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Evaluating the Mechanisms of Coastal Circulation and Their Responses to Climate Change

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Abstract Coastal circulation is driven by factors such as wind, tides, and thermohaline gradients, and is significantly influenced by coastal topography, adding to its complexity. This study systematically evaluates the mechanisms of coastal circulation and their responses to climate change, emphasizing the crucial role of these processes in understanding ocean dynamics and predicting future changes. By examining case studies from various regions, the study discusses the regional variations in coastal circulation and the effectiveness of current models in predicting these changes. Innovations in technology and methodology, such as improvements in modeling techniques and advances in observational technologies, provide new perspectives and tools for researching coastal circulation. Integrating these detailed data into advanced numerical models helps to more accurately predict the performance of coastal circulation under the impacts of climate change, especially in terms of changes in wind patterns, sea level rise, and changes in ocean temperature and salinity. This study also identifies challenges and knowledge gaps in the research, and proposes future research directions to better prepare for and mitigate the impacts of climate change on these critical systems.

Keywords Coastal circulation; Climate change; Observational technologies; Numerical modeling; Environmental impact

1 Introduction

Coastal circulation refers to the movement of water along coastlines, driven by various factors including wind, tides, and differences in water density. This circulation plays a crucial role in transporting nutrients, sediments, and organisms, thereby supporting marine ecosystems and influencing coastal weather patterns. One of the key processes in coastal circulation is upwelling, where deep, nutrient-rich waters are brought to the surface, fueling primary productivity and supporting rich marine biodiversity (Sydeman et al., 2014; Wang et al., 2015; Arellano and Rivas, 2019).

Understanding the mechanisms of coastal circulation is vital for several reasons. Firstly, it helps in predicting the impacts of climate change on marine ecosystems. For instance, changes in wind patterns and ocean temperatures can alter upwelling intensity, affecting marine productivity and biodiversity. Secondly, coastal circulation influences local climate and weather patterns, which can have significant socio-economic impacts, particularly in regions dependent on fisheries and tourism (Howard et al., 2020). Lastly, knowledge of coastal circulation is essential for managing coastal resources and mitigating the effects of environmental changes, such as sea-level rise and increased storm frequency (Dodet et al., 2019).

This study analyzes the impact of climate change on wind patterns and their effects on coastal upwelling systems, investigates the interactions between ocean warming, stratification, and upwelling dynamics, and evaluates the broader impacts of changes in coastal circulation on marine ecosystems and coastal communities. It identifies gaps in current research and proposes future research directions to enhance our understanding of coastal circulation under the backdrop of climate change. By synthesizing the results of multiple studies, this research aims to comprehensively understand how coastal circulation mechanisms are affected by climate change and to address the complex challenges posed by climate change.

2 Mechanisms of Coastal Circulation

2.1 Wind-driven circulation

Wind-driven circulation is a critical component of coastal dynamics, particularly in upwelling systems. Climate change has intensified wind patterns in several major upwelling regions, such as the California, Humboldt, and Benguela systems, leading to increased upwelling of nutrient-rich waters. This intensification is attributed to the growing temperature and pressure differences between land and sea, which enhance alongshore winds (Sydeman et al., 2014; Arellano and Rivas, 2019). The Bakun hypothesis posits that increasing greenhouse gas concentrations will further intensify these winds, a trend supported by recent meta-analyses (Sydeman et al., 2014). This intensification can significantly impact marine productivity and biodiversity in these regions.

2.2 Tidal circulation

Tidal forces play a significant role in coastal circulation by generating periodic currents that can influence sediment transport, nutrient mixing, and overall water movement. While the provided data does not directly address tidal circulation, it is important to note that tidal dynamics can interact with other mechanisms, such as wind-driven and thermohaline circulation, to shape coastal environments.

