

REMOTE SENSING OF OCEAN COLOR AND
DETECTION OF CHLOROPHYLL CONTENT

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ABSTRACT

The chlorophyll enrichment of the water in an equatorial upwelling was surveyed and described during two one month periods in 1975 and 1976 with the aid of a radiometer specially designed for the airborne measurement of ocean color. Based upon the results of this experiment and some theoretical considerations, a relation is proposed between airborne measurement of difference of albedos at two wavelengths in the blue and green, and the concentration of chlorophyll in the ocean.

1. INTRODUCTION

It has for many years been known that ocean color, or more exactly the radiation backscattered by seawater in the visible spectrum, is linked to chlorophyll pigment content, and that this can be employed in the remote sensing of chlorophyll concentration. YENTSCH (1960) measured the absorption coefficients of chlorophyll-a extracted from marine plants and showed that the presence of chlorophyll deplaces the sea water transparency maximum from blue towards green. He suggested that the color of the ocean is closely related to the chlorophyll content. CLARKE, EWING and LORENZEN (1970) performed experiments using this remote sensing method by making airborne measurements of the light spectra backscattered by the ocean. Numerous airborne experiments have since been made, all of which have been based upon a measurement in the blue at the chlorophyll absorption maximum (BAILEY and WHITE (1970), HOVIS, FORMAN and BLAINE (1973), AVERSEN, MILLARD and WEAVER (1973), PEARCY and KEENE (1974). Although easy in the principle, this remote sensing method poses several problems of a practical nature, and in the interpretation of results which are perturbed by other parameters inherent to radiative transfer in the atmosphere-ocean system and to the optical properties of sea water.

The results here presented are founded upon the above principle, but the method employs the calculation of differences between albedos measured at several wavelengths. This permits the measurement of ocean color, and thus determination of chlorophyll content independent of measurement conditions and, moreover, independent of the cloud cover under which the aircraft flew. This result is of particular interest for potential applications in equatorial regions where nebulosity is considerable and very variable. It was in this manner that the chlorophyll enrichment of waters from an equatorial upwelling could daily be observed and described during two one month periods in 1975 and 1976 on a quasi operational basis.

2. MATERIAL AND METHODS

The method is based upon the measurement of the spectral albedo of the sea with a four channel radiometer which simultaneously measures radiation upwelling from the sea and the downwelling radiation. The radiometer is equipped with interference filters having a narrow bandwidth ($\Delta\lambda = 10$ nm) and measures the up-

welling irradiance E_u or radiance I_u , and the downwelling irradiance E_d at 466, 525, 550, 600 nm. The I_u measurement is made with a polarizer at an incidence of 45° , near the Brewster angle in order to minimize surface reflection. The ratio of the two measurements (E_u/E_d or $\pi I_u/E_d$) furnishes an albedo value for the ocean; the relative calibration of the upward and downward sensors is made by aiming them at a single diffuse surface. The reproducibility of the albedo measurements thus obtained was evaluated as $5 \cdot 10^{-4}$. This radiometer and an infrared radiometer measuring sea surface temperature, were borne by an aircraft flying at low altitude in order to minimize the influence of atmospheric scattering.

The exploitation of measurements made in the study area on the equator was particularly problematical due to the fact that in this region the nebulosity is extremely variable, and the sky is rarely perfectly clear. Under these conditions, the upwelling radiation is primarily a function of the incident irradiance. This is illustrated by Fig.1-a, in which is presented a recording of downwelling irradiance, E_d , and of upwelling radiance, I_u , at 466 nm, which was made during the flight of July 13, 1975. As the cloud cover in this case varied from 10% to 50%, the I_u variations are essentially due to changes in E_d . In order to obtain a measurement independent of E_d variations, albedo A is calculated:

$$A = \frac{\pi I_u}{E_d}$$

Albedo thus calculated contains both the term due to backscattering from the sea water, which is affected by the presence of chlorophyll and which has thus to be measured, and the term associated with the sea surface reflection of downwelling radiation, which is a source of error. The nature of this reflection changes when one passes from a clear sky to a cloudy sky, where downwelling radiation becomes more diffuse. The method sometimes suggested (e.g., by HOVIS, FORMAN and BLAINE, 1973) which consists of taking the ratio between upwelling radiances at two wavelengths is not applicable in this case because the measured values include an excessive term of error which is due to reflection in the presence of clouds.

