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Satellite Observation of Phytoplankton Distribution Associated with Large Scale Oceanic Circulation

by

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ABSTRACT

An examination of Coastal Zone Color Scanner (CZCS) 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 and the Florida Current. Variation in the 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 growth in these systems is due to the vertical flux of nutrients which regulate phytoplankton growth. The major source of the 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 problems truly synoptic? What often inhibits the 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 the movement of water masses from those brought about by growth of microorganisms. Recognition of this problem by early oceanographers was the source of the 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 imagery demonstrate that phytoplankton are distributed in patches formed by eddies 10 to 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. There is also the suggestion that the apparent "conservative nature" of the patterns of ocean color (which demark the eddies) argues that the fluid dynamics of this feature is supporting a steady growth of phytoplankton.

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

Arguments for 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 dictated by vertical mixing. Within the oceans, the extremes in vertical mixing are outlined by intense gradients of scalar properties which are termed fronts. Germaine to this discussion are the causes of fronts and how long fronts persist. Bowman (1978) has proposed a general classification for ocean fronts (Table 1). The classification is composed of six categories. These categories suggest that a basis for classification might be frontal dimensions. Another basis is the source of energy required for destratification and maintenance of the front. For example, frontal categories 1 through 3 are generally larger than the other. Because of the global nature of forces involved, one might assign a high degree of synopticity and permanence to these fronts. The potential energy for destratification can come from density differences; that is, specific volume in the geostrophic model for circulation, from wind stress on the surface and tidal 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. My point in making the assignment shown 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 tend 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, we must ask (1) why do these types of frontal situations enhance phytoplankton growth which could impart color change? and (2) how does this change relate with the conservative features of large water masses in motion?

Table 1

Frontal Classification from 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, tide	Periodic
6) Tidal fronts	Tides	Periodic

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 we assign the term "geostrophic" to these currents, the instability in velocity is due to an 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 when in the euphotic zone, stimulates phytoplankton growth in these regions, 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 an unclear understanding of the fluid dynamics associated with the mixing. Woods (draft manuscript) has suggested that isopycnal mixing lies somewhere between the turbulent processes associated with the vertical and horizontal mixing. The implications of this approach is that the inclination of isopycnals markedly increases the vertical flux from a normal horizontal mode. As the isopycnals steepen, the transport approaches that associated with vertical mixing in a non-stratified water column.

The importance of the degree of baroclinicity is shown in Figure 1 and can be seen by visually comparing the slope of the isopycnals with those for nitrate and chlorophyll. High velocity water flowing past the coast of Yucatan 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 concentration being associated with regions of high current velocity is that in these areas, the scalar transport of nitrate (the limiting nutrient) is greater than that in regions where currents are slow.

This may be modeled as follows:

$$Chl_t = \int_o^{Ze} \{Chl_z \, (f_1 \, E_z \cdot f_2 \, N_2 \cdot k_{z:cw} - R_z)\} \cdot d_z$$

Where the total quantity of chlorophyll (Chl_t) within the euphotic zone (Z_e) is primarily a function of light energy ($f_1 \, E_z$) and nutrient availability ($f_2 \, N_2$), $\underline{k}$ is a constant for correcting N and E into chlorophyll. The term $f_1 \, E_z$ refers to the interaction of downwelling light energy $\underline{E}$ and the photosynthetic production processes. If one assumes that this term varies only slightly over the region of interest, that is, that the attenuation coefficient and incoming light energy change only slightly and the rate of removal of chlorophyll (R_z) by zooplankton herbivores and/or sinking is small, then the nutrient availability term, $f_2 \, N_2$ largely determines the total quantity of chlorophyll. Therefore, by way of comparison, the total quantity of chlorophyll is proportional to the nitrate content within the euphotic zone. This, in turn, is determined by the quantity entering by flux processes. For any one euphotic zone, the amount of nitrate depends upon the difference between the quantity of nitrate in the euphotic zone and that below.

Baroclinic features of ocean currents as viewed by CZCS.

In the previous section a case has been made for many areas of the world's oceans that the pattern of productivity should be dictated by vertical mixing primarily because of nutrient limitation, can be counteracted by the nutrient source being found below the euphotic zone.

Furthermore, it was argued that the processes which regulate the horizontal flow augment vertical transport and hence phytoplankton growth. We can now ask if this process, a coincidence between oceanic circulation and phytoplankton distribution, is identifiable from space.

