

SATELLITE (AVHRR/NOAA-9) AND SHIP STUDIES OF A COCCOLITHOPHORID BLOOM IN THE WESTERN ENGLISH CHANNEL

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ABSTRACT: Routine satellite observations conducted in assistance to an oceanographic cruise called attention to anomalously high reflectance in the visible region of the spectrum (channels 1 and 2 of the meteorological radiometer AVHRR) off the northern coast of Brittany in July 1986. In situ measurements showed turbidity to be extremely high in the upper 7 meters although chlorophyll content and phytoplankton populations were moderately abundant throughout the water column. Scanning electron microscopy performed after the cruise revealed the presence of a dense suspension of disintegrated coccoliths of *Emiliana huxleyi* (up to $50 \cdot 10^6$ coccoliths l^{-1}) in the turbid layer. Infrared imagery together with hydrological measurements suggested that the bloom had been initiated in a originally coastal, mixed water mass which had recently undergone seasonal stratification. This is thus the first evidence that coccolithophorids, and not only dinoflagellates, may be responsible for phytoplankton blooms along the Ushant tidal front. The usefulness of real-time assistance of remote sensing to plankton studies is emphasized.

Introduction

Highly reflectant waters associated to a shallowsea thermal front (the Ushant tidal front) were first observed by the satellite Landsat 2 on July 2-3, 1977 (Le Fèvre *et al.* 1983). No sea-truth data were available in this case, however. Various hypotheses were thus suggested, including blooms of coccolithophorids as these phytoplankters are covered with a calcified skeleton. Similar waters were observed later by the Coastal Zone Color Scanner (Nimbus 7, CZCS) further offshore, at the edge of the armorican and celtic shelf (Holligan *et al.* 1983b ; Holligan and Viollier 1986). In May 1982, sea-truth surface observations confirmed, for the first time, that

such phenomena were caused by *Emiliana huxleyi*, a coccolithophorid species (Holligan *et al.* 1983b).

Reflectant waters have since been commonly mentioned every summer in the European shelf waters either on the CZCS images (e.g. July 6, 1985 : Fig. 1) or on visible-spectrum images of the meteorological satellite NOAA (Groom 1986; Groom and Holligar, in press). No more sea truth data could be obtained, however.

On the other hand there have been many mentions, since the beginning of this century, of a change in the usual color and/or aspect of the sea due to a proliferation of this species (references are given in the Discussion together with an overview of the autoecology and physiology of the organism). Different names and epithets have been

1. A group of some 25 scientists from different French institutions under the code RCP. 755 of the Centre National de la Recherche Scientifique. As far as individual authors are concerned, the present paper is co-authored by M. Viollier, A. Sournia, J.-L. Birrien, M.-J. Chrétiennot-Dinet, P. Le Borgne, P. Le Corre, P. Morin and J. P. Olry.

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used to describe these optical characteristics in so far as the human eyes can perceive them : discolored water, milky water, white water, red tide and son on. The following quotation makes it clear that the color is variable and its appreciation rather subjective : "The coccoliths produc-

ed an effect similar to that of chalk suspended in water. The sea water was milky and very turbid. The fingers of the hand were indistinguishable in the Bonne Fjord at a depth of 25 cm. At a distance the water showed pale green, resembling enamel, and its appearance was uni-

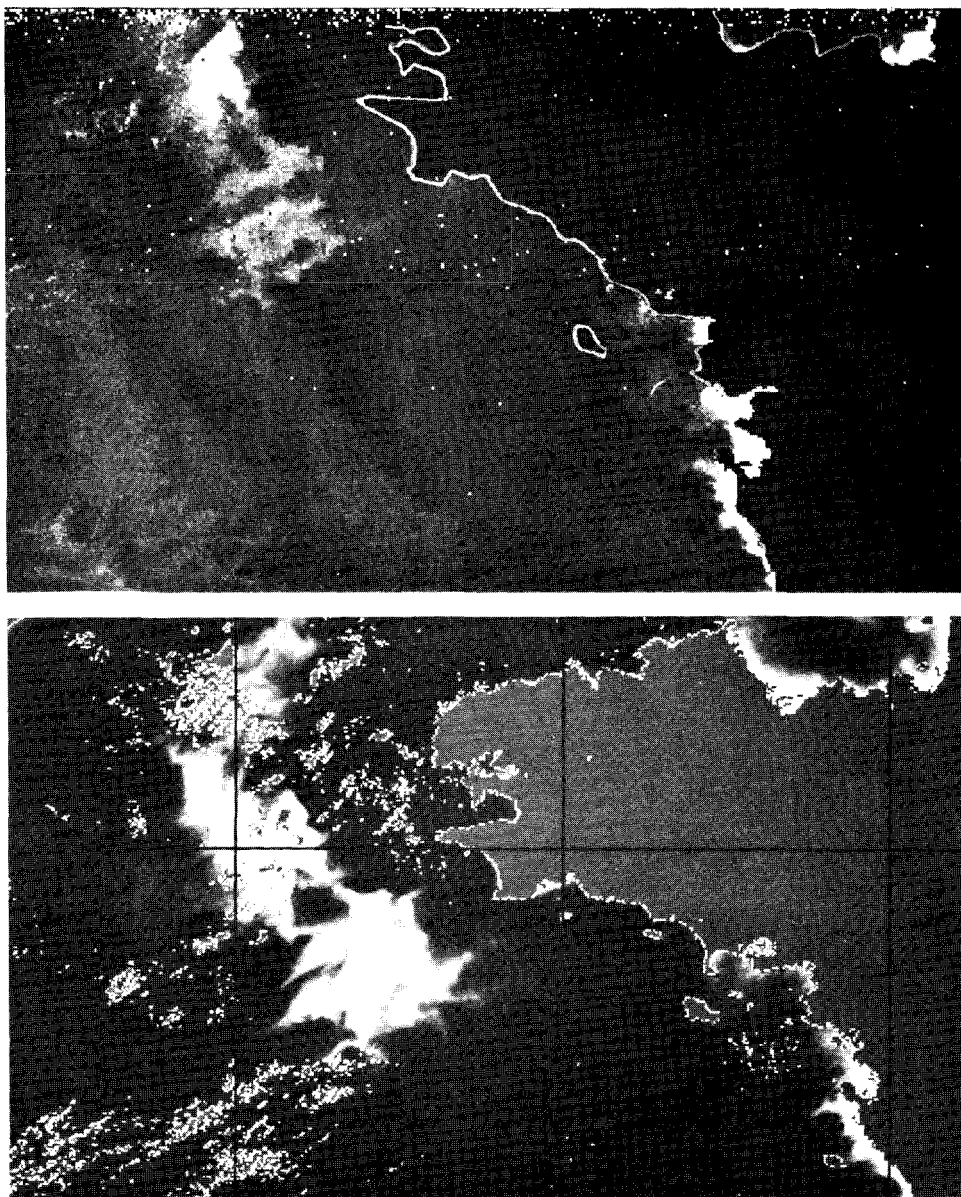


Fig. 1. Comparative images obtained from NOAA-9/AVHRR (channel 2 subtracted from channel 1 ; on top) and Nimbus-7/CZCS (channel 2, corrected for atmospheric effects ; bottom). July 6, 1985, at 14.02 GMT for AVHRR and 11.43 GMT for CZCS. On both images, white patches with eddy outlines are observed West of Brittany ; clouds, also in white, differ by their granular aspect. (No sea-truth measurements were available at this date).

que. In the harbour region it was more gray or brownish" (Braarud, 1945). It may be added that a bluish or pale turquoise tends to predominate in remote sensing from satellites and air planes, as far as "true colour" is concerned. The terms "reflectant waters" or "turbid waters" will be used here after indifferently.

