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Multisensor monitoring of plume dynamics in the northwestern Mediterranean Sea

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Abstract. We used data from various space-borne sensors to monitor the marine ecosystem in the northwestern Mediterranean Sea, at the Costa Dorada, between the City of Barcelona and the estuary of the river Ebro. The aim of this study was to demonstrate that the combination of different remote sensing data (acquired at different electromagnetic frequencies) allows for an improved monitoring system, in particular for a better monitoring of the marine ecosystem and, hence, a better coastal zone management. We present remote sensing data acquired by the Synthetic Aperture Radar (SAR) and the Along-Track Scanning Radiometer (ATSR) aboard the Second European Remote Sensing Satellite (ERS-2), and by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the SeaStar satellite. By combining the different data we are able to overcome specific drawbacks of the single sensors, like an insufficient temporal coverage, or a strong dependence on weather and daylight conditions.

Within the study area two main features have been selected as examples, which are well visible on many of the analysed images. The first one exhibits a higher load of chlorophyll-a and surface-active compounds and a lower sea surface temperature (SST), which is likely to be caused by the plume of the river Llobregat, southwest of Barcelona. It can clearly be seen from the imagery how the river plume is driven along the coast by the local currents. The second feature can be related to cooling water being released from a nuclear power plant and causing turbulence in the water body, which in turn gives rise to signatures visible on the ERS-SAR imagery.

Keywords: Ebro; Imagery; Llobegat river.

Abbreviations: ATSR = Along-Track Scanning Radiometer; AVHRR = Advanced Very High Resolution Radiometer; CZCS = Coastal Zone Colour Scanner; ESR = European Remote Sensing Satellite; SAR = Synthetic Aperture Radar; SeaWiFS = Sea-Viewing Wide Field-of-View Sensor; SST = Sea surface temperature.

Introduction

Recently, a large variety of different sensors has become operational, thus allowing for synoptical studies on the monitoring of the same oceanic (and atmospheric) phenomena, such as marine (oil) pollution (Gade et al. 1998) or ongoing algal blooms (Rud & Gade 2000). However, the usage of some satellite data acquired at visual or infrared spectral bands is limited to cloud-free days and, furthermore, to large-scale patterns due to their low spatial resolution (see, e.g. Kahru et al. 1995; Robinson 1994). Nevertheless, for comparison of long time-series concerning the dynamics of e.g. algal blooms, and near real-time monitoring of ongoing blooms, they have proven to be a useful data source, due to their high temporal resolution (Kahru et al. 1994).

'Clean Seas' was an international project funded by the European Commission which run from December 1996 until November 1999. Over three years, the 'Clean Seas' project team has focused on the problem of monitoring marine pollution and the role that earth observing satellites might play. Starting from the concept of the existing scientific satellites being an ad-hoc system, the project has examined synergy within the data from radar, optical and infrared sensors. In conjunction with hydrodynamic models and routine data acquisition from a range of satellites, the team has examined three test sites in detail during a two-year acquisition campaign. The test sites in the Baltic Sea, the North Sea and the northwestern Mediterranean have produced several significant results (Jolly et al. 1999; Gade & Alpers 1999).

Within 'Clean Seas', data from the Synthetic Aperture Radar (SAR) and the Along-Track Scanning Radiometer (ATSR) aboard the Second European Remote Sensing Satellite (ERS-2), the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) aboard SeaStar, and the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA satellites were frequently received and

