WORKSHOP REPORT

OBSERVING OCEAN BOUNDARY CURRENTS

LESSONS LEARNED FROM SIX REGIONS WITH MATURE OBSERVATIONAL AND MODELING SYSTEMS

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ABSTRACT. Ocean boundary currents are complex and highly variable systems that play key roles in connecting the open and coastal ocean through cross-slope circulation and upwelling of nutrient-rich water. The structure, strength, and variability of boundary currents are associated with a broad range of spatial and temporal scales. For that reason, long-term boundary current monitoring is challenging and requires the use of complementary observing platforms and sensors coupled with numerical simulations. The Ocean Observations Physics and Climate Panel Boundary Systems Task Team recently held a virtual dialogue series to discuss six mature boundary current monitoring systems. The goal of the series was to examine strategies for developing a conceptual design for sustained observing activities applicable to a wide range of boundary current systems. This article provides a brief overview of the six systems, including users and the observational and modeling components needed to achieve scientific, operational, and societal goals. Ocean observing best practices and recommendations are shared to provide guidance for the coordination and sustainability of observing systems at ocean boundaries and to strengthen and integrate partnerships across and within the global observing networks.

INTRODUCTION

Circulation in the coastal ocean impacts marine life and a diverse range of human activities. It is driven by land-sea exchanges, local meteorology, tides, and remote ocean forcing at the shelf-sea/open-ocean boundary. Energetic boundary currents flowing over a continental slope can mediate exchanges between the shelf and the open ocean; the biogeochemical fluxes across this boundary play a vital role in the health and productivity of many shelf ecosystems. Boundary currents transport water masses, heat, and salt, all of crucial importance in basin-scale ocean budgets. As they release large amounts of heat and moisture to the atmosphere, they also play a leading role in Earth's climate system. Combining data from long-term boundary current monitoring at key locations with data from other global ocean observing networks enables the quantification of the transports and air-sea exchanges, improves our understanding of the relationship of boundary currents to basin-scale gyre forcing and to climate variability, and helps characterize the impact of boundary current variability on coastal ocean state. Continued monitoring of boundary currents is also central to assessing ocean and climate models, improving the accuracy and reliability of weather forecasts locally and remotely, reducing biases in global climate models (e.g., the Coupled Model Intercomparison Project [CMIP] simulations), and improving climate change projections. Finally, stand-alone observations or a combination of observations and models lead to real-time and delayed-mode products that are used by government agencies, maritime industries, and civil society.

Direct observation in boundary current regions is challenging due to the difficulties of maintaining observing networks within these energetic flow regimes and of successfully capturing the wide range of temporal and spatial scales of variability. Establishment of sustained observing systems also represents a geopolitical challenge because many boundary current systems lie within the exclusive economic zones of multiple countries. Todd et al. (2019) examined the main scientific and societal reasons for monitoring boundary currents as well as their associated challenges. One recommendation was to "establish an Ocean Boundary Task Team to foster international community development and end-user engagement and to guide evolution of observing systems as user requirements change."

Acknowledging the need to better monitor coastal dynamics and ecosystems and recognizing the influence of boundary currents at the shelf edge, the Ocean Observations Physics and Climate panel (OOPC) of the Global Ocean Observing System (GOOS) established the Boundary System Task Team (BSTT)[1] in 2019. The BSTT is charged with helping GOOS develop a conceptual design for sustained observing systems in boundary current regions globally. (Hereafter, a boundary current and the coastal ocean under its influence are referred to as a "boundary current region" or BC). The OOPC coordinates the BSTT whose participants include scientists from eight countries who have expertise in observational and numerical modeling of BCs.

Between May 2021 and May 2022, the BSTT launched a Virtual Dialogue Series consisting of a series of webinars that aimed to (1) derive knowledge from six historically better observed BCs and mature observing systems; (2) engage the coastal-shelf, climate, and modeling communities to identify knowledge gaps and to inform observing system design and approaches to the synthesis of multiplatform observations; and (3) discuss how innovations in technology, modeling, and their synthesis might enhance capabilities for observing BCs. An overarching

[1] https://stag.goosocean.org/who-we-are/expert-panels/physics-and-climate-oopc/oopc-panel/oopc-activities/boundary-systems-task-team/

FACING PAGE. Photos of instruments and fieldwork in each of the six ocean boundary current regions considered in this study. (left to right) TOP ROW – Spray gliders (*Katherine Zaba/UCSD-SIO*); Smart CTD (*JFE Advantech Co. Ltd*); Retrieval of coastal temperature and velocity mooring off New South Wales (*NSW IMOS*). MIDDLE ROW – Leaving Sydney Harbor at dawn to deploy coastal moorings (*NSW IMOS*); Deep-water moored buoy (*Puertos del Estado*); Bosun of M/V *Oleander* loading AXIS with XBT probes (*Tiffany Wardman, BIOS/Arizona State University*); Spray glider, (*Katherine Zaba/UCSD-SIO*). BOTTOM ROW – 50th anniversary cruise of the Japan Meteorological Agency 137E repeat hydrographic section (*Japan Meteorological Agency*); A tide gauge along the Spanish coast (*Puertos del Estado*); Recovering the LION mooring line in the Northwest Mediterranean Sea (*Anthony Bosse/Aix-Marseille Université*); AXIS loading onto M/V *Oleander* (*Magdalena Andres/WHOI*).

goal of the Dialogue Series was to promote discussion on diverse BCs so that the knowledge gleaned can inform future observational and modeling efforts across the wide range of BC types.

