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Reprint Series **CMRE-PR-2019-110**

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June 2019

Originally published in:

Proceedings of SPIE Ocean Sensing and Monitoring VII, vol. 9459, May 2015, doi: doi.org/10.1117/12.2177044

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Identification of sea surface temperature (SST) variability areas through a statistical approach using remote sensing and numerical ocean model data

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ABSTRACT

An understanding of environmental variability (stability/instability) is important to support operational planning of expeditionary warfare and littoral operations, as well as for preparing the Recognized Environmental Picture (REP). Specifically, the identification of environmentally stable/unstable areas helps the planning of maritime operations, increasing their likelihood of success. The purpose of the paper is to describe a methodology to form and interpret an initial spatial-temporal variability characterization of maritime areas from Remote Sensing (RS) and Numerical Ocean Model (NOM) data. As a case study, the analysis of the sea surface temperature (SST) in the Black Sea from historical time-series of RS imagery and NOM data is considered. The results of the analysis are validated with *in situ* measurements from moorings. Identification of gaps of geospatial information is also done in this study. The analysis is focused on monthly spatial-temporal variability of the SST, generating stability maps displaying the geospatial distribution of environmentally stable/unstable areas along a year. The results show how the proposed methodology captures the temporal variability of the SST in the Black Sea, being compared with *in situ* measurements, and provides useful information for the identification of environmentally stable/unstable areas. The results show a general agreement in the variability with both RS and NOM data, when RS imagery may be used for the present analysis, i.e. when low cloud coverage is given. This paper demonstrates that when RS imagery gaps are not negligible (e.g. due to high cloud occurrence in winter season), these gaps could be filled with NOM data.

Keywords: METOC variability, stability, instability, sea surface temperature, remote sensing, numerical ocean model, statistical analysis, Black Sea

1. INTRODUCTION

The identification of meteorological and oceanographic (METOC) stable/unstable areas in a given area of interest (AOI) supports the operational planning of expeditionary warfare and littoral operations, as well as the preparation of the Recognized Environmental Picture (REP). Consequently, the planning of maritime operations increases its likelihood of success whether uncertainty and variability can be managed. Therefore, a statistically based methodology is presented in this paper to provide a quick assessment of the stability given an AOI.

As an example, the confidence on the path planning performance of autonomous underwater vehicles (AUVs) may decrease due to the variability caused by ocean currents, as shown in

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Hollinger2013.[1] Its authors describe a statistical methodology through machine learning to overcome this problem. Besides, environmental stability can be managed from another point of view. Specifically, the areas where AUVs operate can be characterized by their stability in order to avoid hazardous (i.e. unstable) regions if needed. An example of spatial characterization of stability will be presented in this paper.

Through the analysis of satellite products, such as ocean chlorophyll or ocean optics, other researchers focused the study of the spatio-temporal variability to find the best location for *in situ* sampling instruments, such as moorings or buoys. Usually, these instruments require low variability, so stable areas should be found as published in Pennucci2012.[2] Moreover, the identification of areas with low variability was also studied by Fougnie2002[3] and Fougnie2010,[4] so that space sensors could be calibrated in-flight. A total of fifteen areas were found and their marine and atmospheric properties were characterized.

Acoustical operations is another application where the characterization of the environmental stability is relevant. Indeed, acoustical stability affects to the development of sonar tests, as studied by Hjelmervik2012.[5] The deployment of sonar instruments should be carried out in suitable locations, where stable acoustical conditions (i.e. low variability) are given.

Summarizing, the characterization of marine areas in terms of stability for specific METOC variables and different purposes has been the subject of several studies. This paper represents a first step toward a general methodology able to define the spatial and temporal stability of any parameter of naval importance (PNI). We apply a simple statistical method to historical time-series from remote sensing (RS) and numerical ocean model (NOM) data to provide fast and concise environmental information. As example of application, the study is focused on the sea surface temperature (SST) in the Black Sea. The resulting RS and NOM stability maps are compared in order to verify the degree of similarity. Finally, the outcome of the proposed statistically-based methodology from both data sources is validated with *in situ* measurements, yielding successful results.

The paper is structured as follows. Section 2 describes the NOM an RS data sets; namely, the parameter under study (SST) and the area of interest are explained. Section 3 describes the proposed methodology. Next, the results are shown in Section 4 in addition to a further validation with *in situ* measurements. To conclude, Section 5 presents the achievements and future work.

