OCEAN CARBON HOT SPOTS

US CLIVAR
Climate Variability & Predictability

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OCEAN CARBON HOT SPOTS
Biophysical drivers of carbon uptake in western boundary current regions

Workshop Report

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FRONT COVER IMAGE

Ocean sunset view from MBARI (Credit: Kristan Uhlenbrock)

BACK COVER IMAGES

Group photo of workshop participants (Credit: Kristan Uhlenbrock).

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1 INTRODUCTION

Western boundary currents (WBCs) comprise the poleward return flow of the subtropical ocean gyres and rapidly transport low-latitude heat (Hogg and Johns 1995; Kelly et al. 2010) and chemical properties to the mid-latitudes where their zonal extensions delineate subtropical and subpolar water masses. These ocean realms exhibit mesoscale (processes occurring on monthly time scales and over 10–100 km) variability and spring phytoplankton blooms (Lehahn et al. 2007; Ayers and Lozier 2010; Lin et al. 2014), display the largest magnitude air-to-sea carbon dioxide (CO_2) fluxes of anywhere in the global ocean (Takahashi et al. 2009), and are hubs for the subduction of anthropogenic carbon-laden waters into the ocean interior during the process of mode water formation (Hanawa and Talley 2001; Sabine et al. 2004; Iudicone et al. 2016). While broadly recognized as carbon cycle hot spots, the influence of physical and biological processes on local air-sea CO_2 exchange and the transfer of biogenic carbon to depth (carbon export) has not been rigorously evaluated in most WBC regions. This fundamental knowledge gap exists largely due to the challenges associated with observing patchy, non-stationary domains and navigating the strong currents and seasonally inclement weather common to WBCs (Cronin et al. 2010). However, major breakthroughs in ocean observing technology and modeling approaches over the past decade have positioned the oceanographic community to tackle this important research area. Integrating the perspectives of physical, chemical, and biological oceanographers and modelers, we introduce key questions related to carbon cycle research in WBC regions for which collaboration across disciplines may facilitate rapid discovery.

1.1 Carbon cycling in WBC regions

WBC regions are unique areas to study the carbon cycle due to their outsized role in anthropogenic carbon uptake and a growing recognition of their contribution to the natural carbon cycle through dynamic physical processes such as subduction and obduction (Levy et al. 2013). With large air-sea CO_2 fluxes (Takahashi et al. 2009; Landschützer et al. 2014) and subtropical mode water (STMW) formation on their equatorward fringes (Hanawa and Talley 2001), WBC regions are conduits for anthropogenic carbon invasion into the ocean and its interior (Sabine et al. 2004; DeVries et al. 2017). Subsequent diapycnal transfer of anthropogenic carbon from STMWs to higher density class waters (e.g., subpolar mode waters) is thought to further extend the storage duration of anthropogenic carbon before re-emergence (Iudicone et al. 2016). Yet the water mass transformation processes governing these diapycnal exchanges are not fully understood nor is the sensitivity of these processes to changes in ocean circulation (e.g., Toyama et al. 2017). These remain important questions for understanding long-term anthropogenic carbon storage and its variability.

Natural carbon cycling in WBC regions is arguably even less understood, primarily due to the absence of a preindustrial baseline (as in all ocean regions), coupled with the elevated complexity of natural variability that occurs over a range of spatiotemporal scales. Strong linkages between mesoscale activity and biological productivity (e.g., chlorophyll) are widely recognized (Chelton et al. 2011; Lin et al. 2014; Gaube and McGillicuddy 2017), and WBC regions are littered with evidence of such biophysical interactions occurring on daily-to-interannual timescales. Yet chlorophyll expressions associated with certain types of mesoscale features are generally observed below the sea surface, hidden from the view of satellites (McGillicuddy et al. 2007, 2016). This complicates our ability to generalize how mesoscale ocean physics may influence biology and carbon export over broad spatial scales using remote sensing. Further, some WBC regions such as the Kuroshio Current and its Extension are known to exhibit large interannual variability in mesoscale and associated submesoscale activity (i.e., processes occurring over daily time scales, spatial scales from 100 m to 10 km). Submesoscale activity influences the depth of winter mixing through the creation of mixed-layer instabilities that stratify the water column. As a result, less mode water is formed during some years, which has been shown to influence the chemistry of regional STMWs (Oka et al. 2015).

Variability in the winter mixed-layer depth is also relevant to biological carbon export since particles produced during the spring bloom must sink below this depth in order to be exported rather than entrained (Figure 1; Palevsky and Doney 2018). Winter mixed-layer depth variations may also affect the balance between sea-air CO_2 fluxes driven by seasonal solubility (e.g., cooling) and biological activity. Sustained observations are needed to evaluate these processes and their influence on WBC carbon cycling.

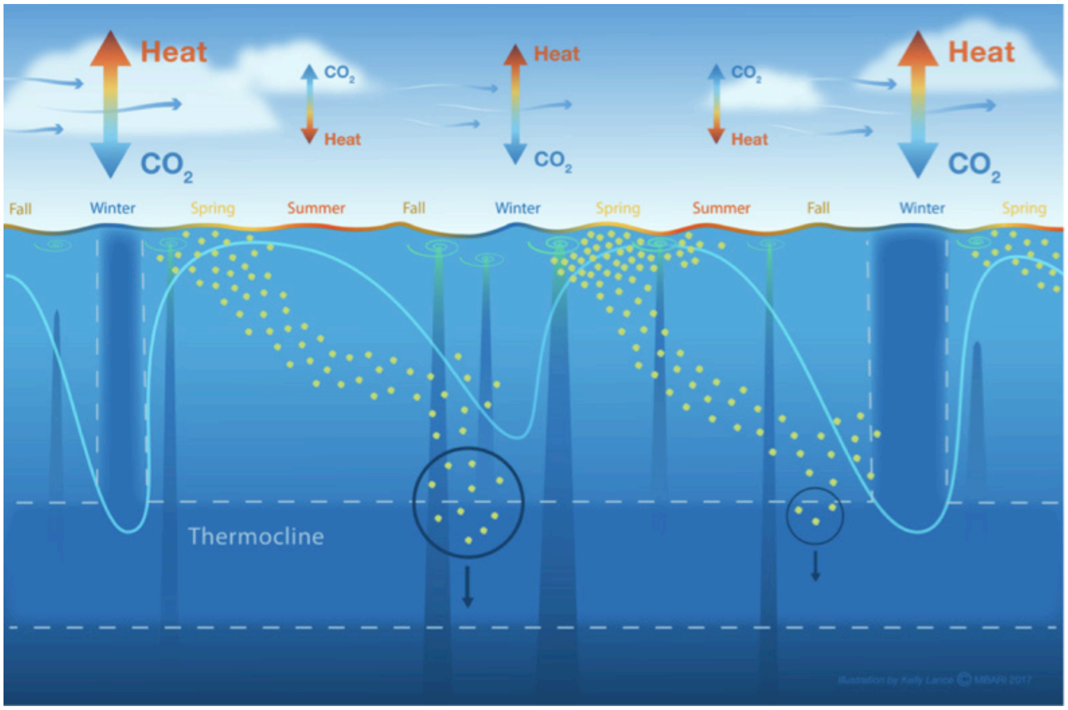

Figure 1. Schematic depicting interannual variability in mesoscale activity and the winter mixed-layer depth, and the hypothesized influence on local air-sea CO_2 and heat fluxes, mode water formation (dashed white lines connecting the thermocline and surface), and the export of biogenic particles (green dots within black circles). The schematic highlights seasonal, vertical variations in a WBC; however, lateral processes are equally important sources of variability in mixed-layer depth and the supply of carbon and nutrients. Schematic courtesy of Kelly Lance, MBARI.

1.2 Challenges associated with studying WBCs

In the past decade and a half, there have been four major field programs conducted in WBC regions to evaluate the interplay of air-sea interactions and ocean circulation processes. These include the Kuroshio Extension System Study (KESS) from 2004 to 2006, Climate Variability and Predictability Mode Water Dynamic Experiment (CLIMODE) in the Gulf Stream from 2006 to 2007, Agulhas Current Time-Series Experiment (ACT) from 2010 to 2013, and Hot Spot in Climate System near the Kuroshio Current from 2010 to 2014. Additional field programs linking WBC physics with biogeochemical observations and/or ecosystem variability have also been implemented. These include the Integrated Physical-Biogeochemical Ocean Observation Experiment (INBOX) in the western North Pacific in 2011 and the currently underway Ocean Mixing Study: Impacts on Biogeochemistry, Climate, and Ecosystems (OMIX) study in the western North Pacific from 2015 through 2019. These field campaigns have improved our understanding of WBC processes. However, one particular component of climate variability that has not yet been explicitly targeted in WBC regions is the linkage of physical and biological processes to ocean carbon uptake and storage.

