WESTERN BOUNDARY CURRENT–SUBTROPICAL CONTINENTAL SHELF INTERACTIONS

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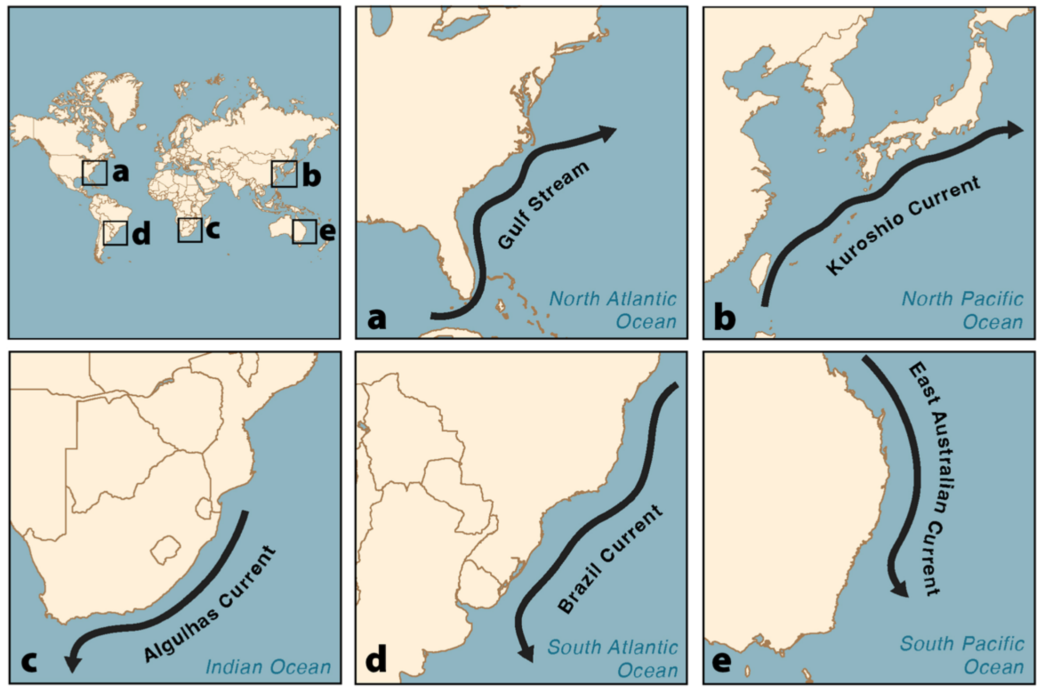

FIGURE 1. The western boundary currents and adjacent subtropical shelves discussed at the Western Boundary Current–Subtropical Continental Shelf Interactions Workshop.

Western boundary currents (WBCs) adjacent to subtropical continental shelves (STCSs; between ~25° and 35° latitude; Figure 1) transport heat, nutrients, and biota poleward along the western margins of major ocean basins, interacting with the continental margins and influencing their physics and biology. Eddies and meanders along the shelf edge upwell deep, nutrient-laden water that can be advected onto the adjacent shelves with a corresponding export of particle-rich shelf water (e.g., Lee et al., 1991; Kimura et al., 1997; Campos et al., 2000; Roughan and Middleton, 2002, 2004; Lutjeharms, 2006; Savidge and Savidge, 2014). Despite their similarities, the various STCS regions display key differences with respect to boundary current strength and variability, shelf width and geometry, and trophic structure. Comparative analyses of the physical forcing and biological responses among STCS have the potential to reveal common underlying properties, forcing mechanisms, and sensitivities to climatic perturbations that are not possible to elucidate with region-specific studies. This kind of fundamental understanding of relationships between physics and biological responses is critical to predicting consequences of environmental change across a wide range of spatiotemporal scales.

In May 2023, the Western Boundary Current–Subtropical Continental Shelf Interactions Workshop brought together researchers from around the world to Savannah, Georgia, USA, to discuss dynamics of WBC-STCS systems and to explore potential strategies for observing and modeling these systems in a comparative and cooperative fashion. Participants in the workshop included representatives of several recent regional and international initiatives, including

Integrated Marine Observing System (IMOS, Australia), Processes driving Exchange At Cape Hatteras (PEACH, USA), Macro coastal oceanography (Macrocoast, Japan), and the Global Ocean Observing System (GOOS) Boundary System Task Team (Global). Workshop breakout sessions focused on six themes: effective observational strategies, modeling WBC-STCS systems, scaling of processes, cross-shelf exchange, ecosystem processes, and future climate-related impacts.