Six BCs were identified as being sufficiently well observed, yet clearly different in character, to warrant inclusion in the series (online supplementary Table S1). Typically, two Virtual Dialogue presenters for each BC addressed common themes and questions: one provided perspective on the observational system, users, successes, gaps, and recommendations, while the other addressed how well models perform and how they are used in conjunction with observations to improve ocean state estimates, evaluate model skill and the adequacy of the observing system, and potentially inform how observing system design or operation might be improved. All webinars were recorded and shared publicly on the GOOS YouTube channel.[2]

The six BCs considered here are diverse in their geographical locations, physical characteristics, and impacts on the coastal zone (Figure 1). We chose three western subtropical BCs that are essential to the global climate system: the Gulf Stream (GS), the Kuroshio (KC), and the East Australian Current (EAC). They are also characterized by large mesoscale variability, and they impact the adjacent shelf seas. The other three BCs have weaker transports but play key roles in shelf-open ocean exchanges: the California Current (CC), one of the four biologically productive eastern boundary upwelling systems; the Northern Current of the Northwestern Mediterranean Sea (NWM), which extends from the Ligurian Sea to the Catalan Sea; and the Iberian Poleward Current (IPC), an eastern boundary current.

This article provides a synthesis of ocean observing best practices and other lessons learned from the webinar presentations. A brief overview of the evolution of each of the observing networks in the six systems is followed by a discussion of users and impacts. The observational and modeling components are then presented. We close with recommendations for the coordination and sustainability of existing and planned observing systems.

ORIGINS AND ORGANIZATION OF THE BC OBSERVING SYSTEMS

Origins

The first lesson learned is that, although all six observing systems share many similarities in terms of the platforms deployed (see Figure 2), the initial reasons that led to their establishment are varied. A simplistic view suggests that early observations of near-coastal BCs (IPC, CC, and in the coastal regions around Japan) tended to be strongly motivated by societal needs, such as fisheries management and port engineering. In contrast,

