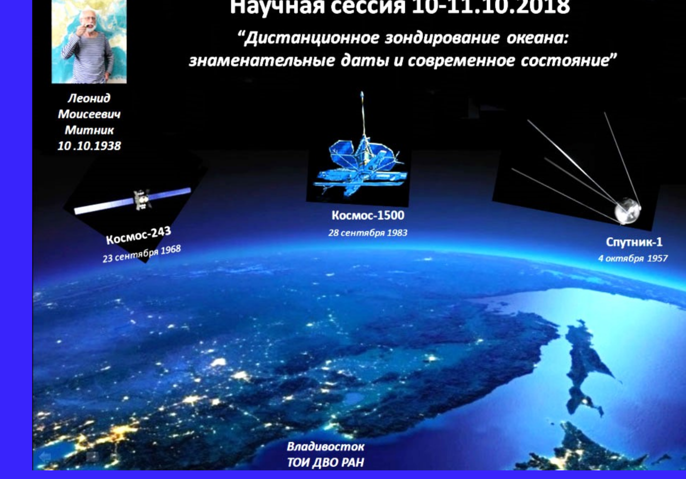
River plumes investigation using Sentinel-2A MSI and Landsat-8 OLI data



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Introduction

River waters flowing into the sea differ significantly from the seawater in physical, chemical and biological properties. Strong temporal and spatial variability of river plumes hinder their field study. The solution is brought about by the rapidly developing remote sensing techniques and relatively easy access to satellite survey data. Color sensors onboard recently launched satellites provide operational data with high spatial and spectral resolutions and open new possibilities for detailed studies of processes associated with river water spreading over sea shelf.

The Landsat-8 satellite, was launched on February 11, 2013. It carries two instruments: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). A short time ago, on 23 June 2015, the ESA launched the Sentinel-2A satellite. The satellite is equipped with Multispectral Imager Instrument (MSI) that provides high-resolution optical imagery in 13 spectral bands. Built essentially as land monitoring missions, Landsat-8 and Sentinel-2A are steadily finding their way into marine applications. One of them is monitoring the transport of suspended particulate matter (SPM) through river mouths, in river plumes and estuaries. Remote sensing investigations of SPM propagation are mostly based on ocean color data and a wealth of literature is devoted to the problem. Beside SPM dynamics, it is also of interest to look at hydrodynamic processes that may be induced by river outflows, for example, internal waves (IW). Signatures of IWs in SAR and ocean color images may differ very much due to peculiarities of signal formation physical mechanisms. Using data of high temporal and spatial resolution sensors, such as OLI/L8 and MSI/S2, is expected to provide optimal remote sensing capabilities for observing surface dynamics in coastal waters, including river plumes.

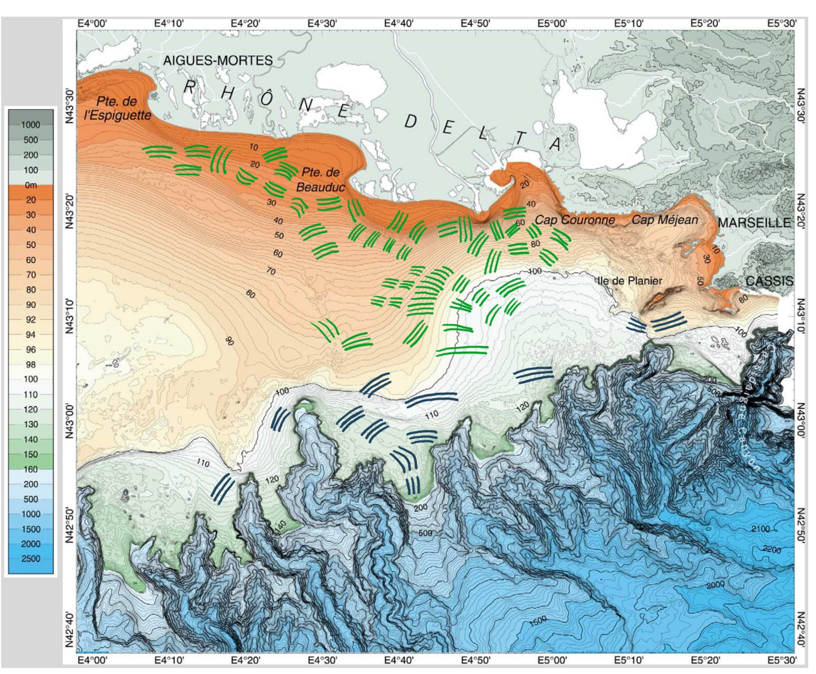
The research was conducted on the basis of satellite data obtained by MSI/S2 and OLI/L8. MSI/S2 has 13 spectral bands in the VNIR (Visible and Near Infra-Red) and SWIR (Short Wave Infra-Red) ranges at different spatial resolutions: four bands at 10 m, six bands at 20 m, and three bands at 60 m. OLI/L8 has 8 bands at 30 m and a panchromatic band at 15 m resolution.

