Airborne Remote Sensing of Chlorophyll Content Under Cloudy Sky as Applied to the Tropical Waters in the Gulf of Guinea

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A special radiometer has been constructed to perform aerial measurements of ocean color in order to obtain the chlorophyll content of ocean water This radiometer measures the spectral albedo at four wavelengths (466, 525, 550 and 600 nm) and was used during fourteen flights over the Gulf of Guinea in June and July of 1975. All measurements were performed from 150 m altitude The acquisition of measurements independent of cloud cover was made possible by the calculation of differences between albedos at different wavelengths Differences between albedos were mapped after each flight, and showed the detailed structure of a thermal front due to coastal upwellings. A theoretical interpretation, based on computations of radiative transfer in the ocean, shows that the difference of albedos at 466 and 525 nm is very sensitive to chlorophyll content, whereas the difference of albedos at 550 and 600 nm is sensitive to the presence of light scattering particles

Introduction

Many upwellings occur off West African Coasts. During June and July, a strong thermal front due to cold upwelled waters is established off Gabon, in the Gulf of Guinea, and particularly in the area near Cape Lopez (Dufour and Stretta, 1973; Voituriez, Verstraete and Le Borgne, 1973; Hisard and Morliere, 1973). Since 1972, aerial measurements of sea surface temperature by infrared radiometry have been made over this front by the "Laboratoire d'Optique Atmosphérique" jointly with an oceanographic research team of O.R.S.T.O.M. (Office de Recherche Scientifique et Technique d'Outre-Mer). The results demonstrated the value of remote sensing techniques for oceanography and fisheries (Stretta, Noël and Vercesi, 1975). In 1975, an instrument designed and developed by our laboratory was tested in order to determine chlorophyll content from measurements of "ocean color" in accordance with the method first suggested by Clarke, Ewing and Lorenzen (1970), and most recently discussed in a paper by McCluney (1976). The description of the coastal upwelling was improved by this new technique for the remote sensing of ocean color.

Tropical regions are very often cloudy, and this hinders the airborne measurement of water color even when flying below the clouds. Changes in cloudiness cause variations of the downwelling radiation on the ocean and also cause variations of the sea surface reflection. Another problem common to all chlorophyll remote sensing experiments is that the relationship between changes in the

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spectra of backscattered light from the ocean and changes in the phytoplankton population is not well established.

This paper deals with a method by which the problem of cloud cover can be resolved, and tries to make a contribution to the establishment of a relationship between backscattered light and chlorophyll content.

Method

A few authors have made airborne recordings of the spectra of upwelling radiation. Clarke, Ewing and Lorensen (1970), and Bailey and White (1970), demonstrated the influence of chlorophyll content and turbidity on the shape of spectra. Arvesen, Millard and Weaver (1973) made measurements at two wavelengths, 443 and 525 nm, and found a relation between the differential signal and the chlorophyll concentration. Pearcy and Keene (1974) used a multispectral scanner and computed the differences between the channels. From high altitude flights Hovis (1973) found a relation based on the ratio of the radiation at 443 nm and at 525 nm. From all these studies it can be noted that the chlorophyll concentration in the ocean is linked to the changes of the upwelling radiations at two wavelengths, one in the blue, and the other in the green.

All of these experiments were made under clear skies. When the sky is cloudy, the interpretation of measurements is much more complex. The intensity and the spectral distribution of the downwelling irradiance change very rapidly, as does the ratio between the radiation reflected by the sea surface and the backscattered radiation. A method in which ratios are made between the upwelling radiances at two wavelengths decreases the effects of the changes of the downwelling radiation, but not the effects of changes in surface reflection The changes in the spectral distribution of the downwelling radiation can also be taken into account by the measurement of albedo, which is the ratio between simultaneously measured upwelling and downwelling irradiances. With this method a term containing a variable error due to surface reflection once again subsists

The method proposed in this paper consists of low altitude measurements of the apparent albedos A of the sea surface at four wavelengths, in the blue A_B (466 nm), in the green A_G (525 nm), in the yellow A_Y (550 nm) and in the red A_R (600 nm), following which the differences between albedos are calculated. This method is of interest because the surface reflection is practically independent of wavelength and thus is eliminated. $A_B - A_G$ is mainly sensitive to the chlorophyll absorption of blue light As found in the previously mentioned studies, this difference is positive for low amounts and becomes negative for high amounts. $A_Y - A_R$ is a good index of turbidity, which influences $A_B - A_G$. In practice, the downwelling and upwelling irradiances $F_{\lambda d}$ and $F_{\lambda u}$ at the wavelength λ are measured, and ocean surface albedo A_λ is deduced as

$$A_\lambda = \frac{F_{\lambda u}}{F_{\lambda u}} .$$

The measurements of $F_{\lambda u}$ include the radiation backscattered by the water and all of the radiation reflected by the sea surface. The reflected irradiance is assumed to be about 2% of the downwelling radiation for clear sky and high sun, and 6% for cloudy sky (Payne, 1972). These values are equal to or greater than the values of the backscattered radiation. If the differences between albedos are calculated the error due to the reflection of sun radiation is minimized.