2. METOC INFORMATION AND SOURCES

As an example of identification of METOC stability areas, we focused on the SST METOC variable. Since this METOC variable may affect to a variable degree the success of naval operations, such as submarine warfare, mine warfare or amphibious and diving operations and it is widely available from both RS, NOM and *in situ* sources, it is selected as PNI in our case study.

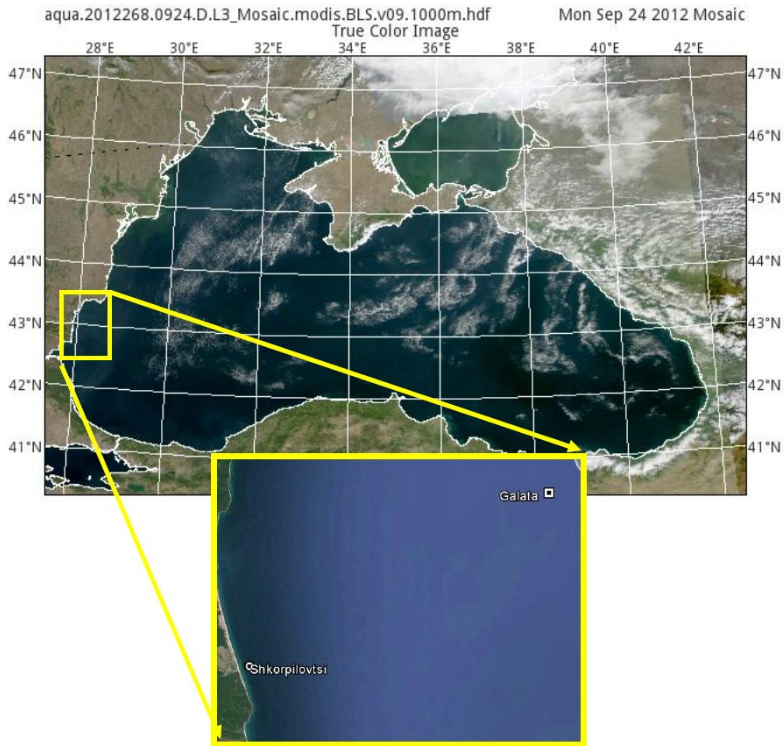
As an example of AOI, the Black Sea is considered. RS and NOM data-sets present simultaneous public availability in this AOI, i.e. SST has similar spatial and temporal resolution in both data-sets. The predicted region is delimited by the latitudes 40.86°N and 46.68°N, and the longitudes 27.41°E and 41.89°E in both NOM and RS. Figure 1 illustrates the selected AOI by RS imagery, as well as the location of moorings from where used *in situ* measurements were collected. The proposed methodology uses historical time-series of the SST from NOM and RS databases given a time frame. Besides, the validation is done by means of *in situ* measurements. As follows, *in situ* measurements, RS and NOM data-sets are presented.

- **Remote Sensing** (RS) data-set comes from satellite imagery. The measurements were captured by the Moderate-Resolution Imaging Spectroradiometer[6] (MODIS) onboard the EOS-Aqua platform, a satellite from NASA. Besides, MODIS captures the entire Earth in a maximum of 2 days through a swath width of 2330 km. The level-2 MODIS products (at 1 km of spatial resolution) is enhanced with interpolation to fill up the missing area owing to orbit transition and other environmental factors, achieving a final spatial resolution of 4 km (level-3 Mapped products). For the implementation of the proposed methodology, MODIS night SST data are used.

