Multi-Sensor Remote Sensing of Coastal Discharge Plumes: a Mediterranean Test Site

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Abstract. Various spaceborne sensors have been used to assess environment features in the north-western Mediterranean Sea, at a test site along the Catalan coast, between the Ebro river delta and the greater Barcelona area. The aim was to demonstrate that the combination of different kinds of data allows for an improved monitoring potential, in particular for applications to coastal zone management. The sample imagery considered for this task was acquired by the ERS-2 Synthetic Aperture Radar (SAR), the Along-Track Scanning Radiometer (ATSR) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). By combining different data, it proved possible to overcome the specific drawbacks of each sensor, like insufficient temporal coverage, or dependence on weather and daylight conditions. Within the target area, three main features, visible on many of the analyzed images, were selected as test cases. The Ebro river plume, as seen by SeaWiFS, presents a high load of water constituents, changing seasonally and interacting with offshore dynamics. The plume system in the Barcelona area, mostly due to the Llobregat river, exhibits similar traits and high surface-active compounds, so that it is detected by both the SeaWiFs and the SAR, as well as low surface temperature, detected by the ATSR. A smaller plume of cooling water, released from a nuclear power plant, cannot be detected in the optical or thermal images, but causes surface turbulence in the coastal zone, giving rise to signatures detected by the SAR.

1. Introduction

Coastal zones occupy less than 15% of the Earth's land surface, but they accommodate more than 60% of the world's population (EEA, 1999). If the trend continues, this number will rise up to 75% in 2025 (UNCED, 1992), thus causing an increasing pressure on coastal zones by urban and industrial developments. Land use along European coastlines has already manifested itself, in the past, with a higher level of pollution, be it by direct release of urban or industrial waste water, by indirect release via rivers, or by spillages from ships travelling to or from major harbours.

Passive Remote Sensing (RS) in the visible/infrared spectrum can be used to quantify surface optical properties, which depend on the concentration of water constituents (phytoplankton, suspended sediments, and yellow substance), or surface temperature, which describes selected physical processes in the sea. Sensors working in this spectral range provide high temporal resolution and spatial coverage, but are limited to cloud-free conditions and, moreover, to large-scale assessments, because of their low spatial resolution. Nevertheless, they have proven to be a useful data source for near real-time monitoring and long-term comparisons of environmental dynamics, as *e.g.* in the case of algae blooms (Mobley 1994). Active RS in the microwave spectrum can be used for the evaluation of surface roughness and elevation, which are linked to surface phenomena such as winds, waves, wakes, slicks and to dynamical topography, respectively. These sensors, albeit working with low temporal resolution and spatial coverage, have proven to be a powerful tool to monitor small-scale features such as marine oil pollution (Gade *et al.* 1998).

In the following, a collection of images generated by various spaceborne sensors will be used to appraise the coastal environment of the north-western Mediterranean Sea, along the Catalan coast. The aim is to demonstrate, with some simple examples, that the combination of different kinds of data, generated by complementary RS techniques, allow for an improved monitoring potential for applications to coastal zone management.

2. Test site and data sets

The test site, chosen to demonstrate the use of multi-sensor RS data for monitoring the coastal environment, is the Catalan near-coastal region. It is located in the north-western Mediterranean Sea, between the Spanish mainland and the Balearic islands, and comprises a strech of the Costa Dorada, from the Ebro river delta in the south-west, to the greater Barcelona area, in the north-east (Figure 1). Such a target area is well suited for studies of the increasing anthropogenic pressure on European coastal zones, because it suffers from the impact of various potential sources of pollution:

- a large river (Ebro) delta with an extensive agricultural outflow;
- a small river (Llobregat) mouth collecting urban and industrial runoff;

- major urban developments (*e.g.* Barcelona);
- major port facilities (*e.g.* Tarragona) and shipping lanes terminals;
- onshore and offshore industrial facilities (*e.g.* power plants and oil rigs);
- mass tourism facilities (along the Costa Dorada).

