Mesoscale Patterns Identification through SST Image Processing

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Abstract: Mesoscale marine phenomena represent important features to understand and include within predictive models, which provide valuable information for proper environmental policy making. For example the rearrangement of the organic substances, consequent to the dynamics of the water masses affected by the mentioned phenomena, meaningfully modifies the actual condition of local habitats. Indeed it may facilitate the onset of non resident living species at the expense of resident ones, eventually affecting related human activity, such as commercial fishery. Objective of this work is the detection and identification of mesoscale events, in terms of specific marine surface patterns that are observed throughout such events, e.g. water filaments, countercurrents, meanders due to upwelling wind actions stress. These phenomena can be studied and monitored through the analysis of Sea Surface Temperature images captured by satellite missions, such as Metop, and MODIS Terra/Aqua. A quantitative description of such events is proposed, based on dedicated algorithms that extract temporal and spatial features from the images, and exploit them to provide a signature discriminating different observed scenarios. Preliminary results of the application of the proposed approach to a dataset related to the southwestern region of the Iberian Peninsula are presented.

1 INTRODUCTION

The impact of climate change on marine ecosystems is often expressed by simplified warming trends (Hansen et al., 2010). Although this approximation may be valid for oceanic regions, in coastal areas the impact of warming on the ecosystems is far from being homogeneous. This is mainly due to the fact that coastal regions host some of the most biodiverse and variable environments of the ocean.

Near the coast, global drivers are modified by topography and by local atmospheric and oceanographic circulation patterns, including upwelling. Ekman dynamics and large-scale thermocline processes control the coastal upwelling occurring at the Eastern Boundary Upwelling Ecosystems (EBUEs) (Messié et al., 2009; Ramajo et al., 2020). Winds directed towards the Equator drive upwelling by transporting deeper, colder and nutrient-rich waters to the surface, where phytoplankton production is triggered by sunlight (Sydeman et al., 2014). As a result, these areas, through the upwelling, give strength to the most productive ecosystems in the global ocean (FAO, 2018), playing a major role in the marine primary production and the worldwide fisheries (7% of global marine production and more than 20% of global fish catches), thus providing a high number of subsistence and benefits to human society (Levin and Le Bris, 2015). Apart from the nutrient load, it was recently shown that upwelled water's low long-term warming rates may provide thermal refugia, stabilize changes in species distributions and enhance local biodiversity (Varela et al., 2018).

According to related literature, more than 71% of coastal zones are experiencing a net heat gain due to global warming (IPCC, 2019). Yet, it is difficult to systematize the trends observed in different upwelling ecosystems across the global oceans, as

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positive trends were observed in the coastal areas of Benguela, Peru, northern California, and Canary while significant negative trends were found along Chile, Somalia, and southern and central California coasts (Varela et al., 2015). Therefore, it is surmised that every upwelling ecosystem reacts differently to the changing climate.

Among the world's EBUEs, the Iberia/Canary Current System (ICCS) is one of the least studied (Chavez and Messié, 2009). Several research studies have focused on the western Iberian oceanography (Relvas et al., 2007). Despite a general circulation similar to other EBUEs, in ICCS the discontinuity imposed by the Mediterranean Sea, combined with the seasonality of the large-scale atmospheric circulation, have a profound impact on the regional oceanography. Time scales of a few tens of days explain more than 70% of the variability of the coastal alongshore wind stress, a major factor governing the regional coastal circulation (Álvarez-Salgado et al., 2003). The region's continental shelf, with less than 10 km wide south of Lisbon, 30–40 km wide off central Portugal and somewhat narrower again off northern Portugal and Galicia, is characterized by a large number of topographical features, such as prominent capes, promontories and submarine canyons, whose spatial scales are tens to hundreds of kilometers (Relvas et al., 2007). All the above highlight the importance of sub-seasonal temporal scales and sub-basin spatial scales, which explain the observed oceanographic patterns. In a review paper (Relvas et al., 2007), the physical oceanography of the western Iberia system is described and characterized through the main mesoscale features related to that region. They include a succession of mesoscale structures such as jets, meanders, ubiquitous eddies, upwelling filaments and counter-currents, superimposed on the more stable variations at seasonal timescales, as suggested by several authors (Relvas et al., 2007).