A method using difference between albedos was developed in order to obtain a measurement which is as independent as possible of this reflection. This albedo difference method permits the elimination of most sources of error, such as surface reflection, which is independent of wavelength in the spectral bandwidth considered, and the effects of whitecaps and light scattering due to aerosols, which vary slowly in function of wavelength. In Fig. 1-b, the radiance ratio method is compared with the albedo difference method at 466 and 525 nm. Although the general allure is similar, with a minimum at point B (near 10h00), it is noted that the radiance ratio is much more noisy, particularly in the period between 9h40 and 9h50 during which the cloud cover and downwelling radiation E_d (Fig.1.a) were highly variable. The measurement of I_u with a polarizer greatly diminishes the effect of reflection. Reflection on the sea surface is somewhat diffuse due to the sea state however, and part of this radiation still comes from reflection. This effect is particularly evident for the diffuse radiation corresponding to an overcast sky. It thus can be concluded that the albedo difference method is much less affected by measurement conditions than is the radiance ratio method.

In Fig.1.c, are found the albedo differences $A_{466} - A_{525}$ and $A_{550} - A_{600}$, and sea surface temperature (Fig.1.d) recorded for the same period as referred to in the preceding paragraph. The elimination of variations in downwelling radiation allows albedo difference variations associated uniquely with the internal optical properties of the ocean to appear. The "blue-green" $A_{466} - A_{525}$ difference diminishes when the thermal front is traversed, and is nul at the minimum temperature near point B, indicating that the colder waters are green and chlorophyll rich. The $A_{550} - A_{600}$ difference increases at the same time, indicating greater turbidity which is associated with chlorophyll. Variations in these albedo differences are associated with variations in the optical properties of sea water.

3. MEASUREMENT INTERPRETATION

A theoretical model was constructed in order to correlate albedo differences to contents in absorbing matter (chlorophyll-a) and scattering matter (sediments). The model was verified by comparison with several samples taken in-situ by boat.

3.1 - The theoretical model.

The medium of the model is assumed homogeneous, and optical properties adopted for the constituents of this medium are the results of previous measurements. Optical properties are defined by

a , the absorption coefficient (m^{-1}),
 b , the scattering coefficient (m^{-1}),
 $p(\theta)$, the scattering phase function which represents the light fraction deviated at the angle θ .

The principal terms contributing to coefficients a and b are described in tables 1 and 2, and it is possible to write

$$a = a_o + n_{chl} \cdot a_{chl} + a_y \quad (1)$$

where a_o is absorption by pure water,
 n_{chl} , chlorophyll concentration (mg/m^3)
 a_{chl} , absorption by chlorophyll (for $1 mg/m^3$),
 a_y , additional absorption by yellow substance if present,

and :

$$b = b_o + b_p \quad (2)$$

where b_o is scattering by pure water,
 b_p , scattering by particulate matter.

The numerical values of b_o , a_o and a_{chl} which are need in the model are found in table 3. The coefficients b_p and a_y are defined by their values at 500 nm, and are λ^{-1} and $\exp(-k\lambda)$ dependent

$$b_p(\lambda) = b_p(500) \frac{500}{\lambda} \quad (3)$$

$$a_y(\lambda) = a_y(500) \exp\{0,014(500-\lambda)\} \quad (4)$$

with λ is nm. The phase function can be developed as follows

$$p(\theta) = \frac{b_o p_o(\theta) + b_p p_p(\theta)}{b_o + b_p} \quad (5)$$

where $p_o(\theta)$ is relative to molecular scattering, and $p_p(\theta)$ is relative to particle scattering. In that which follows, phase functions $p_o(\theta)$ and $p_p(\theta)$ are from MOREL (1973), and their respective weights are varied by way of b_p . All of the above data are introduced into the theoretical model.

The theoretical computation of backscattered albedo necessitated the solution of the radiative transfer equation for an absorbing and scattering medium. Several computation methods can be used, and have been compared by DEVAUX, FOUQUART, HERMAN and LENOBLE (1973). Examples of the application of the theoretical computations to the ocean have been given by KATTAWAR and HUMPHREYS (1976), GORDON and BROWN (1973), and PRIEUR (1976). Computations based upon the successive scattering order method are developed in this paper.

In this computation, an expansion of the radiance in a Fourier series in azimuth is obtained by representing phase function as an expansion in Legendre polynomials. Computation time is reduced by the use of the so-called "trun-

cation of the forward peak" approximation, which permits the reduction of terms entering into the development of the phase function to 28. The accuracy obtained by this method should be excellent (2%), but the results for backscattered albedo, A, can be expressed by the following simplified formula whose lower 10% precision is acceptable due to a similar imprecision in the absorption and scattering data

$$A = m \frac{b_0}{a} + n \frac{b_p}{a} \quad (6)$$

where constants m and n are determined from the computations as

$$m = 7.55 \cdot 10^{-2}$$

$$n = 0.23 \cdot 10^{-2}$$

Computations demonstrate that A is only weakly influenced by the geometrical repartition of the incident radiation. This equation permits the direct relation of measurement of A to the internal optical properties of the ocean.