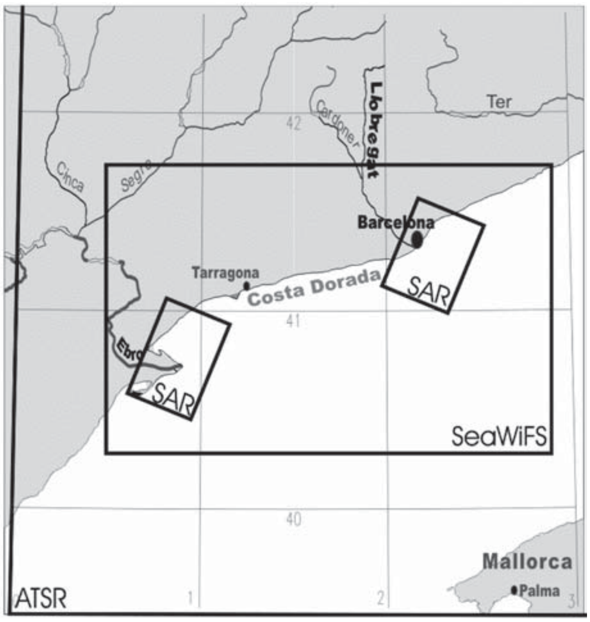

Fig. 1. Map of the northwestern Mediterranean (0°-3° E; 39.5°-42.5°N). The Costa Dorada is located in the centre, between the City of Barcelona and the mouth of the river Ebro. The added rectangles depict the locations of the used satellite data shown in Fig. 2 (SAR images), Fig. 3 (SeaWiFS images), Fig. 4 (ATSR image), and Fig. 6 (SAR images).

archived by the project team. We have searched these archives in order to find data sets from certain test sites, acquired by different sensors within a short time period. The detailed analysis and the intercomparison of such data sets may give rise for a better understanding of oceanic (and atmospheric) phenomena and their imaging by the different sensors working at different electromagnetic frequencies.

Focussing on the Costa Dorada, the northeastern Spanish coast between Barcelona and the mouth of the river Ebro, we have found two interesting features, which are both associated with outflow plumes and which are visible on many of the analysed images. Because of their different origin, visibility, and influence on the local marine ecosystem they have been selected for a more detailed analysis and will be presented herein.

River outflow near Barcelona

As an example of multi-sensor investigations of river plume dynamics and the plume's impact on the local ecosystem the mouth of the river Llobregat was chosen as study area. The river Llobregat is 170 km long and originates in the southeastern Pyrenees. Its mouth is located southwest of Barcelona, where the original marshy area of the Llobregat delta has been transformed into urbanized and industrial zones during the past decades. In particular, the growth of population and industry in the Llobregat valley has caused an increasing load of pollution within the river outflow. Regularly, this river plume entering the Mediterranean is well visible by eye.

On a regular basis, data from the ERS-2 SAR, ERS-2 ATSR, AVHRR, and SeaWiFS have been acquired and analysed. In this paper, we demonstrate how the river plume is imaged by the different optical and microwave sensors. In Fig. 2 a sample of subsections of ERS-2 SAR images of the Mediterranean Sea off Barcelona are shown. All images were acquired between January and October 1998, i.e. during different seasons and under different environmental (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 river Besòs in the north. On Panels a and b (acquired on 11 January and 15 February, respectively) the plumes of both rivers can easily be seen as dark patches reaching from the river mouths towards the open sea.

Apart from other phenomena causing such dark patches on the available SAR images, the Llobregat plume can be delineated on every SAR image we observed, whereas the plume of the river Besòs is visible only on SAR images acquired during winter time. In some cases the plumes are driven by the local current towards south-west (see Panels a and e in Fig. 2), and in other cases it stays diffuse and patchy while floating off the coast (Panels b, c, and d in Fig. 2). The large dark area in the upper part of Panel e is likely to be caused by atmospheric effects (low wind speed due to wind shadowing), rather than by any river outflow.

Surface-active material floating on the river surface, like any kind of oily substance, seems to be causing the permanently visible river plume. A high load of such material may be a result of municipal or industrial waste water, but also of high agricultural productivity. The surface films dampen the small-scale surface waves (Barale & Folving 1996) which in turn results in reduced radar backscattering. Moreover, other phenomena, like a significantly reduced sea surface temperature (SST), wind shadowing, or turbulence can also cause a reduction of the radar backscattering. At several stations along the river Llobregat water samples are frequently taken. Sample data acquired at the station 'Prat de Llobregat', which is located close to the river mouth, do not, however, give information on the hydrocarbon content at the very water surface. Nevertheless, 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

