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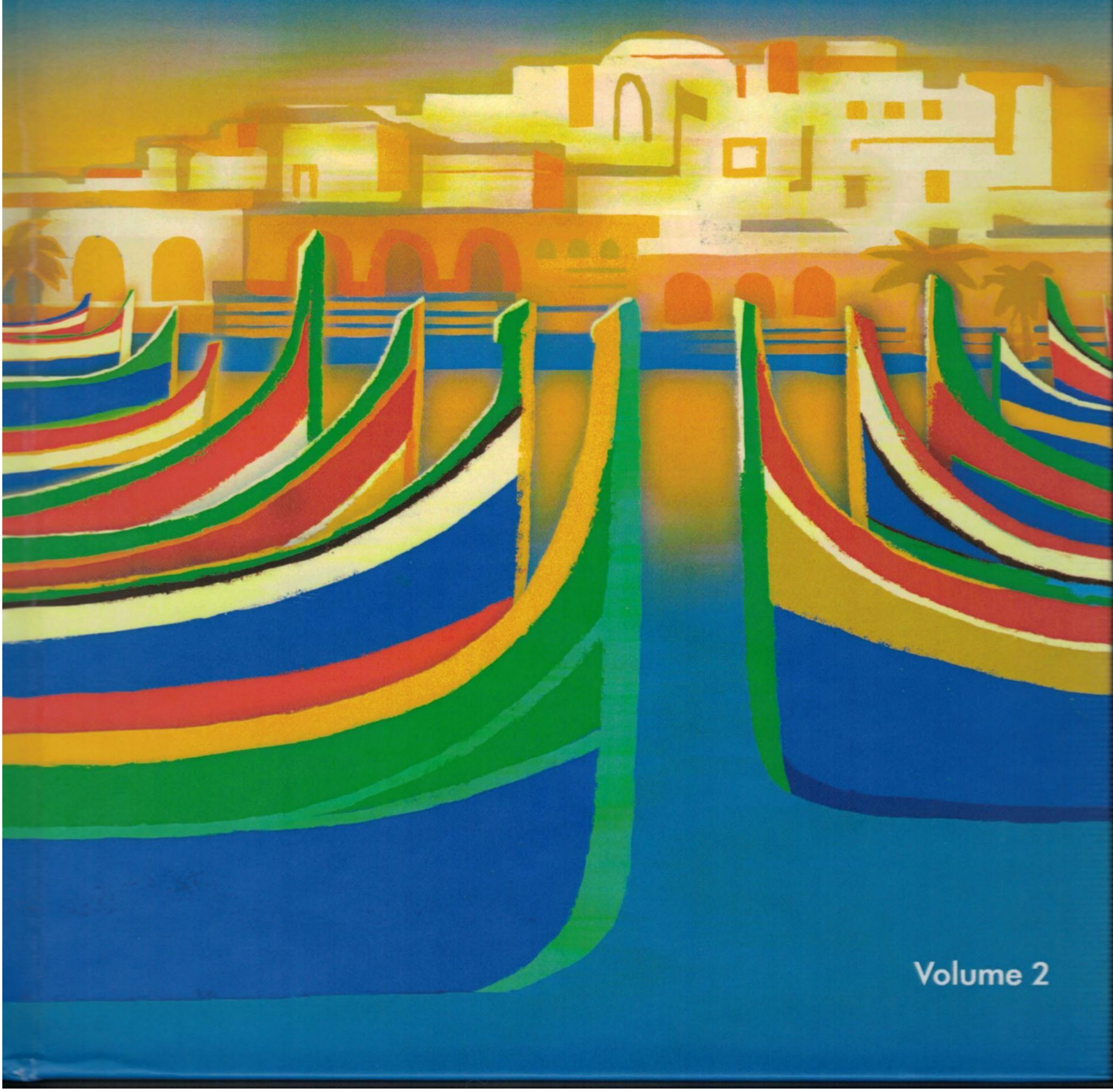

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Investigation of Rhone River Plume Based on Satellite Data

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Abstract

This paper describes an integrated study of Rhone River plume. The aim of our research was to widen current knowledge of distribution Rhone River plume under ocean dynamics and meteorology conditions. About 479 available satellite images (SAR and optical data) for the region of the Rhone River Delta in the Gulf of Lions was analysed for the period from 01/01/16 to 01/03/17. We present the results of a comparative analysis of different satellite data and demonstrate the benefits of each instruments (ETM+, OLI, MSI etc.). The results of statistical analysis of the size and shape of the Rhone River plume, depending on the season and weather conditions are also presented. To achieve this goal meteoblue simulation data was used. Schematic map of inter-annual variability of the river plume was demonstrated.

