MONITORING DISPERSAL PATTERNS SEA FOAM INJECTED BY REGASIFICATION PLANTS USING SATELLITE OPTICAL MULTISPECTRAL IMAGERY

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ABSTRACT:

Liquefied natural gas regasification plants can use seawater as a fluid in the process of converting gas from liquid to gas. In some cases, in correspondence with the discharge into the sea of the water used in the regasification process, "foams" may develop. In order to assist the overall evaluation of the phenomenon, an initiative was launched aimed at identifying foams with the use of satellite Earth observation data. Satellite optical multispectral imagery acquired by MSI sensor aboard Copernicus Sentinel-2 satellite constellation have been used to map areal distribution of sea foam generated from offshore platform and dispersed over sea. A sea foam detection procedure has been developed, including the following processing steps: i) cloud masking; ii) cloud mask refinement; iii) sea foam detection; iv) spatial filtering.
Sea foam spatial patterns, identified from Sentinel-2 MSI satellite acquisitions in the period 2015-2022, have been complemented with information related to dispersal direction and maximum distance from platform discharge point, and related to sea state and weather conditions, specifically, wind, waves, currents, and rainfall data. Results showed that the proposed procedure is effective in sea foam dispersal patterns identification and can be extended to other high-resolution remote sensing imagery.

1. INTRODUCTION

The phenomenon of foam formation at the regasification plant, in some cases, appears to be related to the breakdown of microorganisms naturally present in the sea water, subjected to mechanical stress and thermal shock along the water flow circuit in the vaporization systems and in relation to local weather and climatic conditions.
An example of this phenomenon can be seen in northern Adriatic Sea, where the Adriatic LNG offshore regasification terminal (Figure 1) is located 15 nautical miles from the coast of Porto Viro (RO), a platform 375 meters long and 115 meters wide, resting on the seabed at 29 meters deep approximately.
For this installation, the formation of foams was observed from the early stages of operation of the plant, also in consideration of the trophic state of these marine systems and the configuration of the discharge, which releases water in free fall inside a basin during regasification plant activities, trapping air and contributing to the amplification of the phenomenon.
To control and mitigate foams dispersal, initiatives have been launched aimed at the mechanical abatement of foams by nebulized sea water, for which the Italian Institute for the Environmental Protection and Research (ISPRA) and the regional environmental agency (ARPAV), monitors its operation. To assist the overall evaluation of the phenomenon, the Institute has launched a study phase aimed at identifying foams with the use of satellite Earth observation data. Experimental radiometric samplings demonstrated that sea foam reflectance decreases substantially with wavelength in the near-infrared, with values in the visible (0.44 μm) reduced by typically 40% at 0.85 μm, 50% at 1.02 μm, and 85% at 1.65 μm (Frouin and Deschamps, 1996). The spectral effect can be explained by the nature of the foam, which is composed of large bubbles of air separated by a thin layer of water and of bubbles of air injected in the underlayer. The presence of bubbles in the underlayer enhances water absorption and thus reduces reflectance in the near-infrared (Frouin and Deschamps, 1996).
Use of multispectral satellite observations to investigate marine debris characteristics, highlighted that spectral discrimination from other sea surface features (e.g., ships, foam) is not straightforward (Acuña-Ruz et al., 2018). Indeed, differentiating floating plastic debris from bright features, such as sea foam, sun-glint, clouds, is currently considered very challenging (Martínez-Vicente et al., 2019). Sea foam recorded at river fronts or coastal wave breaking area resulted in lower evaluation scores than other spectral targets when using classification models trained with the machine learning algorithms (Kikaki et al., 2022). Shoreline detection methods using very-high spatial resolution satellite images can be hampered by sea foam spectral target and require sea foam to be taken into account when discriminating between land and ocean pixels in coastal waters (Minghelli et al., 2020).

Figure 1. Adriatic LNG

This research study aims at proposing an approach to identify sea foam injected by regasification plants using satellite optical multispectral imagery, in order to provide an operational system to monitor spatial distribution over time, to support practitioners environmental control and to verify the effectiveness of mitigation strategies. Statistical analysis on detected sea foam allowed to identify typical dispersal patterns and to further analyse physical forcings role for selected cases resulting in broader distribution.

