Proposal for a SCOR-WCRP Sponsored Working Group

Carbon Hot Spot: Drivers and Sensitivities of Large Carbon Uptake in Western Boundary Currents

Abstract

The goal of this SCOR working group is to develop an interdisciplinary and international research community that will facilitate better understanding and awareness of the role that Western Boundary Currents (WBCs) play in climate and anthropogenic carbon dioxide (CO_2) sequestration. Understanding the drivers and sensitivities of carbon uptake in WBCs, as well as the associated climate feedbacks, requires collaboration between physical and chemical oceanographers, who have traditionally worked independently of each other. This international group of researchers will include observationalists and modelers from the chemical and physical oceanography communities who share the common goal of improving climate models through enhanced dynamical understanding of ocean processes. We will achieve this goal by organizing annual meetings, producing a review article, and coordinating a field program and pilot study called Carbon Hot Spot in the Kuroshio Extension region. These activities will culminate in a Chapman Conference on "Improving climate model physical-biogeochemical interactions in Western Boundary Currents."

Scientific Background and Rationale

The ocean is responsible for absorbing nearly a quarter of the anthropogenic carbon emitted into the atmosphere each year, making it an essential component of the climate system that has a damping effect on modern climate change. However, the amount of ocean carbon uptake estimated from climate projections performed with coupled climate models can vary by as much as 29% [Frölicher et al., 2014]. The reasons for these differences are not clear, but the models tend to vary in their representation of lateral mixing by mesoscale eddies, which has been shown to play a significant role in oceanic carbon uptake [Gnanadesikan et al., 2015]. WBC regions are the most eddy-rich locations in the ocean, making them particularly relevant to the study of ocean carbon uptake and storage. Due to these characteristics, the focus of our working group is to better understand physical-biogeochemical interactions and reduce model biases in these eddy-rich WBCs.

WBC regions exhibit intense sea-to-air heat loss, $\mathcal{O}(1000 \text{ W m}^{-2})$, during winter, in connection with cold-air outbreaks. Atmospheric circulation feedback mechanisms associated with this heat exchange have important impacts on the jet stream path, which affect regional climate downstream as well as the formation of Subtropical Mode Water (STMW). Mode waters are thick water masses of nearly constant temperature that form during winter from convective cooling and mixing at the ocean surface, which deepens the mixed layer and increases its thickness. Mode waters have been observed on the equatorward side of all WBCs and their formation accounts for a majority of the anthropogenic CO_2 sequestration that occurs outside of the polar deep-water-formation regions [Sabine et al., 2004]. Figure 1A shows the global pattern of annual net sea-air CO_2 flux and clearly displays the significant role of WBC regions in annual ocean carbon uptake. Although this spatial pattern is well resolved, there are still many open questions about what processes drive the formation and long-term evolution of mode waters, and how this relates to ocean carbon transport and storage. In order to adequately make and understand regional and future climate projections on decadal time scales and longer, it is pivotal that we characterize the drivers of mode water formation and determine how variability in these processes influence carbon and biogeochemical cycling.

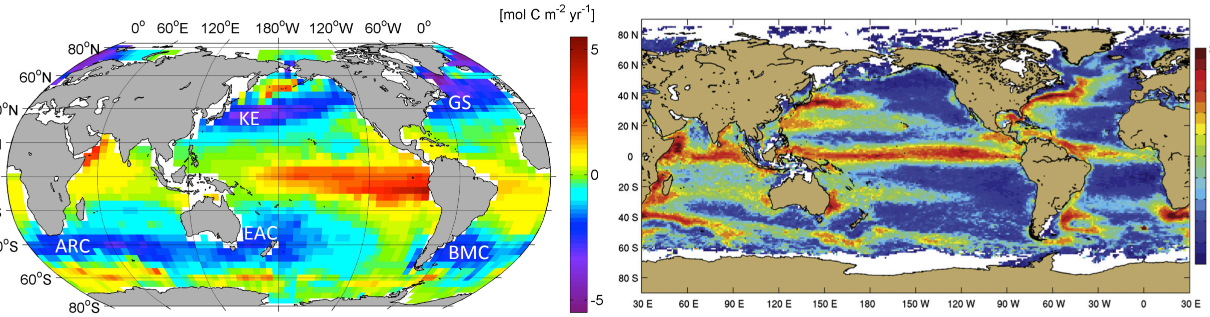

Figure 1: (**A**) Global maps of sea surface annual net sea-air CO_2 flux in units of mol m^{-2} yr^{-1} referenced to year 2000. Negative values indicate net ocean CO_2 uptake. KE = Kuroshio Extension, GS = Gulf Stream, ARC = Agulhas Return Current, EAC = East Australian Current, BMC = Brazil/Malvinas Confluence. Adapted from Figure 5 in [Park et al., 2010]. (**B**) Global map of eddy kinetic energy in units of cm^2 s^{-2} from surface drifters. Figure 14.16 in [Talley et al., 2011].

