An evaluation and interpretation of CZCS-derived patterns on the Adriatic shelf

CZCS
Multiple scattering
Adriatic Sea stratification
Po river discharge
Wind forcing

CZCS
Diffusion multiple
Stratification de la Mer Adriatique
Décharge du fleuve Po
Coups de vent

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ABSTRACT

The aim of the present paper is to investigate further the previously observed dichotomy in the Adriatic waters influenced by the Po river. To that end, an existing algorithm for pigment concentration retrieval has been improved and applied to the reprocessing of selected summer 1981 and winter 1981/1982 images of the Adriatic Sea. The sensitivity loss correction procedure has been included in the retrieval algorithm and rendered coherent with the atmospheric correction model. The model was also updated to allow for multiple Rayleigh scattering, and site-specific calibrated for case 2 waters of the Northern Adriatic.

Our analysis of the images reinforces the previous finding (Clément *et al.*, 1987) that two types of CZCS-derived patterns can be observed on the Adriatic shelf: one, elongated, trapped along the Italian coastline; and another wide, irregularly spread into the basin interior. However, according to our results, the two patterns are not seasonally restricted, *i. e.* both may occur in summer and in winter. In summer, when the Northern Adriatic is stratified, the Po-influenced waters spread at the surface into the basin interior. A lower Po discharge may restrain the river-affected waters to a narrow coastal band. In winter, when the Northern Adriatic is vertically well mixed, the river-affected waters remain confined to the Italian coastal strip all the way down the shelf edge and into the Southern Adriatic. However, strong episodes of spatially heterogeneous bura wind can provoke intrusions into the basin interior.

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RÉSUMÉ

Évaluation et interprétation des échantillons dérivés de CZCS sur la plateforme adriatique

L'objectif de cet exposé est une investigation approfondie de la dichotomie - déjà remarquée et observée auparavant - dans les eaux de l'Adriatique sous l'influence du fleuve Po. Dans ce but, on a amélioré un algorithme - déjà existant - pour déterminer la concentration du pigment et on l'a appliqué pour retraiter les images sélectionnées de la Mer Adriatique pendant l'été 1981 et l'hiver 1981/1982. On y a inclus la procédure pour la correction de la perte de sensibilité et on l'a rendue cohérente avec le modèle de la correction atmosphérique. Le modèle a été mis à jour pour une diffusion de Rayleigh multiple dans le cas 2 des eaux de l'Adriatique septentrional.

Notre analyse des images confirme les résultats précédents (Clément *et al*., 1987) et la possibilité de distinguer deux types d'échantillons de CZCS sur la plateforme adriatique. Le premier est allongé, bloqué le long de la cote italienne, et l'autre est large, étendu irrégulièrement sur le bassin intérieur. Pourtant - ainsi que nos explorations l'ont prouvé - les deux échantillons ne sont pas conditionnés par la saison, c'est-à-dire qu'ils peuvent apparaître aussi bien en été qu'en hiver. En été, quand la Mer Adriatique est stratifiée, les eaux sous l'influence du Pô se dispersent en surface vers le bassin intérieur. La décharge de l'estuaire du Pô peut retenir les eaux touchées par le fleuve dans l'étroite région côtière. En hiver, quand l'Adriatique septentrionale est bien mélangée le long de la verticale, les eaux touchées par le fleuve restent coincées dans la ligne côtière italienne, tout le long du bord de la plateforme et dans la direction de l'Adriatique méridionale. Pourtant, les bourrasques du vent «bura», très hétérogène dans l'espace, peuvent provoquer les intrusions dans le bassin intérieur.

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INTRODUCTION

The Adriatic Sea is a shallow inland sea with significant fresh water input, about half of which is due to the Po river discharge. Its bio-optical properties are therefore profoundly influenced by the dissolved and suspended organic and inorganic material brought by the Po river. Consequently the basin is particularly suitable for the remote sensing detection of changing optical features. In recognition of this, it was selected as one of the test sites for the Coastal Zone Color Scanner (CZCS), a sensor launched in October 1978 on board the Nimbus-7 satellite. That, in turn, permitted a number of Adriatic-related studies involving both retrieval algorithm development and remote-sensing aided oceanographic work.

In one of the earliest attempts to establish a correspondence between satellite-observed features and known oceanographic aspects of the Adriatic Sea, Barale *et al*. (1984) used CZCS-visible and IR data to study the circulation features of three Adriatic regions (northern, central and southern), applying satellite imagery in a qualitative way to explore the surface dynamics. Evaluating patterns of optical and thermal properties on synoptic and seasonal scales, they managed to confirm the knowledge previously established using empirical and mathematical modelling data. Viollier and Sturm (1984) used Adriatic data, among other sets, to show that general CZCS algorithms can be improved when adjusted to account for specific/prevailing oceanographic conditions in the area. In particular they found the ratio algorithms generally suitable for retrieval of chlorophyll content, but coefficient-dependent on phytoplankton type. In their sediment algorithm they successfully combined the use of reflectance ratio and amplitude reflectance to distinguish between the offshore upwelling fronts and turbid frontal structures in the nearshore coastal waters.

Alberotanza *et al*. (1985) attempted to confront a satellite remote sensing image (CZCS) and a computer simulation of advection/diffusion of a passive tracer in a field of tidally induced (vertically integrated) currents, reporting encouraging albeit qualitative agreement. Barale *et al*. (1986) used a time series of CZCS scenes for the years 1979 and 1980 to study the surface colour field and circulation patterns of the Northern Adriatic on monthly and interannual scales. They were able to use different pigment levels to distinguish coastal and open sea water masses, and thereby outline principal surface circulation patterns. The authors also considered the possible relevance of prevalent wind fields and concluded that, on the considered scales, wind was ineffective in relation to pigment distribution. In a later paper Barale *et al*. (1987) reported a study of the Po river impact on physical and biological characteristics of the Northern Adriatic basin. They followed the spatial and temporal evolution of a chlorophyll-like pigment concentration in a series of 110 CZCS-derived images collected during 1979 and 1980. The authors were able to confirm the Po river profound influence on hydrological properties and circulation in the basin, in particular the direct relationship between the Po flow rate and the size of surface colour features. The fact that some 30 % of the scenes, mostly falling in the October to February period, proved unsuitable for analysis testifies well to the problem of representing the winter Adriatic conditions. Clément *et al*. (1987) reported a work similar to Alberotanza *et al*. (1985) in the sense that a CZCS image was compared to a computer simulation (dominated by seven-harmonic tidal signal), again with encouraging but essentially qualitative agreement. One important difference came from the use of a more sophisticated mathematical model (baroclinic, three-dimensional, turbulent energy). Sturm (1987) addressed the accuracy of the determination of pigment concentration from CZCS data and attempted to calculate the temporal distribution of a chlorophyll-like pigment mass in a Northern Adriatic area.