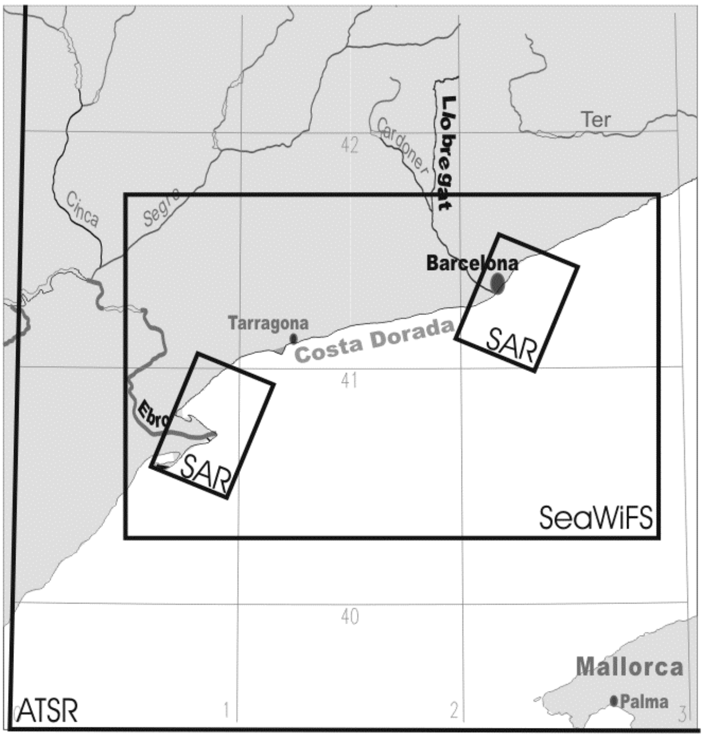

Fig. 1. Map of the north-western Mediterranean region, between 0°E and 3°E, and 39.5°N and 42.5°N. The rectangles show the coverage of the satellite data used (SAR, SeaWiFS and ATSR).

A set of images acquired by the SAR and the ATSR aboard ERS-2, as well as by SeaWiFS aboard OrbView-2 (previously know as SeaStar), was selected to cover the target area above. Particular effort was spent to find data sets not only covering the same geographical district, but also acquired by the various sensors within short time periods. The goal of the analysis and inter-comparison of such data sets was to acquire a better understanding of the coastal and marine processes under investigation and of their imaging by different sensors working in different spectral ranges.

Focusing on the Catalan coastal test site, many of the analysed images revealed a wealth of features that document the anthropogenic pressure put on the local environment, at the interface between drainage basin and open sea. Coastal plumes, in particular, were selected for a more detailed analysis, because of their different origin, visibility, and influence on the local marine ecosystem, and will be presented herein.

3. The Ebro river plume

The characteristics of the marine environment in the Catalan coastal region can be highlighted using surface optical properties as tracers of its main ecological features. Figure 2 shows a series of SeaWiFS images of the target area (about 200 km x 260 km) collected in 1998. The original data were processed, as indicated in Barale (2005) and references therein, to derive concentrations of chlorophyll-like pigments. Of course, large uncertainties can arise in the computation of this parameter in coastal waters, owing to the presence of optically active materials other than phytoplankton and related pigments (*i.e.* dissolved organic matter and suspended inorganic particles) with partially overlapping spectral signatures. However, by restricting the analysis to patterns and gradients of water constituents in general, rather than considering absolute values of the planktonic pigment concentration, the SeaWiFS imagery can be effectively used to assess coastal anthropogenic loads, runoff areas and pollution sources, even erosion patterns and sediment transport, as well as biological production, monitoring both changes in space and evolution in time (as not possible with the smaller and less frequent coverage of the SAR).

In the series of Figure 2, one image per month was selected to give an indication of the seasonal changes that can occur in the target area. The variability is most noticeable when considering the background water constituents concentration, which appears to be higher in the cold season and lower in the warm one. This is essentially due to the fact that, for the region considered, biological production – the main source of pigments in the open sea – is limited primarily by nutrient availability. Hence, it will be greater when the supply of nutrients from coastal runoff and deep waters, by virtue of vertical mixing, is maintained by the climatic conditions (rain over the continental drainage basins, low temperatures and strong wind regime over marine areas) of the Mediterranean winter (Barale 2005). The same seasonal variations are also displayed by the near-coastal features – the plume originating from the Ebro delta, in particular – superimposed on the background optical signal. Accordingly, the main river plume appears to be larger in winter and smaller in summer, and highly dynamical.

