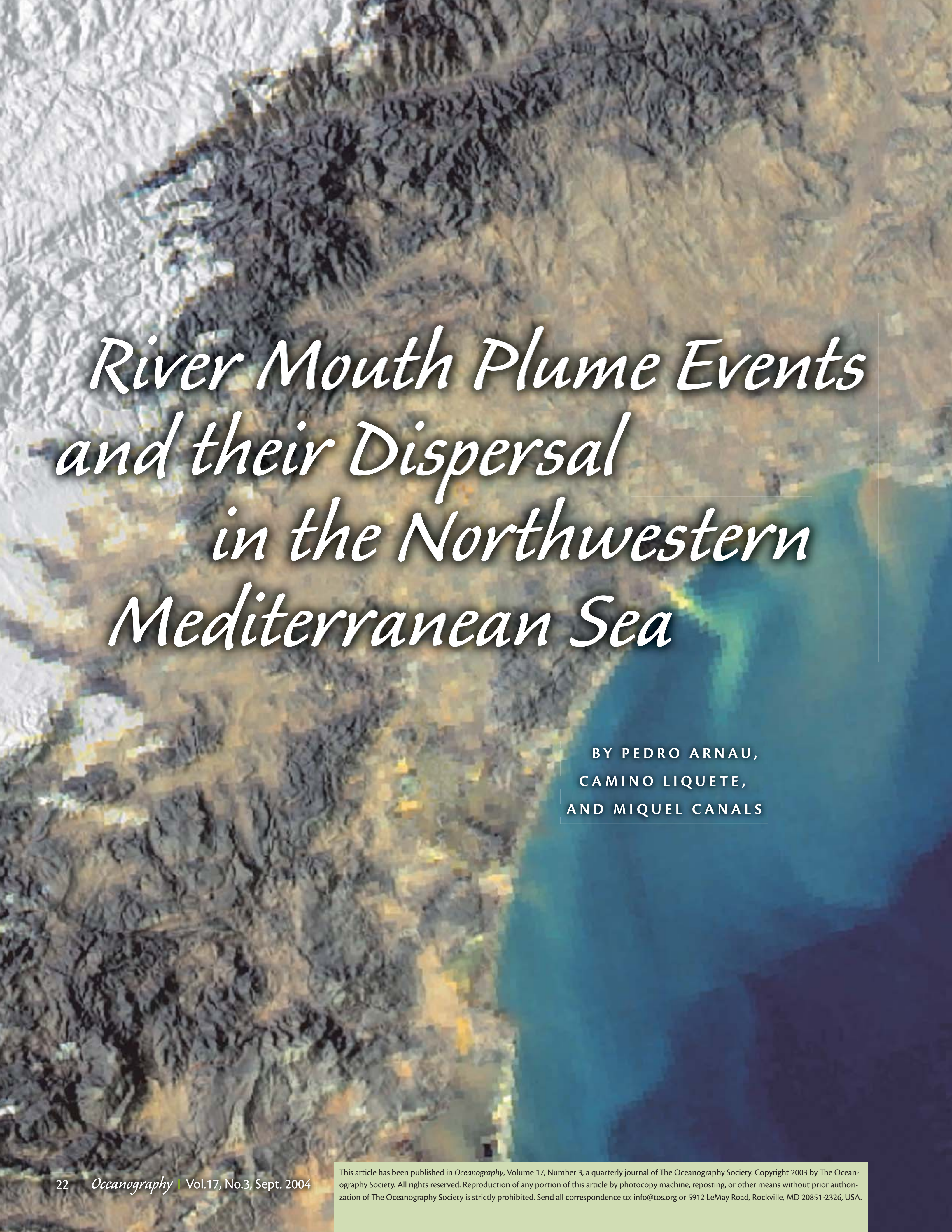
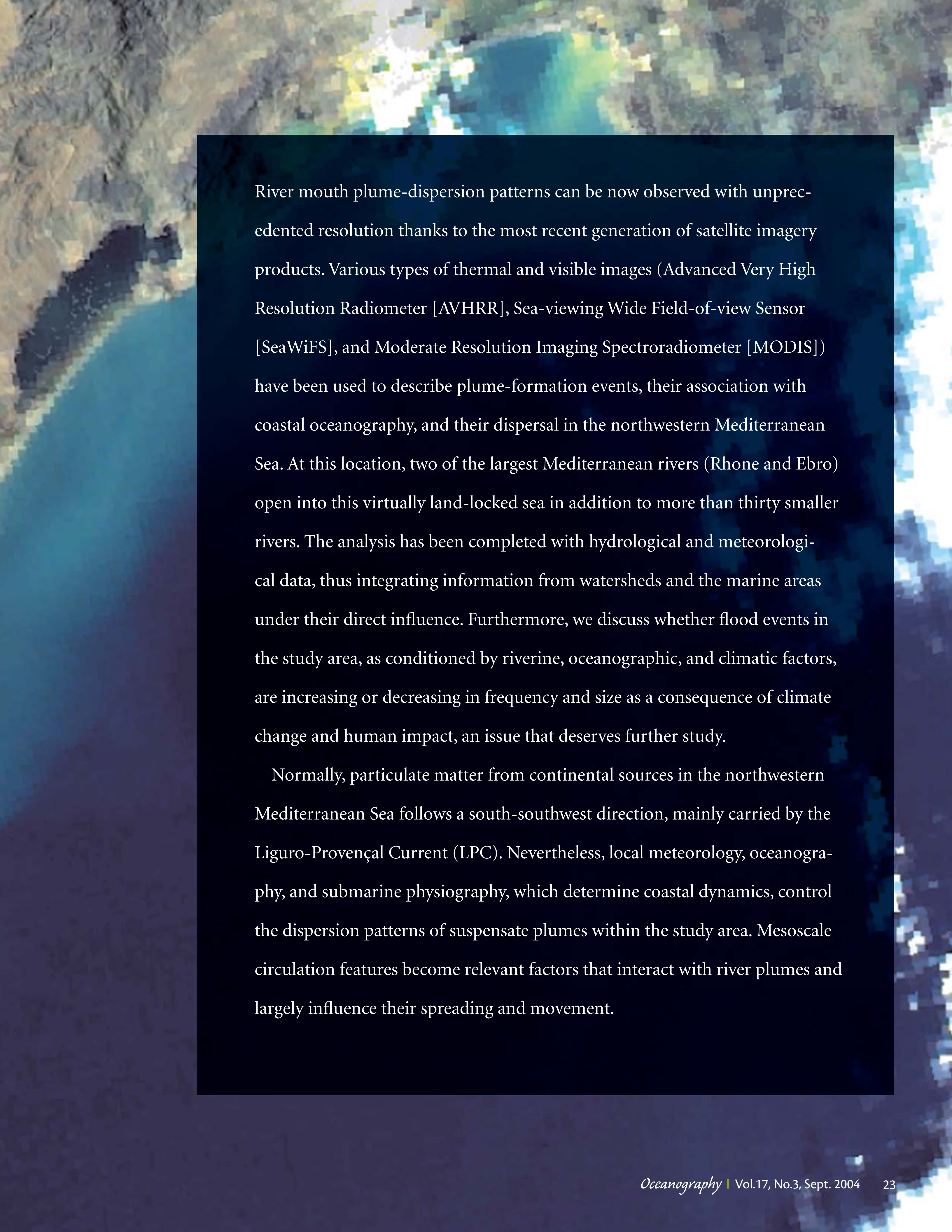