WBC regions are characterized by the highest eddy kinetic energy in the global ocean (Fig. 1B). One intriguing example of physical-biogeochemical interaction in a WBC comes from the North Pacific Ocean; the Kuroshio Extension (KE). The KE exhibits a clear bimodality in its meandering state within the first 1000 km east of Japan [Qiu and Chen, 2005] and it has been hypothesized that variability in the KE jet modulates the volume of North Pacific Subtropical Mode Water (NPSTMW) formation [Qiu et al., 2007, Cerovecki and Giglio, 2016, Rainville et al., 2014]. In addition, Qiu et al. [2007] argue that year-to-year NPSTMW variability is not correlated with atmospheric forcing, but rather the "dynamic state" of the Kuroshio Extension. More recently covariability in biogeochemistry has been linked with these trends in NPSTMW formation [Oka et al., 2015] and surface chlorophyll [Lin et al., 2014], which has important implications for interannual variability in and future projections of carbon sequestration.

Global climate models are routinely run in a configuration where eddies are parameterized. The results of Gnanadesikan et al. [2015], using a single model, show significant sensitivity in ocean carbon uptake to the parameterization of mesoscale eddy lateral mixing. The sensitivity found in their single model is remarkably similar to the 29% spread seen across climate models in Frölicher et al. [2014], providing further evidence that accurate eddy parameterizations are needed. When models are run in a configuration that explicitly resolves mesoscale eddies, they tend to show better agreement with observations. For example, the Kuroshio Extension bimodality is not present in coarse resolution models, but emerges when mesoscale eddies are resolved [Bishop et al., 2015]. New theories regarding mode water formation and variability have also shed light on the importance of eddies [Deremble and Dewar, 2013]. Climate models that include biogeochemistry are still relatively new and rely on parameterizations of eddy physical-biogeochemical interaction. Due to computational costs, the research community is more than a decade away from routinely resolving mesoscale eddies, and even further away from resolving submesoscale eddies. Therefore it is imperative that researchers better understand the physical-biogeochemical interactions in and around eddies to ensure the best possible parameterizations in climate models.

In the past decade there have been three major field programs in WBCs focusing on the physics:

The Kuorshio Extension System Study (KESS) in the Kuroshio Extension, CLIvar MOde Water Dynamic Experiment (CLIMODE) in the Gulf Stream, and the Agulhas Current Time-Series (ACT) experiment in the Agulhas current. Each of these efforts highlight the importance of extended time series that resolve mesoscale and submesoscale eddies and their order one importance in these systems. The next step in advancing our understanding of WBCs and their role in carbon cycling and climate change, is to link the physical dynamics with the biogeochemical processes that are fundamentally coupled to them. In addition to measurements for estimating air-sea heat, moisture, and momentum fluxes (e.g. wind speed and direction, air and sea surface temperature, humidity, solar and longwave radiation, precipitation, barometric pressure) as well as physical ocean parameters (e.g. temperature, salinity, and near-surface currents), the NOAA Kuroshio Extension Observatory (KEO) moored buoy[1] has been measuring surface ocean and atmosphere partial pressures of CO_2 (pCO_2) since 2007 and surface ocean pH since 2011. Most importantly, KEO is the only buoy making biogeochemicaly relevant measurements in a WBC region.

Observations of sea surface pCO_2 at the KEO mooring between 2007 and 2014 were used by Fassbender [2014] to quantify the annual biological export of organic and inorganic carbon from the ocean surface to the interior using a mixed layer carbon budget approach. This approach was also applied to seven years of sea surface pCO_2 observations from the NOAA Ocean Station Papa (OSP) mooring located in the eastern subarctic North Pacific [Fassbender et al., 2016a]. Results from this work indicate that the annual export of organic carbon, commonly referred to as net community production (NCP), is almost twice as large at KEO as at OSP. The ability of the KEO region to support significantly higher biological productivity is primarily the result of sufficienct iron supply from the Asian continent coupled with seasonal replenishment of mixed layer nutrients (including iron) caused by deep winter mixing during mode water formation [Yasunaka et al., 2013]. Subsequent shoaling of the mixed layer depth in spring results in a massive spring bloom that exhausts all nutrients within a few months [Fassbender, 2014, Fassbender et al., 2016b]. The maximum depth of winter mixing coupled with the balance between the rate of mixed layer shoaling and light availability fundamentally controls the amount of nutrients phytoplankton can utilize before seasonal stratification is complete. Further productivity may be supported by eddy-induced mixing events; however, direct evidence is lacking due to the paucity of observations.

The tight link between biogeochemical cycling and physical mixing processes in the KE region makes this the prime location to study the interplay of physics, chemistry, and biology. The biggest challenge in resolving a modern baseline for biogeochemical cycling in this region and other WBCs is the inability to resolve vertical and horizontal chemical gradients in physical and chemical parameters in real time within dynamic eddy fields. As a result, there are many unknowns regarding how ocean warming and acidification may influence biogeochemical cycling in these important carbon sink regions. Thus, a coordinated effort is needed to quantify the impact of mesoscale and submesoscale eddies on ocean carbon cycling as well as the biological response times to these features in WBC regions.