New satellite and *in situ* observations on the Ushant front were made available during the oceanographic cruise "Iroise" in the summer of 1986 and are presented in this paper. Whereas most of the cases of reflectant waters have been recorded, so far, West or South-West of Brittany (Fig. 1; see also Le Fèvre et al. 1983), the 1986 event occurred northward, along that part of the Ushant front which enters the English Channel.

Originally, our attention to this phenomenon was first called by satellite information which was transmitted on board in (nearly) real time from the Centre de Météorologie Spatiale (Lannion, France). The route of the ship could be modified subsequently and allowed the turbid patches to be explored and sampled. At Station 205-3, on July 24, vertical profiles of temperature and nephelometry exhibited an extremely high turbidity in the upper 7-10 meters above a well-marked thermocline. Waters samples were immediately collected for various purposes (see below). Although light microscopical observations were carried out on board, the origin of turbidity could be elucidated only after the end of the cruise with help of scanning electron microscopy, and the reason for this will be given.

We thank J. Le Vourch and M. Derrien (Etablissement d'Etudes et de Recherches Météorologiques, CMS, Lannion) for real-time assistance and image processing of the satellite data. The CZCS image was provided by Earthnet Station (Mas Palomas, Spain) and the AVHRR data were made available through SATMOS (CNES, CNRS and CMS). The CTD system was loaned by INSU and operated by Cl. Bournot. The cooperation of the crew

on board N.O. "Cryos" is gratefully acknowledged. This work was mainly supported by CNRS/INSU funds. Thanks are expressed to Dr P.M. Holligan and Prof. A. Morel for their comments on the manuscript.

Methods

Satellite image processing—The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA series of meteorological satellites is provided with 5 channels, namely: two in the thermal infrared (10.2–11.3 and 11.5–12.5 μm), one in the middle infrared (3.55–3.93 μm) and the last two in the "solar reflection" region (580–680 and 725–1100 nm). For reasons of mere convenience, the two latter channels will be referred to here after as "visible channels". The thermal infrared channels allow variations of the sea surface temperature (SST) to be mapped with an absolute accuracy of 0.6 K using a multispectral algorithm (Castagné et al 1986) and a relative accuracy of 0.1 K when using the channel 10.2–11.3 only. The two visible channels have been designed for the mapping of clouds, snow and ice coverage; they have also been used for the estimation of land albedo and vegetation index (Townshend et al 1985). A new application of the two latter channels is dealt with here, namely: the remote sensing of turbid waters.

Table 1 shows the radiometric characteristics of the reflected sunlight channels (1 and 2) of AVHRR and compares them to channels 3 and 4 of CZCS. It can be seen that AVHRR channel 1 overlaps CZCS channels 3 and 4 but its radiometric resolution is lower by a factor 4 and 2 respectively. Consequently, coccolithophorid blooms should appear on the AVHRR channel 1 at the limit of its detection capability, typically over a range of 10 digital levels, versus 40 for CZCS channel 3.

When processing AVHRR channels 1 and 2, a difficulty arose from the so-called sun glitter effects. Actually,

Table 1. Comparative radiometric characteristics of the reflected sunlight bands of CZCS and AVHRR

Channel number	Nimbus-7/CZCS		NOAA-9/AVHRR	
	3	4	1	2
Spectral range(nm)	540-560	660-680	550-680	710-1100
Reflectance saturation(R_{sat})	0.108	0.06	1.06	1.04
Number of digital levels(N)	256	256	1024	1024
Radiometric resolution (R_{sat}/N) 10^4	4	2.3	10	10
Variability over coccolithophorid blooms(digital levels)	59	21	16	6

CZCS was provided with a tilt mechanism which avoided the scanner to observe at angles close to the solar specular reflection angle. Such is not the case with AVHRR on the images of which sun glitter appears as a bright North-South band, and as a roughly gaussian distribution on the beam line profiles (Cox and Munk 1954, Wald and Monget, 1983 ; Fig. 2 herein). However, since the signal enhancement due to sun glitter varies only little with wavelength

and is approximately the same in channels 1 and 2, the mere subtraction of reflectance of AVHRR channels 1 and 2 allows most part of the perturbing effects to be eliminated, as is demonstrated on Fig. 2.

Two types of documents were thus available to us from NOAA/AVHRR :

- SST deduced from channels 4 and 5 ;
- water reflectance (R_w) as an index of water turbidity,

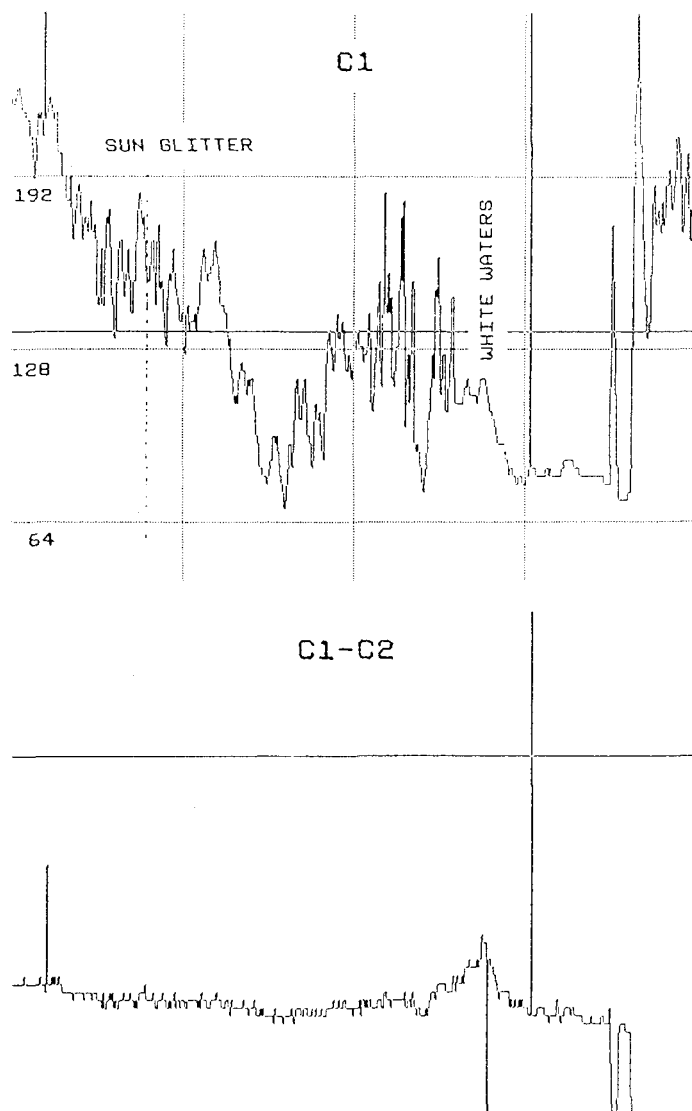


Fig. 2. Scan line of AVHRR through the reflectant patch shown on Fig. 1. On top : sun glitter appears to be the main component of channel 1 data (C1). This effect was largely eliminated after subtraction of Channel 2 (C1-C2, at bottom).

deduced from the difference between channels 1 and 2.

