NAFO Sci. Coun. Studies, 4: 53-59

Satellite Observation of Phytoplankton Distribution Associated with Large Scale Oceanic Circulation[1]

Charles S. Yentsch
Bigelow Laboratory for Ocean Sciences
West Boothbay Harbor, Maine 04575, USA

Abstract

Examination of satellite CZCS (Coastal Zone Color Scanner) imagery of the western Gulf of Mexico and the coast of Florida confirms that the major features of phytoplankton chlorophyll distribution are associated with boundary regions of major ocean currents such as the Gulf Loop Current and the Florida Current. Variation in surface distribution of chlorophyll is believed to be related to the baroclinicity of the density field associated with the movement of the water masses. The mechanism for augmenting phytoplankton growth in these systems is due to the vertical flux of nutrients. The major source of energy for vertical mixing is believed to be supplied by bottom friction. The satellite observations confirm that patterns of phytoplankton distribution obtained from conventional shipboard observations have provided a reasonably accurate representation of global patterns of primary production.

Introduction

Are shipboard observations truly synoptic? What often inhibits understanding of phytoplankton distribution are so-called problems concerning time and space. One problem is recognized as the inability of a stationary observer to separate changes due to local events such as movements of water masses from those brought about by growth of microorganisms. Recognition of this problem by early oceanographers was the source of ideas as to how patches of phytoplankton are formed and sustained in water masses. This is generally explained as local or individual change. Indeed, there is great difficulty in obtaining synoptic samples. Satellite imagery now offers a means of obtaining synoptic data on phytoplankton distribution.

Gower *et al.* (1980), using LANDSAT satellite imagery, demonstrated that phytoplankton is distributed in patches formed by eddies 10–100 km in diameter. These high energy features are associated with marked differences in density formed between ocean currents and adjacent gyres. This important observation suggests that the pattern of large-scale plankton patchiness is more complex than would be anticipated from general features of ocean circulation.

The identification of patchiness at the 10–100 km scale raises questions about distribution of phytoplankton at larger scales. The pattern of primary productivity is known to be associated with large-scale changes in the density field of the oceans (Yentsch, 1974), which in turn is a reflection of oceanic circulation. Thus, Gower *et al.* (1980) have set the stage for comparison of different size scales of phytoplankton distribution patterns. If mesoscale patterns are dominated by high energy gyres, can the situation at much larger scales be expected to be more synoptic? Can these patterns be resolved by CZCS colorimetry?

Results and Discussion

Synoptic features in phytoplankton production

In the broadest sense, the crux of the discussion in this paper concerns the question of the degree to which the pattern of distribution of phytoplankton is determined by vertical mixing. Within the oceans, the extremes in vertical mixing are outlined by intense gradients of scalar properties which are termed fronts. Germane to this discussion are the causes of fronts and how long fronts persist. Bowman (1978) has proposed a general classification for ocean fronts composed of six categories (Table 1). These categories suggest that a basis for size classification might be frontal dimensions; for example, frontal categories 1-3 are generally larger than the others. Another basis is the source of energy required for destratification and maintenance of the front. Because of the global nature of forces involved, a high degree of synopticity and permanence might be assigned to these fronts. The potential energy for destratification can come from density differences and from wind stress on the surface and tidal bottom friction in coastal areas.

The inadequacy of such an energy partitioning scheme is recognized. Practically every type of front must contain input from all known energy sources. The

[1] Contribution number 81015 from the Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine, USA.

TABLE 1. Classification of ocean fronts according to Bowman (1978).