Internal waves in the Gulf of Lions

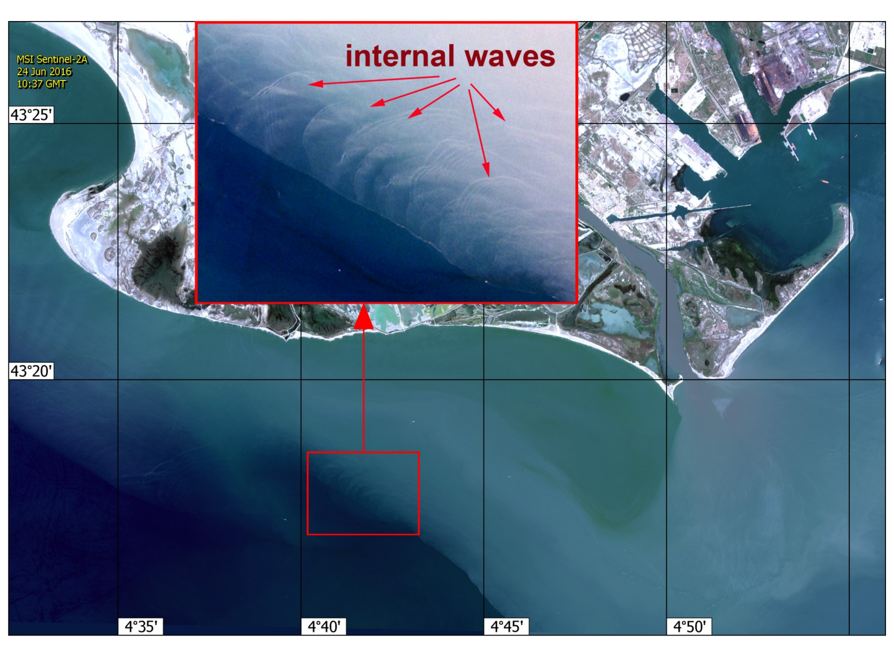
The existence of IWs in the depth of marine waters is caused by stable stratification, which corresponds to water density increase in the direction of gravity force. Internal waves play an important role in processes of horizontal and vertical exchange and mixing of waters, and in the formation of thermohaline circulation of water objects. In the images, the smooth (divergence) front zone appears as a bright band, while the rough (convergence) front zone appears as a dark one, because smooth surface can reflect more light to the sensor than rough surface.

All available MSI/S2 data obtained over the Gulf of Lions from 12 August 2015 to 26 August 2016 were analyzed. So, images for various seasons were examined. Of 49 images, clouds covered the river embouchment area in 14 images; they were discarded.

We found SMIWs in June – August months, with August featuring the most extended network of IW trains. All the SMIWs were plotted on a bathymetric map of the Gulf of Lions (left figure). As seen from the figure, the SMIWs are distributed between the two areas: 1 - near the edges of underwater canyons where the IWs are generated (black); 2 – plume areas of the Grand Rhône and the Petit Rhône (green). The crests of IW trains generated in result of propagation of non-stationary river plume front are parallel to the front. At the same time, there are multiple IW trains that are not explicitly generated by the non-stationary fresh water front, but whose effect on IW propagation is quite evident. A good illustration is a case of 24 June 2016 presented in right figure. Multiple IW trains were not generated due to the plume, otherwise their crests would have been parallel to the plume front visible as a bright line in the image. Nevertheless, the trains seem to slip along the front line having propagation direction perpendicular to it. Parameters of these IW trains are: distance between trains about 500 m; crest length 1300 m, train length 300 m, maximum wavelength 50 m. Obviously, IW trains of such a scale could be revealed only in high resolution images, like MSI/S2.