There is a second way in which the influence of the radiation reflected by the ocean surface can be notably minimized. Instead of measuring the upwelling irradiance, it is possible to measure the upwelling radiance $I_{\lambda u}$ in a direction which avoids the glitter due to direct sunlight reflection. The diffuse sky and cloud radiations reflected by the ocean surface can be further reduced by using a polarizing filter and viewing at the Brewster angle (about 45° from vertical). If $I_{\lambda u}$ is isotropic, backscattered albedo can be defined as:

$$A_\lambda = \frac{\pi I_\lambda}{F_{\lambda d}}.$$

This method is theoretically the better of the two, because the contribution of the backscattered radiation becomes proportionally greater as the amount of surface reflection is reduced. But, as the radiation backscattered by the ocean surface may be anisotropic, the angle between the sun and line of sight must not vary to a large extent if the results are to be reproducible. Another problem is that changes in the direction of the flight path make orientation of the radiometer away from sun glitter inconvenient. Although theoretically better, this method poses some practical problems.

We have tested both methods. Under cloudy sky, the interchanging of the measurement methods did not significantly influence the values of the differences between albedos, and results were not improved by radiance measurements.

Material and Examples of Measurements

The radiometer developed by our laboratory is shown in Fig. 1. Light collectors are connected to the instrument by optical fibers. For each channel, the upwelling and downwelling radiations are directed into same interference filters by two optical fibers. The half bandwidth of the filters is about 10 nm, and the peaks of transmission are located at 466, 525, 550 and 600 nm. Radiation is modulated at 20.88 Hz with a light chopper operated by a synchronous motor. An optical device including two lenses focuses the radiation on photodiodes, and the eight signals are finally amplified and demodulated. The time constant is of approximately one second. A data acquisition system allows one to obtain simultaneous values for the eight signals every thirty seconds on a printer and punched tape.

The relative sensitivity of upwelling and downwelling channels of identical wavelength were measured after each flight by orienting the two light collectors towards a sunlit teflon plate which served as a source of diffuse and isotropic light. This systematic calibration permitted us to obtain highly precise values of albedo.

The data of July 6 are here used as an example illustrating the interest of our measurement technique. For the first leg of this flight pattern, between points A and B on the map (Fig. 8), Fig. 2 shows the continuous record of downwelling irradiance F_{Bd} and upwelling radiance I_{Bu} at 466 nm. Large variations are mainly

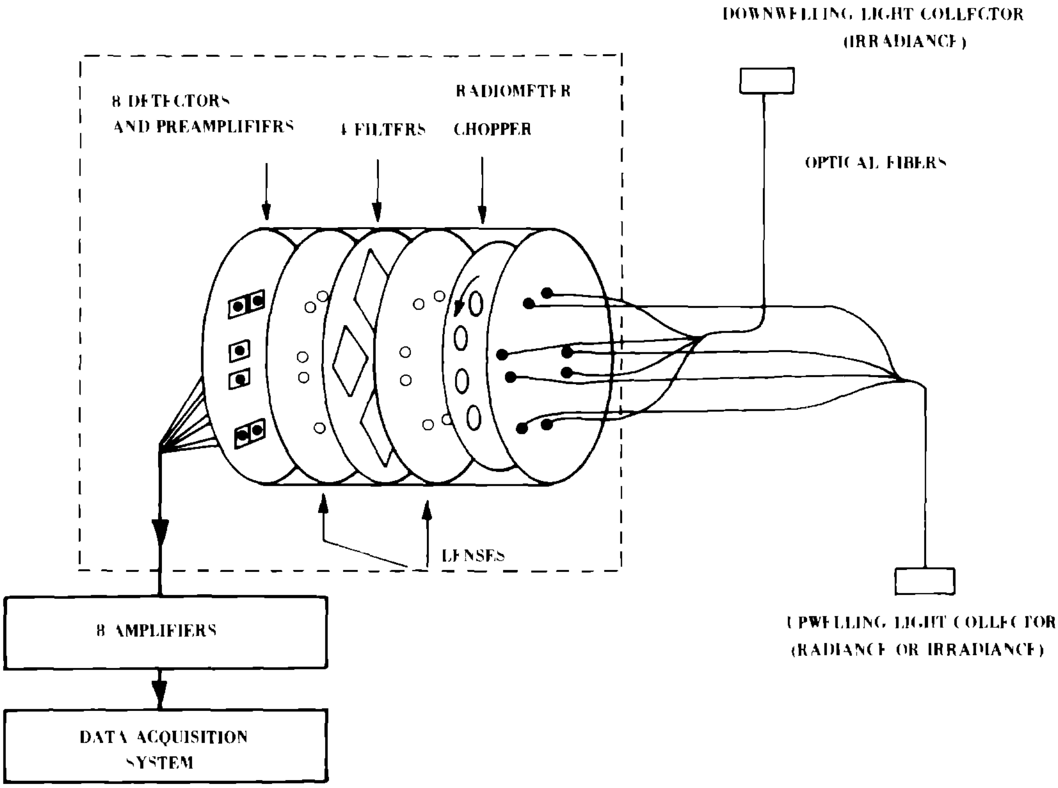

FIGURE 1 Radiometer description

due to variations in cloud cover (75% to 100%). Figure 3 shows the differences of albedos compared with the sea surface temperature obtained by a Barnes PRT 5 infrared radiometer. The strong variations (decreases of $A_B - A_G$ and $A_G - A_Y$, but increase of $A_Y - A_R$) are associated with the sudden change in temperature. It can be seen that the values of differences between albedos are independent of downwelling irradiance, and thus linked to ocean color, or more precisely to the backscattered albedo Albedo difference measurements were shown to be independent of cloud cover and sun elevation by the comparison of measurements made repeatedly over the same locations during several flights and under different conditions.