By introducing Eq. 1,2,3 and 4 into Eq.6, the influence of each factor can easily be evaluated at any wavelength. It again is found that chlorophyll is the main cause of albedo variation near 450 nm, while the turbidity characterized by b_p has a maximal influence near 550 nm. All of the parameters considered, however, including the absorption by yellow substance a_y , have an influence upon the measurements at different wavelengths, and a method permitting the separate evaluation of each of each parameters is called for.

3.2. - Measurement of the turbidity coefficient b_p .

Between 525 and 650 nm, outside of the chlorophyll absorption band, the albedo is primarily sensitive to the coefficient b_p . This is shown in figure 2, where the albedo difference $A_{550} - A_{600}$ is plotted as a function of $b_p(500)$ with the aid of Eq.1,2,3,4 and the data found in table 3. The measurement of $A_{550} - A_{600}$ thus constitutes a method of b_p determination, but it must be noted that the presence of yellow substance (or an other absorber) can modify the anticipated results.

Experimentally, an increase of $A_{550} - A_{600}$ was regularly observed while flying over zones rich in phytoplankton. A slight increase of $A_{550} - A_{600}$ thus is observed in Fig.1.c at 9H55. Although variations of $A_{550} - A_{600}$ are often, as in this case, at the limit of experimental sensitivity, it nevertheless was possible to map this difference. Maps of the two albedo differences, $A_{550} - A_{600}$ and $A_{466} - A_{525}$, have the same general features, demonstrating the close relationship between turbidity and chlorophyll content.

3.3. - Determination of chlorophyll content.

Knowing b_p , it is possible to evaluate the correction which should be applied to the chlorophyll content deduced from measurements in the blue region. It was demonstrated how the measurement of two differences ($A_{466} - A_{525}$ and $A_{550} - A_{600}$), permits an independent determination of b_p and n_{chl} (chlorophyll concentration) (VIOLLIER, DESCHAMPS and LECOMTE, 1977). As it is evident that these two coefficients are dependent, however, it is probably possible to directly deduce chlorophyll concentration uniquely from the $A_{466} - A_{525}$ difference. This more practical method was used in this paper, but is presupposes that a mean relationship between b_p and n_{chl} be known for the study area.

The relationship between b_p and n_{chl} is not well known, and probably depends upon the type of phytoplankton encountered. Lacking better knowledge of this subject, the following relation is assumed

$$b_p = 0.05 + 0.5 \cdot n_{chl} \quad (7)$$

(b_p in m^{-1} , n_{chl} in mg/m^3)

The values of the coefficients are based upon the observed extreme values of b_p and n_{chl} in the study area :

$$b_p \text{ from } 0.05 \text{ to } 0.6 \text{ m}^{-1}, \quad n_{chl} \text{ from } 0 \text{ to } 1 \text{ mg/m}^3.$$

This relation may be associated with Eq.1,2,3,4 and 6. The two curves found in Fig.3, which in one case corresponds to the absence of yellow substance, and in the other to a high yellow substance content, give the obtained relation between the albedo difference $A_{466} - A_{525}$ and chlorophyll content n_{chl} .

In Fig.3, there is also presented an experimental relation (curve 3) established upon the basis of four in-situ measurements made by R.V. CAPRICORNE. Chlorophyll content measurements made between 0 and 20 meters are found in table 4. Chlorophyll content values which vary with depth can not be directly compared with the theoretical values of a homogeneous model. In order to make the comparison, the content value at a given depth was therefore weighted by a coefficient equal to the transmission of light to twice that depth. The results of this weighting were placed in Fig.3 as a function of simultaneous airborne measurement of $A_{466} - A_{525}$. It is noted that the experimental curve (3) is in fairly good agreement with that inferred from the theoretical model, although the theoretical curve (1) clearly overestimates the chlorophyll concentration. This difference could derive from one of the numerous approximations introduced into the theoretical model (that furnished by Eq.7, for example) or due to yellow substance. This result demonstrates that the improvement of this method would require the taking of a few sea truth measurements during the aerial survey, in order to adjust the relationship between albedo difference and chlorophyll content.

4. RESULTS OF THE AIRBORNE MEASUREMENT SURVEYS.

Two airborne remote sensing surveys of chlorophyll content, totaling more than thirty flights, were made during June-July of 1975 and 1976 off shore Gabon (Central West Africa) in the Gulf of Guinea. The study area is situated on the equator, between Sao Tomé Island and Cape Lopez. During the June-July study period, the hydrological conditions favor the development of coastal upwellings (DUFOUR and STRETTA, 1973 ; VOITURIEZ, VERSTRAETE and LE BORGNE, 1973 ; HISARD and MARLIERE, 1973).