SST mappings were received on board every day or so, weather permitting, from Lannion with a delay of about one day. Due to their experimental nature, R_w maps required a few days more.

It should be recalled here that the CZCS imager, although it has worked some 6 years more than expected, ceased practically functioning in 1985 and was formally abandoned in January 1987 (circular letter from NASA). It has not been replaced, as yet by any similar sensor.

Continuous measurements at sea—The cruise "Iroise" (named after the "mer d'Iroise", off the West coast of Brittany) took place from July 11 to August 11, 1986 on board N. O. "Cryos".

Continuous surface monitoring and discrete vertical profiles at stations were achieved during the whole cruise for temperature, turbidity and fluorescence. Horizontal measurements were performed by pumping surface water into two Turner Design fluorometers (model 10-005R), one in the fluorescence mode and the other in the nephelometry mode. For vertical profiles, a Variosens III (Implusphysik, Hamburg) was lowered at sea simultaneously to a CTD probe. The flashes emitted by the Variosens (10 Hz) are filtered in the range 350–500 nm. A first receiver measurement the light scattered at 90° in the same spectral range (Frügel and Koch 1976); this measurement is converted into Formazin Water Turbidity Units, FTU (Frügel and Koch 1980). A second receiver measures the *in vivo* fluorescence of chlorophyll in red light, 685 nm.

Chemical and biological procedures—Water samples were collected at the different depths with Niskin bottles on a rosette sampler. Nutrient analyses were performed with routine techniques (Strickland and Parsons 1972); most nutrient analyses were automatized by means of the Technicon[®] Autoanalyser II (Tréguer and Le Corre 1975) with an analytical precision of $\pm 0.02 \mu\text{atg P}$, $\pm 0.1 \mu\text{atg N}$ and $\pm 0.1 \mu\text{atg Si l}^{-1}$; ammonia was measured manually using following the method of Koroleff (1970) with a precision of $+0.05 \mu\text{atg N l}^{-1}$. Dissolved oxygen was measured with the Winkler method as described in Stickland and Parsons (1972) with a precision of $+0.02 \text{ ml. l}^{-1}$. Chlorophyll *a* and derivatives were estimated fluorimetrically using one of the Turner Design instruments and Lorezen's equations.

Unconcentrated phytoplankton samples were examined

on board under a standard microscope using a counting slide when blooms were suspected to occur. Routine countings were made ashore, one month after the cruise, by means of the sedimentation technique under an inverted microscope. Scanning electron microscopy was practiced five months after the cruise as follows. 10 ml aliquots of the preserved (neutral formaldehyde) samples were filtered on Nucleopore[®] membranes ($1 \mu\text{m}$ pore size; 13 mm diameter) using a glass syringe and Sweeney Millipore[®] system. After rinsing with distilled water and air drying, the preparations were coated with gold-palladium (Nanotech[®] Sempreg II). A Stereoscan 200 (Cambridge Instruments[®]) was used at low magnification (ca 1,000) for counting the coccoliths and at higher magnification (ca 10,000) for detailed observations of the coccoliths and the coccospheres. Coccoliths (which proved to be distributed at random on the filters) were enumerated on photographs and their abundance was determined after due consideration of the subsampling factor and magnification.

Results

Although the number of available satellite data was severely reduced by the cloud cover, a major patch of turbid water was observed twice on July 9 and 17 (Figs 3B and 4B). Temperatures are shown on Figs 3A and 4A respectively. On July 9, the patch was located in a zone of relatively warm waters (16°C) limited to the South and East by the cold, mixed coastal waters (14°C) and to west by warmer, stratified waters (17°C). On July 17, the coldest mass has spread northward (unless some tidal effect was neglected) and the warmest one has disappeared (Fig. 4A). The white patch then fits the limits of mixed waters more closely (Fig. 4B). Although the maximum of reflectance is still located at the same place ($49^\circ 05' \text{N}$; $4^\circ 20' \text{W}$), extensions towards North-East may be noted on the second image. Other cloud-free images which were obtained either before (June 30) or after these observations (August 4) did not reveal any more turbid waters in the area.

Due to the time delay for processing and interpreting the visible AVHRR imagery and the various commitments of the cruise, the ship was not able to explore the patch until July 24. The nephelometric signals recorded with the continuous pumping system gave the first indication that some oceanographic phenomenon was implicated (Fig. 5b). Visual observations were not so convincing, so difficult it is to estimate the colour of the sea from a vessel; a discolouration was obvious for some of us, however.