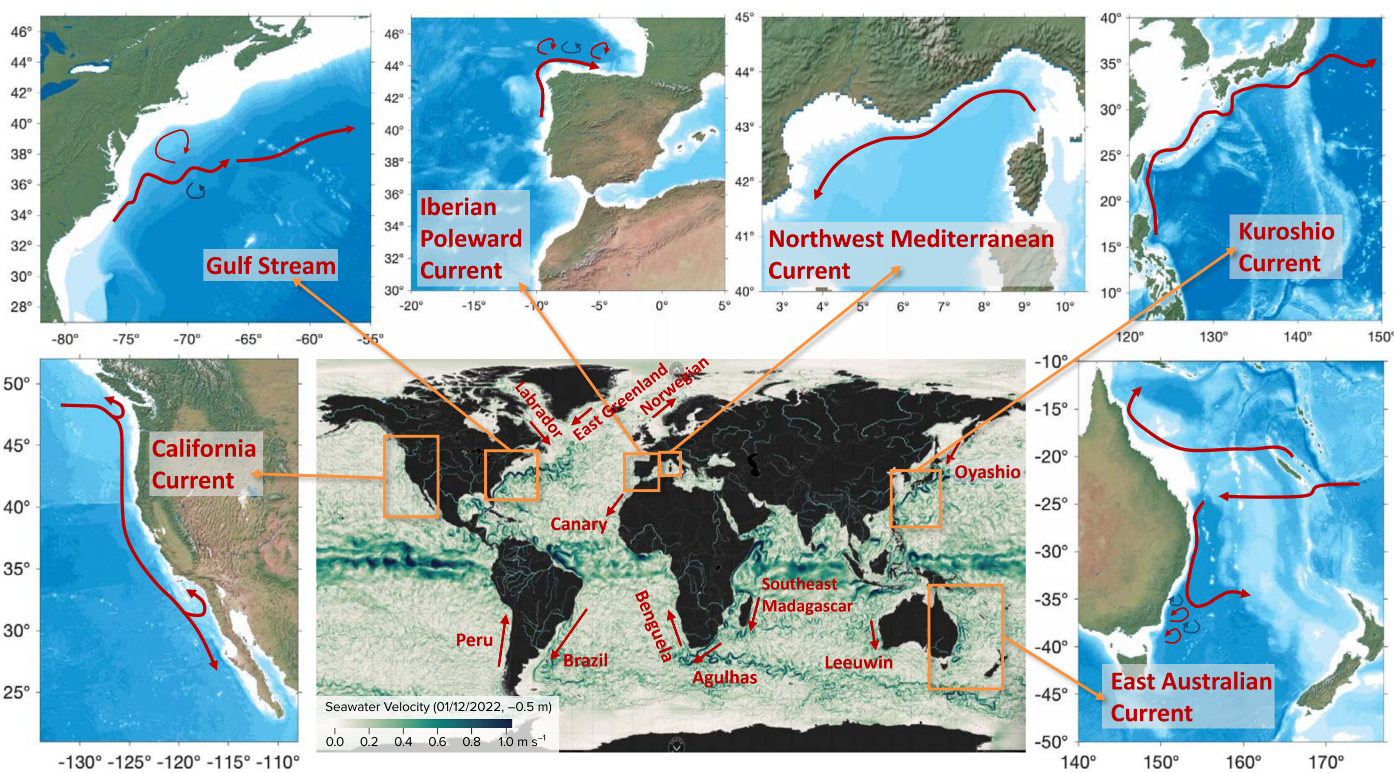


FIGURE 1. (central panel) Map of the daily averaged sea surface current velocity for December 1, 2022, provided by the EU Copernicus Marine Service (https://doi.org/10.48670/moi-00016) and main boundary currents (red arrows). (side panels) Bathymetric maps of the six regions examined in this paper and schematic representation of the boundary currents.

[2] https://youtube.com/playlist?list=PLW0pjUOdFzLmUo5QcJpi8PNAbOLrpyF-j&feature=shared

in the EAC, NWM, and open regions of the GS and KC, the initial motivation for modern observational programs was to gain a better understanding of the dynamics that characterize BC variability, continental shelf processes, and biogeochemical cycles.

The six observing systems were assembled either by government agencies or by research groups (typically funded by government agencies) and date to the mid-twentieth century or earlier. In the CC and coastal KC, the observations were initiated by fisheries management agencies, the California Cooperative Oceanic Fisheries Investigation (CalCOFI) program (established 1949) and the Japanese prefectural fisheries research institutes (1930s), respectively. The KC path, velocity, and volume transport have been studied through a network of tide gauges since the 1980s, while the Japan Meteorological Agency has conducted repeat transects across the KC since the 1960s (e.g., Oka et al., 2018). NOAA-funded monitoring of the temperature structure across the continental shelf to the northern edge of the GS was initiated in the late 1970s; in the early 1990s, measurements of ocean velocity profiles were added, first supported by the US Office of Naval Research, later by the National Science Foundation. Transport of the GS through the Florida Straits began to be monitored in the 1980s using an abandoned submarine telephone cable (Meinen et al., 2010). In the EAC, the first observations at fixed stations date to the 1940s, and expendable bathythermograph (XBT) lines were inaugurated in 1991. In the early 2000s, a group of ocean experts began to advocate for a coordinated ocean observing system for Australia that culminated in large-scale government funding of the Integrated Marine Observing System (IMOS) in 2006/2007. A similar evolution occurred for the NWM: building upon observations initiated by scientists in the 1990s, the Mediterranean Ocean Observing System for the Environment (MOOSE) was established in 2010 by the French Centre National de la Recherche Scientifique (CNRS) (Coppola et al., 2019). The oldest and most comprehensive component of the IPC observing system is Portus, developed by the Spanish government agency Puertos del Estado and now integrated in the Copernicus Marine Environment Monitoring Service (CMEMS) and the European Marine Observation and Data Network (EMODnet) framework. Evolving from a few coastal buoys in the 1980s, the IPC observing system expanded between the 1990s and 2010. The current concept of Portus as an integrated service and one-stop information hub for the region was born around 2010 (Alvarez-Fanjul et al., 2018).

In the six regions studied, the observing systems were designed by regional experts using local knowledge about dynamics and important processes that