Introduction

The regions where fresh river water mixed with sea water are most important and interesting places. River discharge is the source of the huge amount of terrigenous suspended and dissolved substances, nutrients, and products of anthropogenic pollution. Getting from river to the sea, fresh waters form there adjacent to the mouth mesoscale structures with low salinity, different temperature and high content of suspended matter and organic matter. Such structures in the modern literature are called plumes. These structures - one of the subjects of research in different sciences such as geology, hydrology, oceanography, biology and ecology. But still not enough studied. This is due to several reasons, one of that is the difficult conditions in the area around the mouth for in-situ measurements (especially for large rivers, where near river mouth the flow velocity can reach tens of meters per second). Therefore, remote sensing is practically one of the single ways to study the river plumes. At present time available a large number of satellite data in optical and radar ranges. The advantages of the remote sensing is: ability for regular monitoring research area; instantaneous coverage of large areas; high spatial resolution and free access to the databases. In this article, we consider distribution of Rhone river plume under ocean dynamics and meteorology conditions using different kind of satellite data.

Study Area

The Gulf of Lions (GoL) is a big gulf (length - 93 km, wide - 245 km, maximum depth - more than 1000 m) in the Northeastern part of Mediterranean sea along the coastal line of southern France (from the city of Toulon - east to the Spanish border - west) with wide continental shelf mostly influence by freshwater and particulate matter inputs from the Rhone River. The Rhone River is 812 km long with catchment area about 97 800 km^2. It supplies 80% of the sedimentary input to the Gulf of Lions. The Rhone River surface plume can spread over several kilometres off the mouth. Many G. et al. (2016) highlight the role of the particle concentrations in the coastal ecosystem and in the hydrodynamic sea structure across the whole shelf. The main aims of their research were characterizing the spatial variability of turbid structures and determining the particle assemblage properties (size, shape, composition). These authors based their research on comprehensive set of measurements *in-situ* (mooring, shipboard and glider) during flood events. Similar works in GoL are dedicated to another river in GoL - the Tet River, for example Bourrin F. et al. (2008).

Wind patterns in GoL region affecting to the whole coastal zone and generated complex current dynamics. The main winds are the northwesterly "Mistral" and the southeasterly "Marin". The Mistral induces a cyclone mesoscale circulation in the western part of the GoL. Southeasterly winds generate a counter clockwise circulation. In Allou A. et al. (2010) and in Andre G. et al. (2009) authors investigate the meandering structures of the Northern Current (NC) - submesoscale and mesoscale eddies in GoL. These authors used numerical modelling and HF radars to analyse high frequency fluctuations of NC and estimate the minimum vortex occurrence in this area.

Furthermore, in GoL, there are many deepwater canyons that may be the location for internal waves (IW) generation. Inertial oscillations are often observed and indicated on satellite images. In Lavrova et al. (2016) authors focused on exploring the possibility to investigate hydrodynamic processes associated with river outflows. Their parameters were suggested by using satellite data obtained by MSI Sentinel-2 and OLI Landsat-8 optical sensors.