The cold upwelled water ($< 23^{\circ}\text{C}$) from the south encounters the warm water ($> 25^{\circ}$) of the Guinea Current coming down from the north, and this provokes a fairly clearcut thermal front with a surface temperature difference on the order of 2°C within several nautical miles. The movements of this front can easily be watched by airborne sensing methods (STRETTA, NOEL, and VERCESI, 1975). When the upwelling starts, the cold water invades the whole sector, starting from Cape Lopez and propagating to the north. The warm water returns a few days later by moving towards the south. Several cycles of north-south oscillations of the surface thermal front are observed, and the study area between Cape Lopez and Sao Tomé Island accordingly passes through a series of warm and cold phases.

After each flight, the measurements are used in the drawing of maps of surface temperature and albedo difference. The daily flight plan is formulated as a function of previous maps so as to cross the thermal front several times.

The appearing of cold waters rich in mineral salts is translated as phytoplankton development and a greener ocean color. This corresponds to the extreme $A_{466} - A_{525}$ measurement values which pass from $120 \cdot 10^{-4}$ for warm, chlorophyll poor water (less than 0.3 mg/m^3), to $-30 \cdot 10^{-4}$ for cold, chlorophyll rich water (about 1 mg/m^3). Coastal waters are much richer, particularly near the estuaries of the Ogooué and Gabon rivers.

In Fig. 4a,b,c, are found three of the maps obtained in 1975 for three typical flights :

- July 6, 1975, corresponds to the maximal northerly development of a cold phase with a well defined thermal front forming an arc between Cape Lopez and Sao Tomé Island.
- July 11, 1975, corresponds to a warm phase subsequent to invasion of the whole area.
- July 13, 1975, at the beginning of a new cold phase.

The temperature and chlorophyll content deduced from $A_{466} - A_{525}$ (from curve (1) in Fig.3) at the point most frequently flown over ($0^{\circ}30'S$, $8^{\circ}E$), were selected in order to describe the succession of warm and cold phases. This point is situated 40 nautical miles from the coast, and is only very slightly influenced by the Ogooué river effluent.

In 1975 (Fig.5.a) there thus are successively observed :

- a warm phase until July 2,
- cold phase from July 3 to 8,
- a warm phase from July 9 to 12,
- a cold phase starting July 13.

In 1976 (Fig.5.b), the most pronounced phases are :

- warm phases from June 20 to 26, and from July 6 to 11,
- cold phases from June 27 to July 4, and starting July 12.

The chronology of the observations thus shows a good local correlation between chlorophyll content and sea surface temperature at the point considered. Maximal concentrations are obtained during cold phases and attain 1 mg/m^3 . The evolution of chlorophyll content seems to be about one day late with respect to changes in surface temperature, which may be interpreted as the time needed for phytoplankton growth. In 1976, cold phase temperatures were lower and chlorophyll concentrations were higher than in 1975.

5. CONCLUSION.

The albedo difference method developed for the remote sensing of ocean color and the measurement of chlorophyll content has shown itself to be particularly useful in the making of airborne measurements under cloudy skies, which permits the technique to enter into operational service. Although chlorophyll content values measured with method generally run parallel to the in situ values, they must be used with precaution due to the incertitude existing in the relationship between the optical properties of sea water and the chlorophyll content. Results obtained from two airborne survey campaigns observing an equatorial upwelling off the Gabon coast demonstrate the potential use of this remote sensing technique in the spatial and temporal study of the phenomenon.

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TABLE 1. - ABSORPTION CHARACTERISTICS

| | Substances absorbing light | λ -dependence (wavelength = λ) | References |
|-----------|---|---|--|
| a_o | sea water | window of maximum transmission at 450 nm | Clarkes et James (1939) Prieur (1976) |
| a_y | dissolved material (yellow substance) | increase towards short λ $a_y(\lambda) = a_y(\lambda_1)e^{0,014(\lambda_1 - \lambda)}$ (λ in nm) | Jerlov (1968) Prieur (1976) |
| a_{chl} | chlorophyll a (pigment in particulate matter) | absorption band around 440 nm and 675 nm | Yentsch (1960) |
| a_p | other absorbed in particulate matter | variable, assumed nul in this study. | |

TABLE 2. - SCATTERING CHARACTERISTICS.

| | Substances absorbing light | λ -dependance (wavelength = λ) | References |
|-------|----------------------------|--|--------------|
| b_o | sea water | $\lambda^{-4,3}$ | Morel (1973) |
| b_p | particulate matter | λ^{-1} (law assumed for the purposes of this study) | |

TABLE 3. - NUMERICAL VALUES OF OPTICAL COEFFICIENTS INTRODUCED IN THE THEORETICAL MODEL.