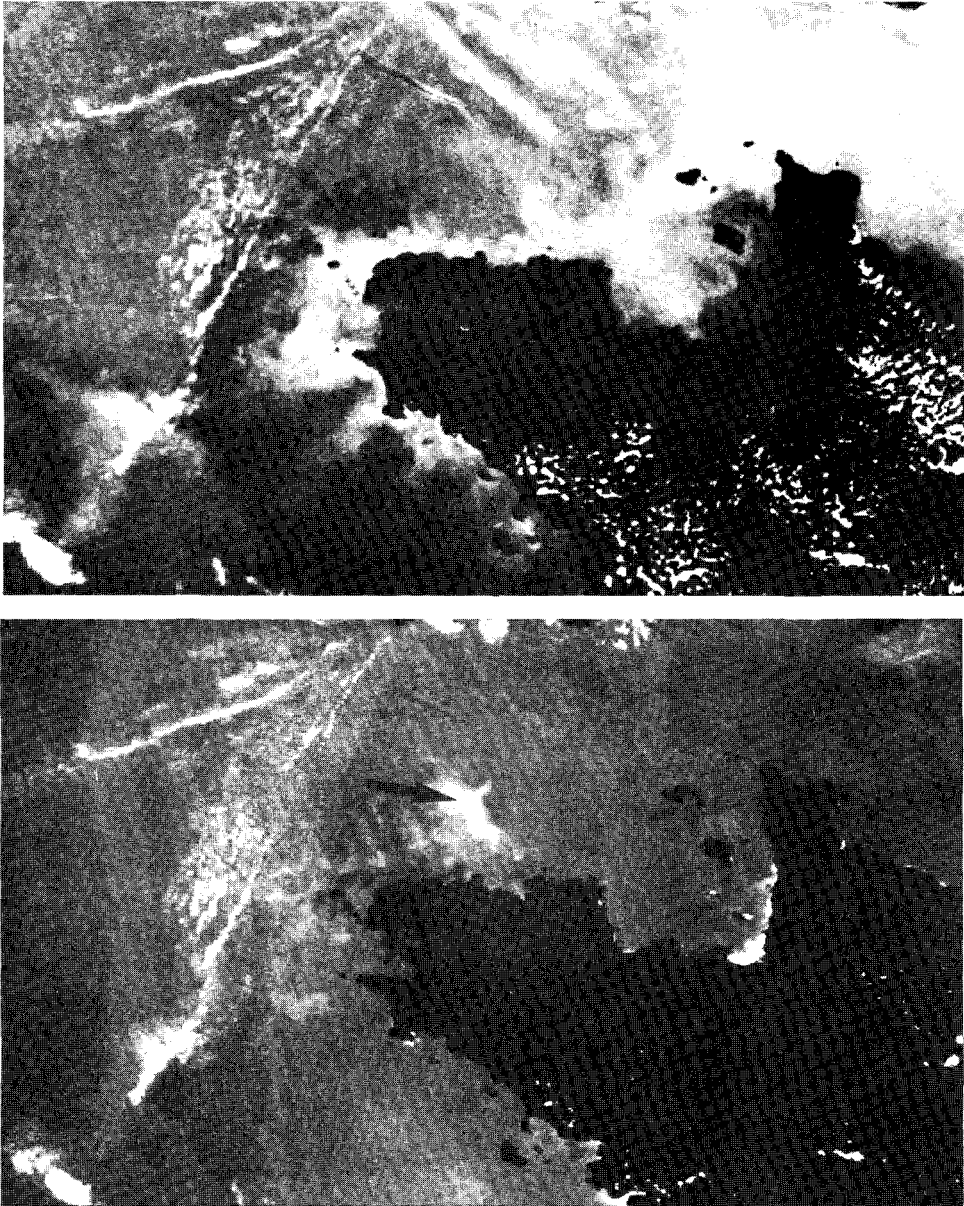


Fig. 3. AVHRR, July 9, 1986, 14.00 GMT. *On top* : sea surface temperature as deduced from Channels 4 and 5 ; colder waters appear in light tones. *Bottom* : sea surface reflectance in the visible spectrum as the difference between Channels 1 and 2 ; the more reflectant waters (arrow) appear in white. Clouds can be identified after their elongated or granular appearance and/or their common presence on both images.

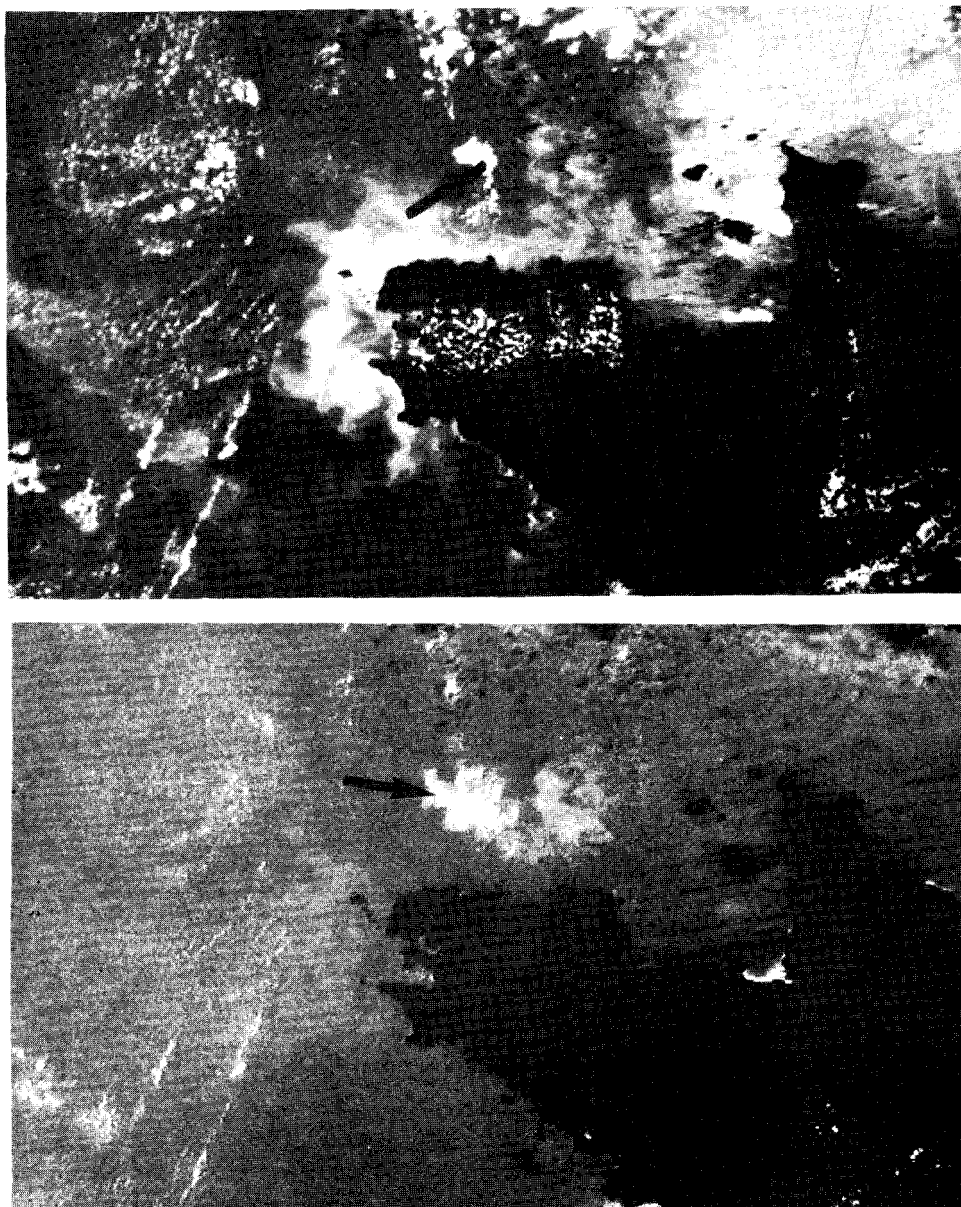


Fig. 4. AVHRR, July 17, 1986. 14.05 GMT. Same as Fig. 3. The location of the station and transect of July 24 (Fig. 5) is shown on top as a black bar.

Continuous horizontal records of temperature, chlorophyll and turbidity (Fig. 5b) indicate a basic asymmetry on the two sides of the turbid patch. While the western border (Fig. 5b, left) exhibits a characteristic frontal structure with increased temperature and a chlorophyll peak, the eastern limit of the patch (right) is only underlined by slight changes of temperature and chlorophyll.

At station 205-3 (49°09'N ; 4°23'W ; depth: 99m), located near the turbidity maximum, the temperature profile showed that the 7 upper meters were warmer by 4°C than the underlying waters (Fig. 5a). The nephelometric profile gave exceptional high values in this surface layer. By contrast, *in vivo* fluorescence (Fig. 5a) and chlorophyll content (Table 2) were almost constant, except for a slight increase at the thermocline. Phytoplankton examination on board, as well as the enumeration made later on sedimented samples, showed moderately abundant and fairly diversified populations, including small numbers of the coccolithophorid *Emiliana* (Table 2) while some kind of unispecific outburst was expected, such as occurs in "red tides". The remaining samples were thus prepared for electron microscopy, and the explanation followed: large numbers of isolated, disintegrated coccoliths of *Emiliana*, which had not been seen under the light microscope, were discovered on the filters. Dividing their number by an approximate number of coccoliths per cell (Table 2) leads to a potential concentration of organisms in the order of magnitude of the usual "red tides" (2-3 millions cells per liter). As also shown on Table 2, the coccoliths and the "potentially present" cells of coccolithophorids (as well as the relatively few cells actually observed) were mostly confined in the upper layers. Fig. 6 shows the abundance of the coccoliths on the filters and three cells of *Emiliana* at different stages of growth or disintegration.