Here, we summarize group discussions in the context of the interplay between observations, models, and theory; their combination is required to make progress in understanding physical drivers of physical and biogeochemical variability. More thorough and higher-resolution observations would improve model skill and illuminate theoretical deficiencies by resolving the underlying processes being modeled (see sections on scaling, observing, and modeling). Such progress would be useful for quantifying cross-shelf exchanges of biogeochemical constituents and addressing their ecosystem and climate change ramifications (see sections on exchange, ecosystems, and climate).

SCALING OF PROCESSES

Historically, physical oceanography can be characterized by three powerful assumptions: (1) there is a single relevant scale in play for each physical parameter for any given process in a particular environmental setting; (2) small perturbations of the parameters in time and space about those expected scales will result in the equations being separable into different sets for different diminishing scales; and (3) each of those different scales presumably does not interact with other scales of motion. Observing and modeling oceanic circulation at increasingly smaller scales has made it apparent that these three assumptions do not hold for many processes relevant to biogeochemical-physical oceanographic (BGC-PO) interaction (e.g., carbon cycling, sequestration, and fisheries), because the scales of particular BGC processes may not match "predominant" PO scales. For example, relevant BGC scales may change rapidly as phytoplankton blooms are overtaken by responding consumers. Moreover, similar physically driven events may result in a range of BGC responses; conversely, BGC processes may be related to multiple physical scales simultaneously, contradicting the classic physical oceanographic worldview of statistical stationarity, periodicity in time, and in many cases, an assumption of homogeneous spatial character in one or more directions at all scales below those being measured or modeled. This PO worldview is not reconciled with BGC reality simply by expanding the ranges of physical scales examined.

Wide-ranging discussions during the workshop provided numerous examples of the logistical strategies and difficulties of measuring evolving BGC processes at small scales over wide inhomogeneous areas subject to strong physical forcing. Nonetheless, understanding and predicting shelf PO-BGC interactions motivates observing and modeling the biology and chemistry within the physical environment over a widening range of spatiotemporal scales. Equally important will be addressing process linkages across scales. This requires refining physical, analytical, and idealized modeling approaches to retain the terms that induce interactions between scales. Better analytic exposition of important processes is extremely useful in designing observational strategies. Interdisciplinary discussions will continue to help identify weaknesses in even spatially/temporally dense, equations-based, and integrative output from numerical PO and BGC modeling.

EFFECTIVE OBSERVATIONAL STRATEGIES

Increasing the effectiveness of observational strategies rests on increasing spatiotemporal resolution and improving the range/accuracy of observed properties. To complement limited sustained government investment in long-term observatories, other preexisting assets should be leveraged to help fill observational gaps on STCS shelves. Instrumentation provided to volunteer fishing vessels (e.g., Van Vranken et al., 2023); fixed to turtles, seabirds, and marine mammals (Harcourt et al., 2019); and placed on existing weather buoys could be expanded and diversified to sample a wider variety of parameters, including BGC variables.

To maximize the applicability of observations to elucidating key biological and physical mechanisms, along with forecasting and hindcasting capability, workshop participants stressed the need to combine sensors that collect data on overlapping spatiotemporal scales. The instrument suite available for in situ BGC observations remains limited, especially for sustained efforts. Observations of BGC parameters are often averaged over large spatiotemporal scales at much lower resolution than PO parameters and are typically either limited to the near surface (e.g., remote sensing) or collected sporadically during ship-based research projects. Improving the consistency and resolution of biogeochemical observations should be a priority. The advective nature of WBC-STCS systems makes observational hurdles especially acute for biological variables, because an observation at any given location may reflect conditions encountered well upstream. Mobile sampling platforms, such as ship-towed imaging vehicles (Lombard et al., 2019) or gliders (Ohman et al., 2018), coupled with oceanographic sensors, can resolve biological and BGC properties along Lagrangian trajectories, or at least provide high-resolution oceanographic context to measurements.