The only WBC domain in which *in situ* biogeochemical observations are sustained is the Kuroshio Extension (KE), where a NOAA Kuroshio Extension Observatory (KEO) moored buoy has been maintained since 2004. The buoy is located near the center of seasonal STMW formation and south of the KE to avoid the strong currents associated with the meandering jet. A sensor for measuring the partial pressure of CO_2 (pCO_2) in the surface ocean and atmospheric boundary layer was added in 2007, and a pH sensor was added in 2011. Observations from the buoy have been used to estimate air-sea fluxes of heat, CO_2, moisture, and momentum, and budgets for heat, salinity, and carbon have been evaluated (Cronin et al. 2015; Fassbender et al. 2017a). While the KE is the only WBC with sustained, autonomous biogeochemical observations, measurements from the KEO buoy reflect just one portion of the KE domain, which exhibits broad spatial patchiness that changes over time (e.g., Lin et al. 2014). Additionally, the surface buoy occasionally breaks free of the mooring (Figure 2), demonstrating the difficulty of sustained observing in WBC regions.

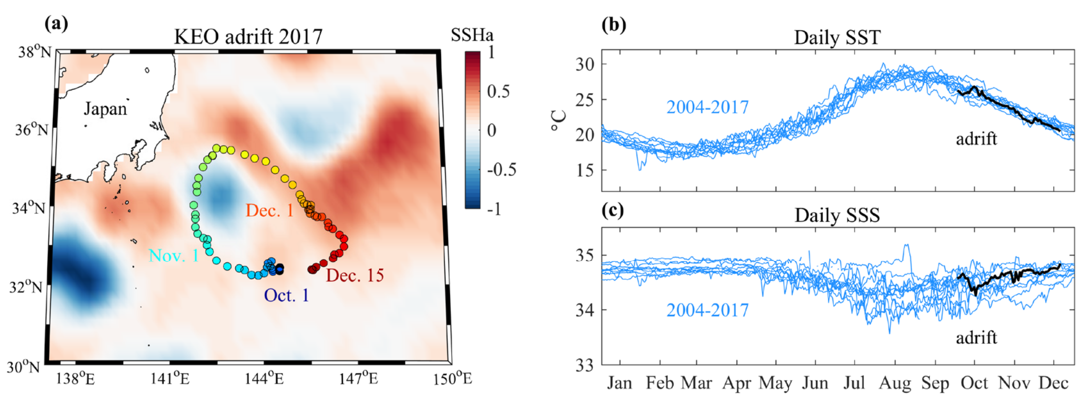

Figure 2. (a) Trajectory of the NOAA KEO surface buoy after breaking free of the mooring on October 19, 2017. Background color shows the October 19, 2017 satellite sea surface height anomaly (SSHa) in meters relative to the long-term mean. Data are from Copernicus Marine Environment Monitoring Service. Daily (b) sea surface temperature (SST) and (c) sea surface salinity (SSS) at the KEO buoy before (blue) and after (black) the mooring broke free through mid-December 2017. Buoy data courtesy of NOAA PMEL. The buoy was captured and redeployed by NOAA colleagues at the Japan Agency for Marine Science and Technology (JAMSTEC) on December 23, 2017.

Though observing challenges persist, novel tools are creating new opportunities to augment existing infrastructure and address carbon cycling in WBC regions. For example, biogeochemical profiling floats now allow for autonomous, upper water column (0–2000 m) observations of biogeochemical properties, which can be used for regional biogeochemical assessments (e.g., Plant et al. 2016; Bushinsky and Emerson 2015; Johnson et al. 2017a; Williams et al. 2018). These floats provide accurate data (Johnson et al. 2017b; Bushinsky and Emerson 2018) that can be used to estimate surface ocean pCO_2 and calculate air-sea CO_2 fluxes (Williams et al. 2017; Gray et al. 2018). Autonomous surface vehicles capable of navigating strong ocean currents and carrying numerous biogeochemical sensors are also now available (i.e., Saildrone), completing targeted missions in challenging environments (Meinig et al. 2015; Mordy et al. 2017). Further, novel shipboard tools for automated cytometric imaging and sample collection are coming online to study phytoplankton diversity while underway (Ribalet et al. 2010). Still, satellite remote sensing of sea surface chlorophyll, height, temperature, and other variables remains a critical tool for linking *in situ* observations from autonomous platforms and ships with the broader environmental context.

In addition to advancements in observing technology, coupled general circulation models that resolve mesoscale eddies are now significantly improving the simulation of modeled physical-biogeochemical interactions in WBC domains (Figure 3). The added resolution in these models suggests that carbon cycle processes are sensitive to whether eddies are resolved or parameterized. However, due to computational costs, the research community is more than a decade away from routinely resolving mesoscale ocean eddies in climate models and even further away from resolving submesoscale processes. Therefore, it will be necessary to observationally characterize physical-biogeochemical interactions in and around mesoscale features to ensure that the best possible parameterizations are applied in models. This will require close collaboration between the observing and modeling communities to merge state-of-the-art tools and address questions that have previously been out of reach.

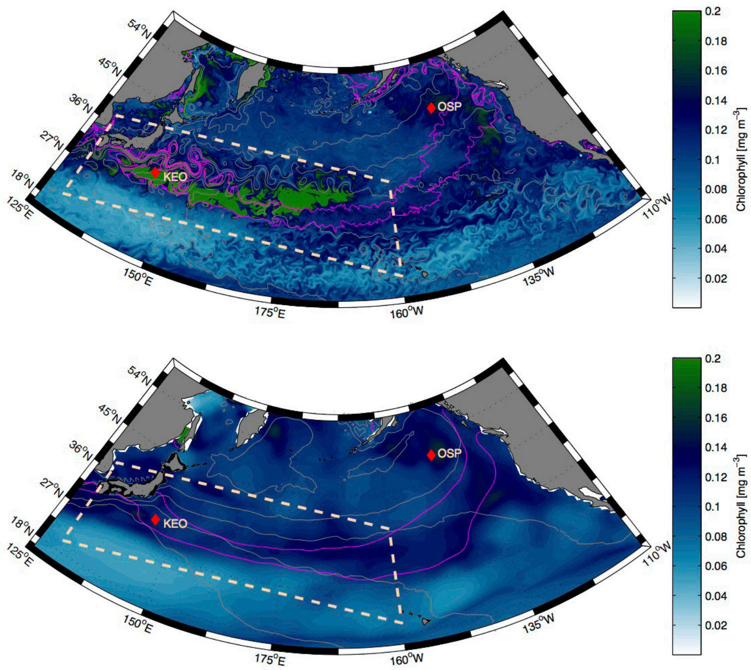

Figure 3. April sea surface chlorophyll concentrations from high- (top) and standard low-resolution (bottom) model runs over the same time period. Colors show chlorophyll concentrations (mg m^{-3}), gray contours are SSH (interval = 25 cm), and magenta contours are the 25 and 25.5 σ_θ surfaces, which show the density outcrop area in which North Pacific subtropical mode water forms. Red diamonds display the KEO and Ocean Station Papa (OSP) surface buoy locations. The high-resolution model output (top) exhibits elevated surface chlorophyll concentrations relative to the standard low-resolution model output (highlighted by the white dashed box), depicting the impact of mesoscale eddies on the surface expression of primary productivity.

1.3 Workshop motivation, goals, and structure

In order to effectively leverage all of the newly available observing technologies and modeling capabilities for WBC research, effort is needed to coordinate the observing and modeling communities. The Ocean Carbon Hot Spots Workshop was developed for this purpose. Biological, chemical, and physical oceanographers and modelers studying WBC regions were brought together to discuss gaps in understanding, observing and modeling challenges, and newly available tools. The primary goals of the workshop were to:

- Bridge disciplinary divides to create a community of observationalists and modelers with diverse skill sets to collaborate on carbon cycle research in WBC regions.
- Increase the coordination between modelers and observationalists to leverage observational capabilities to fill in modeling gaps and leverage modeling tools to inform observational strategies in WBC regions.
- Identify critical observational needs that would significantly improve model parameterizations of key biophysical interactions that influence ocean carbon uptake.

To achieve these goals, the workshop focused on three overarching scientific questions related to WBC regions:

- How do mesoscale and submesoscale processes influence nutrient supply, biological activity, and air-sea CO_2 fluxes?
- Do phytoplankton contribute to carbon export primarily through $p\mathrm{CO_2}$ drawdown during mode water formation (e.g., enhancing the solubility pump during deep mixing) or particle export via the biological pump?
- How does natural variability modulate carbon export carried out by mode water formation and the biological pump?

Carbon cycling in WBC regions is a topic that engages scientists from various oceanographic disciplines, and this was reflected in the diversity of workshop participants and the robust discussions. Of the 50 participants in attendance, 18 were early career scientists and 11 were scientists from institutions outside of the United States (including China, Japan, Brazil, Mexico, and South Korea). To encourage early career scientist and student participation, travel support was provided.