Apart from the coccoliths and coccospheres, moderate phytoplankton crops were observed at all depths in terms of cell counts (Table 2) as well as chlorophyll content (Table 3), and waters were thoroughly oxygenated (Table 3). In counterpart, a shallow thermocline was present and accompanied by a slight increase in pigment concentration; dinoflagellates were relatively more numerous in the surface layers, and bottom waters were significantly enriched with respect to ammonia (Tables 2 and 3). Such a set of data, in the regional context (Wafar et al. 1983, Morin et al. 1985) can only be understood if one admits that St. 205-3 took place in a body of coastal (mixed) waters which had been quite recently stratified. This is also substantiated by the examination of the infrared imagery of June 30, 1986 (Viollier 1986) which shows cold surface waters at the future location of station 205-3.

Discussion

Emiliana huxleyi (Lohmann) Hay and Mohler (improper or obsolete synonyms: *Pontosphaera huxleyi* Lohmann = *Hymenomonas huxleyi* (Lohmann) Kamptner = *Coccolithus huxleyi* Kamptner = *Gephyrocapsa huxleyi* (Lohmann) Reinhardt belongs to the class Prymnesiophyceae (= Haptophyceae), order Coccolithophorales.

The main stage of its life cycle consists of small (usually 4-6µm diameter) coccospheres bearing several discoid calcareous platelets called coccoliths. A detailed morphological description may be found in McIntyre and Bé (1967) and comments on the taxonomy of *E. huxleyi* are given by Heimdal and Gaarder (1981). Motile, naked and flagellated cells as well as non-calcified stages are also found in culture (Braarud 1963; Klaveness and Paasche

Table 2. Phytoplankton counting at Station 205-3.

Depth (m)	Sedimentation and optical microscopy				Filtration and scanning electron microscopy	
	Diatoms	Dinoflagellates	<i>Emiliana</i>	<i>Chilomonas</i>	Dissociated coccoliths	Intact <i>Emiliana</i> cells potentially present*
			10 ³ l ⁻¹		ml ⁻¹	10 ³ l ⁻¹
0	56	27	129	76	31,400	1,570-2,093
3	70	26	77	45	53,380	2,670-3,560
5	149	22	34	6	21,520	1,076-1,435
20	110	0.6	67	6	8,080	404-538
30	94	0.6	55	4	3,600	180-240
50	146	6	44	8	3,800	190-253

* Assuming an average number of 20-15 coccoliths per coccosphere; see text.

Table 3. Hydrological measurements, nutrients and chlorophyll content at Station 205-3 (July 24, 1986 : 49°09'6 N; 4°23'3 W-depth; 99 m)

Dept (m)	Temp. °C	Diss. oxygen		Nutrients, $\mu\text{at g l}^{-1}$					Pigments, $\mu\text{g l}^{-1}$	
		ml l^{-1}	% sat.	N- NO_3	N- NO_2	N- NH_4	Si(OH) $_4$	P- PO_4	Chlor. <i>a</i>	pheoph.
0	16.60	6.14	111.6	0.3	0.05	0.21	0.2	0.04	0.64	0.35
3	16.59	6.18	112.3	0.4	0.05	0.14	0.0	0.04	0.96	0.28
4	13.58	6.45	110.4	0.8	0.11	1.18	0.1	0.14	1.02	0.76
5	13.91	6.32	108.9	1.0	0.11	0.89	0.2	0.13	1.57	0.59
6	13.26	6.28	106.7	1.4	0.15	0.67	0.5	0.15	1.22	0.50
10	12.75	6.16	103.1	1.9	0.16	1.18	0.5	0.18	0.96	0.57
21	12.62	6.14	103.1	2.0	0.17	1.19	0.6	0.19	0.90	0.49
31	12.58	6.07	101.7	2.0	0.18	1.28	0.6	0.19	0.96	0.28
49	12.57	6.08	101.9	2.0	0.19	1.32	0.6	0.19	0.93	0.38
79	12.57	6.08	101.9	2.0	0.19	1.37	0.6	0.19	1.06	0.26

1971). "This minute species is doubtless the most widespread coccolithophorid in the sea" (Braarud 1962). Evidence of its wide occurrence in the Atlantic Ocean is plenty (Berge 1962 ; Braarud 1962, and older references therein ; Mc Intyre and Bé 1967 ; Raymont 1980) ; only the colder parts of the polar seas and the warmer parts (or seasons) of the tropical seas are seemingly avoided. Massive blooms have been reported throughout the distribution area, limits included (for instance, blooms are known in the southern Sargasso Sea as well as in Norwegian fjords). The temperature and salinity tolerances and the nutrient requirements are all typically of the "eury-" mode, as verified on cultures. As regards light, *E. huxleyi* sustains low energy levels but also proved to be phototactic (Mjaaland 1956). There seems to be only one specific requirement, namely the need for long photoperiods (> 14 hours), a condition which was obviously satisfied in the present observations ; continuous light does not even affect growth (references in Bonin et al. 1986). A full account of its physiology and growth characteristics is given by Bonin et al. (1986). Note that a large intraspecific genetic differentiation has been found (Brand 1982), including variability within populations of a given sample.

At first glance, from the above account, there would be nothing suprising in this additional account of an *Emiliania* bloom in temperate shallow waters of the NE Atlantic. Several aspects deserve much attention, however.

First, blooms which have been ascribed (with due identification) to *E. huxleyi* seem to have all occurred in either inshore waters, bays and fjords (references in Braarud 1962 or Raymont 1980) or in truly oceanic waters.

Records from the slope waters (Holligan et al 1983 b) are associated with a specific hydrological event, namely : an increased vertical mixing due to tidal friction on the continental margin (Pingree and Mardell 1981 ; Mazé et al. 1986). In the present case, coccolithophorids have developed in the vicinity of a thermal, tidal boundary, the Ushant front. It may be noted that this structure was merely known, so far, as a preferential site for dinoflagellate blooms (Holligan 1983a ; Partensky and Sournia 1986). No reflectant patches were noticed outside the mentioned area, neither before (end of June) nor after (beginning of August) the mentioned dates. In other terms, there is a negative evidence that the phenomenon was a local one rather than a local episode of some regional phenomenon. There are also clear indication from hydrology and chemistry that the water mass was an, originally, mixed one which had recently undergone stratification. Thus, a front effect is typically involved under both its spatial and temporal acception (Legendre and Demers 1985 ; Frontier 1986). It can be noted, on this respect, that on both horizontal (Fig. 5b) and vertical (Fig. 5a) continuous profiles, the highest chlorophyll contents are located at or near the sharpest temperature gradients. Nevertheless, the proximate cause which triggered the phytoplankton outburst are left unexplained. Which is the favourable factor or situation brought about by the tidal front which initiated the explosive growth of *Emiliania*? The question is particularly delicate as this species proved to be an extremely opportunistic one, as shown above.

