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Optical remote sensing of coastal plumes and run-off in the Mediterranean region

Barale, V.[1] **& Larkin, D.**[2]

[1]*Space Applications Institute, Joint Research Center of the EC, 21020 Ispra (VA), Italy;*
Tel. +39 332 789274; Fax +39 332 789034; E-mail vittorio.barale@jrc.it;
[2]*D.J.L. Software Consultancy Ltd, 63 Fellgate Av, Jarrow, Tyne and Wear, NE32 4QR, United Kingdom*

Abstract. Sea surface colour data, derived from the Coastal Zone Colour Scanner (CZCS) archive, have been used to assess the space/time variability of coastal plumes and run-off in the Mediterranean Sea. A time series of 2645 scenes, collected by the CZCS from 1979 to 1985, was processed to apply sensor calibration algorithms, correct for atmospheric contamination, and derive chlorophyll-like pigment concentration. Individual images, remapped on a 1-km^2 pixel grid, were generated for each available day, and then mean values calculated pixel by pixel to form monthly, seasonal and annual composites. The results obtained must be taken with caution, due to the CZCS limitations in the quantitative assessment of bio-optical pigments when high concentrations of dissolved organics or suspended sediments are present, e.g. along littorals or within plumes. Marked differences appear in the distribution of water constituents between coastal zones and open sea, northern and southern near-coastal areas, western and eastern sub-basins. The oligotrophic character of the basin contrasts with areas of high concentration related to river plumes – Ebro (Ebre), Po, Rhone, Nile –, coastal run-off patterns, and persistent mesoscale features (e.g. coastal filaments and eddies). Seasonal variability appears to be high, with higher concentrations occurring over most of the basin in the cold season, when climatic conditions are favourable to coastal run-off and vertical mixing. Atmospheric forcing (wind and rainfall over continental margins) could play an important role in establishing the observed space/time distribution of water constituents. The impact of continental interactions (fluvial and coastal run-off), or that of exchanges between coastal zone and open sea, could have paramount influence on the biogeochemical fluxes in the entire basin.

Keywords: Coastal zone; River plume; Sea surface colour.

Introduction

The great potential of sea surface colour observations to provide novel information on biological, geochemical and physical processes of the sea, has opened new perspectives for the understanding of marine environmental processes (cf. Barale & Doerffer 1993). The optical properties of surface waters, in fact, depend on the presence and concentration of water constituents - parameters closely related to a variety of environmentally important variables and, in particular, for marginal and enclosed basins, to the impact of coastal and fluvial run-off, coupled to water circulation patterns (Ojeda et al. 1995. The outstanding capabilities of optical remote sensing techniques have been demonstrated by the Coastal Zone Colour Scanner (CZCS) experiment (Hovis et al.1980), which collected a (quasi) global sea surface colour data set from late 1978 to early 1986. In spite of its many limitations, the CZCS historical time series is still being exploited, and will continue to provide a significant statistical reference for future ocean colour assessments.

In the present study, a multi-annual time series of high-resolution sea surface colour data derived from the historical CZCS archives, recently developed for the European Seas (Barale & Zibordi 1994), has been used to assess the typical space/time variability of various near-coastal features in the Mediterranean Sea. Even though the environmental characteristics of the Mediterranean are generally well documented, at least locally, the new synoptic perspective offered by a systematic analysis of CZCS data, indicates the role played by near-coastal processes in shaping the surface water constituent field.

The historical archives used for the present study was developed in the framework of the OCEAN Project, which was set up in 1990 in order to generate a data base of CZCS data on the European seas, and to set up the scientific tools needed for its exploitation (Anon. 1990). In its five years of activity, the OCEAN Project has processed ca. 15000 CZCS images at level_1 (original top-of-the atmosphere radiances, archived in standard format), 7000 images at level_2 (surface reflectances and derived geophysical parameters) and 3500 images at level_3 (remapped, composited statistical products) of the major European basins. The Project has generated an archive of 180 GB worth of level_1 data products, 160 GB of level_2 data products, and 60 GB of level_3 data products, and has distributed thousands of data products and dedicated software to more than 40 user groups in Europe and beyond , as part of an Application Demonstration Programme.

In the following, some examples of coastal run-off patterns, river plumes and mesoscale features appearing in the sea surface colour imagery of the Mediterranean Sea, when the data are composited at the basin scale and over a period of several years, will be described. Further, the potential links between observed patterns and climatic characteristics of the Mediterranean region, suggested by the composites, will be briefly addressed.