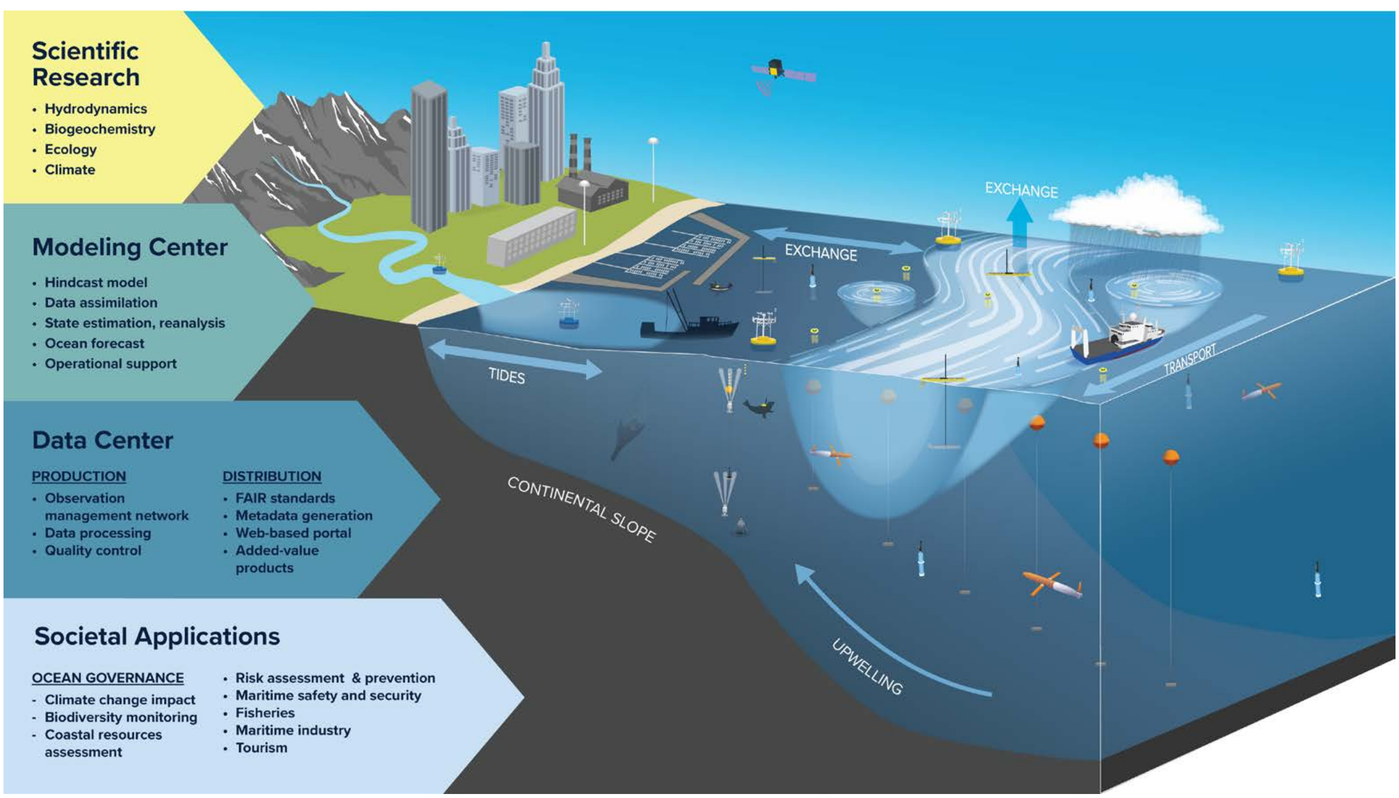


FIGURE 2. Schematic representing the three components of a boundary current observing system—observations, data center, and modeling center—and the roles of users and scientists. The types of observational sensors and platforms shown are scientific vessels, gliders, XBTs, fixed moorings, ocean bottom sensors, tide gauges, high-frequency radars, hydrological stations in rivers, animal telemetry, and satellites. *Figure by Natalie Renier, Woods Hole Oceanographic Institution*

needed to be observed. In the IMOS case, regional experts were first brought together in state-based nodes to debate the observing system design. These ideas were crystallized in written plans that were circulated internationally for peer review in order to benefit from the advice of experts in other regions with prior experience. In addition to the advice of regional experts, input into observing system design can be sought from funding agencies or regional agencies interested in a particular phenomenon or application (e.g., fisheries).

Over the past decade there has been a move toward observing system simulation experiments (OSSEs) in which ocean modeling and data assimilation are used to evaluate the effectiveness of observations in informing models. On a smaller scale, regional data assimilation experiments are now more widely used to infer the optimal location of observations and to guide model integration. Yet, from the webinars, none of the six systems appear to have been designed from OSSEs. Instead, OSSEs are conducted a posteriori to assess the ability of the observing systems to provide observations relevant to the study of specific processes or to constrain numerical models.

Evolution and Current Organization

Over time, as the motivational underpinnings and users have broadened, all six observing systems have been enriched through the evolution of the global observing system (NRC, 1997) and the introduction of new platforms and sensors as well as the evolution of modeling systems. Governance and organization have also evolved. In some cases, efforts have coalesced into structures managed by one or several agencies with centralized governance and sustained funding, dedicated human resources, and infrastructures for data management and distribution. This is the case for the EAC and MOOSE. The KC and GS observing systems are less centralized and composed of national or regional components that coexist with varying degrees of coordination. For the CC, CalCOFI and three Regional Coastal Ocean Observing Systems of the US Integrated Ocean Observing System that operate along the southern, central, and northern coasts of the US West Coast are complemented by the NSF Ocean Observatories Initiative and by Ocean Networks Canada and Investigaciones Mexicanas de la Corriente de California. All of these systems are primarily funded by national and local governments through numerous agencies. Industry engagement and co-investment are also sought when observing systems are designed to bring greater benefit to marine industries.

We distinguish three types of funding: (1) long-term funding allocated in different forms that include purchase and maintenance of instruments, building and governance of data management and distribution infrastructure, and dedicated human resources; (2) funding (often shorter term of 3–5 years) for research projects, led by scientists, that specifically support the observing systems; and (3) occasional funding for research projects that can benefit the observing systems.

USERS AND IMPACTS

Scientific Community

The scientific community is not only a key contributor to the establishment of an observing system but also a major user of the observations to improve knowledge of ocean and climate variability. Observations are also used for model assessments or assimilation into the models. Scientific process studies encompass a wide range of fields, such as alongstream/along-coast transports; cross-stream/cross-shore, air-sea exchanges; BC impact on shelf circulation; mesoscale and submesoscale processes; low-frequency climate variability and extremes; marine ecosystem variability and response to climate change; impacts of continental water, sediment, and biogeochemical material exchanges; budgets of greenhouse gases; ocean biogeochemical cycles; acidification; and biodiversity.