2.3 Thermohaline circulation

Thermohaline circulation, driven by differences in water density due to temperature and salinity variations, is a major driver of global ocean circulation. Climate change can alter thermohaline circulation patterns, leading to significant impacts on coastal regions. For instance, the warming of the tropical Atlantic Ocean and the associated slowdown of thermohaline circulation during the last deglaciation highlight the sensitivity of this mechanism to climate shifts. Additionally, the potential for abrupt climate changes due to thermohaline circulation instability has been well-documented, with implications for both regional and global climate systems (Clark et al., 2002; Guemas and Salas-Mélia, 2008). Coastal topography can also dampen internal oscillations of thermohaline circulation, further influencing its behavior.

2.4 Influence of coastal topography

Coastal topography significantly affects circulation patterns by modifying the flow of water and the distribution of currents. The damping effect of bottom topography on internal decadal-scale oscillations of thermohaline circulation is one example of how physical features can influence ocean dynamics. Coastal topography can also enhance or inhibit upwelling processes, depending on the interaction with wind and current patterns (Ou, 2017). For instance, the generation of barotropic flow in response to topographic features can aid in the adjustment of baroclinic currents, thereby influencing overall circulation.

In summary, the mechanisms of coastal circulation are complex and interdependent, with each responding to climate change in unique ways. Understanding these interactions is crucial for predicting future changes in coastal environments and their broader ecological and climatic impacts.

3 Coastal Circulation Models

3.1 Overview of circulation models

Coastal circulation models are essential tools for understanding the complex dynamics of coastal environments. These models simulate the movement of water and its interaction with various physical, chemical, and biological processes. They are crucial for predicting the impacts of climate change on coastal regions, including sea level rise, changes in wave patterns, and alterations in sediment transport. Coastal circulation models can be broadly categorized into three types: empirical models, analytical models, and numerical models. Each type has its strengths and limitations, and the choice of model depends on the specific research question and the available data (Marshall et al., 2015).

3.2 Numerical modeling techniques

Numerical modeling techniques are crucial for the development and refinement of coastal circulation models. These techniques involve solving mathematical equations that describe fluid dynamics, heat transfer, and other relevant processes. Advanced methods, such as the Kalman filter and the adjoint method, are used to assimilate observational data into models, thereby improving their accuracy and predictive capabilities.

3.3 Data assimilation in coastal models

Data assimilation is a powerful technique used to integrate observational data into numerical models, thereby improving their accuracy and reliability. This process involves adjusting the model state based on observations to minimize uncertainties and better represent the true state of the system. In the context of coastal circulation models, data assimilation can significantly enhance the understanding of ocean dynamics and climate feedbacks. The study by Widmann et al. (2009) explores the use of data assimilation in palaeoclimatology, demonstrating how combining empirical data with model simulations can provide better estimates of past climate states. Similarly, Ghentet et al. (2011) investigates the implications of data assimilation for land surface models, emphasizing its role in constraining model predictions and understanding biogeochemical cycling.

In summary, coastal circulation models, supported by advanced numerical modeling techniques and data assimilation, are vital for understanding the complex interactions between ocean dynamics and climate change. These models provide critical insights into the mechanisms driving coastal circulation and their responses to anthropogenic influences, thereby informing climate predictions and mitigation strategies.

4 Observational Methods

4.1 Remote sensing technologies

In assessing coastal circulation mechanisms and their response to climate change, various advanced observational methods were utilized to ensure the accuracy and comprehensiveness of the data. These methods include remote sensing technologies, in-situ measurements, and autonomous observation systems. Remote sensing technologies have played a key role in observing coastal circulation, particularly through the provision of sea surface temperature (SST) and sea surface height (SSH) data from satellite platforms. These data have provided significant support for the analysis of 4D variational data assimilation systems (4D-Var), significantly enhancing the accuracy and predictive capabilities of coastal transport analysis (Moore et al., 2011). High-frequency (HF) radar has also been widely used in coastal ocean observations, providing real-time data on surface currents, with unprecedented coverage and resolution (Manso-Narvarte et al., 2019). Additionally, satellite synthetic aperture radar (SAR) and infrared scanners have been used to map ocean current patterns, such as monitoring circulation in the Gulf of Mexico through thermal imaging (Ladner et al., 2009). The integration of these technologies has made it possible to monitor and predict changes in coastal ecosystems, significantly enhancing the ability to address climate change (Klemas, 2012).