River Mouth Plume Events and their Dispersal in the Northwestern Mediterranean Sea

BY PEDRO ARNAU, CAMINO LIQUETE, AND MIQUEL CANALS



River mouth plume-dispersion patterns can be now observed with unprecedented resolution thanks to the most recent generation of satellite imagery products. Various types of thermal and visible images (Advanced Very High Resolution Radiometer [AVHRR], Sea-viewing Wide Field-of-view Sensor [SeaWiFS], and Moderate Resolution Imaging Spectroradiometer [MODIS]) have been used to describe plume-formation events, their association with coastal oceanography, and their dispersal in the northwestern Mediterranean Sea. At this location, two of the largest Mediterranean rivers (Rhone and Ebro) open into this virtually land-locked sea in addition to more than thirty smaller rivers. The analysis has been completed with hydrological and meteorological data, thus integrating information from watersheds and the marine areas under their direct influence. Furthermore, we discuss whether flood events in the study area, as conditioned by riverine, oceanographic, and climatic factors, are increasing or decreasing in frequency and size as a consequence of climate change and human impact, an issue that deserves further study.

Normally, particulate matter from continental sources in the northwestern Mediterranean Sea follows a south-southwest direction, mainly carried by the Liguro-Provençal Current (LPC). Nevertheless, local meteorology, oceanography, and submarine physiography, which determine coastal dynamics, control the dispersion patterns of suspensate plumes within the study area. Mesoscale circulation features become relevant factors that interact with river plumes and largely influence their spreading and movement.

INTRODUCTION

Flood events are characteristic of most Mediterranean river systems and lead to the formation of sediment plumes off river mouths. These plumes play a major role in the overall water and sediment discharge and, consequently, in the development of prodeltaic bodies and their fine-grained extensions alongshore, towards the continental shelf, and beyond. The environmental importance of these flood events comes from their close relationship with the spread of pollutants and with biological productivity.

Once the water carried by the river flood enters the sea and the suspensate plume starts to form, its spreading, evolution, and dispersal are largely dependant on mesoscale circulation, i.e., the oceanic circulation involving features such as gyres, meanders, filaments, and fronts from tens to a few hundred kilometers in size and from days to months in duration.

In this paper we illustrate river mouth plume-formation events as well as the factors controlling the dispersal of these suspensate plumes in the northwestern Mediterranean Sea by analysis of AVHRR, SeaWiFS, and MODIS satellite images collected during the last decade, complemented by hydrological and meteorological data. The first two types of images were primarily used to model the interaction between coastal and mesoscale surface flows because fluvial plumes can only be observed indirectly from the water thermal signal (AVHRR) and chlorophyll distribution (SeaWiFS). On the other hand, MODIS images, thanks to their high radiometric, spatial, and temporal resolution, show the suspended sediment concentration itself, allowing us to define accurately plume formation and development.

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HYDROLOGIC SETTING

The present work focuses on the river basins, coasts, and continental shelves extending along the Gulf of Lions, the Catalan margin, and the Ebro sector (Figure 1). All 34 significant river systems in terms of basin size and discharge at the mouth have been considered, covering an overall area of nearly 230,000 km^2. These river systems extend from Huveaune River (1 in Figure 1) to Palancia River (34 in Figure 1). More than half of this area (53.9 percent) contains rivers flowing directly into the Gulf of Lions continental shelf. Another subset, representing 40.1 percent of the total area, flows into the Ebro continental shelf. Only 6 percent of the total catchment area corresponds to rivers opening into the North Catalan shelves, which are located between the wider shelves of the Rhone and Ebro Rivers and are incised by two of the largest submarine canyons in the Mediterranean Sea, the Blanes and La Fonera canyons. Because of the size of their catchments, the Rhone and Ebro Rivers dominate the study area.

The Rhone River has the largest catchment with 98,890 km^2. Its mean liquid discharge at the mouth is 1,700 m^3 s^{-1} and peak discharges up to 13,000 m^3 s^{-1} have been measured in December 2003. The Ebro River catchment is the second in size with 85,362 km^2. Its liquid discharge averages 400 m^3 s^{-1} with recent maximum values up to 2,500 m^3 s^{-1} in February 2003.