From Nimbus 6 on orbit 130, November 2, 1978, the CZCS (Hovis *et al.*, 1980) imaged most of the Western Gulf of Mexico. This was the first image processed by NASA using the methods and algorithms proposed by Gordon *et al.* (1980). These correct for atmospheric effects and result in the chlorophyll content of the waters. The chlorophyll computations yield values in the central region of the Gulf between 0.05 to 0.10 milligrams per cubic meter. Nearer shore, these values approach 5.0 milligrams per cubic meter. Off the Mississippi Delta values exceed 10. In light of sea truth measurements made in this region at this time (see Gordon *et al.*, 1980) as well as what is known from previous studies, these values are considered realistic.

The image (Figure 1) shows a wide variety of mesoscale features, however, the reader is asked to concentrate on the general pattern of chlorophyll for the entire region -- that is the shape of this pattern. Note that the chlorophyll front on the Western side of Florida is much broader than the front on the Atlantic side. The differences in physical dimensions of these fronts correspond to the physical dimensions of the continental shelves on either side of the Florida Peninsula. In case of the West Coast Shelf, the distance from shore to the two hundred meter isobath is over three hundred kilometers at latitude 26°N. On the East Coast, at the same latitude, the shelf width is only a few kilometers but broadens moving northward towards Cape Hatteras.

In Figure 3, I have outlined the three major frontal boundaries for chlorophyll which outline the general sequence of decreasing chlorophyll moving seaward from land. 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 front appears as a boundary which distinguishes oligotrophic waters from slope waters.

With the exception of the Northern area of the Gulf of Mexico, all of the fronts outlined lie within the 200 meter isobath and probably between the 50-100 meter isobath. Lacking other geophysical information immediately 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 existing on the straits 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 (Figure 4) which parallels the Florida escarpment along the west coast shelf. In this case the sea level surfaces slopes about 50 centimeters from the ridge to the edge of the escarpment at the 1000 meter isobath. Niiler's (1976) data, a transhelf section at latitude 26°N, shows isopycnal surfaces inclining at a constant slope onto the shelf until the 200 meter isobath - at this point the isopycnals are markedly inclined vertically. This inclination extends beyond the 100 meter isobath. Using the image and bathymetric charts, the positions of the most seaward fronts on either coast begin around the 100 meter isobath inside the 200 meter isobath and increase in density of color to the 50 meter isobath. Proceeding toward the shore, chlorophyll-color increases, but at a reduced rate.

Relationship between surface temperature and water color.

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

On orbit 1965, March 15, 1979, water color and temperature were imaged over the Western Gulf of Mexico. At the time, the atmosphere was very clear. Shown in Figure 5 the upper image is uncorrected for atmospheric effects in the total upwelled radiance seen by channel #1 (443 nm), CZCS. The lower half of this image is the thermal presentation by channel #6, CZCS.

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 (Figure 5, lower), equatorial water exiting from the Straits 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 Mauls "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: water temperatures colder than equatorial temperatures are not observed until the shelf widens north of Palm Beach. At this point the thermal front closely reflects shelf dimensions.

Examination of corresponding color distribution shows that on the Eastern Coast, color and temperature patterns are nearly identical and representing an abrupt transition between phytoplankton poor and rich waters associated with the cold wall of the Gulf Stream (Yentsch, 1974). The color image for the Western Gulf of Mexico can be viewed as a large mass of chlorophyll poor water which extends as far as latitude 30°N. However, in the region at the western shelf escarpment, where the loop current is impinging, the water masses are rich in chlorophyll (reduced radiance at 443 nm, channel #1, CZCS). The chlorophyll rich water covers the entire shelf extending south paralleling the escarpment. Therefore, the higher chlorophyll along this escarpment is associated with the southerly high velocity transport of the current loop.

Synopticity and the conservative nature of ocean color.

The first question posed in the introduction concerns the possibility of resolving the effects of large scale ocean currents on the spatial distribution of phytoplankton chlorophyll using satellite CZCS imagery. In my opinion, the colorimetry shown by the images presented in this paper are testimony needed to demonstrate that color features like those previously shown by remotely-sensed surface temperature are easily resolved and are the dominant features of global patterns of phytoplankton. The introduction also questioned the validity of past sampling technique: Has shipboard coverage been adequate? Some caution should be used in answering, as only a limited number of CZCS images are available. From what we now know, I would answer yes. For the most part sea sampling has delineated these regions and the general pattern of "ocean richness" has been adequately described. If this is indeed true, what then is the expected contributions of satellite imagery at this spatial scale?

The study of the interaction of global primary production with global climate on seasonal time periods and those of decades, is of extensive interest to those interested with heat and carbon dioxide flux and other climatic processes. These studies are possible using satellite systems.

