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A satellite observation of the Adriatic Sea response to a spatially heterogeneous wind

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Coastal Zone Colour Scanner (CZCS) derived fields of pigment concentration were used in this paper to assess the Adriatic Sea response to a spatially heterogeneous wind. By observing changes in the pigment fields of the Northern Adriatic surface waters further evidence was sought for previously studied effect of bura, a gusty katabatic wind of north-easterly direction. CZCS registered similarities and differences in response to three bura episodes were analysed using available wind and Po River discharge data and a mathematical model prediction of the wind-induced circulation. In comparing the modelling results with spaceborne observations the bura-induced gyre emerged as the mechanism responsible for particular change of spatial pattern observed in CZCS detected radiance and derived pigment concentration field. In this process relative timing of bura episodes and availability of Po-supplied tracing material seem to be important.

Satelitsko opažanje odziva Jadranskog mora na djelovanje prostorno nehomogenog vjetra

U ovom se radu razmatra odziv Jadranskog mora na djelovanje prostorno nehomogenog vjetra, preko polja koncentracije pigmenta izračunatih iz signala detektiranih putem senzora CZCS (Coastal Zone Colour Scanner). Opažanjem prostornih promjena u polju pigmenta površinskog sloja sjevernog Jadrana tražena je daljnja potvrda već istraživanog utjecaja bure – mahovitog, katabatičkog vjetra sjeverno-istočnog smjera. Analizirane su sličnosti i razlike u satelitski registriranom odzivu mora na tri epizode bure koristeći dostupne podatke o vjetru i protoku rijeke Po, te rezultat matematičkog modeliranja vjetrom uzrokovane cirkulacije. Usporedba modelskih i daljinski registriranih podataka je ukazala na burom inducirani vrtlog kao mehanizam koji dovodi do prostornih promjena uočenih u detektiranim poljima radijancije, te izvedenim poljima koncentracije pigmenta. Pri tome izgleda važan relativni vremenski odnos pojave epizode bure te dotoka, rijekom Po, materijala koji uzrokuje detektirane optičke promjene.

1. Introduction

In the eighties, the decade of growing interest in oceanography from space, the Northern Adriatic basin received considerable attention of the remote sensing community. It was one of the test sites for the Coastal Zone Colour Scanner (CZCS), a sensor launched in October 1978 on board Nimbus-7. This sensor offered a unique possibility to study bio-optical properties of marine ambient. The Northern Adriatic is such an ambient, particularly suitable for aforementioned studies due to its shallowness (maximum depth less than 60 m) and considerable freshwater inflows (the Po River). Consequently, the basin has inspired both retrieval algorithm development and improvement as well as remote sensing aided oceanographic studies. Sturm (1990), for example, used Northern Adriatic data samples to derive correlations among suspended matter, yellow substance and chlorophyll-like pigments. Sturm (1987a) has also presented an application of CZCS data to productivity and water quality studies in the Northern Adriatic demonstrating the need for *in situ* measurements and site-specific interpretation algorithms. 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 have considered, among other topics, possible relevance of prevalent wind fields and concluded that, on the considered scales, wind was ineffective regarding the pigment distribution. 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 conditions in an area. In particular they found the ratio algorithms generally suitable for retrieval of chlorophyll content, but coefficient dependent on phytoplankton type.

The influence of wind on forced motions in the Northern Adriatic has also been intensively studied, both empirically and theoretically. For example, Stravisi (1977) formulated a vertically integrated model for the uppermost part of the Northern Adriatic sea, whereas Malanotte-Rizzoli and Bergamasco (1983) forced their two-layer model with temporally variable but spatially homogeneous wind. It has been shown in a series of papers (Kuzmić et al., 1985; Orlić et al., 1986; Kuzmić and Orlić, 1987) that during winter the wind induces the most pronounced although transient component of the Northern Adriatic current field. More precisely, bura – gusty, katabatic wind of NE direction – has emerged as the dominant driving force on a scale of several days. Furthermore, its spatial heterogeneity (variability along northeastern coast in particular) has been shown, by both modelling and empirical studies (Orlić et al., 1986; Kuzmić and Orlić, 1987; Zore-Armanda and Gačić, 1987) to be of major importance. Positive vorticity in the bura field has been found to induce a large cyclonic gyre over the upper part of the Northern Adriatic basin, while negative vorticity drives anticyclonic gyre in the lower part of the basin. Unfortunately, temporal and spatial resolution of the available wind data has been inadequate to model, more precisely and more reliably, spatial extension and dynamics of the two gyres.

Most recently Kuzmić (1991) reported the first attempt to verify results of wind-induced current modelling of the Northern Adriatic using remotely sensed data (CZCS). The purpose of the present paper is to further analyse and interpret in more detail three episodes of bura wind, relating the space-borne observed CZCS data to mathematical modelling results, as well as to the Northern Adriatic wind and Po River data. To facilitate comparison of model-generated and satellite-observed data, a hydrodynamical model has been extended with a simple two-dimensional random-walk dispersion model, and selected CZCS scenes were processed to yield the fields of pigment concentration.

The paper is organized as follows. After the introduction, selection and processing of the CZCS data are described in section 2. Numerical model is briefly presented in section 3 together with the reference numerical experiment. Remote sensing results, the data and the simulation are discussed and analysed in section 4. Results are summarized in the final section.

