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Fourier-based optimization for multivariate spatial-temporal regression model in chlorophyll-a presence prediction around Galápagos Islands

(Optimización del modelo de regresión espacio-temporal multivariado basado en Fourier para la predicción de la presencia de la clorofila-a alrededor de las Islas Galápagos)

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Abstract: Chlorophyll-a (Chl-a) is an indicator of phytoplankton biomass, which can be used to predict the presence of fish in the ocean. By predicting the Chl-a with sufficient time, this data can be used to better plan naval operations that combat illegal, unreported and unregulated fishing by increasing surveillance of the identified areas where the greatest fishing activity would take place. In this work, a new technique is proposed, based on the application of the discrete Fourier transform theory to develop multivariate spatial-temporal regression model, which considers physical and biogeochemical ocean variables to predict the presence of Chlorophyll-a around Galápagos Islands. This work considers open access data taken from the Copernicus space program, used in the European Union.

Keywords: Spatial temporal regression, Illegal fishing prevention, Discrete Fourier transform, biogeochemical ocean variables.

Resumen: La Clorofila-a es un indicador de la biomasa del fitoplancton, que puede ser utilizado para predecir la presencia de peces en el océano. Al predecir la Chl-a con suficiente tiempo, se puede utilizar en la planificación de las operaciones navales que combaten la pesca ilegal, no regulada y no reglamentada, por cuanto se identifica el lugar donde existirá mayor actividad pesquera, para incrementar su vigilancia. En este trabajo, proponemos una novel técnica basada en la aplicación de la teoría de la transformada discreta de Fourier, al modelo de regresión multivariable espacio-temporal desarrollado, que considera las variables físicas y biogeoquímicas del océano para la predicción de la clorofila-a, alrededor de las Islas Galápagos. Este trabajo considera datos de acceso libre del programa espacial Copérnico de la Unión Europea.

Palabras claves: Regresión espacio temporal, Prevención de la pesca ilegal, Transformada discreta de Fourier, Variables biogeoquímicas del océano.

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1. INTRODUCTION

The increase in the world population and the demand for fish protein are causing pressure on the oceans [1], depleting their resources, mainly because the most populous countries and some developed countries fail to meet their fishing quota catches in their seas. They are forced to cross borders and find shoals offshore or in other countries' territorial waters. In this case, it is a real challenge to early detect these vessels if their vessel monitoring systems (VMS) are disconnected, or if the affected country does not have the support of satellite surveillance or the permanent support of air-maritime exploration aircrafts.

It is essential to mention that illegal, unreported and unregulated fishing (IUU) is a severe global problem that destroys marine ecosystems and that will also bring about the collapse of the fishing sector, threaten the diet of the population and cause poverty in the societies depending on seafood and legal fishing as their way of life [2]. Unfortunately, illegal fishing acts involve from artisanal fishermen to large fleets with links to criminal organizations, as IUU fishing turns out to be a good option to maximize gains, with low operating costs, aggravating this situation [3].

Commercial exploitation of fish in the Galapagos Islands began in the mid-1900s, with a catch estimation, from 1950 to 2010, of 797,000 tons, of which 80% represented by the industrial tuna catch. It is also worrying that shark finning practices have increased since the 1980s and continue to be carried out even within the Galapagos Marine Reserve, as evidenced by the capture of the Chinese fishing vessel Fu Yuan Yu Leng 999, carrying about 300 tons [4]. This event, which is not isolated, highlights the severe problem of IUU fishing around the marine protected areas of Galapagos Islands. To further emphasize the need to contribute to the protection of the marine species of the islands, the international community is on alert for news presented during July 2020, which reported that more than 260 ships are currently under international waters on the outskirts of the Exclusive Economic Zone (EEZ) and warns that the aggressiveness of this vast fleet is putting at risk the delicate marine ecosystem and the natural balance of species in Galapagos, [4].

Additionally, illegal, unreported and unregulated fishing is considered a stress factor for the ocean, due to the over-fishing that occurs, which is influencing in the ecosystem, by changing the abundance of fish and the performance of other organisms, [5]. This leads to changes in predator-prey dynamics and competition between species and intra-species. This factor has a negative impact on marine life, which directly affects sustainable development, being necessary to formulate policies that allow managing the multiple stress factors that the ocean has nowadays [4].

