Satellite images of a "red tide" episode off Southern California

Remote sensing
Ocean colour
Phytoplankton
"Red tide"
Southern California

Télédétection
Couleur de l'océan
Phytoplancton
« Marée rouge »
Californie du Sud

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ABSTRACT

The evolution of a "red tide" episode, and of related water structures, was observed using satellite images of phytoplankton pigments and of sea-surface temperature. Intense phytoplankton growth started at coastal upwelling centres. The very high pigment concentrations observed along a segment of the coast apparently resulted from a combination of *in situ* growth and transport of a high-pigment "attached" eddy into that coastal area by ocean circulation. Onshore advection of warm water dissipated the "red tide". In addition, the sequence of satellite images allowed the visualization of some oceanographic processes and showed potential for short-term oceanic forecasting.

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RÉSUMÉ

Images satellitaires d'une « marée rouge » sur la côte de Californie du Sud

L'évolution d'une « marée rouge » et des structures hydrologiques associées a été observée par télédétection des pigments phytoplanctoniques et de la température superficielle de l'océan. Le développement rapide de la population phytoplanctonique a démarré dans des centres d'upwellings côtiers. Les très fortes concentrations de pigments phytoplanctoniques observées sur une partie de la côte semblent résulter de la croissance phytoplanctonique *in situ* et de l'arrivée dans cette zone côtière d'un tourbillon riche en pigments. L'advection d'eau chaude vers la côte a ensuite dissipé la « marée rouge ». De plus, la séquence d'images satellitaires a permis de visualiser quelques phénomènes océaniques et a montré des possibilités de prévision à court terme dans l'océan.

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INTRODUCTION

Episodic dinoflagellate blooms known as red tides, or discoloured water, can have significant effects on marine life, fishery resources, coastal economics, and public health (Prakash, 1975; Blasco, 1975). The oceanographic processes related to these blooms, however, are still poorly understood (for a general discussion of dinoflagellate blooms, *see* LoCicero, 1975; Taylor, Seliger, 1979; Anderson *et al.*, 1985).

In the last third of July 1980, a coastal band of yellow water suddenly became apparent off La Jolla, California. Cullen *et al.* (1982) measured some physical, chemical, and biological properties of the yellow water at a station 2-3 km west of the Scripps Institution of Oceanography, between July 26 and 31, 1980, and Huntley (1982) conducted grazing experiments with organisms from this water. Complementary information concerning this event can be found in these two references. Some of their major findings are: *Gymnodinium flavum*, a small (about 35 µm), naked dinoflagellate with yellow chromatophores, was the dominant organism (up to 6 000 cells/ml, comprising 80-99% of the phytoplankton). Chemical composition of the phytoplankton did not indicate progressive nutrient stress, and no significant grazing on *G. flavum* could be detected. Nonetheless, the yellow water disappeared rapidly by the end of July—early August. Moreover, little information on the early aspects of the episode was available, and spatial coverage during sampling was inadequate (Cullen *et al.*, 1982). The bloom of *G. flavum*, however, was also observed in late July, off Los Angeles (Kleppel, pers. comm.; *see* also Kleppel *et al.*, 1982).