| λ (nm) | 466 | 525 | 550 | 600 | References |
|------------------------|--------|--------|--------|--------|----------------|
| b_o (m^{-1}) | 0,0039 | 0,0023 | 0,0019 | 0,0014 | Morel (1973) |
| a_o (m^{-1}) | 0,0155 | 0,050 | 0,068 | 0,245 | Prieur (1976) |
| a_{chl} (m^{-1}) | 0,065 | 0,01 | 0,006 | 0,007 | Yentsch (1960) |

TABLE 4. - IN SITU MEASUREMENTS MADE BY R/V CAPRICORNE.

| Date | location | Chlorophyll content (mg/m^3) | | | | | Aerial Measurement of $A_{466} - A_{525}$ | |
|---------|------------|----------------------------------|------|------|------|------|---|--------------|
| | | depth | 0 m | 5 m | 10 m | 15 m | | 20 m |
| 20.6.76 | 1°S 7°30 E | | 0,20 | 0,19 | 0,19 | 0,48 | 1,41 | 38.10^{-4} |
| 21.6.76 | 0° 8° E | | 0,18 | 0,18 | 0,25 | 0,15 | 2,15 | 57.10^{-4} |
| 22.6.76 | 1°S 7°30 E | | 0,11 | 0,07 | 0,11 | 0,58 | 0,87 | 74.10^{-4} |
| 13.7.76 | 1°S 8°23 E | | 0,55 | 0,73 | 0,64 | 0,31 | 0,33 | 21.10^{-4} |

(the time intervals between the "in situ" and aerial measurements are of less than 4 hours).

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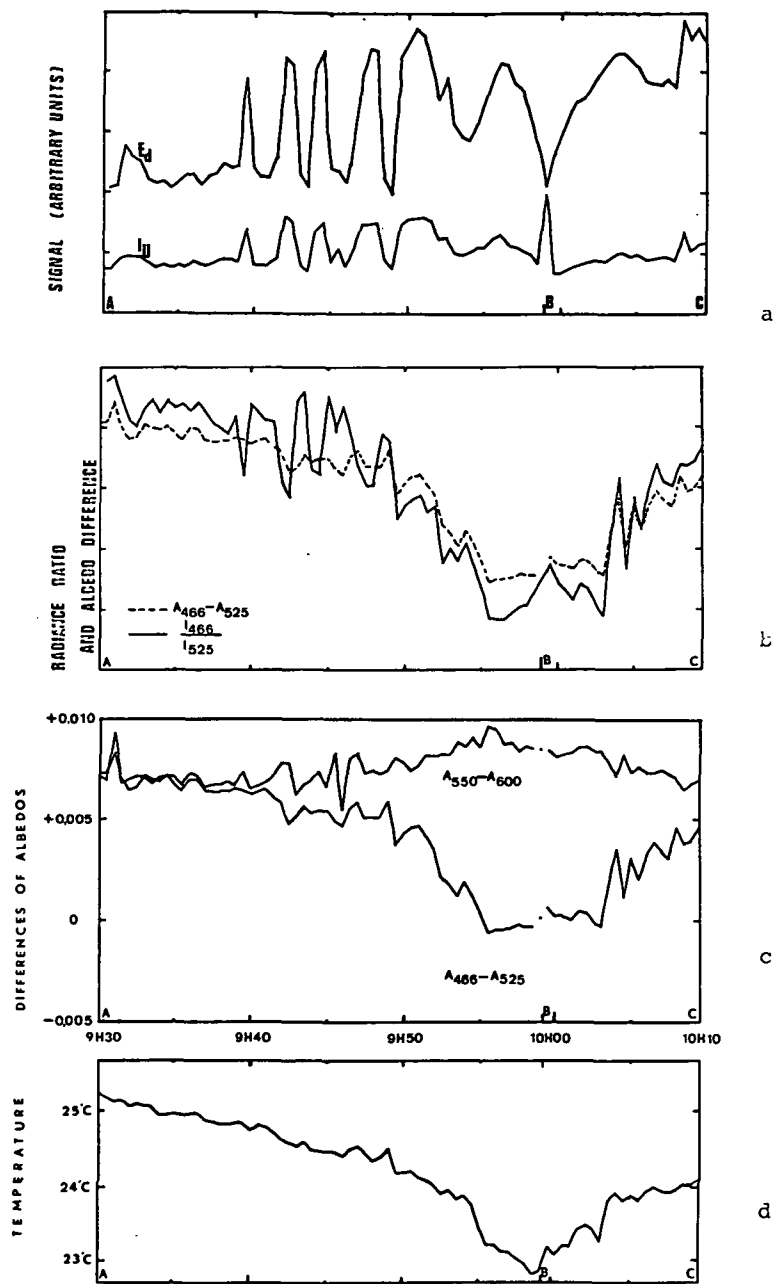


FIGURE 1. - FLIGHT RECORD 0930 to 1010 a.m., July 13, 1975

- a) Downwelling irradiance, E_d , and upwelling radiance I_u , at 466 nm.
- b) Comparison between ratio and difference methods at 466 nm and 525 nm.
- c) The two albedo differences $A_{466} - A_{525}$ and $A_{550} - A_{600}$.
- d) Sea surface temperature.