The identification and cataloguing of upwelling features occurring in an EBUE is an important achievement towards the characterization of the system. Traditionally that task has been performed subjectively by experts, analyzing Sea Surface Temperature (SST) maps of the area of interest. The use of upwelling indices has also been used as a first guess directing the experts towards the dates and events to be analyzed (Lamont et al., 2018), but a visual inspection has been always needed to certify the presence of an upwelling and, above all, to classify the type of upwelling. This procedure is manageable if few tens or even hundreds of images are used but it turns into an impossible task to analyze thousands of images, as needed to identify the effects of climate change.

The main objective of this work is to design and develop automatic methods capable of accepting massive datasets of oceanographic SST imagery as input and returning the classified images as output. The output classification labels reflect the different regimes of observable upwelling patterns. The identification of a specific temperature pattern will be based on the extraction of quantitative features from the SST maps. Particular attention will be devoted to those features that reflect the signal variability (e.g. gradient-based indicators). Indeed the emergence of a certain pattern is usually highly correlated with peculiarities in the temperature spatial arrangement at time fixed (e.g. the presence of abrupt variations in the temperature values within a certain neighborhood) as well as with the observation of specific temperature trends at fixed locations, providing insights about the flowing of water masses between points at different temperature values. A dedicated visualization tool has been developed to organize the relevant information in a single plot, so that SST patterns relative to specific mesoscale events are easily recognizable.

The proposed methods will be applied to the South Iberian region, contributing to the understanding of the effects of climate change in this particular EBUE. In this article, a preliminary methodology is proposed, and demonstrated using SST remote sensing images. In its preliminary form the metrics used are able to identify different types of mesoscale features, but different variables and arrangements still need to be tested, as discussed in the text.

The paper is arranged as follows: Section 2 concerns a detailed description of the employed dataset, the related ground truth classification, visually performed by expert users, and a description of the developed processing tools; Section 3 presents some preliminary outcomes resulting from the application of the proposed methods to the selected dataset; Section 4 concludes the paper with a final discussion and future works.

2 MATERIALS AND METHODS

2.1 SST Imagery

Seasonal mesoscale features shape the regional ocean surface circulation of the South Iberian coast, affecting the physical, chemical and biological processes that occur at the surface layer (Lopes et al., 2014).

To look for seasonal mesoscale circulation patterns, satellite images from both NASA's Aqua and EUMETSAT's METOP satellites were selected starting from 2009. Aqua's satellite data was retrieved

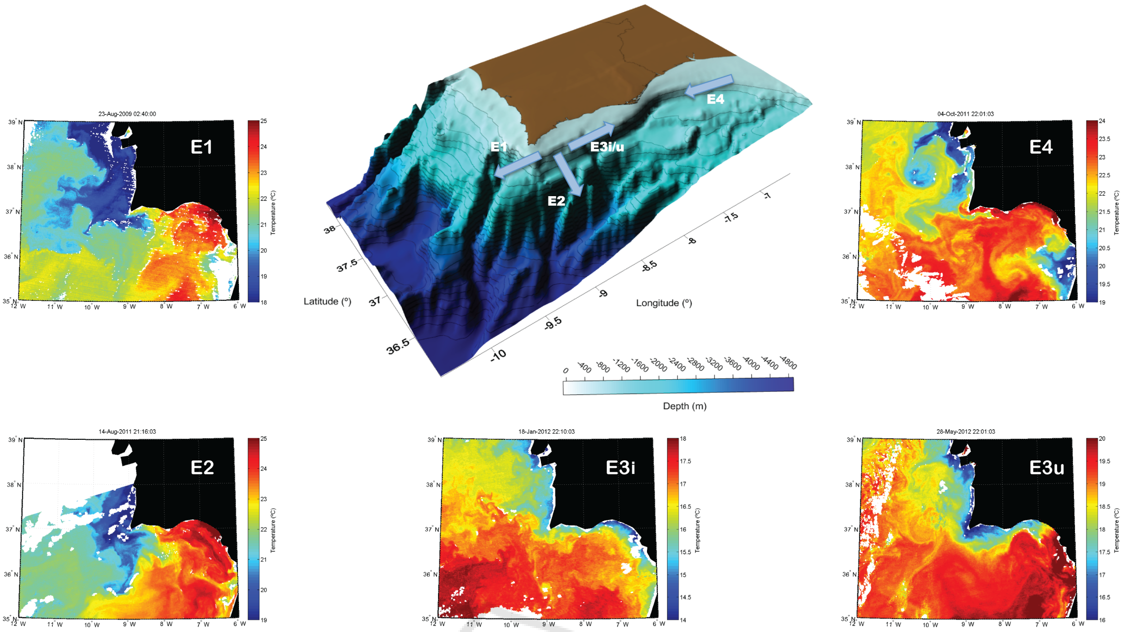

Figure 1: Mesoscale patterns in the South-Western Iberian Peninsula.