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2. MATERIALS AND METHODS

Satellite optical multispectral imagery acquired by MSI sensor aboard Copernicus Sentinel-2 satellite constellation have been used to map areal distribution of sea foam generated from offshore platform and dispersed over sea. The high spatial resolution (10 m, 20 m and 60 m), the high revisit time (5 days with two satellites), and the 13 spectral bands (from the visible to shortwave infrared) are the characteristics of the S2 Multi-Spectral Instrument (MSI) sensor. All Sentinel-2 MSI acquisitions (top of atmosphere reflectance – L1C) acquired in the period 2015-2021, with cloud cover lower than 90%, were collected for the area of interest (about 700 images).

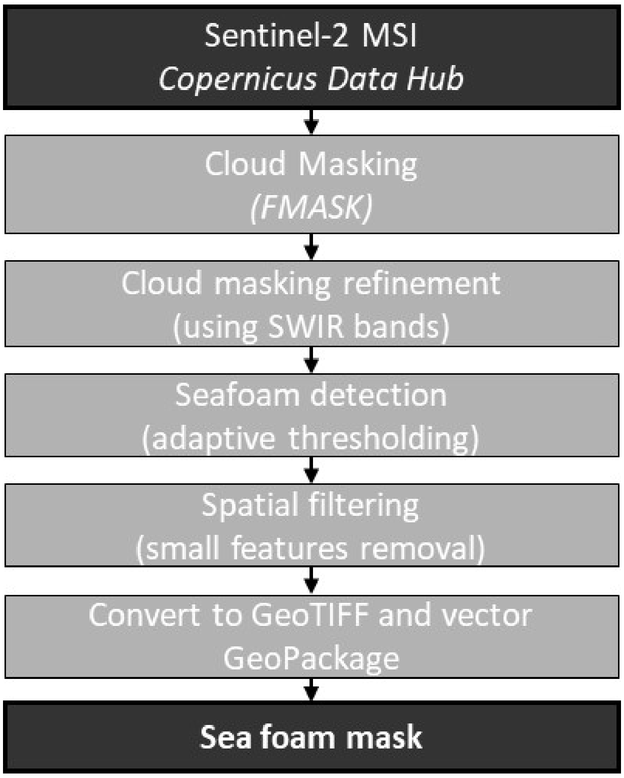

Figure 2. Detection procedure flowchart.

A sea foam detection procedure (Figure 2) has been developed, including the following processing steps: i) cloud masking; ii) cloud mask refinement; iii) sea foam detection; iv) spatial filtering.

In situ spectral measurements, acquired using a portable spectroradiometer, allowed to identify sea foam spectral signatures (Figure 3) in radiometric interval 400-900 nm. Measured sea foam reflectance showed significantly higher values than background seawater reflectance.

Taking under consideration sea foam spectral characteristics, and its similarity with cloud spectral signature in the visible and near-infrared radiometric interval, MSI SWIR spectral bands have been used to refine detected cloud pixels identified using 'fmask' cloud masking algorithm (Frantz et al., 2018), while all available spectral bands at 10 m spatial resolution have been used to locate pixels corresponding to floating sea foam.

The detection processing step consists of an adaptive thresholding method, to find brighter pixels than the background ones within a 0.5 km spatial buffer. Sum of reflectance value of all the available spectral bands at 10 m spatial resolution in the visible and near infrared radiometric interval has been used for the analysis. Threshold value has been set to value 0.25, which has been selected from the inspection by expert operators of sum of reflectance values over seafoam pixels, performed on 5% of the acquisitions. Spatial filtering of detected bright pixels is finally applied, in order to remove small patches corresponding to false positives (i.e. whitecaps, sun-glint, ship-generated sea foam, etc.). As a result, sea foam raster binary mask is generated from each satellite acquisition date.