2 WORKSHOP SESSIONS

The workshop was organized around four sessions to explore ongoing physical, chemical, and biological research in WBC regions as well as modern observing and modeling challenges and opportunities. The following sections summarize presentations from each session and the subsequent group discussions. Speaker presentations can be accessed from the workshop website.

2.1 Session I: Introduction to WBCs

In addition to fostering a cohesive WBC community, the workshop provided an opportunity to synthesize ideas about future WBC observing systems for the upcoming OceanObs'19 initiative in which the research community identifies important research needs requiring targeted observing effort. OceanObs'19 will rely on a framework where observing requirements are identified in the context of specific scientific issues. Requirements will determine which variables to measure and the necessary accuracy, precision, and spatiotemporal coverage. The observing system should be capable of evolving, as insights derived from the observations will enable evaluation of whether requirements have been met. In the context of sustained observations, WBC regions present significant challenges, as they are characterized by high spatial and temporal variability (Cronin et al. 2010). Moreover, as advectively dominated systems, it is difficult to achieve adequate coverage with Lagrangian platforms since these assets are continuously swept clear of the region by strong currents. Thus, new autonomously piloted technologies are being tested for application in WBCs. Moored instrumentation can provide a strong backbone for observational networks. The KEO mooring, for instance, provides high-temporal resolution observations of air-sea fluxes, enabling investigations of water mass transformation rates and processes. Process studies can leverage and extend these datasets to advance our understanding of WBC systems, thereby enabling appropriate requirements to be defined for broader, sustained observing initiatives.

In constructing a WBC observing system, climate variability is an essential consideration for interpreting the observations. Internal variability is an intrinsic feature of the climate system, arising from nonlinear dynamical processes and interactions between the ocean, atmosphere, and land surface that each integrate forcing over different timescales (Hasselmann 1976). Human-caused warming is expected to drive strong trends in many ocean variables over the coming decades, but these trends are superimposed on natural variability, leading to a combined signal that can be complicated to disentangle. To attribute trends to external forcing, the magnitude of these trends must surpass the noise contained in natural variations (Long et al. 2016; Santer et al. 1994). This situation applies to air-sea fluxes of CO_2, where there is keen interest in determining whether climate change is impacting the oceanic sink for anthropogenic CO_2. Earth system models provide a means of assessing the combined influence of natural variability and forced trends. These models generate internal variability that is representative of nature but randomized in phase according to the evolution of a particular integration. Thus, a large ensemble of an Earth system model leads to independent realizations of historical and future periods, each with its own distinct sequence of natural variability (Deser et al. 2012). The ensemble mean can provide a forced signal, which can be compared in magnitude to natural variability. Results from the Community Earth System Model Large Ensemble (CESM-LE) have been used to assess when forced changes in the ocean CO2 sink can be statistically distinguished from natural variability (McKinley et al. 2016). Over much of the ocean at present, observations of pCO_2 are consistent with the forced trend inferred from CESM-LE, but natural variability in many places is too large to enable detection of a forced climate signal with current observations.

As highlighted earlier in this document, WBC regions are hot spots for many biogeochemical variables and play a strong role in ocean carbon uptake. However, to understand the impact of air-sea fluxes on net anthropogenic carbon storage, we must address the issue of re-emergence of anthropogenic CO_2— that is the resurfacing of carbon absorbed in surface waters of previous decades. While WBCs are hot spots for air-sea flux, much of the anthropogenic carbon they absorb is entrained within subtropical overturning cells, such that it re-emerges at the surface on timescales of decades (Toyama et al. 2017). Another consideration for understanding the relationship between carbon uptake and carbon storage involves the details of water mass transformation in the context of carbon fluxes. Iudicone et al. (2016), for instance, demonstrate that poleward-flowing subtropical waters absorb large amounts of CO_2 and contribute to subpolar water masses, leading to an interconnected carbon reservoir at depth. This raises the possibility that net carbon storage can be modulated by the relative volume contributions of subtropical and subpolar waters during sub-thermocline water mass formation.

A diverse set of physical processes is involved in controlling water mass transformation and subduction in WBC regions. In particular, the dynamics of frontal processes, including stability and submesoscale restratification, can modulate buoyancy fluxes and transformation rates. In the Kuroshio system, these dynamical processes are known to exhibit strong variability, with eddy kinetic energy fluctuating on a decadal timescale (Qiu et al. 2013). Mesoscale eddies in the KE region modulate surface stratification, thereby influencing water mass transformations, air-sea fluxes, and very likely surface productivity and the biological pump. Fluctuations in eddy kinetic energy (i.e., mesoscale activity) can be characterized on the basis of SSH anomalies and are associated with basin-scale variability in wind forcing that has been attributed to the Pacific Decadal Oscillation (Mantua et al. 1997). Periods of enhanced eddy kinetic energy within the KE region lead to jet instability (e.g., longer path lengths) and notable attenuation of winter mixed-layer depths (Figure 4), which reduces the volume of STMW formed. Variability in STMW formation volumes has been shown to influence the chemical properties of the STMW (Oka et al., 2015), and the associated SST variations can have significant impacts on atmospheric storm tracks (Bishop and Watts 2014; Qiu et al. 2007).

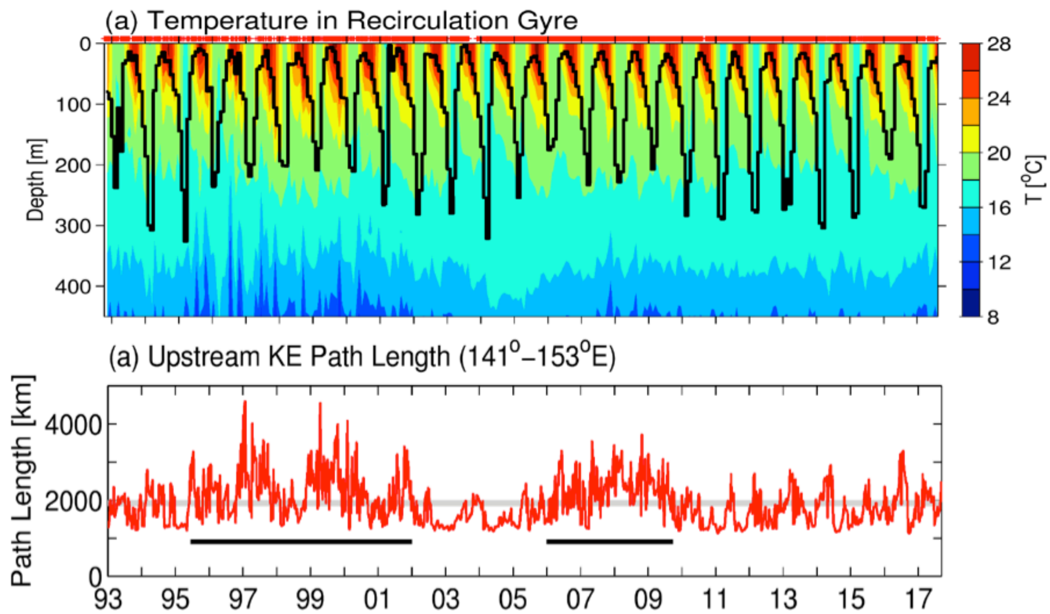

Figure 4. (Top panel) Monthly time series of upper-water-column temperature in the KE southern recirculation gyre. The thick line marks the base of the mixed layer, defined as where the temperature drops by 0.5°C from the surface value. A detailed method of constructing the time series can be found in Qiu and Chen (2006). (Bottom panel) Time series of KE path length 141°E to 153°E. Straight solid lines indicate periods when the KE had a convoluted path and was in a dynamically unstable regime. Faint gray line shows the long term mean path length. Time series extended after Qiu and Chen (2005).

2.2 Session II: WBC physics: Eddies, cross-frontal exchange, mixed-layer instabilities, and mode water

Submesoscale processes are characterized by ageostrophic flows with horizontal length scales between 100 m and 10 km (Figure 5; Thomas et al. 2013). These flows form at fronts and under destabilizing atmospheric forcing (e.g., ocean heat loss to the atmosphere or down-front winds), making them ubiquitous near gyre boundaries such as WBC regions. Lateral mixing across the gyre boundary and vertical exchange are enhanced by strong lateral and vertical shear, resulting in large chemical fluxes due to the sharp biogeochemical gradients common to these domains (Palter et al. 2011). The lateral shear at gyre boundaries gives way to submesoscale instabilities (Gula et al. 2015) and lateral stirring with inferred diffusivities on the order of 100 m^2 s^{-1} (Klymak et al. 2016). Down-front winds or cooling at fronts with weak stratification, low Richardson numbers, and strong vertical shear can lead to overturning (or symmetric) instabilities, which mix tracers along sloping density surfaces. Eddies and meanders can also lead to strong vertical shear near-gyre boundaries, resulting in submesoscale flows with large vertical velocities (10–100 m d^{-1}). These characteristics are not isolated to the upper water column, and WBC deceleration by bottom friction with the continental margin can produce thick bottom boundary layers and submesoscale instabilities that cause large vertical exchanges of shelf water (Benthuysen and Thomas 2012; McWilliams 2016). The wide range of submesoscale flows initiated by destabilizing conditions makes WBCs desirable research laboratories for small-scale ocean physics.