from NASA's Ocean Color webpage and it consists of a dataset of 470 binned 4 km (night time) SST images obtained through its MODIS sensor. The data was visually selected and only swaths with relevant coverage were downloaded. The METOP dataset comprised approximately 7800 daily world SST images from its Advanced Very-High-Resolution Radiometer (AVHRR) sensor with 1 km resolution and was retrieved from OSI-SAF webpage for the period of interest. The data was pre-processed applying a filter to select the images covering the geographical limits of the study area.

2.2 Patterns of Interest

A visual inspection of the combined MODIS/METOP SST dataset has been performed by experts, in order to identify a minimal set of temperature patterns, whose occurrence is repeatedly observed throughout the dataset time range. As a result of this labeling generation process, five typologies of mesoscale events have been recognized as the most representative within the South Iberian coast area (see Figure 1).

The first mesoscale pattern, here defined E1, is associated with the meander of the southward upwelling jet to the west, near Cape S. Vicente, alongside occurring the development of upwelling filaments. Pattern E2 is depicted by the southwards flow of the upwelling jet overpassing the Cape S. Vicente forming an extended meridional filament. A clear signal of cool water throughout the southern Iberian coast without detachment is what defines pattern E3. After a careful analysis of the dataset, it has been verified that pattern E3 usually takes place in a twofold mode. When the signal of cool water throughout the southern Iberian coast was associated with a small thermal gradient within the adjacent Gulf of Cadiz waters, the pattern has been classified as E3i. In the satellite image dataset, this event is more frequent during winter with the warm water along the Iberian shelf edge and slope being associated with the upsurge of a poleward flow (Peliz et al., 2005), a direct effect of the shift in wind direction verified during wintertime. The second type of E3 pattern, named E3u, is related to the occurrence of a significant thermal gradient within the Gulf of Cadiz waters. The cool water signal was associated with the upwelling jet turning Cape S. Vicente while flowing through the south Iberian coast. Finally, in pattern E4, a warm counter-current (Relvas and Barton, 2005) develops near the south Iberian coast, turning around Cape S. Vicente and flowing northwards near the coast.

Based on this ground truth labeling, dedicated image processing methods have been designed and preliminary developed with the objective of automatically detect and classify the above mentioned mesoscale patterns in the South-Western Iberian coast.

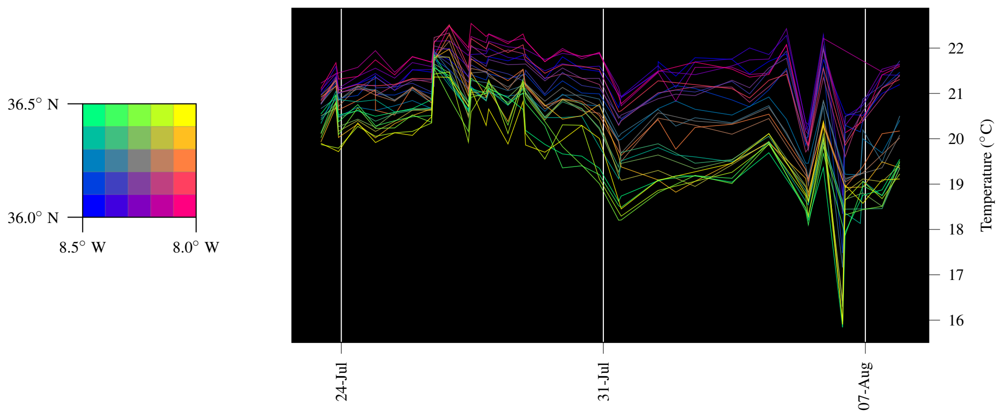

Figure 2: Example of a spaghetti plot. Each square in the reference grid (on the left) corresponds to the plot of the same color in the graph on the right, so it is easy to associate SST trends with a geographical area.

2.3 Processing Methods

In order to extract and organize the information from the satellite SST data a small suite of custom Python scripts has been developed.

The main goal of the analysis is to detect a specific event at a given time, recognize its typology, but also inspect the dynamic evolution preceding the considered observation time. The occurrence and the type of an event is analyzed by looking at the SST trend in small selected areas off the coast.

