyclonic water movement to the east of the eddy. This movement brings deeper water to the surface where another carbon rich region can be expected to occur.

CONCLUSION

The model and the analysis of satellite data predicted the building of separated regions rich in organic matter which were confirmed by chlorophyll measurements. Nevertheless, more models and more satellite radiation data are needed for an understanding of the relationship between water movements and their chemical and biological processes. In upwelling regions like the Somali Coast satellite data provide an important new tool for probing quasi-synoptically the water structure near the surface.

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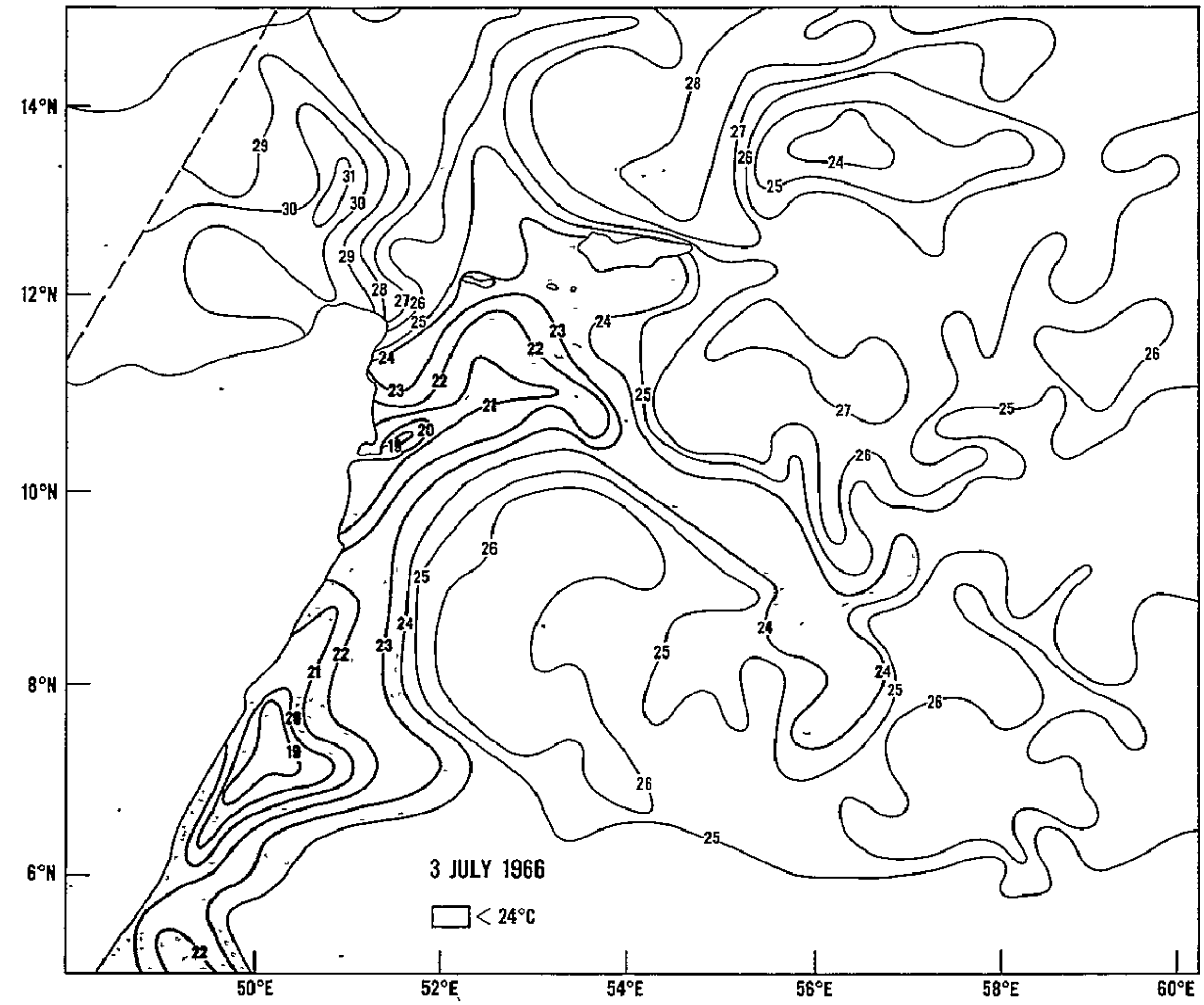

Figure 1. Equivalent Black Body Temperature distribution at the beginning of upwelling near the Somali Coast as recorded by Nimbus II HRIR, 3 July 1966.