The marked difference in liquid discharge between the Rhone and Ebro Rivers, as measured in gauging stations close to the river mouths, can be attributed to (a) rainfall variations linked to latitude and altitude including orographic effects, (b) differences in catchment sizes (Rhone's catchment is larger), and (c) water regulation (dams) in each of the two river basins. The main tributaries of the Rhone River flow from Alpine regions, which are under the frequent influence of precipitation fronts associated with pressure lows brought by the Polar Front Jet Stream. Mean precipitation values in the mountainous sources of the Rhone River can attain 2,000 mm yr^{-1}. Most Ebro tributaries come from the drier western and central Pyrenees and the Iberian Massif. There, mean annual rainfall does not exceed 1,000 mm largely because of the orographic barrier exerted by the Pyrenees and the Cantabrian Cordillera. River regulation and damming along the Rhone is mostly located in the uppermost course, while along the Ebro, many large dams have been built in the middle and lower river course. Though punctuated by years of enhanced precipitation and discharge, the Ebro has shown during the last century a net decline in the volume of water released to the Mediterranean Sea (Canals et al., 2004). Up to 96 percent of the area in the Ebro Basin is currently regulated by dams, and has been since the construction of the low-course large Mequinensa and Ribarroja dams during the 1960s. It has been estimated that more than 99 percent of the sediment discharge carried by the

Ebro River at the beginning of the 20th century is now retained behind its almost 200 dams (Guillen and Palanques, 1992; Ibañez et al., 1996).

The study of river basins in the northwestern Mediterranean region must be placed into perspective as related to global trends in river discharge. Some authors (e.g., Milly et al., 2002) state that global warming can cause an increase in fluvial peak floods, although others (e.g., Ludwig et al., 2004) point out the persistence of uncertainties about the influence of global trends at local scales. Figure 2 shows temperature data gathered from Perpignan, southeast coastal France, midway between the Ebro and Rhone River basins, and the liquid discharge from these two rivers. While both Ebro and Rhone watersheds undergo large interannual discharge variations, there is no sign of a recent increment in flood events as could be inferred from the temperature trend. In addition, Rhone River liquid discharge shows no significant variation from 1920 to 2000, while the Ebro River displays a tendency towards flow reduction since the late 1950s. This decreasing trend is probably related to the intense damming and water diversion carried out in the Ebro Basin in recent decades, similar to the large impact regulation has had on the Tet River (14 in Figure 1) referred to by Ludwig et al. (2004).

OCEANOGRAPHIC SETTING

In general terms, surface circulation in the northwestern Mediterranean Sea

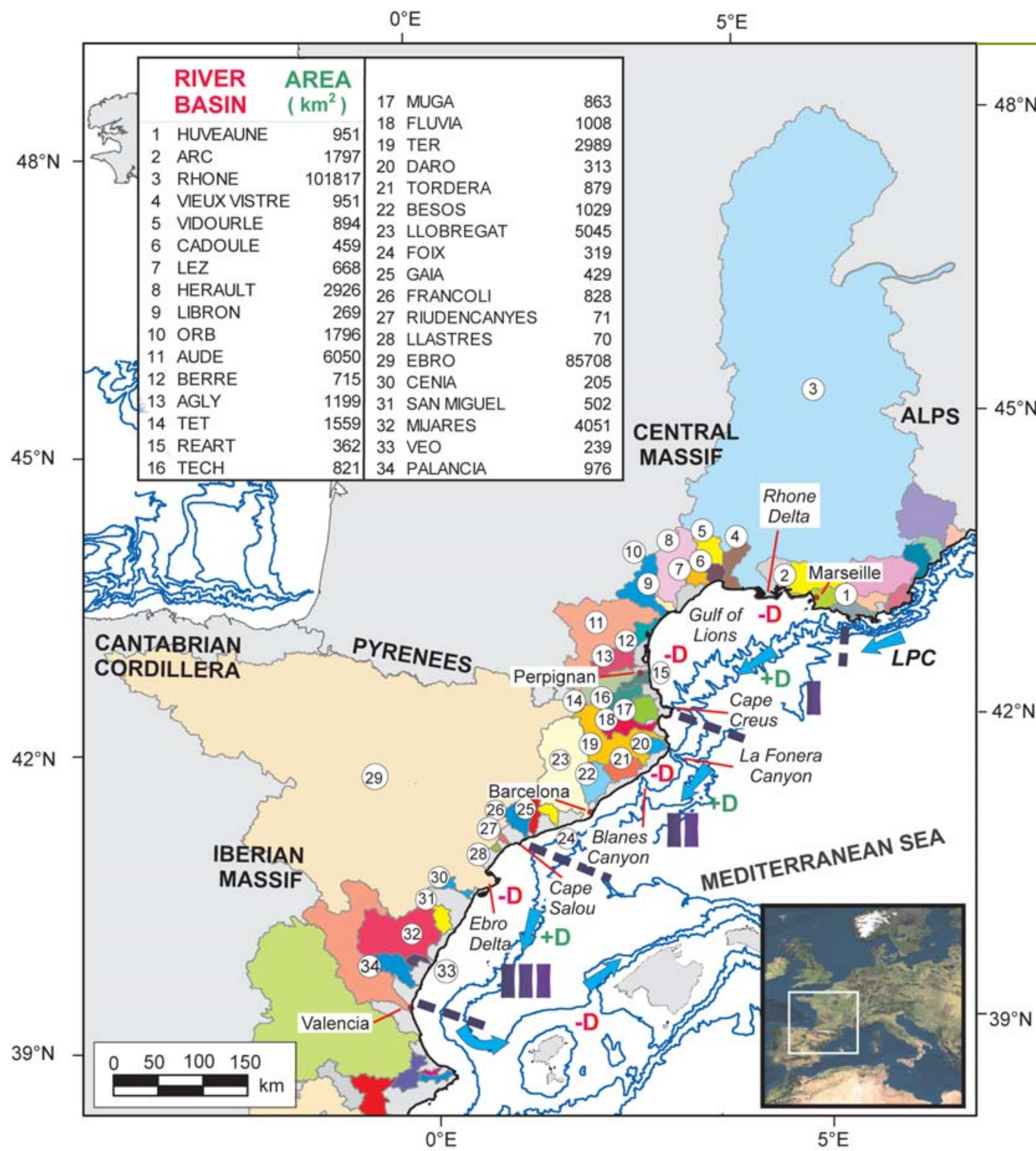
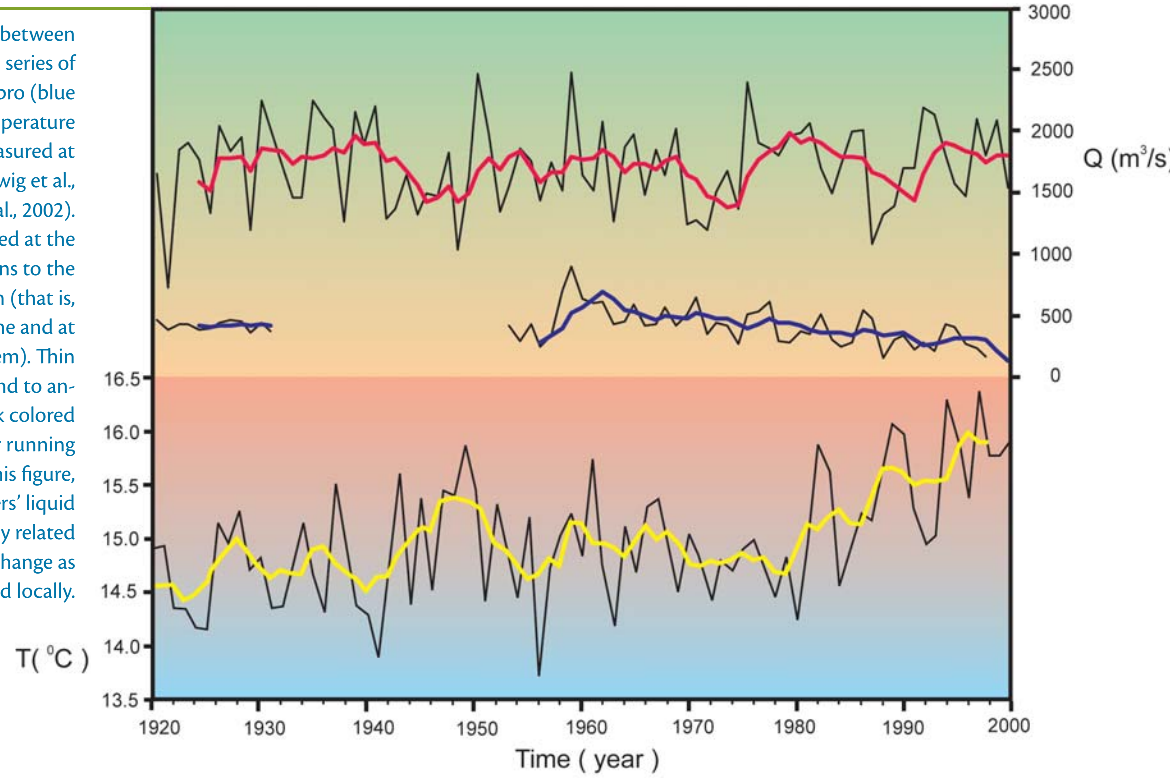