The developed tool takes as input a folder containing files from the datasets, a time range and the coordinates of a rectangular area and returns a *spaghetti plot* obtained in the following way:

1. the area is divided into a grid of very small squares of fixed dimension (typically 0.02–0.05 degrees of latitude/longitude);
2. for each square, a mean temperature value is computed by taking the file corresponding to a given time and averaging all the SST data with geographical coordinates contained in the square;
3. for each square, a series of temperature values is computed, following the instructions of the previous step, for every step in the considered time range and the resulting temperature series is plotted against time;
4. the spaghetti plot is composed by superimposing the plots relative to all the squares.

Each square of the grid is color-coded so that similar colors are assigned to neighboring squares. The graphs in the spaghetti plot are colored according to the corresponding square in the grid. This way it is easier to identify the behavior of different zones inside the target area (see Figure 2).

The main problems encountered while processing the signals and generating the spaghetti plots relate to the quantity and quality of the data. In fact, the satellites provided only a few (two or three) images per day over the area of interest, and it was very likely that those images couldn't be used at all because of missing data (which may be caused by some external factor, e.g. presence of clouds). One possible solution to these issues, also aim of future research activity, will be to introduce additional datasets (possibly from different remote sensing missions) to fill the missing gaps.

Another aspect that has to be taken into account is the reliability level of the signal in the SST maps, which sometimes may cause misleading interpretations. For example, it is usual to observe that the temperature measured at the boundary of a region of missing data (marked as “cloud” in the file) is very low compared to the temperature that we expect when looking at the neighboring data. Indeed, the exploited datasets are provided with a quality label among the usual metadata, i.e. a quality level that is assigned to each point for which SST is measured. In the example above, both the missing data region and the surrounding low temperature points are marked in the product metadata as “bad quality” data. This information can be used to improve the overall quality of the spaghetti plot — in fact, we included in our scripts a couple of control switches that allow the user to adapt the computation in the above described step 2 by either discarding completely the bad quality data, or computing a weighted average with lower weight given to bad quality data.

Once the spaghetti plots have been obtained, an analytical reasoning is performed in association with the ground truth defined by experts as defined above in Section 2.2. The goal is to identify and associate different dynamic patterns with different events (including also a no-event situation), so that an automatic supervised association could be made out of the

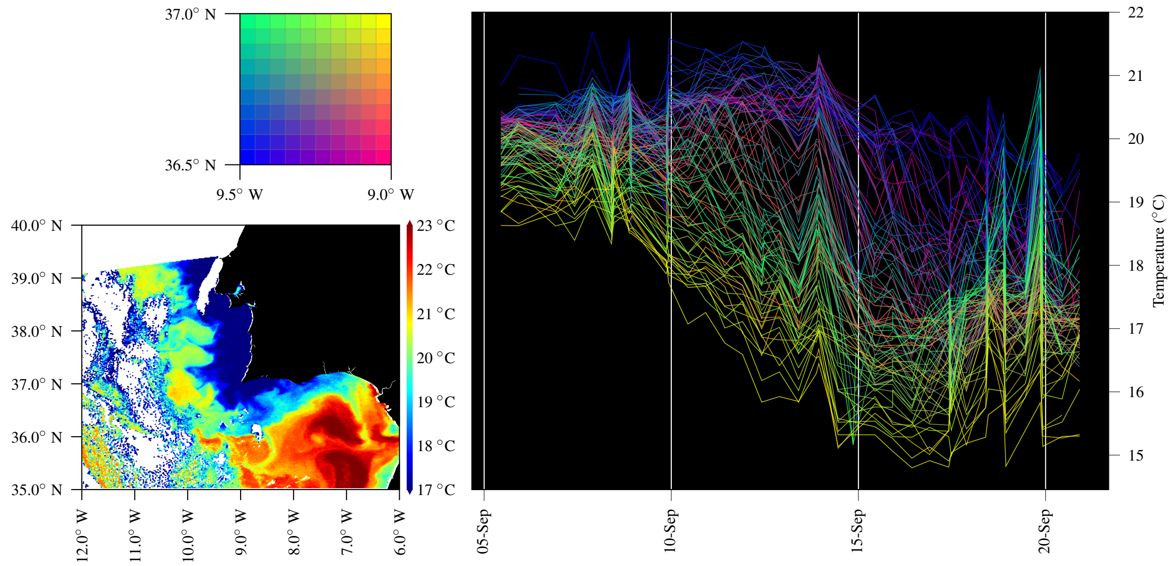

Figure 3: Event of 19 September 2017. Top left: reference map for the plot; bottom left: SST map at the date of the event; right: generated spaghetti plot.

described computations. The following section concerns the description of some preliminary results of this ongoing analysis, including the analytical reasoning behind.