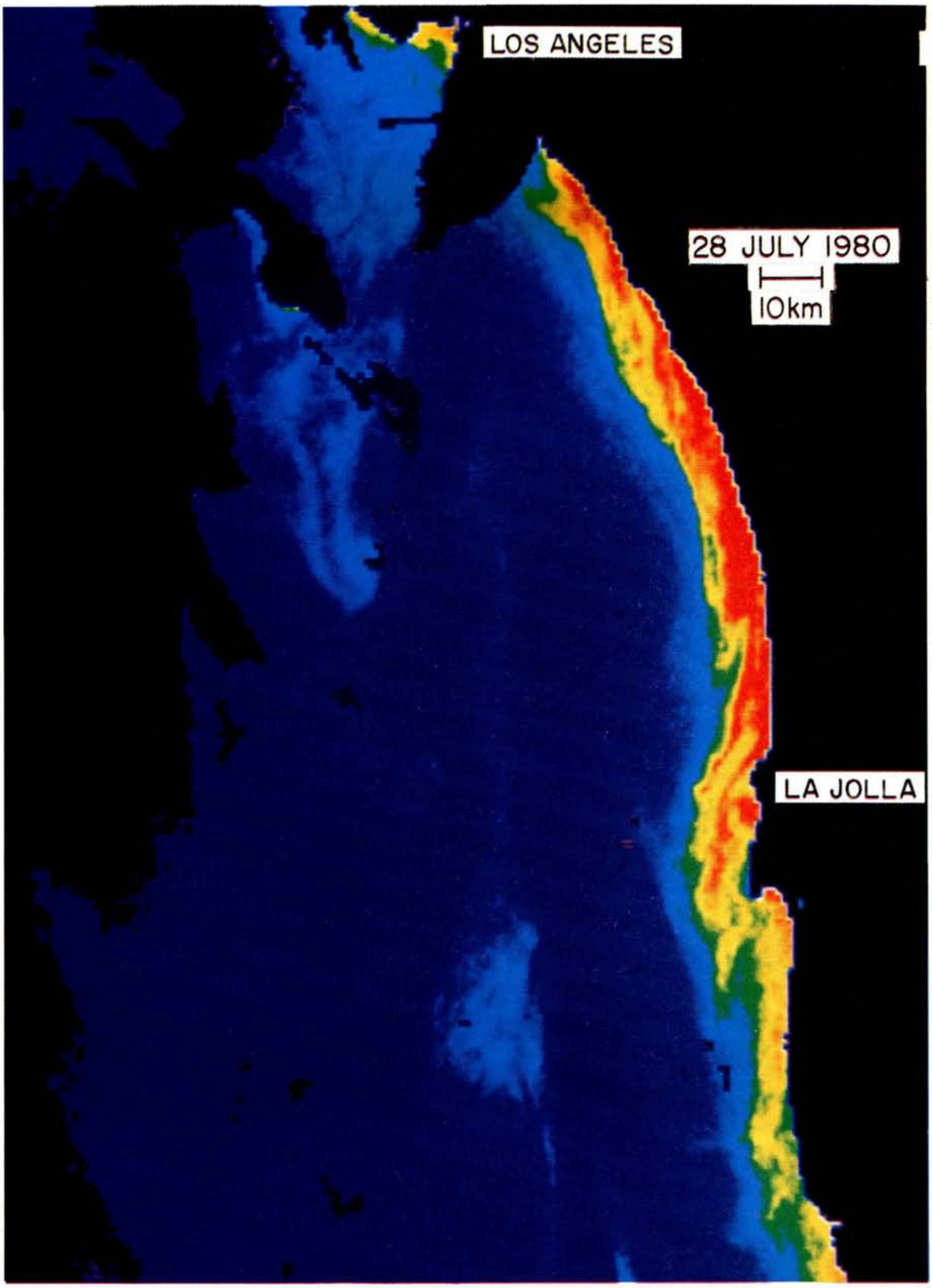

Figure 1

Arbitrary-colour image of phytoplankton pigments showing the extent and configuration of the "red tide" when the episode was at its peak (land and clouds are masked in black). The data (same as in Fig. 3 a) were obtained by the Nimbus-7 CZCS (ground resolution is about 825 m), near local noon on 28 July 1980. Vertical size of image corresponds to approximately 210 km. Phytoplankton pigments measured in situ *three hours after the satellite overpass at a station 2-3 km off La Jolla yielded a concentration of 19.9 mg/m³ (Cullen* et al., 1982)*; the satellite estimate at the same location is 15.2 mg/m³. Satellite estimates within the red area reach values up to about 30 mg/m³, but a few kilometres offshore, pigment concentrations drop drastically (less than 0.5 mg/m³ in the deep blue region).*

Pigments phytoplanctoniques au stade de développement maximum de la « marée rouge ». Les couleurs ont été choisies arbitrairement pour mettre en évidence l'extension et la structure de la « marée rouge » (la terre et les nuages sont masqués en noir). Les données (les mêmes que celles de la fig. 3 *a*) ont été obtenues par le CZCS (résolution d'environ 825 m) du satellite Nimbus-7, vers midi le 28 juillet 1980. La hauteur de l'image correspond à peu près à 210 km. La concentration en pigments phytoplanctoniques mesurée *in situ* trois heures après le passage du satellite dans une station située à 2-3 km au large de La Jolla est de 19,9 mg/m³ (Cullen *et al.*, 1982); la valeur estimée par satellite pour cette station est de 15,2 mg/m³. Les concentrations estimées par satellite dans la région de couleur rouge s'élèvent à environ 30 mg/m³, mais à quelques kilomètres au large elles diminuent fortement (moins de 0,5 mg/m³ dans la région bleu foncé).

MATERIAL AND METHODS

Data obtained by satellites and collected at the Scripps Satellite-Oceanography Facility offered the possibility of producing some of the missing spatial and temporal information associated with this event.

Forty-three satellite overpasses were analysed to investigate the oceanographic processes related to the initiation, maintenance, and dissipation of the yellow-water episode. The data were obtained from late June to early August, 1980, by the Coastal Zone Color Scanner (CZCS) and by the Advanced Very High Resolution Radiometer (AVHRR) on board the Nimbus-7 and NOAA-6 satellites, respectively. The CZCS data (Hovis *et al.*, 1980; Gordon *et al.*, 1983) were processed to yield quantitative phytoplankton pigment estimates (a detailed description and evaluation of the processing method can be found in Peláez, 1984; and in Guan *et al.*, 1985). Further processing of the images was done to obtain full definition of the pigment structures (and, therefore, equal grey shades of different images may not represent the same pigment concentration). The accuracy of the AVHRR data (Schwalb, 1978; McClain, 1981; Bernstein, 1982) was improved by incorporating some *in situ* sea-surface temperatures with the satellite data. The conclusions of this study, however, come from the synoptic observation of oceanographic processes using satellites, rather than from the absolute accuracy of the measurements.