Connecting synoptic BGC observations to key processes could be improved by resolving in situ biological rates (e.g., Carvalho et al., 2020) in order to add value to modeling cross-disciplinary questions in ocean science. Workshop attendees stressed the need for sustained, long-term WBC-STCS observations to generate climate-relevant datasets.

MODELING OF WBC-STCS SYSTEMS

Numerical modeling can effectively surmount many of the resolution and scale interaction hurdles discussed above to provide not only detailed representations of PO-BGC processes and variability but also the ability to predict responses to future changes in forcing. Modern computing resources are increasingly capable of meeting the challenges posed by meandering, strongly sheared, unstable WBCs superposed with extreme bathymetric gradients at the shelf edge. Models may conceivably also facilitate regional intercomparisons via common numerical frameworks.

Because models are often purpose built to address specific regional conditions, the group began by speculating whether a general conceptual model could be designed to represent core properties of all WBC-STCS systems. Such a model would need to include an incomplete but sufficient suite of processes encompassing important PO, BGC, and ecosystem variabilities. Systematic manipulation of the parameters of idealized WBC shelves could be used to identify dominant processes and the most consequential parameters in different regions, and to suggest a set of metrics to evaluate numerical modeling effectiveness.

The group segued into a more general discussion of the problem of model validation. Difficulties in representing and imposing both remote and local forcing of WBC variability on regional coastal models were recognized. Metrics defining model performance in PO might include WBC separation point or retroflection specifics, eddy statistics, and latitudinal gradients in momentum exchanges. Coupled physical-biogeochemical models can represent cross-shelf nutrient exchanges by exploiting the extent to which they may (like nitrate) correlate with physical parameters (like temperature). But BGC variability may be quite sensitive to vertical velocities and mixing, whose realistic representation demands accurate bathymetry at high spatial resolution and careful attention to the consequences of particular bottom boundary closure schemes. The non-conservative nature of shelf pools of BGC constituents requires more information than PO correlations can represent. Identifying a sufficient subset of the myriad BGC components that modern models cover may point to a useful array of metrics to compare model performance across systems. However, it is possible to reasonably demonstrate skill in modeling cross-shelf momentum and nutrient fluxes and still not be confident that carbon fluxes are adequately represented. Capturing ecosystem responses in models will require the capacity to evolve to a range of outcomes, because similar momentum and nutrient fluxes can result in very different ecosystem responses (Paffenhofer et al., 1995).

The group noted that the capacity to model WBC-STCS systems has greatly outstripped the capacity to observe them, potentially unmooring model outputs from effective empirical validation. Given the often episodic and patchy nature of WBC-shelf interactions, high resolution, sustained measurements are necessary, including proxies for and actual measurements of biological variables.

CROSS-SHELF EXCHANGE

For the purposes of this workshop, we defined cross-shelf exchanges as water volume displacements across shelf lateral boundaries or isobaths that contribute to changes in biogeochemical budgets or ecosystem evolution on the shelves. Such exchanges affect virtually all topics of interest in the coastal ocean (Brink, 2016). The difficulties in addressing these exchanges on STCSs as enumerated above include the range of scales involved in intrusion, upwelling, and export processes; the importance of ageostrophic processes in facilitating cross-isobath flow in defiance of geostrophic constraints on such flow; the contrast in controlling dynamics on wide vs narrow shelves; and the historically inadequate resolution in models or observations to represent processes and outcomes in sufficient detail or verifiable magnitude.

Discussions of cross-shelf exchange focused primarily on the potential magnitude of carbon export to the open ocean from WBC-influenced shelves that contributes to the global continental shelf pump. However, the spatiotemporal scales of shelf export events may not correspond well to the scales of CO_2 uptake seen in global and regional models. Shelf edge eddies and filaments can facilitate extensive cross-shelf exchanges over limited spatial and temporal scales (e.g., Berden et al., 2022; Suthers et al., 2023). Along the US southeast coast and the southern Brazilian margin, for example, a large fraction of the annual shelf water exchange and shelf primary production is effectively isolated from the atmosphere by a seasonal thermocline. Organic carbon exports may be largely independent of atmospheric carbon exchanges in the surface layer (Savidge and Savidge, 2014). These discrepancies leave open the possibility that carbon exports from WBC-influenced shelves are poorly represented in current models. However, development of accurate shelf carbon budgets in order to estimate carbon export empirically is a daunting proposition. Velocity measurements supporting estimates of cross-shelf fluxes must capture the dominant circulation scales, and these range from geostrophic to turbulent. Biogeochemical variables should be measured (or modeled) on the same spatiotemporal scales as the relevant physics and constrained by reasonable error estimates.