Even the "Artisanal Fishing Community of Galapagos" is concerned about the protection of fishery resources, as many of them agree that the country should take action to try to curb illegal fishing; however, despite being aware of the impact that large-scale fishing has on the marine ecosystem, they do not agree with the imposition of fishing quotas or the implementation of strict regulatory rules to control fishing [6]. For this purpose, Art. 61 of the United Nations Convention on the Law of the Sea (UNCLOS) establishes that the coastal State has the right to set fish catch quotas in its exclusive economic zone, as it is its duty, together with the regional fisheries management organizations, to take measures that seek to maintain or restore fish stocks for the conservation of the marine ecosystem. [7].

This paper is organized as follows. In Section 2, a short overview of the current literature concerning the use of the Fourier series theory applied to oceanography and the use of machine learning applied to the prediction of chlorophyll is provided. In Section 3 is presented the methodology which includes the procedures, description of the study area and the data used in the research. Then, in Section 4, the results are explained and discussed. Finally in Section 5, a conclusion is provided

2. RELATED WORK

The constant formation process of the islands, coupled with the influence of several ocean currents, positively affects biodiversity, producing and distributing nutrients, plankton and krill throughout this geographical area. Among the prevailing currents, there is the cold Humboldt, the warm El Niño and the Cronwell counter current, [8]. Another aspect to consider is the behavior of the study area's climate, a region where there are only two types of season, the warm season from December to May and the cold season, from June to November. [9]

The prediction model for the concentration of Chlorophyll-a developed in [10], had the main motivation to design a model based on multivariate linear regression, which allows forecasting the possible areas of illegal fishing, so that the naval forces can plan with enough time the naval operations that fight the IUU.

In oceanography, spectral analysis of temporal series can be done by making use of the Fourier Series method, since it can research the interrelation between observed dynamic processes. Any periodic function following certain requirements, mainly convergence, can be represented as a series of complex exponential functions, allowing the transformation of a time signal on the frequency domain, with the objective of analyzing its frequency content in terms of amplitude and phase, because the Fourier coefficients of the transformed function represent the contribution of each sine and cosine function at a given frequency [11].

The concept of frequency spectrum was introduced in the field of analysis of oceanographic temporal series between late 1940s and early 1950s. It was first used in the study of oceanic wind waves around 1950. During the last five decades, its use has been quickly developed and spread, despite the fact that it has shown some drawbacks for the analysis of temporal series observed in nature, as most applications use real values, while the Fourier transform uses complex arithmetic, transforming a sequence of real data of the time domain in a sequence of complex numbers in the domain of frequency [11].

The discrete Fourier transform (DFT), is the discrete version of the Fourier transform (FT). This technique allows doing the spectral analysis of signals and can be used in various areas like science and engineering. A data series can be considered as a linear combination of frequency components, where the time domain can be represented as the sum of the frequency components, and so all waveforms can be reconstructed with an infinite number of sinusoids of various frequencies. In practice, only a finite number of sinusoids is used to reconstruct the wave [12].

In Fourier decomposition, any N points of signal can be decomposed into N+2 signals, half of them in sine waves and the others in cosine waves where the lowest frequency corresponds to the DC signal. It is possible to create any waveform from superimposed sinusoids. Fourier decomposition provides a direct analysis of the waveform composition, including information about the frequency, phase and amplitude of its components [13]. The variables related with the ocean constantly oscillate their values and can be considered as signals that can be decomposed into its components, in order to analyze their behavior depending on the seasonality where they are found.

It is often difficult to analyze biological signals due to their non-linear and non-stationary characteristics. To solve this problem, time-frequency decomposition methods are used to analyze the very slight changes that exist between these signals and that may be related with an external phenomenon. If a signal is uniformly sampled and its characteristics change slowly with time, it can be considered that the seasonality is maintained during this time interval, and then the Fourier transform can be applied to this part of the signal. [14].

