OCEAN'S CARBON AND HEAT UPTAKE: UNCERTAINTIES AND METRICS

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COVER IMAGE

Southern Ocean waves, credit: British Antartic Survey.

BACK COVER IMAGES

Clockwise from top-left: Deep SOLO deployment, credit: LEARNZ, www.learnz.org.nz—part of CORE Education http://www.core-ed.org/; Pacific krill, credit: Mike Maher, NOAA; Tara Howatt (McGill University) deploys a glider, credit Robin Matthews (MUN); CTD deployment, credit: NASA; Iceberg near Palmer Station, credit: Robin Solfisburg, NSF.

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Executive Summary

A workshop jointly sponsored by the US Climate Variability and Predictability (CLIVAR) and Ocean Carbon and Biogeochemistry (OCB) Programs was convened in December 2014 on “Ocean’s Carbon and Heat Uptake: Uncertainties and Metrics” and the challenges of improving observations, process understanding, and modeling. The rationale for holding this workshop, jointly organized by the Ocean Carbon Uptake and Southern Ocean Working Groups, was that despite the fact that the ocean has absorbed over 90% of the anthropogenic heat imbalance and over 30% of the anthropogenic carbon emissions, our ability to observe and simulate the “how,” the “where,” and the “how fast” these uptakes occur has significant shortcomings. Due to the scope and logistical difficulties of the task, our observing network is at best incomplete, and in some cases, non-existent, and our efforts at simulating past, present, and future climate have large uncertainties due to inter-model differences and a lack of benchmarks.

This workshop brought together physical, chemical, and biological oceanographers, as well as atmospheric, ice, and climate scientists from observational, theoretical, and modeling backgrounds to assess our current understanding of the role of the ocean in the uptake of heat and carbon and our ability to observe and simulate this uptake, with the express objective of reducing the uncertainty in future climate projections. The 82 attendees included academic, government, and non-governmental scientists and program managers, including at least 20 from non-US organizations representing nine different countries.

The objectives of this workshop were to:

- Build upon and synthesize the Working Groups’ efforts to develop metrics for evaluating biases in CMIP-5 model simulations;
- Estimate uncertainties in model projections of heat and carbon uptake; and
- Inform future observations, model development, and analysis strategies for addressing biases and uncertainties (including protocols for CMIP-6).

The workshop was organized into five main sessions covering the following themes: Model Biases and Uncertainties in CMIP-5 Models; Observational Gaps and Uncertainties; Process Studies: Gaps, New Measurements, and Parameterizations; Southern Ocean: Circulation and Carbon Cycle; and New Initiatives.

The main conclusions of the workshop include:

1. Circulation and stratification biases occur primarily in mid- to high-latitudes, where subsurface water masses are formed, and these regions are critical to uptake, storage, and distribution of heat, carbon, and nutrients, especially the regions where mode and intermediate waters form, as these supply nutrients globally. Uptake biases in the models can influence simulation of future climates. Processes with significant bias/uncertainty include convection, eddy mixing and large-scale advection, and interactions between large-scale and subgrid-scale dynamics. More high-latitude winter hydrographic observations are needed in order to better assess the models.

2. The Argo array has revolutionized the field and the next two programs – Deep Argo and BGC-Argo – are both critical to closing the budgets for heat and carbon in the ocean. “Climate quality” measurements, defined as absolute rather than relative quantities, standardized analyses, and calculated error bars associated with every measurement are needed to reduce the uncertainty in climate model projections. And funding agencies need to provide for syntheses of biogeochemical data. The highest priority new observations would be: an estimate of the total heat flux, higher resolution measurements of atmospheric gases, and more wintertime observations at and under the ice edge in both hemispheres.

3. Key processes in need of further study, both for reducing model uncertainty and for a deeper theoretical understanding, include: the roles of eddies in transport and mixing, carbon exchange and storage in coastal regions, convection and water mass overflows at high-latitudes, and the seasonal cycle of exchange of $p\mathrm{CO}_2$ with the atmosphere. All of these processes could strongly affect the net uptake of anthropogenic heat and carbon and therefore the trajectory of future climate.