This working group will build upon past studies of physical and chemical processes in WBCs and create a community of diverse researchers that will engage in international interdisciplinary climate science. One of the main goals of this working group is to plan and conduct a field program near KEO to better understand the role of ocean eddies in upper ocean carbon transformations and provide guidance to the modeling community on how best to parameterize these key process interactions in climate models.

[1] http://www.pmel.noaa.gov/co2/story/KEO

Terms of Reference

The specific goals of our proposed working group are:

1. *Workshop*: Organize a workshop to coordinate physical and chemical oceanographic research on this topic and foster new collaborations. The goals of the workshop will be to synthesize current research activities related to the topic, develop future initiatives, identify strategic collaborations, and determine how best to monitor the WBC systems to improve ocean modeling of biogeochemistry.

2. *Panel Guidance*: This working group will determine how best to monitor CO_2 fluxes in all WBCs and give guidance to CLIVAR panels based on results from the field/pilot study.

3. *Review Paper*: A review paper will be written for publication in an open access peer-reviewed journal that will showcase the importance of WBC regions in carbon sequestration and climate.

4. *Field/Pilot Study*: Plan and conduct a field/pilot study in the Kuroshio Extension region near the KEO surface mooring using autonomous instrumentation in 2018. The goals of this field program will be to better understand the role of eddies in biogeochemical cycling and annual carbon sequestration in WBCs. This study will benefit any future WBC experiment and modeling exercise to see what scales are needed to be resolved to adequately simulate carbon budgets.

List of Products

1. Kick-off article in EOS or BAMS.

2. Review paper in a peer-reviewed open access journal

3. CLIVAR Report on recommendations for future and continuous monitoring of the WBC regions targeting physical and biogeochemical observations.

4. Chapman Conference on "Improving climate model physical-biogeochemical interactions in Western Boundary Currents."

Timeline

The working group anticipates three years of funded support to fulfill the terms of reference. The first course of action will be to put together a kick-off article to announce the group to the greater community in either EOS or BAMS in hopes of attracting other scientists conducting research related to the working group efforts.

Meeting 1

The first working group meeting will take place in April 2017, in conjunction with the IOC/WESTPAC Open Science Meeting in Qingdao, China. Member Xiaopei Lin will be submitting a proposal for a session on WBCs at this meeting. The meeting foci will be on:

- Putting together a review article.

- Planning of Field/Pilot study to take place in winter 2018 in coordination with OMIX/AIKEC experiments.

- Discussing strategies for observations in other WBCs.

Carbon Hot Spot

In between meeting 1 and 2 the Carbon Hot Spot Field/Pilot study will take place tentatively from December 2017–May 2018 during the winter to summer transition encompassing the spring bloom.

Meeting 2

The second working group meeting will take place in conjunction with the 2018 Ocean Sciences meeting to take place in Portland, OR. This meeting will focus on:

- A status update of the Carbon Hot Spot Field/Pilot study in progress.
- Final discussion of the review article to be submitted.
- Plan for Chapman Conference proposal to be submitted a couple months following the meeting.

Meeting 3

A third meeting will take place in conjunction with EGU in summer 2018. This meeting will focus on:

- Preliminary results from the Carbon Hot Spot Field/Pilot study.
- Begin drafting a CLIVAR report for guidance on future observational efforts in all WBCs as well as a CLIVAR process study proposal.
- Final planning for Chapman Conference to take place in winter/spring 2019.

Chapman Conference

The working group will culminate in the Chapman Conference. This conference will bring together observationalists and modelers with expertise in physical and chemical oceanography. The meeting will focus on the status of the research topic, include discussion of new insights gained from Carbon Hot Spot, address how to improve modeling efforts based on Carbon Hot Spot, and determine future directions and collaborations beyond the SCOR working group.

Collaboration and Capacity Building

This working group will collaborate and coordinate with Dr. Lin's research group (also a member of this working group) at the Ocean University of China on the Air-Sea Interaction in the Kuroshio Extension and its Climate impact (AIKEC) experiment. A cruise will take place in early summer 2017 as part of the AIKEC experiment. Lin has offered this cruise as an opportunity for collaborated observations. This working group will also build stronger collaborations with the Ocean Mixing Processes Impact on Biogeochemistry, Climate and Ecosystem (OMIX[2]) experiment. Dr. Oka (also a member of this working group) is involved with OMIX. It is a coordinated effort amongst the Japanese to understand physical-biogeochemical interactions caused by tidal-induced diapycnal mixing in the upstream Oyashio and Kuroshio. Both AIKEC and OMIX will span the SCOR Working Group period. In order to build further collaboration and capacity building, we will invite early career scientists to the Chapman conference and bridge the international community by building mentor-mentee relationships across disciplines, institutions, and countries.