Most recently, Kuzmić (1991) reported the first attempt to verify the results of wind-induced current modelling for the Northern Adriatic using CZCS data. In particular, remotely sensed evidence was found for the previously studied effect of spatially heterogeneous bura (gusty, katabatic wind of NE direction). Comparison of model-generated and sensor-collected information suggested that bura-induced gyre was the mechanism responsible for the particular spatial pattern change observed in the CZCS detected radiance and derived pigment concentration.

The purpose of the present paper is to probe further the previously observed dichotomy in the Adriatic waters influenced by the Po river (river-affected waters being trapped within a narrow coastal strip *vs.* buoyant, surface offshore spreading). To that end an existing algorithm for pigment concentration retrieval (Sturm, 1990) has been improved and applied to reprocess selected summer 1981 and winter 1981/1982 images for the Adriatic shelf. The algorithm, improvements and image processing are presented in the second section. The processing results are analysed and discussed in the third section. To aid the discussion, available relevant empirical data, namely the Po river flow rate and temperature, the Northern Adriatic temperature, and wind in the area, were also used. The results are summarized in the final section.

CZCS DATA PREPARATION AND PROCESSING

Our concern has been with the satellite-detectable response of Adriatic shelf waters (Fig. 1) to various forcings and changes in meteorological and/or hydrographic conditions. In order to facilitate later qualitative oceanographic analysis, the preparation of pigment maps (chlorophyll *a* + phaeophytin) was done in two steps: atmospheric and geometric correction. An effort was made to render the retrieval algorithm up to date and site-specific.

The satellite-measured total pixel radiance was corrected for atmospheric effects using software previously developed at the CEC Joint Research Centre Ispra (Sturm and Nykjaer, 1985). The software has been improved by introducing updated sensitivity loss correction factors (SLCF), evaluated with a method described by Sturm (1986). The correction procedure has been applied in response to indications that the radiometric sensitivity of the CZCS has been decreasing with time. This sensitivity decay has been evaluated previously by Gordon *et al*. (1983), Mueller (1985) and Sturm (1986) by comparing expected and CZCS-measured sensor aperture radiances over clear water zones of the ocean. According to our experience, such evaluations are extremely sensitive to the model used for the calculation of the atmospheric path radiance, especially of its Rayleigh component. In order to minimize systematic errors, the model used for the simulation of the expected aperture radiances and that later used for atmospheric correction must be coherent. For this reason the SLCFs have been reevaluated using the most recent version of the CZCS processing software updated to allow for multiple Rayleigh scattering (Gordon *et al*., 1988). The result of the applied procedure is given in Figure 2. It may readily be observed that the sensitivity decay affects primarily the blue region (channel 1) thus affecting in major part the evaluation of the blue-green ratio which is sensitive to the pigment content of the water. The updated software also allows for the evaluation of a spatially varying wavelength dependence of the aerosol scattering (Angstroem exponent) over case 1 waters using the procedure proposed by Bricaud and Morel (1987).

To develop a site-specific interpretation algorithm for the Northern Adriatic, a CZCS calibration campaign was carried out in the area in the autumn of 1984. The campaign, designated *Adria 84*, included among other activities measurements of depth profiles (at 22 stations) of chlorophyll-like pigments (chlorophyll *a* + phaeophytin), total suspended matter concentration and of yellow substance absorp-

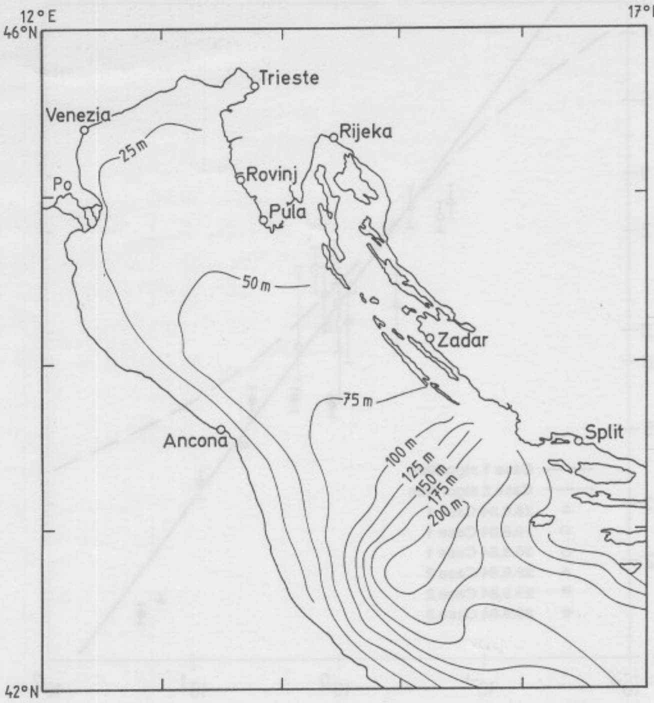

Figure 1

Bathymetry and lateral geometry of the Adriatic shelf.

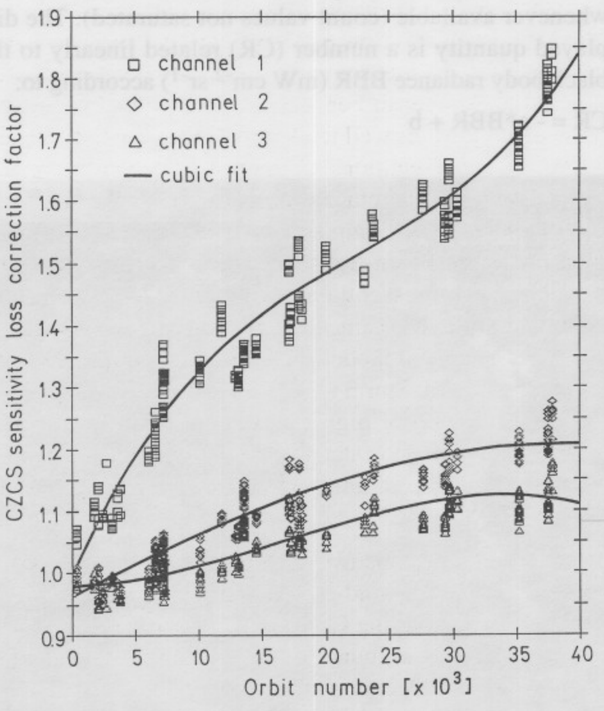

Figure 2

CZCS sensitivity loss correction factor variability in time (presented as orbit numbers). Discrete data points and cubic fit to them are indicated for the first three channels (the fourth is assumed to have no sensitivity loss). The fitted equations are:

$SLCF_{443} = 0.997 + 4.592\,N - 15.387\,N^2 + 22.95\,N^3$,

$SLCF_{520} = 0.962 + 1.086\,N - 0.68\,N^2 - 1.265\,N^3$,

$SLCF_{550} = 0.981 + 3.375\,N^2 - 7.37\,N^3$,

where N = Orbit 100 000.