4. With respect to the Southern Ocean, rigorous assessment of the input of wind energy into the ocean and the uncertainties (spatial and seasonal) associated with the observing system are needed. Specifically, more direct observations and a coordinated program to observe and model both oceanic and atmospheric biogeochemical parameters at the same place and time are needed. Understanding why climate models still simulate the Southern Hemisphere westerly winds equatorward of the actual position is still a critical issue. Models should be rigorously assessed against observationally-based metrics and only high performing models for the specific process should be included in intercomparisons. Finally, the use and reporting of tracers, both biogeochemical and idealized, in model simulations should become routine.

1 Introduction

The global ocean is a key component of the climate system, due in large part to its ability to absorb, store, and redistribute vast amounts of anthropogenic carbon and anomalous heat. The relevant processes, however, are complex and remain poorly understood. Regional changes in the ocean state can feed back positively on atmospheric carbon dioxide (CO_2) concentrations and warming trends via a slowdown in ocean carbon and heat uptake. The strength of these feedbacks depends on the complex interplay between physical and biogeochemical processes regulating the sensitivity of ocean heat and carbon uptake to climate perturbations.

Heat fluxes and carbon fluxes are each affected by the same physical processes – advection, convection, and mixing – but there are several important differences between the two. In particular, temperature changes affect buoyancy of the water, and thus the density-driven circulation, and the cooling and warming are in turn modified by circulation changes, resulting in a strong feedback loop and a large divergence of results for the simulated heat uptake in climate models. In contrast, dissolved carbon is a dynamically passive tracer, and circulation changes do not impact surface dissolved inorganic carbon (DIC) nearly as much as surface temperature. Heat distribution also exhibits significant spatial variability. For example, ocean heat uptake exhibits large latitudinal fluctuations, as a large proportion of the heat taken up by tropical waters is redistributed to higher latitude oceans with attendant feedbacks on the atmosphere. Atmospheric CO_2 concentrations increase globally, and the climate is affected by how much total carbon is left in the atmosphere, not where it is taken out.

Recent advances in observational and modeling capabilities have deepened our understanding of these processes. New observational datasets (e.g., Argo, Repeat Hydrography, SOCCOM) are beginning to shed light on changes in the global heat and carbon distribution. The intercomparison of Earth system models (e.g., CMIP-5) is starting to tease out the complex interplay among processes involving wind forcing, large-scale ocean circulation and stratification, turbulent eddies, sea ice, and biogeochemistry. Identification of critical observational targets and development of data/model metrics represent a promising approach for reducing uncertainties associated with climate projections.

1.1 Workshop Goals

This workshop was part of the original mission of both the Southern Ocean (http://usclivar.org/working-groups/southern-ocean) and the Ocean Carbon Uptake (http://usclivar.org/working-groups/ocu) Working Groups. Its primary purpose was to assemble broad expertise (ocean, atmosphere, cryosphere, climate dynamics), including observational, theoretical, and modeling backgrounds in order to assess our current understanding of the role of the ocean in the uptake of heat and carbon and our ability to observe and simulate this uptake, with the express objective of reducing uncertainty in future climate projections.

Specific meeting goals were:

1. Advancement of the science through improved communication, coordination, and collaboration between the diverse communities interested in various aspects of ocean heat and carbon uptake in the climate system;
2. Establishment of a foundation for multidisciplinary efforts that will lead to improved understanding of physical and biogeochemical processes, better representation of these processes in climate models, and, consequently, more reliable, physically based projections of heat and carbon uptake by the ocean;
3. Training and community building across disciplines for scientists at all career stages, including a focus on advanced graduate students and early career scientists; and
4. Identification of synergies between national and international projects.