The Mediterranean CZCS data set

A set of composite images of the Mediterranean basin was derived from 2645 individual scenes collected by the CZCS from 1979 to 1985. The image selection took into account geographical coverage and cloud cover, illumination conditions and instrument settings at the time of data collection, as well as intermediate data processing results. The data volume distribution over time (see Fig. 1) reflects the higher collection rates during the early part of the CZCS lifetime, with a slight increase in the number of scenes collected during the spring/summer periods, due to the climatic characteristics of the region. The raw data were processed to calibrate the sensor-recorded signal, correct the calibrated signal for atmospheric contamination, derive surface reflectances, and then calculate the concentration of the water constituents of interest (see Barale et al. 1994; Sturm 1993, for a detailed description of the algorithms).

In brief, the atmospheric correction was performed on the basis of a reflectance-model-based algorithm. The correction for Rayleigh scattering was applied consistently for all water pixels, using a multiple scattering approach, and introducing atmospheric pressure and ozone concentration data in the computation. The marine aerosol correction used a pixel by pixel iterative procedure, which allowed successive estimates of both the marine reflectance in the red spectral region (670 nm) and the Ångstrom exponent, which links simple wavelength ratios to reflectance ratios. For case-1 waters, the optical properties of which are essentially dominated by planktonic pigments, the interrelations between marine reflectances and reflectance ratios at various wavelengths were derived from modelled calculations (Bricaud & Morel 1987). For identified case-2 waters, where water constituents other then planktonic pigments (i.e. dissolved organics and suspended sediments) dominate the water optical properties, the evaluation of marine reflectances was approximated by means of interpolated Ångstrom exponent values computed over case-1 water pixels and of empirical relationships derived from *in situ* measurements (Austin & Petzold 1981; Viollier & Sturm 1984). The computation of water constituent concentrations (namely of chlorophyll-like pigments, hereafter referred to as pigments) was performed with algorithms based on blue/green (443/550 nm) reflectance ratios, for lower pigment concentration, or on green/green (520/550 nm) reflectance ratios, for higher pigment concentration. As for the case of atmospheric corrections, the interrelations between pigment concentration and reflectance ratios were model-derived for case-1 waters, and empirically determined for case-2 waters (Bricaud & Morel 1987; Viollier & Sturm 1984; Sturm et al. 1992).

Finally, individual images of pigment concentration, remapped on a standard 1-km^2 pixel grid of the whole Mediterranean basin, were generated for each available day. Mean values for daily images were ob-

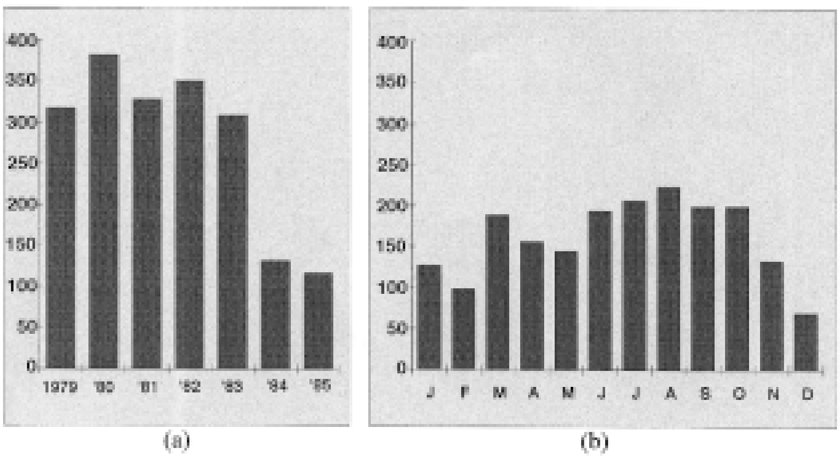

Fig. 1. Mediterranean Sea data set generated by the OCEAN Project: number of CZCS images (**a**) per year, and (**b**) per month, over the seven years considered (1979-1985).