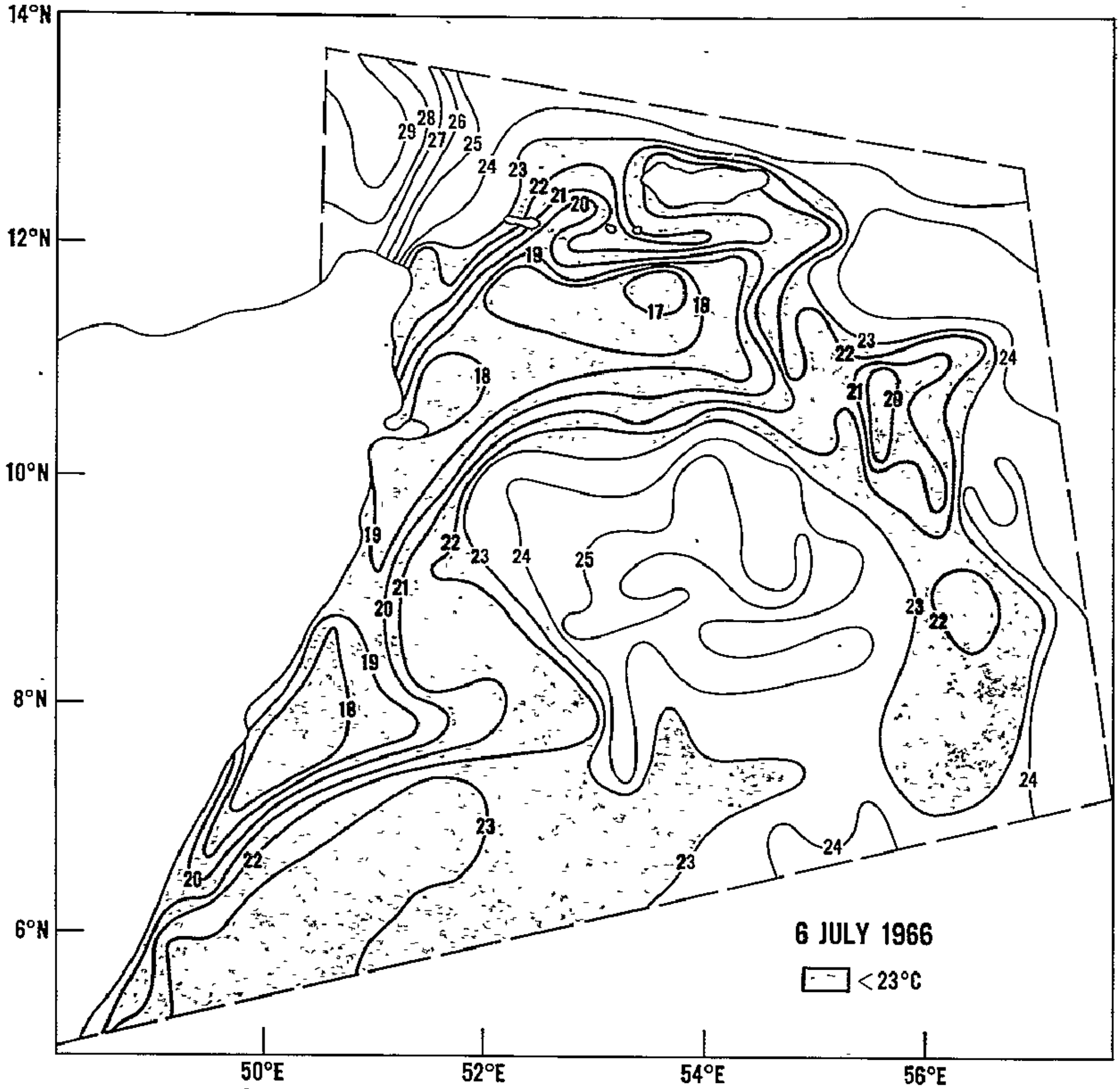

Figure 2. Equivalent Black Body Temperature distribution at the beginning of upwelling near the Somali Coast as recorded by Nimbus II HRIR, 6 July 1966.