Type	Energy of destratification	Persistence
1. Planetary scale, open ocean	Geostrophy, Ekman transport	Quasi-synoptic
2. Fronts on edges of western boundary currents	Geostrophy	Quasi-synoptic
3. Shelf-break fronts	Geostrophy, density differences, tides	?
4. Upwelling	Ekman transport	Periodic
5. Plume fronts	Density differences, tides	Periodic
6. Tidal fronts	Tides	Periodic

reason for making the assignment given in Table 1 is that, for specific fronts, the energy spectra will be documented by a particular source. Because of the "global consistencies" of such features as global heat and wind fields, the combination of geostrophic and Ekman mechanisms tends to promote frontal patterns approaching synopticity. This is in contrast to such factors as local winds, tides and freshwater input, which are more variable. Before examination of satellite images, two questions must be asked: Why do these types of frontal situations enhance phytoplankton growth which could impart color change? How does this change relate to the conservative features of large water masses in motion?

Baroclinicity and phytoplankton chlorophyll

The vertical motions associated with large-scale ocean currents are believed to be due to instabilities in horizontal transport. In the sense with which the term "geostrophic" is assigned to these currents, instability in velocity is due to imbalance between the pressure gradient (differences in specific volume) and the force due to the earth's rotation. These forces in combination cause cold water of high density to be inclined and therefore near the surface to the left of the axis of horizontal flow of currents in the northern hemisphere. The imbalance between forces causes vertical mixing. The presence of cold nutrient-rich water nearer the surface in the euphotic zone stimulates phytoplankton growth in these regions, and hence the chlorophyll content is high (Yentsch, 1974). The degree of departure of the density surfaces from the horizontal is termed baroclinicity. In terms of vertical transport, mixing does not erase the density surfaces. Mixing occurs along the lines of equal density, which in turn transports the scalar substances.

Historically, this mechanism has been referred to as isopycnal mixing. Although empirical evidence abounds which relates changes in the slope of isopycnals (baroclinicity) to plankton production, the difficulty in applying it in models is due to unclear understanding of the fluid dynamics associated with the mixing. Woods (1977) suggested that isopycnal mixing lies somewhere between the turbulent processes associated with vertical and horizontal mixing. The implication of this approach is that the inclination of isopycnals markedly increases the vertical flux from a normal horizontal mode. As the isopycnals steepen, transport approaches that associated with vertical mixing in a non-stratified water column.

The importance of the degree of baroclinicity can be seen in Fig. 1 by comparing the slope of the isopycnals with those for nitrate and chlorophyll. High velocity water flowing past the Yucatan coast is associated with inclined water masses containing high nitrate and chlorophyll. The inclination of isopycnals along the Florida coast is due to the return flow of the Loop Current.

The reason for the high chlorophyll concentrations being associated with regions of high current velocity is that the scalar transport of nitrate (the limiting nutrient) in these areas is greater than that in regions where currents are slow. This may be modeled as follows:

$$C_t = \int_0^{Z_e} \left\{ C_z \left(f_1\, E_z \cdot f_2\, N_2 \cdot k - R_z \right) \right\} \cdot d_z$$

where the total quantity of chlorophyll (C_t) within the euphotic zone (Z_e) is primarily a function of light energy ($f_1\, E_z$) and nutrient availability ($f_2\, N_2$), and k is a constant for converting N and E into chlorophyll. The term ($f_1\, E_z$) refers to the interaction of downwelling light energy (E) and photosynthetic production processes. If it is assumed that this term varies only slightly over the region of interest, i.e. the attenuation coefficient and incoming light energy change only slightly and the rate of chlorophyll removal (R_z) by zooplankton herbivores and/or sinking is small, the nutrient availability term ($f_2\, N_2$) largely determines the total quantity of chlorophyll. Therefore, the total quantity of chlorophyll is proportional to the nitrate content within the euphotic zone. This quantity of nitrate is regulated by the amount used by photosynthetic growth plus that which is mixed upward from below the euphotic zone.

Baroclinic features of ocean currents from CZCS

In the previous section, it was emphasized that the pattern of productivity should be regulated by the degree to which water masses are mixed vertically.