Figure 1. River basins flowing into the Gulf of Lions (Zone I, river systems 1-16), the North Catalan margin (Zone II, river systems 17-26) and the Ebro shelf (Zone III, river systems 27-34) in the northwestern Mediterranean Sea. Blue lines are 200 m, 1000 m and 2000 m bathymetric contours. Green "+D" symbols indicate denser water masses, while red "-D" symbols indicate lighter waters. Blue arrows show the most common pattern followed by the coastal Liguro Provençal Current (LPC). The difference between the lighter water mass over the continental shelf and the denser water mass over the slope leads to the establishment of a geostrophic equilibrium that determines the direction followed by the LPC.

Figure 2. Comparison between liquid discharge time series of Rhone (red line) and Ebro (blue line) Rivers and the temperature trend (yellow line) measured at Perpignan (from Ludwig et al., 2004, after Moisselin et al., 2002). Discharge was measured at the nearest gauging stations to the respective river mouth (that is, at Beaucaire for Rhone and at Tortosa for Ebro System). Thin black lines correspond to annual means, while thick colored lines represent five-year running means. As observed in this figure, the Rhone and Ebro Rivers' liquid discharge is not directly related to the temperature change as recorded locally.



is cyclonic and of thermohaline origin (Font et al., 1988). In the whole study area, oceanographic circulation is dominated by the Liguro-Provençal Current (LPC), which generally flows southwest along the coast. Movement of the LPC is determined by a geostrophic equilibrium established between two opposite forces: (1) the force due to the pressure gradient existing between the lighter (less salty) shelf waters and the denser water masses over the continental slope, and (2) the Coriolis force induced by Earth's rotation. This situation results in a corridor through which the LPC flows, separating the shallower waters from the offshore ones (labelled as "-D" and "+D", respectively, in Figure 1).

Oceanographic and physiographic characteristics led us to differentiate three sub-zones (I, II and III from north to south) within the study region.

Influence of regional circulation on plume dispersal in the Gulf of Lions (Zone I)

In the Gulf of Lions, the dominant LPC flows west-southwest. River plumes usually expand over a wide continental shelf at a relatively short distance from the coast. Due to the low density of fluvial liquid discharge, sediment-laden plumes can deviate toward the shoreline (Figure 3), where they can accumulate as lenses of relatively low-salinity water.

When northwestern winds blow, the coastal brackish waters can even reach the outer shelf and slope located several tens of kilometers away from the coastline (Figure 3 inset). This situation generates a wind-induced coastal upwelling of deeper and denser waters. The existing gradient between low-salinity coastal waters and upwelled waters contributes to the development of mesoscale anticyclonic gyres, which are also stimulated by the slight weakening of the LPC. Such gyres may occupy the whole continental shelf. Figure 4 shows a joint analysis of wind speed and direction and sea surface thermal images during 1996, which characterizes the local conditions generating anticyclonic gyres in the Gulf of Lions.

After a wind pulse from the northwest, mesoscale gyres can propagate together with the LPC from northeast to southwest entering the Catalan Sea (Figure 3 inset). This current can eventually penetrate the continental shelf, influencing the shallow water masses and the dispersal of river plumes significantly. Nevertheless, most often, river plumes issued from the Rhone mouth are deviated toward the southwest and onshore, contributing to the formation of a coastal cloudy layer that is also fed by smaller rivers opening along the Gulf of Lions (Figure 5a).