1.2 Workshop Structure

i) Organizing Committee

The Organizing Committee was tasked with the organization of the workshop in a way that suited the common (though not identical) interests of the two working groups, planning the workshop format, and selecting invited speakers. The committee included co-chairs from each working group, as well as project managers from the sponsoring organizations.

ii) Workshop Format

An overarching goal of the meeting was to ensure that the most up-to-date knowledge was reflected in the meeting presentations, and to engage the workshop participants in focused discussions on how to evaluate uncertainties in the observations and the models, identify major unknowns, and formulate requirements for new observations and process studies. The initial plan to achieve these goals consisted of a mix of (i) invited talks by working group members and other leading experts, (ii) panel discussions open to all attendees following the plenary talks in each session, and (iii) a poster session to increase the breadth and depth of the presented material and to encourage input from and interaction among all workshop participants. The final format consisted of five distinct topical sessions that each included five, 15-minute talks (four during the New Initiatives session) followed by one hour of panel discussion moderated by members of the Organizing Committee at the end of each session. The meeting included 27 poster presentations.

The following questions motivated the panel discussions for each of the first four sessions:

Model Biases and Uncertainties in CMIP5 Models

1. Which model biases have the largest impact on the uncertainties in the heat/carbon uptake in climate models?
2. What observational metrics (among those available now or in the near future) can most reliably identify these biases?
3. What model improvements are needed to reduce these biases?

Observational Gaps and Uncertainties

1. What are the most fruitful opportunities for extracting important climate signals from existing historical datasets? And what methods can help increase the signal-to-noise ratio?
2. Which observational datasets (parameters, regions, seasons) are needed to provide tighter constraints on climate models?
3. What new types of observations (sensor, platforms) or modification of sampling strategy would yield the largest reduction in uncertainty about the current ocean state or future projections?

Process Studies: Gaps, New Measurements, and Parameterizations

1. What are the physical and biogeochemical processes that state-of-the-art coupled climate models do not capture/represent and may be responsible for the largest uncertainty in simulations of ocean heat and carbon uptake?
2. What are the physical and biogeochemical processes that state-of-the-art coupled climate models include but are still subject to very large biases in their representation, therefore contributing large uncertainty to simulations of ocean heat and carbon uptake?
3. What types of process studies (geography, temporal and spatial scales, etc.) would improve our understanding and representation of these physical and biogeochemical processes in models?

Southern Ocean: Circulation and Carbon Cycle

1. Is there motivation to continue the Drake Passage time series program for another decade?
2. What can we learn from model intercomparison in the Southern Ocean?
3. What is needed or can be done to produce a Southern Ocean surface flux dataset/reanalysis that is suitable for climate applications, including for forcing ocean-only models and for validating coupled climate models?
4. Robust simulation of the dynamics that govern Southern Ocean circulation requires resolving mesoscale eddies. This is challenging in terms of computing power and storage, typically restricting the length of simulations, especially the spin-up. Yet, reliable estimates of ocean heat and carbon uptake require well-equilibrated models. What are the best approaches to ensure adequate resolution and model equilibration given finite resources?

iii) Attendees

This workshop brought together physical, chemical, and biological oceanographers, atmosphere, ice, and climate scientists, from observational, theoretical, and modeling backgrounds to assess our current understanding of the role of the ocean in the uptake of heat and carbon and our ability to observe and simulate this uptake, with the express objective of moving toward reducing the uncertainty in future climate projections. The 82 attendees included academic, government, and non-governmental scientists and program managers including at least 20 from non-US organizations representing nine different countries. A list of attendees is included in Appendix B.

iv) Venue

The workshop was convened at the Park 55 Hotel in San Francisco on December 12-14, the weekend prior to the start of the 2014 American Geophysical Union (AGU) Fall Meeting. The San Francisco venue and dates were purposefully selected to leverage and capitalize on community participation in the AGU meeting, thereby reducing travel costs and carbon footprint for the workshop.

Additional details, including the presentations and posters, can be found on the workshop website: https://usclivar.org/meetings/2014-ocean-carbon-workshop.

2 Session Highlights & Recommendations

Each session of the workshop featured five, 15-minute presentations, followed by 60 minutes of discussion guided by the session questions stated above. During the discussion, participants also raised questions and concerns and offered their insights on the topic at hand. This section of the report provides the highlights of the talks and discussion for each session. The specific recommendations from each session are presented in Section 3 of this report.