2. CZCS data preparation and processing

Increasingly accurate satellite observations of the sea extend and complement in situ measurements offering a synoptic view of large areas. Ocean colour is among variables measurable from space on interesting temporal and spatial scales. Since light penetrates below water surface, backscattered photons can be used to characterize oceanographic or water quality features of the upper layer of the water column. So far, the only spaceborne sensor specifically designed to detect visible-wavelength marine radiances was the CZCS. This high-gain spectrometer imaged the ocean in six spectral bands, the first five in visible and near IR, and the sixth in thermal IR. Further details about the sensor can be found *e.g.* in Maul (1985). Although primarily designed to study living marine resources the CZCS data can also be used to trace movement or delineate oceanographic features of the water masses. It is this aspect of the CZCS imagery that has been exploited in the present study.

For the purpose of tracing effects of bura-wind episodes in the Northern Adriatic velocity field one would prefer a sequence of remotely sensed scenes, of at least one image per day, during bura as well as some time before and after. Although exact repetition of particular Nimbus-7 orbit was possible after about 6 days, 3 to 4 consecutive day coverage was possible at the mid and higher latitudes. Although impressive archives of CZCS data has been collected during the period 1978–1986, a sequence of good Northern Adriatic scenes, several consecutive days long, has been difficult to find for a number of reasons. Considerable restriction came from adverse meteorological conditions; even when particular scene was registered it was often too cloudy or too hazy to be of much use. For example, in the Barale et al. (1986) two-year time series of scenes there was no single good scene for the months of November, December and January for neither 1979 nor 1980, and only 3 scenes for February 1980.

Despite adverse meteorological conditions and other problems, not discussed here, an effort was made to produce useful winter sequences because bura is predominantly winter wind and our previous modelling activity has been concentrated on barotropic response, corresponding to winter-like conditions. To that end available quick-look catalogues and other sources have been searched for the years 1979 to 1984, and the months of November to March. After the search, the period March – April 1982 was found most suitable for further study. The period coincided with special observing period (SOP) of the ALPine EXperiment (ALPEX) and its oceanographic subprogramme named MEDiterranean ALPEX (MEDALPEX). The MEDALPEX was undertaken to understand better the response of the western Mediterranean and the Adriatic Seas to wind forcing, especially under severe weather conditions. Although not designed as an integrated international experiment it brought about more coordinated national programmes and greatly intensed oceanographic activity and meteorological observations over the sea. Although the chosen period essentially covered winter to spring transition its first part in particular was still representative for winter, vertically homogeneous conditions. The quick look search suggested that several useful scenes were available for that period. Eventually, a set of 10 scenes has been collected from three different sources: local JRC Ispra archives, Maspalomas station (Gran Canaria Island, Spain) and the University of Dundee. Characteristics of these scenes are summarized in Table 1.

Table 1. Basic characteristics of the selected CZCS scenes

Orbit no.	Date	Time		Pixel Coordinates				CCT SRC
		Start	Stop	FL	LL	FE	LL	
17112	15.03.82	10:34:05	10:36:04	180	691	1180	1691	MP
17126	16.03.82	10:52:30	10:54:00	90	601	1457	1968	JRC
17264	26.03.82	10:30:04	10:31:59	290	801	1080	1591	MP
17347	01.04.82	10:37:22	10:38:37	86	597	1200	1711	DUN
17361	02.04.82	10:55:46	10:57:01	91	601	1457	1968	DUN
17402	05.04.82	10:08:38	10:09:53	86	597	500	1011	DUN
17416	06.04.82	10:25:52	10:27:04	30	541	950	1461	JRC
17485	11.04.82	10:14:06	10:15:50	60	571	700	1211	JRC
17582	18.04.82	10:40:05	10:42:04	458	969	1200	1711	MP
17596	19.04.82	10:58:50	11:00:50	459	970	1457	1968	JRC

Notes: FL = first line, LL = last line, FE = first element, LL = last element, CCT = computer compatible tape, SRC = source, MP = Maspalomas, JRC = Joint Research Centre, DUN = University of Dundee

All the scenes were processed at the Institute for Remote Sensing Applications (IRSA) of the CEC Joint Research Centre Ispra with locally developed software. Before any further processing original full scenes were reduced to square 512 by 512 pixel subimages as centered as possible on the Northern Adriatic. Visual, screen inspection of relevant channels was commonly performed on selected scenes. The water leaving radiances were then obtained after an iterative process aimed at separating marine from atmospheric contribution. This step, usually referred to as atmospheric correction, was done with two programmes: CZCS (Sturm and Nykjaer, 1985) and IMA (Sturm, 1990). Prime reason for running two different programmes was possibility for an additional check that particular feature apparent in a CZCS scene could be observed regardless of applied atmospheric correction. Atmospheric correction particulars could be found in quoted references. We will only note here that Sturm (1987b) proposed the use of Sobolev approximation to multiple scattering as a means to overcome inadequacy of single scattering approach. This particular approximation was used to correct the scenes presented in this paper. Atmospherically corrected radiances were further processed with both programmes to yield values of pigment concentration. The CZCS programme also yields an estimate of the total suspended matter. In either case no attempt was made to validate empirically the accuracy of concentration calculations. For the purpose of tracing effects of bura, observation of relative changes has seemed adequate. One can question the wisdom of using a non-conservative material, like chlorophyll-like pigment, as a tracer of oceanographic features, but in some cases that can be the only choice. A case in point is the Northern Adriatic in March when the Po waters are thermally indistinguishable from the surrounding marine ambient (Sturm et al., 1992). To facilitate comparison of different images all of them were eventually geometrically corrected (Mercator projection) with longitudinal resolution of 102.4 pixels per degree. It should be noted here that all the scenes were processed into false colour images for the purpose of analysis. Unfortunately, only black and white copies are presented later in the paper. The lack of colour-enhanced distinction among various concentration values precludes any fine-point analysis of the images, but it does not eliminate the consideration of some gross effects relevant in the context of the paper. Further details of the remote sensing data analysis and processing can be found in Kuzmić (1989).