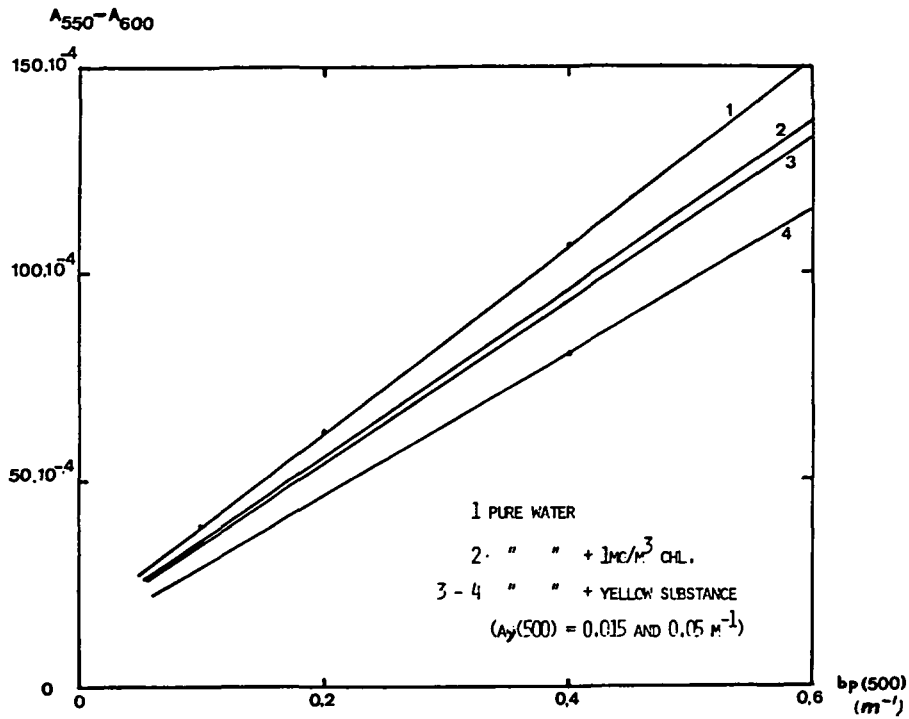


FIGURE 2. - Theoretical computation of the albedo difference $A_{550} - A_{600}$ as a function of the scattering parameter $b_p(500)$.

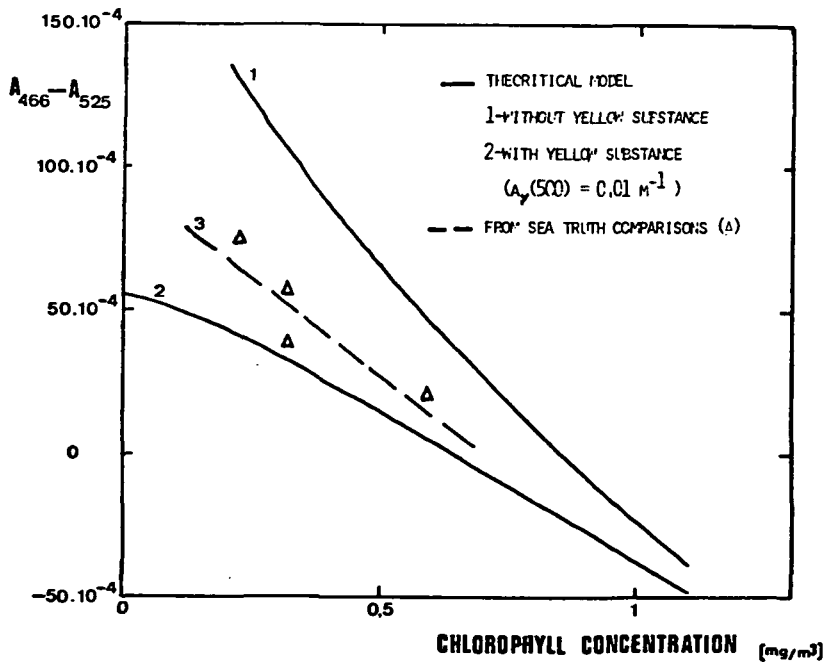


FIGURE 3. - Theoretical computation of the albedo difference $A_{466} - A_{525}$ as a function of chlorophyll concentration. Obtained sea truth comparisons are plotted by Δ .