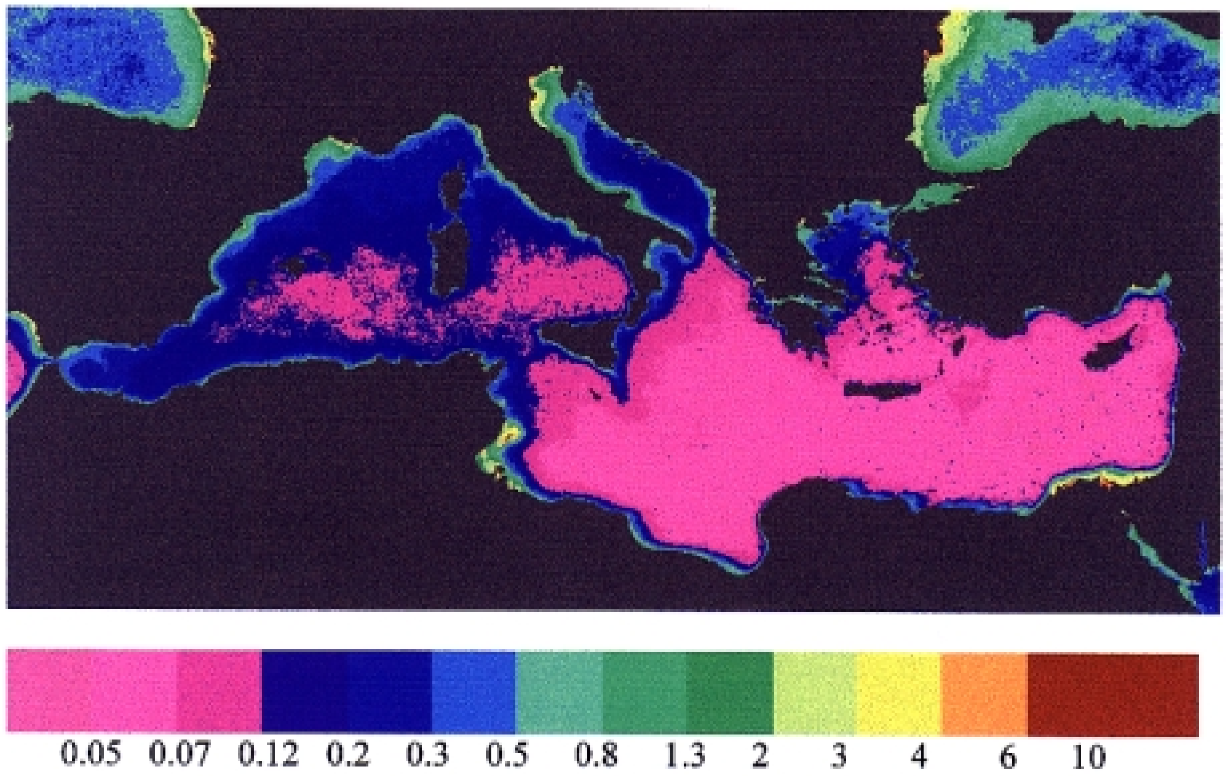

Fig. 2. Mean CZCS annual image of the Mediterranean basin, composed from 2465 individual images (1979-1985). The original data were processed to derive chlorophyll-like pigment concentration (shown by the scale as mg/m^3), re-mapped to the same equal area geographical projection, with 1-km^2 pixels, and composed by obtaining mean values on a pixel-by-pixel basis.

tained on a pixel-by-pixel basis, to generate monthly, seasonal, and annual composites, by means of simple statistical operators providing temporal means and standard deviations of images covering the same spatial domain. The composite images are sometimes rather poor from a statistical point of view (due to the low number and uneven distribution in the time domain of the individual images from which a particular composite is obtained), but remain of particular interest for the assessment of time and space scales of the sea surface colour field.

Coastal features, plumes and run-off patterns

Typical patterns of near-coastal features were derived from the composite pigment images (e.g. Fig.2). The results obtained should be considered with caution, due to the CZCS limitations in the quantitative assessment of biogenic pigments when significant concentrations of dissolved organics or suspended sediments are present, e.g. along littorals or within plumes. In general, however, it is possible to exploit the image data for a qualitative analysis of the marked differences which appear in the distribution of water constituents, such as those differentiating between the open sea and the coastal zone.

In general, the basin interior has oligotrophic characteristics which contrast with the areas of high pigment concentration, influenced by persistent mesoscale dynamic features, like coastal filaments and eddies, by the spreading of river plumes, and by widespread coastal run-off patterns. Further, the difference between inshore and offshore domains is superimposed on that between the northern and the southern near-coastal areas, as well as that between the western and eastern sub-basins.