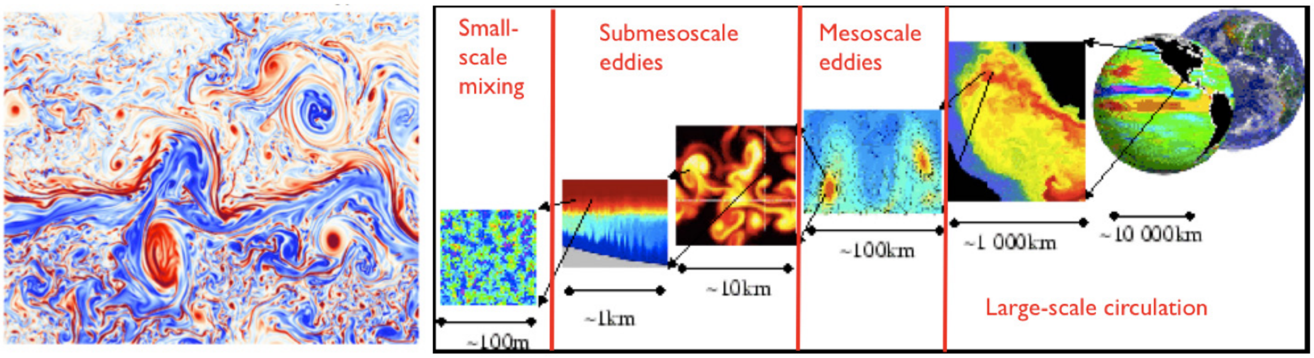

Figure 5. (left) Surface vorticity field from a high-resolution (500 m) simulation of the Gulf Stream illustrating the multitude of submesoscale features (i.e., jets, filaments, and eddies) that are found near WBCs (figure from Gula et al. 2015). (right) Schematic illustrating the lateral scale of submesoscale eddies (100 m to 10 km) relative to other oceanic flows. Submesoscale eddies are smaller than mesoscale eddies yet larger than the small-scale turbulent motions found in the mixed layer or associated with breaking internal waves. Figure courtesy of Raffaele Ferrari, MIT.

Mesoscale processes near WBCs play an important role in modulating ocean physics at a larger scale, displaying strong coupling with the atmosphere that influences the mid-latitude storm tracks (Nakamura et al. 2004). High-resolution models are required to simulate mesoscale eddies; however, when implemented, these eddies are often too energetic (Yu 2012; Charine 2014). Accurate simulation of storm-track eddies is needed to study mechanisms of air-sea coupling and the associated impacts on weather and climate.

Recently, Ma et al. (2017) emphasized the importance of air-sea coupling by quantifying the effect of turbulent heat exchange on the KE jet stability using model simulations with and without the suppression of air-sea heat exchange. The authors showed that turbulent heat fluxes between the atmosphere and ocean in mesoscale eddies spinning off the jet act to dissipate eddy potential energy. This process accounted for ~75% of the eddy potential energy loss, with a much smaller fraction (~22%) converted to eddy kinetic energy (stirring). The dissipation of eddy potential energy through air-sea coupling minimizes the intensity of eddy flow around the jet, leading to a stronger, less convoluted KE jet than would evolve in the absence of air-sea coupling. These types of interactions also have an important influence on atmospheric cloud cover (Frenger et al. 2013). Thus, accurate eddy representation in models is needed to better constrain ocean circulation as well as projections of weather and climate.

Eddies also play an important role in modulating ocean biogeochemistry at the ocean surface and its interior. A significant amount of research has been conducted by JAMSTEC on this topic in the western North Pacific, with recent emphasis at their S1 mooring (30°N, 145°E). Within the mode water formation region, north of S1, a relatively predictable seasonal cycle of deep winter mixing followed by extensive spring biological production occurs (Oka et al. 2018). Less predictable is the quasi-decadal variability in the KE jet stability (Qiu and Chen 2005), which influences mesoscale eddy activity and the formation of STMW. During stable jet states, there is less eddy activity, winter mixed-layer depths are ~100 m deeper, and more STMW is formed. Argo data were used to evaluate STMW biogeochemistry characteristics from 2005–2014, and Oka et al. (2015) discovered discernible short-term trends in dissolved oxygen that were correlated with the volume of STMW formed, similar to what has been found in the North Atlantic for oxygen (Palter et al. 2005) and other properties (Bates et al. 2002; Gruber et al. 2002). This finding suggests that long-term observations will be required to discern anthropogenic trends in mode and intermediate water biogeochemistry.

2.3 Session III: WBC biogeochemistry: Carbon, nutrient and oxygen tracers

WBC regions are stark biogeochemical fronts, typically separating nutrient- and dissolved inorganic carbon (DIC)-poor, oxygen-rich STMW on the gyre side from nutrient- and DIC-rich, oxygen-poor water masses on the continental shelf side. Because of this dramatic contrast, it is often hypothesized that cross-WBC mixing could provide an important source of nutrients and DIC (and a sink of oxygen) to the subtropics, although the quantitative importance of such mixing has only recently been brought to light in modeling and observational studies (e.g., Williams and Follows 1998; Lee and Williams 2000; Williams et al. 2006; Letscher et al 2016; Palter et al. 2011, 2013)

Tagklis et al. (2017) argued that the advection of nutrients in the Gulf Stream is essential in shaping the response of the North Atlantic to future warming. This work shows that in CMIP5 models, ocean deoxygenation is slower in the North Atlantic than North Pacific, despite faster warming in this basin. The faster warming translates to a greater loss of oxygen due to the solubility effect. Thus, this solubility loss must be partially offset by decreasing apparent oxygen utilization. The cause of decreasing apparent oxygen utilization is a slowdown in the delivery of nutrients in the Gulf Stream, as the current speed is projected to slow in the future. The reduced nutrient delivery slows export production and, accordingly, the subsurface respiration fueled by the exported organic carbon. Open questions related to the projection of future nutrient transport in the WBCs include: Are these models, which must parameterize the net effect of mesoscale motions, able to represent the mechanisms of nutrient delivery and their evolution in the future? How can we improve such model representations and what kind of model experiments will best help us to interpret observations?

The controls on the Kuroshio oxygen budget have been recently scrutinized. With the help of oxygen concentrations measured on Argo floats in the KE region, Bushinsky and Emerson (submitted) recently constrained as many terms in the oxygen budget as possible. Integrated over the annual maximum mixed layer (i.e., to the base of the North Pacific STMW), air-sea exchange and solubility effects due to cooling along the Kuroshio pathway were found to be the dominant supply terms in the O_2 budget, with Net Community Production (NCP; where NCP is the balance between community autotrophy and heterotrophy) integrating annually to a relatively small term. This result contrasts with other studies that have evaluated NCP using carbon budgets (Wakita et al. 2016; Fassbender et al. 2017a) and sediment traps (Honda et al. 2017) at time series sites in the region. However, NCP assessments integrating over a broader study domain (Yasunaka et al. 2013; Palevsky et al. 2017) show mixed agreement with the recent regional float study by Bushinsky and Emerson (submitted). Methodological differences and spatial heterogeneity likely contribute significantly to the diverging estimates across studies, suggesting that further analysis using consistent approaches is warranted.

Given that the motivation for several studies presented at the workshop was to understand the role of WBCs in anthropogenic carbon uptake, it is important to develop a coherent conceptual framework to differentiate natural and anthropogenic carbon uptake and storage, and understand where this conceptual separation breaks down. A modeling study recently suggested that the global uptake of anthropogenic carbon may be controlled by shallow overturning circulation in which the WBCs deliver tropical waters to higher latitudes where they are cooled to become mode and intermediate waters (Iudicone et al. 2016). An ocean data synthesis likewise suggested that such shallow overturning cells are critical to both natural and anthropogenic carbon uptake and a leading cause of interannual variability in global ocean carbon uptake (Figure 6; DeVries et al. 2017). Mode waters are typically formed on the equatorward fringe of the WBCs and influenced by exchange with the currents. Their anthropogenic carbon burden is determined by the entire Lagrangian history of the water parcels that ultimately contribute to the mode water volume and properties. Because of their high buffer capacity, tropical waters are more efficient at absorbing anthropogenic carbon than surface waters at higher latitudes (Sabine et al. 2004; Fassbender et al. 2017b), and the role of tropical carbon uptake in setting the preformed carbon concentrations in mode and intermediate waters is only now coming to light.