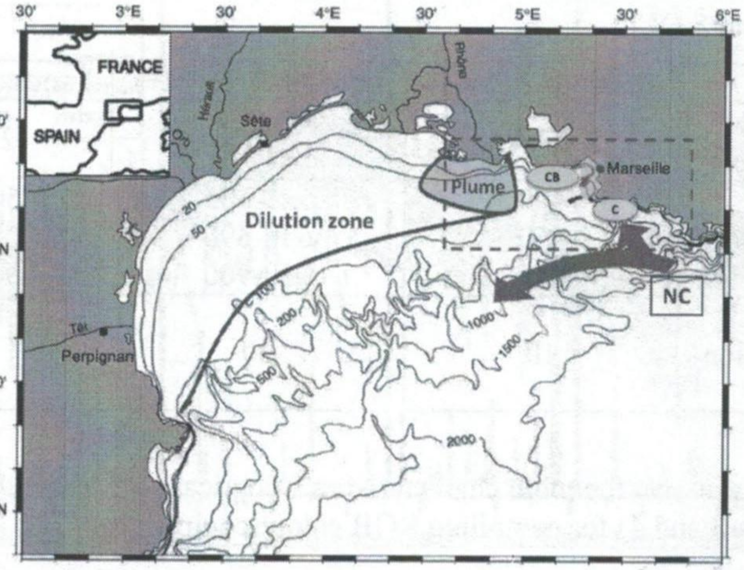

Fig.1: Map of the Gulf of Lion. The Rhone River plume, intrusion zone and the Northern current (NC) are represented (Fraysse M. et al., 2013).

However, a serious weakness of all research works is short-time measurements. The GoL ecosystem is influence by developed marine traffic, rising anthropogenic pollution from big cities (Marseille, Toulon and etc.) and by polluted waters from the Rhone River. Sea monitoring of this region is necessary. In this paper we present the example of how can be useful different kind of available satellite data to every day hydrological situation in GoL, in particular distribution Rhone river plume under ocean dynamics and meteorology conditions. It aims to 1) demonstrate the benefits of each instruments (ETM+Landsat-7, OLI Landsat-8, MSI Sentinel-2 and etc.); 2) determining spatial variability of Rhone River plume (statistical analysis of the size and shapes).

Materials and Methods

We used a multi-platform strategy to characterize Rhone River plume. We coupled remote sensing data from different kinds of satellites obtained by Modis Aqua/Terra, ETM+ Landsat-7, OLI Landsat-8, MSI Sentinel-2 and SAR-C Sentinel-1 with meteorological conditions during one year from 01/01/16 to 01/03/17. Every winter IFREMER take measurements in this region from research vessel (ADCP, CTD measurements and water sampling) and also use time-series observations of ocean conditions from SLOCUM glider (Many et al., 2016). So, it is potentially possible to verify satellite data with measurements in-situ.

Remote sensing data

All remote sensing data were provided by ESA (Copernicus Open Access Hub), USGS (The USGS Global Visualization Viewer) and Modis subset images from NASA database. Mainly, in our research we used SAR-images (Sentinel-1) and high resolution satellite data in optical range. The main difference between these types of satellite data is that SAR-data work with clouds, but optical not.

Table 1: Comparison of characteristics of Sentinel-2A MSI, Landsat-7 ETM+ and Landsat-8 OLI.

	Sentinel-2 (MSI)	Landsat-7 (ETM+)	Landsat-8 (OLI)
Band Number	2,3,4	1,2,3	2,3,4
Wavelength (nm)	490 560 665	525-605 630-690 750-900	450-515 525-600 630-680
Spatial Resolution (m)	10	30	30

Table 1 presents the main characteristics of optical sensors. In this work we used only 3 bands (2, 3 and 4) for compiling RGB colour composites.

Scenes from Sentinel-1 have high spatial resolution too - 5 m with wavelength 5,55 sm and with width 20 m. Also, we used MODIS sensor (Moderate Resolution Imaging Spectroradiometer) mounted on the spacecraft Terra. This sensor has medium resolution - 250 m. The main advantage is daily scenes of the same area.

For data processing we used ENVI (Environment for Visualizing Images) and SNAP (Sentinel Application Platform) software and toolkit provided by the Sea the Sea (STS) portal developed in the Space Research Institute of the Russian Academy of Sciences (SRI RAS, Moscow, Russia).

Meteorological observations

Weather simulation data were provided by the Meteoblue database (www.meteoblue.com). Hourly weather simulation for Cap-Couronne (43 20.23'N, 5°01.38'E) included next parameters: air temperature, precipitation, wind speed, wind direction, mean sea level pressure and total cloud cover.