Boundary system measurements have constantly improved our scientific knowledge about these processes. For instance, the advent of gliders and high-frequency (HF) radars has led to a better understanding of the processes in the transition area between the coast and the open ocean and the fine-scale variability in coastal areas, respectively (e.g., Rudnick et al., 2017, regarding the CC). Many results are achieved by combining datasets from various observing platforms, sometimes to build indices of ocean and climate variability. For instance, variability in the Kuroshio's path has been assessed using hydrographic observations, coastal tide gauge measurements, and satellite altimetry (e.g., Qiu and Chen, 2005). In the NWM, gliders, moorings, and acoustic Doppler current profiler (ADCP) measurements have been used to study the impact of wind on Northern Current shelf intrusions (Barrier et al., 2016) and on frontal instabilities (Bosse et al., 2021).

The webinars also highlighted the importance of systematic, sustained long-term monitoring programs. Time series extending over decades are often achieved through repeated research cruises or continuous-in-time measurements at fixed platforms. For instance, one major success of CalCOFI is long-term monitoring that has allowed characterization of past extreme environmental events (e.g., marine heatwaves, hypoxia, and ocean acidification). In addition, the long CalCOFI time series serves as a standard for emerging sensors and regional model validations. Ship-of-opportunity measurements have also proved invaluable over the long term, such as the 25-year GS transport time series conducted with M/V *Oleander* (Rossby et al., 2019). Long time series are also obtained by consistently aggregating datasets from different sensors (e.g., Roughan et al., 2022).

Finally, the webinars evidenced the crucial role of observations in calibrating models and assessing simulations as well as the importance of assimilating observations into models for both hindcasting and prediction.

Operational Community

All six of the BC systems provide data to national or international operational agencies and weather and ocean forecasting centers. Routine observations with high spatial and temporal resolution are assimilated in global, regional, or coastal systems and are found to have a large impact on model assessment and on prediction. However, no quantitative assessment of the impact on predictions was presented during the webinars.

In some cases, such as the KC, observations obtained by state and local government agencies are routinely assimilated into numerical models operated by other national agencies. Forecasts are then provided to the former agencies: this steady feedback cycle has led to significant improvements in forecast quality and reliability and in practical use of forecasts by the agencies. Recently, stakeholders such as regional fisheries have been added to the cycle, especially for coastal areas. Fishers measure temperature and salinity with mobile CTD instruments that are relatively easy to handle in their own fishing fields, and the measured data are transmitted directly to the assimilation system.

In data assimilative models, impacts of observations can be far reaching in space and time. For instance, in the EAC, Kerry et al. (2018) show that surface radial velocity observations from HF radars constrain vorticity estimates inshore of the EAC both up- and downstream of the radar location, and that in situ observations are key to correctly representing the structure of the thermocline. Their results, reinforced in OSSEs conducted by Gwyther et al. (2023) to examine the utility of assimilating XBT data, highlight the importance of observing a BC's dynamic downstream eddy field.

Government Agencies, Industry, and Civil Society

National and local governments rely on observations and on reliable forecasts and long-term predictions for improved ocean governance (e.g., marine protected area management), for risk assessment and prevention (e.g., in cases of pollution, harmful algal blooms, storm surges), and for maritime safety and security. Another downstream beneficiary of the observing systems is the blue economy sector: fisheries, the aquaculture industry, maritime offshore enterprises (oil and gas and renewable energy), and tourism and recreational organizations. Additional end users include civil society, journalists, nonprofit organizations, and educators. For instance, groups of about 10 students are trained every year during a three-week cruise in the MOOSE framework.

The webinars provided various examples of impacts on non-scientific end users. First, observing systems allow monitoring of the ocean state (physical parameters, water quality, ecosystem health), coastline variations, and resources (e.g., fish stocks). Within the CC, environmental forecasts and nowcasts are used to improve management decisions for fisheries, protected species, and ecosystem health. In the NWM, chlorophyll and zooplankton observations at fixed stations are used to build biodiversity indicators for a governmental agency, in line with the European Marine Strategy Framework Directive. Short- and mid-term forecasts are used to prepare or facilitate offshore operations (e.g., search and rescue, industrial activities) and navigation. For example, the Portus tools for societal use (e.g., website) and the downstream products that allow optimization of operations and cost reduction for 46 ports typically have about 8,000 users per day.

Second, managing the risks associated with industrial accidents or natural hazards requires a reliable network of observations, numerical simulations to examine different scenarios, and forecasts to anticipate impacts. For instance, current research is seeking to establish metrics from observations for detecting and characterizing marine heatwaves (e.g., MOOSE). Portus established an early warning system for storm surges that has resulted in significant cost savings through increased preparedness, as demonstrated during Storm Gloria in 2020 in the Mediterranean.