3. Mathematical model and the basic prediction

In numerical modelling studies of shallow coastal seas vertically integrated equations of motion have often been used, providing prediction of the free surface height and horizontal transport components. However, scientific and engineering studies often demand consideration of vertical current structure necessitating use of three-dimensional models. In our modelling studies of wind induced barotropic dynamics of the Northern Adriatic we have taken the approach pioneered by Heaps (1972) in which the problem is partitioned into horizontal and vertical one, via an integral transformation. The basic set of equations has been derived assuming homogeneous water, hydrostatic motion, and constant Coriolis parameter. Neglecting the advective terms and lateral shear, the equations of continuity and motion read:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\int_0^h u \, \mathrm{d}z + \frac{\partial}{\partial y}\int_0^h v \, \mathrm{d}z = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} - f u = -g \frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial z}\left(N \frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial v}{\partial t} - f v = -g \frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial z}\left(N \frac{\partial v}{\partial z}\right) \tag{3}$$

where t denotes time;
z is the elevation of the water surface;
u, v are the horizontal components of currents at depth z
h is the undisturbed depth of water;
N is the coefficient of vertical eddy viscosity;
f is the Coriolis parameter; and
g is the acceleration of gravity.

The Cartesian coordinate axes (x and y) are located at the undisturbed sea surface with the z axis positive downwards. The state of rest has been assumed initially. Boundary conditions at the sea surface and the bottom have been applied assuming stresses defined as:

$$\tau_{xs} = C_D \rho_a u_a \left(u_a^2 + v_a^2\right)^{1/2}, \quad \tau_{ys} = C_D \rho_a v_a \left(u_a^2 + v_a^2\right)^{1/2} \tag{4}$$

and

$$\tau_{xb} = k \rho u_h , \quad \tau_{yb} = k \rho v_h \tag{5}$$

In the above relations subscript s refers to the surface and b to bottom, u_a and v_a denote the wind components, ρ_a is the density of the air, ρ is the density of sea water, C_D is a nondimensional drag coefficient and, k is the coefficient of bottom friction. Zero normal horizontal flow has been assumed along the solid boundary while a radiation condition has been postulated at the open boundary. Before numerical solution of the equations (1) to (3) was attempted an integral transformation was applied. Details of the method can be found in

Heaps (1972) or Kuzmić et al. (1985). We will note in passing that the method increases number of equations to be solved (from 1 + 2 to 1 + 2×M, where M is number of vertical modes) but offers more flexibility regarding vertical resolution. In the simulation to be presented 10 vertical modes were used.

The part of the Adriatic considered in the model is shown in Fig. 1. Natural lateral boundaries are overlaid in the figure with the computational grid boundaries [29 by 22 boxes of 7.5 km in northeastward (x) and northwestward (y) directions]. Also indicated in the figure is the wind stress variability along the northeastern coast. It is based on ten-year statistics (1956–1965) of monthly mean wind frequency and force for 6 stations along the Northern Adriatic coast from the data set compiled by Yoshino (1972). Further details regarding the modelled stress can be found elsewhere (Orlić et al., 1986; Kuzmić and Orlić, 1987). Numerical values of other parameters used in the model and justification for their use are detailed in Kuzmić et al (1985).

A characteristic field of vertically integrated currents in the 5 m deep surface layer is also given in Fig. 1. The choice of 5 m depth is somewhat arbitrary; the bura-induced gyre can be traced down to any depth in the

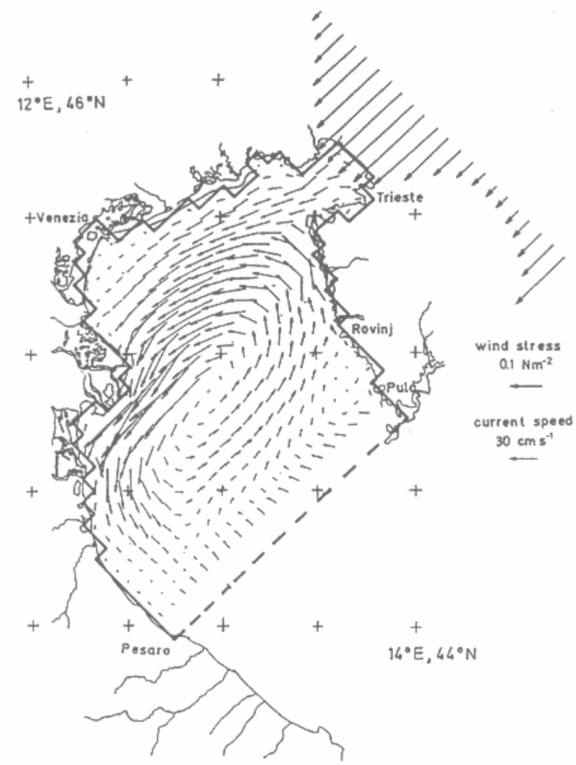

Figure 1. Vertically integrated currents in the 5 m deep surface layer as predicted with the numerical model. Also indicated is the geometry of the Northern Adriatic overlaid with the model boundaries, and the wind stress used in calculations. Crosses mark half-degree change of longitude and latitude. (modified after Kuzmić, 1991).