- **Numerical Ocean Model** (NOM) database is provided by the Marine Hydrophysical Institute (MHI) in Sevastopol through MyOcean.[7] The MHI model is a primitive equation eddy-resolving circulation model described in Demyshev1992.[8] The outputs include Sea Surface Height (SSH) above the mean sea level and three-dimensional fields of current velocity, temperature and salinity. Fields are distributed under the sea surface at 38 irregularly spaced horizontal levels, starting at 2.5 m depth and ending at 2100 m depth. The model grid has a latitude resolution of 0.044°($\sim$ 4.9 km) and a longitude resolution of 0.061°($\sim$ 5.5 km), equivalent to an average spatial resolution of approximately 5 km. The output files from the model contain instantaneous daily fields of the cited variables at midnight (00:00:00 UTC). The atmospheric forcing fields required to drive the simulations are calculated from the 12-hour ERA-interim reanalysis of atmospheric fields produced by the European Centre for Medium-Range Weather Forecasts[9] (ECMWF). The system assimilates the SST, the sea surface height (SSH) and the annual-mean profiles of temperature and salinity based on cruise observations. SST data from the Ocean and Sea Ice Thematic Assembly Center[10] (OSI TAC) were used. Aside, since SST is studied, the shallowest model level was considered, placed at 2.5 m depth. Additionally, the next model level, placed at 5 m depth, is considered for the validation procedure with the Galata mooring, described below. The temperature measurements collected from this mooring are also located at 5 m depth and provided by MyOcean.

- ***In situ* measurements** collected by Galata and Shkorpilovtsi moorings and provided through MyOcean.[7] These moorings provide temperature measurements to study the temporal variability at specific depths in different locations in the Black Sea. Galata mooring is located off-shore, at latitude 43.04°N and longitude 28.19°E (see Figure 1), and provides its measurements at 5 meters depth. Shkorpilovtsi mooring is located on the coast, at latitude 42.9580°N and longitude 27.899°E (see Figure 1), and provides water temperature measurements at 3 meters depth. The available sampling period for the Galata mooring covers from January 1^{st}, 2012, until August 31^{st}, 2012. For the Shkorpilovtsi mooring, the time frame extends from August 1^{st}, 2012, till the December 31^{st}, 2012. This data is used in Section 4.2 to validate the results obtained by the proposed statistically-based methodology to provide stable/unstable areas.

  From the introduced RS and NOM data-sets, similar spatial resolutions are observed. Specifically, 4 km for RS data-set and approximately 5 km for NOM data-set. With regard to the temporal resolution, NOM yields a daily forecast at midnight. Likewise, RS offers daily imagery close to midnight. The measurements of Galata and Shkorpilovtsi moorings correspond to mean daily values. Consequently, the results among them can be compared.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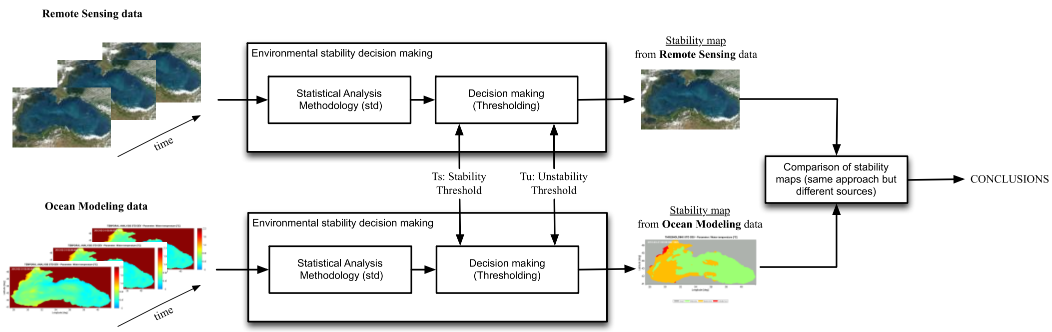


Figure 2: Flowchart of the methodology using RS and NOM data-sets

- The second step consists in a re-projection of RS data (i.e. Lambert projection, see Pennucci2012[2]) and in a data interpolation of the RS data to obtain images with the same (similar) spatial resolution of NOM.
- At the third stage, RS and NOM data are processed under a **historical time-series analysis**, which is based on the temporal variability of the SST. Generally speaking, the temporal stability analysis examines the variability at a spatial location considering its evolution along time. In particular, the SST measurements at a specific location during a chosen period are stored; then, the statistical *standard deviation* (stddev) function computes the variation of these measurements around their average value. This process is repeated for all spatial locations of the selected AOI. Thus, a map of standard deviation values is yielded, called **SD map**.