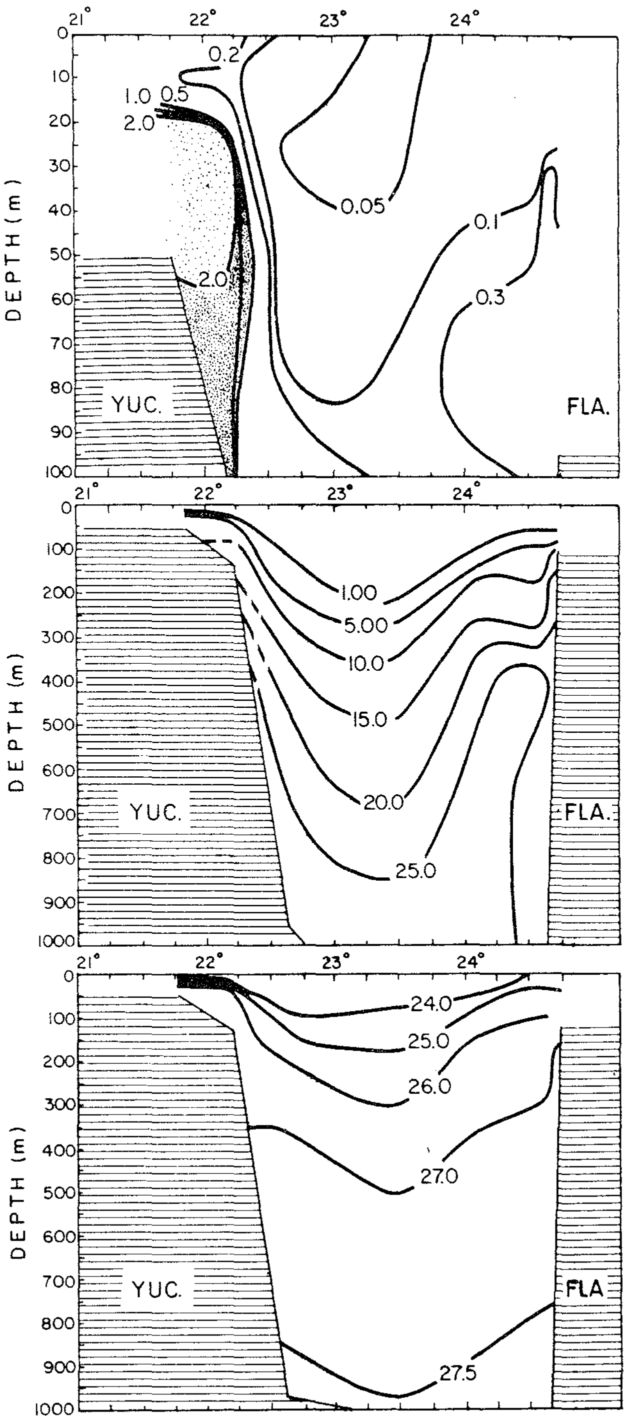

Fig. 1. Distribution of chlorophyll (top), nitrate (middle) and density (bottom) by depth between Yucatan, Mexico, and Dry Tortugas off Florida.

Furthermore, the processes which control the horizontal advection influence the amount of vertical mixing and hence phytoplankton growth. It can be asked whether or not the major aegeostrophic features associated with large ocean currents can be identified by satellite colorimetry.

From NIMBUS-6 on orbit 130, 2 November 1978, the CZCS (Hovis *et al.*, 1980) imaged most of the western Gulf of Mexico. This was the first image processed by NASA (National Aeronautics Space Administration), using methods and algorithms (Gordon *et al.*, 1980) which correct for atmospheric effects and result in estimates of the chlorophyll content of the waters. The chlorophyll computations yield values in the central region of the Gulf between 0.05 to 0.10 mg/m^3. Nearer shore, the values approach 5.0 mg/m^3. Off the Mississippi Delta, values exceed 10 mg/m^3. In light of sea truth measurements made in this region at this time (see Gordon *et al.*, 1980) and what is known from previous studies, these values are considered realistic.