3. METHODOLOGY

3.1 Methods and procedures

A prediction model with enough anticipation can help to plan better and quicker maritime surveillance routes, in order to ensure an early vessel detection. The presence of Chlorophyll-a in combination with relevant physical, chemical, and biological variables at a certain geographical point can be thought as a multivariate spatial-temporal series, in which the Chlorophyll-a ([Chl-a]) plays the role of dependent variable, which is interesting to predict because it is used as an indicator of phytoplankton biomass [15]. Likewise, multivariate spatial-temporal regression can be used to estimate not only the functional model, but also the temporal component for each predictor. Multivariate spatial-temporal regression is simply a multivariate regression in which the spatial-temporal component is explicitly taken into account via suitable data transformations. In its simplest form, it consists of adding suitable lagged data to the original ones so that the temporal history of an element plays a role in the regression. In [10] it is proven that lagged data improves the Chlorophyll-a prediction, but some limitations could be appreciated, as the data used for testing consists of one month and there is no bathymetric study that allows to specify the study area. The use of data from 01-December-2020 to 30-November-2021 makes it possible to take into account the seasonality, which also influences the Chlorophyll-a behavior. In addition, a bathymetric study around the Galápagos Islands was included in order to select the study area.

Also, we consider open access data taken from the Copernicus space program to predict Chlorophyll-a presence surrounding Galapagos Islands. The main objective is to optimize the prediction of chlorophyll levels, that is conducted by using the multivariate spatial-temporal regression technique, for which the discrete Fourier transform is applied in order to first determine the behavior of the physical, chemical and biological variables (independent variables), in relation to the dependent variable (Chl-a), to subsequently optimize the model by restructuring the dataset, taking into account the lag (delay) between the variables and the Chl-a.

In order to compare the variables, a normalization of the data series is performed, to subsequently apply a decomposition of the data series applying the one-dimensional discrete Fourier transform. Next, the data series is recomposed again by applying the inverse discrete Fourier transform in n-point using the first 15 main frequencies. In this way, the noise that can occur in the data series is eliminated, and the measurement of the lag between variables is possible. Once the lag is determined, the dataset is finally reconstructed, considering the lag between different variables. Although the method is used to determine the variables which are ahead and behind in relation to the chlorophyll, in the prediction model, only those variables which are ahead of chlorophyll are taken into account, as their variation affects the Chl-a level. With the reconstructed dataset, the multivariate spatial-temporal regression is applied, predicting the chlorophyll, trying to improve the correlation between the calculated value and the real value of Chl-a. Finally, up to 10-days lag of each variable are considered, and the dataset is restructured again to create a new regression model, trying to further improve the correlation between the calculated value and the real value of Chl-a. The analysis is conducted in the 2090 geographical points that compose the dataset, and in the period of one year. Half of the dataset is used to train the model and the other half, to test the model.

3.1.1 Optimization Model Conceptualization

DFT and IDF. A periodic time domain sequence $x(n)$, with period N, can be expressed as summation of a set of N harmonically related complex sinusoids with coefficients $X(k)$ as

$$x(n) = \sum_{K=0}^{N-1} X(k) e^{j\frac{-2\pi}{N}nk}, n = 0,1,\dots,N-1 \quad (1)$$

Applying Euler's formula, we can express this equation in terms of sines and cosines:

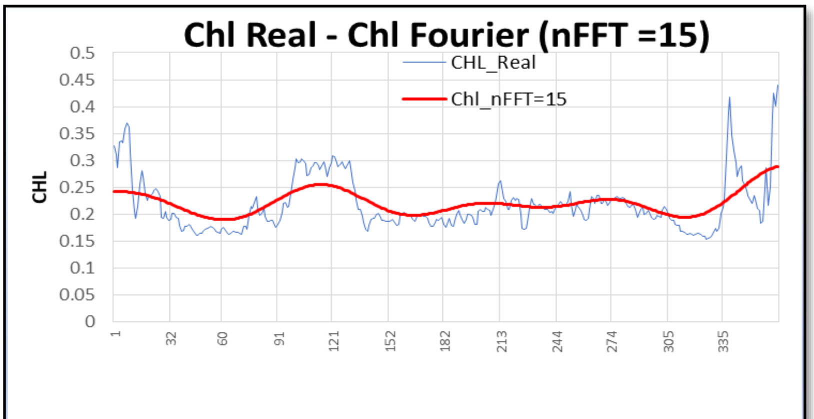
$$x(n) = \sum_{K=0}^{N-1} x_n \cdot \left[cos\left(\frac{2\pi}{N}kn\right) - i.sin\left(\frac{2\pi}{N}kn\right)\right] \quad (2)$$

Discrete Fourier transforms (DFT) are extremely useful because they indicate the periodicities in the data of a signal, as well as the contribution of each of its periodic components, and can be used on samples containing certain numbers of points. In our case, the analyzed data consist on daily samples of physical, chemical and biological values, represented as a data series, to which we can apply DFT, determining its components.