RESULTS OBTAINED FROM THE SATELLITE IMAGES OF PHYTOPLANKTON PIGMENTS

The phytoplankton pigment images in Figures 1 and 3 *a* (July 28) show the extent and configuration of the yellow water observed from land. The yellow water consisted of a narrow (about 10 km), long (about 150 km), coastal band of very high pigment concentrations (up to about 30 mg/m^3). The yellow-water coastal band had a considerable amount of finer structure, usually in the form of streaks or sub-bands (Kamykowski, 1973; 1974), oriented almost parallel to the coastline. This image corresponds to the maintenance period of the yellow-water episode.

The image in Figure 2 *a* (July 11) shows that high-pigment areas started as localized centers of algal development, or "hot spots". The largest and most intense "hot spot" was over the Coronado shelf, south of La Jolla. This high-pigment patch (0.8 to about 2 mg/m^3) extended offshore into a counterclockwise "attached" eddy about 50 km in diameter. Secondary centres were located between La Jolla and Los Angeles, off Los Angeles, and a small one just off the heads of the La Jolla and Scripps submarine canyons (Fig. 2 *a*).

The images in Figures 2 *b* and 2 *c* (July 15 and 16, respectively) correspond to the strong algal-growth period. They show transport and intensification of the high-pigment structures (the assessment of transport was done in conjunction with analyses of the infrared imagery. The phytoplankton pigment images, however, kept the dynamic history of the waters longer, probably due to the reproductive capability of the cells.) In five days, the Coronado shelf eddy was displaced north by about 35 km, while being deflected towards the northern coastline in a clockwise advective motion (Fig. 2 *a*, 2 *b* and 2 *c*). In that time, the eddy also increased the length of its cross-shore axis by about 15 km. Apparently, an approximately one-half counterclockwise turn of the eddy core occurred in one day (Fig. 2 *b* and 2 *c*). The pigment feature between La Jolla and Los Angeles unexpectedly inverted its sense of rotation (Fig. 2 *a* and 2 *b*) and developed into a counterclockwise eddy attached to a coastal band of phytoplankton pigment stretching southwards (Fig. 2 *b* and 2 *c*). Thus, strong algal growth by mid-July was associated with a highly dynamic coastal region and with enhanced eddy activity.

It has been pointed out that some mechanism of physically concentrating dinoflagellates at the surface must operate in discoloured water blooms to account for the high cell densities observed (Holmes *et al.*, 1967; Eppley, Harrison, 1975). Nutrient concentrations available in the entire water column are usually insufficient to account for the nutrient content of the cells (*ibid*). Figures 2 *a*, 2 *b*, 2 *c* and 3 *a* suggest that progressive northern transport and clockwise advection of the Coronado shelf eddy converging towards the coast [in conjunction with the vertical movement of dinoflagellates (*see* Eppley, Harrison, 1975; Cullen, Horrigan, 1981)], result in the accumulation, or concentration, of cells in a narrow band along a segment of the coast. Thus, the very high pigment concentrations observed along a segment of the coast (Fig. 1 and 3 *a*) apparently resulted from a combination of *in situ* growth and transport of a high-pigment "attached" eddy into that coastal area by ocean circulation. The nutrients contained in the high cell densities are therefore obtained not only from the waters in the narrow coastal band of yellow water but also from a broader region of the ocean.

By early August, the yellow-water coastal band had dissipated (Fig. 3 *b* and 3 *c*). Also, pigment concentrations in the Southern California Bight became quite low (about 0.1 to 0.6 mg/m^3), except in some specific places. Dissipation of the yellow water and change to an oligotrophic regime (Strickland *et al.*, 1970; Eppley *et al.*, 1970; Cullen *et al.*, 1982) were apparently related to a low-pigment water mass intruding from the south (darker tongue immediately offshore of the yellow-water coastal band in Figures 1 and 3 *a*). Additional evidence of a southern intrusion is provided by the deflection, or compression (10-15 km in one day) towards the north, of the coastal patches in Figures 3 *b* and 3 *c*.

A slight digression here: the images in Figures 3 *b* and 3 *c* also show that coastal plumes or patches of higher than background pigment content occurred in the vicinity of major ocean outfalls in Southern California (*see* also Eppley *et al.*, 1972; Mearns, 1981). Four major ocean sewage outfalls (indicated by arrows in