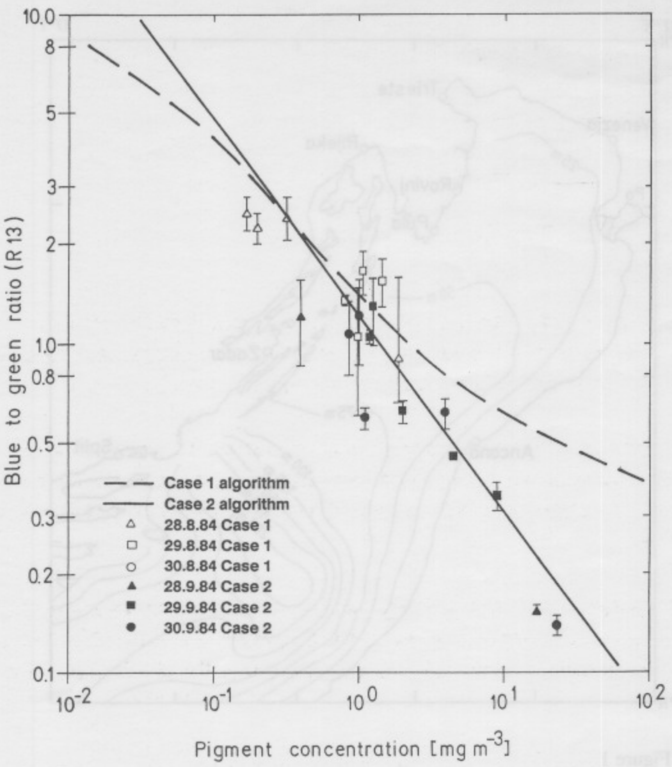

Figure 3

Correlation between the blue-green ratio and optically weighted pigment concentration. Solid symbols indicate case 2 pixels according to the criterion R_{sub} (550) > R^{lim}_{sub}(550), where term on the right is the upper limit of subsurface reflectance for case 1 water (Bricaud and Morel, 1987). Error bars estimate uncertainty in R13 due to sea truth location misalignment and inaccuracies in sensitivity correction factors.

tion at 450 nm (for more details *see* Schlittenhardt, 1986). Optically weighted pigment concentrations that correspond to the optical signal measured by the CZCS were obtained by weighting the pigment depth profiles taken at each station with an exp (- 2Kz) function over an attenuation length (equal to K^{-1} m; K is the diffuse attenuation coefficient and z is depth coordinate) following Clark (1981).

To derive a case 2 water algorithm, 21 pigment measurements from three successive days (28, 29 and 30 August) were correlated with the CZCS-derived blue-green ratios at their ship positions on the scene of 29 August 1984. The result is shown in Figure 3; it shows the channel 1 to 3 ratio of the water-leaving reflectances as a function of the optically weighted pigment concentrations measured at the stations shown in Figure 4. In the figure the solid line is the best fit to data:

$$\text{Pigment (mg m}^{-3}) = 1.4*(R1/R3)^{-1.68}$$

and the dashed line (obtained following André and Morel, 1989) represents the case 1 water algorithm. The discrimination criterion for case 2 waters was the requirement that

$$R_{sub}\ (550) > R^{lim}_{sub}\ (550)$$

where the term on the right is the upper limit of subsurface reflectance for case 1 water (Bricaud and Morel, 1987). When the case 2 water curve is compared to that of case 1, it may be observed that the case 2 waters have lower pigment concentrations at decreasing blue-green ratios. This can be explained by the greater amount of dissolved and suspended absorbent material present in turbid coastal waters. This method of deriving an algorithm by correlating multitemporal sea truth data with a single satellite observation assumes that the water masses move only slowly during the considered three day period so that the scene of 29 August will describe equally well the pigment concentrations for the other two days. This assumption has been verified, within the limits of the location accuracy of the stations mentioned below, for the meteorologically stable period during the campaign by comparing CZCS scenes of 22 and 23 August 1984. The accuracy of determination of a research vessel position on the satellite image is of the order of 1 to 1.5 pixels, which corresponds to about 1 to 1.2 km. The reflectance values used in the correlation analysis were therefore averaged over a 3 x 3 pixel area centered around the pixel closest to the vessel position. Position mislocation error as well as those due to patchiness of the pigment field and statistical fluctuations in the sensitivity loss evaluation were taken into account by estimating error margins. The error bars in Figure 3 were obtained by taking minimum and maximum of R13 calculated over the 3 x 3 area of two images with two different SLCF sets that differed by 3, 2, and 1 % in channel 1, 2, and 3 respectively. A scatter plot of the ship-measured and CZCS-estimated pigments for the 11 points of 29 August is given in Figure 5. It readily shows that, in turbid waters, the accuracy of pigment estimation is good only within a factor of two.

Although the CZCS infrared sensor failed within the first year of the mission, we have tried to use the channel 6 data whenever available (count values not saturated). The displayed quantity is a number (CR) related linearly to the black body radiance BBR (mW cm^{-2} sr^{-1}) according to:

$$CR = - a*BBR + b$$

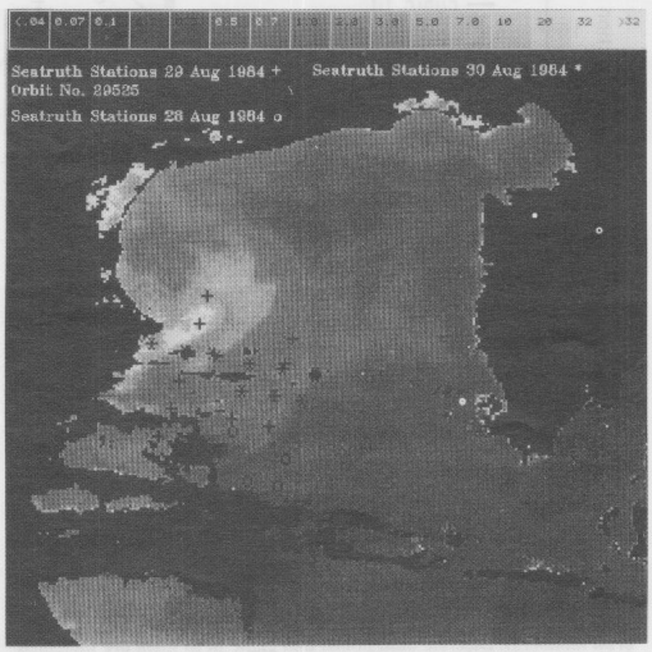

Figure 4

Position of the sea truth stations used in development of site-specific case 2 water algorithm. Background image was collected on 29 August 1984, and in situ *data on the same day, but also a day before and after.*