Northern Adriatic. However, the choice does relate to the fact that observed backscattered radiance and derived concentration are representative for the first few meters – a fact that will be called upon later in the text. The current field was obtained after 48 simulated hours, when reasonably steady viscous balance was attained. The field contains a bottom-slope contribution due to the variable Northern Adriatic topography, and a wind-curl contribution due to spatially heterogeneous bura. The simulation shows that vorticity in bura wind induces double-gyre response in the sea, with the large cyclonic gyre covering most of the basin, and smaller anticyclonic one covering the lower part. The latter gyre, although consistent with expected effect of the wind vorticity, is somewhat contaminated by the closeness of the open boundary and an imperfect condition there. Of particular interest for the present study is strong upwind flow, *i.e.* bura spun-up a gyre which carried upwind the waters from the Italian coastal strip (into which the Po River is discharged). This response has been partially empirically verified (Kuzmić and Orlić, 1987) using current measurements from a mooring deployed about 20 km offshore the city of Rovinj (Fig. 1). Now, if bura indeed induces such a response it would be rewarding to see if it could be also observed remotely. We will address this question in the next section.

4. Results and discussion

In this study we have been concerned with tracing effects of bura wind in the CZCS data. To that end selected scenes were processed without any temporal averaging. In order to relate these spaceborne detected scenes to the Northern Adriatic environmental conditions during the selected period, two sets of empirical data were used (Fig. 2).

One was a wind data series (Fig. 2a) collected at a meteorological station in the area (Pula Airport, see Fig. 1) and used in our previous modelling studies. The wind time series in the figure is the low-pass filtered north-eastern component of the wind in general direction of bura. One can readily observe in the figure three pronounced bura episodes that occurred on 4–8 March, 20–25 March and 12–16 April 1982. Cases of strong bura wind occur after invasion and accumulation of cold air in the northeastern upstream region, on the inland side of the ridges along the Croatian coast. The wind is a result of the flow of this air over low orographic barriers into the Adriatic region. Prolonged situation of this kind is generated when an anticyclone is stationed over the continental Europe while cyclonic center is formed on the Mediterranean side. The first episode in the Fig. 2 (A), the strongest and most intense case of bura during the ALPEX SOP, was one such situation of large increase of the pressure gradient between the cold upstream air and a cyclone on the lee side of the Alps (Bajić, 1988). The second episode shows two distinct maxima which have been ascribed to different bura geneses (Ivančan-Picek

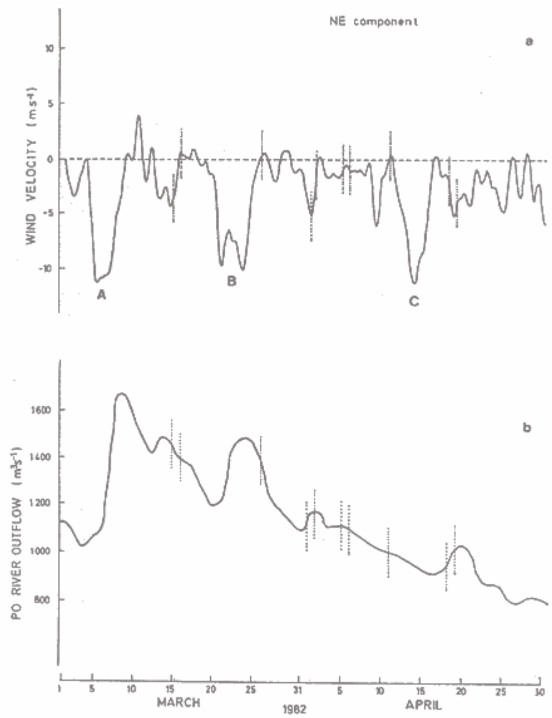

Figure 2. (a) Low-pass filtered time series of the northeasterly component of the wind measured at Pula station; (b) Daily valued of the Po River outflow measured at Pontelagoscuro. Also marked in the figure are the dates of available CZCS scenes (modified after Kuzmić, 1991).

and Vučetić, 1990). In the present analysis it was treated as one strong and prolonged episode. The mid-April bura (episode C) developed as a consequence of the cold air supply in the upstream region and a mesocyclone over the middle Adriatic (Vučetić, 1988). It is interesting to note that original time series (Kuzmić and Orlić, 1987) started on 15 March 1982 (in accord with available oceanographic data). Analysis of images on the 15th and 16th of March suggested existence of an earlier bura episode, which indeed was found in the wind data, when the time series was extended to its present length.

As bars in Figure 2 indicate, available CZCS scenes cover the three bura episodes rather unevenly. Not a single bura episode has been covered by a useful scene, which seems to be largely due to adverse meteorological conditions. Unfavourable atmospheric conditions seem to be rather important part of the problem. Quick look of the CZCS channel 5 for 17 April, for example, shows almost complete cloud coverage over the Northern Adriatic. Due to such a less than ideal coverage the effect of the first bura episode (A) has been difficult to assess. It was poorly covered even on the before/after basis. The first available scene that could be related to this episode comes 6 days after the episode ceased (Fig. 3). As already mentioned the pattern seen in the