One important lesson that emerged from the webinars is that there is a significant lack of systematic accounting for end users, which can adversely affect long-term funding. While most users understand how observations can improve ocean management and support economic endeavors, the direct economic benefits of the observing systems are often poorly accounted for when measuring their impacts. Measuring these impacts is crucial, however, because it helps guide system funding, management, and design. The scientific knowledge gained from observations is directly assessed through classic academic metrics (e.g., publications), but the added value for societal and economic uses is more difficult to measure systematically, and no specific examples were given in the webinars. Eventually, the impact is assessed through the use of products resulting from data assimilation, either at global or regional scales. This situation is likely to change in the near future for two reasons. First, the increasingly improving quality and reliability of weather and ocean forecasts and of climate predictions should lead to stronger societal reliance on continued in situ ocean observations. Second, there are growing efforts toward mitigating and adapting to global changes. For example, IMOS is examining how data are used to advance sustainable development goals by studying industry patents and how the data are used in five societal benefit areas: biodiversity and conservation, coastal populations, energy security, food security and maritime safety, and sovereignty.

OBSERVING SYSTEM COMPONENTS

Measurement Requirements

Observing system components vary from region to region to allow a balance among the scientific, societal, and operational needs that vary from one region to another. Nonetheless, primary requirements common to all systems can be summarized as follows:

1. Measure essential ocean and climate variables (EOVs, ECVs): surface and subsurface temperature, salinity, currents, sea state, ocean surface heat flux and stress, sea surface height, nutrients, oxygen, inorganic and dissolved organic carbon, particulate matter, transient tracers, nitrous oxide, stable carbon isotopes, ocean color, biomass and diversity of phytoplankton and zooplankton, fish abundance and distribution. Other EOVs for biology and ecosystems were not specifically mentioned in the webinars, which primarily focused on the physical systems, but should be considered for comprehensive observation of the BCs.
2. Resolve along-stream variability at scales of O(100) km, cross-stream variability and shelf-deep ocean exchanges at scales of O(1–10) km.
3. Resolve temporal scales from seconds to years (ranges differ from variable to variable).
4. Maintain measurements at historical sites to create long-term climate-scale records.
5. Build redundancy to cross-check observations from different platforms/sensors and to ensure resiliency when individual observing system components fail.

Fulfilling these requirements, particularly considering the wide range of spatial and temporal scales, requires a mix of complementary platforms and technologies (**Figure 2**). Cronin et al. (2010) and Todd et al. (2019) provide comprehensive discussions on the variables that should be observed and their requirements. The platforms typically used and recommended are those described in Send et al. (2010) for all BCs and in Cronin et al. (2010) more specifically for monitoring air-sea fluxes in western BCs. The BCs also benefit from platforms operating at global scales, particularly the Argo program and satellite data (e.g., altimetry, sea surface temperature). As technology evolves, more autonomous platforms, with more interdisciplinary measurements (e.g., biogeochemistry on Argo, waves on gliders) and low-cost instruments (e.g., mobile CTD), could be added to previously published lists.

The observing systems are designed according to regional ocean variability and accessibility. Practical concerns of maintainability and survivability also need to be considered. For instance, autonomous observation platforms are not as active in the KC due in part to ongoing fishing activities.

Over time, observing systems often serve a broader set of users, which can lead to adjustments in observation strategies. As these changes can present risks to the long-term consistency of data, maintaining standards for minimum types and quantities of observations can mitigate the risks. In the CC for instance, the approach has focused on long-term integrity by maintaining strategic historical measurements along various CalCOFI lines when updating sampling sites and methodologies.

None of the six observing systems are capable of measuring all the important variables at all desired scales and times. In addition to the gaps inherent in the designs, unplanned gaps occur due to environmental hazards, accidents and vandalism, and unavailability of funds or ships. Good regional cooperation and partnerships are essential in minimizing these gaps (e.g., Barth et al., 2019). In the United States, observing systems are generally networked through regional associations. The approach in European countries is slightly different, as most nations benefit from larger European structures such as CMEMS.

We did not hear in the webinars a distinction between what is needed for research and what is needed for societal or operational uses. We heard that the initial motivations for the observing networks were diverse, with some systems more oriented toward science, others toward applications (fisheries, navigation), but they all evolved toward systems with multiple kinds of users.

Data Distribution and Products

Successful presentation of oceanographic data requires unified quality assurance and quality control under the FAIR principles (findable, accessible, interoperable, reusable; Wilkinson et al., 2016). Usage and re-usage are facilitated by offering consistent metadata. Operational centers for weather and ocean state forecasting and nowcasting rely heavily on high quality real-time data. The FAIR standards impose substantial demands on the data providers. Challenges can be faced by obtaining buy-in to fund the requirements for open access data policies. While the BC systems reviewed here mostly conformed to these data dissemination methodologies, different pathways were taken to success. Certainly, all of the reviewed systems adhered to providing open access data in real time or near-real time. In the European (Portus, MOOSE) and EAC/IMOS systems, all near-real-time data were distributed by central operational services, namely CMEMS and the Australian Ocean Data Network, respectively. Delayed-mode data are stored in local, national, and sometimes international databases, such as EMODnet for MOOSE. In the CC and GS, the requirements for open access data are met through platforms' individual Data Assembly Centers, or alternatively, data are aggregated and distributed through the relevant regional offices of the US Integrated Ocean Observing Systems. For the KC, the observing system and data management are less unified. So far, data distribution is not fully centralized and remains the domain of each agency, but there is a single portal for visualizing data layers for different applications, called MSIL (Maritime domain awareness Situational Indication Linkages).