The image (Fig. 2) shows a wide variety of mesoscale features. However, the reader is asked to concentrate on the shape of the general pattern of chlorophyll for the entire region. The chlorophyll pattern on the western side of Florida is much broader than the front on the Atlantic side. The physical dimensions of these fronts correspond to the physical dimensions of the continental shelves on both sides of the Florida peninsula. In the case of the west coast shelf, the distance from shore to the 200 m isobath is over 300 km at latitude 26° N. On the east coast, at the same latitude, the shelf width is only a few kilometers but it broadens moving northward towards Cape Hatteras.

The three major frontal boundaries for chlorophyll which outline the general sequence of decreasing chlorophyll moving seaward from land are outlined in Fig. 3. The frontal positions have been redrawn to correct for distortion caused by orbital configuration. The fronts, excluding small-scale perturbations, can be seen to parallel the isobaths along both coasts of Florida. The more seaward part of the front appears as a boundary which distinguishes oligotrophic water from slope water.

Except for the northern area of the Gulf of Mexico, all of the fronts outlined lie within the 200 m isobath and probably between the 50 and 100 m isobaths. Lacking other geophysical information pertinent to this image, the general position of the fronts can be interpreted to be due to the flow of the Loop Current in the Gulf and the Florida Current on the eastern side of Florida. The dynamic topography in this region shows that channel-shelf constraints markedly influence horizontal velocities and thus the pattern of mass transport (Nowlin and McLellan, 1967; Molinari and Yager, 1977; Brooks and Niiler, 1977). For example, in the western Gulf of Mexico, the effect of the Loop Current is seen as forming a high level ridge (Fig. 4) which parallels the Florida escarpment along the west coast shelf. In this case, the sea-level surface slopes about 50 cm from the ridge to the edge of the escarpment at the 1,000 m isobath Niiler's (1976) data, a