Various factors concur in shaping the dynamical features observed along the Catalan coast, namely a large input of nutrients/sediments of continental origin; several special sites (river mouths, urban centers) where runoff concentrates, generating high concentrations of water constituents; a dynamical current system, interacting with coastal plumes. Sometimes, the structures developing along the coast appear to be confined close to shore and to be separated from the offshore patterns. More often, however, the main plumes and filaments are seen to be entrained in the meso-scale circulation, due to eddies or current meanders, which contribute to the mixing of inshore and offshore waters. As will be seen in the following, the same happens episodically also to the minor plumes of this area.

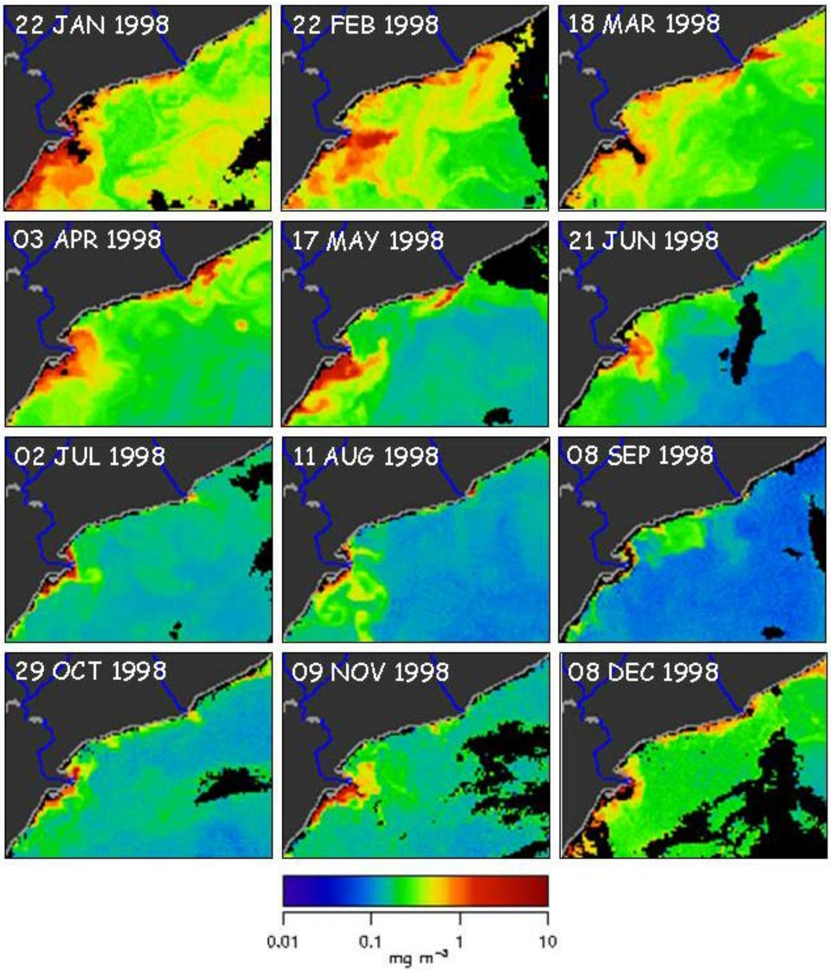

Fig. 2. SeaWiFS-derived images of the Catalan coast (1998). The colour coding indicates chlorophyll-like pigment concentration (co-varying with other water constituents in near-coastal areas). Geographical location in Figure 1.

3. The plume system in the Barcelona area

The mouth of the river Llobregat was chosen as a suitable area for more detailed observations, in order to provide an example of multi-sensor investigations of plume dynamics and impact on the local ecosystem. The river Llobregat originates from the south-eastern Pyrenees and is 170 km long. Its mouth is located south-west of Barcelona, where the original marshy terrain of the Llobregat delta has been transformed into urbanised and industrial areas during the past decades. The growth of population and industrial development in the Llobregat valley has caused an increasing load of pollution within the river outflow. The river plume entering the Mediterranean is a regular feature of the coastal zone near Barcelona.