Value-added products are also made available by the data centers, such as real-time visualization displays or early warning systems for anomalous and extreme conditions. In Japan, comments are frequently provided by Japanese scientists to facilitate interpretation of forecasts by ordinary citizens through the

Kuroshio-Oyashio Watch website of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Modeling Requirements

Observations are essential for the model validation and data assimilation that enable model development, state estimation, operational forecasting, and research. These different uses imply the need for different types and qualities of observations: sampling in space and time, accessibility (e.g., real time or delayed mode), quality control, calibration, uncertainty estimates, etc. Operational forecasting systems require routine, easily accessible, and quality-controlled observations in real time. For reanalyses, consistent time series are preferred for the duration of the model run, although all observations are useful. For free running models, independent datasets with broad spatiotemporal coverage are required for validation. For specific model developments, dedicated measurement campaigns (process studies) are usually required in addition to regular observations. In all cases, consistent metadata and good characterizations of errors and uncertainties are required.

The main challenge in modeling BCs is to resolve the dynamics across multiple temporal and spatial scales simultaneously: the highly energetic boundary current in the deep ocean, the coastal dynamics and the shelf-deep ocean exchanges that are mostly driven by the interactions of the flow with bathymetry. Model-observation synergy in the coastal ocean raises specific issues, in particular because of the fast dynamics due to tidal, atmospheric, and hydrological (continental) forcings (De Mey-Frémaux et al., 2019). To assess the dynamics at all scales and, for data assimilation, to constrain different scales simultaneously, synoptic observations are needed at the relevant scales. In particular, full-depth, in situ observations are crucial when the circulation interacts with the sloping topography. The representation of mesoscale and submesoscale processes requires high density observations in time and space (in both horizontal and vertical dimensions) in order to capture relevant structure and variability. The webinars provided examples of combined uses of satellite altimetry with tomography, moorings, gliders, hull-mounted ADCPs, and high-resolution XBTs (KC, EAC, CC, GS) and of modeling strategies based on nested models from regional to coastal domains, sometimes to the scales of ports (Portus).

While the webinars provided numerous examples of observations complementing modeling, they also showed how modeling activities (including data assimilation) benefit the observing systems. Models complement and enhance the value of the observations, assist in the interpretation of data, and contribute to the design of observation networks. Development of new measurement technologies and products should rely on feedback from modelers and the needs for data assimilation (Miyazawa et al., 2021).

The degree of integration between modeling and observing groups varied across regions, and this is a growth area for many observing systems. For example:

1. In Portus, the observing and modeling activities are integrated within the same infrastructure and were co-designed to address the operational needs of Spanish ports while also serving many different socioeconomic sectors.
2. In MOOSE and the EAC, the observing network and data distribution are managed by one body; the data feed into various databases, research modeling systems (e.g., SEA-COFS in the EAC; Roughan and Kerry, 2023), and operational forecasting centers (e.g., CMEMS for MOOSE). Whereas the modeling and observing systems are tightly connected, they are usually funded and operated independently.
3. In the KC, CC, and GS, the structure is more complex; the observation networks are managed by several national or regional bodies that are linked to each other with varying degrees of coordination. Some of them integrate a modeling component while others are connected to external forecasting centers. For instance, the Japan Meteorological Agency, JAMSTEC, and Japan Fisheries Research and Education Agency have been operating both observation and modeling systems. In the CC, NOAA supports forward and data assimilative models within regions of coordinated observing networks such as the recent West Coast Operational Forecasting System (Kurapov et al., 2017).

RECOMMENDATIONS

In this study, we examined six diverse boundary current systems (western boundary, eastern boundary, slope currents) whose observing systems differed in their organization and main motivations, from ocean-weather-climate predictions assembled through assimilation of data into models for the most energetic regions to fisheries management, navigation, or port operations and safety in coastal systems. Although network design varies significantly, we found that instrumentation and observation platforms are largely the same across the systems as they are designed to measure the main physical and biogeochemical EOVs and ECVs. An important lesson learned is that in all six cases, the observations serve a wide range of uses beyond the initial targets.

Given the roles of boundary currents in heat and mass redistribution and in air-sea exchanges, and their impacts on coastal regions, we advocate for maintaining the present observing systems and establishing new ones in poorly observed BCs. The lessons learned from the webinars together with the internal expertise of the BSTT members lead us to propose the following recommendations to guide programs in the development of BC observing systems.

1. Observing System Design

To ensure a fit-for-purpose and sustained observing system, a co-design approach should be adopted, gathering scientists, users, organizations, and funding agencies to define the objectives, to identify the essential observational targets and the appropriate sampling approach, to identify the needs and the strategy from observations to end products, and to set up a feedback loop between the observing system managers and the users. There is no need for operational and societal requirements to oppose research requirements in designing the observation network, as most observations are useful to both requirements. However, as all BCs are different in their physical characteristics and impacts on the coastal zone, there is no standard observing system that could be transferred from one BC region to another.