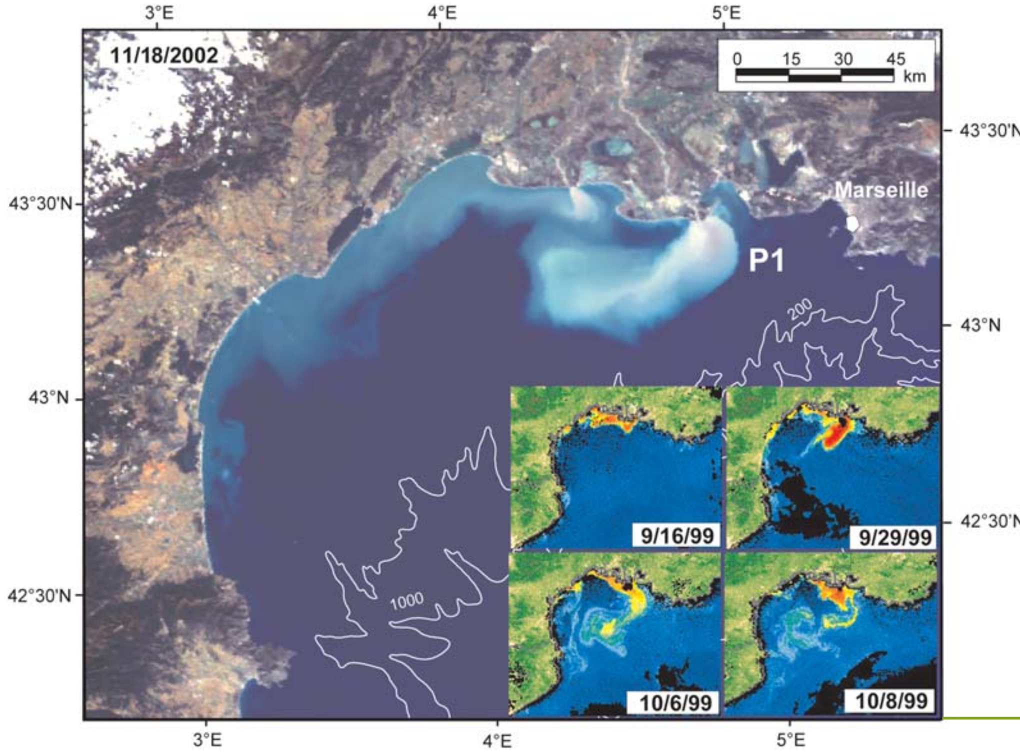


Figure 3. MODIS image showing a maximum discharge episode (7068 $m^3 s^{-1}$ measured near the river mouth) from the Rhone River (number 3 in Figure 1) on 11/18/02. Bathymetric lines representing 200 m and 1000 m depth are in white. The large suspensate plume (P1) is deflected westward and landward. The inset figure shows that, on occasion, Rhone River plumes reach the shelf edge and evolve toward the southwest. The four consecutive SeaWiFS images show chlorophyll concentration evolution on surface waters (red corresponds to maximum productivity waters). This sequence of images illustrates the generation (9/16/99), development (9/29/99), and spreading of the coastal plume led by the LPC and an anticyclonic gyre (10/6/99), which later moves toward the southeast (10/8/99).

Plume coalescence and gyre transfer in the North Catalan margin (Zone II)

South of Cape Creus, the LPC generally flows southwestward with maximum intensity over the shelf edge. River plumes usually expand at relatively short distance from the coast, and river-influenced waters accumulate near the seashore. In the North Catalan margin, the shelf is quite narrow until Cape Salou. It only broadens faintly between some of the large submarine canyons cut into the shelf. When there is no shift of mesoscale features from the Gulf of Lions, the development of numerous, relatively small gyres caused by local winds and favored by the topographic effect of the continental shelf (anticyclonic gyres) or submarine canyons (cyclonic gyres) prevails.

Most commonly, after northwestern wind conditions, the transfer of mesoscale gyres and suspended sediment from the Gulf of Lions to the North Catalan margin passes over the shelf edge and continental slope (Figure 5a). These gyres travel along with the LPC redistributing surface waters along the Catalan margin (Figure 5b). Though the largest gyres have been observed during the months of maximum stratification of the water column (e.g., August 1994), they occur throughout the year. Off the Catalan coast, mesoscale gyres propagate at a speed of about 5 cm s^{-1}. The mean time interval for the passage of two consecutive gyres is about 20 days (Arnau, 2000). That is why in the Catalan margin mesoscale structures from previous episodes are usually present.

The southward movement of mesoscale structures may induce a nearshore flow toward the east-northeast and redirect river plumes and coastal waters toward the shelf edge and continental slope. Figure 6 illustrates such a situation after a flood event south of Cape Creus. Floods in this area are a consequence of eastern storms (locally known as “llevantades”) that bring moisture captured while blowing over the Mediterranean Sea. The eastern Pyrenees and the Catalan Coastal Ranges force those winds to ascend and quickly release the water they carry. During “llevantades” torrential rains often coincide with high sea levels causing serious damage to coastal infrastructures and eroding beaches along the Catalan shoreline. These resulting storms and the flash floods are the most serious natural hazard in Catalonia, costing millions of euros in damages annually. As observed in the Gulf of Lions, plumes fed during flood events by the relatively small rivers of the Catalan watersheds tend to coalesce and form an almost continuous layer of turbid waters along the coast.