Data from the ERS-2 SAR, ATSR and SeaWiFS were analysed to detect the surface signature of the Llobregat's plume. Figure 3 shows a series of sub-sections of the SAR images (30 km × 40 km) off Barcelona. The pixel size, 12.5 m × 12.5 m, allows to detect small-scale features, around a few hundred metres in size. All images were acquired in the same year, 1998, but during different seasons and under different atmospheric (wind and temperature) conditions. The city of Barcelona can be seen in the left half of every image, as a light grey area of enhanced radar backscattering, roughly between the river Llobregat in the south and the (much) smaller river Besòs in the north. Different wind speeds in the area caused different sea surface roughness, resulting in the different gray levels of the panels. On Panels (a) and (b), acquired on 11 January and 15 February, respectively, the plumes of both rivers can be seen as dark patches reaching from the river mouths into the open sea. If oily substances within the river outflow were floating on the water surface, the radar backscattering would be reduced, thus causing dark (irregular) patches. The surface films, in fact, dampen the small-scale surface waves, which in turn result in reduced radar backscattering (Gade *et al.* 1998).

The Llobregat plume can be observed on every SAR image analysed, whereas the plume of the river Besòs is visible only in winter data. Given its small size, this is possibly due to the fact that it is only in the wet (winter) season that the Besòs presents a discharge large enough to have an impact on the coastal waters. Note that in some cases the plumes are driven by the local current towards south-west (see panels (a) and (f) in Figure 3), and in other cases they remain diffuse and patchy while floating off the coast (panels (b), (c), and (d) in Figure 3). The large dark area in the upper part of panel (f) is likely to be caused by atmospheric effects (low wind speed due to wind shadowing), rather than by any river runoff.

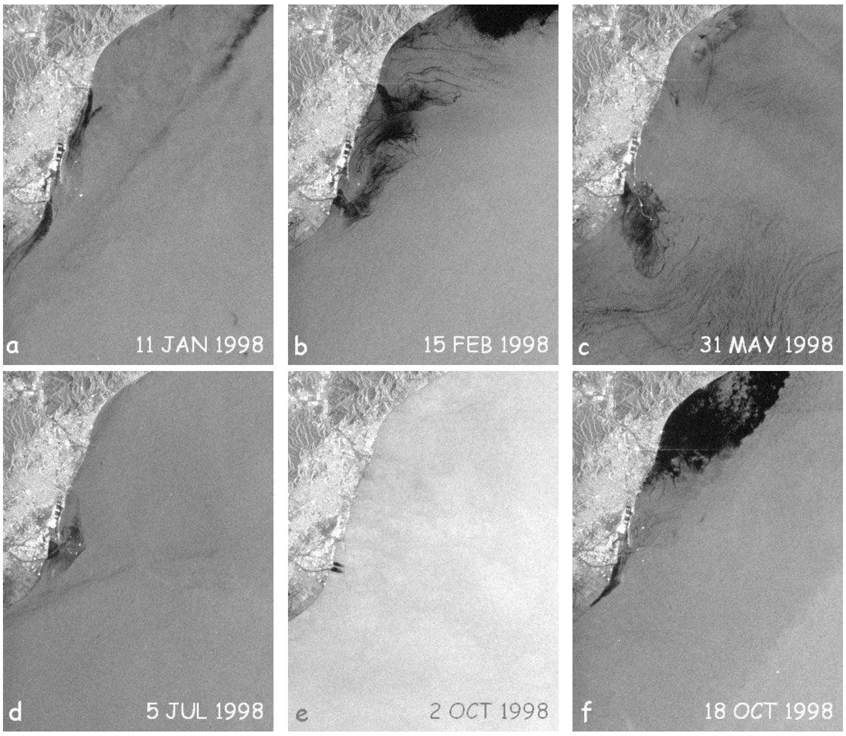

Fig. 3. Subsections (30km x 40km) of ERS SAR images of Barcelona and the mouth of the river Llobregat. The Llobregat plume is visible on every image as a dark patchy area. Geographical location in Figure 1.