After applying DFT, it has been chosen to reconstruct the data series using exclusively its first 15 components of the data series, this way it is possible to remove noise and understand the behavior of Chlorophyll in relation with other variables. For this effect, the Inverse Discrete Fourier Transform (IDFT) is used, serving as pass band filter, where the first few components are selected to reconstruct the signal in N-dimensional complex vectors.

$$x(n) = \frac{1}{N}\sum_{K=0}^{N-1} X(k)e^{j\frac{2\pi}{N}nk}, n = 0,1,\ldots,N-1 \quad (3)$$

The result obtained after applying the DFT and then the IDFT can be observed in the Figure 1.



* Comparison of real Chl-a data series vs Chl-a reconstructed with 15 components

Figure 1. Chl real vs Chl Fourier (nFFT=15).

As it can be observed in Figure 3, the CHL, reconstructed with 15 components, shows the tendency of the variables observed in the analysis. A previous analysis helped to identify that 15 components adequately reconstruct the signal. This transformation must be performed for every variable and for every one of the 2091 geographical points in the dataset, per day.

Afterwards, a comparison between the different variables is performed, relative to the CHL, in order to determine the phase lag between these waves. Due to the fact that the analyzed waves use different units and magnitudes, it is first necessary to normalize the datasets.

The phase angles are calculated from a one cycle discrete Fourier transform (DFT), based on phase to phase between data series Chl-a and each variables in all 2091 points. For this calculation, specialized Python libraries of signal processing have been used. This process is used to increase the correlation in the dataset used to design the multivariate spatial-temporal regression model. It is estimated that if the waves are in phase, the Chlorophyll prediction must improve, being this the hypothesis of our study. In Figure 2, you can see an example of the gap between the behavior of the O2 and Chl-a data series at a specific point in the dataset.

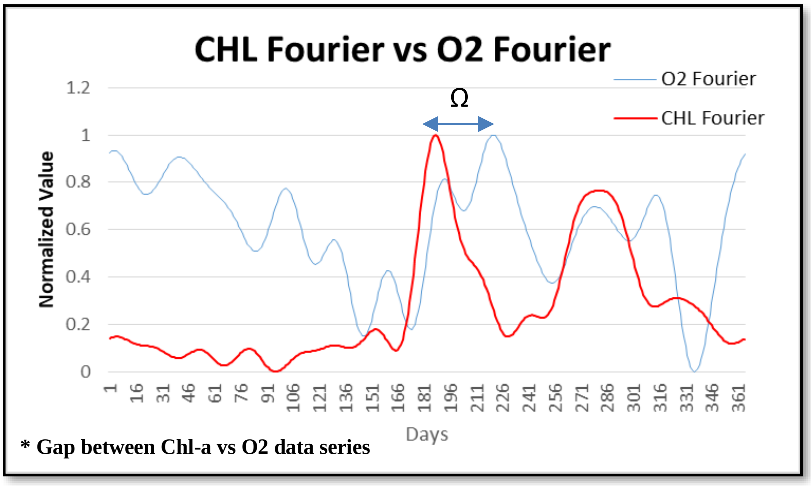


Figure 2. Example of the gap between the O2 and Chl-a data series at specific point.

3.2 Study area

The Galápagos Islands located 965 km westward of mainland Ecuador in the eastern Pacific Ocean, have had a continuous evolving process since Cretaceous, for more than 20 million years ago (m.a.), and are the result of the ongoing interaction between the Galapagos hotspot located on the Isabela Island and the Cocos Nazca Plates (CN) [16]. This interaction has allowed the formation of the islands' platform composed of 13 large islands, 9 small islands, and 107 islets, as well as the Carnegie and Coco's submarine volcanic ridges, [17].

The hot spot of the islands' platform is under Isabel Island, considered the most active of the archipelago [16], having 190 km from this point to the CN ridge. The expansion of this ridge ranges from 90° to 98° West, and the strong influence of the hot spot on the western side has caused the formation of underwater ridges in a depth range of -3500 to -1000 m. It is noteworthy that the evolving process of the Galapagos Islands and submarine ridges is permanent, since the Cocos Plate moves 8 cm/year NE, while the Nazca plate moves 5.8 cm/year E [18]. In the figure 3, it can see the submarines ridges of Galápagos.