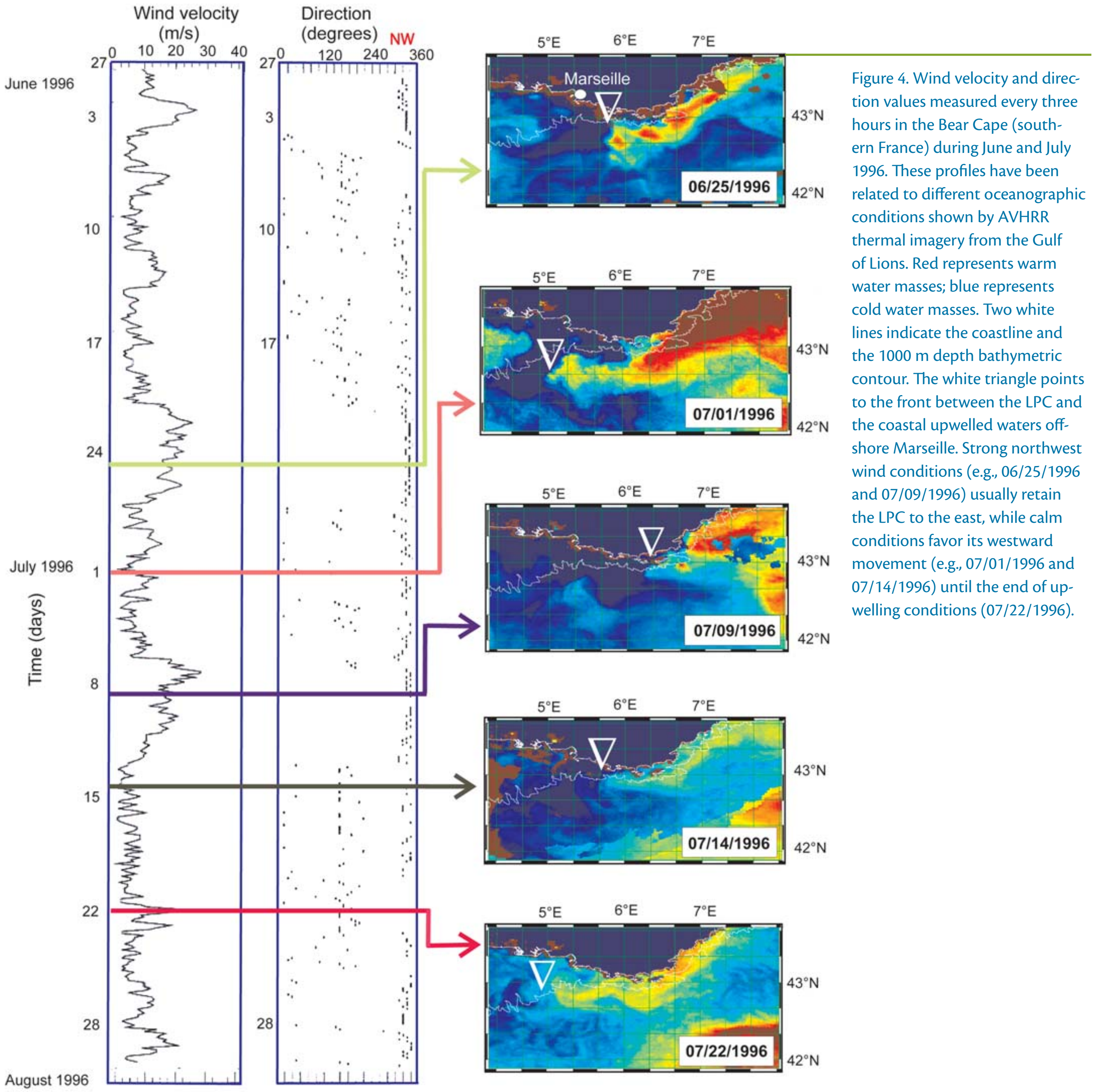


Figure 4. Wind velocity and direction values measured every three hours in the Bear Cape (southern France) during June and July 1996. These profiles have been related to different oceanographic conditions shown by AVHRR thermal imagery from the Gulf of Lions. Red represents warm water masses; blue represents cold water masses. Two white lines indicate the coastline and the 1000 m depth bathymetric contour. The white triangle points to the front between the LPC and the coastal upwelled waters offshore Marseille. Strong northwest wind conditions (e.g., 06/25/1996 and 07/09/1996) usually retain the LPC to the east, while calm conditions favor its westward movement (e.g., 07/01/1996 and 07/14/1996) until the end of upwelling conditions (07/22/1996).

Plume spreading off the Ebro Mouth (Zone III)

In front of Cape Salou, north of the Ebro Delta, where the continental shelf widens significantly, the LPC deviates seaward following the continental slope. The Ebro plumes usually remain close to shore and do not reach the continental slope. After peak discharge times (e.g., during May 2003 in Figure 7), the plume is quickly redirected southwards thus developing an anticyclonic gyre south of the delta. Less dense waters concentrate in the center of such a gyre, similar to what can be observed in the Gulf of Lions.

In general, Ebro coastal waters are not influenced by northern waters. Nonetheless, there are some observations about the arrival of mesoscale structures from the North Catalan area. An example of such a situation, which occurred in October 2003, is shown in the inset of Figure 6, where a northern anticyclonic gyre bounds the LPC and restricts the evolution of the Ebro plume southwards.

a.

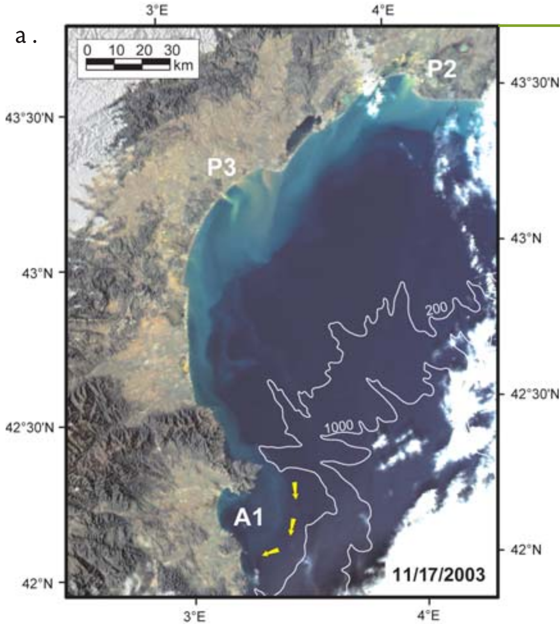
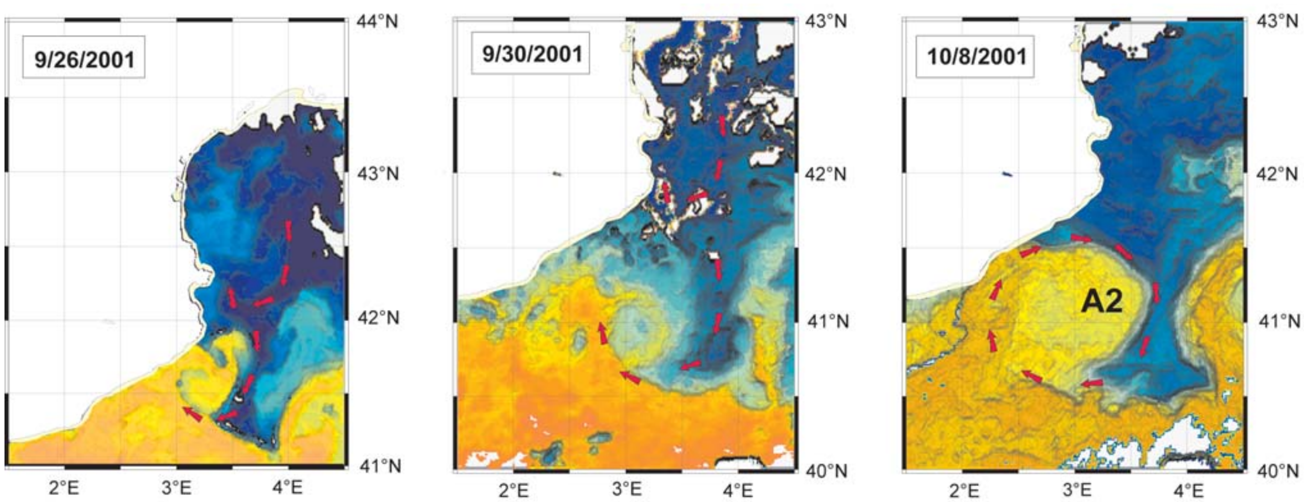