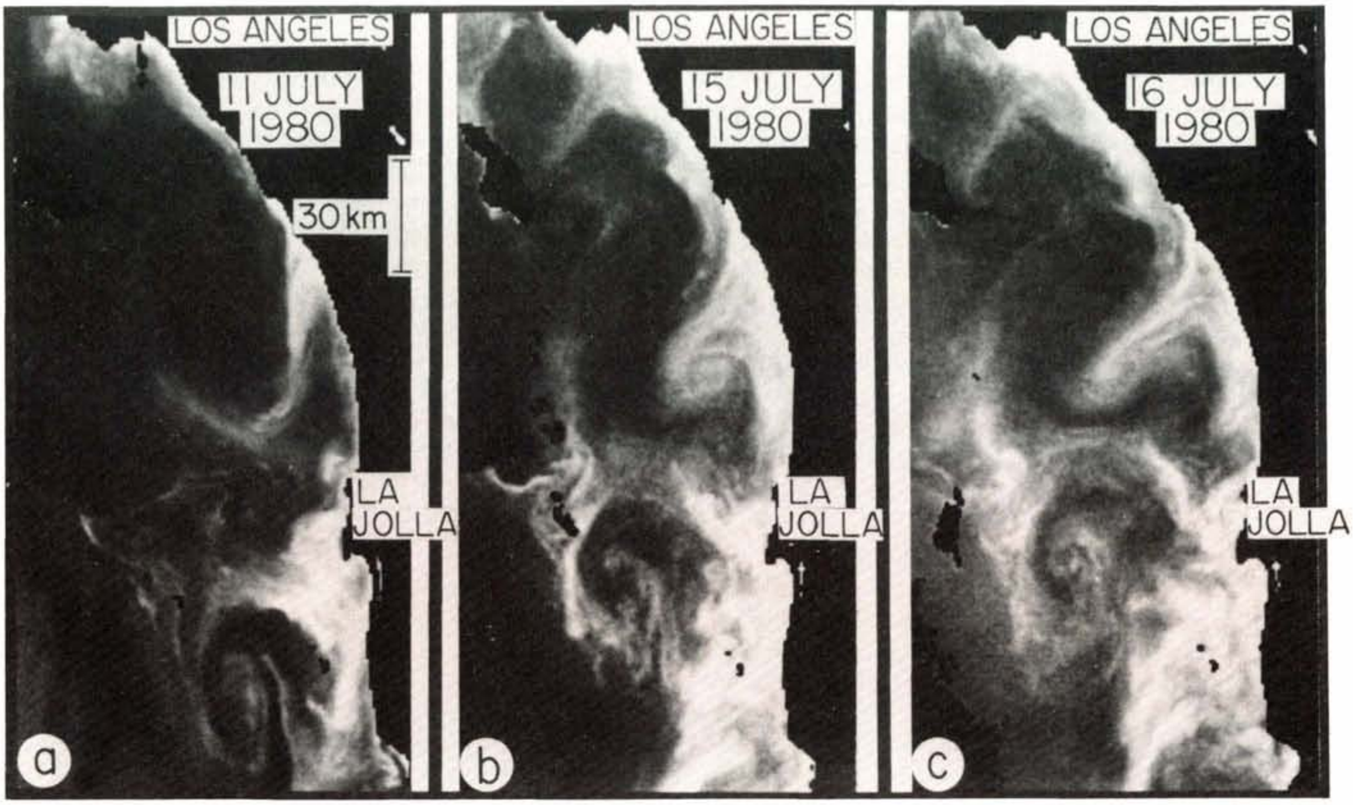

Figure 2

Phytoplankton pigment images off Southern California derived from Nimbus-7 CZCS data. Vertical size of images corresponds to approximately 210 km. Lighter grey shades represent higher pigment concentrations (land and clouds are masked in black). Here, pigment concentrations range from about 0.1 to about 6 mg/m^3. Successive aspects of the yellow-water episode are as follows: a) early algal development; b) and c) intense algal growth (see text for further details).

Pigments phytoplanctoniques le long de la côte de Californie du Sud. Images obtenues à partir de données du CZCS du satellite Nimbus-7. La hauteur des images correspond à peu près à 210 km. Plus la teinte est claire, plus la concentration de pigments est élevée (la terre et les nuages sont masqués en noir). Ici, les concentrations en pigments varient d'environ 0,1 jusqu'à environ 6 mg/m^3. Les étapes successives du développement de la « marée rouge » sont les suivantes : *a*) développement phytoplanctonique initial; *b*) et *c*) poussée phytoplanctonique intense (*voir* le texte pour informations complémentaires).

Figures 3 *b* and 3 *c*), at approximately 60 m depth, account for about 90% of the estimated 4.5. 10^9 l of sewage and sewage sludge discharged daily along the Southern California coast (Mearns, 1981). However, alternative explanations for the origin of these plumes cannot be ruled out using only the satellite images (*e. g.*, effects due to submarine canyons or rapidly deepening slopes in the vicinity of the outfalls, or entrainment of deep, nutrient-rich waters into the euphotic zone during initial dilution of the effluent by the diffusers, or other possible explanations). Further study is clearly needed, but, in any case, Figures 1, 2, and 3 show that the coastal plumes stood out only after establishment of the oligotrophic regime and after the yellow-water event had ended. Thus, this yellow-water event apparently was not sewage-induced (similar conclusions were reached by Lackey, Clendenning, 1963; Holmes *et al.*, 1967; and Mearns, 1981). In case the plumes are of outfall origin, Figures 1, 2, and 3 show that the outfall monitoring capabilities of the processed CZCS imagery may be restricted to oligotrophic conditions.

