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Methodologies on Researches on the Spatiotemporal Dynamics of Plankton in the Chilean Upwelling Zone

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Abstract. The dynamics of plankton in the Chilean upwelling zone is one of the focal points of current research, with close ties to the study of the marine environment in this region, the economic development of countries along the coast, and the forecasting of the ocean's effects on global warming. Although some general patterns and driving factors for the plankton dynamics have been identified by researchers, the methods currently in use are diverse and complex, and a universal, efficient, and comprehensive model for simulating the environmental and biological indicators of this sea area has not yet been developed. Consequently, this paper compiles recent research on the dynamics of plankton in the Chilean upwelling area, synthesizes various research methodologies, and conducts a comparative analysis to explore the path toward the development of a universal large-scale model. The study reveals that the main constraints on the development of the aforementioned model are the immaturity of existing models and the limitations of computational power. By refining current models, initiating research on a smaller scale, and collaborating with the field of computer science to enhance computational capabilities, it is anticipated that a new generation of models can be developed, while also providing guidance and assistance for further research on the dynamics of plankton in the Chilean upwelling area.

Keywords: Methodology; Plankton; Dynamics; Chilean Upwelling Zone.

1. Introduction

As one of the most productive Eastern Boundary Upwelling Systems (EBUS) in the world's oceans, Chile's upwelling zone is celebrated for its elevated primary productivity [1], which has been instrumental in sustaining a substantial fishery yield, primarily composed of benthic and pelagic species [2], over an extended duration. This has been pivotal for the economic prosperity of the surrounding nations [2]. Within this maritime expanse, the high productivity is intricately connected to the fluctuations of plankton, which engage in the carbon cycle and influence fishery output, thus being regarded as a critical parameter for forecasting the marine repercussions of global warming [3].

At present, a multitude of studies have been conducted on the chronological and spatial dynamics of plankton within the Chilean upwelling zone, with a principal focus on employing modeling techniques to delineate, replicate, or anticipate the shifts in plankton within the Chilean upwelling system, and to subsequently investigate the impetuses behind these variations [4-7]. Certain investigations have centered on the distribution of specific planktonic organisms within their high-nutrient milieu and the factors influencing their presence, offering a conceptual framework for examining the alterations of planktonic fauna within the upwelling ecosystem [8]. However, the methodologies employed in these studies are not standardized, and a comprehensive and holistic simulation that encapsulates the dynamic fluctuations of various biological indices of plankton over a temporal span within this upwelling zone has yet to be realized.

This research endeavors to analyze the methodologies from prior investigations, distilling the strengths of each approach, thereby aiding future researchers in the selection of more efficacious techniques and potentially fostering the emergence of novel methods that amalgamate these strengths. Initially, the study will enumerate the diverse methodologies, assessing their practical contexts and the outcomes they yield. Secondly, make suggestions for existing methods, identify current limiting factors, and point out where these methods can be further refined. Ultimately, the study will delineate the prospective trajectories for ongoing research endeavors.

2. Analysis and Evaluation of Existing Research Methods

2.1. Research Methods for Spatiotemporal Dynamics of Planktonic Organisms in the Upwelling Zone of Chile

Existing research on the temporal and spatial dynamics of planktonic organisms has employed a multitude of distinct methodologies. These approaches can be divided into two categories: modeling and non-modeling methods. The modeling method entails the creation of a model, the production of simulation outcomes, and the validation of its correctness with data gathered on-site, thus confirming the hypotheses put forward. In relation to the research topic at hand, non-modeling methods are primarily employed to facilitate the analysis of planktonic biological indicators, constituting a swift method for data processing.

2.1.1. Modeling methods

The modeling method is an important approach in studying the dynamics of plankton, among which PISCES occupies an important position. PISCES--Pelagic Interactions Scheme for Carbon and Ecosystem Studies, is a biogeochemical simulation tool that focuses on the organisms at the lower trophic levels of marine ecosystems, such as phytoplankton, microzooplankton, and mesozooplankton, and their roles in the cycles of key nutrients like phosphorus, nitrogen, iron, and silicon [9]. Vergara et al. utilized the above approach and a three-dimensional eddy-resolving ocean circulation model coupled with a medium-complexity biogeochemical model to simulate the spatial and seasonal variability of nutrients and chlorophyll in the high-nutrient salinity area off south of the central coast of Chile (30–40°S) [4]. The simultaneous restrictive effects created by light exposure and several types of nutrients on the growth of phytoplankton were also revealed in the identical method. The seasonal patterns of physical, chemical and biological parameters observed at the stationary site in the research were replicated, utilizing PISCES which relied on a 3-D physical-biogeochemical retrospective simulation [5].