4.2 In-situ measurements

In-situ measurement methods include the use of Acoustic Doppler Current Profilers (ADCP), Conductivity, Temperature, and Depth sensors (CTD), and autonomous profiling floats, which are used to obtain sub-surface current speeds and other critical oceanographic parameters. These data are essential for validating and calibrating numerical models. For example, in the study of the California Current System, data from Argo floats, CTDs, and tagged marine mammals have had a significant impact on the analysis and prediction of coastal transport (Moore et al., 2011).

4.3 Autonomous observing systems

Autonomous observation systems, such as autonomous gliders and buoy networks, provide continuous and high-resolution ocean data. These systems can cover the entire coastal marine continuum from regional oceans to estuaries and river deltas, greatly increasing the value of observational data. High-resolution models play a crucial role in applications such as monitoring sea level rise, coastal management, and marine ecosystem conservation by connecting and synthesizing these sparse observational data. Additionally, the combination of numerical models and data assimilation methods further enhances the effectiveness of these autonomous observation systems (Manso-Narvarte et al., 2019).

5 Impacts of Climate Change on Coastal Circulation

5.1 Changes in wind patterns

Climate change has led to significant alterations in wind patterns, particularly in coastal upwelling ecosystems. Research indicates that increasing greenhouse gas concentrations have intensified upwelling-favorable winds in several major coastal regions, such as the California, Humboldt, and Benguela upwelling systems, over the past 60 years. This intensification is attributed to the growing differences in temperature and pressure between land and sea, which drive stronger winds. These changes have profound implications for marine productivity and biodiversity in these regions (Sydeman et al., 2014). Additionally, changes in wind patterns can affect the general circulation and residence time in semi-enclosed seas, as seen in the Persian Gulf, where future wind field changes could significantly alter the region's capacity to flush out dissolved pollutants (Ranjbar et al., 2020).

5.2 Sea level rise and its effects

Sea level rise, driven by climate change, poses a substantial threat to coastal ecosystems. Rising sea levels can lead to the loss of marsh habitats, increased intrusion of marine waters, and changes in circulation patterns that affect the retention of indigenous species. These changes can exacerbate hypoxia and increase the frequency and intensity of storm surges, further impacting coastal and estuarine systems. In the southeastern United States, for example, rising sea levels combined with changes in the frequency and intensity of tropical storms and hurricanes are expected to have significant impacts on coastal wetland patterns and processes, affecting hydrology, geomorphology, and nutrient cycling. Moreover, sea level rise can slightly decrease current velocities, leading to increased residence times in certain regions, as observed in the Persian Gulf (Ranjbar et al., 2020).

5.3 Ocean temperature and salinity changes

Rising ocean temperatures and changes in salinity are critical factors influencing coastal circulation. Increased global air and ocean temperatures are expected to alter estuarine stratification, residence time, and eutrophication, impacting estuarine productivity and the distribution of marine species. Higher ocean temperatures can also lead to poleward shifts in species ranges, affecting predator-prey dynamics and overall ecosystem functioning. Additionally, surface warming is a dominant factor accelerating upper ocean currents, particularly in the subtropical gyres and equatorial currents, due to increased vertical stratification (Peng et al., 2022). Changes in ocean salinity, driven by altered precipitation patterns and freshwater input, can further influence regional current systems and circulation patterns (Peng et al., 2022).

In summary, climate change is driving significant changes in coastal circulation through alterations in wind patterns, sea level rise, and ocean temperature and salinity. These changes have wide-ranging implications for marine ecosystems, biodiversity, and the services they provide to human societies. Understanding and mitigating these impacts will require comprehensive and interdisciplinary research efforts.