Surface-active material floating on the river surface, like any kind of oily substance, would be the most probable cause of the permanently visible river plumes. A high load of such material may be a result of municipal or industrial waste water, but may also be caused by high agricultural productivity. Other phenomena such as a significantly reduced sea surface temperature (SST), wind shadowing, or local turbulence can also cause a reduction in the radar backscattering. However, because of the shape of the observed patches, their sharp edges, and their visibility throughout the year, we conclude that the main effect of the river plume, which causes signatures in SAR imagery, is the high load of surfactants (or, more generally, dissolved organic matter).

A multi-sensor approach allows us to gain insight into the influence of river outflow on the local marine ecosystem. It has been seen already that SeaWiFS data can be used to track the evolution of the plumes and their variation in time. In Figure 2, both the Llobregat and the Besòs plumes can be seen in the February, March and possibly April images (again, when the rivers are likely to have a substantial discharge). At other times during the year, only the Llobregat plume is detectable, as it interacts with the coastal current in a number of ways. More details of such interaction, on very short time scales, appear in Figure 4, where two sequences of three (almost) consecutive SeaWiFS images are shown. The images were acquired within only three weeks, on 4, 5, 9 July and on 20, 22, 26 July, 1998.

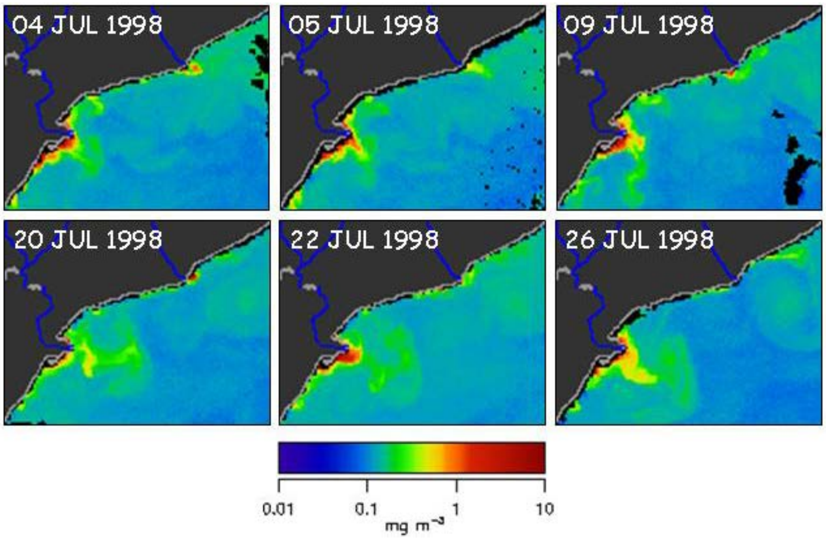

Fig. 4. SeaWiFS-derived images of the Catalan coast (July 1998). The colour coding indicates chlorophyll-like pigment concentration (co-varying with other water constituents in near-coastal areas). Geographical location in Figure 1.

In the earliest image, dated 4 July, the Llobregat plume starts diffusing offshore, possibly as the result of a (rain-driven, as suggested by the thermal image below) outburst of runoff (see also the image dated 2 July, in Figure 2). The spreading continues on the next day, 5 July, but is already gone on 9 July, when a prevailing coastal current from the north-east compresses the plume along the coast, south of the river mouth (displacing even the much larger Ebro river plume toward the south-west). Later on, the 20 July image presents the opposite situation, with a prevailing coastal current flowing from the south-west, compressing the plume along the coast north of the river mouth (and displacing the Ebro plume to the north-east). Interestingly, this sistuation is maintained also in the following days, 22 and 26 July, even if the costal current is probably changing (as testifyed by the Ebro plume behavior). The likely reason for this is the offshore anticyclonic eddy, seen off the Barcelona area, which moves closer to shore and causes a northward drift of all coastal waters.