One additional remark: real-time analyses of pigment images may help forecast the appearance of "red tides". To do this, sequential images should be examined searching for areas with higher than normal pigment concentrations, or with unusually rapid algal growth (*i. e.*, the early stages of a possible bloom). Then, *in situ* determination of algal species at selected locations should be made (dinoflagellates cannot be identified using only CZCS data). If dinoflagellates are dominant at these locations, transport of high-pigment patches should be assessed, watching carefully for processes that may lead to accumulation of the algae (*e. g.*, convergence situations, like high-pigment patches being transported towards the coastline, or against each other). Accordingly, areas that may be attained by such parcels of high-pigment water can be given early notice.

RESULTS OBTAINED FROM SATELLITE INFRARED IMAGES AND SCRIPPS PIER MEASUREMENTS

An effort was made to understand the physical oceanography of a broader region of the ocean using satellite infrared imagery. Figure 4 (July 11) and analyses of previous imagery show an intrusion of warmer southern and offshore waters (large dark area near the coast in Figure 4). This intrusion was definitely established in the Southern California Bight by late June 1980. Analyses of satellite data for other years (Peláez, 1984) and of historical shipboard data (Wyllie, 1966; Tsuchiya, 1980) show that this intrusion of southern

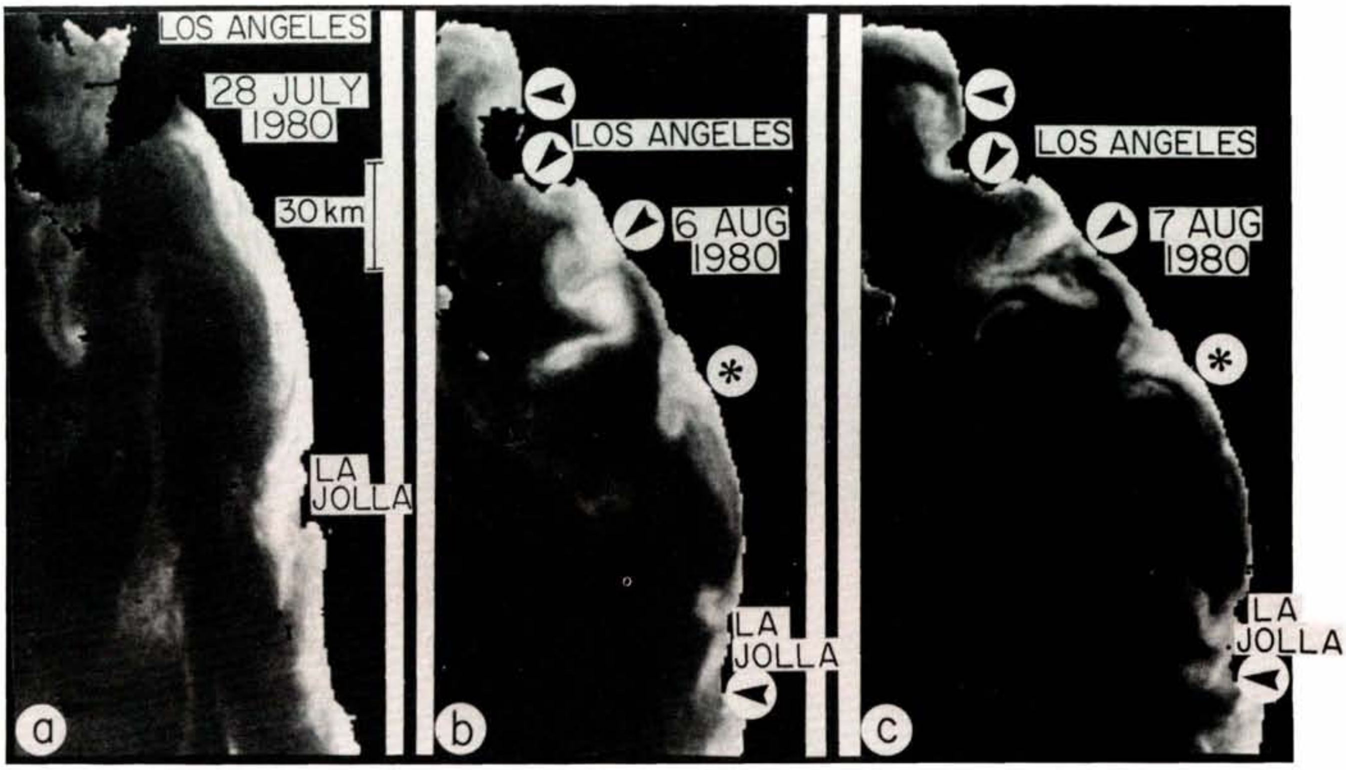

Figure 3

Analogous to Figure 2, but for subsequent aspects of the episode: a) compressed coastal band of yellow water. Highest pigment concentrations are about 30 mg/m³; b and c) post-episode situation. Pigment concentrations off Southern California became quite low (concentrations here go from less than 0.1 to about 2 mg/m³). Arrows indicate the four major ocean sewage outfalls along the Southern California coast and the asterisk indicates the San Onofre Nuclear Power Generating Station.