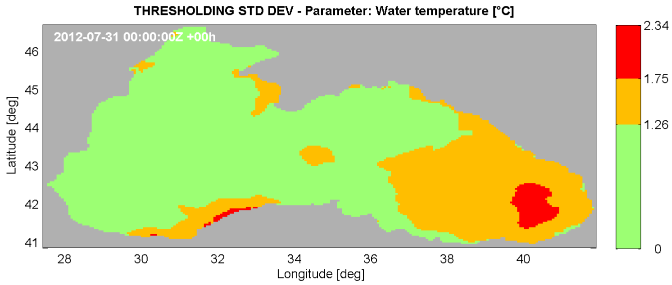
Once the data from RS and NOM has been processed, the environmental stability, marginality and instability have to be identified. This is obtained by means of the **generation of stability maps**. The stability maps are numerical representations of data that, in our case, define three delimited areas. Stable, marginal and unstable areas are determined according to two thresholds. These thresholds are described by the variables T_s (stability threshold) and T_i (instability threshold). Namely, the stable, marginal and unstable areas are defined as follows,

$$x \in \begin{cases} \text{Stable area} & \text{if } x \leq T_s \\ \text{Marginal area} & \text{if } T_s < x \leq T_i \\ \text{Unstable area} & \text{if } x > T_i, \end{cases} \tag{1}$$

where x represents the value of a METOC variable (SST in our case) at a given time and position in the AOI.

The definition of stability depends on the specific application and on the AOI. One application may require that the area remains stable within say $1°C$, another one within $2°C$. And for the same kind of application, the SD range defining stability in Caribbean Sea may not fit with the Baltic Sea's or the Sargasso Sea's one. As a result, the values of low variability ($x \leq T_s$) define the stable area in this paper. The values between the two thresholds belong to the marginal area. And the unstable area comprehends the values above T_i.

In order to check the results of the proposed methodology, stability maps are generated by applying the T_s and T_i thresholds to the SD maps. Effectiveness is evaluated through a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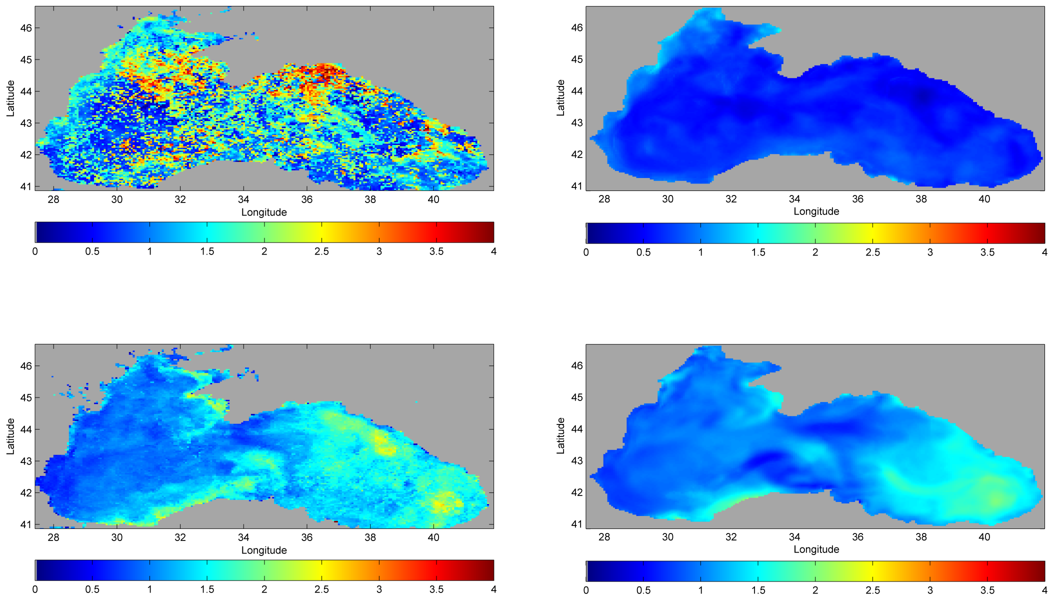
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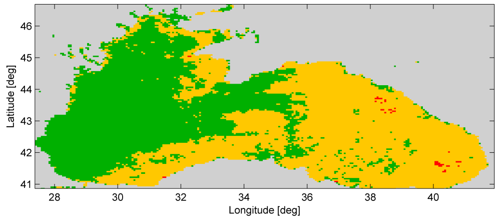
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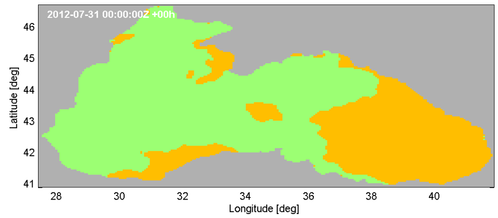
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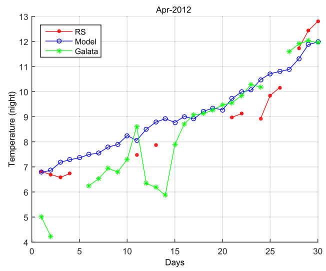