As shown by the mean annual pigment concentrations in Fig. 2, the transition between the western and the eastern basin corresponds rather precisely with a line connecting the Sicilian Channel, the Strait of Messina, and the Strait of Otranto. Contrary to geographical subdivisions commonly used, this qualifies the Adriatic Sea as one of the western sub-basins, at least as far as sea surface colour field is concerned. The similarities of pigment concentrations and dynamics in the Adriatic

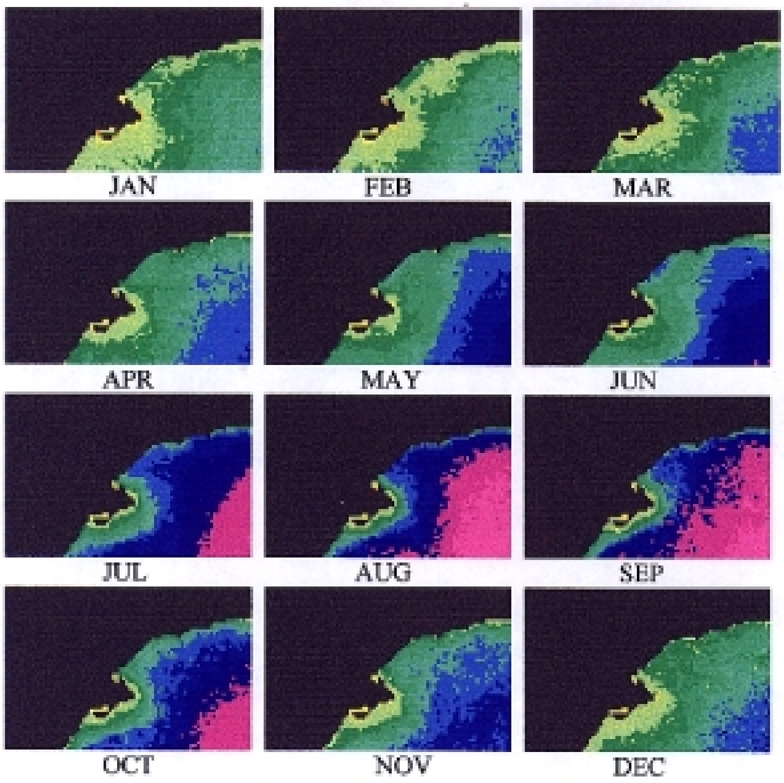

Fig. 3. Composite monthly images of the Balearic basin (1979-1985), showing the variability of the Ebro river plume over the annual cycle. The original data were processed to derive estimates of chlorophyll-like pigment concentration, then remapped to the same equal area geographical projection, with 1-km^2 pixels, and composed by obtaining mean values on a pixel-by-pixel basis. Colour scale as in Fig. 2.