Other models constructed to support research were also observed in recent years. The distribution of *C. chilensis*, a copepod species, in the high-nutrient salinity area, along with the environmental drivers influencing this distribution, has been evaluated under current climatic conditions and potential future global climate change scenarios [6]. To assess environmental impacts, occurrence records of *C. chilensis* and environmental factors were employed to forecast the probable geographic spread of this species and determine its influencing factors, by utilizing Bayesian Additive Regression Trees (BART) and Ensembles of Small Models (ESM) across two separate depth zones. The models were expanded to predict how the species' geographic range may shift in response to future climatic conditions.

A study focusing on zooplankton in the southeast Pacific region near Chile was conducted, which included sampling and statistical analysis [7]. The distribution of pelagic calanoid families and their species along coastal-oceanic (zonal) and alongshore (meridional) gradients within pre-defined areas were assessed, to test the hypothesis that ecological zonation is determined by environmental gradients, with the temperature gradient potentially playing a distinctive role. The leverage of the power of models was also applied in this study for correlating the copepod community with the environment.

2.1.2. Non-modelling methods

Other non-modeling methods have also played a role in this research topic. Automated Plankton Identification (API) was applied to analyze zooplankton biomass, categorized by taxonomy, over a time period from 2003 to 2012 at a stationary location off the central southern coast of Chile [9-10].

This method employed ZooImage software to swiftly evaluate the size and composition of zooplankton. Subsequently, these data were integrated into established growth models derived from global meta-analyses, which take into account temperature, body size, taxonomy, and diet, to yield estimates of biomass, growth, and secondary production [11].

2.2. Conclusions Related to the Temporal and Spatial Dynamics of Plankton in the Aforementioned Studies

Researchers, utilizing modeling and non-modeling approaches, have derived varied conclusions in their respective studies. This paper refines these conclusions into three distinct categories: those pertaining to the temporal dynamics of plankton, those pertaining to the spatial dynamics of plankton, and those related to the methodologies employed in their individual research endeavors.

2.2.1. Conclusions featuring the temporal dynamics of plankton

In the upwelling ecosystem of southern Chile, the time series of zooplankton biomass, production, and growth rates show a significant seasonal pattern, with higher values observed during the upwelling season (spring to summer) compared to the downwelling season (autumn to winter), according to research [8]. While euphausiids, small copepods, and chaetognaths become prevalent during the downwelling phase, the biomass of giant copepods, decapods, and the larvae of annelids, cnidarians, and siphonophores increases during the upwelling period.

Significant seasonality is seen in mid- to high-latitude regions in studies conducted in chronological order of zooplankton featuring their biomass and abundance because of strong seasonal influences caused by temperature, radiation, stratification, and primary productivity, which show distinct seasonality from bottom-up processes [12]. Nevertheless, neither the zooplankton's seasonal patterns nor the environmental cycles repeat themselves exactly year following year. Seasonal timing varies significantly between one and three months, according to recent analysis of multiple long-term zooplankton series [13].

2.2.2. Conclusions featuring the spatial dynamics of plankton

It is shown that the presence of *C. chilensis* is affected by productivity levels and mesoscale occurrences, factors that shape its geographic spread within the Humboldt Current System (HCS) [6]. It reveals the roles and advantages of two methodologies (BART, ESM).

Employing the BART methodology for geographic prediction between 0 to 200 meters depth, it is evident that *C. chilensis* inhabits offshore regions from 1° to 55° South latitude. In particular, areas with a higher probability of occurrence are pinpointed in the distant offshore regions west of central Chile, where a significant presence of *C. chilensis* has been noted. This observation is hypothesized to be the consequence of eddy-induced advective processes [14].