Early results from the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project provide additional evidence that the subtropical WBCs may be critical for understanding anthropogenic carbon uptake. Based on sparse historical observations and modeling studies, the Southern Ocean was expected to provide a huge carbon sink of 0.77–0.88 PgC yr^{-1}, more than a third of the global ocean carbon sink (e.g., DeVries 2014). Biogeochemical Argo floats from the SOCCOM project are telling a different story: outgassing in the Polar Frontal-Antarctic Zone (PAZ) released much of the CO_2 uptake that occurred elsewhere south of 35°S (where

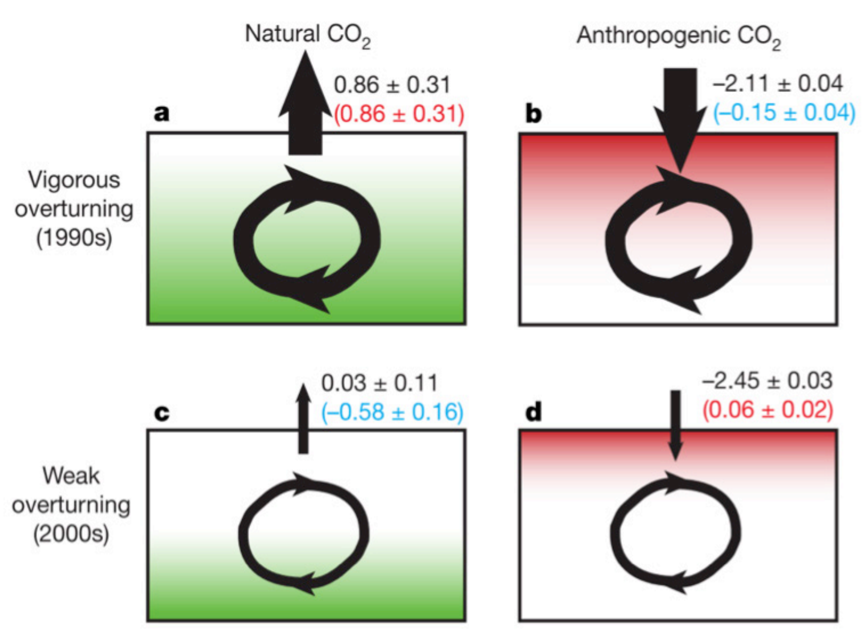

Figure 6. A schematic of the shallow overturning cells and their impact on natural (left panels) and anthropogenic (right panels) carbon uptake and storage. The color shading indicates the vertical gradient for carbon, which generally increases with depth for natural carbon and decreases with depth for anthropogenic carbon. Black numbers indicate the globally integrated air-sea flux of each CO_2 component (PgC yr^{-1}, negative values indicate ocean uptake), and include the increase in anthropogenic CO_2 uptake due to rising atmospheric CO_2. Numbers in parentheses represent the anomalous flux driven by circulation variability, which included vigorous shallow overturning cells in the 1990s (upper panels) followed by weaker ones in the 2000s (lower panels). Figure from DeVries et al. (2017).

float observations were maximized), essentially reducing the estimate of the total Southern Ocean contemporary carbon sink to zero (Gray et al. 2018). Wind-driven upwelling south of 35°S brings old, DIC-rich waters to the surface, allowing for CO_2 outgassing, despite the growing concentration of CO_2 in the atmosphere. Due to the dearth of historical wintertime observations in the PAZ, this outgassing flux was substantially underestimated in previous Southern Ocean CO_2 sink reconstructions.

One hypothesis to explain the unexpected Southern Ocean outgassing is that SOCCOM sampled during an anomalous period of enhanced wind-driven upwelling, considering the SOCCOM project years, thus far, have coincided with strengthened upwelling-favorable winds. However, a comparison with historical conditions suggests that only about half of the outgassing can be attributed to interannual variability. The absence of a net CO_2 sink in the SOCCOM observations leads to a conundrum. Atmospheric inversions demand a carbon sink in the Southern Hemisphere of nearly 1 PgC yr^{-1}, so if the result of net zero contemporary carbon uptake in the Southern Ocean south of 35°S stands up to ever growing sampling of the Southern Ocean, it implies a missing Southern Hemisphere CO_2 sink. Because vast regions of the Southern Hemisphere's subtropical gyres (including the WBCs) are chronically under sampled, it is natural to hypothesize that these regions are the key to finding that missing sink, especially given the theoretical and modeling work suggesting their quantitative importance to anthropogenic carbon uptake. SOCCOM observations do not cover the subtropics or WBCs, so the grand challenge of evaluating their role in the global ocean carbon sink and its variability will persist until this region is adequately sampled in all seasons.

2.4 Session IV: WBC biophysical interactions: Ecosystem structure and the biological pump

Observational and numerical approaches have been used to quantify and understand ocean productivity and the biological pump at basin scales to submesoscales (Siegel et al. 2016; Gaube et al. 2014; Clayton et al. 2017). On the larger scale, underway dissolved oxygen (O_2) and Argon (Ar) measurements have been used to calculate basin-scale NCP (Li and Cassar 2016; Palevsky et al. 2016) with a high enough spatial resolution O(1 km) for informative comparison with satellite productivity estimates derived from ocean color data (Figure 7). NCP integrates the net effect of photosynthetic O_2 production and community respiratory O_2 loss, which is closely related to the export of organic matter when integrated over the annual cycle under steady state assumptions. Underway O_2/Ar measurements in the KE demonstrate that the region is indeed a hot spot for biological activity, where seasonal NCP as well as remotely sensed chlorophyll-a concentrations are elevated.

In contrast to broad, regional studies, moored time series capture temporal variability in carbon cycling at a specific location. Moorings in the KE region have provided a wealth of biophysical data over multiple years (e.g., Fassbender et al. 2017a). In particular, deep sea (5,000 m) sediment traps in the KE region have revealed multiple occurrences of elevated particle export that were unrelated to the spring bloom, indicating the importance of episodic events to annual carbon export (Honda et al. 2017). Comparing the sediment trap observations with altimeter data revealed that mesoscale eddies passing over the mooring location approximately two to three times per year were likely responsible for the export events. This finding suggests that eddy uplift of the nutricline into the

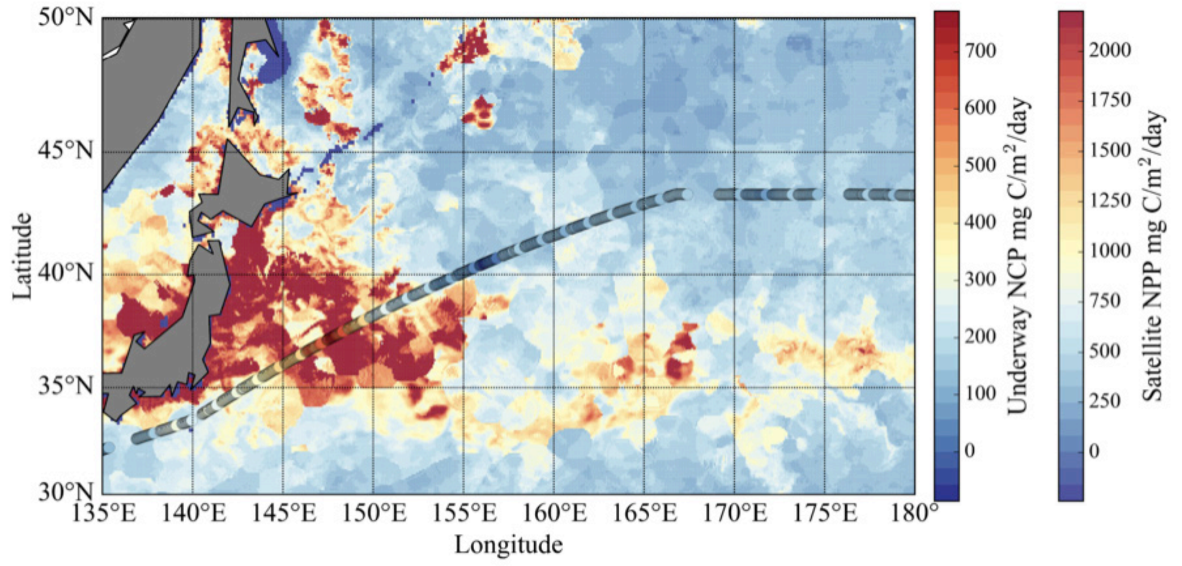

Figure 7. Observed surface ocean net primary production (NPP) and NCP (mgC m^{-2} day^{-1}) based on satellite ocean color and underway sampling. The satellite NPP data is based on the vertically generalized productivity model (Behrenfeld and Falkowski, 1997; data provided by the OSU Ocean Productivity group). Discrete NCP was determined using underway O_2/Ar measurements as described in Palevsky et al. 2016. Figure courtesy Sophie Clayton, Old Dominion U.

euphotic layer may cause the observed sporadic carbon export, implicating the role of mesoscale features in subseasonal modulation of the biological pump in WBC domains (Honda et al. 2018).