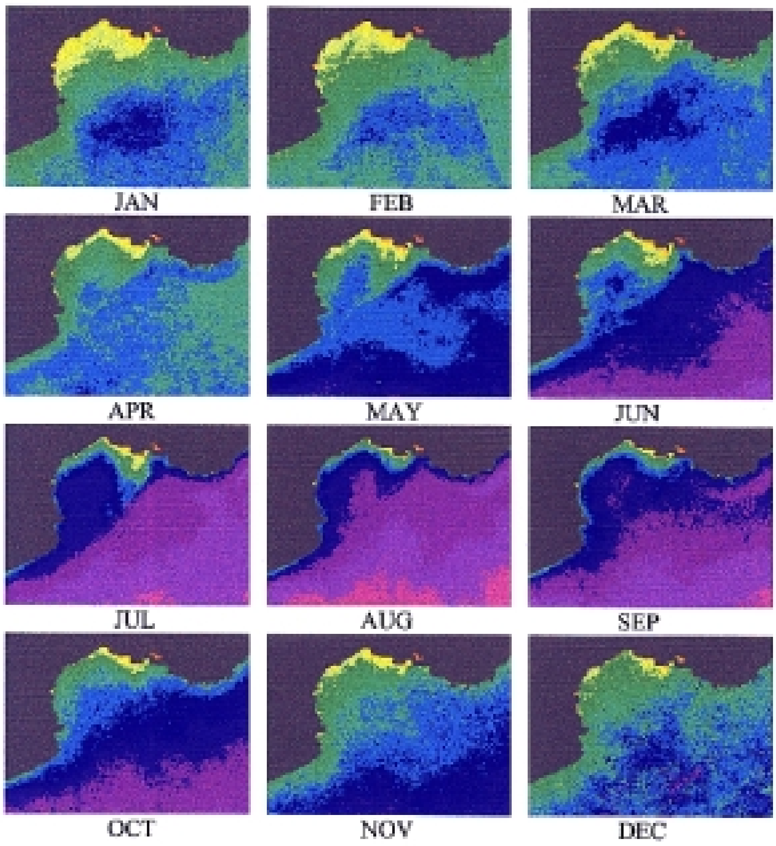

Fig. 4. Composite monthly images of the Golfe du Lion area (1979-1985), showing the variability of the Rhone river plume over the annual cycle. The original data were processed to derive estimates of chlorophyll-like pigment concentration, then re-mapped to the same equal area geographical projection, with 1-km^2 pixels, and composed by obtaining mean values on a pixel-by-pixel basis. Colour scale as in Fig. 2.

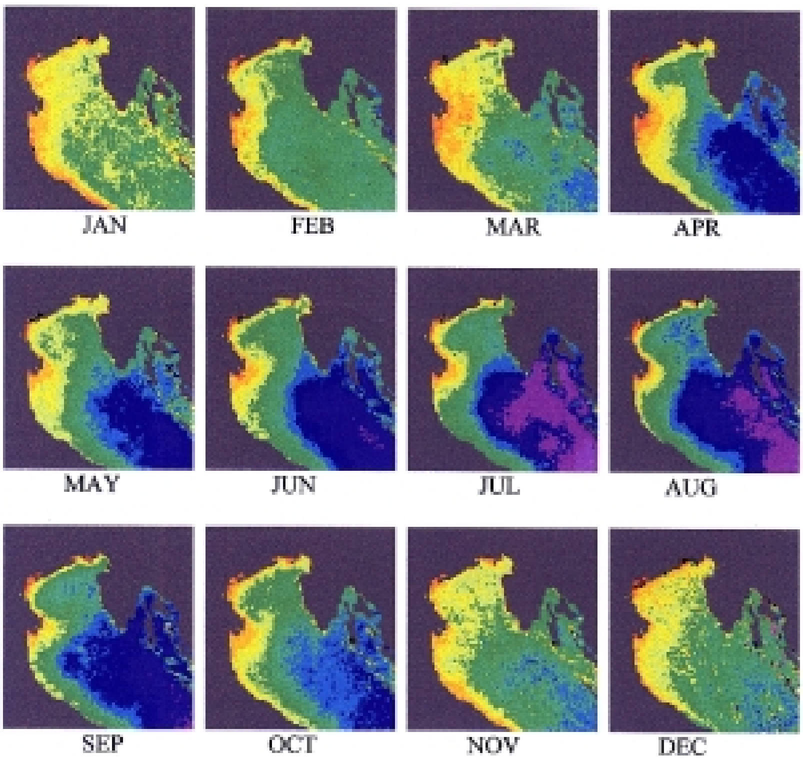

Fig. 5. Composite monthly images of the northern Adriatic basin (1979-1985), showing the variability of the Po river plume over the annual cycle. The original data were processed to derive estimates of chlorophyll-like pigment concentration, then re-mapped to the same equal area geographical projection, with 1-km^2 pixels, and composed by obtaining mean values on a pixel-by-pixel basis. Colour scale as in Fig. 2.