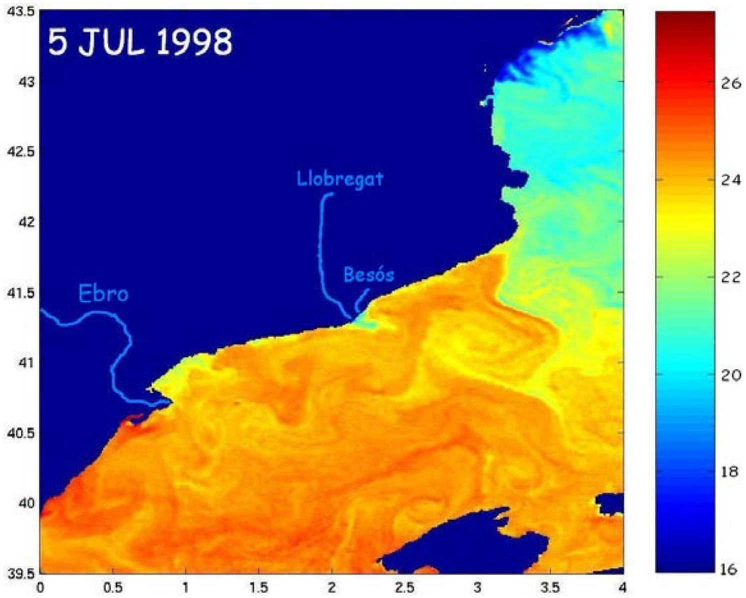

Fig. 5. ATSR-derived image of the Catalan coast (5 July 1998). The colour coding represents SST in °C. Geographical location in Figure 1.

The combination of data from different sensors is of particular interest on 5 July, 1998, when ERS-2 SAR data (acquired at 10:35 UTC) and SeaWiFS data (12:48 UTC) are available (Figures 3 and 4), together with data from the ATSR (21:53 UTC). The Sea Surface Temperature (SST) map derived from ATSR data is shown in Figure 5. Aside from the meso-scale eddies in the southern half of the image and cold upwelling in the north-eastern section, the Llobregat river plume is clearly delineated as an area of lower SST. Note that the plume looks spatially similar in both ATSR and SeaWiFS (Figure 3) images is well correlated, whereas the area of reduced radar backscatter in the SAR image (panel (d) in Figure 2) is much smaller. Therefore, it can be concluded that the observed plume is due to cold, turbid, fresh waters of fluvial origin spreading in a laminar way on top of denser (salty) marine water, whereas an enhanced accumulation of surface films is observed only over a short distance from the river mouth. Note that the Ebro plume is well visible in the SeaWiFS imagery (Figure 4), but it cannot clearly be identified on the SST map (Figure 5), except in the near-coastal area north of the delta. This suggests that the bulk of the Ebro runoff is not coming from a local outburst of rain water (as was suggested for the Llobregat runoff), but rather is composed of “older” water that warmed considerably while flowing through the delta area.

4. The "Vandellòs II" industrial plume

The area between the Ebro delta, in the south, and l'Hospitalet de l'Infant, in the north, also constitutes an interesting test site where irregular patches can be observed in the SAR images (Figure 6).