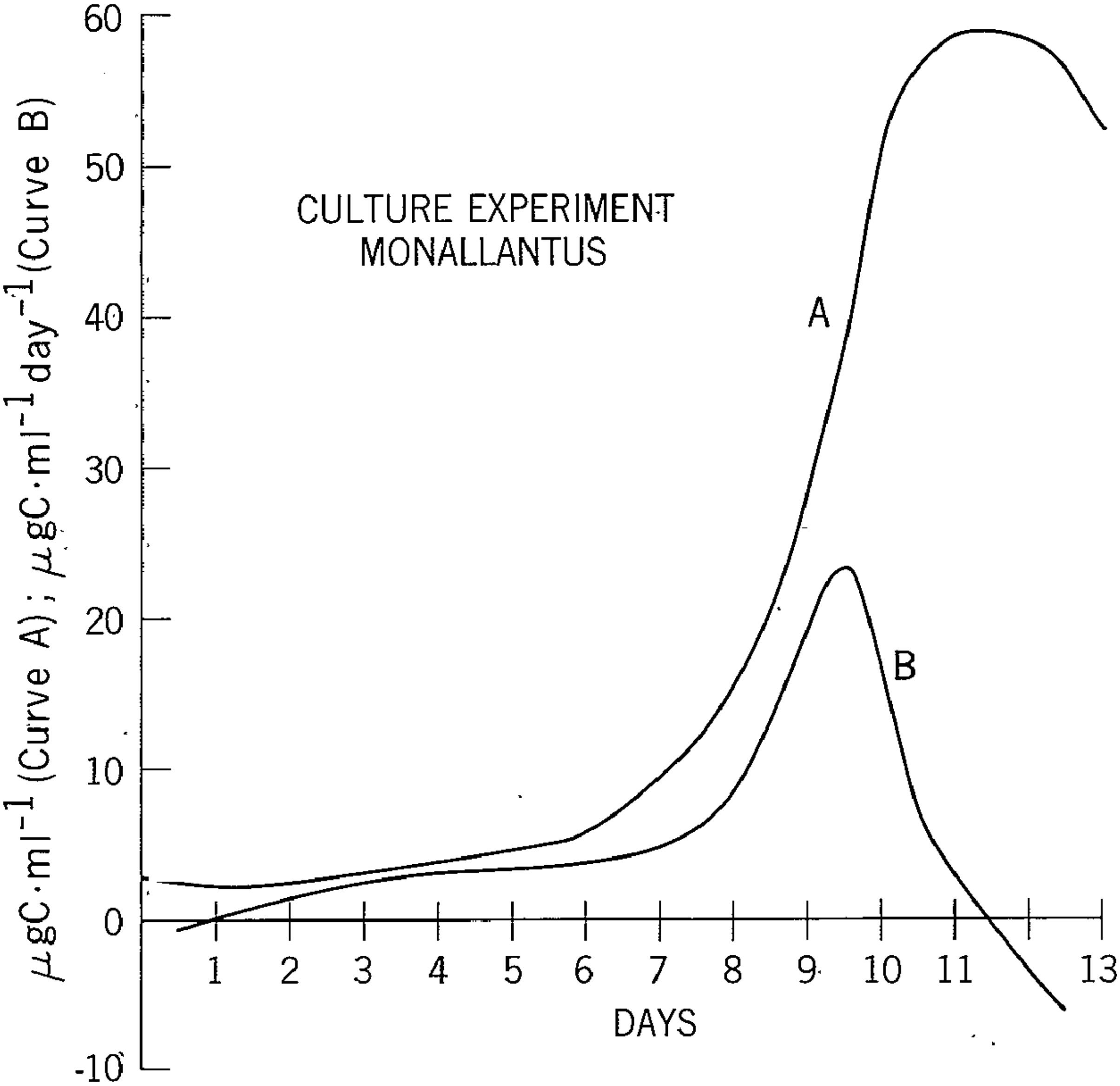

Figure 3. Culture experiment with Monallantus in 22‰ sea water. The decomposition of the carbon is seen between the 9th and 10th day where $\frac{dC}{dt}$ reaches negative values.