C. chilensis is recognized for living in the top 250 meters of the water column so its presence at greater depths might be incidental or indicative of sinking populations from upper layers that operate within a source-sink ecological model [15-17]. In this stratum, factors accounting for the spatial distribution are associated with Edler Kinetic Energy (EKE) and Net Primary Production (NPP). EKE reveals the presence of mesoscale eddies [18], which, along with chlorophyll-a as a productivity indicator, significantly regulates the distribution of *C. chilensis*, particularly in deeper waters.

Under future scenarios (medium-term and long-term), the geographical range of *C. chilensis* is projected to contract significantly, as it is highly dependent on marine conditions that may change with global warming. The key elements comprise nutrient accessibility, salinity fluctuations, and the extent of the mixed layer's depth.

2.2.3. Conclusions featuring the utilized methods

Some of the conclusions presented in the aforementioned literature pertain to discussions on the validity and applicability of their respective research methodologies. These diverse approaches offer inspiration for future applications in upcoming studies. Phytoplankton photosynthesis is crucial for oceanic biogeochemical cycles. A comprehensive understanding of the physical-biological coupling in the southern HCS has been achieved [4], filling a research gap by analyzing the interplay of physical oceanographic and ecological factors, utilizing a modeling framework that integrates biogeochemical and physical dynamics. This research has notably enhanced our knowledge of the seasonal variations in surface chlorophyll and their connection to nutrient dynamics in the upper layer of the southern HCS. The breakthrough of their model is the ability to simulate the full seasonal cycle, which was not accomplished by previous models.

The phenomenon of light and multiple nutrients co-limiting phytoplankton growth was examined through the use of a model. This study delineated the spatial configuration and seasonal fluctuations of silicate inputs within the uppermost layer (0–20 m). It marks the commencement of simulating the seasonal oscillations of three-dimensional integrated physical-biogeochemical dynamics in central-southern Chile, forming a crucial basis for examining the temporal shifts in plankton populations.

The study's modeling approach indicates that the advective processes that take place along the coastline and across the shelf are the main causes of variability in plankton productivity within the of central-southern Chilean coastal upwelling zone [5]. Although there were some significant discrepancies, the seasonal patterns of physical and biological variables observed could be reasonably replicated by the physical-biogeochemical hindcast simulation. These differences were mostly caused by the underestimating of nutrient supplies. The biological reactions to physical processes exhibited temporal lags that were consistent with expected ranges, indicating that the modeling technique was apt for depicting the complex and volatile characteristics of an upwelling ecosystem rich in diversity.

At smaller scales, ecological factors that affect species physiology can alter the spatiotemporal distribution of species based on their tolerance levels and optimal population ranges, thereby regulating patterns of diversity [7]. Such spatiotemporal variations across scales, from micro to macro, work in concert to drive speciation events, thus shaping the actual patterns of biodiversity among pelagic organisms. From this viewpoint, the open-ocean ecosystem of the Southeast Pacific could act as an ideal model to deepen our understanding of the mechanisms that govern the distribution of zooplankton and higher trophic level organisms within the food web. The ultimate aim of this paper is not to directly investigate the spatiotemporal dynamics of zooplankton, but by examining patterns of biodiversity, it can refine our understanding of the distribution patterns of zooplankton, potentially aiding further research into the factors that drive the spatial dynamics of zooplankton in upwelling regions.

The varied conclusions on plankton dynamics can be summarized by the three key points mentioned previously. It is clear that ongoing research predominantly utilizes computational models for data processing during field sampling. A growing body of research is committed to verifying the precision of the models in application and making the necessary modifications. Meanwhile, investigators re-evaluate the processed data to reinforce their hypotheses and extract overarching conclusions.

2.3. Evaluation of Research Methodologies

At present, the modeling approach is a widely favored research methodology, largely due to the ongoing practice and refinement of existing models by the academic community, along with their integration with other models and data systems. This has led to the development of models such as PISCES, which have seen extensive application. Other methodologies have also contributed to the study of plankton dynamics, but their applications are relatively limited in scope or are not specifically targeted at plankton dynamics. To date, no model has been able to fully simulate the dynamics of plankton and other biological indicators, along with the relevant physical and oceanographic indices in the Chilean upwelling zone over specific time periods, primarily due to several limiting factors.