2.1 Model Biases and Uncertainties in CMIP-5 Models

Discussion questions:

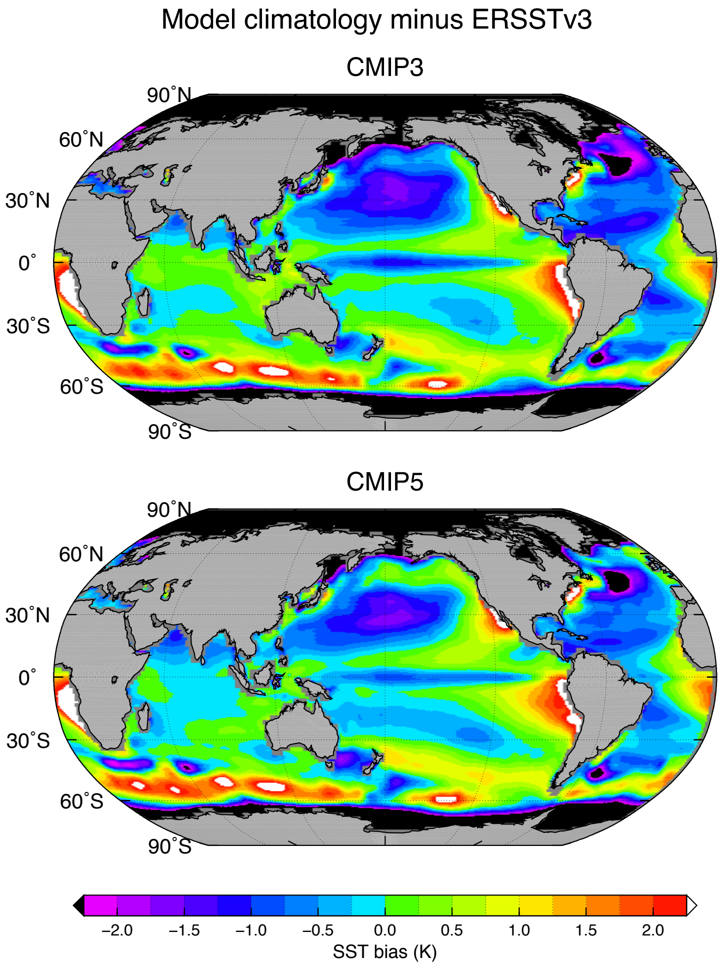
1. Which model biases have the largest impact on the uncertainties in the heat/carbon uptake in climate models?
2. What observational metrics (among those available now or in the near future) can most reliably identify these biases?
3. What model improvements are needed to reduce these biases?

Model biases

Climate models exhibit significant biases in many simulated properties, but the focus of the discussion was on those biases that have the largest impact on the heat and carbon uptake in climate models. These biases fall into three general categories: (i) surface properties and air-sea exchanges; (ii) subsurface circulation and stratification; and (iii) specific physical and biogeochemical processes.

Several surface properties and exchanges that exhibit significant biases in model simulations were noted during the workshop. There are biases in the simulated seasonality of surface temperatures, isopycnal outcrops, and biogeochemical tracers that affect the uptake of heat and carbon at the surface and project onto the simulated interior distributions. There are biases in the simulated position and properties of the "Cold Tongue" and location of the Intertropical Convergence Zone (ITCZ) that affect the global tropical circulation and strongly influence mid-latitude circulation and global interannual variability. Biases in the simulation of the spatial distributions of heat and carbon uptake in the present-day climate likely influence simulations of future climate.

Locations with significant subsurface circulation and stratification biases are found primarily in high- and mid-latitude regions in which subsurface water masses are formed (intermediate, deep, and bottom waters around the globe). The simulation of high-latitude physics and biogeochemistry, particularly in the Southern Ocean and the North Atlantic, directly affect heat and carbon uptake and storage and nutrient supply and redistribution within the models. Of particular concern are the properties and formation rates of mode and intermediate waters in the Southern Ocean and Northern Hemisphere, as these are the primary nutrient sources to the global thermocline that support the base of the marine food web. In particular, Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) exhibit large simulation biases in the Southern Ocean, and though simulations of the Atlantic Meridional Overturning Circulation (AMOC) in the North Atlantic generally have the right mass, the simulated heat transport is often incorrect and the simulated thermocline is too diffuse.