Figure 5. Satellite images showing the suspended sediment transfer pattern from the Gulf of Lions to the Catalan shelf. "P" refers to plumes and "A" to anticyclonic gyres. (a) MODIS image illustrating plume formation after flood events off Vidourle (P2, number 5 in Figure 1), Herault, Libron, Orb, and Aude (P3, 8-11 in Figure 1) Rivers. Suspended sediment is transported along the continental shelf from north to south. Once in the Catalan sector, to the south of Cape Creus, a typical anticyclonic vortex (A1) recirculates the incoming shelf flow. (b) Processed AVHRR images collected during fall 2001 that show the evolution of a typical mesoscale gyre (Rubio et al., In press). On October 8, 2001, a well-developed anticyclonic gyre (A2) was reinforced offshore Barcelona. The displacement of these kinds of mesoscale features along the Catalan shelf induces a nearshore flow towards the east-northeast and redirects river plumes and coastal waters toward the shelf edge and continental slope.

b.



CONCLUDING REMARKS

River discharge evolution

- The Rhone and Ebro Rivers dominate sediment discharge into the northwestern Mediterranean Sea. Sediment discharge through tens of smaller catchments becomes important after frequent flood events, which are typical of the Mediterranean climate.
- The mean discharge of the Ebro River shows a slight decrease since the late 1950s, probably due to intensive watershed regulation. Damming along the Rhone River is mostly concentrated in its uppermost course, while along the Ebro River, several large dams have been built in the middle and lower course.
- Rhone and Ebro Rivers liquid discharge is not directly related to temperature trends. It cannot be concluded at what level global warming is influencing river discharge.

Circulation and particle dispersal

- Overall fluvial particle dispersal in the study area is to the south-southwest because of the LPC flow. Mesoscale structures play a substantial role in redirecting suspended plumes.
- River plumes formed in southern France can either stay in the coastal area or move toward the shelf edge. In both cases, after the largest floods, they flow toward the southwest and enter the Catalan margin.
- With northwestern local winds, anticyclonic vortices form offshore Marseille, move toward the slope, and join the LPC southwestward, thus contributing to the spreading of sediment plumes generated in southern France.
- Plumes formed after flood events