Firstly, the total duration of research is relatively short, as the development of a model necessitates the ongoing collection of field data and refinement of algorithms over an extended period. The verification of model predictions for accuracy and the subsequent calibration is an ongoing process.

Observations by the academic community that span over a decade are still insufficient to draw definitive conclusions regarding the specific regularities of particular marine areas. Therefore, the development of more comprehensive models with broader spatiotemporal coverage will require a significant amount of additional time. Secondly, there are numerous uncertainties in marine areas that impede the process of data refinement. Many current models address this issue by employing methods such as interpolation.

Ultimately, a significant constraining factor is technological capacity. The development and application of models require the use of high-quality, highly accurate data, an area where existing technology still encounters challenges. Concurrently, as models become more sophisticated, they demand a corresponding increase in computational capabilities. However, access to high-performance computing resources is limited. Climate change may have an impact on the behavior of marine ecosystems, necessitating models that are capable of adapting to and forecasting these long-term and large-scale changes.

3. Future Direction on Advancing Research on Plankton Dynamics in the Chilean Upwelling Zone

Current research on plankton dynamics in the Chilean upwelling zone can evolve in multiple directions. Initially, there can be advancements in small-scale studies, which can persist in utilizing a variety of methodologies, including both modeling and non-modeling approaches, to outline the general physical oceanographic features of the region and select representative plankton species to examine various indicators such as abundance and biomass. By conducting research within a confined scope, the precision of models for specific areas can be initially honed. The findings from these studies can underpin larger models that are suitable for more extensive scopes, fostering the progression of these large-scale models. Secondly, interdisciplinary collaboration can augment the capabilities of current technologies in data processing. This necessitates an enhancement in computational capacity to expedite the iteration pace of existing models. Thirdly, researchers involved in this field are anticipated to keep supplying high-precision data to rectify the models' accuracy. Moreover, cross-system comparisons and biogeographical studies could be initiated. Comparative studies with other upwelling systems globally can identify similarities and disparities in plankton dynamics. This may offer insights into the elements propelling variations in plankton communities and their reactions to environmental stressors. Biogeographical analyses might also disclose patterns and processes that shape the distribution of marine biodiversity on broader scales.

Furthermore, climate change significantly influences the study of plankton in the Chilean upwelling zone. Consequently, it is imperative to integrate considerations of climate change into the construction of models to evaluate the immediate and enduring effects of extreme climatic events, such as El Niño and La Niña, on upwelling intensity, marine productivity, and plankton distribution [19]. Moreover, climate scenarios within ecosystem models should be scrutinized, employing these models to simulate a range of climate change projections and anticipate future transformations in the structure and function of plankton communities. Detection and observation of sensitive plankton species impacted by climate change could be conducted, acting as bioindicators of the effects of climate change.

4. Conclusion

The paper uncovers the characteristics and potential for development of current research methodologies concerning the dynamics of plankton in the Chilean upwelling area. The existing research methods each have their merits, achieving effective results within their respective research topics, yet they necessitate ongoing refinement and development to aspire towards a model that can fully simulate the dynamic changes in plankton indicators within the Chilean upwelling area over a defined period. The main limiting factors at present include multiple aspects. Firstly, the research duration is relatively short—model development cycles are comparatively long, requiring the continuous collection of valid data, real-time algorithm optimization, and ongoing correction. Secondly, the uncertainty of marine environmental parameters disrupts the accuracy of the collected data. Finally, the constraints imposed by current technological capabilities—models necessitate high-performance computing for data processing, and high-performance computational resources are currently scarce. This paper conducts a comprehensive assessment of the recent research methodologies for the dynamics of plankton in the Chilean upwelling area, analyzing their respective application contexts, and enumerating the characteristics and advantages of these methods, thereby filling the research gap in the horizontal comparison of the main existing methods. The primary contribution lies in assisting researchers in swiftly selecting and refining the methods suitable for their research projects, and establishing a research methodology guide, lays the groundwork for the emergence of new methods and ideas. Future research on this subject can be broadly categorized into two directions. On one hand, continue to employ existing methods, tailoring them to the needs of the research topic, and delve into the general patterns within a smaller scope of the upwelling area, striving for precision as a complement to broader models. Concurrently, collect more field data during on-site investigations to enhance the accuracy of the model. On the other hand, conduct interdisciplinary collaboration to augment the computational power of existing computers and expedite the iteration rate of current models.