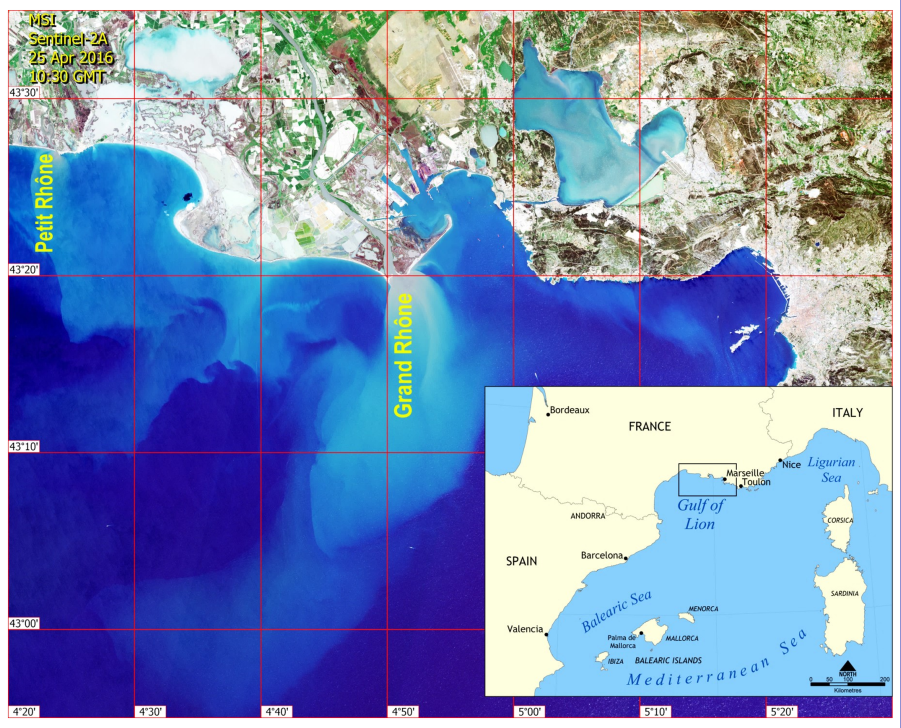
Map of the Gulf of Lions with locations of SMIWs trains revealed in MSI/S2 images.



Propagation of multiple small scale IW trains along the River Rhône plume front. Fragment of an MSI/S2 image of 24 June 2016.

Study area

The Gulf of Lions is a gulf of the Mediterranean Sea extending along the coast of southern France from the city of Toulon (east) to the Spanish border (west). This coastal region is one of the largest continental shelves of the Mediterranean Sea and is strongly affected by the outflow of the Rhône River. The Rhône plume can extend over hundreds of kilometers offshore making it easily detectable on ocean color satellite data. On the south of the Gulf of Lions, there are many deepwater canyons that play an important role both in the hydrodynamics of the gulf and exchange of SPM between the shelf zone and deep sea. They may be the locations of IW generation.