[2]http://omix.aori.u-tokyo.ac.jp/en/

Chairs and Working Group Members

Members

Name	Gender	Affiliation	Expertise
Stuart Bishop (co-chair)	M	NCSU (USA)	PO
Andrea Fassbender (co-chair)	F	MBARI (USA)	BGC
Kitack Lee	M	Pohang U. of Sci. and Tech. (S. Korea)	BGC
Geun-Ha Park	F	KIOST (S. Korea)	BGC
Xiaopei Lin	M	Ocean U. of China (China)	PO
Ryuichiro Inoue	M	JAMSTEC (Japan)	PO
Eitarou Oka	M	U. of Tokyo (Japan)	PO
Pedro Monteiro	M	SCIR (S. Africa)	BGC
Debby Ianson	F	DFO (Canada)	BGC
Roberta Hamme	F	University of Victoria (Canada)	BGC

Associate Members

Name	Gender	Affiliation	Expertise
Adrienne Sutton	F	JISAO (USA)	BGC
Meghan Cronin	F	NOAA PMEL (USA)	PO

Working Group Contributions

Dr. Stuart Bishop (co-chair): Expertise in WBC dynamics with an emphasis towards understanding mesoscale and submesoscale eddies and their role in ocean circulation. Expertise in using/obtaining observational and modeling data sets using autonomous ocean instrumentation and high-resolution modeling respectively.

Dr. Andrea Fassbender (co-chair): Expertise in quantifying the processes involved in regional biogeochemical cycling to better understand how ocean warming and acidification may influence the drivers of carbon transport and storage in the ocean. She approaches this research by combining ship, mooring, float, and satellite observations in addition to developing new instrumentation for carbon cycle research with the goal of characterizing modern baselines for biogeochemical cycling throughout the ocean.

Dr. Kitack Lee: Expertise in marine carbon cycle dynamics and biogeochemical cycling. His work ranges from the regional to global scale and addresses important linkages between ocean biology and chemistry now and under future climate change scenarios.

Dr. Geun-Ha Park: Expertise in the quantification of anthropogenic CO_2 within the water column and research for changes in sea-air CO_2 fluxes. She recently found unusually high surface partial pressure of CO_2 last summer in the area where the formation of STMW occurs and is trying to figure out the reason for it.

Dr. Xiapoei Lin: Expertise wtih combining observation and numerical simulations, Xiaopei will focus on the multiscale air-sea interaction in the WBC region and its climate impact to improve the understanding of ocean and climate dynamics.

Dr. Ryuichiro Inoue: Expertise working on data taken by Argo floats with DO sensor, BGC mooring, and shipboard measurements to understand biogeochemical responses to a cyclonic eddy in the oligotrophic subtropic ocean. He will analyze floats and glider data to understand impacts of mixing and meso- and submesoscale processes on biogeochemical properties in WBC.

Dr. Eitarou Oka: Expertise working to understand decadal variability of mode waters in the North Pacific by using satellite products, Argo floats and shipboard measurements. He will analyze floats and shipboard data to understand impact of those physical oceanographic conditions on variability of biogeochemical properties.

Dr. Pedro Monteiro: CO_2 work to understand how and why ocean biogeochemistry of oxygen and carbon adjust to climate variability. The use of numerical modeling as experimental platforms to understand scale sensitivities of coupled physics and biogeochemical processes.

Dr. Debby Ianson: Expertise in evaluating interdisciplinary oceanographic problems that are pertinent to climate variability over a variety of time-scales throughout unique oceanic environments. She approaches these problems by integrating traditionally disconnected disciplines using modeling as a tool supplemented by field work to identify crucial aspects within complex systems through model development and validation.

Dr. Roberta Hamme: Dr. Hamme's group makes measurements of dissolved gases and uses them to elucidate the biological and physical mechanisms that isolate carbon from the surface ocean and atmosphere. She holds a Canada Research Chair in Ocean Carbon Dynamics and will contribute her expertise on gas exchange processes and productivity rate measurements.

Appendix: Key Publications

Stuart Bishop (co-chair)

1. Bishop, S.P. and D.R. Watts (2014). Rapid eddy-induced modification of Subtropical Mode Water during the Kuroshio Extension System Study. J. Phys. Oceanogr., 44, 1941-1953.

2. Bishop, S.P. and F.O. Bryan (2013). A comparison of mesoscale eddy heat fluxes from observations and a high-resolution ocean model simulation of the Kuroshio Extension. J. Phys. Oceanogr., 43, 2563-2570.

3. Small, J.R., J. Bacmeister, D. Bailey, A. Baker, S.P. Bishop, F.O. Bryan, J.M. Caron, J. Dennis, P. Gent, H.-M Hsu, M. Jochum, D. Lawrence, E. Munoz, P. diNezio, T. Scheitlin, B. Tomas, J. Tribbia, Y.-H. Tseng, and M. Vertenstein (2014). A new synoptic scale resolving global climate simulation using the Community Atmosphere Model. J. Adv. Model. Earth Syst., 6, 1065-1094.