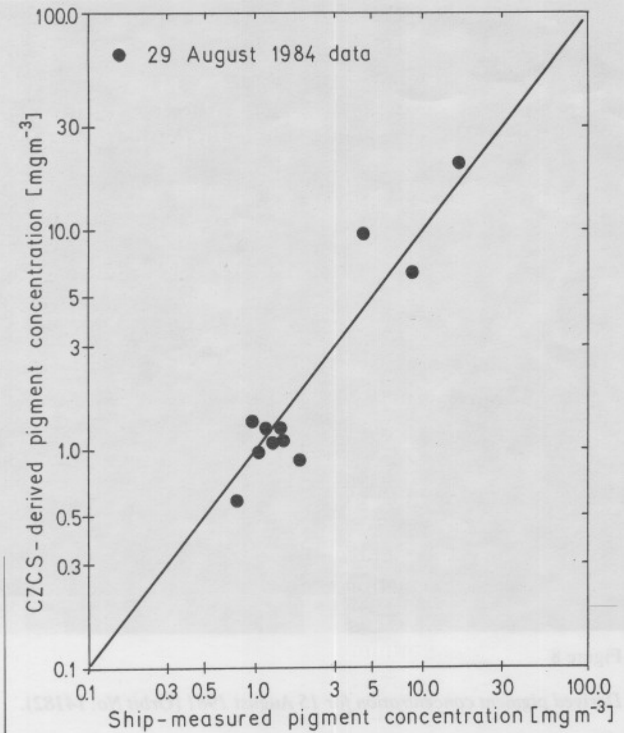

Figure 5

Scatter plot of ship-measured and CZCS-derived pigment concentrations for 29 August 1984 (Orbit No. 29525).

so that high radiance, equal to high temperatures, corresponds to lower digital counts; a and b are correlation constants. Since no valid calibration algorithm was available for the 1981/1982 data we used the digital counts directly as a measure of the relative surface temperature.

Altogether, scenes from 23 orbits were processed using the algorithm just described and eventually rectified geographically and remapped on to a Mercator projection using ground reference points to anchor the remotely-sensed image. As shown in Table 1, it was possible to derive 22 pigment concentration maps and 13 coregistered relative temperature maps of varying quality. Using the spatial extent of the 1 mg m^{-3} pigment concentration as a delimiting criterion it was possible to separate the scenes into two groups: one showing pronounced surface spreading (SS) - extending to the middle of the basin and beyond - and the other exhibiting coastal confinement (CC) - remaining well within the western half of the Adriatic basin. This division reinforces previous finding of Clément *et al.* (1987), but our study further shows that the CC and SS patterns are not necessarily related to winter and summer respectively: apparently, both types can be observed in either season. We selected four scenes to illustrate each type-season combination. The SS type in summer is presented in Figure 6 (pigment) and Figure 7 (relative temperature); summer CC type is given in Figure 8 (pigment). The winter CC type is illustrated with only a pigment field (Fig. 9), whereas Figure 10 and Figure 11 exemplify winter SS response. In the next section we explore the possible dynamics behind the four selected scenes, using available *in situ* data, and then address the generality of conclusions drawn from the analysis.

Table 1

CZCS scenes considered in the analysis.

No	Orbit	Date	P[1]	T[2]	Comment
1	13146	01.06.81	x		clear, good late spring scene
2	13160	02.06.81	x		as above; 2-day sequence
3	13297	12.06.81	x	x	very clear late spring scene
4	13782	17.07.81	x		cloudy; Po discharge zone visible
5	14182	15.08.81	x		very clear summer scene
6	14307	24.08.81	x		clear Northern Adriatic area
7	14693	21.09.81	x		partly cloudy; Chl "flooded" Adriatic
8	16117	02.01.82	x		similar to above
9	16504	30.01.82	x	x	very cloudy Northern Adriatic
10	16545	02.02.82	x	x	rather clear winter scene
11	16656	10.02.82	x	x	very cloudy over W. Adriatic coast
12	17098	14.03.82		x	channel 3 not available
13	17112	15.03.82	x	x	unusually clear late winter scene
14	17126	16.03.82	x		as above; 2-day sequence
15	17264	26.03.82	x	x	perfectly clear early spring scene
16	17347	01.04.82	x	x	partly cloudy; good N. Adriatic scene
17	17361	02.04.82	x	x	similar to above; 2-day sequence
18	17402	05.04.82	x	x	very cloudy N. Adriatic area
19	17416	06.04.82	x		very cloudy Adriatic; 2-day sequence
20	17485	11.04.82	x	x	cloudy but useful spring scene
21	17499	12.04.82	x	x	almost totally cloud-covered Adriatic
22	17582	18.04.82	x	x	very cloudy; clear west coastal area
23	17596	19.04.82	x		clear; small Northern Adriatic area

1: P derived pigment concentration.
2: T relative sea surface temperature.

RESULTS AND DISCUSSION

As pointed out in previous section, the observed pigment patterns appear to fall into two broad categories: one characterized by river-affected water being trapped within the Italian coastal strip (CC); and the other typified by buoyant, surface offshore spreading (SS). It has been sug-

Figure 6

Derived pigment concentration for 12 June 1981 (Orbit No. 13297).

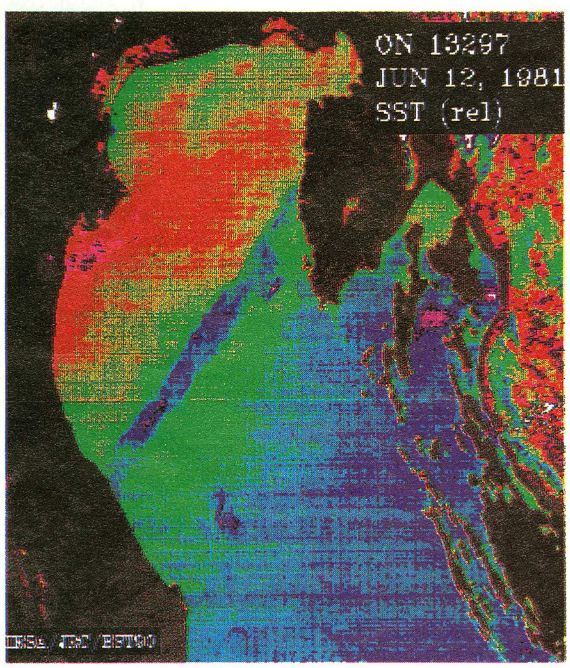

Figure 7

Relative sea surface temperature for 12 June 1981 (Orbit No 13297). Blue marks colder and red warmer waters.

gested, *e. g.* by Clément *et al.* (1987), that the former pattern is found in winter (defined as colder part of the year), whereas the latter coincides with summer (warmer part of the year). Apparently, the suggested seasonal correspondence of patterns is related to differences in stratification between the two seasons (*see* Buljan and Zore-Armanda, 1976; Franco *et al.*, 1982; Orlić *et al.*, 1992). During winter, the sea is well mixed along the vertical in the greater part of the basin, with exceptionally high sigma-t values appearing in the open Adriatic. Such an ambience is conductive to coastal confinement. In summer, a thermocline develops at a depth of about 10-20 m, usually accompanied by a halocline; both processes tend to give a strong vertical density gradient. These ambiental characteristics are conductive to surface spreading.