Validation exercise, through supervision of the produced binary masks superimposed on true-color RGB images in GIS software run expert technicians, allowed to evaluate detection performances, providing information related to false negative pixels, typically in areas with thin clouds removed during cloud masking step, and false positive pixels, remaining after spatial filtering.

Sea foam spatial patterns identified from Sentinel-2 MSI satellite acquisition in the period 2015-2022, have been complemented with information related to dispersal direction and maximum distance from platform discharge point, and related to sea state and weather conditions. Specifically, wind, waves, currents and rainfall data, collected on the offshore platform or by a nearby buoy, have been compared with sea foam spatial distribution, in order to find typical dispersal patterns and identify physical forcings that could contribute broader distribution.

All the analysis was done using software SNAP, QGIS and R-cran.

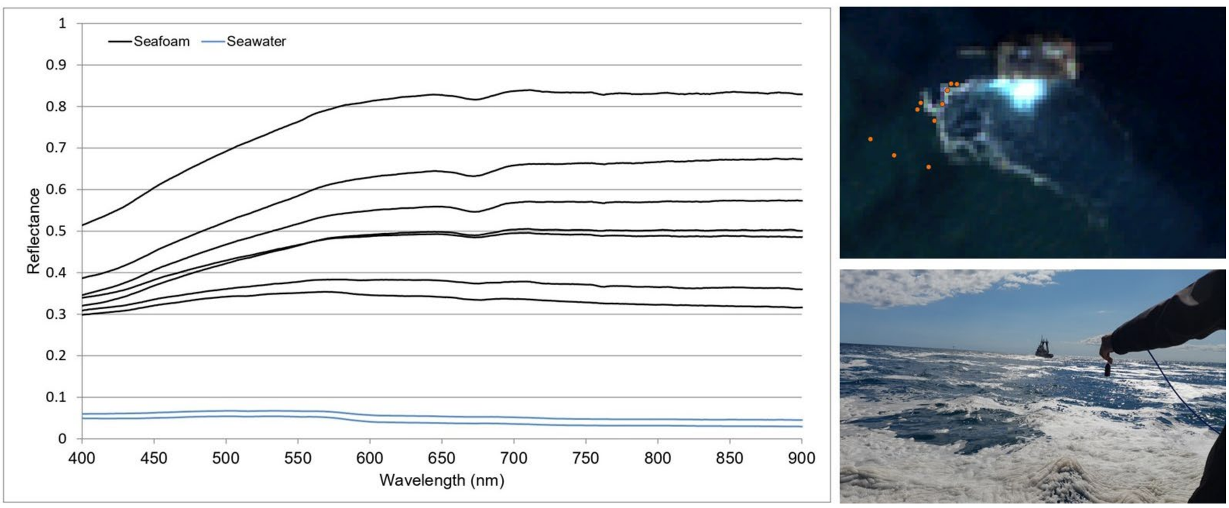

Figure 3. Spectral signatures from in-situ radiometric sampling.

3. RESULTS AND DISCUSSION

Detection approach allowed to reach a classification accuracy of 0.774. A total of 204 acquisitions (29.19 %) do not show any sea foam generated from regasification plant.
Most cases examined show a dispersion that typically concentrates within the distance of 1.5 nautical miles from the point of discharge the regasification water on sea. Maximum detected distance is 4.71 nautical miles. Typically, the direction and position of the dispersion area is in a southerly direction with respect to the terminal, due to the location of the emission point (Figure 4).