Theoretical Interpretation of the Backscattered Albedo

Backscattered albedo A is the ratio of backscattered irradiance to downwelling irradiance. It has recently been studied as a function of inherent optical properties and chlorophyll content, in particular by Ramsey (1968), Gordon and Brown (1973), Kattawar and Humphreys (1976) Prieur (1976), Jain and Miller (1976), and Viollier (1976). The comparison of the various results cannot be made immediately due to differences in the data used by these authors, in particular in the scattering phase function data. However, it seems that simple formulae allow the calculation of albedo with sufficient accuracy

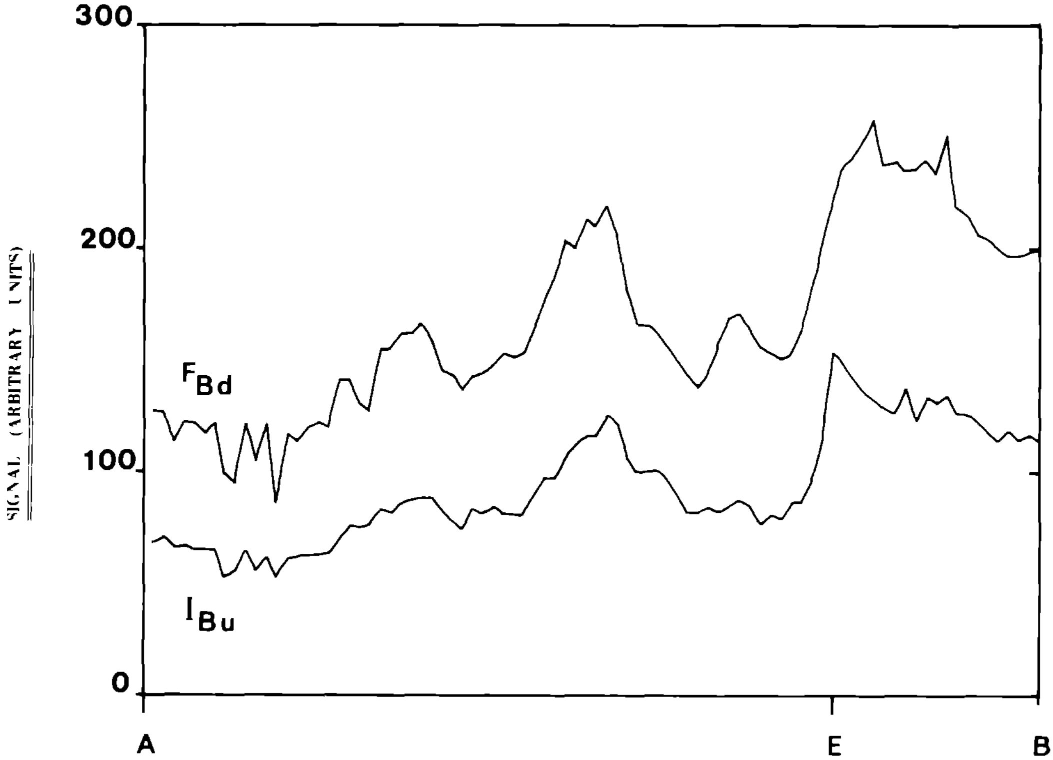

FIGURE 2. Records of downwelling irradiance (F_{Bd}) and upwelling radiance (I_{Bu}) at 466 nm between the points A and B of July 6 flight (see Fig 8). Flight track is the dot-dashed line.

The following formula was used for calculations which assume that the medium is homogeneous:

$$A = m\frac{b_o}{a} + n\frac{b_p}{a}, \qquad (1)$$

where $m = 7.55.10^{-2}$, and $n = 0.23.10^{-2}$, b_o is the molecular scattering coefficient, b_p is the particle scattering coefficient, a is the absorption coefficient.

This formula was adjusted by the values of m and n to the results of computations which Viollier (1976) made with the aid of successive orders of scattering method. The lower 10% accuracy of this approximation is acceptable due to a similar imprecision in the absorption (a) and scattering (b) input data. The albedo for single scattering, $\omega_o = (b_o + b_p)/(a + b_o + b_p)$, and the phase function $p(\theta)$ are the parameters of the computations. $p(\theta)$ represents the light fraction scattered at the angle θ. The phase function for pure water and typical phase function for suspended particles suggested by Morel (1973) are used. To get an expansion of the radiance in a Fourier series in azimuth, the phase function is represented by an expansion in Legendre polynomials. The so-called "truncation of the forward peak" approximation (Potter, 1970) reduces the number of terms used in the expansion to 28. Equation 1 was established for the sun at the zenith, but some tests have shown that it is also valid for sun elevations greater than about 30°, and for an isotropic sky radiance (uniform cloud cover). This independence of