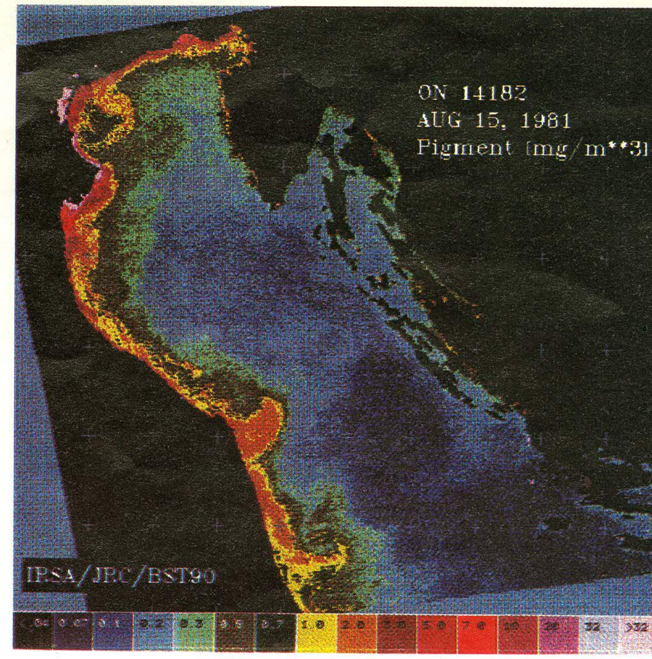

Figure 8

Derived pigment concentration for 15 August 1981 (Orbit No. 14182).

In this section we demonstrate that, besides reported relationship (CC in winter and SS in summer), seasonal cross-appearance (*i. e.* CC in summer and SS in winter) is also observed and try to relate the four observed patterns to particular dynamics. To that end, selected scenes are first analysed separately for each season. At the end of each subsection, the validity of particular conclusions is tested by considering other intra-seasonal scenes.

Summer patterns

The derived field of chlorophyll-like pigment concentration registered on 12 June 1981 (Fig. 6) represents the summer SS situation. At that time of year, the Northern Adriatic is stratified, and the observed Po plume is well developed across the basin. As Figure 12 *a* shows, the Po river discharge (measured at Pontelagoscuro) was rather high at the end of May and beginning of June 1981. On the other hand, during the first twelve days of June 1981 only weak winds were registered above the Northern Adriatic, with speeds not exceeding 5 m s^{-1} at Pula station on the east Adriatic coast. Thus, the remotely sensed image and *in situ* data conform previous finding (Franco, 1970; Barale *et al.*, 1986; Orlić, 1989) according to which the Po water, when injected into stratified Northern Adriatic, spreads evenly over the basin. The wind forcing is relatively unimportant in this process. Analysis of the relative temperature field for the scene reinforces above conclusion. Figure 7 shows a well distinguished Po river thermal signature spread over the basin, with river-influenced waters warmer than the surrounding Northern Adriatic ambient waters. This agrees well with climatological data plotted in Figure 13. Thirteen years of temperature data, collected at a sta-

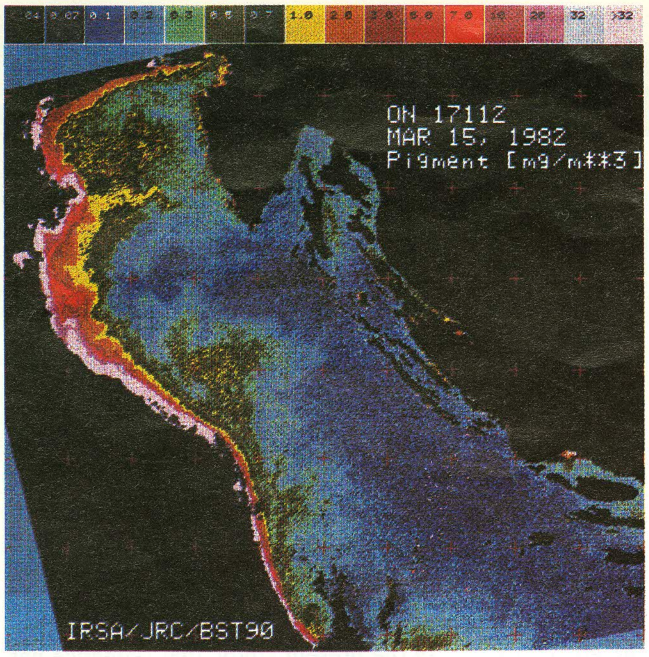

Figure 9

Derived pigment concentration for 15 March 1982 (Orbit No. 17112).

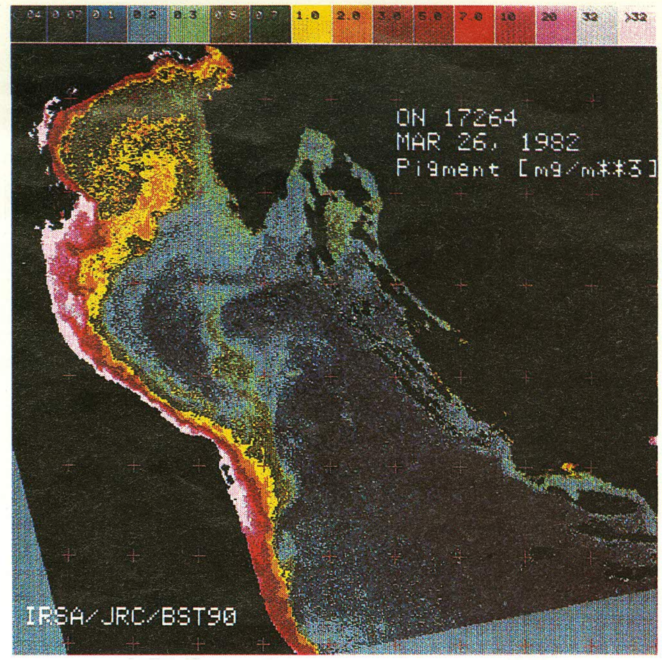

Figure 10

Derived pigment concentration for 26 March 1982 (Orbit No. 17264). This scene is the same one as in Figure 3 of Kuzmić (1991), here reprocessed assuming Rayleigh multiple scattering (Gordon et al., *1988); reprocessing did not affect the pattern.*

tion off the city of Rovinj (Sveti Ivan island), show that the June temperature of the Northern Adriatic is close to 20°C. On the other hand, eleven years of Po river temperature data, collected at Pontelagoscuro, show the June temperature close to 21°C, suggesting that one should expect the river-influenced water to be about 1°C warmer than the ambient water. Uncalibrated, relative temperatures prevent us from checking this difference quantitatively, but the contrast is quite visible in the scene.