References

[1] Montero P, Daneri G, Cuevas L A, et al. Productivity cycles in the coastal upwelling area off Concepción: the importance of diatoms and bacterioplankton in the organic carbon flux[J]. Progress in Oceanography, 2007, 75(3): 518-530.

[2] Pauly D, Christensen V, Guénette S, et al. Towards sustainability in world fisheries[J]. Nature, 2002, 418(6898): 689-695.

[3] Richardson A J, Schoeman D S. Climate impact on plankton ecosystems in the Northeast Atlantic[J]. Science, 2004, 305(5690): 1609-1612.

[4] Vergara O A, Echevín V, Sepúlveda H H, et al. Controlling factors of the seasonal variability of productivity in the southern Humboldt Current System (30–40 S): A biophysical modeling approach[J]. Continental Shelf Research, 2017, 148: 89-103.

[5] Venegas A, Auger P A, Escribano R, et al. Understanding seasonal variability of mesozooplankton biomass in the upwelling system of central-southern Chile: A modelling approach[J]. Progress in Oceanography, 2024, 220: 103193.

[6] Rivera R, Escribano R, González C E, et al. Modeling present and future distribution of plankton populations in a coastal upwelling zone: the copepod *Calanus chilensis* as a study case[J]. Scientific Reports, 2023, 13(1): 3158.

[7] González C E, Medellín-Mora J, Escribano R. Environmental gradients and spatial patterns of Calanoid copepods in the Southeast Pacific[J]. Frontiers in Ecology and Evolution, 2020, 8: 554409.

[8] Medellín-Mora J, Atkinson A, Escribano R. Community structured production of zooplankton in the eastern boundary upwelling system off central/southern Chile (2003–2012)[J]. ICES Journal of Marine Science, 2020, 77(1): 419-435.

[9] Aumont O, Éthé C, Tagliabue A, et al. PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies[J]. Geoscientific Model Development Discussions, 2015, 8(2): 1375-1509.

[10] Huntley M E, Lopez M D G. Temperature-dependent production of marine copepods: a global synthesis[J]. The American Naturalist, 1992, 140(2): 201-242.

[11] Hirst A G, Bunker A J. Growth of marine planktonic copepods: global rates and patterns in relation to chlorophyll a, temperature, and body weight[J]. Limnology and Oceanography, 2003, 48(5): 1988-2010.

[12] Mackas D L, Beaugrand G. Comparisons of zooplankton time series[J]. Journal of Marine Systems, 2010, 79(3-4): 286-304.

[13] Mackas D L, Greve W, Edwards M, et al. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology[J]. Progress in Oceanography, 2012, 97: 31-62.

[14] Morales C E, Torreblanca M L, Hormazabal S, et al. Mesoscale structure of copepod assemblages in the coastal transition zone and oceanic waters off central-southern Chile[J]. Progress in Oceanography, 2010, 84(3-4): 158-173.

[15] Hirche H J, Barz K, Ayon P, et al. High resolution vertical distribution of the copepod *Calanus chilensis* in relation to the shallow oxygen minimum zone off northern Peru using LOKI, a new plankton imaging system[J]. Deep Sea Research Part I: Oceanographic Research Papers, 2014, 88: 63-73.

[16] Pulliam H R. Sources, sinks, and population regulation[J]. The American Naturalist, 1988, 132(5): 652-661.

[17] Dias P C. Sources and sinks in population biology[J]. Trends in ecology & evolution, 1996, 11(8): 326-330.

[18] Ding M, Lin P, Liu H, et al. Lagrangian eddy kinetic energy of ocean mesoscale eddies and its application to the Northwestern Pacific[J]. Scientific reports, 2020, 10(1): 12791.

[19] Aguilera V M, Escribano R, Vargas C A, et al. Upwelling modulation of functional traits of a dominant planktonic grazer during “warm-acid” El Niño 2015 in a year-round upwelling area of Humboldt Current[J]. Plos one, 2019, 14(1): e0209823.