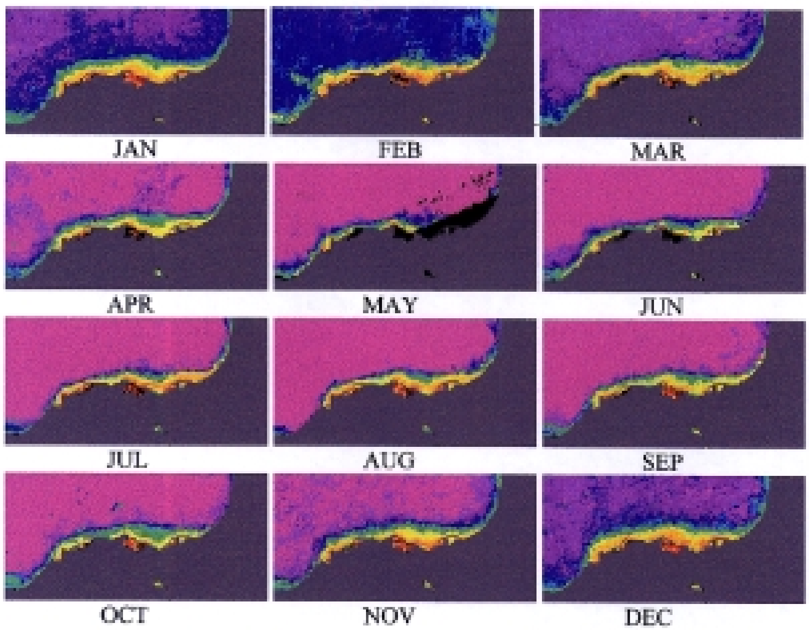

Fig. 6. Composite monthly images of the southeastern Mediterranean basin (1979-1985), showing the variability of the Nile river plume over the annual cycle. The original data were processed to derive estimates of chlorophyll-like pigment, then remapped to the same equal area geographical projection, with 1-km^2 pixels and composed by obtaining mean values on a pixel-by-pixel basis. Colour scale as in Fig. 2.

and the Ligurian, Provençal and Balearic basins is evident for both coastal zone and open sea.

Interestingly enough, even the northern Aegean basin seems to have analogous characteristics. This suggests that the near-coastal rim of enhanced pigment values around the western (and northern) part of the Mediterranean basin might be associated with the impact of run-off from the northern continental margin and with river discharges (i.e. both a direct impact due to the sediment load and one induced on the planktonic flora by the associated nutrient load). In this interpretation, differences in geo-morphology and climate of the western (and northern) coastal zones, therefore, would be associated with the bio-optical characteristics of the various sub-basins. Note that, in the eastern basin, the enhanced pigment values of the shallow banks off southern Tunisia, as well as those along the Libyan/Egyptian coast, must be excluded from such an interpretation. In fact, the first occurrence is due to the reflection from the bottom, which is wrongly interpreted as high pigment concentration in the water column, while the second appears to be associated with the signal contamination due to sensor ringing, in the down-scan direction, after imaging a very bright target such as the Sahara. Other permanent features of the Mediterranean pigment field include the Alboran gyre, the filament at Capo Passero, at the southern tip of Sicilia, and the Rodhos gyre core.

In addition to these features, the composite images show that all of the main rivers entering the Mediterranean Sea, i.e. the Ebro, Rhone, Po and Nile, form distinct permanent plumes. As outlined above, it is often impossible for the CZCS to distinguish the signature of biogenic pigments from that of the total load of dissolved and suspended materials present within the range of the plumes. However, the observation of such features provides important clues on frontal dynamics and potential correlations with nutrient enrichment or pollution. Figs. 3 to 6 show the Ebro, Rhone, Po and Nile plumes, and their interactions with the respective sub-basins, i.e the Balearic basin, the Golfe du Lion, the northern Adriatic and the southeastern Mediterranean. The colour scale used is the same as for Fig. 2.

In the temporal domain, a significant seasonal variability appears to be coupled to a less pronounced, but evident, interannual variability. The general characteristics of the pigment field are rather constant for the whole basin, while major differences occur in the details composing the larger picture. Oligotrophic conditions are most persistent, over the annual cycle, in the eastern rather than in the western Mediterranean. Accordingly, seasonal variations are most pronounced in the western rather than in the eastern Mediterranean, with enhanced patterns and higher concentrations in late winter and early spring - possibly corresponding to the cold, rainy season of this region, when climatic conditions would be most favourable to coastal run-off and vertical mixing at various sites. Examples of the temporal variability in plume size for the four main rivers mentioned above are provided in Fig. 7. The plume index obtained for the rivers was derived from the 1979-1985 monthly composite images, as the number of pixels (i.e. km^2, given the equal area projection and scale used for the imagery) in each plume having a pigment value higher than 1 mg/m^3.

Conclusion

The exploitation of optical remote sensing techniques for the Mediterranean Sea is of considerable interest, due the combination of low cloudiness, predominance of case-1 waters, and availability of historical data in this basin. However, the data record is well documented for hydrological and dynamical phenomena, but less complete for biogeochemical parameters (for which the record is mostly limited to specific test sites). The intensive coverage achieved during the CZCS lifetime allows an extension of our view of bio-optical processes to the entire basin, establishing historical time series as a framework for current research and reference for future work (Hooker et al. 1993). The sea surface colour field of this region has been explored already, using CZCS data, in a score of regional studies dealing with specific phenomena and/or sites (see e.g. Barale et al. 1986; Taupier-Letage & Millot 1988; Morel & André 1991). Now, the availability of a complete, multi-annual data set can provide a synoptic view of the Mediterranean environment, put its near-coastal and open sea characteristics into perspective, and delineate a first partition of the basin into bio-geographical provinces, on the basis of its surface colour features.