4. Bishop, S.P. (2013). Divergent eddy heat fluxes in the Kuroshio Extension at 144°-148°. Part 2: Spatiotemporal variability. J. Phys. Oceanogr., 43, 2416-2431.

5. Bishop, S.P., F.O. Bryan, and R.J. Small (2015). Bjerknes-like compensation in the wintertime North Pacific. J. Phys. Oceanogr., 45, 1339-1355.

Andrea Fassbender (co-chair)

1. Fassbender, A. J., C. L. Sabine, and M. F. Cronin, Net community production at the Kuroshio Extension Observatory and its role in regional carbon cycling. In progress.

2. Fassbender, A. J., C. L. Sabine, and M. F. Cronin (2016), Net community production and calcification from seven years of NOAA Station Papa Mooring measurements, Global Biogeochem. Cycles, doi:10.1002/2015GB005205.

3. Fassbender, A. J., C. L. Sabine, N. Lawrence-Slavas, E. H. De Carlo, C. Meinig, and S. Maenner Jones (2015), Robust Sensor for Extended Autonomous Measurements of Surface Ocean Dissolved Inorganic Carbon, Environ. Sci. Technol., 49(6), 3628-3635, doi:10.1021/es5047183.

4. Fassbender, A. J. (2014), New approaches to study the marine carbon cycle. PhD dissertation, University of Washington. Proquest, 1/11/2016, http://hdl.handle.net/1773/27552.

5. Sabine, C. L. et al. (2013), Surface Ocean CO_2 Atlas (SOCAT) gridded data products, Earth Syst. Sci. Data, 5(1), 145-153, doi:10.5194/essd-5-145-2013.

Kitack Lee

1. Ko. Y.-H., K. Lee, K.-H. Eom, I. Han (2016), Organic alkalinity produced by phytoplankton and its effect on computations of ocean carbon parameters, Limnology and Oceanography, in press.

2. Kim, T.-W., Park, G.-H., Kim, D.-S., K. Lee, R. Feely, F. Millero (2015), Seasonal variations in the aragonite saturation state in the upper open-ocean waters of the North Pacific Ocean, Geophysical Research Letters, DOI:10.1002/2015GL063602.

3. Kim, J.-M., K. Lee, K. Shin, E.J. Yang, A. Engel, D. M. Karl, H.-C. Kim (2011), Shifts in biogenic carbon flow from particulate to dissolved forms under high carbon dioxide and warm ocean conditions, Geophysical Research Letters, 38, L08612, doi:10.1029/2011GL047346. [I.F. 2.397].

4. Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee et al. (2004), The oceanic sink for anthropogenic CO2, Science, 305, 367-371. (2004/7/16).

5. Lee, K., D.M. Karl, J.-Z. Zhang, and R. Wanninkhof (2002), Global estimates of net carbon production in the nitrate-depleted tropical and subtropical ocean, Geophysical Research Letters, 29, 13/1-13/4. (2002/10/4).

Geun-Ha Park

1. Geun-Ha Park, Rik Wanninkhof, Scott C. Doney, Taro Takahashi, Kitack Lee, Richard A. Feely, Christopher L. Sabine, and Joaquin Triñanes and Ivan D. Lima (2010), Variability of global net sea-air CO_2 fluxes over the last three decades using empirical relationships, Tellus, 62B, 352-368.

2. Rik Wanninkhof, Geun-Ha Park, Taro Takahashi, Colm Sweeney, Richard A. Feely, Yukihiro Nojiri, Nicolas Gruber, Scott C. Doney, Galen A. McKinley, Andrew Lenton, Corinne Le. Qur, Christopher Heinze, Jrg Schwinger, Heather Graven, and Samar Khatiwala (2013). Global ocean carbon uptake: magnitude, variability and trends, Biogeosciences, 10, 1983-2000, doi:10.5194/bg-10-1983-2013.

3. Masao Ishii, Richard A. Feely, Keith B. Rodgers, Geun-Ha Park, Rik Wanninkhof, Daisuke Sasano, Hiroyuki Sugimoto, Cathy E. Cosca, Shinichiro Nakaoka, Maciej Telszewski, Yukihiro Nojiri, Sara E. MikaloffFletcher, Yosuke Niwa, Prabir K. Patra, Vinu Valsala, Hideyuki Nakano, Ivan Lima, Scott C. Doney, Erik T. Buitenhuis, Olivier Aumont, John P. Dunne, Andrew Lenton, and Taro Takahashi (2014), Air-sea CO_2 flux in the Pacific Ocean for the period 1990-2009, Biogeosciences, 11, 709-734, doi:10.5194/bg-11-709-2014.