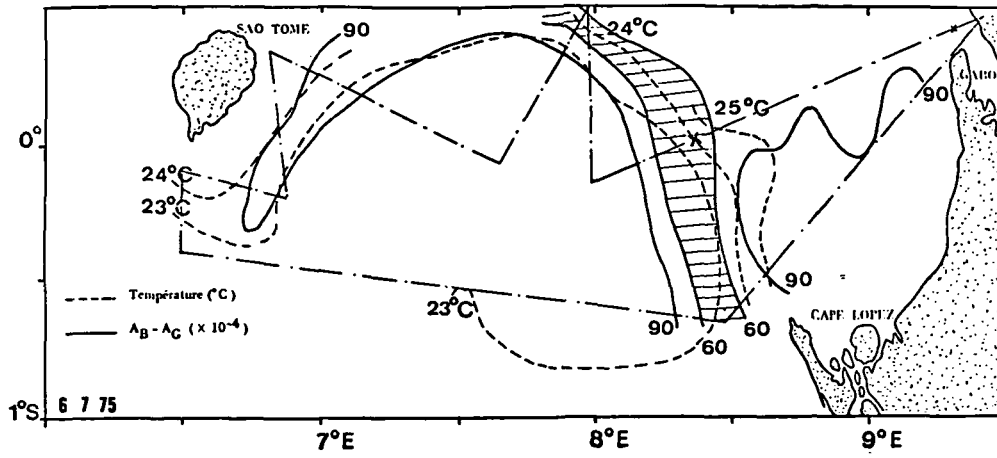


FIGURE 4.a.

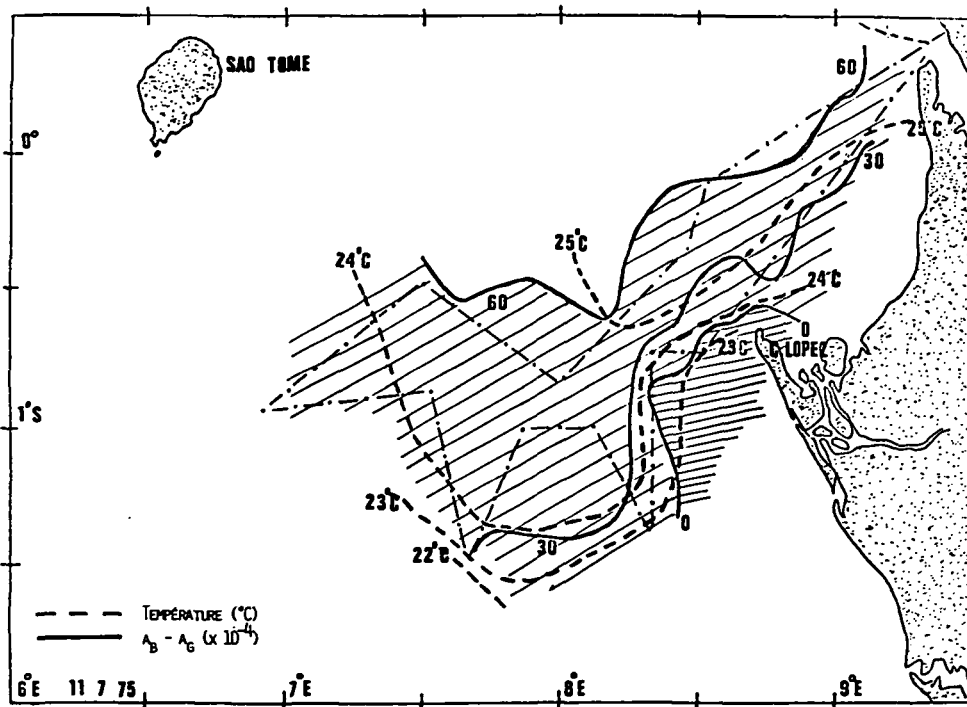


FIGURE 4.b.