3 PRELIMINARY RESULTS

Several processing and analysis have been performed within the dataset, in particular the year 2017 was selected as a preliminary study case. Following the classifications given by experts, with a series of different events identified at specific dates, the dynamic analysis considering n days before the classified event has been processed in a geographical area around the event of interest. The spaghetti plots produced were then associated with the classifications assigned to the specific events and then analyzed together with the experts.

The following table lists three specific events chosen for this paper as a preliminary result, together with the subsequent reference figures, the number of backward days T_n analyzed for the dynamic of the event, and a brief description of the event.

Table 1: List of analyzed events.

Date (T_0)	Ref. Fig.	Time T_n	Type
19-Sep-2017	Fig. 3	-14 days	E3u
5-Oct-2017	Fig. 4	-16 days	E4
27-Jun-2017	Fig. 5	-11 days	No event

Following the application of our methodology, the results in the form of spaghetti graphs, as described in Section 2.3, are shown for each selected event and period. The small map in each figure represent the color identification for the respective spaghetti plot as described in Section 2.3, where each line in the plot is relative to the region of the same color.

The first example (Figure 3) is a typical mesoscale event, identified by the experts as of type E3u representing a cold current going southward to the end of Iberian Peninsula, crossing Cape S. Vicente, and then moving eastward towards the Mediterranean Sea. As it can be seen from the relative spaghetti plot, the temperatures in the upper right corner (close to Cape S. Vicente) are decreasing to a much higher gradient with respect to the other surrounding areas — this identifies a possible first dynamic pattern.

As a second example we show (Figure 4) a different type of event, recognised by the experts as a warm counter-current moving westward from the Gulf of Cadiz. For this case study, considering the type of event, we have selected a narrower shaped rectangle that allows classifying the trend along the coast. In this case the spaghetti plot clearly outlines a dynamic pattern of the easternmost area (red plots) which increases its temperature starting colder than the westernmost (blue plots) but raising up and overcoming it (i.e. much higher positive gradient of the easternmost area, with a close-to-zero gradient of the westernmost one).

Finally, as a third example (Figure 5) we see a situation where no specific event has been detected in

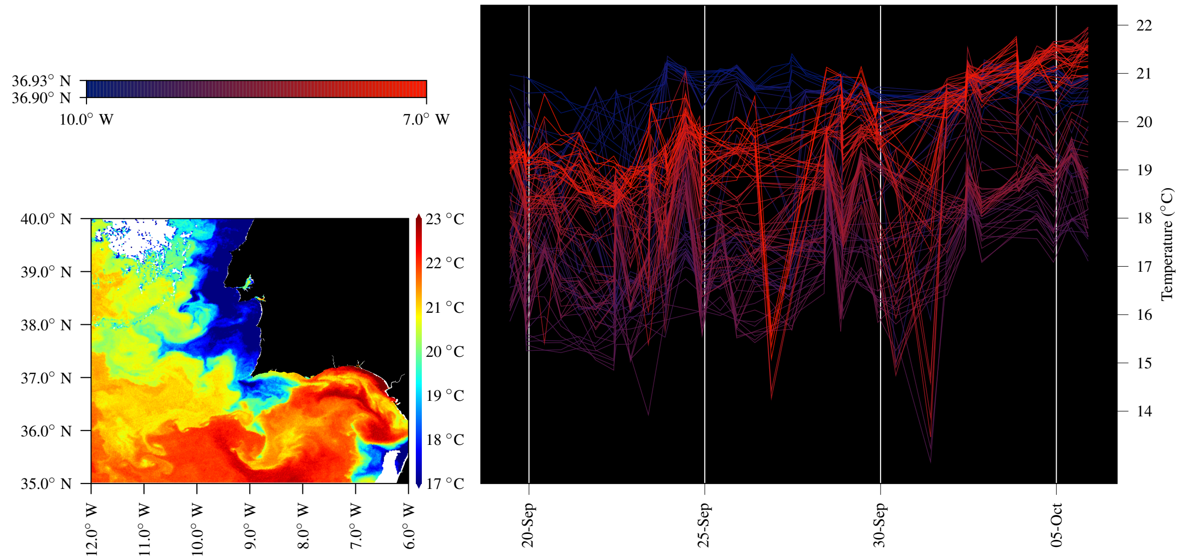

Figure 4: Event of 5 October 2017. Top left: reference map for the plot; bottom left: SST map at the date of the event; right: generated spaghetti plot.