4. Tae-Wook Kim, Geun-Ha Park, Dongseon Kim, Kitack Lee, Richard A. Feely and Frank J. Millero (2015), Seasonal variations in the aragonite saturation state in the upper open-ocean waters of the North Pacific Ocean, Geophysical Research Letters, 42, 4498-4506, doi:10.1002/2015GL063602.

5. Christopher Rdenbeck, Dorothee C. E. Bakker, Nicolas Gruber, Yosuke Iida, Andrew R. Jacobson, Steve Jones, Peter Landschtzer, Nicolas Metzl, Shinichiro Nakaoka, Are Olsen, Geun-Ha Park, Philippe Peylin, Keith B. Rodgers, Tristan P. Sasse, Ute Schuster, Jamie D. Shutler, Vinu Valsala, Rik Wanninkhof, and Jiye Zeng (2015), Data-based estimates of the ocean carbon sink variability-first results of the Surface Ocean $p\mathrm{CO}_2$ Mapping intercomparison (SOCOM). Biogeosciences, 12, 7251-7278, doi:10.5194/bg-12-7251-2015.

Xiaopei Lin

1. Lin, X., J. Yang, D. Wu, and P. Zhai (2008), Explaining the global distribution of peak-spectrum variability of sea surface height, Geophys. Res. Lett., 35, L14602, doi:10.1029/2008GL034312.

2. Lin, X., Yuqi Yin, Ping Zhai, Jiayan Yang (2014), A mechanism for the latitudinal dependence of peak-spectrum sea surface height variability, JGR: Oceans, 119, 1431-1444, doi: 10.1002/2013JC009642.

3. Wenju Cai, Susan K. Avery, Margaret Leinen, Kenneth Lee, Xiaopei Lin and Martin Visbeck (2015), Institutional coordination of global ocean observations, Nature Climate Change, 5, 4-6.

4. Dunxin Hu, Lixin Wu, Wenju Cai, Alex Sen Gupta, Alexandre Ganachaud, Bo Qiu, Arnold L. Gordon, Xiaopei Lin, Zhaohui Chen, Shijian Hu, Guojian Wang, Qingye Wang, Janet Sprintal, Tangdong Qu, Yuji Kashino, Fan Wang, & William S. Kessler (2015), Pacific western boundary currents and their roles in climate, 522, 299-308.

5. Xiaohui Ma, Ping Chang, R. Saravanan, Raffaele Montuoro, Jen-Shan Hsieh, Dexing Wu, Xiaopei Lin, Lixin Wu & Zhao Jing (2015), Distant Influence of Kuroshio Eddies on North Pacific Weather Patterns? Scientific Reports 5.

Ryuichiro Inoue

1. Kouketsu, S., H. Kaneko, T. Okunishi, K. Sasaoka, S. Itoh, R. Inoue, and H. Ueno (2015), Mesoscale eddy effects on temporal variability of surface chlorophyll a in the Kuroshio Extension. J. Oceanogr., DOI 10.1007/s10872-015-0286-4.

2. Inoue, R., and S. Kouketsu (2016), Physical oceanographic conditions around the S1 mooring site. J. Oceanogr., DOI 10.1007/s10872-015-0342-0.

3. Inoue, R., S. Kouketsu, T. Kita, S. Hosoda, T. Kobayashi, K. Sato, H. Nakajima, and T. Kawano (2016), Western North Pacific Integrated Physical-Biogeochemical Ocean Observation Experiment (INBOX): Part 1. Specifications and Chronology of the S1-INBOX floats. Accepted to Journal of Marine Research.

4. Inoue, R., M. Honda, T. Fujiki, K. Matsumoto, S. Kouketsu, T. Suga, and T. Saino (2016), Western North Pacific Integrated Physical-Biogeochemical Ocean Observation Experiment (INBOX): Part 2. Biogeochemical responses to eddies and typhoons revealed from the S1 mooring and shipboard measurements, accepted to Journal of Marine Research.

5. Kouketsu, S., R. Inoue, and T. Suga (2016), Western North Pacific Integrated Physical-Biogeochemical Ocean Observation Experiment (INBOX): Part 3. Mesoscale variability of dissolved oxygen concentrations observed by multiple floats during S1-INBOX, accepted to Journal of Marine Research.

Eitarou Oka

1. Oka E., B. Qiu, Y. Takatani, K. Enyo, D. Sasano, N. Kosugi, M. Ishii, T. Nakano, and T. Suga (2015), Decadal variability of Subtropical Mode Water subduction and its impact on biogeochemistry. Journal of Oceanography, 71, 389-400.

2. Sukigara C., T. Suga, K. Toyama, and E. Oka (2014), Biogeochemical responses associated with the passage of a cyclonic eddy based on shipboard observations in the western North Pacific. Journal of Oceanography, 70, 435-445.

3. Oka, E., B. Qiu, S. Kouketsu, K Uehara, and T Suga (2012), Decadal seesaw of the Central and Subtropical Mode Water formation associated with the Kuroshio Extension variability. Journal of Oceanography, 68, 355-360.