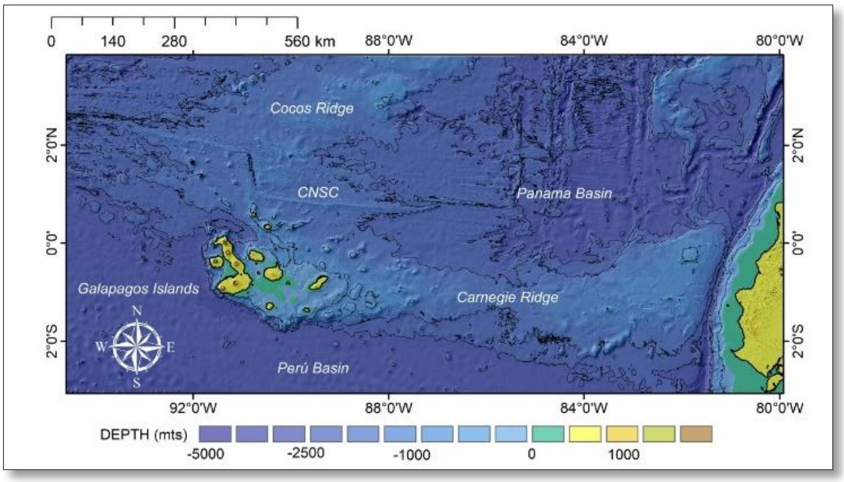


Figure 3. Galápagos' Rides

Based on Galapagos' ocean geomorphology, it was necessary to divide the study area into 12 sub-areas related to different depths existing in that area to increase the model's performance (See Figure 4). For this purpose, we have performed a statistical analysis of both the bathymetry of the area and the variation of chlorophyll, to select the area that will be the basis of this study. It should be mentioned that, according to the study carried out by Renteria et al [19], national and international fishing effort is mainly concentrated in the west of the Galápagos Islands, included inside the Marine Reserve and outside the Insular Exclusive Economic Zone [19].

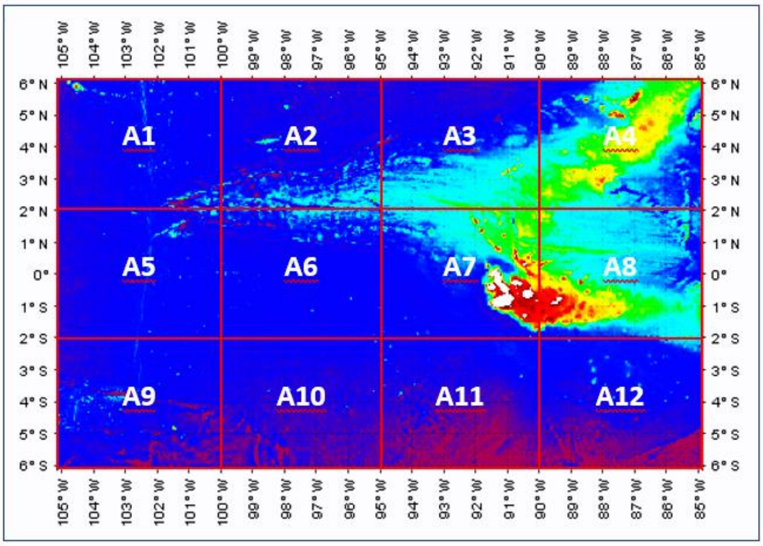


Figure 4. Study area division

Finally, the A6 area was selected because it is located to the west of Galápagos Islands and includes the insular exclusive economic zone (IEEZ), as well as after analyzing the behavior of the bathymetry in that area, variance, and standard deviation of this variable, is low compared with the results obtained in other subareas (see Table No. 1). The basic statistical values of the variable of interest in this study (Chlorophyll-a) were also analyzed and area A6 has a wide range, which will help to generalize the prediction model, its variance and standard deviation are also relatively low, (See Table No. 2). It should be mentioned that in area A6, constant overfishing activities have been identified.

Table 1. Basic statistical values of bathymetry during year, 2021.