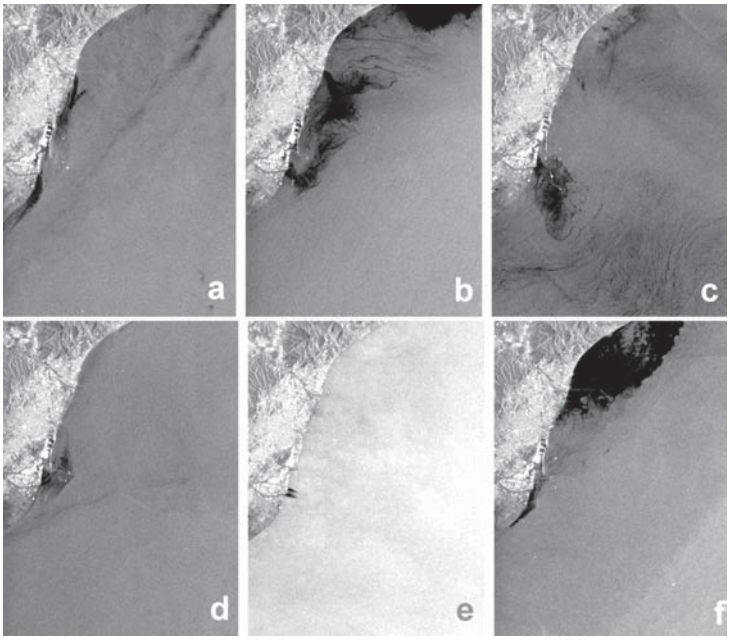

Fig. 2. Subsections (30 km × 40 km) of ERS SAR images of Barcelona and the mouth of the river Llobregat acquired in 1998. Upper row: **(a)** 11 January, **(b)** 15 February, **(c)** 31 May; lower row: **(d)** 5 July, **(e)** 2 October, **(f)** 18 October. The exact location of the SAR scenes is depicted by a rectangle in Fig. 1. The Llobregat plume is visible on every image as a dark patchy area in the left middle.

signatures in SAR imagery, is the high load of hydrocarbons.

Ocean colour images are useful for getting information on phenomena associated with high biological productivity (Barale & Folving 1996). In order to gain more insight into the influence on the river outflow on the local (marine) ecosystem synoptical studies using a multi-sensor approach have been performed. Routinely acquired SeaWiFS data have been used to track the evolution of the plume and its variation in time. Fig. 3 shows as an example a series of five SeaWiFS images of the northwestern Mediterranean covering the Costa Dorade and, in particular, the estuaries of the river Ebro (in the southwest) and of the river Llobregat (in the northeast). The images were acquired within a short time period, between 19 June and 9 July, 1998. On Panel a, both plumes are visible as areas of enhanced chlorophyll-a concentration, but they are very diffuse, which may be

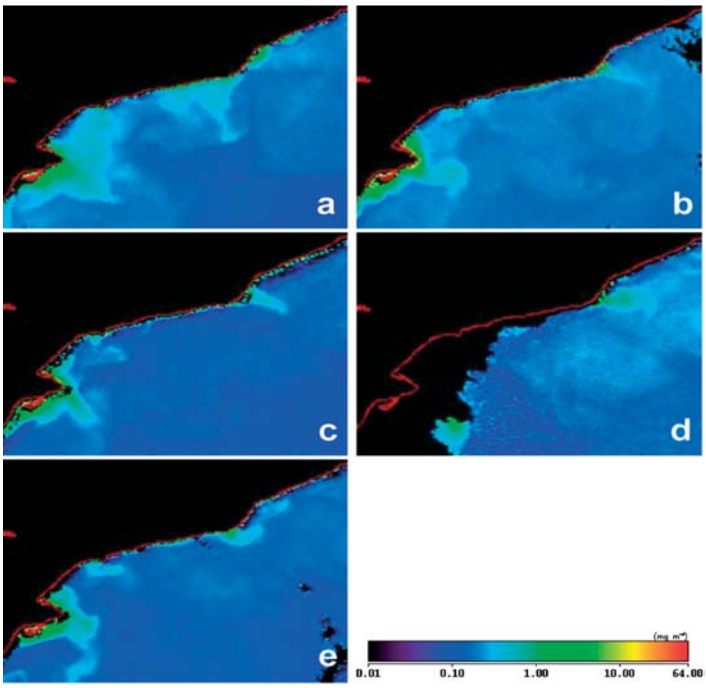

Fig. 3. SeaWiFS images (200 km × 150 km) of the northwestern Mediterranean Sea, off the Costa Dorada, acquired in 1998: 19 June, 2 July, 5 July; lower row: 6 July, 9 July (panels **a-e**, respectively). The Llobregat and the Ebro plumes are visible as areas of higher chlorophyll-a concentration (light green).