2. Observations

The observing systems should consist of multidisciplinary observatories that provide essential physical, geochemical, and biological ocean and climate variables co-located in space and time. Measurements of air-sea fluxes (heat, water, momentum, CO_2) should be included, especially in western boundary currents. Long-term, sustained observations should be secured while allowing for regular reassessment and incorporation of new technologies as they reach more advanced stages of readiness. Diversified observing system composition that includes some level of redundancy, along with solid regional cooperation, could help to limit system vulnerability to various types of crises (e.g., war, pandemics, piracy, economic collapse). Finally, we advocate that sustainability issues and the impacts of observing systems on the environment and the climate should be central to consideration of the future of these systems.

3. Model-Data Integration

Each observing system should include a data center that distributes observations and products derived from the observations along with a modeling and forecasting center for ocean, weather, and subseasonal-to-seasonal predictions, where the observations are assimilated (Figure 2). Strong and continuous interactions between the observing and modeling communities should be encouraged; in particular, models or data assimilation can be used in the design of the observing network. Feedback from modelers should help to refine the data distribution strategy and evolution of the BC observing system. Additionally, modeling systems can lead to value-added data products that increase the use and uptake of the observations.

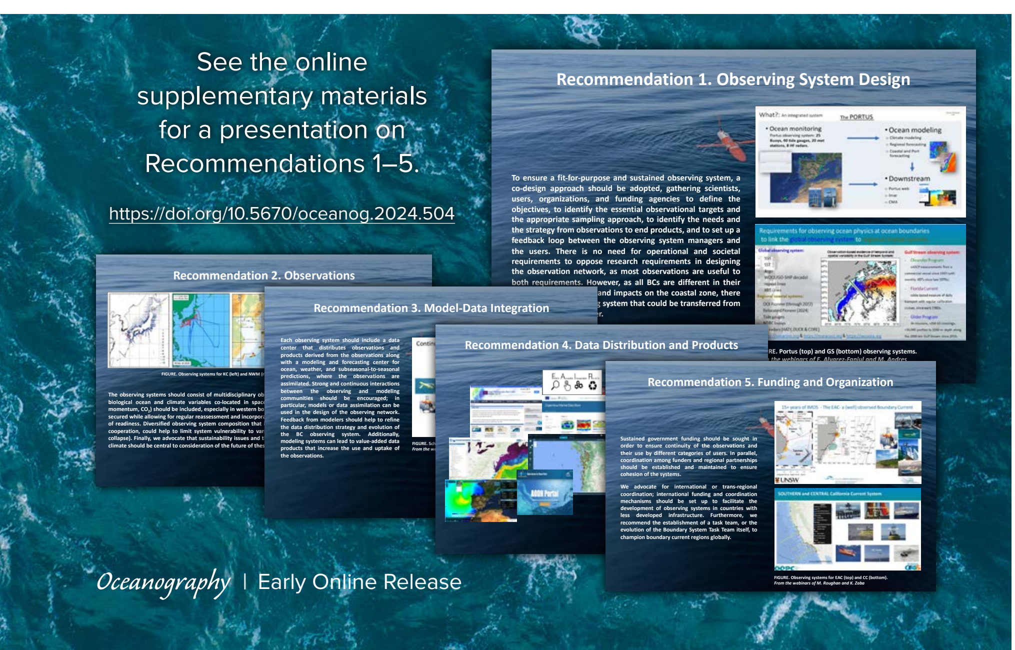
4. Data Distribution and Products

Data distribution and products should rely on FAIR principles and on data portals designed to facilitate and reinforce the (re)use of the observations and products. Metadata and file formats should enable interoperability between data centers, while accurate error estimates for all measurements and derived products must be provided. Allocating financial and human resources is vital in order to move beyond data to products, but strengthening the evaluation of product usage by policymakers, the private sector, and the general public is crucial to ensure user uptake. A first step toward assessing how the observing systems can better meet user needs might be inspired by the concept of "checkpoints" developed by EMODnet (https://emodnet.ec.europa.eu/en/checkpoints).

5. Funding and Organization

Sustained government funding should be sought in order to ensure continuity of the observations and their use by different categories of users. In parallel, coordination among funders and regional partnerships should be established and maintained to ensure cohesion of the systems.

We advocate for international or trans-regional coordination; international funding and coordination mechanisms should be set up to facilitate the development of observing systems in countries with less developed infrastructure. Furthermore, we recommend the establishment of a task team, or the evolution of the Boundary System Task Team itself, to champion boundary current regions globally.



A step toward implementing these recommendations could be to identify opportunities in less observed boundary current systems for developing pilot or process experiments that would prototype new coordinated networks guided by the experiences described here.

The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) provides a framework that should reinforce partnerships and the sharing of best practices. Among the programs endorsed as part of the Ocean Decade, the GOOS Observing Co-Design program aims to enhance ocean observing by working closely with the users of information around six application areas known as exemplars. The Boundary Currents exemplar will provide an opportunity to test the recommendation of the BSTT within the Agulhas Current, which is a very poorly sampled and critical boundary system region. We expect that a coordinated strategic vision might emerge through our recommendations in concert with the BC exemplar group, possibly under the auspices of the Ocean Decade.

SUPPLEMENTARY MATERIALS

The supplementary materials are available online at https://doi.org/10.5670/oceanog.2024.504.

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