However, in summer one can also observe quite a different pattern, as the derived field of pigment concentration for 15 August 1981 illustrates (Fig. 8). Contrary to common perception, in this situation higher values are confined to the Italian coastal area (CC). Data in Figure 12 *b* show that the scene was preceded by two weeks of low Po river discharge (less than 1 000 m^3s^{-1}), and also by a period of low speed winds (a few metres per second, most of the time). Provided that the derived pigment field was not significantly influenced by biological processes, the scene would suggest that, under low discharge conditions, the Po waters do not spread over the Northern Adriatic basin, despite a pronounced stratification. Such a situation has been already observed by Barale *et al.* (1986), also in the CZCS data but for a different year. As in the previous summer case, the wind was neither sufficiently strong nor frequent to be of decisive importance. Unfortunately, there was no usable channel 6 image for this scene. However, the data in Figure 13 suggest that it would be difficult to distinguish river-influenced and ambient waters - in late August and early September, climatological temperature difference is practically nonexistent.

All the analysed summer scenes are summarized in Table 2. For each scene the Po flow rates were averaged over the 7-day period preceding the scene. The result was declared as a low discharge if the flow rate was below 1 000 $m^3\ s^{-1}$, intermediate if between 1 000 and 1 500 $m^3\ s^{-1}$, and high if

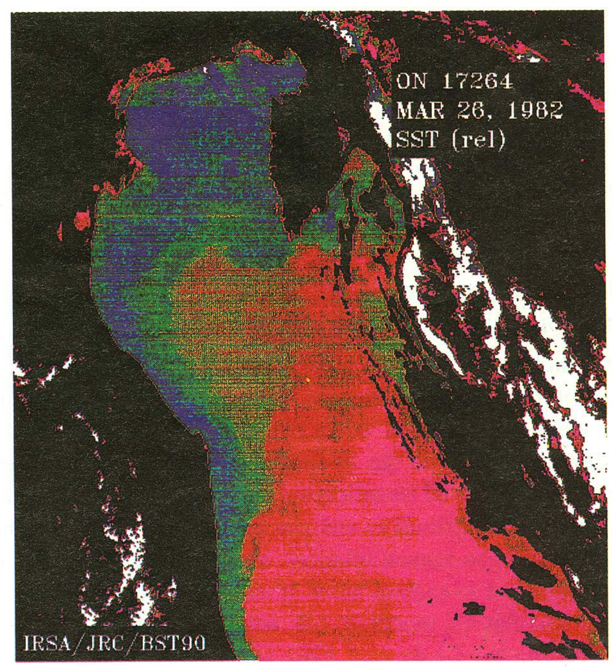

Figure 11

Relative sea surface temperature for 26 March 1982 (Orbit No. 17264). Blue marks colder and red warmer waters.

above 1 500 $m^3\ s^{-1}$. The strongest daily wind was picked in the same period, and was not averaged over it to stress the wind's episodic nature. The wind was declared weak if its magnitude was less than 5 $m\ s^{-1}$, moderate if magnitude was between 5 and 10 $m\ s^{-1}$, and strong if it was more than 10 $m\ s^{-1}$. Of course, it would be equally, if not more, desirable to have some other parameters quantified. For example, in the absence of more detailed information, the summer ambience was defined as stratified in general, without actual quantitative information for any particular

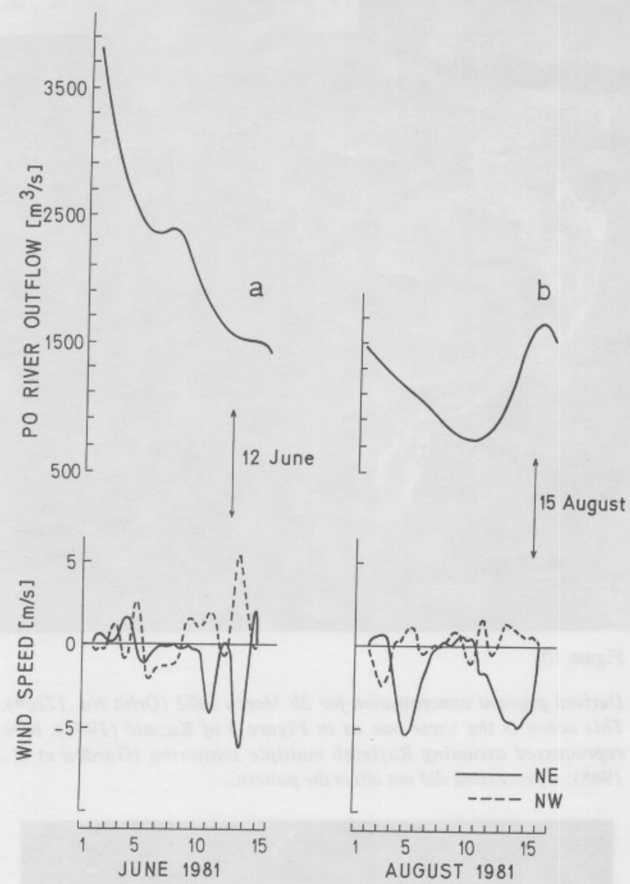

Figure 12

Po river outflow at Pontelagoscuro (Grego and Mioni, 1985) and wind velocity at Pula airport (Hydrometeorological Institute, 1981) for: a) June 1981; b) August 1981. Also indicated are the dates of analysed CZCS scenes.

date. Moreover, we did not have at our disposal comparable biological data for the area and time considered.

As can be seen from the table, out of the seven scenes four are of the SS type, two are of the CC type and one is somewhat undecided. Most of them can be successfully interpreted within the proposed framework. However, mentioned lack of stratification and biological data makes it somewhat difficult to analyze scenes 6 and 7 within the described type-season relations and dynamical interpretation ascribed to each of them. It would be worth to investigate whether the moderate SW wind observed in the week preceding the 24 August 1981 scene had any significant effect on it. It would be also interesting to assess the importance of the ambient stratification and/or biological activity for the "pigment flood" registered on 21 September 1981.

Winter patterns

As pointed out earlier, the Northern Adriatic is vertically well mixed in winter, and confinement of river-influenced waters to the coastal zone is considered typical for the season (Franco, 1972; Orlić, 1989). Along the Italian coast the Po outflow commonly forms a boundary layer of lighter water 10-20 km wide and about 10 m deep (Orlić *et al.*, 1992). Kuzmić (1989) processed and analysed winter CZCS scenes (March-April 1982) with a view to verifying

Table 2

Summary of summer scenes. The flowrates are averaged over 7-day period preceding a scene and classified according to the rules: low = below 1 000, intermediate = higher than 1 000, but lower than 1 500, high = higher than 1 500 $m^3 s^{-1}$). The winds picked were the ones with largest daily magnitude in the same period (weak = less than 5, moderate = between 5 and 10, strong = more than 10 $m s^{-1}$).