caused by strong winds or coastal currents. In early July 1998, however, the situation was different, which can be inferred from the well-pronounced signatures of both plumes. From 6 July on (panel d), the sharp-edged Llobregat plume starts to disperse and it is again diffuse on 9 July (panel e). In contrast, the Ebro plume seems to be less dependent on local wind and current conditions, because of its much higher water volume.

Of particular interest for this investigation is the combination of different sensors for studying the same phenomenon. We have therefore concentrated on 5 July, from which both ERS SAR and SeaWiFS data are available, as well as data from a variety of other space-borne sensors, see Table 1. Apart from SAR (acquired at 10.35 UTC; panel d in Fig. 2) and SeaWiFS (acquired at 12.48 UTC; panel c in Fig. 2) data from ERS-ATSR (21.53; see Fig. 4) and from WiFS and AVHRR (10.34 UTC and 12.55 UTC, respectively; both not shown herein) are available.

The SST map derived from ATSR data is shown in Fig. 4. Apart from other oceanic features, like a cold upwelling in the upper right corner (Gulf du Lion) and meso-scale eddies in the bottom half of the image, the plume of the river Llobregat can clearly be delineated as an area of reduced SST. Note that the spatial extend of the plume in both ATSR (Fig. 4) and SeaWiFS (panel c in Fig. 3) data is well correlated, whereas the area of reduced radar backscatter in the SAR image (panel d in Fig. 2) is much smaller. We may therefore conclude that

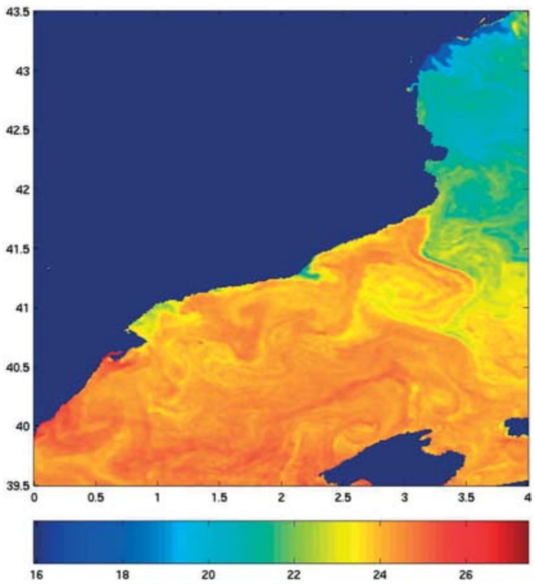

Fig. 4. ATSR SST image (4° × 4°) of the northwestern Mediterranean Sea, north of the Balearic Islands, acquired on 5 July, 1998. The Llobregat plume is visible as an area with lower SST. This area corresponds very well with the bright area on the respective SeaWiFS image (see the middle panel of Fig. 2).

Table 1. Pixel sizes and acquisition times for the data acquired on July 5, 1998; mouth of the Llobregat river.

Sensor	Pixel size (m)	Acquisition time (UTC)
WiFS	188	10.34
SAR	12.5	10.35
SeaWiFS	1120	12.48
AVHRR	1110	12.55
ATSR	1000	21.53

the influence of the plume on the local ecosystem is mainly a reduced water temperature (especially a reduced SST) and a higher chlorophyll-a concentration, whereas enhanced accumulation of surface films was observed only in a short distance from the river mouth. In order to investigate whether the observed phenomena are representative we have also taken into account historical data acquired between 1979 and 1985 by the Coastal Zone Color Scanner (CZCS, flown on NIMBUS 7). They are compared with data acquired in 1998 by SeaWiFS (Jolly et al. 1999) and are shown in Fig. 5 (note the different colour coding). The most pronounced similarities of both data sets are higher chorophyll-a loads in the plumes of the rivers Rhône (north), Ebro (west), and Llobregat (centre) and in the upwelling region of the central Golfe du Lion. It is obvious that the Llobregat plume has already been visible on CZCS data, whereas its shape is oriented parallel to the coast, because of the (long-term) mean surface current pointing in southwesterly directions.