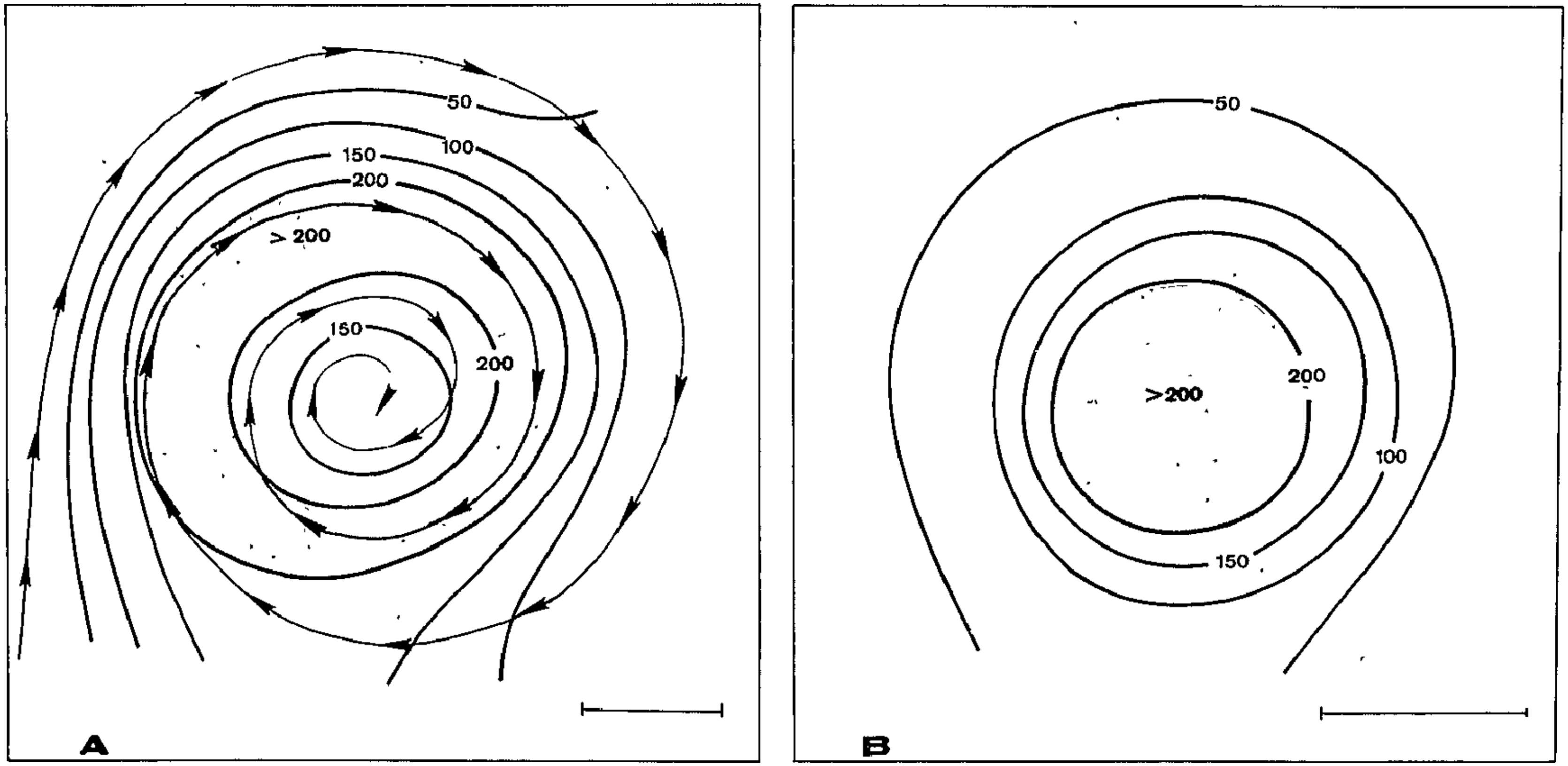

Figure 4. The distribution of organic carbon in μ g - atom $\cdot l^{-1}$ based on equation (3). The scales in the lower right hand corner indicate the relative distance traveled by a parcel of water along a streamline in a day.