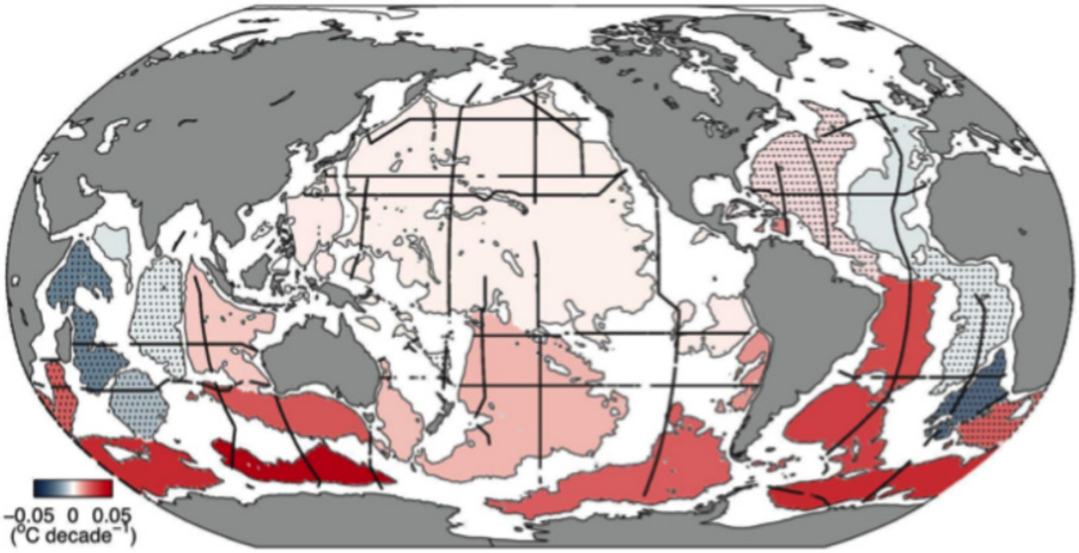


There are still persistent simulation errors in the annual mean sea surface temperature. Shown are ensemble sea surface temperature (SST) biases from the ERSSTv3 dataset for the ensemble means of CMIP-3 models (upper) and CMIP-5 models (lower). [From P. DiNezio]

Several specific physical and biogeochemical processes were also highlighted as leading to significant biases and/or higher levels of uncertainty. Physical processes that export heat and carbon from the surface, including convection, mixing by eddies and internal waves, and large-scale advection need to be rigorously assessed. In addition, the nature of interactions between large-scale circulation and sub-grid-scale (e.g., meso- and sub-mesoscale) dynamics can yield different model responses with respect to heat, carbon, and mesoscale biology. Geochemistry component models also need to be reexamined, as it is unlikely that biases in the simulated carbon cycle can be explained solely by ocean circulation biases.

Effort should be undertaken to understand and address the causes of biases in water mass properties. Hydrographic data are needed; especially high-latitude measurements in winter, when processes leading to ventilation and water mass formation (convection, wind-induced mixing, mixed layer deepening) are most active, particularly in the Southern Ocean and the subpolar North Atlantic. These data would lend insight into physical biases observed in models and sensitivity of carbon uptake to changes in convective activity.

Seawater measurements from the immediate vicinity of seasonal and permanent sea ice in both polar regions are critical for air-sea exchange and biogeochemical cycling simulations. Year round measurements made



The warming and cooling trends (°C) in the deep ocean below 4000 m estimated from CLIVAR/CO_2/Tracer repeat hydrographic sections (black lines; from Purkey and Johnson 2010). Closing the heat budget is critical to projections of the future. Thus, it will require significantly more observations at depth as well as a concerted effort to "observe" all of the components of the heat flux at the surface, especially around and under the sea ice. [From Rhein 2013]

under sea ice with tethered profilers in the Arctic and Southern Ocean would be useful for understanding the role of sea ice in the heat and carbon budgets and assessing model simulations.