AREA	Max. m	Min. m	Mean m	Range m	Var.	Std. Dev.	% CV
A1	-2875	-4222	-3482	1347	52130	228	0.17
A2	-2703	-4214	-3626	1511	31488	177	0.12
A3	-2703	-4221	-3677	1518	71010	266	0.18
A4	-2191	-4152	-3513	1961	123058	351	0.18
A5	-2154	-4048	-3353	1894	35509	188	0.10
A6	-2349	-3737	-3273	1388	36317	191	0.14
A7	703	-3712	-2601	4415	944219	972	0.22
A8	-52	-3452	-2322	3400	450137	671	0.20
A9	-2151	-4679	-3365	2528	48572	220	0.09
A10	-2333	-3953	-3322	1620	108416	329	0.20
A11	-844	-4018	-2995	3174	278410	528	0.17
A12	-2151	-4679	-3365	2528	48572	220	0.09

Table 2. Basic statistical values of chlorophyll-a during year, 2021.

AREA	Max. mg/m^3	Min. mg/m^3	Mean mg/m^3	Range mg/m^3	Var.	Std. Dev.	% CV
A1	2.127	0.135	0.385	1.992	0.070	0.264	0.13
A2	2.146	0.140	0.409	2.006	0.130	0.361	0.18
A3	1.940	0.142	0.387	1.798	0.052	0.228	0.13
A4	1.899	0.165	0.487	1.735	0.061	0.246	0.14
A5	1.572	0.165	0.426	1.406	0.026	0.162	0.12
A6	2.175	0.169	0.486	2.006	0.052	0.228	0.11
A7	1.645	0.111	0.513	1.534	0.038	0.194	0.13
A8	1.976	0.152	0.663	1.825	0.090	0.300	0.16
A9	1.589	0.135	0.271	1.454	0.018	0.134	0.09
A10	2.146	0.140	0.409	2.006	0.130	0.361	0.18
A11	2.146	0.142	0.391	2.004	0.061	0.246	0.12
A12	1.899	0.165	0.487	1.735	0.061	0.246	0.14

The subarea A6 is located between 2° N and 2° S and between 95° W and 100° W. These waters have high potential fisheries resources, so it attracts the world's fishing vessels, especially from Asia.

3.3 Data

Our dataset come from the data base of European Space Program, called Copernicus that provides measurements of several physical, chemical, and biological oceanic variables. The values of physical variables come from data base “Global Analysis Forecast-PHY- 001-024-TDS [20], and values of biochemical variables come from data base “Global Analysis Forecast-BIO-001-028-TDS [21].

Table 3. Description of the physical and the biogeochemical variables.

	Variable	Description	Unit
Biogeochemical variables	Chl	Total chlorophyll-a	mg/m^3
	Fe	Dissolved iron	$mmol/m^3$
	NO3	Nitrate	$mmol/m^3$
	O2	Dissolved oxygen	$mmol/m^3$
	pH	pH	
	PO4	Phosphate	$mmol/m^3$
	Si	Dissolved silicate	$mmol/m^3$
	SPCO2	Surface CO2	Pa
	Nppv	Net primary production	$mmol/m^3$
	Phyc	Phytoplankton concentration in carbon	$mmol/m^3$
Physical variables	ST	Sea water -40m temperature	ºC
	So	Salinity	$1/e^3$
	Zos	Sea surface height	m
	Mlots	Mixed layer depth	m
	Uo	Northward sea current water vel.	m/s
	Vo	Eastward sea current water velocity	m/s

The variables considered in this study are described in Table 3, while our data set was structured with daily mean values of these variables. The training dataset is the values recorded from December-2020 to May-2021 (Atraining) and the test dataset considers the values from Jun-2021 to November-2021 (Atest), with a spatial granularity of 0.1 grade in every direction, for 2091 geographically distinct points per day, in total 7´259.952 measurements. Our data contained no missing values. The correlation one-to-one of 16 physical and biogeochemical variables can be found in Table. 4.

Table 4. Correlation matrix for our variable recorded during Dic-2020 to Nov-2021.

	Chl	**Chl**	**CO2**	**ST**	**So**	**Mlots**	**Zos**	**Vo**	**Uo**	
Chl	1	1	0.68	-0.81	0.75	-0.66	-0.69	0.02	0.67	**Chl**
Nppv	0.79	1	1	-0.62	0.81	-0.55	-0.61	0.11	0.63	**CO2**
phyc	0.87	0.75	1	1	-0.88	0.78	0.89	-0.06	-0.71	**ST**
Fe	0.91	0.84	0.78	1	1	-0.76	-0.81	0.08	0.69	**So**
Si	0.88	0.83	0.78	0.97	1	1	0.76	0.01	-0.56	**Mlots**
NO3	0.88	0.75	0.71	0.94	0.92	1	1	-0.03	-0.63	**Zos**
PO4	0.85	0.76	0.78	0.89	0.95	0.90	1	1	0.05	**Vo**
O2	-0.77	-0.71	-0.55	-0.89	-0.85	-0.92	-0.75	1	1	**Uo**
pH	-0.80	-0.73	-0.72	-0.83	-0.92	-0.83	-0.93	0.74	1	
	Chl	**Nppv**	**Phyc**	**Fe**	**Si**	**NO3**	**PO4**	**O2**	**pH**	