Industrial outflow north of the Ebro Delta

A second example for the monitoring of plume dynamics and of the anthropogenic impact on the marine ecosystem was found on several of the analysed SAR images. In Fig. 6 subsections of SAR images of the southern part of the Costa Dorada, including the delta of the river Ebro, are shown. The images were acquired during different seasons in 1997 and 1998, and the different stages of the vegetation growth are visible as different reflectance (brightness) within the Ebro delta: between autumn and early spring (panels a, d, and e), the overall reflectance in that area is higher, and it decreases with growth of the vegetation (predominantly crops) in late spring and early summer (panels b, c, and f).

A peculiarity can be delineated on the SAR images shown in Fig. 6: between the Ebro delta in the south and l'Hospitalet de l'Infant in the north, irregular patches have been observed, which are surrounded by dark areas (panels c, e, and f). On some images we found signatures that are typical for outflow plumes, having a circular shape and which are either brighter or darker than the

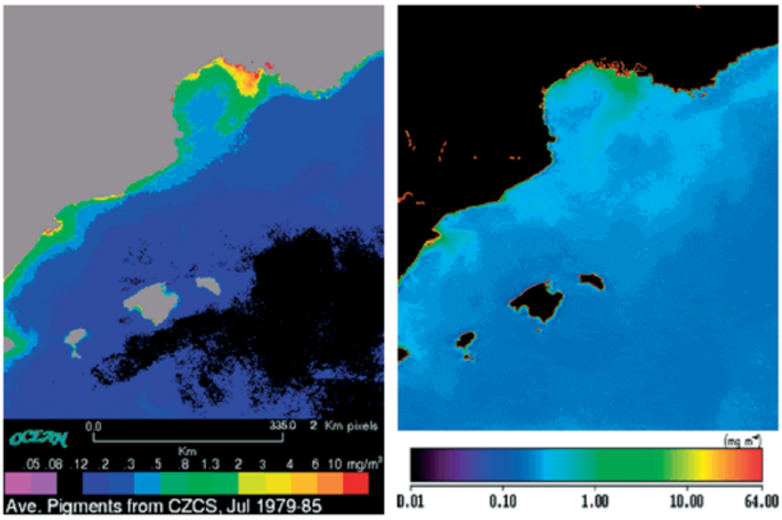

Fig. 5. Comparison of ocean colour data from the northwestern Mediterranean, mean values for July. Left: CZCS data from 1979-1985, right: SeaWiFS data from 1998 (taken from Jolly et al. 1999).

surrounding water (panels a, b, and d). At the place of origin of these features the nuclear power plant 'Vandellòs II' is located, and we therefore assume that the observed features are correlated with waste (cooling) water being released from the nuclear power plant. It seems that under certain 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 15 km long.

Turbulence and/or the upwelling cold water seems to be causing a reduction in radar backscatter (Keller et al. 1989) outside of the plume, whereas the plume itself, because of its higher temperature, appears brighter than the surrounding area on the SAR imagery. In the early stage of such a release the plume causes a small circular dark patch (panel d), which changes after a while to the already described bright feature.

It is noteworthy that we did not find any SeaWiFS image showing distinct changes in the chlorophyll-a content that could be correlated with the observed