One remark may be put forward that could account for many other phytoplankton blooms as well. *E. huxleyi* possesses as its major carotenoid pigment the fucoxanthin

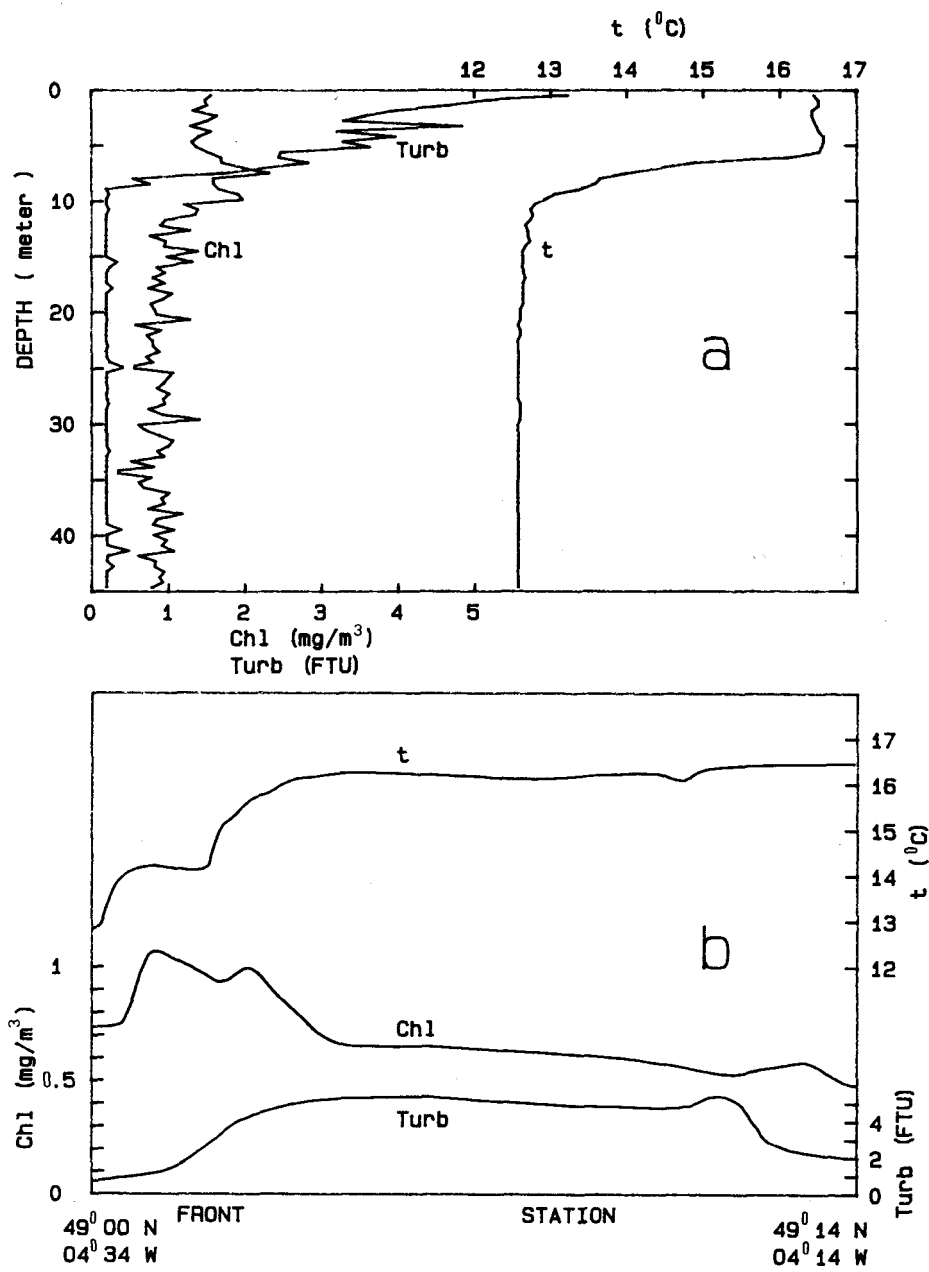


Fig. 5. Continuous measurements of water turbidity (Turb.), chlorophyll *a* (chlor.), and temperature (*t*), in the coccolithophore bloom area. (a) Vertical profile at station 205-3; (b) Surface records over a distance of 40 km. For location in the area, see Fig. 4, top.