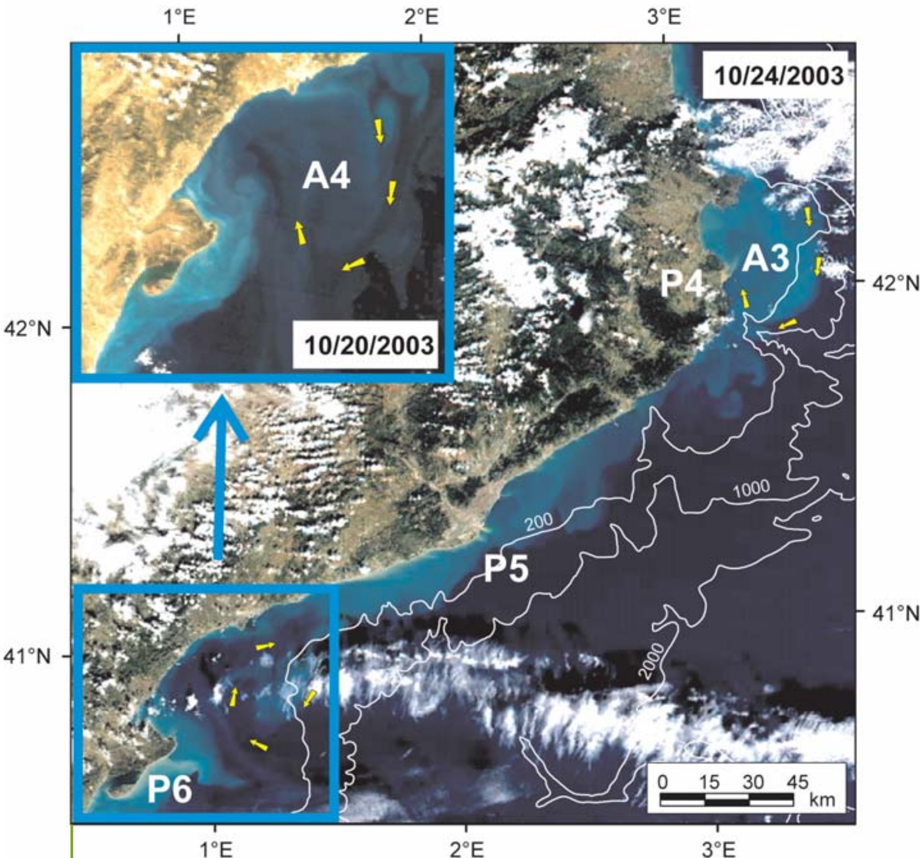


Figure 6. These two MODIS images from October 2003 illustrate the sediment transfer pattern over the Catalan margin. The smaller inset image is a detail of the Ebro Shelf. White indicates 200 m, 1000 m and 2000 m bathymetric contours. During the fall, when sudden flash floods occur in the Catalan coastal area, coalescent plumes spread along the nearby continental shelf. The image from 10/24/2004 shows that sediment plume formation is not related to catchment size. One such example is the Fluvia and Ter Rivers (numbers 18 and 19 in Figure 1) that feed a plume (P4) as noticeable as those of the Llobregat (P5, 23 in Figure 1) and Ebro (P6, 29 in Figure 1) Rivers. The Ebro plume on that date illustrates the influence of human regulation; river discharge was forced to go through the secondary channel of the delta. In the northern part, the controlling role of a mesoscale anticyclonic gyre southwards from the Creus Cape (A3) can be observed recirculating P4 seawards. The inset image of the Ebro Margin draws attention to a similar vortex northwards from the Ebro Delta (A4) that turns the LPC towards the slope.

along the North Catalan coast tend to coalesce in an almost continuous belt of turbid waters.

- The narrowness of the North Catalan continental shelf compared to the Gulf of Lions and the presence of some large submarine canyons reinforce the development of mesoscale structures coming from the north, which usually implies the redirecting of river plumes offshore.
- Along the Ebro Margin, the LPC is deflected seaward following the shelf edge. The Ebro liquid and solid discharge is most often transported southward, where a quasi-permanent anticyclonic gyre exists south of the river mouth. However, locally formed anticyclonic gyres frequently restrict this dispersal pattern.

ACKNOWLEDGEMENTS

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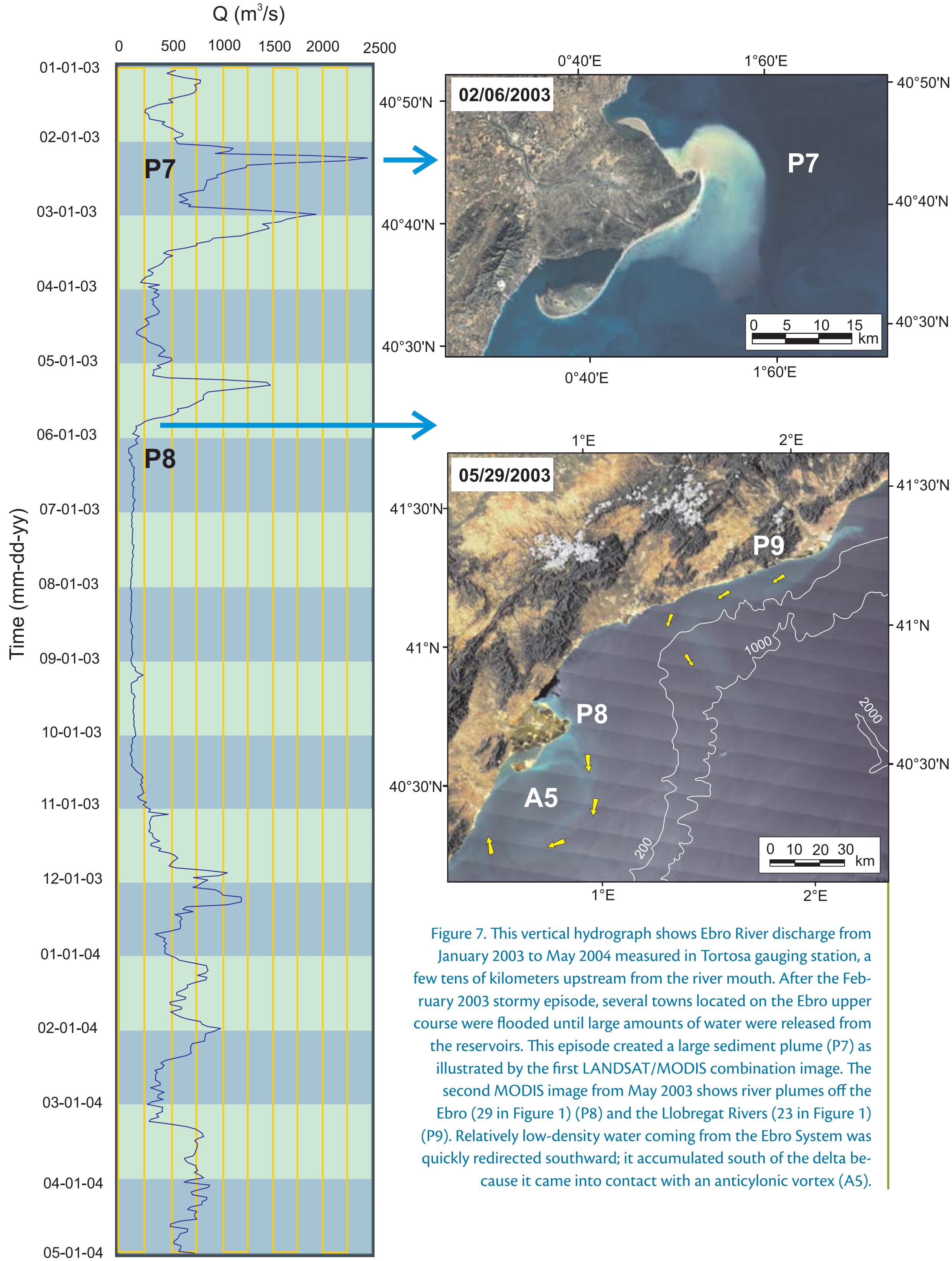

Figure 7. This vertical hydrograph shows Ebro River discharge from January 2003 to May 2004 measured in Tortosa gauging station, a few tens of kilometers upstream from the river mouth. After the February 2003 stormy episode, several towns located on the Ebro upper course were flooded until large amounts of water were released from the reservoirs. This episode created a large sediment plume (P7) as illustrated by the first LANDSAT/MODIS combination image. The second MODIS image from May 2003 shows river plumes off the Ebro (29 in Figure 1) (P8) and the Llobregat Rivers (23 in Figure 1) (P9). Relatively low-density water coming from the Ebro System was quickly redirected southward; it accumulated south of the delta because it came into contact with an anticylonic vortex (A5).