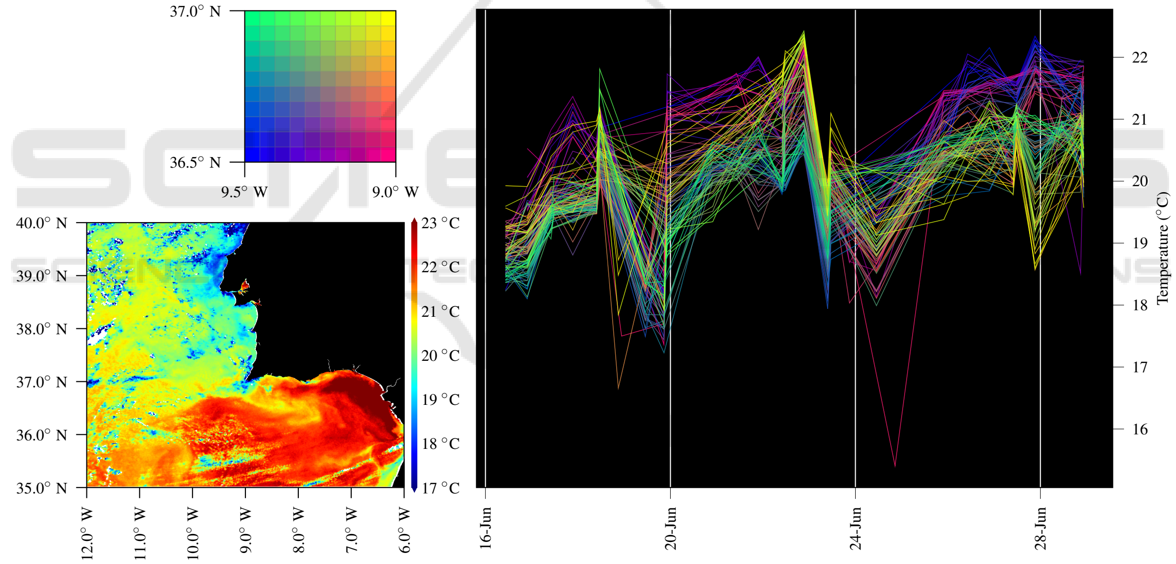

Figure 5: No event in late June 2017. Top left: reference map for the plot; bottom left: SST map at the date of the event; right: generated spaghetti plot.

that period, and this can be associated with the relative spaghetti plot, where large decays or increases in temperature cannot be identified (i.e. the gradients of the plots are not giving a clear indication of specific different trends among the regions, also considering existing outliers).

As it can be seen from this preliminary results different patterns can be identified for several events. In more detail "flat" patterns of temperatures can be seen for the situations where no particular event happens, where distinct decays/increases of temperature while moving from specific regions to others can be identified in the charts related to specific events.

4 CONCLUSIONS

The preliminary results of this ongoing study are promising and show possible patterns of differentiation among different mesoscale events occurring in the analyzed area. Experts initially supported the primary analysis, identifying possible events occurring at specific dates within the data set range we used. Following this, we applied our method to different time intervals before the events specified to understand whether a specific dynamic pattern could be associated with them. Moreover, we also performed the same analysis on periods where no events were identified to analyze a different specific pattern relevant to a "no-event" period.

Future work will be centred on the extension of this preliminary results on pattern identification to more distinct and expanded events, with the goal to define a more complete collection of patterns.

Another focus will be to tackle the implementation of higher-level stages, i.e. those concerning to the classification task. In particular, the feature extraction stage will be refined by selecting the features typologies returning the best possible discriminating power. Also, different classifiers will be devised to identify the most suitable ones for the purpose of this analysis. These latter activities are the foundation for the next step of automatic classification of massive datasets without the need for expert feedback.

The test and validation of the proposed algorithm is carried out and will continue as part of the activities of the EU H2020 project NAUTILOS (Pieri, 2020; Pieri et al., 2021).

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