Neither models alone (because of their unvalidated representation of relevant processes) nor observations (because of their inadequate spatial and temporal resolution) can accurately quantify material exchanges across the shelf edge boundary. At regional to sub-regional scales, combining targeted observational programs with regional models might provide sufficient resolution to accurately depict cross-shelf fluxes. Such models would also provide a consistent framework that could be used to investigate sensitivity of cross-shelf fluxes to different processes and provide guidance on what observations are needed to estimate cross-shelf exchange.

ECOSYSTEM PROPERTIES

Discussions of STCS ecosystems revolved around identifying fundamental properties for a comparative approach to the ecology of WBC-influenced shelves. Each WBC-STCS ecosystem has different environmental characteristics that raise specific questions about its biological structure and ecological function. Potential ecosystem metrics for comparison could include (1) relative annual production, (2) zooplankton biomass and taxonomic composition, (3) overall fisheries production of each system, and (4) comparative production of other specific taxa common to other WBC-STCS shelves. Interactions of WBCs with the continental shelf can drive changes in the intermediate trophic levels (i.e., zooplankton) whose compositions influence the flux of carbon toward both productive fisheries and microbial communities. For zooplankton, statistical models (e.g., Heneghan et al., 2020) and public databases (e.g., Coastal & Oceanic Plankton Ecology, Production, & Observation Database [COPEPOD]; https://www.fisheries.noaa.gov/inport/item/25610) or data from the Continuous Plankton Recorder survey (https://www.cprsurvey.org/) may be analyzed, for example, to quantify the relative importance of trophic groups (herbivore, omnivore, carnivore) or functional groups (crustacean versus gelatinous) within the different WBC-STCS ecosystems. This is analogous to the trait-based approach to ecology, where organisms are pooled into functional categories based on their ecological roles within their environments (Kiorboe et al., 2018). This can also provide an approach for standardizing data collected with different methods and levels of taxonomic detail, as well as to compare across ecosystems to elucidate oceanographic drivers of common zooplankton traits or taxa (Greer et al., 2023).

A trait-based approach to comparing STCS ecosystems may be valuable for characterizing responses of higher trophic levels as well. One cosmopolitan species common to most WBC systems is the predatory fish *Pomatomus saltatrix* (bluefish, tailor), which has been considered as a model for regional comparison (e.g., Juanes et al., 1996; Schilling et al., 2023). Other suitable comparative species or genera are the schooling forage fish (e.g., *Trachurus* sp., sardines, or anchovies) that are abundant and occupy similar niches in different WBC-shelf habitats.

Timescales of some ephemeral mesoscale circulation features may provide optimal growth conditions for zooplankton and larval fishes and have an important role in WBC fisheries (Suthers et al. 2023). The role of coherent eddy features may be interpreted through the lens of the fundamental ocean triad (Bakun, 1996) required for successful fish reproduction: (1) enrichment with nutrients such as by upwelling and vertical mixing, (2) concentration of food by convergence and frontal formation, and (3) retention of larvae in close proximity to habitats needed for their juvenile and adult stages. The ephemeral nature of frontal eddies—they last approximately two to three weeks—is sufficient for the larval duration of fish and their planktonic prey but may be insufficient for establishment of planktonic predator populations such as jellyfish or chaetognaths (Suthers et al., 2023). Submesoscale frontal eddies are ubiquitous in WBC-shelf boundary environments and may provide a focus for ocean observing and future collaborative/comparative studies.