No	Orbit	Date	Type*	Po flowrate	Wind
1	13146	01.06.81	SS	high	strong SE
2	13160	02.06.81	SS	high	strong SE
3	13297	12.06.81	SS	high	weak ENE
4	13782	17.07.81	CC	intermediate	weak NW
5	14182	15.08.81	CC	low	weak E
6	14307	24.08.81	CC/SS	low	moderate SW
7	14693	21.09.81	SS	intermediate	weak SE

** SS = surface spreading; CC = coastal confinement.*

modelling predictions of the effects of spatially heterogeneous bura wind. In the present study, that sequence has been extended to include early winter scenes. Unfortunately, the extension did not bring a clear winter CC pigment pattern. The pigment map derived for 15 March 1982 (Fig. 9) bears the closest resemblance to the expected case. At the time the Northern Adriatic was well mixed along the vertical and the Po waters were confined to an area along Italian coast. The trapped nutrient-rich riverine waters show up rather well in the pigment map. Concentration of 1 mg m^{-3} delineates a sharp coast-following front; the river-affected coastal zone is wider in the vicinity of the Po delta and narrower further south. As for the temperature field, following Zore-Armanda and Gačić (1987) one would expect the Po-influenced Northern Adriatic thermal fronts to be oriented meridionally (shore parallel) unless affected by bura wind. However, Zore-Armanda and Gačić studied December and January scenes, *i. e.* "true" winter cases when temperature difference bet-

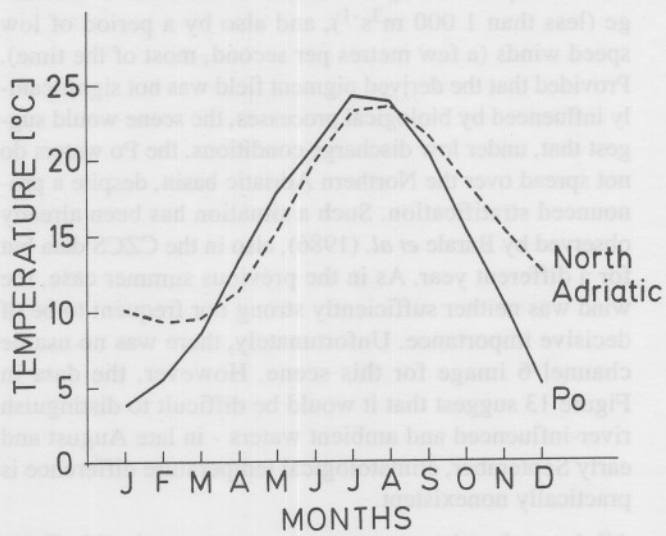

Figure 13

Mean annual variation of temperature of Po river waters (measured at Pontelagoscuro from 1961 to 1971; Cati, 1981) the Northern Adriatic waters (registered at Sveti Ivan, near Rovinj, from 1962 to 1974; Supić, 1988).

ween the Po and ambient waters can be as large as 5°C (Fig. 13). The same climatological temperature data suggest that in March, when this scene was registered, the difference is reduced to 1°C or lower, and between March and April it even changes sign (the Po waters become warmer than the ambient). Typically for the troubled CZCS IR sensor there was no thermal image available for the scene to verify the above statement.

Apparently, the surface spreading can be also observed in winter (Kuzmić, 1991). As Figure 10 demonstrates, on 26 March 1982 an oval structure was registered, well developed into the basin interior. Kuzmić (1991) interpreted the scene in terms of advection by wind-curl currents. Namely, previous modelling studies (Orlić *et al.*, 1986; Kuzmić and Orlić, 1987) have suggested that, in the middle of the Northern Adriatic basin, the spatially heterogeneous bura wind induces upwind, eastward transports. Extending those modelling studies with a simple random walk dispersion exercise Kuzmić (1991) produced a numerical simulation in fair agreement with the pigment field derived for 26 March 1982, as well as with the empirical data (Po river flow rate and wind velocity) for that and the adjacent dates. More specifically, the simulation demonstrated that bura-induced currents can transport Po-influenced coastal waters into the basin interior, producing a pigment pattern very similar to that actually observed.

Part of that data set is reproduced in Figure 14, showing that the scene was registered immediately after a moderate increase in the Po discharge, and following a strong bura episode. Also seen in the figure is another bura episode (between 5 and 10 March 1982). Instead of coinciding with or following an increase in Po discharge, it actually preceded, by several days, another moderate increase in the Po outflow, so its consequence was probably not as pronounced as in the 26 March case. Nevertheless, it is tempting to interpret the protrusion seen in Figure 9 as an "aberration" from coastal confinement due to this bura episode. Kuzmić (1989) reports that the 15 March scene, when first processed, actually inspired a search for possible bura episode preceding it. Another episode was indeed found (5-10 March) and the wind time series appropriately extended, to accommodate the third episode. The presented analysis suggests the importance of relative synopticity of bura episodes and periods of increased Po discharge. However, this synopticity may not be so important if one considers temperature or salinity fields. Some situations, not considered in this paper, suggest that a strong bura episode may leave a pronounced mark in the temperature field, even if an extra riverine discharge is not available.

It appears that the Po waters, while advected, are also subjected to strong mixing (Fig. 10); consequently, they do not exert observable (temperature and salinity) influence along the opposite, Adriatic coast (Orlić, 1989). A usable IR image (channel 6), available for 26 March (Fig. 11), suggests expected winter distribution of the sea surface temperature: warmer waters are found in the south and along the east coast, whereas colder waters appear in the north and along the west coast. The temperature does not delineate the Po river waters protruding into the basin interior.

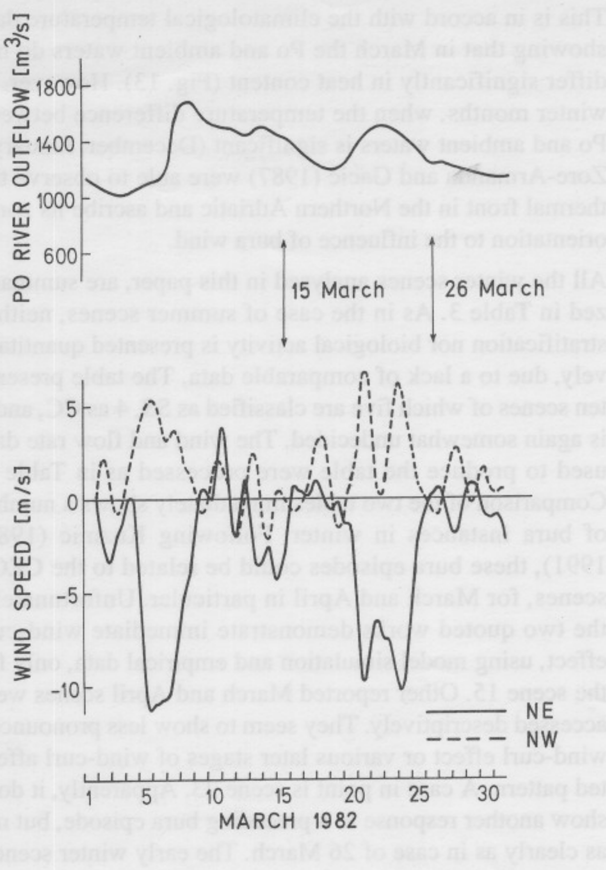

Figure 14

Po river outflow at Pontelagoscuro (Grego and Mioni, 1985) and wind velocity at Pula airport (Hydrometeorological Institute, 1982) for March 1982. Also marked are the dates of analysed CZCS scenes.