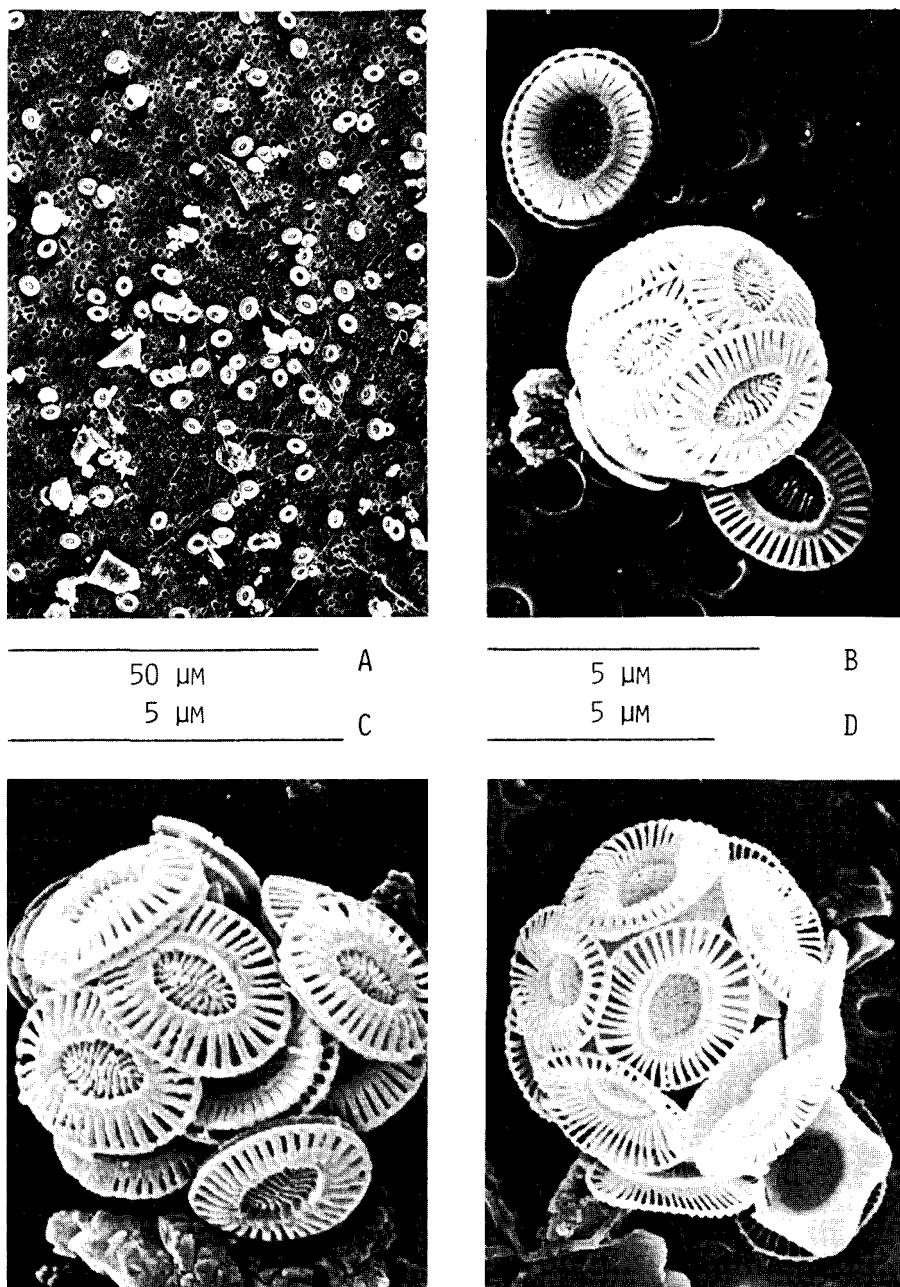


Fig. 6. Scanning electron microscopy on *Emiliana huxleyi* from Station 205-3. A-A counting field of dissociated coccoliths on the Nuclepore filter (surface sample). Note an intact cell which appears as a dense white dot on the left margin of the field ; this part is enlarged on the next photograph. B-Enlargement of the intact cell shown in A. It is presumably a young cell with about 10 coccoliths. One detached coccolith is seen in distal (external) view on top, another one in proximal (internal) view below ; their morphology is typical for warm water cells, with an open (not solid) central area or "shield" (McIntyre and Bé 1967). C-A dislocated cell which consisted of about 15 coccoliths (3-meter depth). D-A presumably older cell with about 15 coccoliths. One each of them the two plates are more separated from each other and the central shield is nearly solid. One coccolith seen in proximal view at the lower right corner shows both heavy calcification and marginal erosion (50-meter depth).

derivative 19' hexanoyloxyfucoxanthin which recently proved to be an efficient light-harvesting pigment (Haxo 1985). This relatively rare pigment is also found in two other organisms which are notoriously known to produce heavy blooms in the N.E. Atlantic: the dinoflagellate *Gyrodinium* cf. *aureolum* (ref. above) and the prymnesiophyte *Corymbellus aureus* (Gieskes and Kraay 1986). Hence the hypothesis that this peculiar carotenoid provides a selective advantage to a few phytoplankton species and allows them to develop a bloom strategy.

Another feature of interest is that the 1986 event was perceived as a suspension of coccoliths rather than a bloom of coccolithophorids. The bloom itself could be traced through the remaining number of disintegrated skeletal pieces. Note that the effective bloom would have yielded chlorophyll concentrations much higher than observed, even if admits that the amount of chlorophyll per cell is relatively small in *Emiliania* (Morel and Bricaud 1981; Bricaud et al. 1983). A "wasteful" overproduction of coccoliths, as considered by Westbroek et al. (1983) may also have taken place to some extent.

We have no indication about the precise date the living cells disrupted, nor do we know how long the coccoliths suspension remained in the upper layers. It is noteworthy, however, that the bloom disintegrated while it was still in the euphotic layer (rather than sinking and slowly disintegrating). On the other hand, the coccoliths have certainly remained in the upper meters of the ocean a matter of days. The sinking rate of intact cells has been estimated by several authors at about 1 m d^{-1} (references in Bonin et al. 1985) but individual coccoliths sink necessarily slower (laboratory measurements made by Honjo (1976) have lead to sinking rates $< 0.13 \text{ m d}^{-1}$ at temperatures $< 18^\circ\text{C}$ for individual coccoliths of *E. huxleyi*). In our observations, the thermocline seemed to act as an effective barrier against sinking, as shown by coccoliths counts at the different depths (Table 2). As a matter of fact, vertical transport seemed to be so low during the period study that an horizontal advection may have taken place between July 9 and July 17 (Figs. 3A and 4A).

The anomaly of reflectance has been detected by remote sensing, its marine (rather than atmospheric) origin has been proved by *in situ* measurements of turbidity and, eventually, its phytoplanktonic nature was elucidated through scanning electron microscopy. Two of these techniques are modern ones and two or three of them are but seldom used simultaneously. It is thus highly probable that similar phenomena have often escaped attention in the past. Yet,

their quantitative importance cannot be overlooked. The reflectant areas in 1986 covered 220 and 680 km^2 , on July 9 (Fig. 3B) and July 17 (Fig. 4B) respectively. The 1977 event (Le Fèvre et al. 1983), in so far as it had the same cause, affected an ocean area of 2100 km^2 ; the 1985 patch (Fig. 1) was about the same size. All these figures are quite smaller than the 1982 bloom on the continental slope which was estimated at 7,200 km^2 from which a production of 72,000 metric tons of calcium carbonate was calculated (Holligan et al. 1983 b). Even if the latter phenomenon was to prove to have been an exceptional one, none of these pelagic blooms should be held for negligible in terms of fluxes and budgets, particularly as regards the entrance of a regional, epicontinental sea such as the English Channel.

This is the second time at least (see Berge 1962) that *Emiliania* is found to be associated with the heterotrophic flagellate *Chilomonas marina* (Braarud) Halldal. Possible trophic relationships should then be looked for in the future. Another matter of interest are the specific optical properties of *E. huxleyi*. Braarud (cited in Berge 1962) was the first to suggest that coloration (or discoloration) of the sea could be related to an active reflection by the coccoliths rather than to absorption by photosynthetic pigments, as usual. Bricaud and Morel (1986) gave theoretical evidence that the backscattering coefficient for detached coccoliths is actually high and accounts for the observed values of reflectance.

Last, two remarks are to be made as regards the use of remote sensing in phytoplankton and primary production studies. First, although another colour analyser that would replace CZCS is desperately and urgently needed, yet the large band (s) of the existing meteorological satellites in the visible spectrum may be quite efficient in locating some types of phytoplankton developments or their remains. On the other hand, real-time assistance to operating vessels in shown here (1) to be practicable, at least within delays of one day (infrared imagery) or a few days (visible imagery); (2) to be of invaluable help for sea-truth measurements; (3) to allow the sampling strategy to be modified according to some unexpected or transient phenomenon.

Reference

- Berge G., 1962. Discoloration of the sea due to *Coccolithus huxleyi* "bloom". *Sarsia*, 6 : 27-40, 1 plate.
Bonin D. J., Droop M.R., Maestrini S. Y., Bonin M.