FUTURE CLIMATE STATES

Climate change is already influencing how WBCs and their adjacent shelves interact. These changes will almost certainly intensify over time and are likely to have significant socioeconomic impacts on coastal populations. Changes in zonal wind patterns have begun to shift the separation zones of some WBCs poleward (Li et al., 2022). Associated with these changes is an increasingly poleward transport of heat along the shelf, leading to more frequent and intense marine heatwaves that disrupt coastal ecosystems and provide a pathway for "tropicalization" of these environments through larval transport and settlement (Vergés et al., 2014). Poleward shifts in the WBC separation zones contribute to changes in regional sea level rise along coasts (e.g., Ezer et al., 2013; Diabate et al., 2021). Climate models predict both increasing (Brazil, Agulhas) and decreasing (Gulf Stream, Kuroshio) transport (Sen Gupta et al., 2021), with changes in WBC strength and eddy formation or meandering characteristics (e.g., Cetina-Heredia et al., 2014; Beal and Elipot, 2016). These changes on different spatiotemporal scales may have significant implications for upwelling, cross-shelf nutrient flux, and productivity on the adjacent shelves.

Prediction of future states is limited by insufficient long-term data records that can be used to construct climatologies and reanalyses. Predicting the consequences of climate change for WBC-shelf ecosystems will also depend strongly on the ability to model these systems accurately. Regional-scale ocean reanalyses can be used to reconstruct historical changes in shelf ecosystems. It may be possible to create multi-model ensembles of downscaled climate models to make shelf-scale climate projections. These efforts could be augmented by idealized modeling exercises forced by different WBC climate scenarios.

CONCLUSIONS

The workshop effort was motivated by at least two primary notions. The first was that bringing together scientific perspectives from the various WBC-adjacent subtropical shelves might inform a more general understanding of all such systems. The second was that the shelf ecosystem response to WBC forcing has been poorly delineated worldwide relative to the physical response to WBC forcing. What has also become clear is that the range of physical responses is incompletely defined and varies considerably by system.

1. The focus of the workshop on interdisciplinary concerns across WBC-STCS systems complements a developing mosaic of global initiatives. These include the GOOS Boundary System Task Team (boundary current physics and models), CoastPredict (https://www.coastpredict.org/; coupled human-coastal systems), and Marine Biodiversity Observation Network (https://marinebon.org/; global marine biodiversity) with interests in coastal ecosystems. These entities have unique and complementary emphases, and their developing synergies will be of benefit to all.

2. Comparative analysis of the physical forcing and biological responses among STCS has the potential to reveal common underlying ecosystem properties and their sensitivities to climatic perturbations in ways that detailed studies of individual systems cannot. The workshop illuminated commonalities among subsets of the represented WBC-STCS systems. Developing common sets of measurements targeting both physical drivers and ecosystem responses will facilitate comparisons among regions. There should be an emphasis upon building climatological databases of critical features such as eddy and meander statistics, boundary current positions and transports, and upwelling indices, along with their connections to shelf ecosystem properties, such as shelf productivity and trophic structure. Articulating an agreed common set of WBC metrics would permit robust comparisons of STCS behavior and rates of change.

3. The scales at which physical processes are effectively measured and modeled may not include scales at which reacting biogeochemistry occurs, nor interactions between relevant scales. Discussions across disciplines and scales can contribute to the design of appropriate sampling schemes and highlight the most glaring observational or modeling deficiencies. Similarly, collaborations between observationalists and modelers addressing both physically and biogeochemically oriented topics can enhance the value of modeling as an integrative tool.

4. Research efforts along the continental margins will remain largely funded by national entities and responsive to regional priorities. Nevertheless, global understanding of WBC-STCS systems can advance by coordinating among international colleagues to identify best practices, establish comparable sampling schemes, and share expertise. Such interactions will be easier if a community of interest—identified by this workshop—can be maintained and expanded over time. There was a strong sentiment among workshop participants that meetings similar to the workshop should continue at regular intervals (if resources are available). To date, post-workshop activities have included sessions at the 2022 and 2024 Ocean Sciences Meetings, development of a SCOR Working Group proposal, and a chapter in the upcoming Frontiers in Ocean Observing supplement to *Oceanography*. All workshop activities (including pre- and post-workshop materials) are available at https://www.skio.uga.edu/international-workshop-on-western-boundary-current-subtropical-continental-shelf-interactions-2/.

It was clear that understanding and improving WBC prediction has great societal value and would benefit from a more global approach to coastal oceanography. Whether the local focus is on fisheries, shelf carbon budgets, effects of climate change, or economic, policy, and safety issues, collaboratively studying these populated regions, and elucidating the underlying mechanisms driving their functions, will continue to be relevant to human and environmental well-being.

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