6 Case Studies

6.1 Coastal circulation in different regions

Understanding coastal circulation in various regions is crucial for predicting and managing the impacts of climate change on coastal ecosystems. A study focusing on the Vanuatu and New Caledonia archipelagos utilized an unstructured-mesh finite-volume modeling approach to simulate coastal circulation. The findings indicated that tidal residual circulation was influenced by flow separation at headlands and islands, while wind-residual circulation was sensitive to wind speed and direction. The study highlighted the importance of wind patterns and sea level rise (SLR) in altering coastal currents and processes, which are critical for sediment transport, pollutant dispersal, and larval transport in these regions (Figure 1) (Lee et al., 2021).

Lee et al. (2021) provided valuable data on the ocean current patterns and seabed topography of the Vanuatu and New Caledonia island regions through detailed modeling and grid analysis. The marine and atmospheric conditions in this area have a significant impact on local communities, especially against the backdrop of global mean sea level rise (SLR) that is higher than average. The research team developed the Van-Fvcom model, validated the model's capability to simulate tidal behavior through tidal gauge observational data, and analyzed the strength and patterns of wind residual circulation by simulating coastal circulation changes under different wind speeds and directions. The study also simulated the impact of 1 m and 2 m SLR on tidal characteristics and coastal ocean currents, analyzing changes in maximum depth-averaged flow velocity. The results not only contribute to scientific understanding but also provide important foundations for regional ecological protection and resource management.