Seasonally varying data (e.g., net primary production (NPP) and other biogeochemical and ecosystem variables) and transient tracer data (e.g., chlorofluorocarbons (CFCs), SF_6) would help quantify upwelling, ventilation, and water mass formation rates that can be used to gauge model performance on both global and regional scales.

Finally, high-resolution (in time and space) measurements of atmospheric gas concentrations would be useful for assessing simulated air-sea fluxes and point-source origins for interior ocean trajectories.

Model improvements needed

The major model improvements needed to reduce the existing biases were grouped into two main categories: i) resolution and sub-grid-scale parameterizations, and ii) tracer implementation and refinements (unique chemical species, biological processes, and idealized tracers).

Increased spatial resolution that is capable of resolving mesoscale dynamics is particularly important in such regions as the Antarctic Circumpolar Current (ACC), where eddies play a key role; in the North Atlantic, where convection is important; in and around western boundary currents, which cannot be simulated adequately by coarse-resolution models; and in upwelling regions like the Pacific cold tongue that tend to have a warm SST bias at low resolution. At the same time, fully mesoscale-resolving simulations demand enormous computing power and storage, particularly at high-latitudes where the eddy scales are short.

Improved parameterizations of sub-grid physical and biological processes for coarse-resolution models would permit less computationally demanding simulations that still meet standard benchmarks. Parameters in these parameterization schemes are often chosen empirically, which leads to significant uncertainty in model simulations. More routine validation of increasingly refined parameterizations using high-resolution, process-oriented simulations is needed before increasing model complexity, particularly with regard to biological processes.

More routine simulations of transient tracers (e.g., CFC and SF_6) would help quantify ventilation and sinking (upward and downward) rates and serve as proxies for anthropogenic carbon uptake. Idealized tracers such as "ideal age" and boundary impulse response (BIR) tracers are particularly effective tools for model analysis and intercomparison, though they do not have a direct analog in nature.

Improvements in simulations of the ocean carbon system will require parameterizations of dissolved organic carbon (DOC) lability and an improved mechanistic understanding of phytoplankton growth, remineralization (location and length scales), and carbon export (e.g., net community production).

The modeling community spends a considerable amount of time running Model Intercomparison Projects (MIPs), which are extremely useful for identifying common biases and reducing uncertainties in climate projections. MIPs provide model output to those members of the scientific community who do not run state-of-the-art models themselves and would not otherwise have access to climate model output. MIPs are also very effective at integrating modeling centers into a larger scientific community. When planning a MIP, participating models should be carefully selected based on MIP focus and model skill in relevant areas. A proposal for another round of MIPs should be carefully weighed against the need to spend more time on individual model development (e.g., increasing spatial resolution, improvement in process representation).