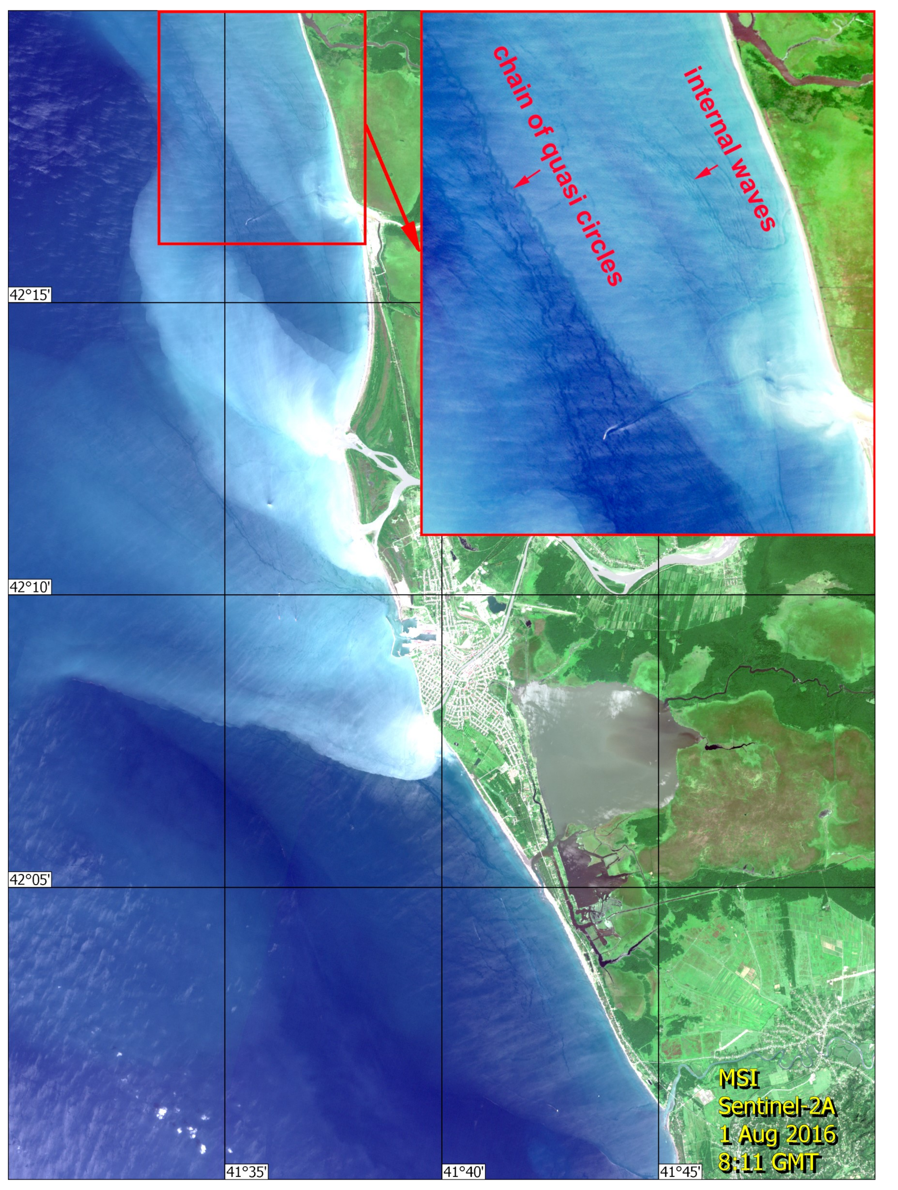
RGB georeferenced MSI/S2 image of the Gulf of Lions of 25 April 2016.

The Black Sea is also an enclosed sea connected to the Aegean Sea through the narrow Bosphorus and Dardanelles Straits. The characteristic feature of the Black Sea is the so-called Rim Current – a strong alongshore cyclonic current, known for its high hydrodynamic instability. The paper discusses the rivers of the Black Sea eastern coast. In this study region, over ten big mountain rivers flow into the sea. Here one can regularly observe long-lasting anti-cyclonic eddies, whose current directions are opposite to the Rim Current which has a particular effect on the spreading of river outflows in the region.

The eastern Black Sea.

Submesoscale processes in the eastern Black Sea

Our investigations based on OLI/L8 and MSI/S2 data of 2015 - 2016 have revealed small-scale processes that, though certainly occurred, but were not observed earlier. A special case is presented in right Figure. An MSI/S2 image clearly depicts plumes of the three River Rioni branches and River Khobi (its mouth is shown in the enlarged fragment). In the region, two river outflows, one of the northern Rioni branch, the other of Khobi, approach each other and apparently through their interaction a chain of quasi circles with diameters of 150-170 m appears. The chain length is about 9 km, it extends along the 30 m isobaths. The formation mechanism of the chain is unclear, but its perfect circle structuring leaves no doubt that the prime cause is inertial motions. The inertial motions are manifested in circles is their localization at the boundary of a slackening intrusion flow where surfactants occurring due to convergence become trapped by inertial water rotation. In the considered case, there were vertical velocity micro shears at the outer thinned plume edge (skin front), and sufficiently massive surfactants carried by the rivers were trapped by inertial oscillations and traced the circular motion pattern. Also, right Figure features a surface manifestation of submesoscale IWs train located closer to the shore. Maximum wavelength in this train is about 60 m. Analysis of manifestations of submesoscale IWs on river plumes in the eastern Black Sea shows that the IWs occur due to inertial currents of (always) unstable sharp plume boundary front that radiates IWs manifested as soliton trains.



Manifestation of a chain of quasi circles and an IW train in an MSI/S2 image of 01 August 2016.

Conclusion

First results of using MSI/S2 data in investigation of processes associated with river outflows are presented. All available MSI/S2 data taken over the embouchment areas of the River Rhône (Mediterranean Sea) and rivers of the eastern coast of the Black Sea available from the moment the access to the data was open to August 2016 were analyzed. High spatial resolution of MSI/S2 data provided new impressive details in terms of small-scale hydrodynamic features. Submesoscale IWs generated by unstable sharp front of a river plume were revealed and their parameters were assessed. A new phenomenon manifested as a chain of quasi circles was discovered.

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