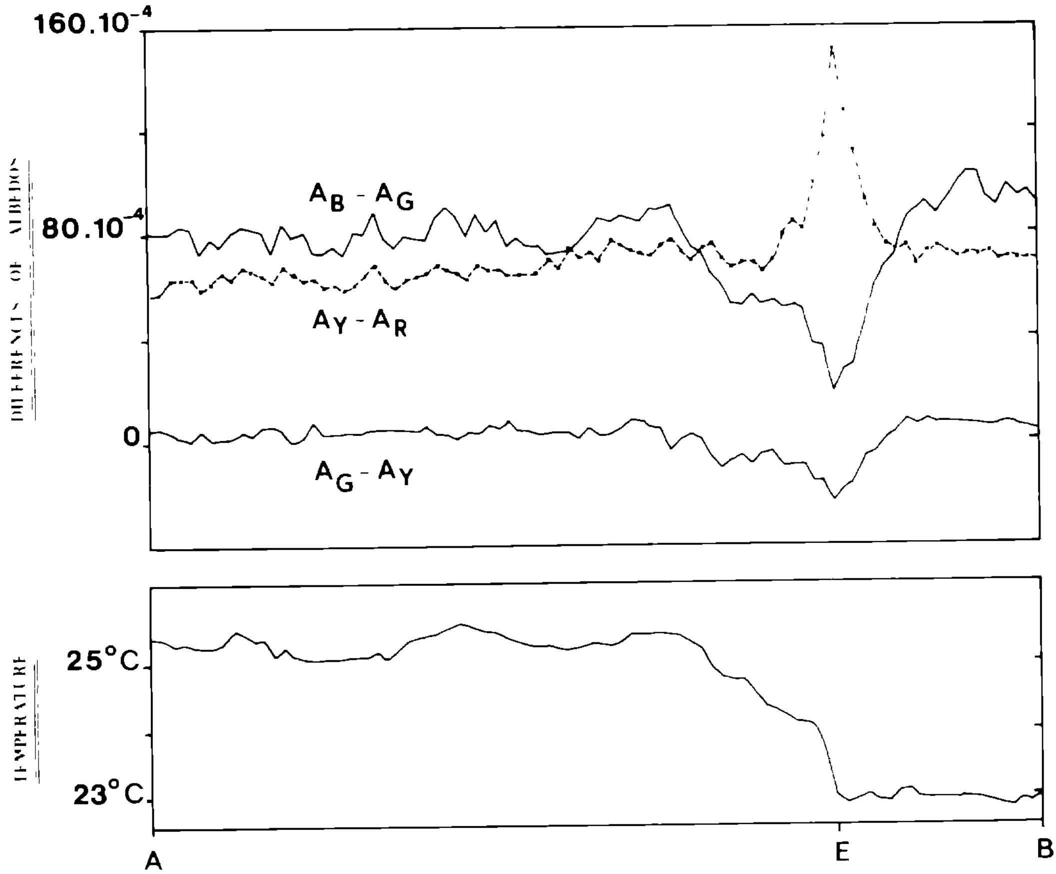

FIGURE 3. Records of sea surface temperature and differences between albedos at 466 and 525 nm ($A_B - A_G$), at 525 and 550 nm ($A_G - A_Y$), and at 550 and 600 nm ($A_Y - A_R$), for the same track AB considered in Fig 2

backscattered albedo upon the form of the incident radiance distribution was also found by Gordon and Brown (1973), and Prieur (1976). The interpretation of backscattered radiation can therefore be based entirely upon Eq. (1)

The absorption coefficient a, in Eq. 1, is not easily determined. Various factors such as pure water, chlorophyll and other pigments, and yellow substance absorption must be taken into account. Most of the variations are due to chlorophyll and in a first approach only pure water and chlorophyll-a absorption coefficients are considered. The absorption coefficient can thus be written as

$$a = a_w + n_{chl} \cdot a_{chl}, \qquad (2)$$

where a_w: water absorption, a_{chl}: absorption by 1 mg/m³ of chlorophyll from Yentsch (1960), and n_{chl}: chlorophyll concentration (mg/m³).

Particle scattering coefficient $b_p(\lambda)$ is assumed to be proportional to the inverse of wavelength λ, and is given relative to its value at 500 nm.

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

where λ is in nanometers. Values of molecular scattering coefficient $b_o(\lambda)$ for sea waters were given by Morel (1973).

Equations (1), (2) and (3) were used to calculate albedos for the curves in Fig. 4 (466 nm) and Fig. 5 (550 nm). In these curves, albedo is a function of chlorophyll content at various values of the particle scattering coefficient. The first wavelength (466 nm) is located near the maximum absorption of chlorophyll and the minimum absorption of water. The second is outside of the major absorption band of chlorophyll. These curves lead us to two remarks. First, albedo at 466 nm depends not only on chlorophyll content, but also on scattering coefficient b_p. If there is no strong correlation between the two parameters, an ambiguity exists. Second, measurement of albedos at