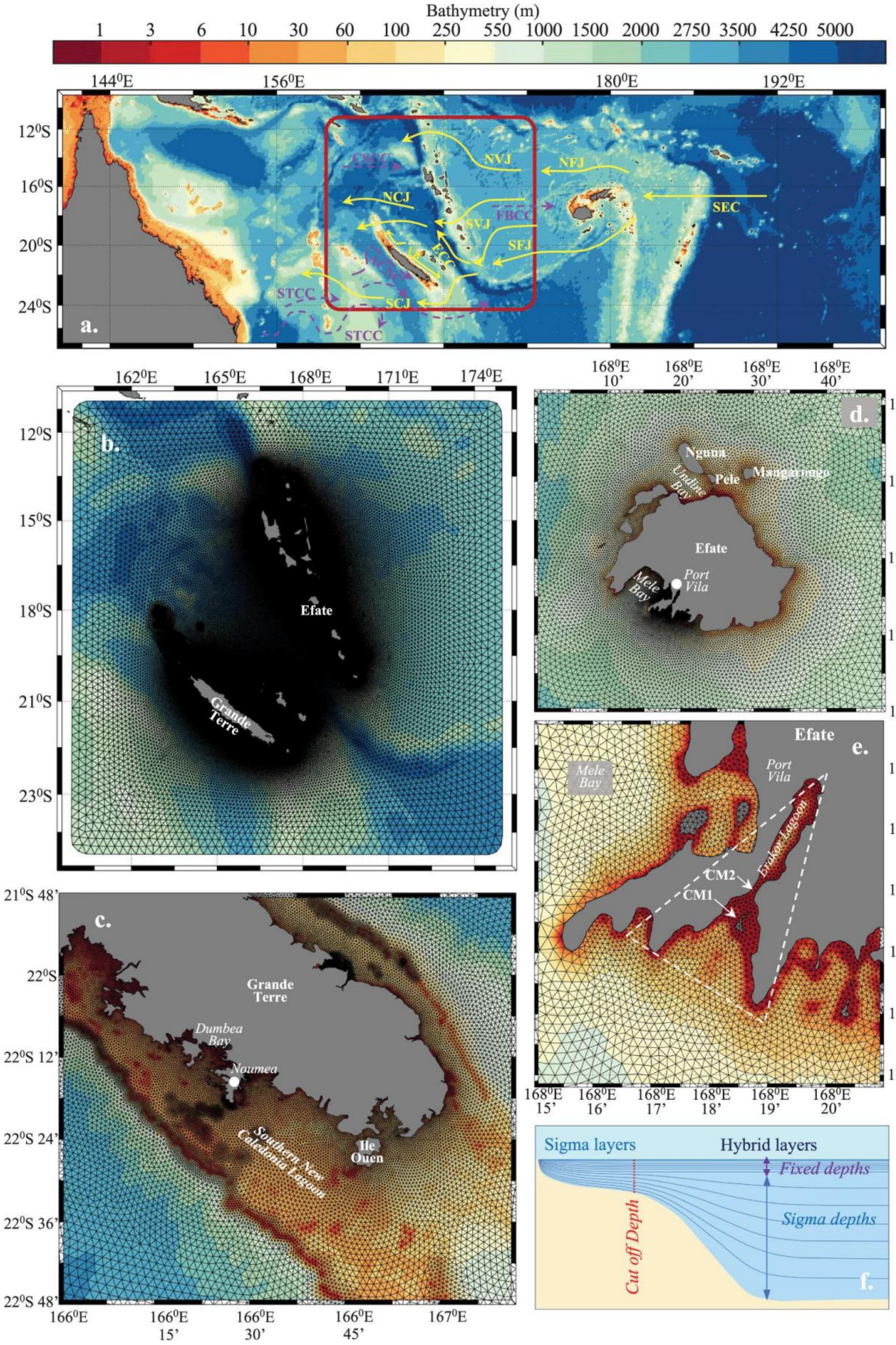

Figure 1 Site map and bathymetry of the Vanuatu and New Caledonia archipelagos (Adopted from Lee et al., 2021)

Image caption: (a) The model domain extent is shown highlighted in the dark red rectangle. The Van-Fvcom model grid constructed for the study (b) overlying bathymetry. Excerpts of the Van-Fvcom model grid covering southern Grande Terre (c), Efate Island (d) and Erakor Lagoon, Efate Island (e) overlying bathymetry. Erakor Lagoon is highlighted in the dashed white triangle (e). The legend shown at the top of the figure applies to panels (a-e). Visual description of the hybrid vertical layer system employed by the Van-Fvcom model (f) (Adapted from Lee et al., 2021)

6.2 Long-term observational data

Long-term observational data are essential for understanding the historical trends and future projections of coastal circulation. In the Zero river basin (ZRB) and Palude di Cona (PDC) coastal ecosystem in the lagoon of Venice, Italy, an ensemble of ten global-regional climate model projections was used to assess the impacts of climate change on hydrological and ecological parameters. The study found significant seasonal variations in nutrient loadings and phytoplankton composition, with a notable increase in cyanobacteria during the summer. These findings underscore the importance of using multiple climate model projections to capture the range of possible future conditions and their impacts on coastal ecosystems (Pesce et al., 2019).

6.3 Model projections of future changes

Model projections are vital for predicting future changes in coastal circulation and their potential impacts. The Atlantic thermohaline circulation (THC) has been extensively studied using a range of models, from earth system models of intermediate complexity (EMICs) to fully coupled atmosphere-ocean general circulation models (AOGCMs). These models have shown that the THC is likely to weaken significantly in response to freshwater input, with associated changes in surface air temperature and shifts in the Intertropical Convergence Zone (ITCZ). The robustness of these projections across different models highlights the potential for significant changes in coastal circulation patterns due to climate change (Stouffer et al., 2006).

By examining case studies from different regions, leveraging long-term observational data, and utilizing model projections, we can gain a comprehensive understanding of the mechanisms driving coastal circulation and their responses to climate change. This knowledge is crucial for developing effective management strategies to mitigate the impacts on coastal ecosystems and communities.

7 Ecological and societal impacts

7.1 Effects on marine ecosystems

Climate change significantly impacts marine ecosystems through various mechanisms, including temperature changes, ocean acidification, and alterations in ocean circulation. These changes affect species distributions, physiology, and ecosystem functioning. For instance, temperature and wave energy are critical drivers of ecological responses, influencing the abundance and distribution of coastal benthic macrofauna (Hewitt et al., 2016). Additionally, changes in ocean chemistry, such as acidification, may be more critical than temperature changes for the performance and survival of many marine organisms. Ocean circulation changes, which affect larval transport and population dynamics, also play a crucial role in these ecosystems (Gennip et al., 2017). The interactions between climate variables and additional anthropogenic stressors, such as fishing pressure, further complicate the ecological consequences of climate change.