Même légende que la figure 2, mais pour la suite de l'évolution de la « marée rouge » : a) bande d'eau de très forte concentration en pigments phytoplanctoniques serrée contre la côte. Les concentrations les plus élevées sont d'environ 30 mg/m³; b et c) situation après la « marée rouge ». Les concentrations de pigments au large de la Californie du Sud sont devenues assez basses, allant de moins de 0,1 jusqu'à environ 2 mg/m³. Les flèches indiquent les positions des quatre principales sorties d'égoûts sur la côte de Californie du Sud et l'astérisque indique la position de la centrale nucléaire de San Onofre.

and offshore water actually occurs every year (Peláez, McGowan, 1986). The establishment of the warm-water intrusion in the bight by late June–early July on a yearly basis most likely represents the turning point from a spring to summer ocean regime in this region.

The dinoflagellate bloom of July 1980 started not long after establishment of the intrusion of southern and offshore warm waters. The change of regime associated with the intrusion appeared to be an important component of the bloom, apparently by establishing conditions [warm, nutrient-poor surface layer, and a deeper nutricline (Strickland *et al.*, 1970; Eppley *et al.*, 1970; Eppley *et al.*, 1978)] in which motile cells have a nutrient-uptake advantage (Eppley, Harrison, 1975) over other algal groups. Blooms of diatoms (non-motile algal cells) apparently do not occur in nearshore Southern California during the second half of the year (Tont, 1976; 1981), *i. e.*, when the intrusion of Southern and offshore waters is present in this region (Peláez, McGowan, 1986).

Only three blooms of *G. flavum* are on record: in 1914, 1961, and 1980, all in July (Kofoid, Swezy, 1921; Lackey, Clendenning, 1963; Wilton, Barham, 1968; Cullen *et al.*, 1982). Besides providing northward transport, the intrusion from the south and offshore in June-July might also be a source of *G. flavum* cells, which apparently are not common inhabitants of Southern California waters. Indications of transport of algal species from subtropical or even tropical waters into the La Jolla area have been reported (Balech, 1960; Tont, 1976). The triggering of potential benthic cysts (Steidinger, 1975; Wall, 1975) probably represents a less likely mechanism for successfully introducing this seemingly occasional species.

After the warm-water intrusion was established in the Southern California Bight, an unusually strong and persistent coastal upwelling episode occurred. It started as small and localized pockets of cooler water (Fig. 4) that enlarged to a coastal band (10-20 km wide) of cool water (13-16°C) with tongues, or jets, projecting offshore (Fig. 5 *a*). Winds measured at Lindbergh Field (Local Climatological Data, NOAA, 1980), about 17 km south of Scripps, show that winds from the WNW (290° on average) prevailed (Reid *et al.*, 1958; Strickland *et al.*, 1970) throughout the cool water period (Fig. 6 *a* and 6 *b*). The July 1980 cooling episode was exceptionally intense (13°C on July 13 is the second coldest day in July, in the 64-year Scripps Pier record), exceptionally rapid (9°C in six days is the strongest cooling event on record), and unusually persistent (three weeks continuously below the 64-year mean of 19.9°C).

Figure 4

Sea-surface temperature image off Southern California obtained from NOAA-6 AVHRR infrared data (ground resolution is about 1.1 km). The image is about 560 km on a side. Lighter grey shades represent cooler sea-surface temperatures (white, puffy features are clouds). The warm-water intrusion from the south and offshore is contoured at about 16°C.

Température de surface de mer au large de la côte de Californie du Sud. Image obtenue à partir de données infrarouges du AVHRR du satellite NOAA-6 (résolution d'environ 1,1 km). Chaque côté de l'image correspond à peu près à 560 km. Plus la teinte est claire, plus la température est basse (les structures blanches pommelées sont des nuages). L'intrusion d'eau chaude venant du sud et du large est délimitée ici par l'isotherme 16°C.

Very intense cooling during the first six days, slow relaxation of the unusually cold temperatures in the following two weeks, and a surge of warmer water followed by more or less progressive warming in the last twelve days resulted in a non-symmetrical episode.

Lower temperatures associated with higher salinities at the Scripps Pier (Fig. 6 *a*) indicate a deeper origin of the cooler coastal waters (Reid *et al.*, 1958; Strickland *et al.*, 1970). Intense algal growth (Fig. 2 *b* and 2 *c*) at or near most of the cooler water areas (Fig. 5 *a*) indicates that the nutrients needed for the bloom were brought into the euphotic zone by the coastal upwelling event (Strickland *et al.*, 1970; Eppley, Harrison, 1975; Eppley *et al.*, 1979; Cullen *et al.*, 1982). Freshwater runoff appears to be unimportant (Holmes *et al.*, 1967) in relation to this bloom: there is little river discharge in this region and less than 0.03 cm of precipitation for June, July and August 1980 (Local Climatological Data, NOAA, 1980).