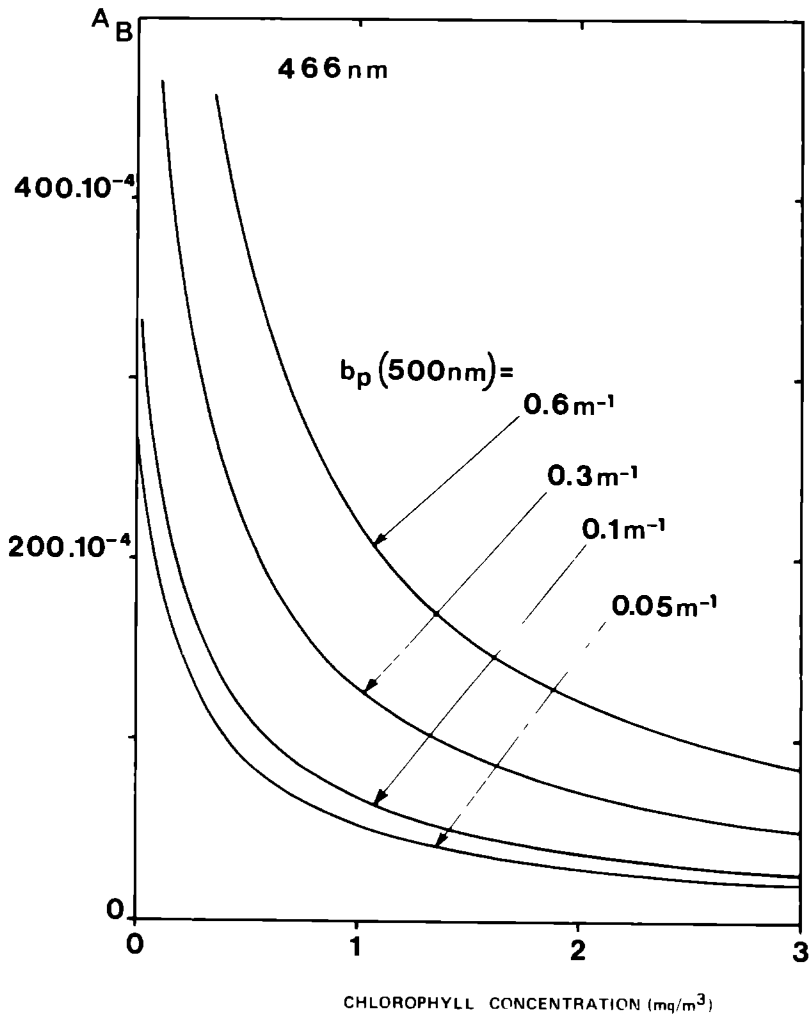

FIGURE 4 Theoretical backscattered albedo at 466 nm versus chlorophyll-*a* concentration (absorption coefficient from Yentsch, 1960) for various values of the particle scattering coefficient.

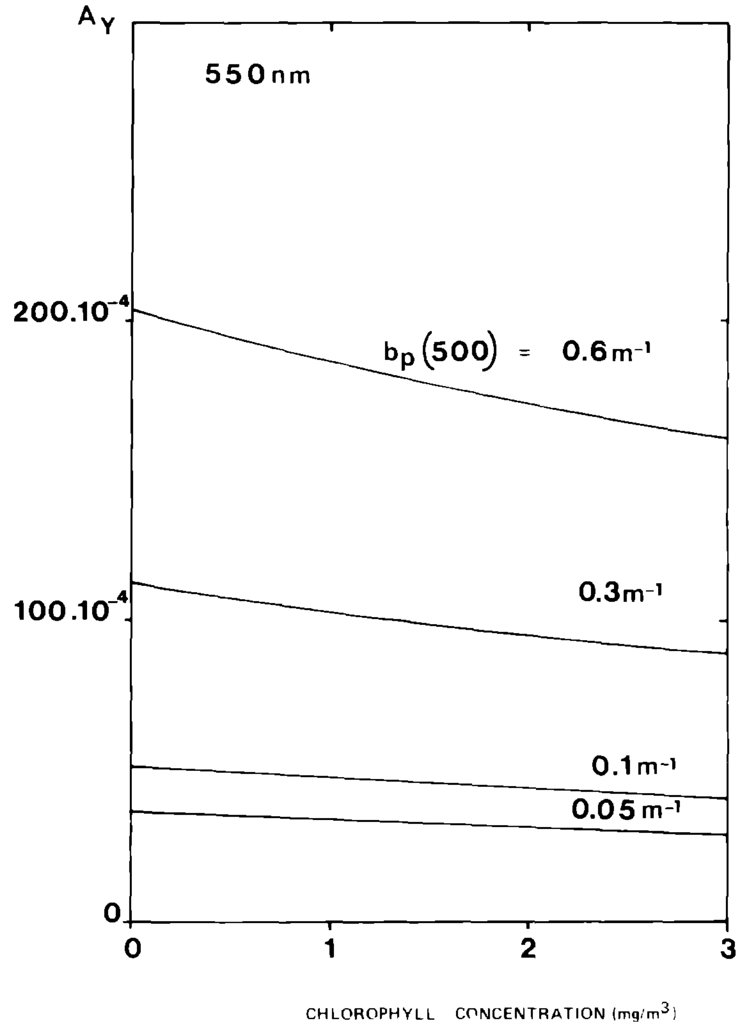

FIGURE 5 Theoretical backscattered albedo at 550 nm versus chlorophyll-*a* concentration for various values of the particle scattering coefficient

550 nm (or occasionally farther into the red) should allow the determination of the value of b_p. The preceding ambiguity is thus resolved by the measurement of both albedos.