7.2 Implications for coastal communities

The impacts of climate change on marine ecosystems have profound implications for coastal communities that rely on these systems for their livelihoods, food security, and cultural practices. Changes in species distributions and ecosystem functioning can disrupt fisheries and aquaculture, leading to economic and social challenges. Furthermore, the alteration of ocean circulation patterns can affect the availability of marine resources, influencing the economic stability of coastal communities (Gennip et al., 2017). The synergistic effects of climate change and other anthropogenic pressures necessitate a comprehensive understanding of these dynamics to develop effective management and conservation strategies.

7.3 Adaptation and mitigation strategies

To address the challenges posed by climate change, coastal communities and policymakers must implement adaptation and mitigation strategies. Coastal wetlands, such as seagrasses, tidal marshes, and mangroves, are recognized as effective long-term carbon sinks and play a crucial role in climate mitigation (Howard et al., 2017). Expanding climate mitigation strategies to include other components of coastal and marine systems, such as coral reefs, phytoplankton, kelp forests, and marine fauna, could enhance the effectiveness of these efforts (Howard et al., 2017). Additionally, improving predictive frameworks to manage and conserve living marine systems in the face of climate change is essential. This includes identifying key demographic transitions, predicting community-level impacts, and understanding the scales over which climate will change and living systems will respond (Stetson et al., 2006). By integrating these strategies, coastal communities can better adapt to the changing climate and mitigate its impacts on marine ecosystems and their associated economic and social systems.

8 Technological and Methodological Advances

8.1 Innovations in modeling techniques

Recent advancements in coastal circulation modeling have led to more accurate and comprehensive predictions of coastal dynamics. Innovations such as the coupling of wave and circulation models have been shown to significantly improve forecast accuracy by addressing the non-linear interactions between strong currents and wind waves. This approach has been successfully applied in regions like the German Bight, demonstrating improved model performance during extreme events (Staneva et al., 2015).

Additionally, the integration of high-resolution nested models, like those developed for the West Florida coastal ocean, has facilitated better downscaling from deep ocean models to estuarine environments. These models have shown high accuracy in simulating tidal and low-frequency variability, demonstrating their utility in both hindcasts and forecasts (Zheng and Weisberg, 2012). Recent studies have also highlighted the importance of data assimilation and real-time integration of observational data to enhance model predictions, as seen in the California Current System (Moore et al., 2011).

8.2 Advances in observation technologies

The development and deployment of advanced observation technologies have been crucial in validating and improving coastal models. The evaluation of various operational ocean forecasting services during extreme events, such as Storm Gloria, has underscored the capabilities of integrated observation and modeling systems. These systems, which include high-resolution models nested within regional models, have demonstrated their effectiveness in predicting storm-induced ocean circulation and enhancing preparedness for maritime disasters (Figure 2) (Sotillo et al., 2021).

Sotillo et al. (2021) demonstrated the hierarchical structure of ocean forecasting systems, ranging from global to regional and then to local coastal forecasting systems nested within each other. Through this nesting, high-resolution regional and coastal forecasts can obtain boundary conditions from large-scale global forecasts, thereby enhancing the accuracy and timeliness of the predictions.

Furthermore, the use of high-frequency (HF) radar, satellite sensing, and autonomous gliders provides an integrated dataset for model validation and assimilation. For example, the NYHOPS system utilizes these technologies to validate surface current forecasts, significantly enhancing the credibility of the system's predictions (Kuang et al., 2012).

8.3 Integrative approaches

Integrative approaches that combine observations, modeling, and data assimilation are essential for advancing coastal circulation studies. The synergy between models and observational data allows for the optimization of observational networks and the development of robust predictive systems. Coastal Ocean Forecasting Systems (COFS) exemplify this integration, linking observational and modeling components to provide seamless data sets and forecasts across different scales (Kourafalou et al., 2015).