- C., 1986. Physiological features of six micro-algae to be used as indicators of seawater fertility. *Cryptogamie-Algologie*, 7 : 23-83.
- Braarud T., 1945. A phytoplankton survey of the polluted waters of inner Oslo Fjord. *Hvalrad. Skrif. Norske Vidensakad.*, 28 : 1-142.
- Braarud T., 1962. Species distribution in marine phytoplankton. *J. Oceanogr. Soc. Jap.*, 20th Anniv. : 628-649.
- Braarud T., 1963. Reproduction in the marine coccolithophorid *Coccolithus huxleyi* in culture. *Pubbls Staz. zool. Napoli.*, 33 : 110-116.
- Brand L. E., 1982. Genetic variability and spatial patterns of genetic differentiation in the reproductive rates of the marine coccolithophores *Emiliania huxleyi* and *Gephyrocapsa oceanica*. *Limnol. Oceanogr.*, 27 : 236-245.
- Bricaud A., Morel A., Light attenuation and scattering by phytoplankton cells. Theoretical modelling. *Appl. Optics*, 25 : 571-580.
- Bricaud A., Morel A., Prieur L., 1983. Optical efficiency factors of some phytoplankters. *Limnol Oceanogr.*, 28 : 816-832.
- Castagne N., Le Borgne P., Le Vourch J., Olry J. P., 1986. Operational measurement of sea surface temperatures at CMS Lannion from NOAA-7 AVHRR data. *Int. J. remote Sens.*, 7 : 953-984.
- Cox C., Munk W., 1954. Measurement of the roughness of the sea surface from photographs of the sun's glitter. *J. opt. Soc. Amer.*, 44 : 838-850.
- Frontier S., 1986. Studying fronts as contact ecosystems, p. 55-66. In J. C. J. Nihoul [Ed.], *Marine interfaces ecohydrodynamics*. Elsevier.
- Frunzel F., Koch C., 1976. Practical experience with the Variosens equipment in measuring chlorophyll concentrations and fluorescent tracer substances, like rhodamine, fluorescein, and some new substances. *IEEE J. Ocean Engin.*, OE (1): 21-32.
- Frunzel F., Koch C., 1980. Fast measurement of fluorescence tracers in flows and their turbidity. In : Intern. Symposium on Flow Visualisation, Inst. für Thermo-und Fluidodynamik, Ruhr Univ. Bochum., 5 p.
- Gieskes W. W., Kraay G. W., 1986. Analysis of phytoplankton pigments by HPLC before, during and after mass occurrence of the microflagellate *Corymbellus aureus* Green during the spring bloom in the Fladen Ground area of the North Sea in 1983. *Mar. Biol.*, 92 : 45-52.
- Groom F., 1986. AVHRR remote sensing of spatial variations of phytoplankton blooms (summary), In: Proceedings 2nd AVHRR Users Meeting, April 1986, Oxford 5 p.
- Groom S. B., Holligan P. M., Remote sensing of coccolithophore blooms. Proc. XXII Cospar Meeting (in press).
- Haxo F., 1985. Photosynthetic action spectrum of the coccolithophorid, *Emiliania huxleyi* (Haptophyceae) : 19'hexanoyloxyfucoxanthin as antenna pigment. *J. Phycol.*, 21 : 282-287.
- Heimdal B. R., Gaarder K. R., 1981. Coccolithophorids from the northern part of the Eastern central Atlantic. II. Holococcolithophorids. "Meteor" Forsch.-Ergebn. D., 33 : 37-69.
- Holligan P. M., Viollier M., 1986. Celtic Sea, Bay of Biscay, p. 75-77. In W. A. Hovis [Ed.], *Nimbus-7 CZCS Coastal Zone Color Scanner imagery, level II*. NASA Goddard Space Flight Center, Greenbelt.
- Holligan P. M., Viollier M., Dupouy C., Aiken J., 1983 a. Satellite studies on the distribution of chlorophyll and dinoflagellate blooms in the western English Channel. *Continental Shelf Res.*, 2 : 81-96.
- Holligan P. M., Viollier M., Harbour D. S., Camus P., Champagne-Philippe M., 1983b. Satellite and ship studies of coccolithophore production along a continental shelf edge. *Nature, Lond.*, 304 : 339-342.
- Honjo S., 1976. Coccoliths : production, transportation and sedimentation. *Marine Micropal.*, 1 : 65-79.
- Klaveness D., Paasche E., 1971. Two different *Coccolithus huxleyi* cell types incapable of coccolith formation. *Archiv Mikrobiol.*, 75 : 382-385.
- Koroleff F., 1970. Direct determination of ammonia in natural waters as indophenol blue, p. 19-22. In : information on techniques and methods for sea water analysis. Intern. Council Explor. Sea CM 1969 (C-9), Hydrogr. Committee.
- LE Fèvre J., Viollier M., LE Corre P., Dupouy C., Grall J. -R., 1983. Remote sensing observations of biological material by Landsat along a tidal thermal front and their relevancy to the available field data. *Estuarine coastal Shelf Sci.*, 16 : 37-50, 3 plates.
- Legenre L., Demers S., 1985. Auxiliary energy. ergoclines and aquatic biological production. *Naturaliste Can.* (Rev. Ecol. Systém.) 112 : 5-14.
- Maze R., Camus Y., LE Tareau J. -Y., 1986. Formation de gradients thermiques à la surface de l'océan, audessus d'un talus, par interaction entre les ondes

- internes et le mélange dû au vent. *J. Conseil perm. int. Explor. Mer.*, 42 : 221-240.
- Mcintyre A., Be A. W. H., 1967. Modern Coccolithophoridae of the Atlantic Ocean. I. Placoliths and cyrtoliths. *Deep-Sea Res.*, 14 : 561-597, 12 plates, tables.
- Mjaaland G., 1956. Some laboratory experiments on the coccolithophorid *Coccolithus Huxleyi*. *Oikos.*, 7 : 251-225.
- Morel A., Bricaud A., 1981. Theoretical results concerning light absorption in a discrete medium, and application to specific absorption of phytoplankton. *Deep-Sea Res.*, A, 28 : 1375-1393.
- Pingree R. D., Mardell G. T., 1981. Slope turbulence, internal waves and phytoplankton growth at the Celtic Sea shelf break. *Phill. Trans. R. Soc. Lond.*, A, 302 : 663-682.
- Raymont J. E. G., 1980. Plankton and productivity in the oceans (2nd ed.), vol. I. Phytoplankton, 489 p. Pergamon.
- Strickland J. D. H., Parsons T. R., 1972. A practical handbook of seawater analysis (2nd ed.). *Fish Res. Board Can., Bull.*, 167 : 311 p.
- Townshend J. R. G., Goff T. E., Tucker C. J., 1985. Multitemporal dimensionality of images of normalized difference vegetation index at continental scales. *IEEE Trans. Geosci. Remote Sensing*, GE 23 (6) : 888-895.
- Treguér P., LE Corre P., 1975. Manuel d'analyse des sels nutritifs dans l'eau de mer. Utilisation de l'"Autoanalyser II, Technicon" (2ème éd.), 110 p. Labor. Océanogr. chim. Univ. Brest.
- Viollier M., 1986. Utilisation des données "visible" de NOAA-9 au cours de la campagne "Iroise" (1-31 juillet 1986). *Bull. mensuel "Satmer", Centre Météor. spatiale Lannion.*, 35 : 20-23.
- Viollier M., Sournia A., Birrien J. -L., Morin P., 1987. Observations satellitaires du phytoplancton dans les zones de discontinuité hydrologique au large de la Bretagne. *Oceanol. Acta* (in press).
- Wafar M. V. M., LE Corre P., Birrien J. L., 1983. Nutrients and primary production in permanently well-mixed temperate coastal waters. *Estuarine coastal Shelf Sci.*, 17 : 431-466.
- Wald L., Monget J. M., 1983. Sea surface winds from sun glitter observations. *J. geophys Res.*, 88 : 2547-2555.
- Westbroek P., De Jong E. W., Van der Wal P., Borman T., De Vrind J. P. M., Van Emburg P. E., Bosch L., 1983. Calcification in Coccolithophoridae-Wasteful or functional? In "Environmental biogeochemistry" Ed. by R. Halberg. *Ecol. Bull. Stockholm.*, 35 : 291-299.

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