4. Oka, E., and B. Qiu (2012), Progress of North Pacific mode water research in the past decade. Journal of Oceanography, 68, 5-20.

5. Oka, E., T. Suga, C. Sukigara, K. Toyama, K. Shimada, and J. Yoshida (2011), Eddy resolving" observation of the North Pacific Subtropical Mode Water. Journal of Physical Oceanography, 41, 666-681.

Pedro Monteiro

1. Monteiro, P. M. S., L. Gregor, M. Lvy, S. Maenner, C. L. Sabine, and S. Swart (2015), Intraseasonal variability linked to sampling alias in air-sea CO_2 fluxes in the Southern Ocean, Geophys. Res. Lett., 42, 8507-8514, doi:10.1002/2015GL066009.

2. Thomalla, S.J., M-F. Racault, S. Swart, and P.M.S. Monteiro (2015), High-resolution view of the spring bloom initiation and net community production in the Subantarctic Southern Ocean using glider data, ICES J. Mar. Sci. 72 (6), 1999-2020.

3. Swart S., S.J. Thomalla, P.M.S. Monteiro, and I.J. Ansorge (2012), Mesoscale features and phytoplankton biomass at the GoodHope line in the Southern Ocean during austral summer, African J. Mar. Sci. 34 (4), 511-524.

4. Swart S., N. Chang, N. Fauchereau, W. Joubert, M. Lucas, T. Mtshali, A.N. Roychoudhury, A. Tagliabue, S.J. Thomalla, H. Waldron, P.M.S. Monteiro (2012), Southern Ocean seasonal cycle experiment 2012: Seasonal scale climate and carbon cycle links. S. African J. Sci. 108 (3/4), doi:10.4102/sajs.v108i3/4.1089.

5. Thomalla S.J., N. Fauchereau, S. Swart, P.M.S. Monteiro (2011), Regional scale characteristics of the seasonal cycle of chlorophyll in the Southern Ocean Biogeosciences. 8, 2849-2866. doi:10.5194/bg-8-2849-2011.

Debby Ianson

1. Moore-Maley, B. L., S. E. Allen, and D. Ianson (2016). Locally driven interannual variability of near-surface pH and ΩA in the Strait of Georgia, J. Geophys. Res. Oceans, 121, doi: 10.1002/2015JC011118.

2. Ianson, D., C. Volker, K.L. Denman, E. Kunze, and N. Steiner (2012). The effect of vertical and horizontal dilution on fertilized patch experiments, Global Biogeochem. Cycles, 26, GB3002, doi: 10.1029/2010GB004008.

3. Haigh, R., Ianson, D., Holt, C. A., Neate, H. E., & Edwards, A. M. (2015). Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific. PLoS ONE, 10(2), e0117533, doi: 10.1371/journal.pone.0117533.

4. W. Evans, B. Hales, P. G. Strutton, D. Ianson (2012). Sea-air CO2 fluxes in the western Canadian coastal ocean. Prog. Oceanog, doi:10.1016/j.pocean.2012.01.003.

5. Tortell, P., Merzouk, A., Ianson, D., Pawlowicz, R., Yelland, D. (2012). Influence of regional climate forcing on surface water *p*CO2, DO2/Ar and dimethylsulfide (DMS) along the southern British Columbia coast. Continental Shelf Research, 47, doi:10.1016/j.csr.2012.07.007.

Roberta Hamme

1. Hamme, Roberta C., Johanna E. Berry, Jody M. Klymak, and Kenneth L. Denman (2015), In situ O2 and N2 measurements detect deep-water renewal dynamics in seasonally-anoxic Saanich Inlet, Continental Shelf Research, doi:10.1016/j.csr.2015.06.012.

2. Giesbrecht, Karina E., Roberta C. Hamme, and Steven R. Emerson (2012), Biological productivity along Line P in the subarctic northeast Pacific: in-situ versus incubation-based methods, Global Biogeochemical Cycles, 26, GB3028, doi:10.1029/2012GB004349.

3. Hamme, Roberta C., Nicolas Cassar, Veronica P. Lance, Robert D. Vaillancourt, Michael L. Bender, Peter G. Strutton, Tommy S. Moore, Michael D. DeGrandpre, Christopher L. Sabine, David T. Ho, and Bruce R. Hargreaves (2012), Dissolved O2/Ar and other methods reveal rapid changes in productivity during a Lagrangian experiment in the Southern Ocean, Journal of Geophysical Research - Oceans, 117, C00F12, doi:10.1029/2011JC007046.

4. Hamme, Roberta C., Peter W. Webley, William R. Crawford, Frank A. Whitney, Michael D. DeGrandpre, Steven R. Emerson, Charles C. Eriksen, Karina E. Giesbrecht, Jim F. R. Gower, Maria T. Kavanaugh, M. Angelica Pea, Christopher L. Sabine, Sonia D. Batten, Laurence A. Coogan, Damian S. Grundle, Deirdre Lockwood (2010), Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific, Geophysical Research Letters, 37, L19604, doi:10.1029/2010GL044629.