These integrative systems not only enhance scientific understanding but also address practical applications such as sea-level rise monitoring, coastal management, and disaster preparedness. For instance, ensemble ocean circulation modeling has been used to improve trajectory forecasting, demonstrating the value of integrating multiple observational platforms and enhancing forecast accuracy (Melsom et al., 2012).

9 Challenges and Future Directions

9.1 Technical and methodological challenges

One of the primary technical challenges in evaluating coastal circulation and its response to climate change is the complexity of accurately modeling these systems. The use of unstructured-grid, finite-volume modeling approaches, such as the Finite-Volume Community Ocean Model (FVCOM), has shown promise in simulating coastal circulation in remote island settings like Vanuatu and New Caledonia. However, these models require extensive verification and calibration with limited observational data, which can be a significant hurdle (Lee et al., 2021). Additionally, the integration of various factors such as wind speed, direction, and sea level rise (SLR) into these models adds layers of complexity that must be meticulously managed to ensure accurate predictions (Lee et al., 2021).

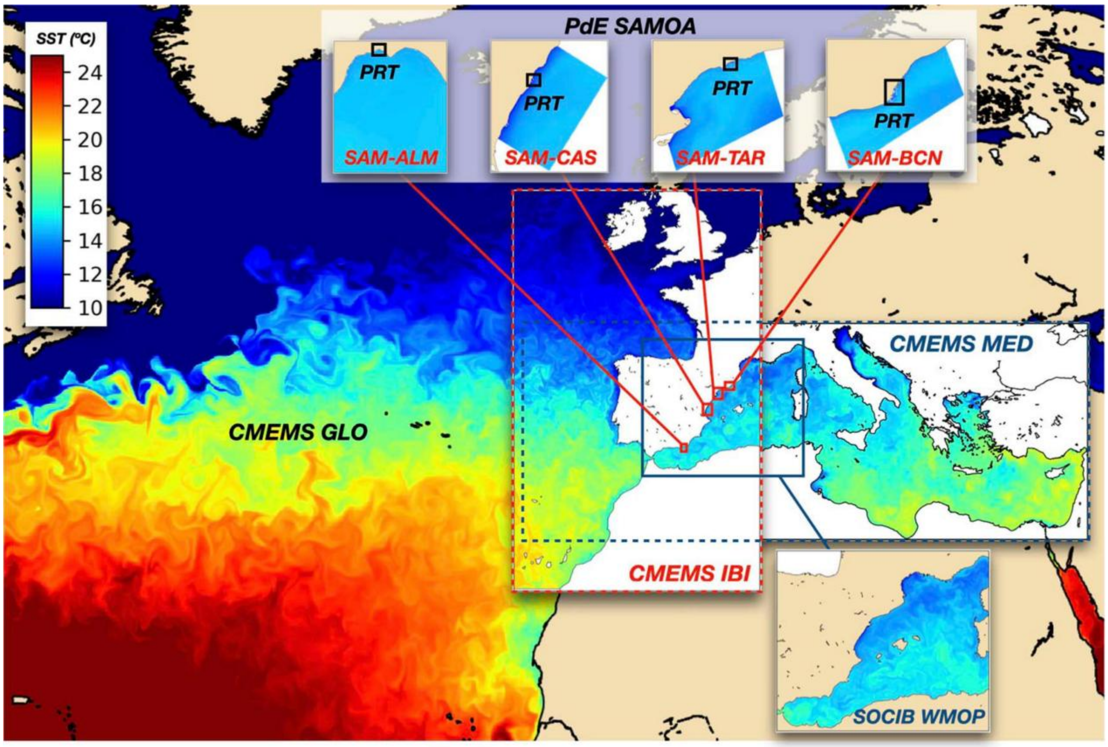

Figure 2 Map of CMEMS (GLO, IBI, and MED) and CMEMS-downstream (SOCIB WMOP and PdE SAMOA) operational ocean forecasts in the Western Mediterranean Waters of Spain (Adopted from Sotillo et al., 2021)
Image caption: Links between forecast services are depicted: CMEMS regional IBI and MED systems nest into the GLO one. Coastal systems nested into CMEMS IBI and MED are depicted in red and blue, respectively (Adopted from Sotillo et al., 2021)