My particular interest concerns a global assessment of the amount of vertical mixing which is the principle fluid process driving productivity. It should be recognized that geostrophic theory, if fully operational, does not support the idea of isopycnal mixing: by theory a balance should exist between the pressure gradient and the Coriolis force. Therefore, "baroclinic chlorophyll patterns" are interpreted as representing the result 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 at continental margins which strongly influences the Coriolis parameter. This situation is analogous to conditions where fronts are formed due to the destratification of water masses by tidal currents. Although, in the case of tidal fronts, the density surface can be completely turned over and the mixing energy source is different, both cases derive vertical mixing from bottom friction which, in turn, stimulates phytoplankton production.

SUMMARY

The sequence and magnitude of vertical covering spatial scales from ocean gyres and current to tidal mixing, suggests to me that the spatial patterns of phytoplankton one observes are the result of change in the degree of vertical mixing-horizontal transport, as a mechanism for passive distribution, is 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, R in the equation. This idea originally introduced by Harvey and Fleming many years ago, if true, means that chlorophyll patterns are reflecting population kinetics. To the biologist, this means growth; to the physicist, patterns are reflecting the buoyancy forces in the water masses. Thus, it is postulated that it is the kinetic nature of phytoplankton steady-state growth that allows many of the fluid features of the ocean to be outlined by color which can be used as a conservative tracer.

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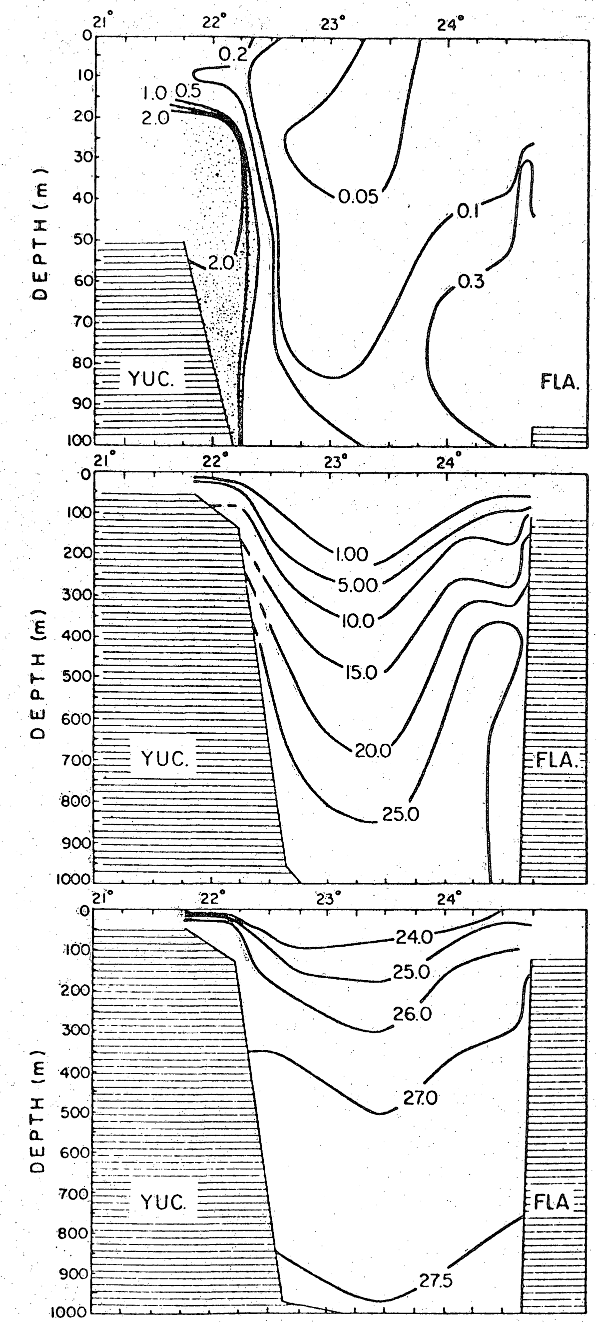

Figure 1. Chlorophyll (top), nitrate (middle), density (bottom), and distribution between Yucatan, Mexico and Dry Tortugas off Florida.