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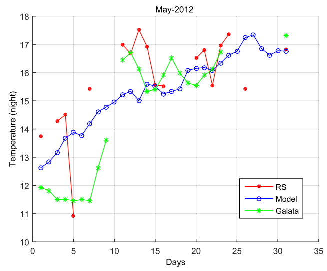

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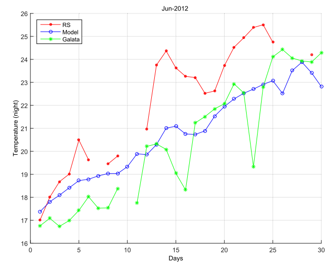

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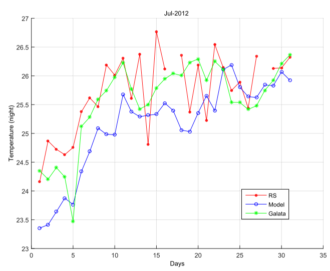

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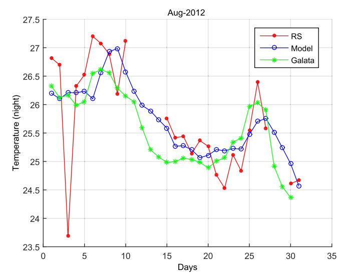
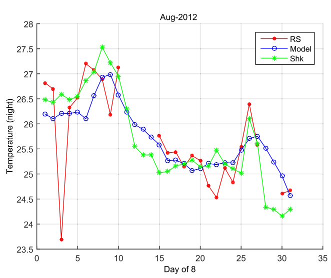


(e) August 2012

Figure 6: SST comparison among RS, NOM (5-meters-depth) and *in situ* measurements (5-meters-depth) at the Galata location.



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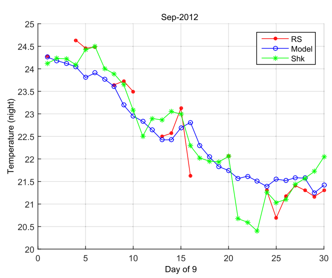

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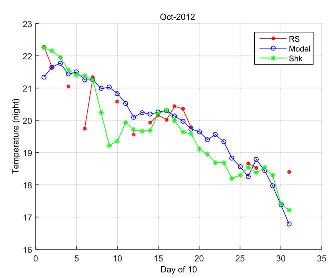

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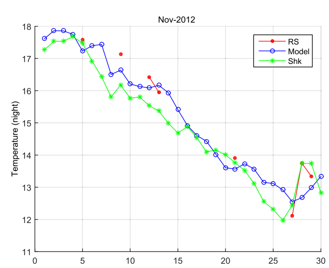
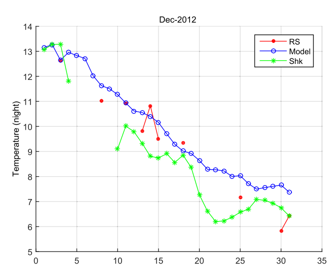
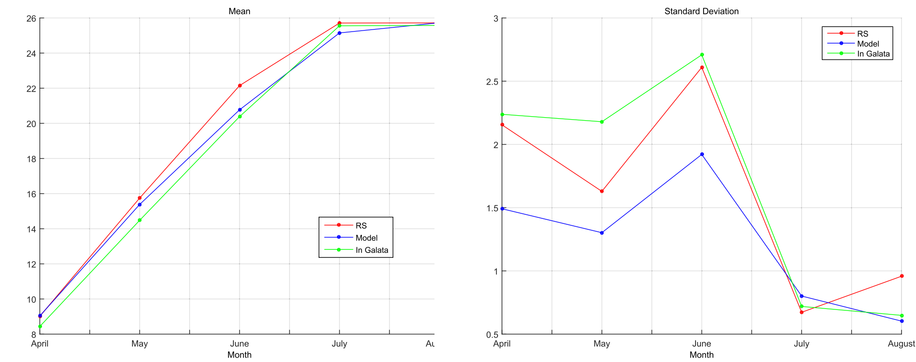