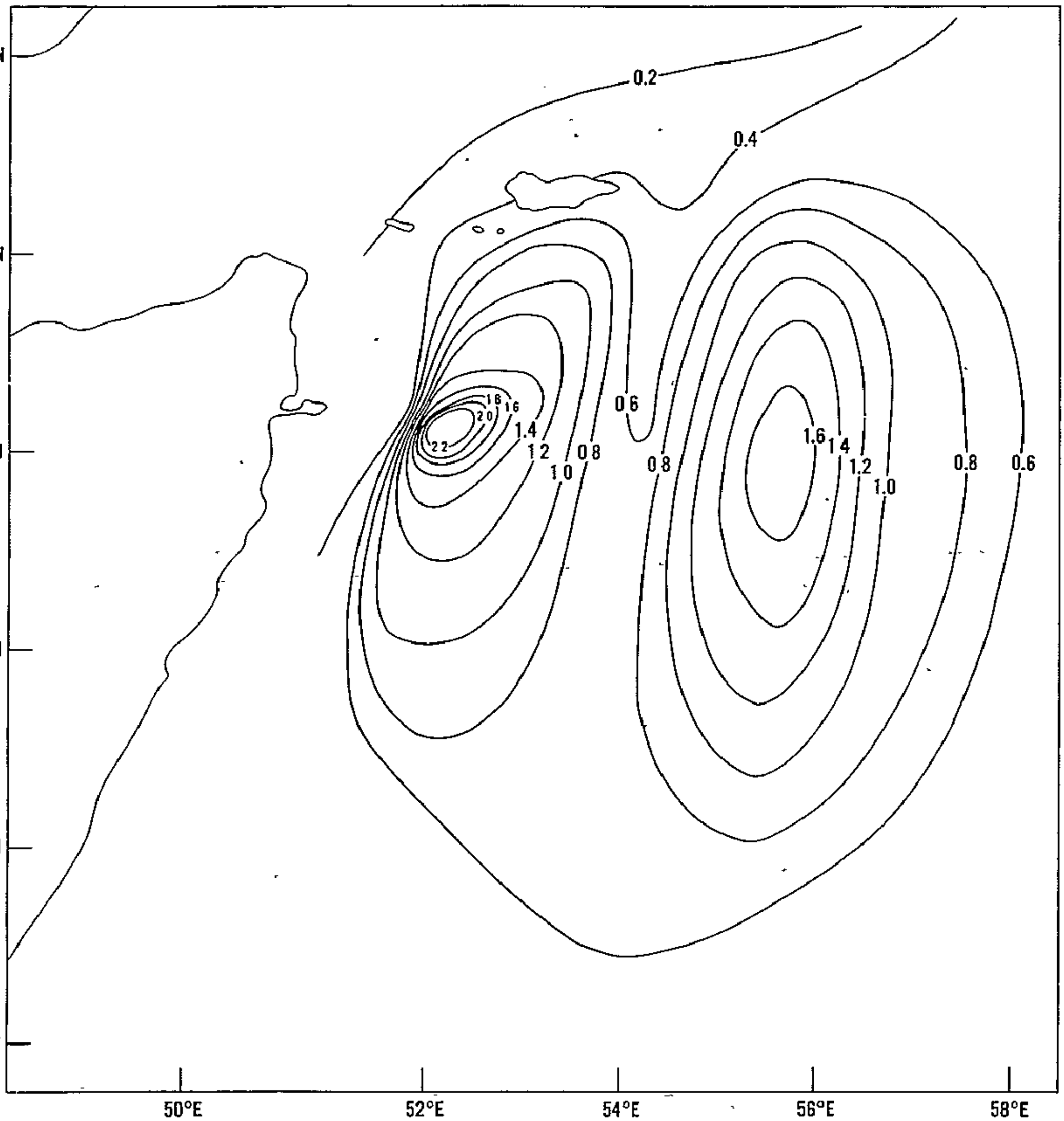

Figure 5. Chlorophyll distribution near the Somali Coast during the southwest monsoon 1963. The samples where the maxima appear have been collected during one day (29-30 August); therefore, their relative positions to each other are significant. Concentrations in $\mu g \cdot l^{-1}$.

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