9.2 Knowledge gaps and research needs

Despite advancements in modeling techniques, there remain substantial knowledge gaps in understanding how coastal circulation will respond to climate change. For instance, the non-linear relationships between SLR and maximum current speeds observed in some coastal reef platforms indicate that more research is needed to fully comprehend these dynamics 1. Furthermore, the influence of trade winds on coastal processes, and how changes in these winds due to climate change might further alter coastal circulation, is not yet fully understood (Lee et al., 2021). There is also a need for high-resolution projections of coastal wave climate and impacts, such as port operability and coastal flooding, which are currently based on statistical models that may not capture all local variations (Camus et al., 2017).

9.3 Emerging trends and innovations

Emerging trends in the field include the development of more sophisticated statistical frameworks for projecting wave climate and coastal impacts. For example, the use of a semi-supervised weather-typing approach to train statistical models has proven flexible and effective in projecting wave climate at different spatial scales (Camus et al., 2017). This method allows for the integration of changes in storminess and SLR, providing a more comprehensive assessment of future coastal impacts (Camus et al., 2017). Additionally, innovations in high-resolution modeling and the use of large ensembles of global circulation models (GCMs) are enhancing the statistical confidence of expected changes in coastal systems (Camus et al., 2017). These advancements are crucial for developing more accurate and reliable predictions, which can inform better coastal management and adaptation strategies.

10 Concluding Remarks

In evaluating the mechanisms of coastal circulation and their responses to climate change, several key findings have emerged. Research suggests that climate change may accelerate coastal upwelling by enhancing coastal wind stress. This change could lead to increased ecosystem productivity in some regions, such as an expected increase in primary productivity along the coast of the Baja California Peninsula. The weakening of the Atlantic Meridional Overturning Circulation (AMOC) is associated with a slowdown in deep ocean convection in the North Atlantic, which may be due to increased freshwater output in the Arctic and sea ice melting. Furthermore, the recent acceleration of global average ocean circulation is mainly attributed to changes in thermodynamic processes, which have enhanced the dynamics of large-scale ocean currents. It was found that the extreme precipitation events in the middle and lower reaches of the Yangtze River in 2020 and the high temperature events in southern China were largely due to the combined effects of atmospheric circulation changes and climate change.

Continued research on coastal circulation and its response to climate change is of great significance. A deeper understanding of coastal circulation mechanisms can enhance our ability to predict the impacts of climate change on marine ecosystems and coastal communities, thereby formulating more effective mitigation and adaptation strategies. Changes in coastal circulation could have profound effects on coastal ecosystems, particularly on fishery resources and biodiversity. Ongoing research will help us better protect these vital resources. Climate change may lead to an increase in the frequency and intensity of extreme weather events. By studying the interactions between coastal and atmospheric circulations, we can improve our ability to predict these events and reduce their negative impacts on human society.

To further deepen our understanding of the mechanisms of coastal circulation and their responses to climate change, future research should consider the following aspects. Develop and apply multi-scale integrated models that can incorporate atmospheric, oceanic, and terrestrial processes to provide more accurate predictions and scenario analyses. Establish and maintain high-resolution long-term monitoring networks, and combine them with advanced data assimilation techniques to obtain more accurate and comprehensive observational data. Additionally, focus on studying the impacts of climate change on specific regional coastal circulations and ecosystems, such as important fishing areas and biodiversity hotspots. Finally, promote interdisciplinary cooperation among oceanography, atmospheric sciences, ecology, and social sciences to comprehensively assess and address the complex impacts of climate change.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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