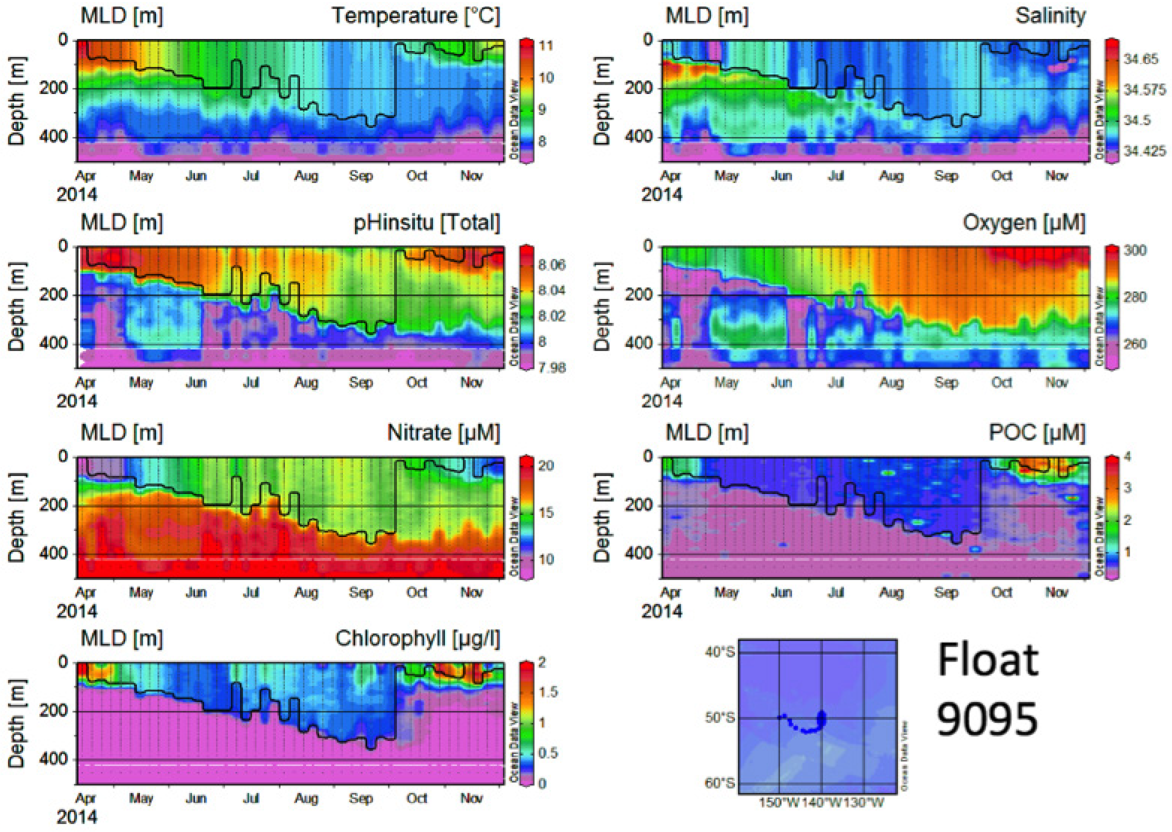
Modeling advances will require continued focus on the analysis and improvement of individual models using idealized simulations, sensitivity testing, process-oriented studies, etc. Process-oriented studies with idealized models that can be done outside of large modeling centers can go a long way toward improving sophisticated climate models. Such individual modeling efforts would benefit from a careful reevaluation of past Climate Process Team (CPT) recommendations with a focus on learning outcomes and lessons learned. Closer cooperation between modeling and observational communities, and among ocean, land, and atmospheric modeling groups, is desired. Such cooperation can lead to metrics that cross boundaries and reveal biases in representation of coupled processes.

2.2 Observational Gaps and Uncertainties

Discussion questions:

1. What are the most fruitful opportunities for extracting important climate signals from existing historical datasets? And what methods can help increase the signal-to-noise ratio?
2. Which observational datasets (parameters, regions, seasons) are needed to provide tighter constraints on climate models?
3. What new types of observations (sensor, platforms) or modification of sampling strategy would yield the largest reduction in uncertainty about the current ocean state or future projections?

Although there has been a concerted effort recently to expand and consolidate ocean data from the wide variety of platforms available (e.g., ships, buoys, satellite, floats, gliders, marine mammals), there are several obvious holes in our observational data in terms of the types of data we are collecting and also the spatial and temporal resolution of the datasets. This session highlighted several of the major issues associated with the data we have and the data we need.



Data from one of the new Southern Ocean BGC-Argo floats from the surface down to 500 m depth over the period April-November 2014. [Data from soccom.princeton.edu]

The Argo program has greatly expanded our capacity to observe the global ocean. Potential new uses for Argo data include the possibility of estimating horizontal and vertical mixing rates and monitoring the evolution of turbulence. Recent and upcoming augmentations of the Argo program, such as Deep Argo and BGC-Argo (e.g., Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM)), have the potential to revolutionize oceanography. Deep Argo will provide deep ocean measurements that are critical to closing global budgets of heat and steric sea level. Simultaneous measurements of physical and biogeochemical variables (temperature, salinity, pH, oxygen, nitrate) on BGC-Argo floats will yield a wealth of information at the temporal and spatial scales required to address important questions about how the oceans are changing with regard to physical circulation, biogeochemical cycling, biological processes, and interactions among them.