By mid-July (Fig. 5 *a*), several eddies [tens of kilometres in diameter (*see* Winant, 1983), apparently all counter-clockwise (Pingree, 1978)], generalized swirling, and extremely patchy conditions prevailed in the Southern California Bight. The cores of the eddies were warm, and cooler water jets, or filaments, projecting offshore were entrained to the interior of the eddies (Fig. 5 *a*). This and the presence of the warmer water intrusion immediately offshore apparently reduced washout and increased the residence time of the nutrient-rich, upwelled waters. The entrainment of recently upwelled coastal waters to the interior of eddies located immediately offshore produced algal patches with spiral shapes (Fig. 2 *a*, 2 *b* and 2 *c*). These patches are a result of algal growth in the nutrient-rich filaments that are being wound up progressively from the coast towards the centres of the eddies.

In the last week of July there was an intensification, or surge, of the warm-water intrusion upon a weakening

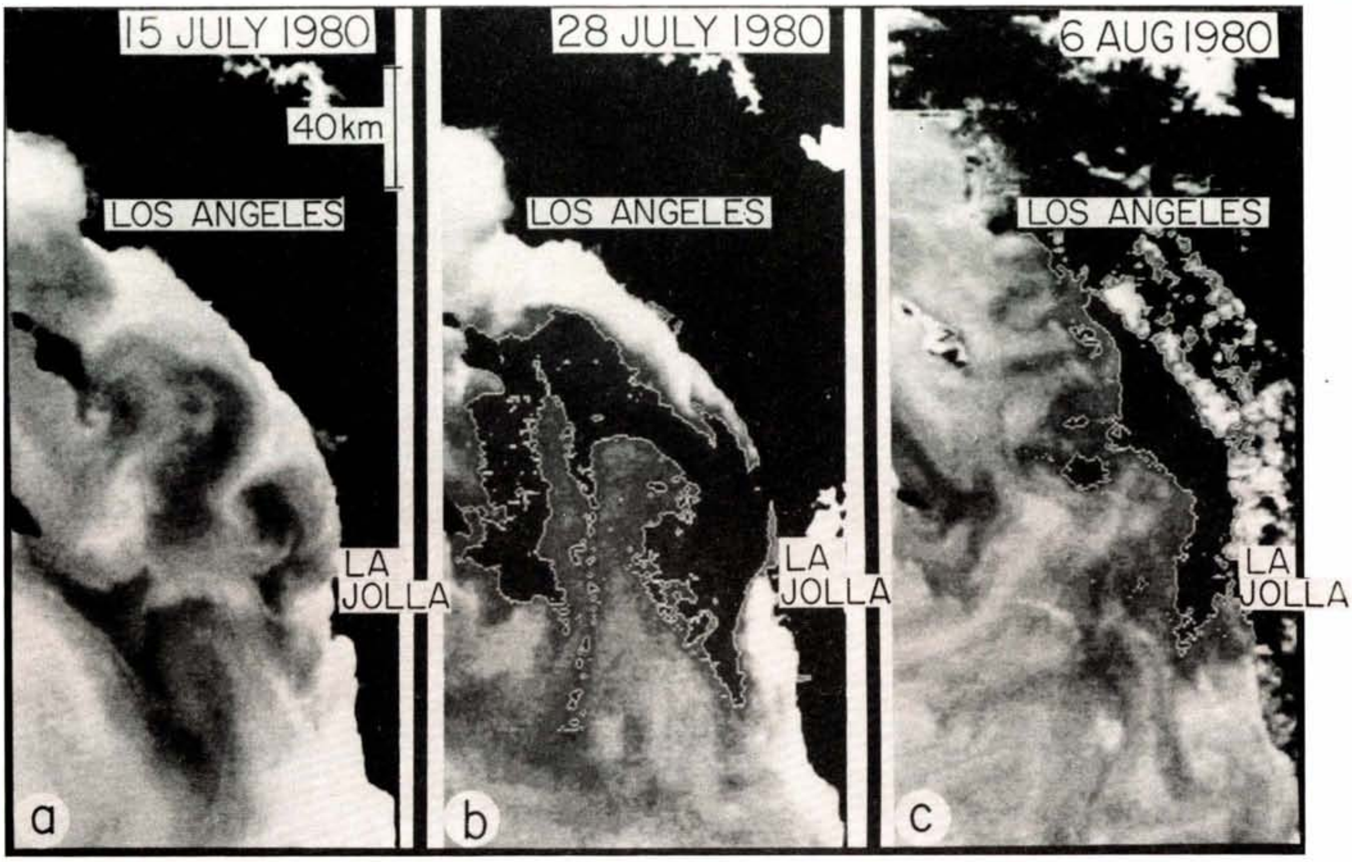

Figure 5

Analogous to Figure 4, but vertical size of images corresponds to approximately 280 km. Subsequent aspects of water structures related to the yellow-water episode are as follows: a) intense coastal upwelling; b) warm water mass (contoured at about 20°C) immediately offshore of the weakening coastal upwelling; c) onshore collapse of the warm water mass (contoured at about 22°C) as it converges towards the coastline (see *text for further details*).