Spatiotemporal variability in ocean productivity and biological carbon export in a given region is likely controlled by both mesoscale and submesoscale processes. In particular, the biophysical interactions at this scale are not yet well characterized due to the requirement of high spatial and temporal resolution observations and numerical models. Submesoscale processes occur at the lateral scale of O(1 km) and are intermediate between the mesoscale O(10–100 km) and the three-dimensional, small-scale O(0.1–100 m) motions (Thomas et al. 2013). They are also known to play an important role in energetics, tracer transport, stratification, and mixed-layer structure. Submesoscale flows are energized by baroclinic instabilities that develop around geostrophic jets and eddies. The energy comes from the lateral density gradient and potential energy stored in the deep winter mixed layer. It is hypothesized that submesoscale eddies may weaken under a warming climate as the mixed layer shoals. This could alter the seasonality and spatiotemporal variability of NCP. Another important feature arising from submesoscale processes is eddy-induced subduction of non-sinking particles, which contributes to the export of organic matter below the seasonal thermocline. Large vertical velocities associated with submesoscale motions (relative to mesoscale motions) can develop inside of fronts and contribute to the downward (along isopycnal) flux of organic matter (e.g., Omand et al. 2015) as well as the upward flux of nutrients (both moving along their concentration gradients). Typically, only a fraction of organic matter formed during the warm seasons is sequestered into the thermocline, but this ratio (and the NCP) can be modulated by submesoscale eddy-induced subduction.

3 RECOMMENDATIONS

A central goal of the workshop was to bring the ocean observing and modeling communities together to assess research priorities for and challenges associated with studying carbon and biogeochemical cycling in WBC regions. An unanticipated finding from this gathering was that each discipline used unique language to describe related and mutually compelling research questions. The workshop, thereby, presented an opportunity to characterize these distinct frameworks and identify common research interests where collaboration could facilitate more rapid advancement of the science.

As with many research topics, scientists studying WBC regions do so from vastly different scales, ranging from the submesoscale to global scale, while applying a diversity of scientific techniques. This breadth can make it difficult to relate elegant global concepts and hypotheses to the seemingly chaotic heterogeneity observed at submesoscales. For example, biogeochemical tracers are often used to infer integrated processes and bulk material transformations in WBC domain research conducted at global and regional scales. While an effective approach, biological and physical oceanographers interested in specific mechanisms require high-resolution (spatial and temporal) information to study individual processes (e.g., phytoplankton succession or submesoscale instabilities) at often much smaller scales. While superficially distinct, the research frameworks applied by these investigators are inherently linked, and much of the workshop was spent identifying conceptual connections to move the community forward as a whole. These discussions led to the following recommendations to advance WBC research:

1. Develop clear frameworks for studying natural and anthropogenic carbon cycle processes and their interactions
    - Apply consistent definitions and metrics for quantifying the biological pump
    - Identify the key observations, processes, and model improvements needed to more precisely quantify anthropogenic carbon uptake and storage
2. Assess modeling capabilities and observational needs across scales to improve process understanding and associated physical-biological-chemical interactions in WBC regions
3. Foster collaboration between WBC observing and modeling communities through formal and informal means

Develop clear frameworks to study natural and anthropogenic carbon cycle processes

Carbon cycling in WBC domains is not well constrained, and there was a clear divergence in familiarity with the differences between natural and anthropogenic carbon pools across the research disciplines attending the workshop. For example, biological oceanographers studying complex biophysical interactions in WBCs are working to develop baseline information (e.g., seasonal variability) about phytoplankton community composition and particle export. While acknowledging that the climate system is in a state of transience, the observing tools, technology, and state of understanding render questions other than natural versus anthropogenic carbon cycling more relevant to the next major breakthrough. On the other end of the spectrum, modelers have the capability to quantitatively differentiate natural and anthropogenic carbon tracers within models, making the separation trivial. We recommend developing clear frameworks for research questions related to the carbon cycle that will enable productive sharing and discussion of ideas.

Apply consistent definitions and metrics for quantifying the biological pump

With regard to natural carbon cycling, most studies agree that there is a large chemical footprint from biological productivity during seasonal stratification in WBC regions; however, it remains unclear what fraction of this production escapes to depths below the subsequent winter mixed layer, which is extensive (~200–1000m) in mode and intermediate water formation regions. Only the carbon that sinks below this depth will escape subsequent re-entrainment and local remineralization, constituting a net change in the annual carbon budget attributable to biology (Körtzinger et al. 2008; Palevsky and Doney 2018). To advance our understanding of biological carbon export in WBCs, we recommend that the community identify and compare independent diagnostics and methods for quantifying carbon export, assess their relative strengths and weaknesses, and review whether the resulting quantifications have promise for converging towards a unified understanding. This will require careful consideration by the community of how best to conceptualize and define biological carbon export. At present, multiple geochemical approaches have been applied over a range of spatial and temporal scales using different platforms and definitions for export. Each method requires unique assumptions that contribute to nontrivial discrepancies between studies. To improve quantification of biological carbon export, consistent definitions are needed to guide observational and modeling approaches and achieve more comparable results. Additionally, the ubiquity of non-stationary submesoscale patchiness suggests that modeling approaches may be necessary to determine the temporal and spatial integration scales required to achieve regionally representative carbon cycling assessments near WBCs.

Actionable Recommendations:

- Conduct observational and modeling studies to evaluate carbon export using a suite of computational methods on the same dataset to determine the strengths and weaknesses of the information gained.
- Compare results from the observational studies to satellite-based estimates of carbon export.

Identify the key observations, processes, and model improvements needed to more precisely quantify anthropogenic carbon uptake and storage

The role of WBCs as conduits for anthropogenic carbon invasion into the ocean is a growing area of research. Air-sea CO_2 fluxes in WBC regions are largest during winter, when mode water formation is also occurring, directly linking the atmosphere and ocean interior. Subsequent diapycnal water mass transformations between STMWs and subpolar mode waters move anthropogenic carbon (and other tracers) to denser waters, facilitating longer-term sequestration from the atmosphere (Iudicone et al. 2016). The physical processes governing this diapycnal transport are not well understood. Additionally, WBCs are regions of large subduction and ventilation, so timescales for anthropogenic carbon re-emergence may be important in modifying the efficiency of future anthropogenic carbon uptake in WBC regions (Toyama et al. 2017). Careful determination of physical processes controlling the distinct anthropogenic carbon flux and storage pathways is needed to accurately characterize carbon cycle sensitivities. Additionally, the potential for a large "missing" carbon sink in the Southern Ocean has drawn attention to the dearth of observations throughout the Southern Hemisphere. There is still a critical need to quantify air-sea CO_2 fluxes throughout this region and verify our understanding of the ocean carbon sink and global carbon budget, in addition to the specific carbon storage mechanisms at play.

Actionable Recommendations:

- Conduct a process study in the Southern Ocean to find the "missing" sink for ~0.8 PgC yr^{-1}.
- Test new autonomous platforms and sensors in WBC regions to assess their performance in harsh environments, which will inform observing system design.
- Perform a comparative analysis of the seasonal anthropogenic carbon tracer movement in WBCs using a suite of biogeochemical models.

Assess modeling capabilities and observational needs across scales to improve process understanding and associated physical-biological-chemical interactions in WBC regions

Observing and modeling capabilities have advanced significantly since the last assessment of WBC monitoring. An updated review of research needs should be used to determine how current infrastructure could be improved and/or augmented. This topic will be explored in a collaborative white paper for OceanObs'19, which will encourage community input and identify a strategic path forward. An observing synthesis should build from the previous one (Cronin et al. 2010) to include a stronger emphasis on biogeochemical cycling. Expanding and implementing observations in WBC regions presents an opportunity to advance the parameterizations of model physics. In particular, the characterization of both physical and biogeochemical discrepancies between observations and models is needed to better understand biases in models and observations. This will require process-level comparisons at multiple scales to catch biases or cascading errors in models.

Recent observations of biogeochemical processes occurring at submesoscales are yielding exciting new research directions. Yet placing the identified mechanisms into a broader carbon cycle context requires greater environmental context to interpret the fine-scale observations. This is where remote sensing data can be helpful to link the submesoscale and basin scales. Models can also assist in this process through the integration of newly discovered biophysical interactions such as advective export driven by submesoscale vertical velocities (Omand et al. 2015) and the effects of phytoplankton community structure on export efficiency. Connecting bulk tracer budget approaches to the physical and biological processes underlying the chemical alterations warrants focused attention. Identifying robust (and quantitative) relationships between local physical-biogeochemical processes and large-scale patterns observable through modeling and remote sensing may be a useful way to link the fine-scale observations with broader regional implications.