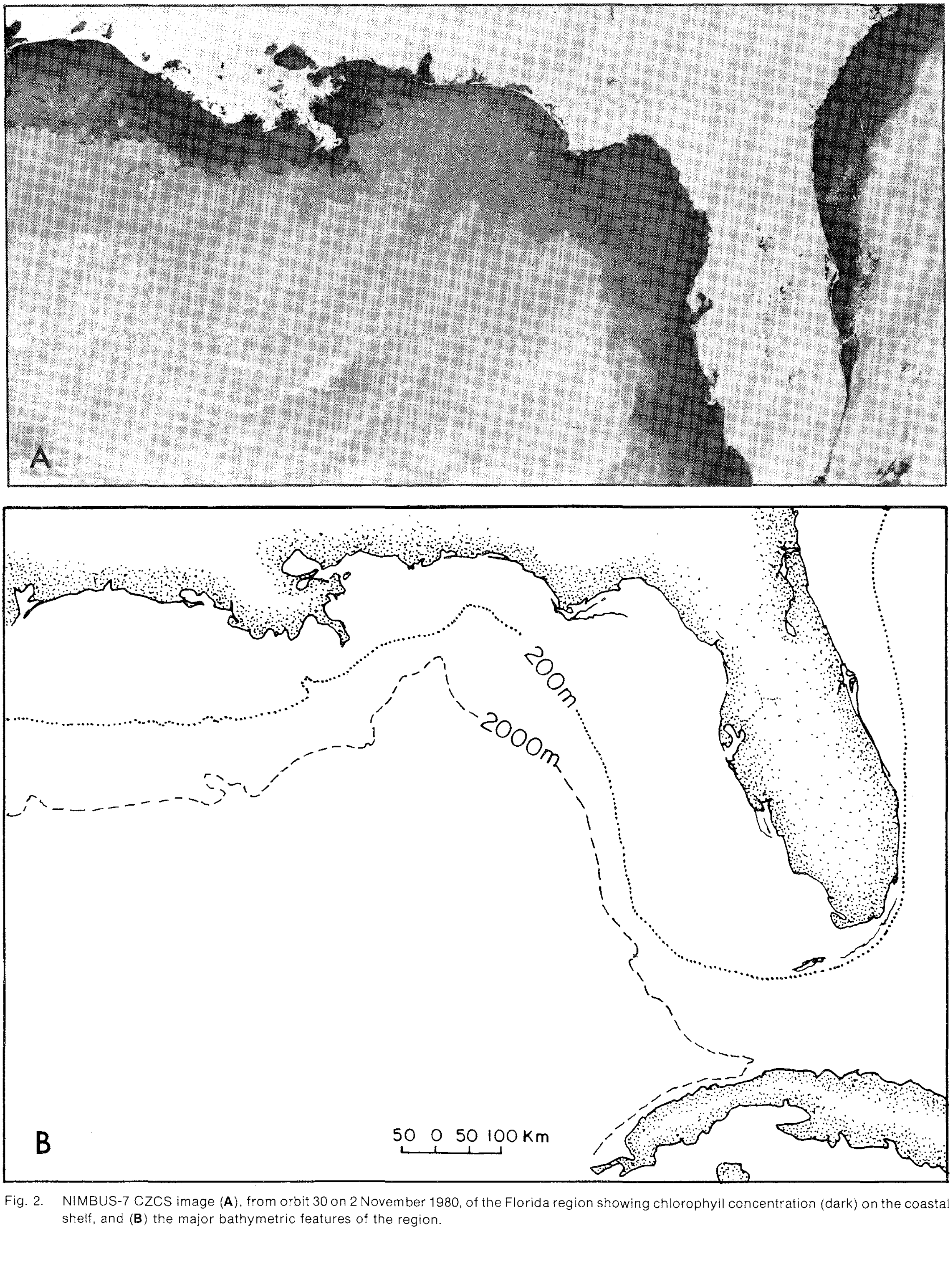

Fig. 2. NIMBUS-7 CZCS image (**A**), from orbit 30 on 2 November 1980, of the Florida region showing chlorophyll concentration (dark) on the coastal shelf, and (**B**) the major bathymetric features of the region.

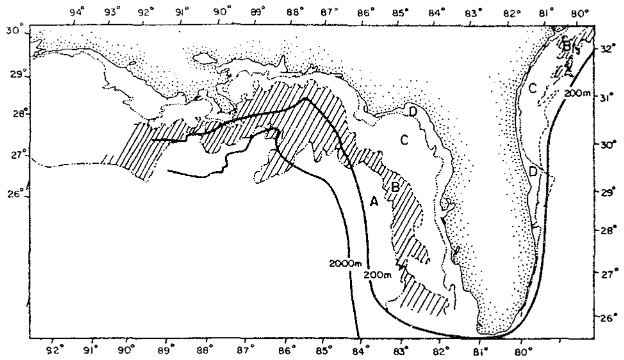

Fig. 3. Locations of fronts A, B, C and D derived from the chlorophyll distribution shown in Fig. 2A.

trans-shelf section at latitude 26° N, shows isopycnal surfaces inclining at a constant slope onto the shelf until the 200 m isobath, where the isopycnals are markedly inclined vertically. This inclination extends beyond the 100 m isobath. From the image and bathymetric charts, the positions of the most seaward chlorophyll fronts on either coast begin in the vicinity of the 100–200 m isobath and increase in density of color to the 50 m isobath. Proceeding toward the shore, chlorophyll color increases but at a reduced rate.

Surface temperature and water color

From the previous discussion on baroclinicity, a close spatial relationship between water color and surface temperature is anticipated, as the inclination of isopycnals represents vertical transport of temperature as well as nutrients.

From orbit 1965 on 15 March 1979, both water color and temperature were imaged over the western Gulf of Mexico (Fig. 5). At the time, the atmosphere was very clear. The upper image is uncorrected for atmospheric effects in the total upwelled radiance seen by CZCS Channel 1 (443 nm). The lower image is the thermal presentation by CZCS Channel 6.