Même légende que la figure 4, mais la hauteur des images correspond à environ 280 km. L'évolution des structures hydrologiques associées à la « marée rouge » est la suivante : a) upwelling côtier intense; b) affaiblissement de l'upwelling côtier et apparition juste au large de celui-ci d'une masse d'eau chaude, délimitée par l'isotherme 20°C; c) diminution progressive de la masse d'eau chaude (délimitée ici par l'isotherme 22°C) au fur et à mesure qu'elle converge vers la côte (*voir* le texte pour informations complémentaires).

coastal upwelling (Fig. 5 *b*). Higher temperatures associated with higher salinities at the Scripps Pier, from late July until the end of the study period (Fig. 6 *a*), also indicate the presence of more southern and offshore waters by the coast. The convergence towards the coast of this large, warm water mass (darker area in Fig. 5 *b*) initially appeared to concentrate the motile dinoflagellates in a surface layer against the coastline (Fig. 1 and 3 *a*). This confirms the preceding accumulation idea. Further onshore advection of this warm water mass, however, changed the coastal regime to oligotrophic, making nutrients suddenly unavailable to the dinoflagellates (rapid change to warm and nutrient-depleted waters was observed *in situ* near Scripps on July 30, 1980, by Cullen *et al.*, 1982).

By early August, additional onshore movement of the warm water mass resulted in its progressive collapse against the Southern California coastline (Fig. 5 *c*), under apparent coastal downwelling (Winant, 1980). Onshore movement of this water mass washed ashore part of the dinoflagellate population (observed at Scripps beach) and dissipated most of the remaining cells (the coastal band has almost disappeared in Figures 3 *b* and 3 *c*; *see* also Cullen *et al.*, 1982). Thus, rapid onshore advection of a warm, nutrient-poor water mass appears to be the major factor terminating this yellow-water event.

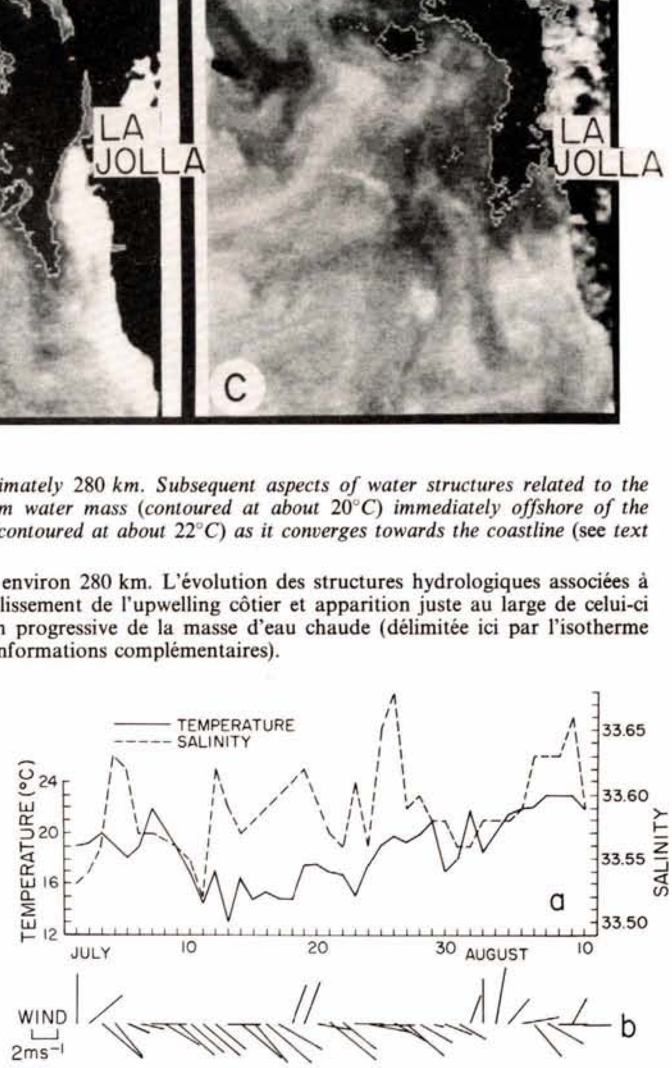

Figure 6

a) Scripps Pier sea surface temperatures (———) *and salinities* (– – –); *b) coastal winds measured at Lindbergh Field (about 17 km south of Scripps).*

a) températures superficielles de la mer (———) et salinités (– – –) relevées à l'extrémité de la jetée de l'Institut océanographique Scripps; b) vents côtiers mesurés à l'aéroport Lindbergh (situé à environ 17 km au sud de l'Institut océanographique Scripps).

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