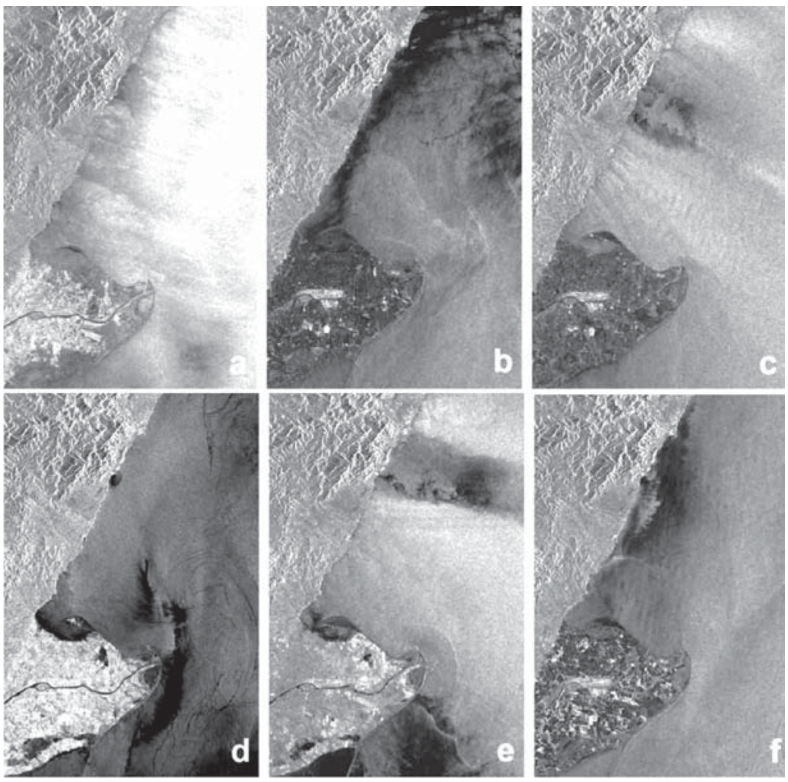

Fig. 6. Subsections (34 km × 51 km) of ERS SAR images of the western Costa Dorada, north of the mouth of the river Ebro. The images were acquired on **(a)** 25 December 1996, **(b)** 14 May, **(c)** 18 June, **(d)** 1 October, 1997, and on **(e)** 25 March and **(f)** 3 June, 1998.

phenomena on the SAR images. That is, although the signatures on the SAR images are of comparable size for both the Llobregat outflow and the waste water plume, SeaWiFS was not capable of detecting the latter. The ATSR SST image shown in Fig. 4 shows areas of colder water along the southern part of the Costa Dorada. However, because of the low resolution of the sensor (1 km, see Table 1) none of the observed patches could be clearly related to the plume visible on the SAR images (there was no ERS SAR image acquired from that area on 5 July 1998). Also, images acquired by the Linear Imaging Self-Scanning Sensor and the Panchromatic Camera aboard the IRS 1C/D satellites in early July 1998, (not presented) have not shown such signatures.

Any kind of industrial waste water may cause signatures on SAR imagery, as observed in the case of the Llobregat plume. However, since the features we found are quite different from those that can be related to industrial waste within a river outflow, we conclude that they are manifestations of the release of cooling water of 'Vandellòs II'.

Conclusions

A heterogeneous set of satellite data has been used to demonstrate the usage of multi-sensor data for the monitoring of the coastal environment, particularly of river plume dynamics. We chose as examples the plume of the river Llobregat, southwest of Barcelona, and an industrial waste water plume, north of the Ebro delta. Depending on the sensor characteristics (e.g. used wavelength, spatial resolution, etc.) both plumes may or may not show up in the different data.

We have shown that a multi-sensor approach for the monitoring of the marine coastal environment enabled us to better interpret the observed phenomena. As a result of our studies, SAR imagery has proven to be suitable for resolving small-scale features within the river plume. The advantage of a SAR sensor as being independent of daytime and cloud conditions, however, may be compensated by the fact that the visibility of the observed effects, namely of the accumulation of surface-active material on the water surface within the river plume, depends on local weather conditions, predominantly on the local wind speed. Moreover, the low temporal coverage makes it difficult to track any plume on a short-time basis.

Our results clearly show that the different sensors complement each other so that a better tracking of the observed phenomena (be it in space or in time) can be performed more easily. Moreover, a better understanding of the mechanisms, which are responsible for some of the observed features, is possible.

Next steps of our studies shall be the further intercomparison of the various data: The Llobregat data set will allow for a detailed study of the quasi-simultaneous imaging of the river plume by two different sensors within just one minute (WiFS and SAR, see Table 1). This data set will allow for better studying of the plume itself as well as the mechanisms causing the observed structures. In any of the presented cases, however, *in situ* data will be essential for a more reliable interpretation of the available data. Future studies should therefore include *in situ* data sampling within the plumes.

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