The thermal front of the Loop Current has been observed to penetrate the Gulf of Mexico following a seasonal cycle (Maul, 1977). In the thermal image (Fig. 5B), equatorial water exiting from the Strait of Yucatan can be seen penetrating, as a warm core, into the Gulf of Mexico as far north as latitude 27° N, which agrees with Maul's "spring position" for the Loop Current. Close inspection of this image shows that the surface thermal characteristics "fan out" through the western Gulf in a pattern similar to the frontal boundary of the central warm core. Along the eastern coast of Florida, the pattern of temperature appears to closely follow the Florida-Hatteras slope, colder water not being observed until the shelf widens north of Palm Beach (26° N). At this point the thermal pattern closely reflects shelf dimensions.

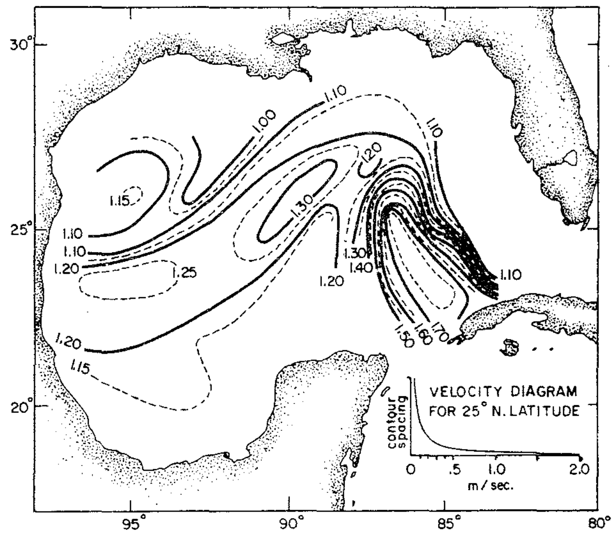

Fig. 4. Dynamic topography of the Gulf of Mexico region, from Nowlin and McLellan (1967).

Color and temperature patterns are clearly identical along the east coast of Florida, with an abrupt transition between waters of rich and poor phytoplankton associated with the cold wall of the Gulf Stream (Yentsch, 1974). The color image for the western Gulf of Mexico indicates a large mass of chlorophyll-poor water which extends as far as latitude 30° N. However, in the region at the western Florida shelf escarpment, where the Loop Current is impinging, the water masses are rich in chlorophyll (reduced radiance at 443 nm, CZCS Channel 1). The chlorophyll-rich water covers the entire shelf extending southward paralleling the escarpment. Therefore, the higher chlorophyll along this escarpment is associated with the southerly high velocity transport of the Loop Current.

Synopticity and the conservation nature of ocean color

The first question posed in the Introduction concerns the possibility of resolving the aegeostrophic effects of large scale ocean currents on the spatial distribution of phytoplankton chlorophyll using satellite CZCS imagery. The colorimetry shown by the images presented in this paper demonstrates that colorimetry can easily resolve the dominant features of global patterns of phytoplankton. The adequacy of past shipboard coverage and sampling techniques was also questioned in the Introduction. Some caution should be used in answering, as only a limited number of CZCS images are available. For the most part, sea sampling has delineated the major regions and the general pattern of "ocean richness" has been adequately described. If this is indeed true, what then are the expected contributions of satellite imagery at large spatial scales?

The study of the interaction of global primary production with global climate on seasonal time periods