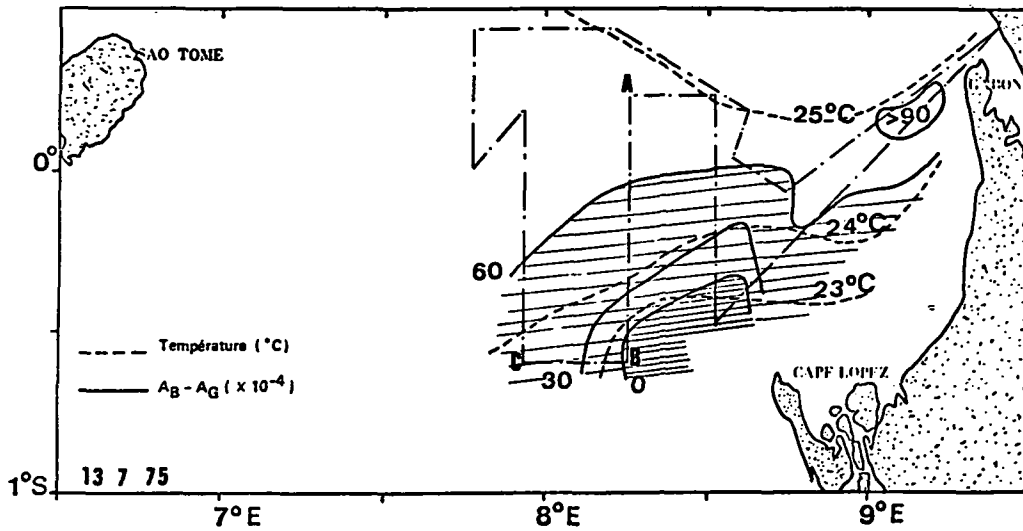


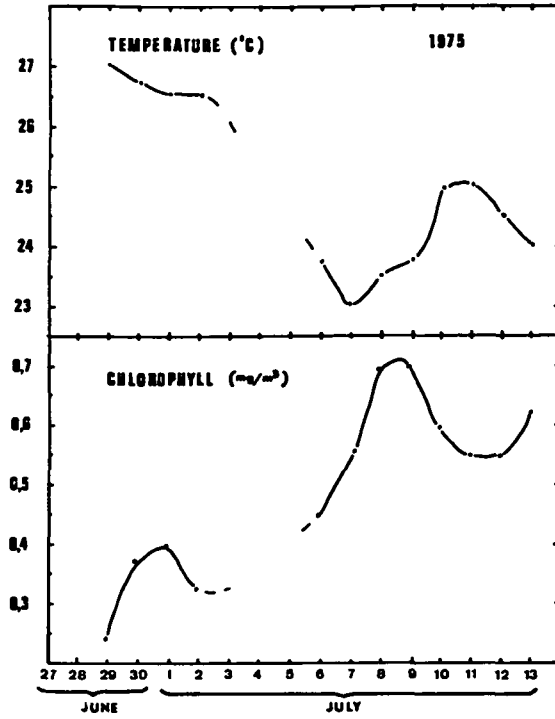
FIGURE 4.c.

FIGURE 4. - Sea surface isotherms and distribution of differences between blue and green albedos. Waters of moderate chlorophyll content ($0 < A_B < A_G < 60 \cdot 10^{-4}$) and of greater chlorophyll content ($A_B - A_G < 0$) are respectively the light and heavy shaded areas. Flight track is the dot dashed line.

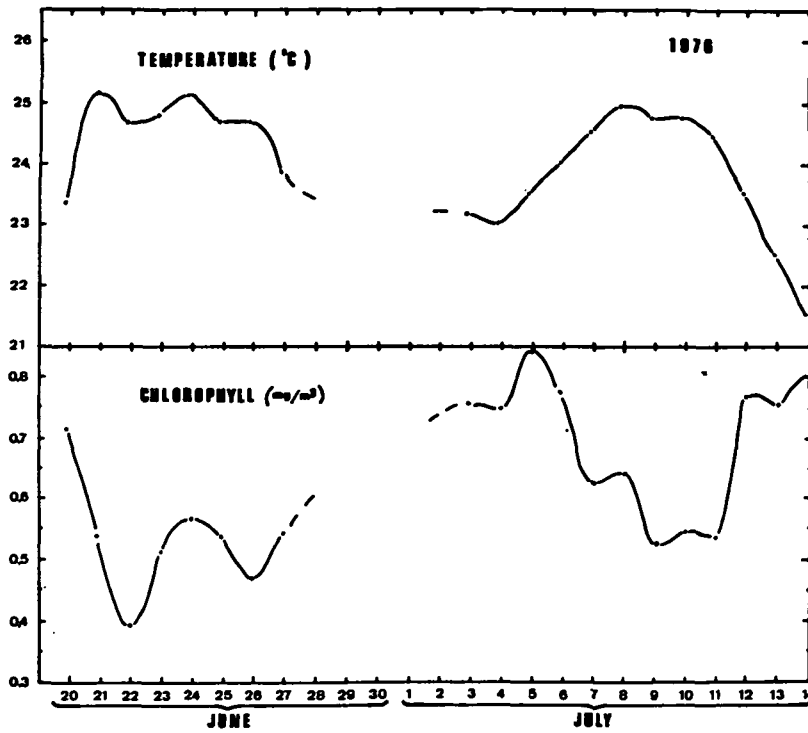
4.a. July 6, 1975

4.b. July 11, 1975

4.c. July 13, 1975



a



b

FIGURE 5. - Evolution of sea surface temperature and chlorophyll content as deduced from A_{466} - A_{525} , at point $0^{\circ}30'S$, $8^{\circ}E$ for June-July 1975, (a) and 1976, (b).