(d) November 2012



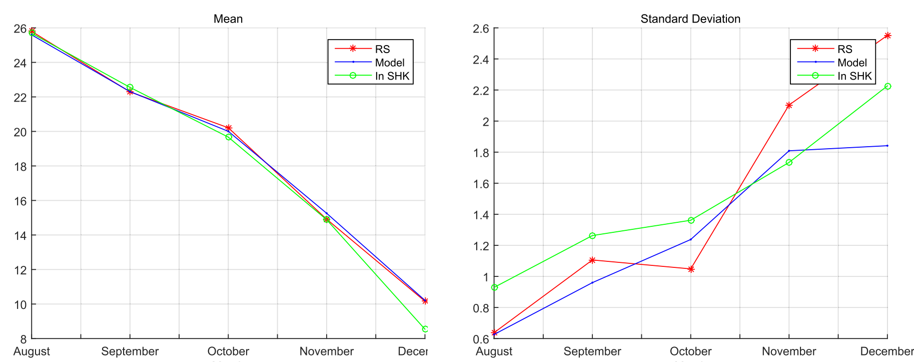
(e) December 2012

Figure 7: SST comparison among RS, NOM (2.5-meters-depth) and *in situ* measurements (3-meters-depth) at the Shkorpilovtsi location.



(a) Monthly average (b) Monthly standard deviation

Figure 8: Monthly time evolution of SST at the Galata location for RS, NOM (5-meters-depth) and *in situ* measurements (5-meters-depth).



(a) Monthly average (b) Monthly standard deviation

Figure 9: Monthly time evolution of SST at the Shkorpilovtsi location for RS, NOM (2.5-meters-depth) and *in situ* measurements (3-meters-depth).

Table 2: Summary of validation results using the Galata and Shkorpilovtsi moorings. *Days* indicated the number of days with available data. *%* resumes the percentage of availability. And *StdDev* represents the standard deviation of the daily SST measurements computed for the current month.

		Galata mooring			RS			NOM			RS Error	NOM Error
Month	Total days	Days	%	StdDev	Days	%	StdDev	Days	%	StdDev	Absolute error	Absolute error
April	30	24	80%	2,24	14	47%	2,15	30	100%	1,49	0,08	0,75
May	31	23	74%	2,18	17	55%	1,63	31	100%	1,30	0,55	0,88
June	30	29	97%	2,71	23	77%	2,61	30	100%	1,92	0,10	0,79
July	31	31	100%	0,72	29	94%	0,67	31	100%	0,80	0,05	-0,08
August	31	31	100%	0,65	25	81%	0,96	31	100%	0,60	-0,31	0,05

		Shkorpilovtsi mooring			RS			NOM			RS Error	NOM Error
Month	Total days	Days	%	StdDev	Days	%	StdDev	Days	%	StdDev	Absolute error	Absolute error
August	31	31	100%	0,93	25	81%	0,64	31	100%	0,63	0,29	0,30
September	30	30	100%	1,26	16	53%	1,11	30	100%	0,96	0,16	0,30
October	31	31	100%	1,36	16	52%	1,05	31	100%	1,24	0,31	0,12
November	30	30	100%	1,73	8	27%	2,10	30	100%	1,81	-0,37	-0,07
December	31	26	84%	2,23	8	26%	2,55	31	100%	1,84	-0,32	0,39

Finally, Table 2 summarizes the absolute error produced from RS and NOM referred to the *in situ* measurements from the moorings at the given depths. As can be observed, the error committed between NOM data and the *in situ* measurements is smaller in accordance with the number of *in situ* measurements; namely, a larger number of samples implies a smaller absolute error. In the case of RS and the *in situ* measurements, two main factors are involved: the number of days with available images and the cloud occurrence in each image. Nevertheless, the error increases when the availability of data decreases.