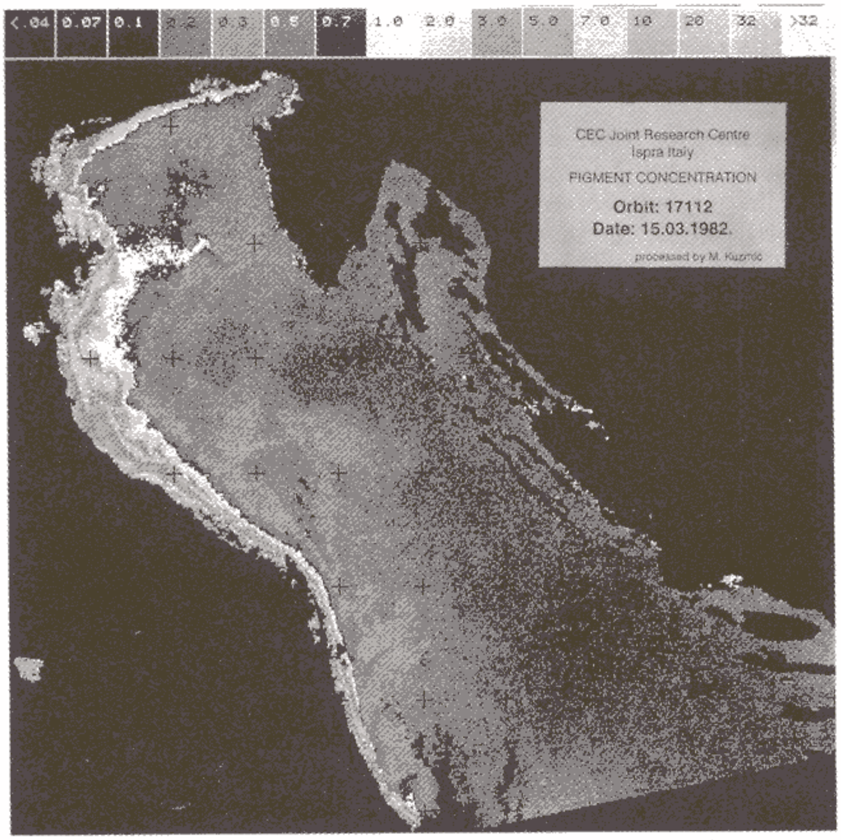

Figure 3. Derived pigment concentration for 15 March 1982 as calculated with IMA programme (Sobolev approximation of multiple scattering). Concentrations are given in mg m^{-3}. Crosses mark half-degree change of longitude and latitude.

image suggests a remnant effect of the previous bura episode. Another scene was available a day latter (Orbit number 171126, 16.03.1982 – not shown); on it one can still see the same pattern, somewhat dissolved, which gives an indication of its persistence.

The next episode (B) seems to be documented better, although again not completely. An interesting image was taken on 26 of March, right after the second bura episode (Fig. 4a). The weather was fine and the atmosphere clear so this cloudless scene is technically the best for the period considered. Circularly shaped pattern suggests rather clearly offshore advection imposed by heterogeneous bura. It is revealing to analyse this scene in its temporal context. The previous figure (Fig. 3) shows the nearest available scene prior to the this episode; it differs considerably from what was observed on 26 of March. The next scene available was taken on 1 of April (Fig 4b). After setting up a cyclonic gyre horizontally and invigourating vertical mixing, bura set down. Consequently, the pattern observed on 26 of March is still recognizable, but seems to be dissolving (Fig. 4b). The pattern is observable, almost unchanged on the scene taken the next day (orbit number 17361, 02.04.1982 – not shown). As a further evidence of robustness of this remotely observed information it is reassuring to analyse the histogram equalized composite image of the first three channels of the same scene, without atmospheric (or geometric) correction. Just by maximizing the contrast of the original channels one finds essentially the same pattern depicted in Fig. 4a.

The third bura episode (C) occurred in the middle of April when hydrographic conditions were already transitory, towards summer stratification. It was covered well by the CZCS sensor on the before/after basis; there is a scene taken on 11 April (orbit 17485) just before it, and another one on 18 April (orbit 17582), a few days after it. However, both scenes are rather cloudy with relatively clear conditions over the Po discharge area. The pigment concentration fields are again used to illustrate the case (Fig. 5). Having in mind nonconservativeness of the pigment field (biological and chemical processes involved), cloudiness of the scenes, as well as changed ambiental conditions it is rather difficult to formulate a convincing interpretation of this case. Nevertheless, the second scene in this sequence, coming after the bura and presented in Fig. 5b, suggests, when compared to situation in Fig. 5a, a change in pigment concentration pattern, upshore and offshore from the Po River near field discharge area, note unlike the expected effect of bura wind.

Another empirical data series considered was the Po River flowrate (Fig. 2b) as registered at an inland station (Pontelagoscuro, about 90 km up the river). The plot in Fig. 2b is a segment of the published annual data set (Anonymous, 1983). Before presenting the simulation results we will address a possible role of the river discharge. It should be born in mind that we will be looking at particular episodes, not at some statistical, average cases. Therefore, a change in flowrate from say 1000 to 1500 m^3s^{-1} over couple of days is significant 50 % increase, although a long-term average for particular month (say March) can be of comparable magnitude (cca 1500 m^3s^{-1}), and the extremes can go as low as 698 and as high as 3410 m^3s^{-1} (Cati, 1981).