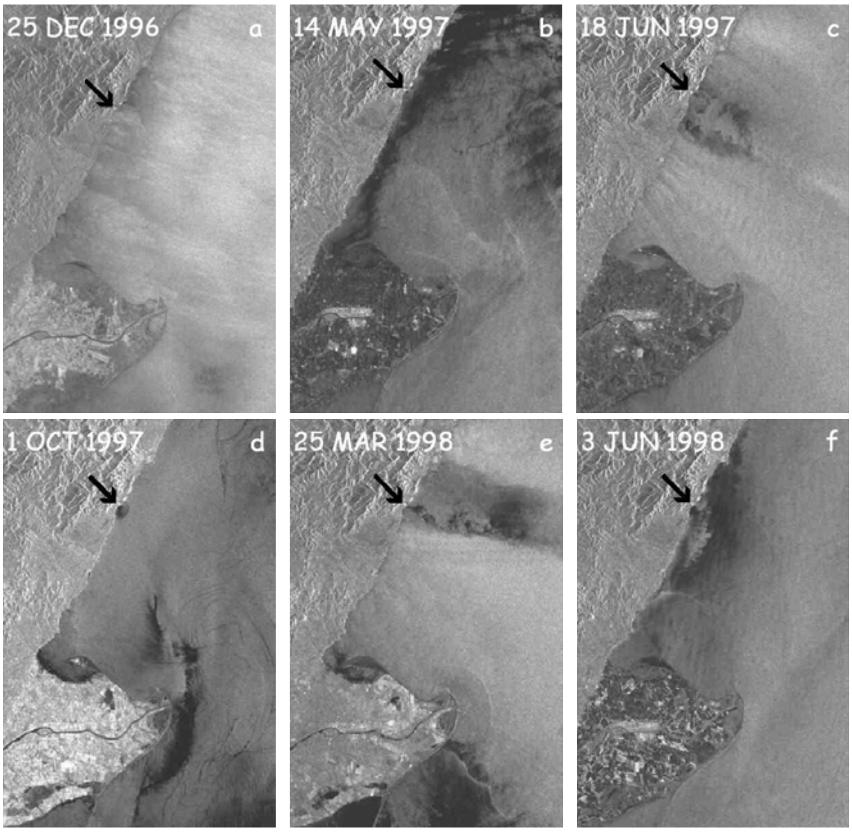

Fig. 6. Subsections (34 km × 51km) of ERS SAR images of the western Costa Dorada, north of the Ebro estuary. The black arrows denote the location of the nuclear power plant “Vandellòs II”. Geographical location Figure 1.

These signatures are typical of local coastal discharges, having a circular shape and being either brighter or darker than the surrounding water surface. Based on information from local sources (J. Redondo, personal communication), it can be safely assumed that the (warm) cooling water of the nuclear power plant "Vandellòs II", located in the area where the observed features reach the land, is producing an elongated outflow plume. Under particular conditions, when the wind is blowing offshore and a considerable amount of cooling water is being released, the plume is visible on SAR imagery, causing the observed features, which may be up to 15 km in length.

Turbulence and/or the upwelling of colder water seem to be causing a reduction in radar backscatter outside of the plume, whereas the plume itself, because of its higher temperature, appears brighter than its surrounding area on the SAR imagery. In the early stage of such a release the plume causes just a small circular dark patch (see *e.g.* panels (a), (b), and (d) of Figure 6), which later changes its appearance into the bright feature described above. The wavy, triangular shape of the plume in panel (c) could be caused by a varying (pulsating) amount of runoff. Although limited to sporadic coverage, the SAR is capable of resolving the power plant runoff, because of its high spatial resolution. The Vandellós plume is visible, in general, neither on the SeaWiFS nor on the ATSR imagery, due to its very limited size, as well as the low contrast in water constituents and in SST, with respect to the surrounding seawater.

5. Conclusions

The multi-sensor satellite imagery presented here provides examples of coastal plumes that can be detected and monitored by at least one of the RS techniques adopted. These plumes may result from river runoff, or from urban or industrial discharges, and manifest themselves in a high occurrence of surface films, an enhanced concentration of water constituents or a change in SST. The simple examples provided for the Catalan coast demonstrate the potential of exploiting complementary RS data for the investigation of runoff impact on coastal zones.

The acquisition of image data by passive sensors working in the visible and infrared bands offers a much higher temporal coverage (up to several images per day) than other techniques. This, coupled with the specificity of the parameters that can be observed and quantified, allows the repeated characterization of a coastal area in terms of its main ecological traits. Basin-wide interactions and seasonal patterns emerge from the analysis of such imagery. On the other hand, the spatial resolution of the data is very low, on the order of 1 km, so that small-scale features become difficult to assess. Moreover, cloud-free weather conditions are needed for monitoring the sea surface, and only daylight data are available using optical sensors.

High-resolution spaceborne SAR proved to be capable of detecting small-scale features, such as minor coastal plumes, but the low temporal coverage of the available SAR data made it difficult to track the single features over time. More recent – as well as future – satellite missions, with wide-swath SAR sensors (*e.g.* ENVISAT, launched in 2002), may be able to fill this gap, even though the resolution of the wide-swath SAR imagery is significantly lower. Finally, the advantage of a SAR sensor as being independent of daylight and cloud conditions is somewhat balanced, on the negative side, by the fact that the visibility of the observed effects, namely of the accumulation of surface-active material on the water surface within a plume, depends very much on the local weather conditions, and predominantly on the local wind speed. These results show that different RS techniques complement each other so that an improved tracking (be it in space or in time) of coastal processes can be achieved.

Acknowledgements

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