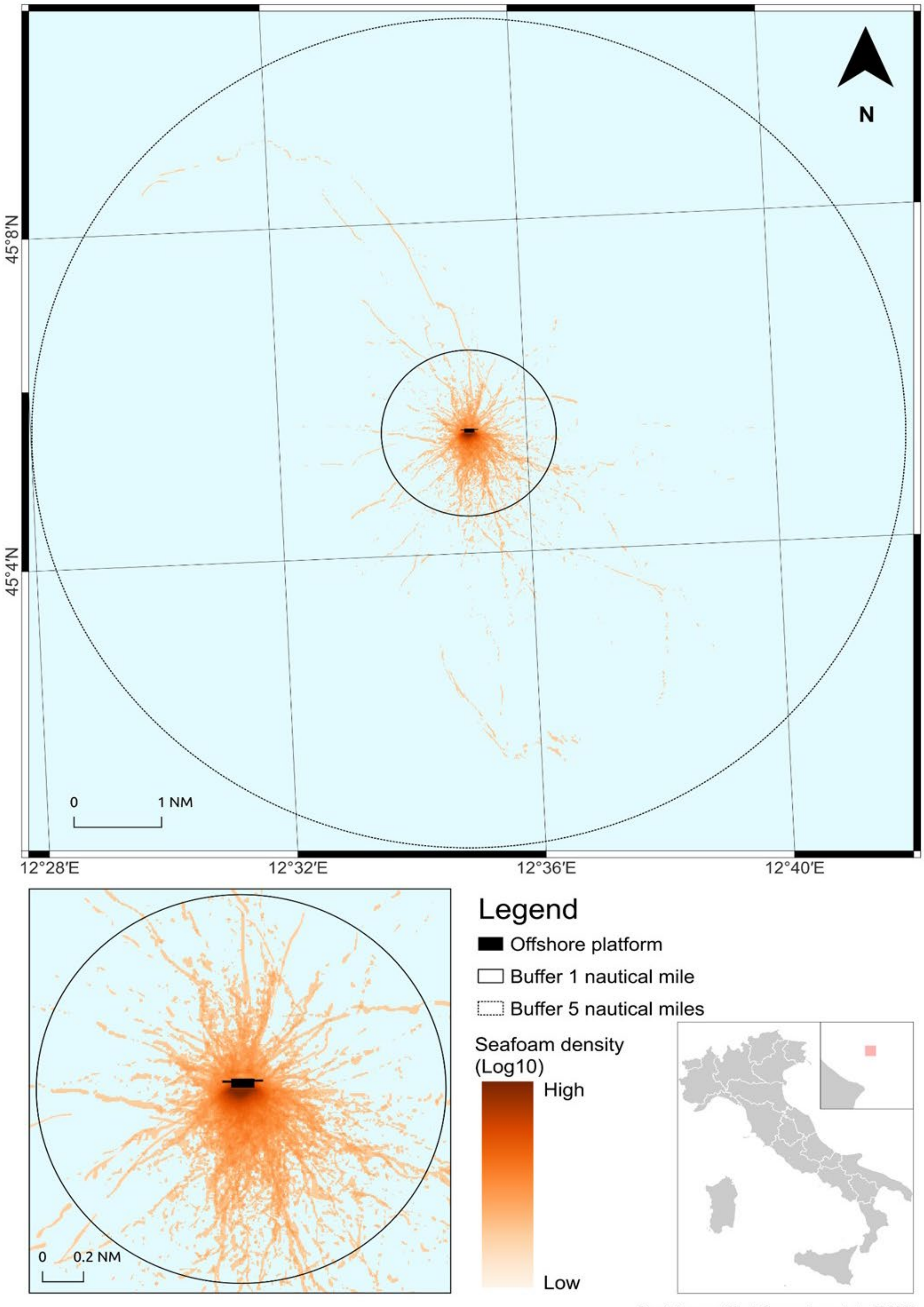

Figure 4. Sea foam dispersal patterns
for the period July 2015 – November 2022.