Results

Meteorological conditions

The main meteorological conditions in Cap-Couronne area are shown in Fig. 2. Vertical lines separate the seasons: winter, spring, summer and autumn. On the chart traced the annual cycle of air temperature with minimum temperatures in winter (up to - 5° degrees in January 2017), the gradual warming in the spring months and summer highs temperatures up to + 37° C, and then a gradual cooling in autumn (the average temperature is 15° C). The annual variation of pressure has inverse negative relationship to temperature: in the summer period pressure has minimum value - about 1000-1010 hPa and in the winter maximum - 1040-1050 hPa.

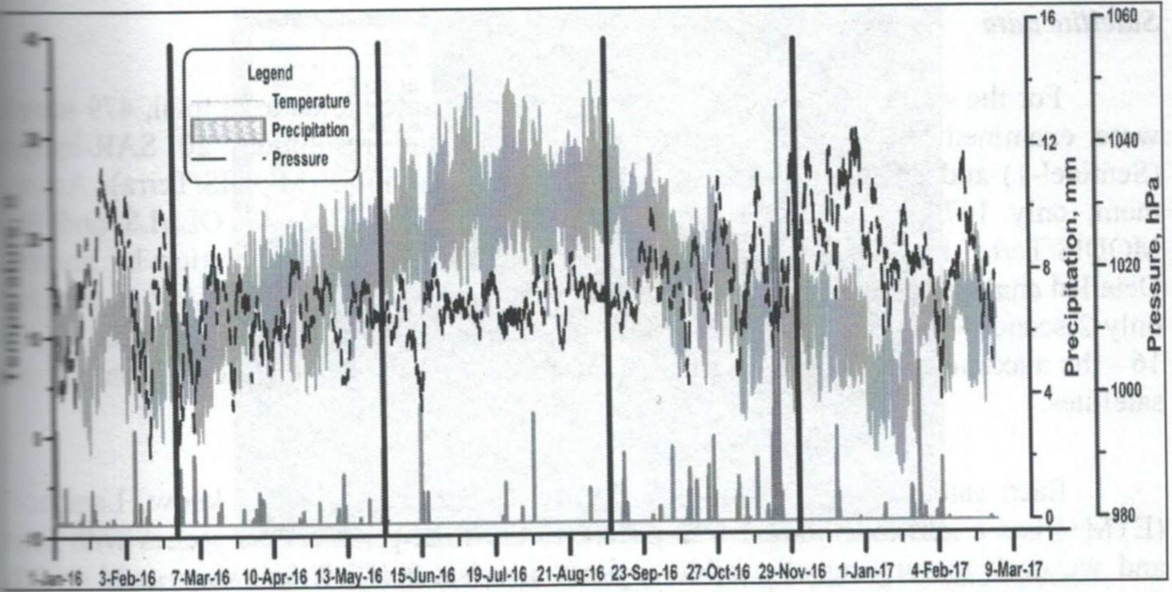

Fig. 2: The annual variation of air temperature, pressure and precipitation in Cap-Couronne area (43 20.23'N , 5°01.38'E) from 01/01/16 to 01/03/17.

Total rainfall for the year amounted to 338,8 mm in research region (Fig.3). The rainiest month was November 2016 (precipitation = 135 mm). The least rainy months were July 2016 and February 2017 (precipitation = 6 mm). Average monthly rainfall is approximately equal to 30 mm.

Wind rose diagram showed the predominating wind direction is NNW (337 - 340°) with speed 10 - 15 m/s. In winter period, wind direction changes abruptly from NNW (337 °) to ESE (112,5 °). Also, winter period is characterized by strong gusts of wind more than 15 m/s. The wind patterns remained the same during year with the exception of the summer period: the wind changes from NNW to SW (225 °) and wind speed varies from 5 to 10 m/s.