Actionable Recommendations:

- Conduct comparative field studies across different WBC systems to improve process understanding and guide observing infrastructure.
- Perform model-observation comparison studies over a range of scales in different WBC systems to identify modeling and observing deficiencies and steps to improve them.
- Compare ecological observations from autonomous platforms, underway ships, and satellites to identify and improve scaling relationships that can be incorporated into models.

Foster collaboration between WBC observing and modeling communities

The Ocean Carbon Hot Spots Workshop attracted participants representing a diversity of oceanographic disciplines and expertise. This resulted in transformative conversations and knowledge transfer (see Appendix D for responses from a post-workshop survey). While much progress was made, it's clear that further community discussion is needed to synthesize the disparate research foci of unique disciplines and identify a common framework. By better characterizing the connections between ongoing biological, chemical, and physical oceanography research in WBC regions, using both observational and modeling approaches, more holistic understanding of the major research questions, challenges, and opportunities will emerge.

Actionable Recommendations:

- Develop a working group to coordinate proposals on complementary observing, modeling, and analysis projects.
- Host town halls and other community events at major conferences.

4 CONCLUSIONS

Western boundary current regions are unique in that essentially all scales of ocean physics are active. The widespread surprise in how WBC carbon cycle research problems were being formulated and tested across research communities with different frameworks and tools for addressing science questions revealed a previously under-appreciated need for improved cross-disciplinary discussion on this topic. Further community coordination will be required to identify research gaps, roadblocks, and opportunities for novel collaborations and creative applications of existing tools. Better understanding of the approaches to carbon cycle research being conducted in different disciplines and through unique disciplinary lenses may result in creative solutions and ideas to fuel advances at the intersections of traditional research disciplines. More than anything, this workshop was a clear reminder of the possibilities for new exploration that can be envisioned when diverse groups are brought together.

Through this workshop, report, and subsequent discussions, we have identified recommendations to achieve progress on WBC carbon cycle research. Actions to address some of these recommendations are already underway. While this cross-disciplinary activity was an important first step to build momentum, continued community effort will be required to coordinate scientists around this research topic in the future.

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Appendix A: Organizers

Scientific Organizing Committee

Andrea Fassbender (Co-Chair), Monterey Bay Aquarium Research Institute
Stuart Bishop (Co-Chair), North Carolina State U.
Meghan Cronin, NOAA Pacific Marine Environmental Laboratory
Takamitsu Ito, Georgia Institute of Technology
Matthew Long, National Center for Atmospheric Research
Jaime Palter, U. of Rhode Island

Program Organizing Committee

Heather Benway, OCB
Mai Maheigan, OCB
Mike Patterson, US CLIVAR
Jill Reisdorf, UCAR
Kristan Uhlenbrock, US CLIVAR

Appendix B: Participants

Participant	Affiliation
Bausell, Jesse	U. California Santa Cruz
Benway, Heather	OCB/Woods Hole Oceanographic Institution
Bif, Mariana	U. Miami
Bishop, Stuart	North Carolina State U.
Bushinsky, Seth	Princeton U.
Calil, Paulo	U. Federal do Rio Grande
Carranza, Magdalena	Scripps Institution of Oceanography/U. California San Diego
Cerovecki, Ivana	Scripps Institution of Oceanography/U. California San Diego
Chen, Shuiming	U. Hawaii at Manoa
Clayton, Sophie	U. Washington
Contreras, Yéssica	Ensenada Center for Scientific Research and Higher Education
Cronin, Meghan	NOAA Pacific Marine Environmental Laboratory
Durkin, Colleen	Moss Landing Marine Labs
Fassbender, Andrea	Monterey Bay Aquarium Research Institute
Flatau, Maria	Naval Research Laboratory
Girton, James	U. Washington
Gray, Alison	U. Washington
Honda, Makio	Japan Agency for Marine-Earth Science and Technology
Inoue, Ryuichiro	Japan Agency for Marine-Earth Science and Technology
Ito, Taka	Georgia Institute of Technology
Johnson, Leah	U. Washington
Li, Qian	The Pennsylvania State U.
Lin, Xiaopei	Ocean University of China

Long, Matthew	National Center for Atmospheric Research
McKinley, Galen	Columbia U./Lamont Doherty Earth Observatory
Morales, Mark	U. California Santa Cruz
Oka, Eitarou	U. Tokyo
Omand, Melissa	U. Rhode Island
Palevsky, Hilary	Woods Hole Oceanographic Institution
Palter, Jaime	U. Rhode Island
Park, Young-Gyu	Korea Institute of Ocean Science and Technology
Patterson, Michael	US CLIVAR
Qiu, Bo	U. Hawaii at Manoa
Reisdorf, Jill	University Corporation for Atmospheric Research
Richards, Kelvin	U. Hawaii
Rodgers, Keith	Princeton U.
Sarmiento, Jorge	Princeton U.
Sasai, Yoshikazu	Japan Agency for Marine-Earth Science and Technology
Sutton, Adrienne	NOAA Pacific Marine Environmental Laboratory/U. Washington
Takeshita, Yui	Monterey Bay Aquarium Research Institute
Thomas, Leif	Stanford U.
Todd, Jim	NOAA Climate Program Office
Uhlenbrock, Kristan	US CLIVAR
Wang, Xiujun	Beijing Normal U.
Wang, Hongjie	Texas A&M U. Corpus Christi
Wenegrat, Jacob	Stanford U.
Williams, Nancy	Oregon State U.
Wu, Baolan	Ocean University of China
Zhang, Dongxiao	NOAA Pacific Marine Environmental Laboratory/U. Washington
Zhu, Yanan	Ocean University of China

Appendix C: Agenda

Monday, September 25

07:30	Registration / Continental Breakfast	
08:00	Welcome remarks	Chris Scholin (MBARI)
08:05	Welcome, logistics, goals	Andrea Fassbender (MBARI) + Stu Bishop (North Carolina State U.)
08:15	Keynote lecture	
08:15	Western boundary currents physics and biogeochemistry	Jamie Palter (U. Rhode Island)
09:15	Break	
09:30	Session 1: Introduction to western boundary currents Chair: Matt Long (NCAR)	
09:30	Motivation for OceanObs19	Meghan Cronin (NOAA PMEL)
09:50	Timescales and mechanisms of change in ocean carbon sink	Galen McKinley (Columbia U.)
10:10	The role of western boundary currents in the ocean uptake and storage of anthropogenic carbon: a modeling perspective	Keith Rodgers (Princeton U.)
10:30	Fronts in the confluence of western boundary currents: A comparative study between the Brazil-Malvinas and the Kurohio-Oyashio systems	Paulo Calil (U. Federal do Rio Grande)
10:50	Decadal variability and impact of the Kuroshio Extension system	Bo Qiu (U. Hawai'i)
11:10	Discussion	
12:00	Lunch	
13:30	Session 2: Western boundary current physics: eddies, cross-frontal exchange, mixed layer instabilities, and mode water Chair: Meghan Cronin (NOAA PMEL)	
13:30	Submesoscale processes in western boundary currents	Leif Thomas (Stanford U.)
13:50	Kuroshio Extension dynamics	Stuart Bishop (North Carolina State U.)
14:10	Decadal variability of subtropical mode water subduction and its impact on biogeochemistry	Eitarou Oka (U. Tokyo)
14:30	Mesoscale eddy in the Kuroshio and its Extension	Xiaopei Lin (Ocean U. China)
14:50	Biogeochemical processes observed in the Kuroshio recirculation gyre	Ryuichiro Inoue (JAMSTEC)
15:10	Break	
15:50	Discussion	
16:30	Break/Beach walk/Tour	
17:30	Evening reception and posters	
17:30	Poster session 1	
19:30	Adjourn	