In order to employ the proposed measurement interpretation method, albedos at 525 nm and 600 nm were also calculated, and the blue-green and yellow-red differences were plotted as functions of the same parameters, i.e chlorophyll concentration n_{chl} and scattering coefficient b_p. The diagram in Fig. 6 allows the direct determination of n_{chl} and b_p from the two differences.

The use of this diagram is illustrated by the location of extreme values of differences of albedos recorded during the July 6 flight. These values correspond to point $A(A_B - A_G = 80.10^{-4}$, $A_Y - A_R = 30.10^{-4})$ and point $E(A_B - A_G = 30.10^{-4}$, $A_Y - A_R = 120.10^{-4})$ of Fig. 3. Point A is

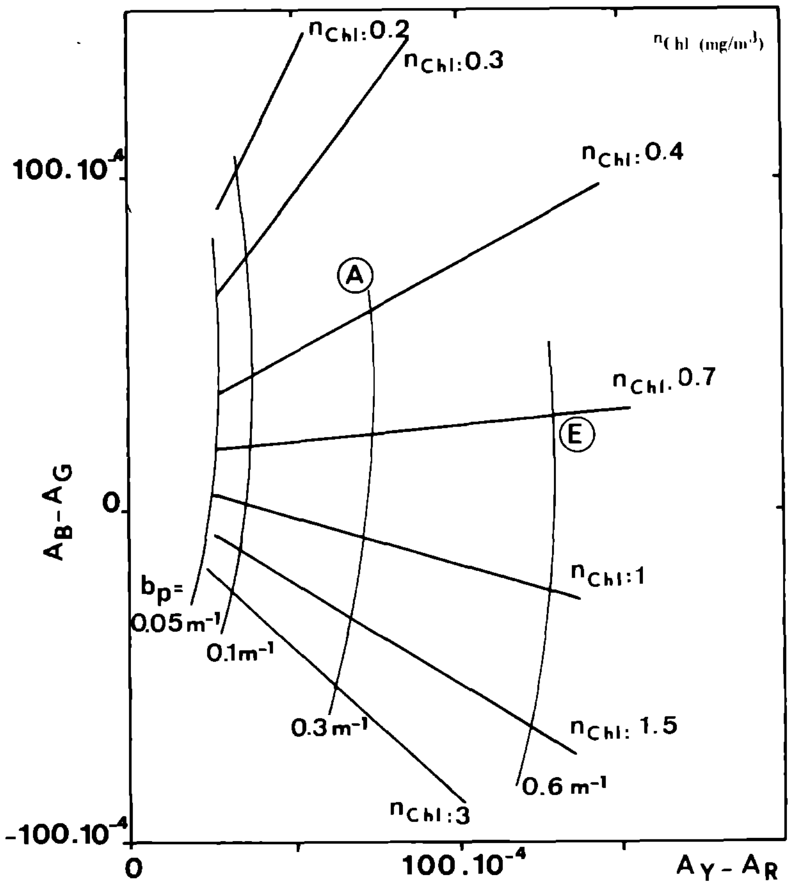

FIGURE 6 Theoretical diagram of the difference between the blue and green albedos $(A_B - A_G)$ versus the difference between the yellow and red albedos $(A_Y - A_R)$ The parameters are the particle scattering coefficient b_p (m^{-1}) and the chlorophyll concentration (mg/m^3) The points A and E represent July 6 measurements made to the north of the thermal front and on the thermal front respectively.

typical of water of low chlorophyll concentration and low b_p value whereas point E is representative of more productive areas of higher chlorophyll concentration and b_p value.

It can in this case be seen that the low value of $A_B - A_G$ is linked to a high value of $A_Y - A_R$. We have, however, found some exceptions to this rule near coasts, for example, and over the center of the Ogoué River Plume in particular. The presence in these coastal waters of materials, probably yellow substances, which absorb and have a maximum effect on the albedo at 550 nm can annul the increase of the difference $A_Y - A_R$. Although Fig. 6 was valid in most cases, the preceding observations demonstrate that it is not universally applicable.

The theoretical model assumes that the medium is homogeneous, but the vertical profile of chlorophyll concentration frequently varies with depth. A maximum is commonly observed at a depth of several dozen meters, especially when the surface concentration is low (see for example Dufour and Stretta, 1973). In this case, the measurements of backscattered radiation give only an integrated value of the vertical profile weighted by the underwater light penetration, so that the inferred chlorophyll concentration may differ from the surface value as well as miss the higher value of a chlorophyll maximum in the depths. This is a general limitation to the accurate determination of chlorophyll concentration by the remote sensing of ocean color.

Aerial Survey of the Upwelling

Fourteen flights were made from June 27 to July 13 1975 over the Cape Lopez area. In order to compare the two methods of albedo measurement, the radiometer measured upwelling irradiance during five flights, and measured upwelling radiance during the other nine. The latter was measured in the vertical plane passing through the axis of the aircraft, with the view angle being held at 45° from the vertical. The aircraft speed was about 200 km/h and the altitude 150 m.