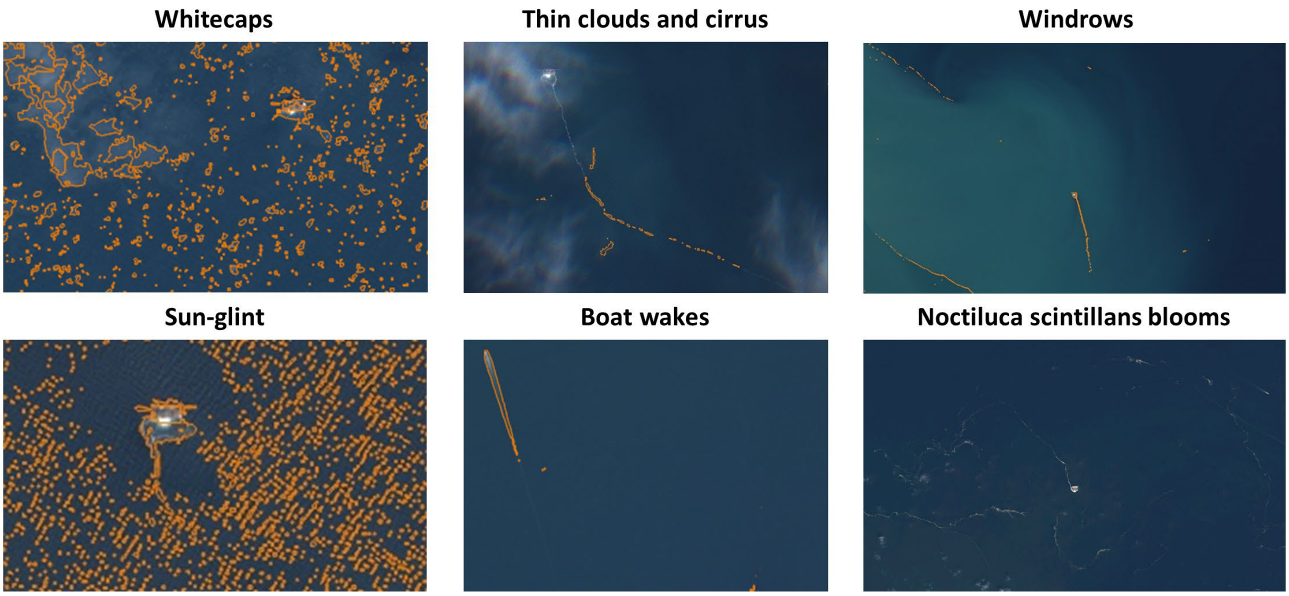

Figure 5. Sea foam false negatives and false positives cases. Detected sea foam is shown in orange color.

The selection of top of atmosphere reflectance in place of bottom of atmosphere reflectance for sea foam identification it is due to two reasons: i) in situ radiometric sampling show a significant difference between seafoam and seawater spectral signatures; ii) atmospheric correction algorithms can alter reflectance values so as to reduce detection capability.

Atmospheric correction algorithm used to process Sentinel-2 MSI data distributed to the users, namely Sen2Cor, performs relatively poorly in the coastal waters due to the land-based methodology, which generates scene parameters requiring a distribution of pixels containing land (Warren et al. 2019). On the other side, atmospheric correction algorithms specifically designed for water applications, used to retrieve bottom of atmosphere water-leaving reflectance, may use a correction for whitecaps, dampening seafoam reflectance. Considering that the objective of the research study is not concerning robust retrieval of optically active water constituents, that requires accurate atmospheric correction over seawater, top of atmosphere reflectance has been used to identify sea foams.

Only spectral bands at 10 m spatial resolution have been used for the sea foam detection, considering the scale of the investigated phenomenon. Same spectral bands set is available on many other very-high spatial resolution sensor onboard satellites and Unmanned Aircraft Systems (UAS), opening the way for extending the proposed detection approach to other optical multispectral acquisitions.

False negatives generated by the proposed detection procedure, corresponding to 22.5%, are mainly related to pixels with sea foam still observable under thin clouds (Figure 5), that are masked out by cloud masking processing step. False positives, partly deleted by spatial filtering for small features removal, are represented by bright pixels whose high reflectance values can be related to the presence of: whitecaps, especially during windy conditions; boat wakes; sun-glint, especially during summer months; algal blooms, like Noctiluca scintillans blooms; and windrows. Windrow is a long-established term for the aggregations of sea foam, seaweeds, plankton and natural debris that appear on the ocean surface, it usually forms stripes from tens up to thousands of meters long (Cózar et al, 2021).