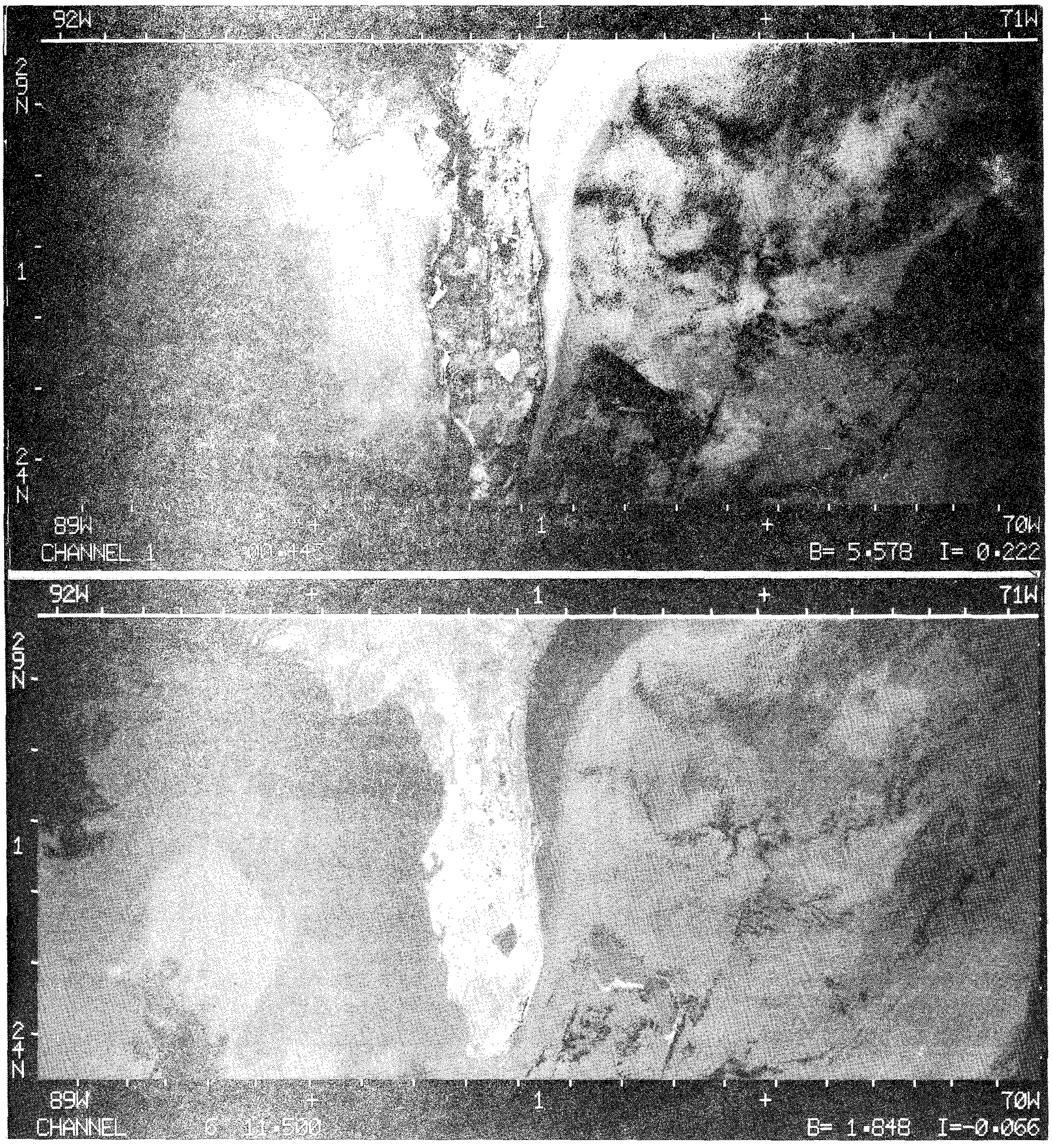

Fig. 5. NIMBUS-7 imagery from orbit 1965 on 15 March 1979. **A**, CZCS Channel 1 (443 nm) image where light tone denotes high attenuation of blue due to phytoplankton chlorophyll. **B**, Channel 6 images of sea-surface temperature variation in which the dark tone depicts cold water.

and those of decades is of extensive interest to those concerned with heat and carbon dioxide fluxes and other climatic processes. Such studies are possible using satellite systems. Of particular interest is a global assessment of the amount of vertical mixing which is the principal fluid process driving productivity. It should be recognized that geostrophic theory, if fully operational, does not support the idea of isopycnal mixing; in theory, a balance should exist between the pressure gradient and Coriolis force. Therefore, "baroclinic chlorophyll patterns" are interpreted as representing the results of imbalances between the two forces. The source of the imbalances becomes of major interest in the interpretation of chlorophyll patterns.