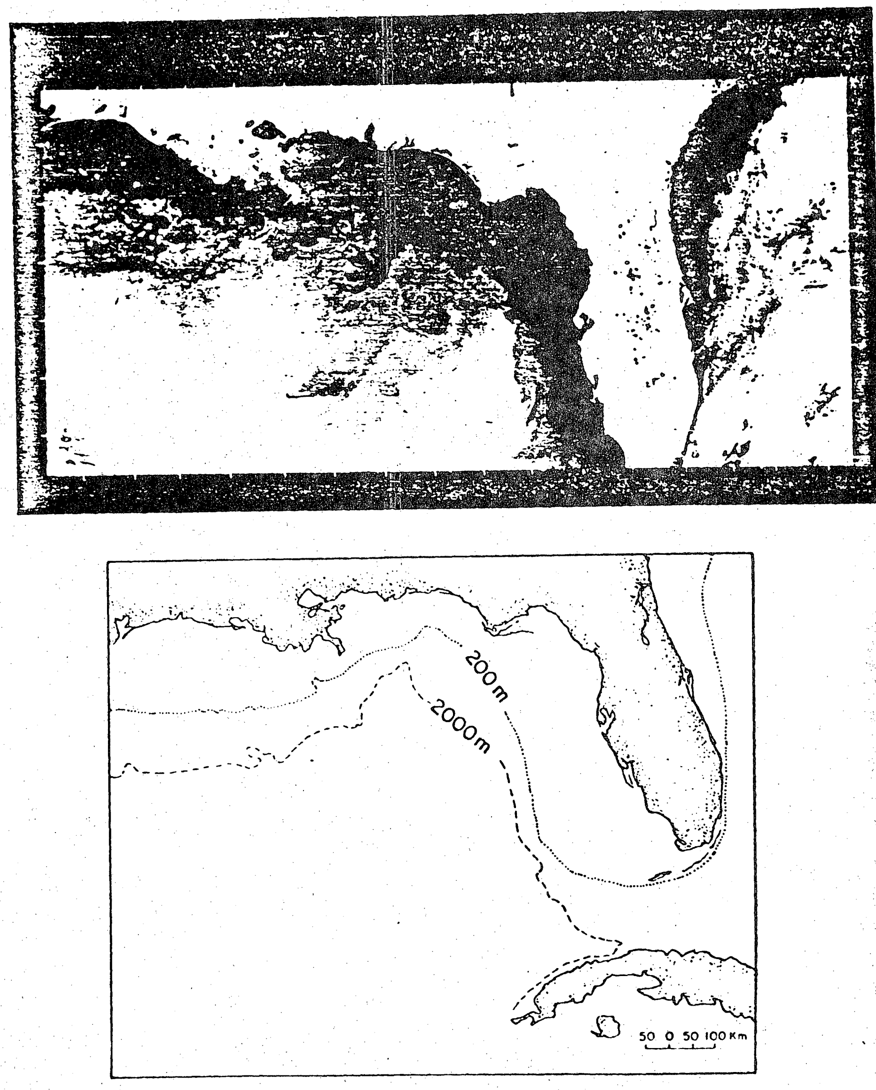

Figure 2. (Upper) Chlorophyll as viewed by Nimbus 7 (CZCS) orbit 130, November 2, 1980. Lower shows major bathymetric outline in the region.