Maps of differences of albedos were made after each flight. Using these maps, Viollier (1976) discussed how some steps of the hydrobiological processes occuring at Cape Lopez may be related to the areal distribution of the difference between blue and green albedos, and to the variations of this difference which occur from one day to another. The results of three flights selected from this study are presented here in Fig 7, 8, 9 and 10. The flight pattern is recorded on each map, along with sea surface isotherms. It is unfortunate that chlorophyll in-situ measurements were not made during this survey, and our description of the results is therefore based upon the previous theoretical discussion.

June 30—The whole area (Fig 7) is

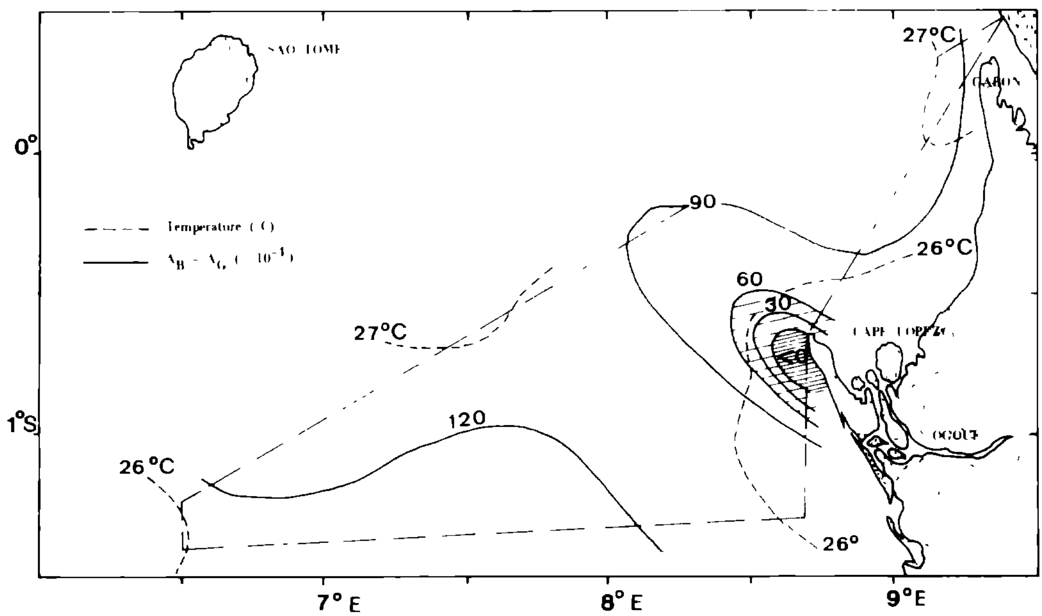

FIGURE 7 June 30 flight sea surface isotherms and distribution of differences between blue and green albedos Blue-green waters ($0 < A_B - A_G < 60\ 10^{-4}$) and green waters ($A_B - A_G < 0$) are respectively the light and heavy shaded areas Flight track is the dot-dashed line

occupied by warm waters from the north. The albedo difference $A_B - A_G$ is high and positive in the whole area, except over the Ogoué River Plume near Cape Lopez. The higher values (about 120.10^{-4}) correspond to the warmer, chlorophyll poor waters. Cloud cover varied from 0 to 100%.

July 6 (Figs. 8 and 9)—Upwelling developed between the June 30 and July 6 measurements. A 200 km long thermal front is found between Cape Lopez and Sao Tomé Island. The thermal front is blue green (low value of $A_B - A_G$ on Fig. 8) and turbid (high value of $A_Y - A_R$ on Fig. 9), although this effect is less noticeable as one goes away from Cape Lopez. To the contrary, the colder waters to the south ($\cong 22.5°C$) seem relatively poor in chlorophyll and are perhaps the product of a too recent upwelling to be enriched. Cloud cover varied from 75 to 100% during the flight.

During the period extending from July 9 through July 12, warm waters push the cold waters southwards. The lower $A_B - A_G$ value is still noted on the thermal front, but the whole area seems to be "greener" (the average $A_B - A_G$ value is 50.10^{-4}), and therefore enriched if compared to the same area when observed during the first flight, i.e. before the cold waters appeared.

July 13—The upwelling begins to develop again near Cape Lopez (Fig. 10) and it is accompanied by a high chlorophyll content ($A_B - A_G < 0$). The thermal front once again starts to move northward. Cloud cover varied from 0 to 100%.

Conclusion

During the aerial surveys of the Gulf of Guinea, significant water color measurements were obtained, even in cloudy weather, by the method of albedo differences. This method allows the elimination of the error due to reflection of sky and clouds by the ocean surface, but requires a very high degree of accuracy in the monochromatic measurement of albedo, that is the absolute uncertainty should be less than 5.10^{-4}. The necessary accuracy was attained by the use of a specially designed radiometer and by the daily recalibration of the radiometer as described above.