The data in Figure 2b show an increase in the Po outflow around 8 of March, and then a downward trend, with some oscillations, throughout March and April. If we look at the Po River as a source of tracing material then the following situation emerge. The mentioned increase seems to coincide with the beginning of set down of the first (A) bura episode. However, one has to bear in mind the inland position of the measurement station and related delay in arrival of the increase at the river mouth. Consequently, the tracing material seems to be available when bura-induced gyre was already considerably

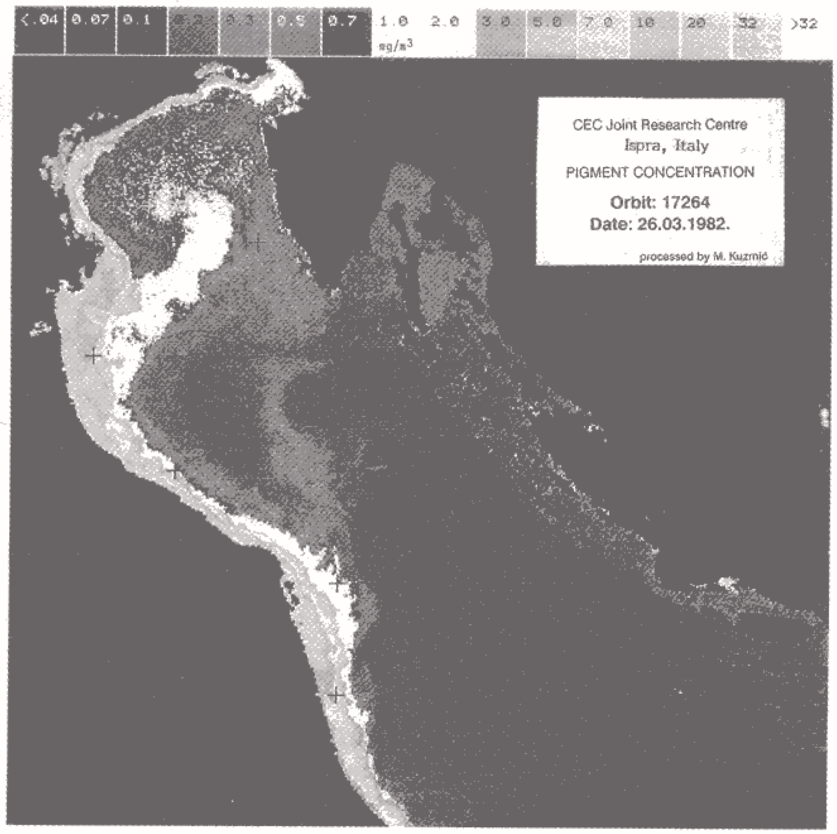

Figure 4a

Derived pigment concentration (a) for 26 March 1982, (from Kuzmić, 1991); (b, next page) for 1 April 1982 as calculated with IMA programme (Sobolev approximation of multiple scattering). Concentrations are given in mg m^{-3} .

spun down. There was another rise of the Po discharge, later in March, apparently coinciding, taking into account the mentioned delay, with the second (B) bura episode. We will remember that the B episode was the longest, but as energetic as the other two. In case of the third (C) episode, a slight increase in the outflow can also be observed, but it came after the bura, and was much weaker than the previous two. It seems that these differences in relative timing between Po discharge and bura wind do affect, and at least partially explain, the observed differences in CZCS patterns. This consideration of the wind and Po discharge data singles out the second episode as the most promising for comparison with model prediction.

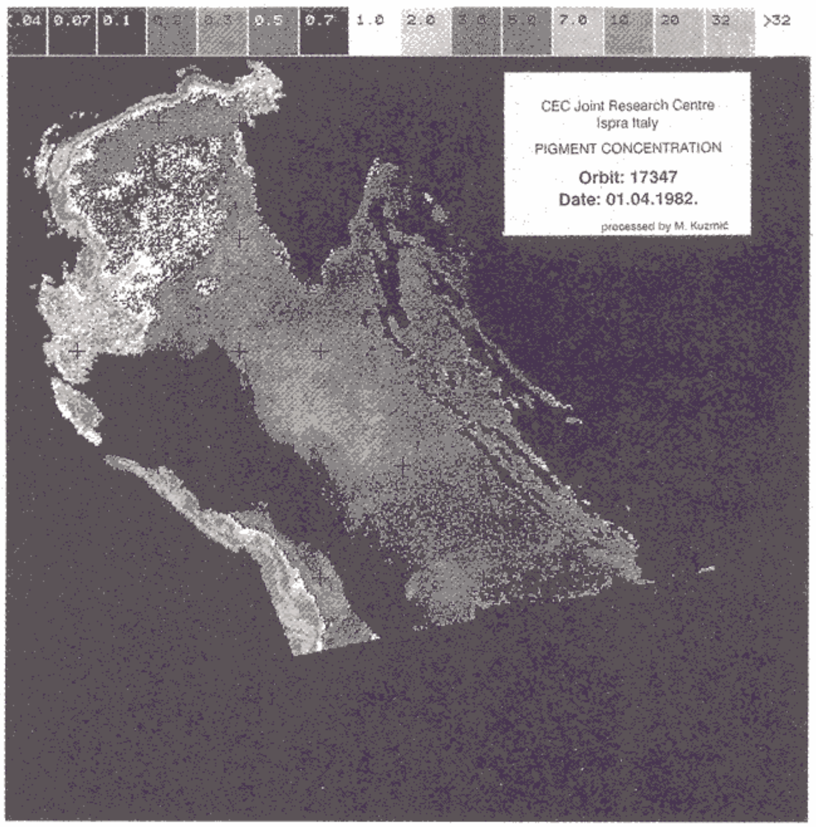

Figure 4b (see caption of Fig. 4a)