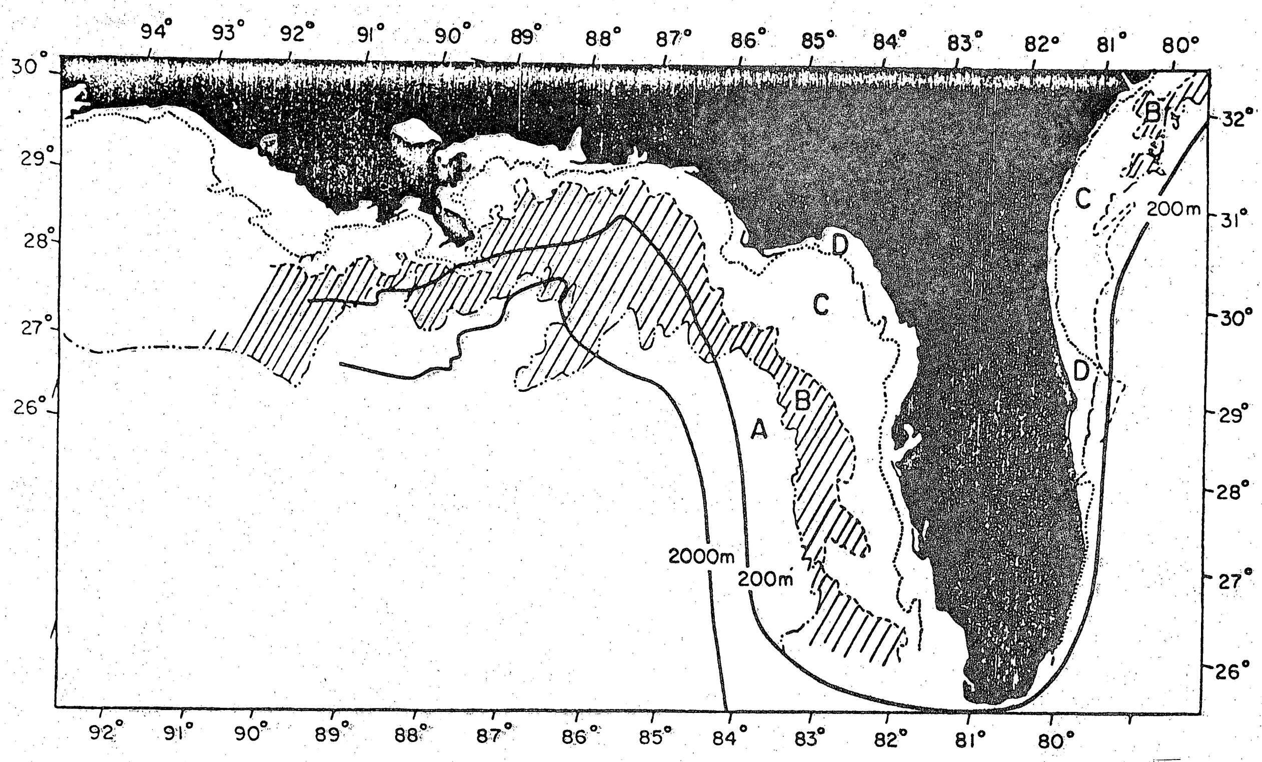

Figure 3. Positions of fronts A, B, C and D, taken from orbit 130.

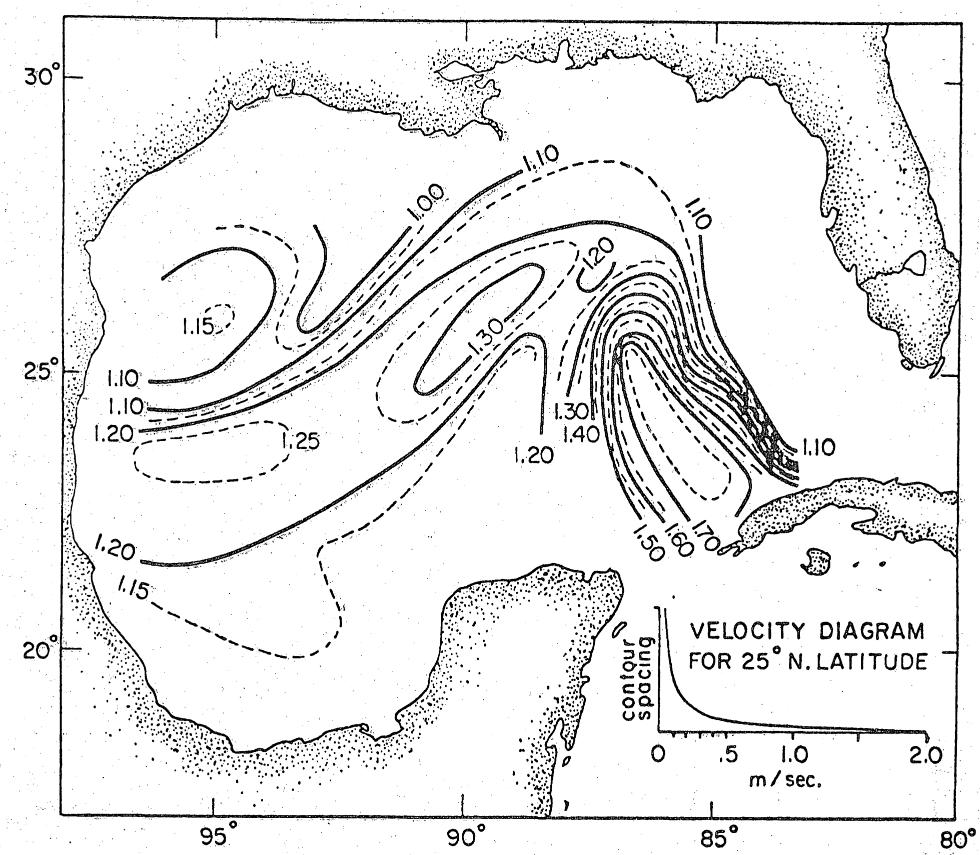

Figure 4. Dynamic topography of the region from Nowlin and McLellan (1967).

Figure 5. Orbit 1965, March 15, 1979. Nimbus 7 CZCS channel # 1 (upper). Light tone denotes high attenuation of blue (443 nM) lightly due to phytoplankton chlorophyll. Lower-sea surface temperature -- dark tone, cold water.