The range of coastal phenomena observed in the present work suggests a significant relationship between the resulting basin-wide seasonal patterns and the climatic cycle of the Mediterranean region. In particular, atmospheric forcing (wind, causing thermohaline reactions or even carrying Saharan dust and rainfall, primarily as related to run-off) over the Mediterranean continental margins could play an important role in establishing the observed spatial and temporal distribution of water constituents. Similarly, the impact of continental interactions such as fluvial and coastal run-off, or that of exchanges between coastal zone and open sea, may have paramount influence on the bio-geo-chemical fluxes in the entire basin.

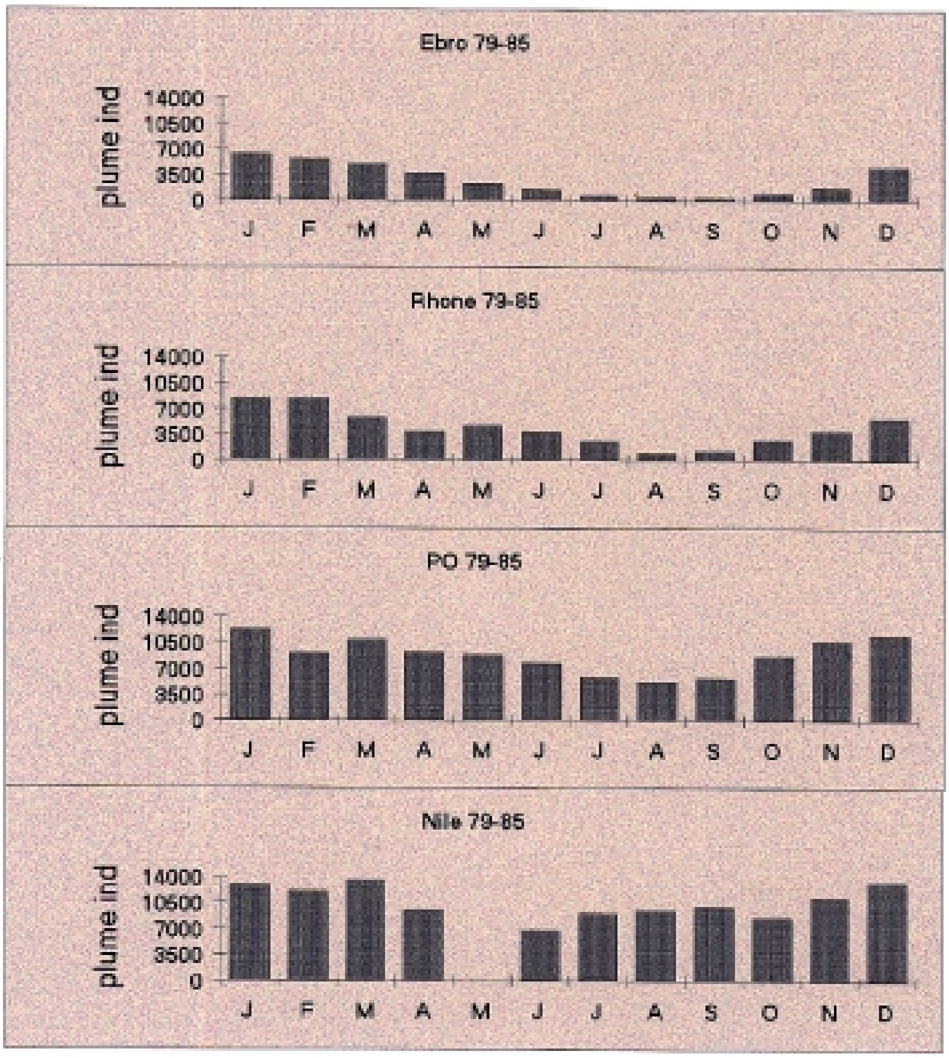

Fig. 7. Temporal variability in plume size for the four main rivers entering the Mediterranean Sea (Ebro, Rhone, Po, Nile). The plume index was derived from the 1979-1985 monthly composite images, as the number of pixels (i.e. km^2, given the equal area projection and scale used for the imagery) in each plume having a pigment value higher than 1 mg/m^3.

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