The position of the baroclinic color fronts in relation to water depth suggests that vertical mixing is increased by the frictional effects of ocean currents being restricted by depths at the continental margins. This situation is analogous to conditions where fronts are formed due to destratification of water masses by tidal currents. Although, in the case of tidal fronts, the density surface can be completely turned over, both cases derive energy for vertical mixing from bottom friction.

Summary

The sequence and magnitude of vertical mixing, covering spatial scales from ocean gyres and currents to tidal mixing, suggests that the observed spatial patterns of phytoplankton are the result of changes in the degree of vertical mixing, horizontal transport as a mechanism for passive distribution being of minor importance in the oceans as a whole. This argument is partially supported by the idea that phytoplankton not growing are quickly removed from the system by sinking or grazing. This idea, originally introduced many years ago, means that color patterns viewed by satellite are reflecting phytoplankton growth. Thus, it is the dynamics associated with the movement of water masses which regulate the growth of phytoplankton. This growth causes specific features of ocean fluids to be outlined by color.

Acknowledgements

This work was supported by the National Aeronautics and Space Administration and the State of Maine, although much of the shiptime costs can be traced to the National Science Foundation, the Office of Naval Research and the National Oceanic and Atmospheric Administration. Katherine Kilpatrick corrected the images for orbit distortion, Pat Oathout processed the manscript, and Jim Rollins did much of the photography, and I am extremely grateful to them for assistance.

References

BOWMAN, M. J. 1978. Oceanic fronts in coastal processes. *In* Proceedings of a workshop held at the Marine Sciences Center, 25-27 May 1977, M. J. Bowman and W. E. Esaias (eds.), Springer-Verlag, New York, 114 p.

BROOKS, I. H., and P. P. NIILER. 1977. Energetics of the Florida Current. *J. Mar. Res.*, **35**(1): 163-191.

GOWER, J. F. R., K. L. DENMAN, and R. J. HOLYER. 1980. Phytoplankton patchiness indicates the fluctuations spectrum of mesoscale oceanic structure. *Nature*, **288**(5787): 157-159.

GORDON, H. R., D. K. CLARK, J. L. MUELLER, and W. A. HOVIS. 1980. Phytoplankton pigments from Nimbus-7: comparison with surface measurements. *Science*, **210**(4465): 63-66.

HOVIS, W. A., D. K. CLARK, F. ANDERSON, R. W. AUSTIN, W. H. WILSON, E. T. BAKER, D. BALL, H. R. GORDON, J. J. MUELLER, S. Z. EL-SAYED, B. STORM, R. C. WRIGLEY, and C. S. YENTSCH. 1980. Nimbus-7 Coastal Zone Color Scanner — system description and initial imagery. *Science*, **210**(4465): 60-63.

MOLINARI, R. L., and R. E. YAGER. 1977. Upper layer hydrographic conditions at the Yucatan Strait during May 1972. *J. Mar. Res.*, **35**(1): 11-20.

MAUL, G. A. 1977. Annual cycle of the Loop Current. Part I. Observations during a one-year time series. *J. Mar. Res.*, **35**(1): 29-47.

NIILER, P. P. 1976. Observations of low frequency currents on the western Florida continental shelf, p. 331-359. *In* Memoires de la Societe Royal des Sciences deLiege, Seventh Liege Colloquium on Ocean Hydrodynamics — Continental Shelf Dynamics, Siège de la Sociêtê Universitê, Belgium, 395 p.

NOWLIN, W. D., Jr., and H. J. McLELLAN. 1967. A characterization of Gulf of Mexico waters in winter. *J. Mar. Res.*, **25**(1): 29-59.

WOODS, J. D. 1977. Parameterization of unresolved motions in modelling and prediction of the upper layers of the oceans, p. 118-140. *In* Modelling and prediction of the upper layers of the ocean, E. B. Krauss (ed.), Pergamon Press, 325 p.

YENTSCH, C. S. 1974. The influence of geostrophy on primary production. *Tethys*, **6**(1-2): 111-118.