To facilitate better comparison of the image and the hydrodynamical model prediction the model was extended with some tracing facility. In particular, a simple particle tracking scheme has been added, patterned after an existing one for the Ionian Sea (C. Koutitas, 1988, personal communication). The particle tracking was based on often used partition of the current field into deterministic and stochastic component, *i.e.* at each time step each particle is subjected to a combined deterministic and random move, according to the following relations:

$$x_{\text{new}}(i) = x_{\text{old}}(i) + (u_{\text{det}} + u_{\text{sto}})\,\Delta t \tag{6}$$

$$y_{\text{new}}(i) = y_{\text{old}}(i) + (v_{\text{det}} + v_{\text{sto}})\,\Delta t \tag{7}$$

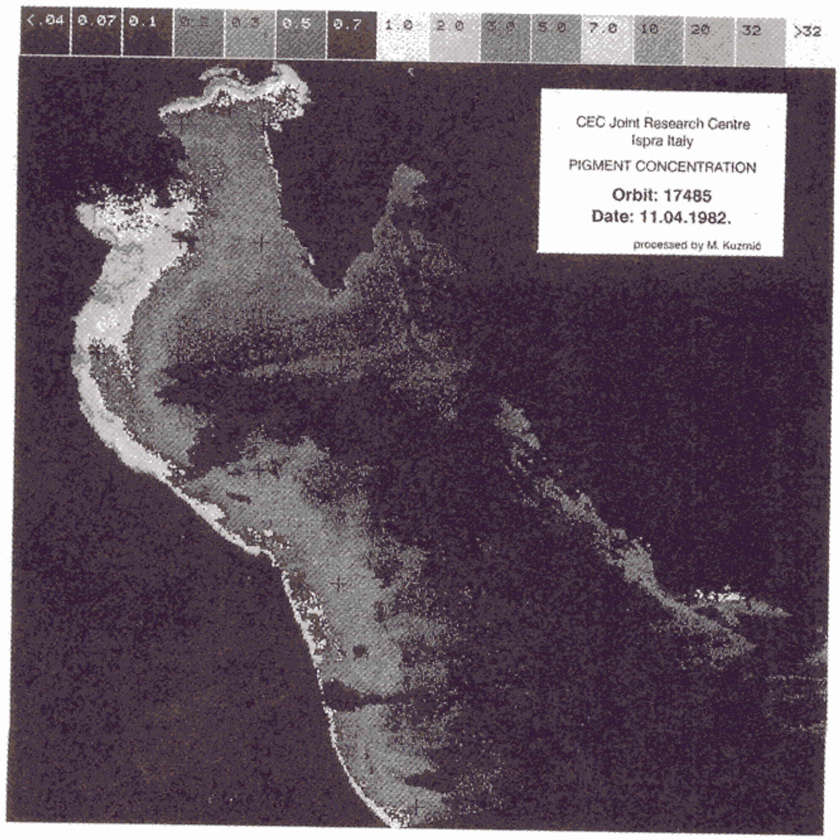

Figure 5a
Derived pigment concentration (a) for 11 April 1982; (b, next page) for 18 April 1982 as calculated with IMA programme (Sobolev approximation of multiple scattering). Concentrations are given in mg m^{-3}.

where x and y are coordinates of the i-th particle. Deterministic components u_{det} and v_{det} are surface layer (5 m) velocities from the hydrodynamical model (Fig. 1). A two-dimensional interpolation procedure was used to obtain component values at the positions not available directly. The stochastic components u_{sto} and v_{sto} were obtained using a random walk procedure based on the expression which relates the diffusion coefficient K_{H} to spatial and temporal steps (in two dimensions):

$$K_{\mathrm{H}} = \lim_{\substack{\Delta x \to 0 \\ \Delta t \to 0}} \frac{(\Delta x^2)}{4\Delta t}$$

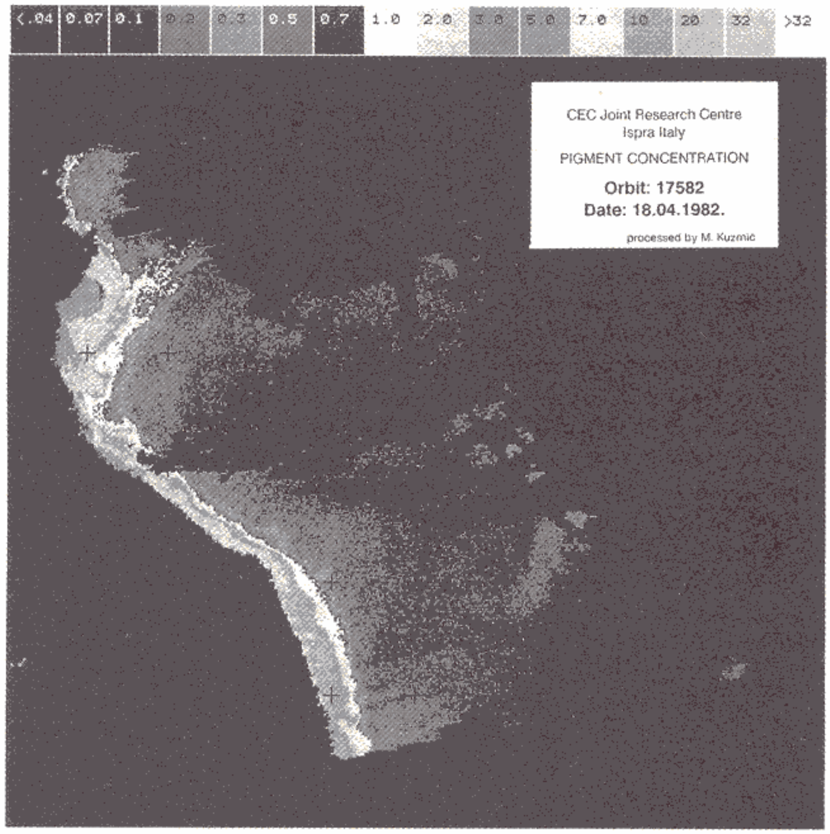

Figure 5b (see caption of Fig. 5a)