5. Hamme, Roberta C., and Ralph F. Keeling (2008), Ocean ventilation as a driver of interannual variability in atmospheric potential oxygen, Tellus B, 60(5), p. 706-717, doi:10.1111/j.1600-0889.2008.00376.x.

References

Stuart P. Bishop, Frank O. Bryan, and R. Justin Small. Bjkerknes-like compensation in the wintertime North Pacific. *Journal of Physical Oceanography*, 45:1339–1355, 2015.

Ivana Cerovecki and Donata Giglio. North pacific subtropical mode water volume decrease in 2006-09 estimated from argo observations: Influence of surface formation and basin-scale oceanic variability. *Journal of Climate*, 29:2177–2199, 2016.

Bruno Deremble and William K. Dewar. Volume and potential vorticity budgets of Eighteen Degree Water. *Journal of Physical Oceanography*, 43:2309–2321, 2013.

Andrea J. Fassbender. *New approaches to study the marine carbon cycle*. PhD thesis, University of Washington, 2014.

Andrea J. Fassbender, Christopher L. Sabine, and Meghan F. Cronin. Net community production and calcification from seven years of NOAA Station Papa Mooring measurements. *Global Biogeochemistry Cycles*, 30:250–267, 2016a. doi: 10.1002/2015GB005205.

Andrea J. Fassbender, Christopher L. Sabine, and Meghan F. Cronin. Annual net community production at the Kuroshio Extension Observatory and its role in regional carbon cycling. *in prep*, 2016b.

Thomas L. Frölicher, Jorge L. Sarmiento, David J. Paynter, John P. Dunne, John P. Krasting, and Michael Winton. Dominance of the Southern Ocean in anthropogenic carbona nd heat uptake in CMIP5 models. *Journal of Climate*, 28:862–886, 2014. doi: 10.1175/JCLI-D-14-00117.1.

Anand Gnanadesikan, Marie-Aude Pradal, and Ryan Abernathey. Isopycnal mixing by mesoscale eddies significantly impacts oceanic anthropogenic carbon uptake. *Geophysical Research Letters*, 42:4249–4255, 2015. doi: 10.1002/2015GL064100.

Pengfei Lin, Fei Chai, Huijie Xue, and Peng Xiu. Modulation of decadal oscillation on surface chlorophyll in the Kuroshio Extension. *Journal of Geophysical Research*, 119:187–199, 2014.

Eitarou Oka, Bo Qiu, Yusuke Takatani, Kazutaka Enyo, Daisuke Sasano, Naohiro Kosugi, Masao Ishii, Toshiya Nakano, and Toshio Suga. Decadal variability of Subtropical Mode Water subduction and its impact on biogeochemistry. *Journal of Oceanography*, 71:389–400, 2015.

Geun-Ha Park, Rik Wanninkhof, Scott C. Doney, Taro Takahashi, Kitack Lee, Richard A. Feely, Christopher L. Sabine, and Joaquin Triñanes. Variability of global net sea-air CO_2 fluxes over the last three decades using empirical relationships. *Tellus*, 62B:352–368, 2010.

Bo Qiu and Shuiming Chen. Variability of the Kuroshio Extension jet, recirculation gyre, and mesoscale eddies on decadal time scales. *Journal of Physical Oceanography*, 35(11):2090–2103, November 2005.

Bo Qiu, Shuiming Chen, and Peter Hacker. Effect of mesoscale eddies on Subtropical Mode Water variability from the Kuroshio Extension System Study (KESS). *Journal of Physical Oceanography*, 37(4):982–1000, April 2007.

Luc Rainville, Steven R. Jayne, and Meghan F. Cronin. Variations of the North Pacific Subtropical Mode Water from direct observations. *Journal of Climate*, 27:2842–2860, 2014.

Christopher L. Sabine, Richard A. Feely, Nicolas Gruber, Robert M. Key, Kitack Lee, John L. Bullister, Rik Wanninkhof, C.S. Wong, Douglas W. R. Wallace, Bronte Rilbrook, Frank J. Millero, Tsung-Hung Peng, Alexander Kozyr, Tsueno Ono, and Aida F. Rios. The oceanic sink for anthropogenic CO_2. *Science*, 305:367–371, 2004.

Lynne D. Talley, George L. Pickard, William J. Emery, and James H. Swift. *Descriptive Physical Oceanography: An Introduction*, chapter 14. Elsevier, 2011.

Sayaka Yasunaka, Yukihiro Nojiri, Shin ichiro Nakaoka, Tsuneo Ono, Hitoshi Mukai, and Norihisa Usui. Monthly maps of sea surface dissolved inorganic carbon in the North Pacific: Basin-wide distribution and seasonal variation. *Journal of Geophysical Research*, 118(8):3843–3850, 2013. doi: 10.1002/jgrc.20279.