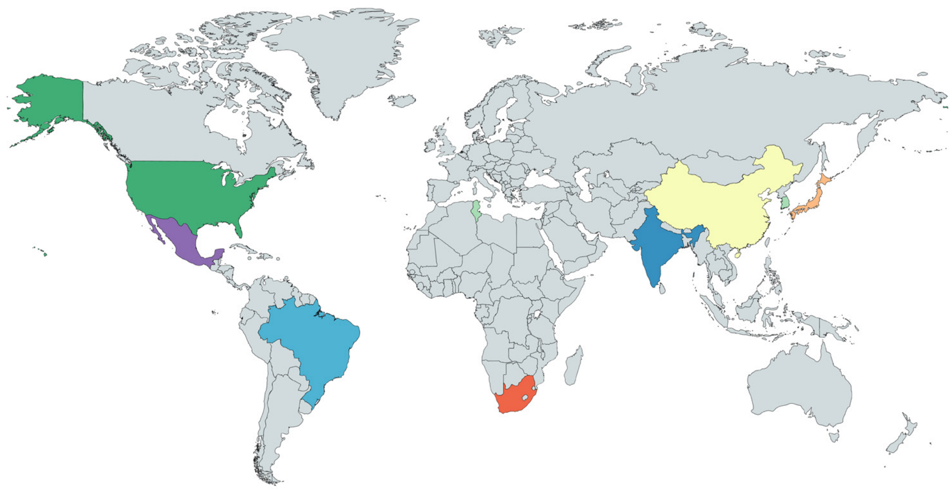
Tuesday, September 26

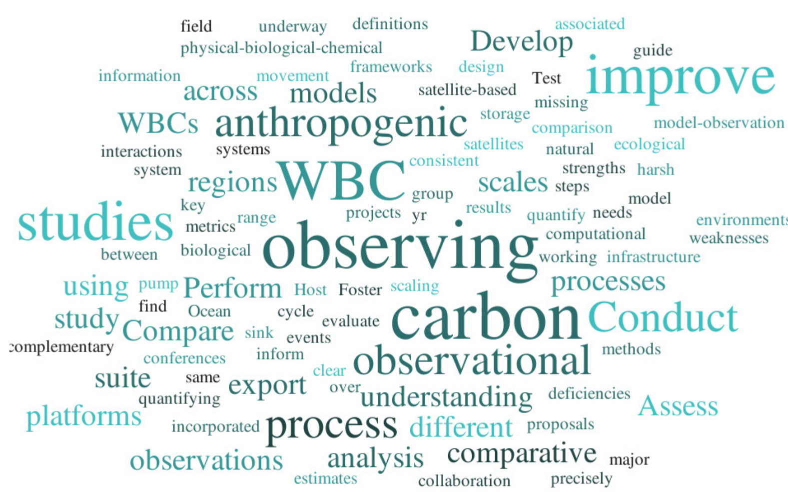
08:00	Breakfast and posters	
08:00	Poster session 2	
09:30	Session 3: Western boundary currents biogeochemistry: carbon, nutrient, and oxygen tracers Chair: Stu Bishop (North Carolina State U.)	
09:30	Discovery of a Southern Ocean carbon source: implications for carbon uptake in southern hemisphere western boundary regions	Jorge Sarmiento (Princeton U.)
09:50	The role of western boundary currents on the biogeochemical cycling and its centennial trends under global warming	Taka Ito (Georgia Tech)
10:10	The effects of jet-scale overturning circulations on the air-sea CO2 flux and chlorophyll in the Southern Ocean and Gulf Stream Extension	Qian Li (Penn State U.)
10:30	Biological and physical controls on the Kuroshio Extension oxygen cycle from an array of profiling floats	Seth Bushinsky (Princeton U.)
10:50	Mixed-layer carbon cycling and drivers of air-sea CO2 exchange at the Kuroshio Extension Observatory	Andrea Fassbender (MBARI)
11:10	Discussion	
11:45	Lunch at Haute Enchilada	
13:15	Session 4: Western boundary current biophysical interactions: ecosystem structure and the biological pump Chair: Taka Ito (Georgia Tech)	
13:15	The impact of climate change on the physics and biogeochemistry of the ocean on scales down to the submesoscale	Kelvin Richards (U. Hawai'i)
13:35	Seasonal and regional variations in net community production in the Kuroshio Extension from in situ measurements	Sophie Clayton (U. Washington)
13:55	Impact of cyclonic eddies on biogeochemistry in the oligotrophic ocean based on biogeochemical/physical/meteorological time-series at station KEO	Makio Honda (JAMSTEC)
14:15	Imaging marine snow with a fleet of miniature, neutrally buoyant, floats	Melissa Omand (U. Rhode Island)
14:35	Discussion	
15:15	Break	
15:30	Synthesis and community planning	
15:30	Breakout groups (4)	
16:30	Breakout group reports/discussion	
17:15	Closing remarks	Andrea Fassbender (MBARI) + Stu Bishop (North Carolina State U.)
17:30	Meeting adjourns	

Appendix D: Workshop & Survey Results

BY THE NUMBERS

50 Participants
8 Countries
18 Early Career Scientists
2 Days
19 Posters
20 Presentations
4 Breakout Groups
5.5 Hours of Discussion





Did you learn something valuable?

Yes, definitely. I was essentially unaware of the distinctions drawn between natural carbon uptake, and anthropogenic carbon uptake. Knowing these different mechanisms will be important for guiding future work.

It was a pivotal meeting for me. I felt it really enhanced discussion and understanding not only between physical and biogeochemical oceanographers, but also between those who focus on anthropogenic impacts on the carbon cycle and those who study the biological pump.

Yes, definitely. A broader view on WBC dynamics, mode waters, and BGC interactions.

I wasn't really used to thinking about carbon being partitioned between natural and anthropogenic, so that aspect of the discussion was enlightening!

Yes, I learned more (e.g., physics, other data) in the WBC of the Pacific Ocean.

Yes. Particularly, I gained a better understanding of mode water formation and role in carbon storage.

Yes, I learned many thing, but the result that stood out the most is that the biological pump does not play much of a role in the sequestration of anthropogenic CO_2.

Yes. Renewal time of water mass is important.

Yes. I heard evidence that O_2 in the Kuroshio was driven by physical processes and not dominated by biological. This was a new idea to me, as frontal/bio interactions are usually praised for being a major driver in the carbon cycle, but maybe physical drivers are the real importance here.

Yes! Revelle numbers, Martin Curves, ... still many unknowns about if and how eddies affect carbon cycle.

Yes, several things. Memorably that phytoplankton experience a fertilizing effect from CO2, which questions the assumption of separability of anthropogenic carbon and the biological pump. Second, seeing the size of the "missing Southern Ocean" carbon uptake was eye-opening.

Definitely! I learned a lot about the physical, chemical, and biological processes in western boundary currents.

I learned a lot about the causes of variability in the Kuroshio and impacts on mode water formation. I also learned about the role of WBCs in supplying nutrients.

This workshop was a valuable update on the state of ocean chem/bio/phys science related to carbon.

Yes, as a modeler I was able to learn about observational efforts.

I learned a lot about which questions involving western boundary currents are most important to physical and biological oceanographers relative to chemical oceanographers. I also learned more about the impact of stable and unstable states of the Kuroshio Extension.

Lots. The biggest thing was what an eddy was (and technical details about them).

Yes. Relationship between western boundary currents and carbon sequestration.

What scientific advances do you hope will emerge?

It's a broad topic, so direct advances may be challenging. That being said, I think the workshop helped bridge the divide between several distinct research communities.

I hope it will contribute to an interdisciplinary, observational vision for OceanObs'19 for quantifying carbon pathways in dynamics regions like WBCs.

Hopefully a concerted field campaign in the Kuroshio Extension region.

I think that we still need to really define the question (or questions) that we are interested in. I am hoping that continuing the discussion may help to focus that.

Collaboration and better understanding of the physical-biogeochemical interactions.

Better communication/collaboration between physical and biogeochemical researchers in determining key questions and sharing relevant data

Assessing the potential importance of submesoscale processes on the biogeochemistry of the subtropical gyres.

To figure out how physical oceanographers can help to solve uncertainties in chemical oceanography, such as Revelle factor.

What are the large/mesoscale scale questions? Do we know this enough to start asking about the importance of small scale.

Some plan about how to determine if eddies are important in carbon cycle, and if so, what to do about it.

I'd like to see a field program proposed to quantify WBC and subtropical gyre carbon uptake in one sector of the Southern Ocean.

Better conversation between physical and chemical folks.

I hope more international collaborations to conduct community-coordinated field campaigns. I think an intercomparison study of all the different WBC regions would be great. A review paper of what we know in each region about the circulation, air-sea interactions, the solubility and biological pumps and how much we think each contributes to carbon export, etc. can help highlight the science questions we need to work on to advance knowledge in the most well studied regions, as well as identify potential transferable knowledge between the regions that can help to establish priorities for future experiments in less studied/surveyed regions.

I didn't hear a clear consensus from this workshop about what the top priorities for further research are (or even the degree to which WBCs or mode waters are particularly significant locations of anthropogenic carbon sequestration), but reaching that consensus will require sustained interactions of this (or a similar) interdisciplinary groups. It certainly makes sense to focus scarce observational assets on regions of outsize importance, so identifying those likely locations is a key step.

Better mechanistic understanding of controls on ocean uptake of carbon dioxide.

I think this workshop helped to make clear the importance of western boundary currents on different time and space scales. I hope that a more nuanced understanding of the role of WBCs in carbon and heat uptake will emerge over the next several years.

A more detailed assessment on specific processes that occur on western boundary currents and their relationship to carbon sequestration. This relationship needs to be clarified.

It made me realize how difficult it was to observe these meso to sub-mesocale features, and the lack of tools we have as a community for studying them. This workshop acted as a good starting point on bringing researchers from different backgrounds together who work on this problem, and get them aware of questions from other disciplines. I hope the conversation continues, and observational needs are communicated in the future to provide a better, more comprehensive understanding of these processes from both a physical, biological, and chemical perspective.

usclivar.org/meetings/ocean-carbon-hot-spots-workshop

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