Table 3

Summary of winter scenes. The flow rates are averaged over a 7-day period preceding a scene and classified according to the rules: low = below 1 000, intermediate = higher than 1 000, but lower than 1 500, high = higher than 1 500 m^3 s^{-1}). The winds selected were the ones with largest daily magnitude in the same period (weak = less than 5, moderate = between 5 and 10, strong = more than 10 m s^{-1}).

No	Orbit	Date	Type*	Po flow rate	Wind
8	16117	02.01.82	SS	low	strong SE
10	16545	02.02.82	SS	low	moderate NE (bura)
13	17112	15.03.82	CC	intermediate	moderate ENE (bura)
14	17126	16.03.82	CC	intermediate	moderate ENE (bura)
15	17264	26.03.82	SS	intermediate	strong ENE (bura)
16	17347	01.04.82	SS	low	strong ENE (bura)
17	17361	02.04.82	SS	low	strong ENE (bura)
19	17416	06.04.82	CC	low	weak NE
20	17485	11.04.82	CC	low	moderate NE (bura)
23	17596	19.04.82	CC/SS	low	strong ENE (bura)

* *SS = surface spreading; CC = coastal confinement.*

This is in accord with the climatological temperature data showing that in March the Po and ambient waters do not differ significantly in heat content (Fig. 13). However, in winter months, when the temperature difference between Po and ambient waters is significant (December, January), Zore-Armanda and Gačić (1987) were able to observe the thermal front in the Northern Adriatic and ascribe its zonal orientation to the influence of bura wind.

All the winter scenes analysed in this paper, are summarized in Table 3. As in the case of summer scenes, neither stratification nor biological activity is presented quantitatively, due to a lack of comparable data. The table presents ten scenes of which five are classified as SS, 4 as CC, and 1 is again somewhat undecided. The wind and flow rate data used to produce the table were processed as in Table 2. Comparison of the two tables immediately shows a number of bura instances in winter. Following Kuzmić (1989; 1991), these bura episodes could be related to the CZCS scenes, for March and April in particular. Unfortunately, the two quoted works demonstrate immediate wind-curl effect, using model simulation and empirical data, only for the scene 15. Other reported March and April scenes were accessed descriptively. They seem to show less pronounced wind-curl effect or various later stages of wind-curl affected pattern. A case in point is scene 23. Apparently, it does show another response to a preceding bura episode, but not as clearly as in case of 26 March. The early winter scenes, in the extended set, are even more difficult. Scene 8 is another "pigment flood" case that fits neither of the four type-season cases, probably requiring biological interpretation as well. One should also bear in mind the difficulties in processing and interpreting winter scenes, and consequently the possible artificiality of this one in particular. Scene 10 could be related to moderate bura episode preceding it, but the expected visual effect is not easily established.

CONCLUSIONS

The purpose of present paper has been to investigate further the previously observed dichotomy in the Adriatic shelf waters influenced by the Po river. To that end, selected summer 1981 and winter 1981/1982 CZCS images of the Adriatic shelf have been reprocessed using an improved algorithm for pigment concentration retrieval. The sensitivity loss correction procedure has been included in the retrieval algorithm to compensate for radiometric sensitivity loss, and rendered coherent with the atmospheric correction model. The model was also updated to allow for multiple Rayleigh scattering, and site-specific calibrated for the case 2 waters of the Northern Adriatic.

Several conclusions can be drawn from the remotely sensed data presented in this study. Our analysis reinforces the previous finding (Clément *et al.*, 1987) that two types of CZCS-derived patterns can be observed on the Adriatic shelf: one, elongated, trapped along the Italian coastline; and another wide, irregularly spread into the basin interior. However, according to our results, either pattern can occur both in summer and in winter.

In summer, when the Northern Adriatic is stratified, the Po-influenced waters typically spread into the basin interior. The Po-shelf interaction appears to be primarily controlled by the river discharge. Higher flow rates induce more pronounced spreading, whereas a lower discharge restricts the river-affected waters to a narrow band adjacent to the Italian coast. The winds in summer are usually too weak, infrequent and short-lived to contribute significantly to these processes.

In winter, when the Northern Adriatic is vertically well mixed along, the river-affected waters commonly remain confined to the Italian coastal strip all the way down the shelf and into the Southern Adriatic. However, strong episodes of spatially heterogeneous bura wind seem to be able to provoke intrusions into the basin interior.

The above findings, based on derived pigment patterns, seem to be in accord with relative sea surface temperature, derived from channel 6 of the CZCS sensor and with available empirical data (Po river flow rate and temperature, Northern Adriatic temperature and wind). In particular, the August 1981 IR image clearly traces the Po river thermal signature, whereas a comparable temperature difference is not visible in the March 1982 scene. Both results conform with expectations based on climatological data for the Po river and Northern Adriatic. The wind and flow rate data support the dynamic interpretations suggested by pigment patterns.

Despite the consistent pattern that has emerged from the present analysis, its limitations must be borne in mind. For example, the relatively limited number of CZCS images, unevenly covering different seasonal and response patterns has to be considered. As in most previous uses of CZCS data, the analysis has been largely descriptive. Previously gained dynamic insight, *via* numerical simulations, has been limited to winter bura-dominated cases; and even those cases merit further, less descriptive consideration. Certainly, the complex interaction of riverine and wind-affected, stratified shelf waters warrants more elaborate models and more intensive modelling exercises. Concurrent hydrographic *in situ* data would bring further confidence in conclusions drawn from remotely sensed data. Furthermore, it has been tacitly assumed in the analyses that pigment concentration is a conservative enough tracer. Biological processes associated with spatial and temporal dynamics of various Po-related nutrients have therefore been ignored. This simplification carries different weight for different periods of the year. However, it seemed an acceptable first approximation, enabling us to delineate the Po-influenced water boundary.

Further work along any of these lines seems desirable as a step towards better understanding of the hydro- and thermodynamics of the Adriatic Sea. The considerable existing remote sensing data base, as well as input from future missions, will, it is hoped, contribute to that end.

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