The analysis was deepened on a set of cases selected on the basis of relevant events (significant distance of the foams from the terminal) and clear identification of the foams via algorithm (i.e. in the absence of those phenomena that disturb the identification of the area occupied by the foams). A selection of satellite acquisitions for which the identified seafoam dispersal exceeded 1.66 nautical miles from the emission point allowed to identify 30 cases.

Spatially explicit database of detected sea foam was complemented with the meteorological conditions (waves, currents, winds) observed by measuring instruments positioned near the terminal.

Assuming that the area occupied by the foams develops due to the meteorological conditions occurring in the last few hours, each parameter analysed is evaluated in average terms considering the average of the six hours preceding each satellite acquisition time. Two cases among the identified ones are showed, being marine physical forcings perfectly describing the development of foam in the area. The analysis of the first selected case (Table 1) highlighted that the applied algorithm, given the good visibility conditions at satellite acquisition time, was able to clearly identify the imprint taken by the formation of the foams (Figure 6). From the analysis of the foam dispersion during the case, it was possible to verify how much the marine physical forcings active on that day correspond to the direction of propagation that the foams assumed.

Figure 6. Sea foam dispersal pattern (in yellow) as seen by Sentinel-2 MSI acquired on 30/01/2022.

The platform position is often decisive in influencing the prevailing direction towards a south-south-east direction. meteorological conditions may correspond to a prevailing direction of distribution of the foams.

Sea foam dispersion: South (first branch), south-east (second branch), 138° (from North, clockwise)	
Satellite acquisition date	30/01/2022
Maximum distance	4543 m
Total area of the sea foam	54100 m^2
Current speed (last 3 hours)	0.25 m/s
Current direction (last 3 hours)	132°
Current speed (last 6 hours)	0.25 m/s
Current direction (last 6 hours)	123°
Wave height (last 3 hours)	0.21 m
Wave direction (last 3 hours)	133°
Wave height (last 6 hours)	0.18 m
Wave direction (last 6 hours)	118°
Wind speed (last 3 hours)	3.1 m/s
Wind direction (last 3 hours)	144°
Wind speed (last 6 hours)	2.5 m/s
Wind direction (last 6 hours)	133°

Table 1. Information related to selected case identified from Sentinel-2 MSI acquired on 30/01/2022.

In the other case shown, relating to the satellite acquisition of 24/05/2019 (Figure 7), it can be clearly highlighted how the direction taken by the foams was conditioned by the current and wind forcing (Table 2), which on that specific day showed a prevalent component towards the west. The height of the waves and their direction, given the mild intensity, do not affect the direction of propagation of the foams originating from the terminal.

Figure 7. Sea foam dispersal pattern (in yellow) as seen by Sentinel-2 MSI acquired on 24/05/2019.

Sea foam dispersion: West -87° (from North, anti-clockwise)	
Satellite acquisition date	24/05/2019
Maximum distance	3522 m
Total area of the sea foam	49800 m^2
Current speed (last 3 hours)	0.33 m/s
Current direction (last 3 hours)	-135°
Current speed (last 6 hours)	0.37 m/s
Current direction (last 6 hours)	-119°
Wave height (last 3 hours)	0.12 m
Wave direction (last 3 hours)	104°
Wave height (last 6 hours)	0.13 m
Wave direction (last 6 hours)	108°
Wind speed (last 3 hours)	2.0 m/s
Wind direction (last 3 hours)	-108°
Wind speed (last 6 hours)	2.3 m/s
Wind direction (last 6 hours)	-100°

Table 2. Information related to selected case identified from Sentinel-2 MSI acquired on 24/05/2019.

4. CONCLUSION

The proposed approach showed a good capacity in identifying sea foam injected by regasification plants from satellite optical multispectral acquisitions, as well as monitoring the dispersal patterns. It was possible to verify, for selected cases examined, that certain marine weather conditions affect the development and the areal propagation of foams. The analysis also tried to explain what are the physical forcings that determine the broader dispersal, representing cases that need special attention. Further development should test the proposed approach for the analysis very-high spatial resolution optical multispectral data and identify strategies to reduce the detection of false positives.

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