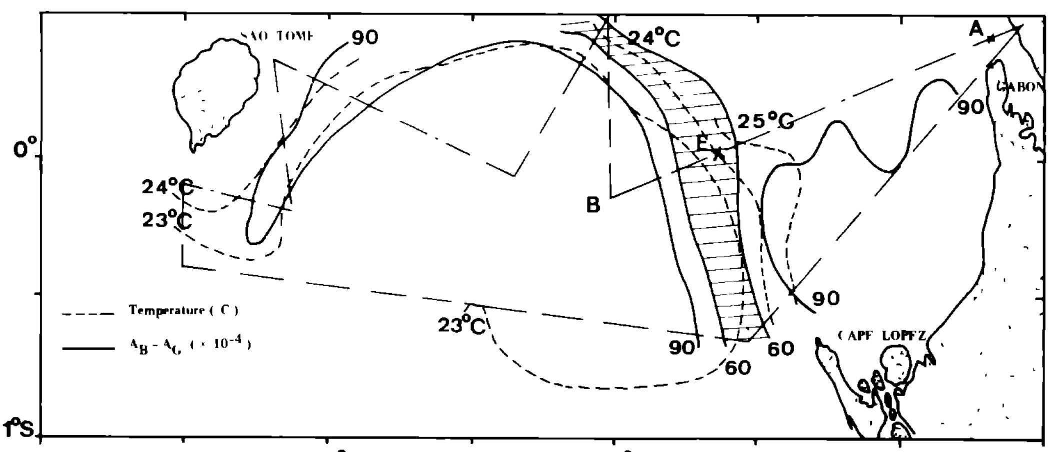

FIGURE 8. July 6 flight same as Fig. 7

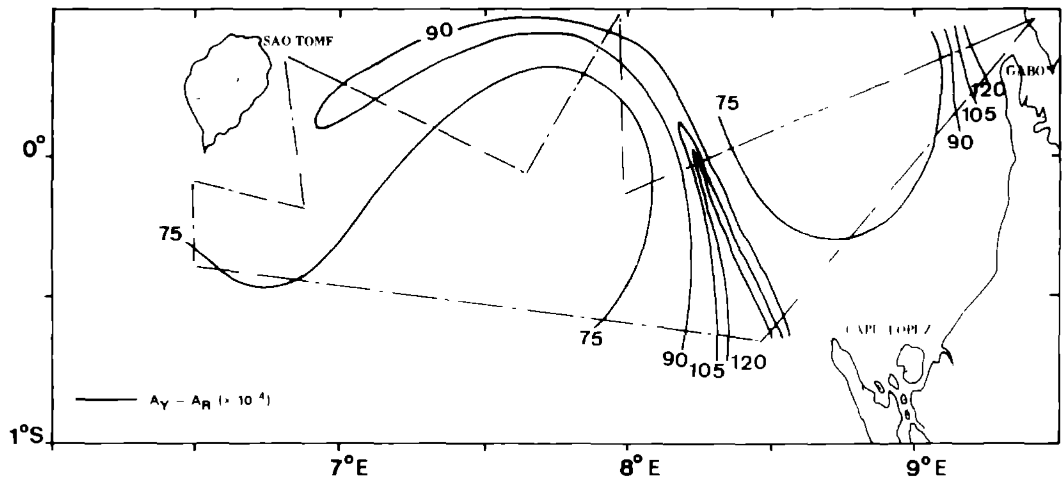

FIGURE 9 July 6 flight Distribution of differences between orange and red albedos

The two differences of albedos give the two variables which are necessary for the deduction of the chlorophyll concentration from a theoretical model and the elimination of the influence of turbidity. They usually were found to give two criteria to discriminate zones rich in phytoplankton from poorer waters.

(1) low values of the difference between blue (466 nm) and green (525 nm) albedos (mainly due to chlorophyll absorption), and

(2) high values of the difference between yellow (550 nm) and red (600 nm) albedos (due to particle scattering).

The difference between blue and green albedos is more sensitive than the second difference and varies from 120.10^{-4} (June 30) to -15.10^{-4} (upwelled water on July 13).

The relationship between measurements and chlorophyll content must be used with care due to the potential error introduced by vertical inhomogeneity or yellow substance absorption

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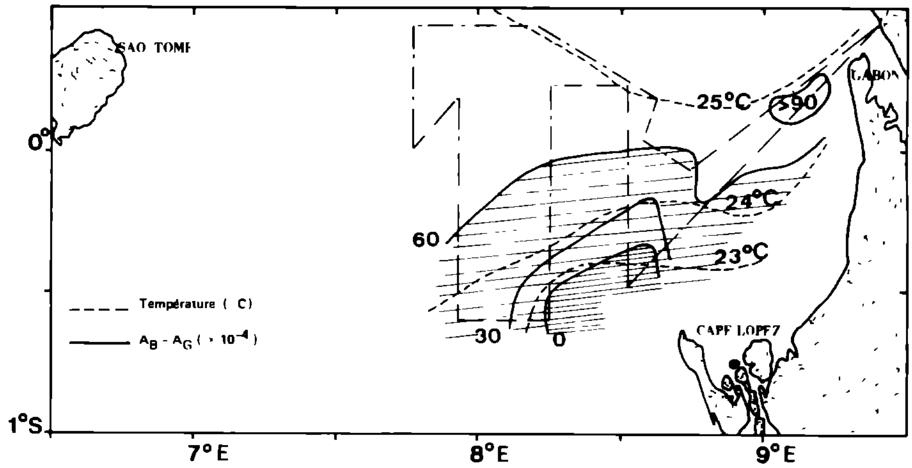

FIGURE 10. July 13 flight same as Fig 7

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