4.3 Analysis of limitations and proposed solutions

According to the previous research, two main limitations are found. First, the availability of RS data is not always possible. Due to the appearance of clouds, satellite imagery is limited, so that the identification of the stability areas sometimes becomes impossible. In these cases, imagery gaps can be substituted by NOM data in order to reduce the error. And second, the moorings represent a good solution to study the variability of the SST. However, the mooring measurements are sampled at specific locations and may not be representative of the larger scale variability; oppose to RS and NOM data, which gives large scale variability. So, since it has been proven that the proposed methodology is able to fit the results provided by moorings (*in situ* measurements) when using RS and/or NOM data, it is proposed to use the maps provided by the statistically-based methodology for the SST analysis in a large area as the Black Sea.

5. CONCLUSIONS AND FURTHER WORK

This paper provides a statistical methodology to characterize the spatial and temporal variability of maritime areas from RS and NOM data sources, and identify the stable, marginal and unstable areas by means of stability maps. These stability maps represent the main output from this methodology. Namely, they are the result of applying two given thresholds to the standard deviation of the temporal evolution of a PNI in a chosen AOI. For demonstration purposes, SST and Black Sea have been considered as PNI and AOI, respectively. The traditional statistical analysis of historical time-series may be considered for studying the stability analysis. In addition, the information given by the stability maps should be considered for operations or trials (e.g. sonar or sea glider operations).

The results yielded by the proposed methodology from the RS and NOM data were compared with *in situ* measurements, confirming that both information sources provide an accurate representation of the reality. From this results, main conclusions are drawn. First, the identification of METOC stability areas approach may be carried out by using RS data sources as well as NOM data sources; and, besides, they present a similar behavior. Secondly, many areas of the world ocean may be frequently cloudy for quite long periods. Therefore, satellite data gaps may appear in RS imagery. Due to this fact, the results given by RS and NOM data may differ in certain periods. RS and NOM data agree in periods, when cloudy days are less numerous. NOM data might be used to complete information gaps from RS data in time frames with higher cloud coverage.

Another key point resides in the definition of stability. The delimitation of stable, marginal and unstable areas depends on the user requirements (which may vary from application to application), so the final user would choose tailored thresholds. In addition, the time window also changes the concept of stability, given the possibility to provide short -and middle- term temporal analysis of stability in selected AOIs. Since operators of the system being developed will be allowed to change the stability/instability thresholds as well as areas and time frames of interest, this provides a very powerful tool for decision makers. In real applications, the temporal frame of datasets will be extended to several years (ideally, the last 30 ones) in order to take into account also inter-annual variations and extremes of METOC parameters.

Finally, future work is oriented to the study of a new methodology based on this paper. Specifically, a maximum covariance analysis (MCA) would replace the current standard deviation approach. Then, both methodologies would be compared. MCA offers a complex procedure so that the processing time will be apparently higher. Nevertheless, MCA would solve part the problem of satellite imagery gaps as shown in Alvarez2011.[11]

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Document Data Sheet

Security Classification		Project No.
Document Serial No. CMRE-PR-2019-110	Date of Issue June 2019	Total Pages 13 pp.

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Identification of sea surface temperature (SST) variability areas through a statistical approach using remote sensing and numerical ocean model data

Abstract

An understanding of environmental variability (stability/instability) is important to support operational planning of expeditionary warfare and littoral operations, as well as for preparing the Recognized Environmental Picture (REP). Specifically, the identification of environmentally stable/unstable areas helps the planning of maritime operations, increasing their likelihood of success. The purpose of the paper is to describe a methodology to form and interpret an initial spatial-temporal variability characterization of maritime areas from Remote Sensing (RS) and Numerical Ocean Model (NOM) data. As a case study, the analysis of the sea surface tem- perature (SST) in the Black Sea from historical time-series of RS imagery and NOM data is considered. The results of the analysis are validated with in situ measurements from moorings. Identification of gaps of geospatial information is also done in this study. The analysis is focused on monthly spatial-temporal variability of the SST, generating stability maps displaying the geospatial distribution of environmentally stable/unstable areas along a year. The results show how the proposed methodology captures the temporal variability of the SST in the Black Sea, being compared with in situ measurements, and provides useful information for the identification of environmentally stable/unstable areas. The results show a general agreement in the variability with both RS and NOM data, when RS imagery may be used for the present analysis, i.e. when low cloud coverage is given. This paper demonstrates that when RS imagery gaps are not negligible (e.g. due to high cloud occurrence in winter season), these gaps could be filled with NOM data.

Keywords

METOC variability, stability, instability, sea surface temperature, remote sensing, numerical ocean model, statistical analysis, Black Sea

Issuing Organization

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