*** Correlation of chlorophyll vs. physical** (White color) **and biogeochemical** (Grey color) **variables.**

4. RESULTS AND DISCUSSION

4.1. Chlorophyll-a prediction (30 days) without optimization model

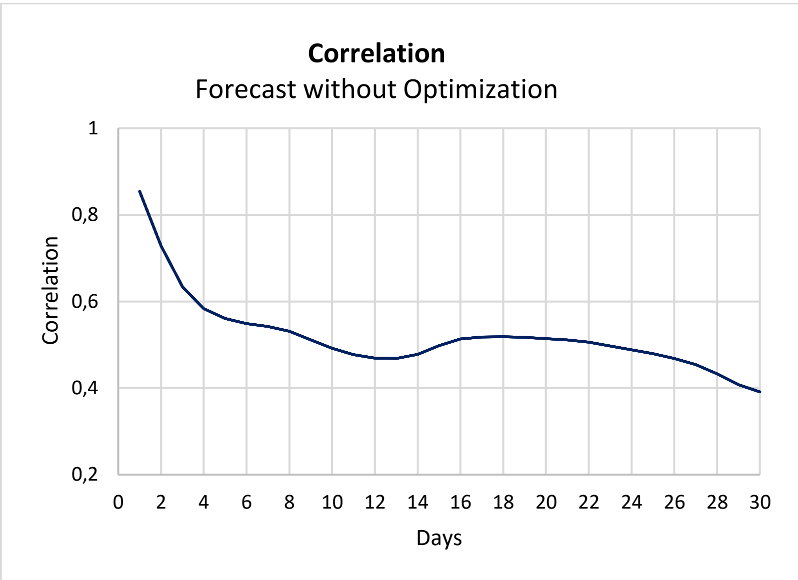


Figure 5. Correlation of Chlorophyll-a prediction without optimization.

First, the chlorophyll-a prediction is conducted using the multivariate spatial-temporal regression method, in order to determine the efficacy of this method without applying any kind of optimization. Two datasets are configured; the first one will be used for model training and the second one will be used for its evaluation. Each dataset contains data of 180 days, evaluated from each of the 2091 geographical positions and the 16 analyzed variables. The correlation between the real value and the predicted value is evaluated, and this will be our reference value to evaluate the method optimization. In the Figure 5, the results from the preliminary evaluation can be observed. The prediction without optimization of the chlorophyll substance decreases from 0.85 to 0.39, this prediction is made during the following 30 days, on each day considered in the training dataset.

4.2 Chlorophyll-a prediction (30 days) applying optimization model

Once the phase lag is determined for each of the variables, the dataset is once again restructured, taking into consideration the variables that are ahead of phase with respect to Chl-a, given that these are the ones that influence its variation. For the variables that are delayed with respect to Chl-a, their last known value is kept. It must also be mentioned that it has been tested taking into account only the delayed variables, but the performance of the model did not improve.

After the dataset restructuration, the prediction model is executed and the result can be observed in Figure 6.