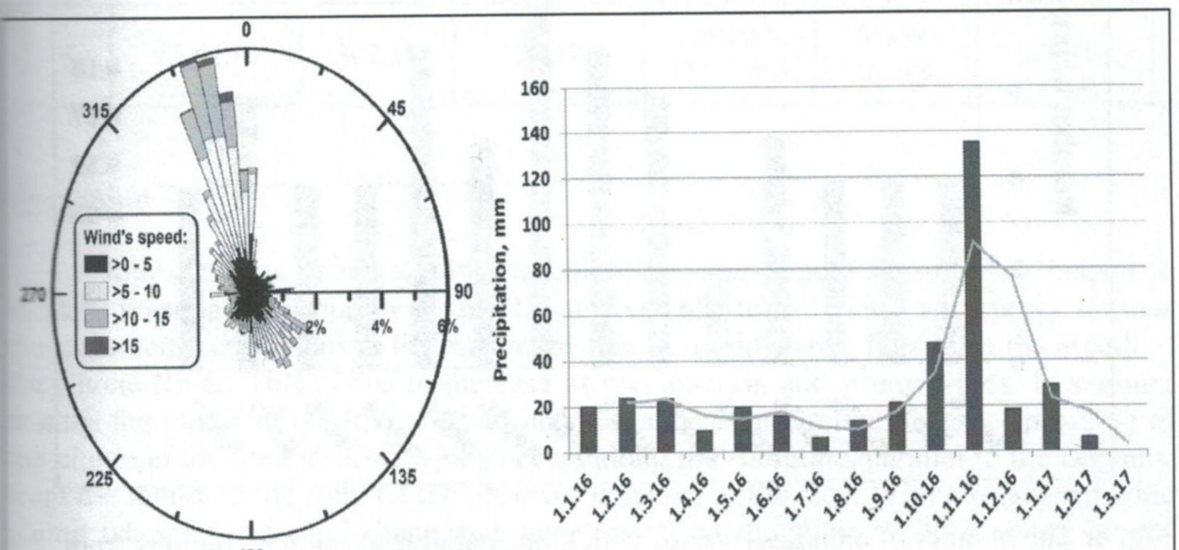

Fig. 3: Wind rose (at the left) and monthly distribution of precipitation throughout research period (at the right).

Satellite data

For the study region we analysed all available satellite data. In total, 479 scenes were examined: 95 optical scenes with high spatial resolution, 20 SAR-images (Sentinel-1) and 365 optical scenes with medium resolution (MODIS/Terra). Among them, only 167 cloudless scenes: 28 MSI/S2, 12 ETM+/L7, 12 OLI/L8 and 115 MODIS/Terra. Fig. 4 shows the distribution scenes with high resolution by months. Detailed analysis showed that a fairly irregular satellite overflights. On May 16 we have only 2 scenes - the absolute minimum during this period, against 10 scenes on August 16 - the maximum. And only seven cases when in one day we have scenes from several satellites.

Each satellite sensor has its own characteristics. As we all know, Landsat-7 (ETM+) has a malfunction and it impacted to the final product (the scenes with lines and we can't monitoring all visible region). Landsat-8 (OLI) has very good optical characteristics, but in this region we have a small amount of scenes. For our opinion the best optical instrument for the Rhone mouth river region is MSI (Sentinel-2A): the largest number of scenes, high resolution, almost monthly coverage of the region.

We have identified five cases with a maximum spread of the Rhone river plume during research period: 21/02/16, 15/05/16, 27/11/16, 05/02/16 and 25/04/16 (Fig.5). All their characteristics are described below in Table 2. The biggest plume (21/02/16) has area 501 km^2 and swept away at 30,2 km from the coast.