(for details see *e.g.* Lin and Segal, 1974). This relation, appropriately rearranged, provides maximum fluctuation velocity; an uniform random generator was used to sample the top-hat distribution limited with extreme fluctuation values. In present simulation the value of K_H was set to a realistic level of 10 m^2s^{-1} , and the time step was 30 min (since the velocity field was supplied a priori the HD model stability restrictions did not apply). To simulate a continuous release, 336 particles were discharged during 168 simulated hours; a particle per time step. Furthermore, three point sources with the above characteristics were positioned in the studied domain in a manner that resembled a horizontal line source. The latter choice was made in an attempt to visualize the possible fate of the Po River waters without having to simulate *ab initio* the Po and shelf waters interaction. It is not ment to question the significance of the river shelf interaction problem. Surface coastal discharge of lighter water produces a plume whose interaction with the shelf waters is inherently nonlinear, dominated by buoyancy and wind forces and controlled by bottom friction. The problem poses serious challenges to mathematical modelers, as recent efforts testify (*e.g.* O'Donnell, 1990; Oey and Mellor, 1993). However, these and similar studies seem to suggest that the Po River discharge is not likely to dominate the far field dynamics in the presence of wind-induced vorticity. That justifies the simplification applied in the present study, until more elaborate modelling studies are available.

The simulation we want to compare the 26 March scene with, is given in Figure 6. Applied random walk procedure visualizes suggestively the dispersion pattern that the bura spun-up gyre produces akin to the one in derived field of pigment concentration (Fig. 4a). This similarity can hardly be coincidental, but it is in order to remember here several approximations that may have influenced it. Firstly, spatial heterogeneity of the wind stress was defined using climatological data from Croatian coastal stations, thereby ignoring possible influence of the open sea and the Italian coast; equally ignored was its temporal variability. Secondly, random diffusion was added to the

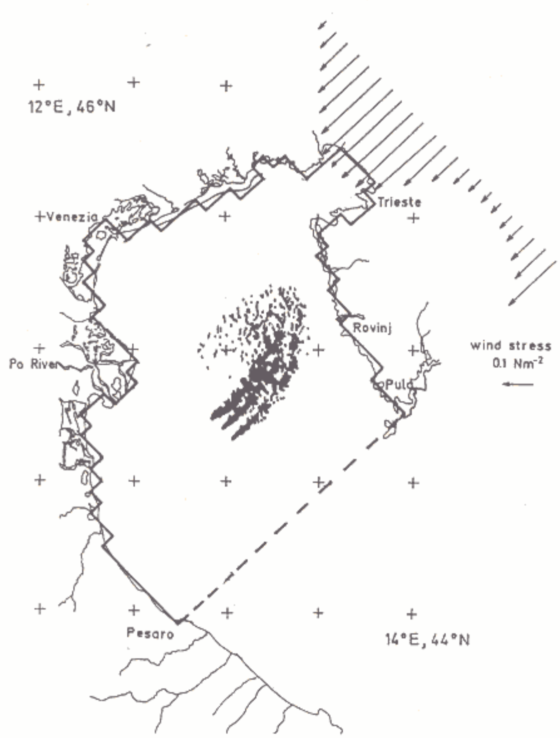

Figure 6. Simulated, random-walk dispersion in the current field depicted in Fig. 1. Situation corresponds with the 26th of March scene presented in Figure 4a.

steady current field, ignoring the effects of onset and decay. Thirdly, only the far field effect was simulated, ignoring the intricacies of a strong river discharge onto a sloping continental shelf. (Woods and Beardsley, 1988). Apparently, disregard of these factors does not prevent the effect of bura to emerge, provided other requirements, like relative timing of the Po discharge, are fulfilled.

5. Conclusions

The objective of this paper was an assessment of the Adriatic Sea response to a spatially heterogeneous wind relying on spaceborne observations. Original CZCS radiances and derived field of pigment concentration were used to that end. By observing changes in the spectral reflectance and derived fields of the Northern Adriatic waters, further evidence was found for previously studied effect of spatially heterogeneous bura wind. Three bura episodes were considered and their similarities and differences were analysed, relying on available wind and Po River data. Recognizing the hydrographic and meteorological differences between the cases, relative timing of bura episodes and availability of tracing material emerged as an important factor. Extending the hydrodynamical model with some tracing facility (random walk dispersion) helped to compare mathematical modelling results and spaceborne observations in a simplified manner. In comparison of model-generated and sensor-collected information bura-induced gyre emerged as the mechanism responsible for particular change of spatial pattern observed in the radiance field detected by CZCS sensors and in derived field of pigment concentration, used as a tracer. The exercise demonstrates convincingly that effect of spatially heterogeneous bura wind is observable in remotely sensed CZCS data. Nevertheless, a closer look at the problem, with more empirical data and better, front-resolving baroclinic model, would build further confidence and help elucidate intricate dynamics of this phenomenon.

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