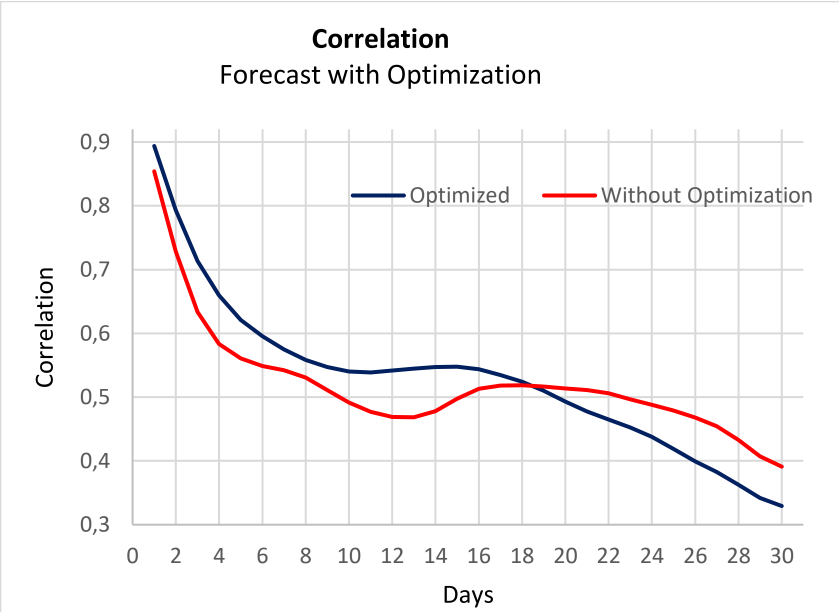


Figure 6. Correlation of Chlorophyll-a prediction with optimization.

As it can be observed on this graph, when taking into account the phase lag of the variables with respect to Chl-a, the Chlorophyll prediction is improved on average 6% up to the 18th day, after which the optimization model turns out to not be very efficient.

4.3 Chlorophyll-a prediction (30 days) applying optimization model and lags.

The multivariate spatial-temporal regression mode is performed, including 10-days lag transformation to the data set Atraining, determining that the model becomes even more optimized, obtaining an improvement of up to 10% in the Chl-a prediction on days 10 and 11; nonetheless, the effectiveness does not improve after the 18th day, remaining at 52%. From this day, this optimization model is not suitable. In the Figure 7, the final model optimization is presented, considering the number of phase delays with better performance for each prediction day.

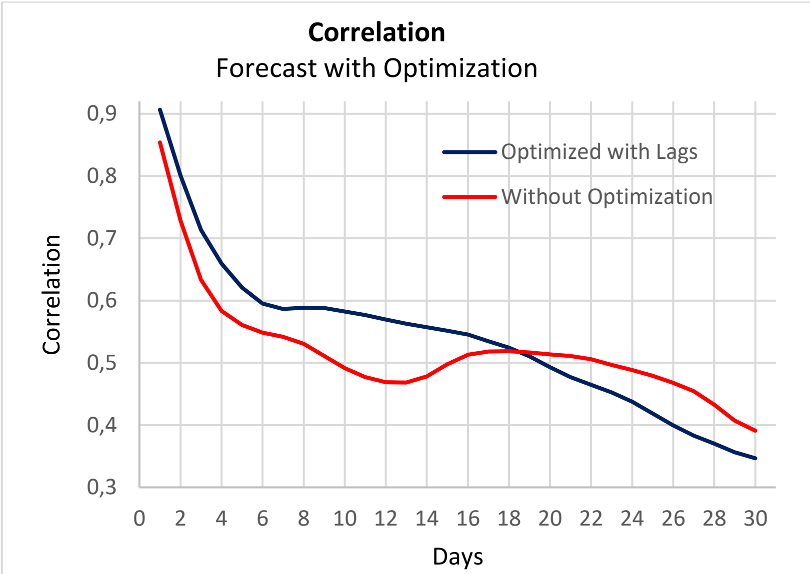


Figure 7. Correlation of Chlorophyll-a prediction with optimization including lags.

5. CONCLUSION

In this work, a model that optimizes the prediction of the concentration of Chlorophyll around the Galapagos Islands has been designed, making use of the discrete Fourier transform theory, that allows, on one hand, to understand the relationship between the physical and biogeochemical variables of the ocean in relation to the Chl-a, as well as, on the other hand, to restructure the dataset, considering the displacement of the variables that are ahead of the Chlorophyll, in order to optimize the prediction using the multivariate spatial-temporal regression model. This prediction makes it possible to identify the areas which will be more productive in the ocean, so that the naval forces can intensify maritime surveillance at these points, in order to combat illegal, unreported and unregulated fishing. The best correlation is given in a time gap of 3 days (>0,7), while it remains above 0,5 up to 18 days. It is necessary to mention that the Ecuadorian Navy takes 0.6 days (14 hours) to deploy a Coast Guard from San Cristobal Island to the furthest point in Galapagos (200 Mn), and if it is necessary to send a Coast Guard from Manta (Mainland Ecuador) to the furthest point (930 Mn), it takes 3 days of navigation.

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