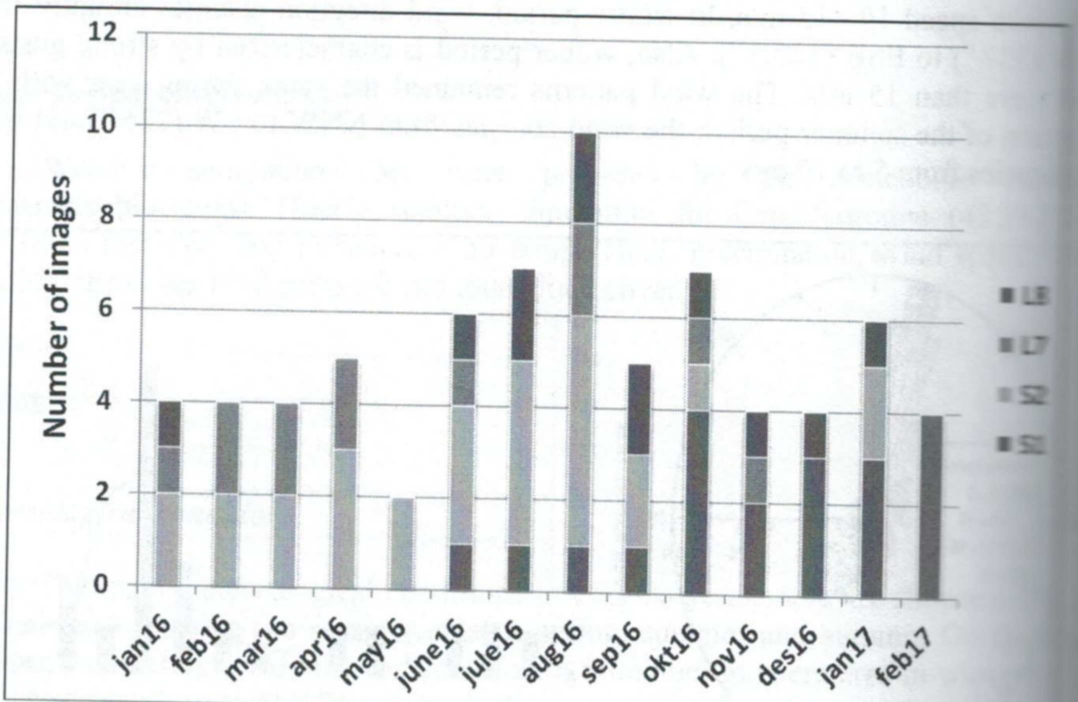

Fig. 4: The number of cloudless scenes with high spatial resolution by months from 01/01/16 to 01/03/17.

Fig. 5: The maximum distribution of the Rhone river plume during research period.

Table 2: Characteristics of the largest river plumes during research period.

	Date	Plume area, S [km^2]	Distance from coast, [km]	Wind direction and speed	Before event	
					Wind	Precipitation (period)
1	21.02.16	501	30,2	NNW 1-2 m/s	NNW 16 m/s	+ (12/02-15/02)
2	15.05.16	450,2	29	NNW 10-12 m/s	N-NW 16 m/s	+ (05/05, 10/05)
3	27.11.16	410	25,5	NE-E 2-3 m/s	SEE 15 m/s	+ (21/11-25/11)
4	05.02.16	387	24,74	NNW 5-7 m/s	NW 10 m/s	-
5	25.04.16	302,28	25,12	NNW 11-13 m/s	NNW 16 m/s	+ (23/04-24/04)

Discussion

Joint analysis of meteorological conditions and remote sensing data helped to identify seasonal distribution of the Rhone river plume. In winter and spring seasons there are better conditions to the maximum area of turbid waters flow from the mouth of the Rhone River. This is due to increase of precipitation and strong winds. In summer months the plume of the Rhone River may not appear on satellite images. Spreading of the plume in the Southeastern winds occurs along the shoreline, parallel to the isobaths, from the mouth to the right (if the observer is facing to the sea). With a weakened wind plume takes on a domed shape and swept away on the West. With a strong North-Western winds, flows with a high content of suspended matter are distributed perpendicular to the coast (to the South) and the surface plume reaches the edge of the shelf (30-50 km from the shore).

Conclusions

First results of using different kind of satellite data to investigation Rhone river plume are presented. All available remote sensing data and meteorological conditions for this region were analysed. Seasonal distribution of the Rhone river plume under weather and dynamic conditions was observed. Spatial variability (size and shapes) of Rhone River plume was assessed.

We are going to continue collecting and analysed satellite data and we hope that further work will include verification with in-situ data (hydrological and hydrodynamics structure).

Acknowledgements

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