Achieving "climate-quality": Data calibration, standardization, and synthesis

A key need of this community is to have access to "climate-quality" biogeochemical and biological data – such requirements include: i) absolute rather than relative quantities, and ii) calculated error bars associated with each measurement. Accordingly, biogeochemical and biological observations need to be standardized in terms of collection methods, collection depths, and laboratory procedures, and calibrations of sensors on autonomous and semi-autonomous platforms need to be performed at sea during deployment. In order to reduce uncertainties in projections of future climate, we need to have reliable quantifications of long-term trends, but many of the biogeochemical measurements from floats aren't standardized or calibrated and are thus not useful for climate. Our discussions highlighted concerns that large oceanographic data collection programs such as the Ocean Observatories Initiative (OOI) must perform necessary calibrations, and provide accompanying calibration data and protocols, in order for these datasets to be useful for climate studies. As biogeochemical data are increasingly being developed into consolidated data synthesis products analogous to the World Ocean Atlas, there are concerns about whether the calibrations and the metadata associated with the data collection are sufficient. However, the biogeochemical community is making progress in its pursuit of climate-quality data. With regard to sensor development and calibration, field-deployed oxygen sensors now routinely show good agreement with Winkler titrations of bottle samples. To align with the hydrographic data standards of large programs like Argo, newer observational campaigns (e.g., SOCCOM) are providing both the raw data and adjusted datasets with error estimates.

The workshop participants strongly expressed the need for greater investment by funding agencies in the synthesis of biogeochemical data. There are high-quality hydrographic data products (World Ocean Atlas), but biogeochemical synthesis products, while excellent, have been developed voluntarily or on shoestring budgets (e.g., GLobal Ocean Data Analysis Project (GLODAP) and GLODAP2). There is also great interest in a global carbon reanalysis, similar to the Southern Ocean State Estimate (SOSE), that would incorporate data from multiple sources (biogeochemical floats, surface ocean $p\mathrm{CO}_2$ measurements, atmospheric fluxes on land and at sea, coastal ocean and lateral fluxes (land-ocean interactions), and satellite-based estimates (OCO2), etc.) into a data assimilation model with uncertainty bars. Such a reanalysis would allow rigorous evaluation of freestanding climate simulations (without the assimilated data) as well as address the upcoming questions associated with treaty verification of the new international agreements.

Observing priorities

In the ocean, the most critical data needed by this community are estimates of total surface heat flux, including measurements of radiative fluxes combined with simultaneous latent and sensible heat fluxes from the ocean and atmosphere. However, in the absence of such a measurement program, uncertainties could be reduced by independent estimates of heat storage and convergence of subsurface fluxes. When heat flux estimates are combined with freshwater fluxes, the resulting buoyancy flux can provide estimates and metrics for water mass formation (and transformation) rates. There is also a need for higher resolution (space and time) atmospheric gas measurements.

More winter measurements are needed from rapidly changing Arctic and Antarctic regions. A sustained time series in the subpolar North Atlantic is needed to simultaneously monitor changes in physical (deep convection) and biogeochemical parameters. Existing arrays (e.g., Overturning in the Subpolar North Atlantic Program, OSNAP) provide the infrastructural foundation for such a sustained monitoring effort but currently only include physical measurements. Recent evidence and analyses from the Southern Ocean have shown that there is a critical need to monitor warming beneath sea ice and around the ice edge. The British Antarctic Survey remotely piloted a tethered vehicle under the ice and showed that Circumpolar Deep Water (CDW) is penetrating the Antarctic continental shelf. Unfortunately, very little austral winter under-ice data are available, except from marine mammals, which have inherent biases. We do have summer GO-SHIP estimates, but these data are more coastally focused. A few locations have been visited frequently enough to construct trends (e.g., Ross Sea shelf, Palmer Long Term Ecological Research (LTER)), but more and longer records are needed. Current technology allows ice-enabled floats to get within 6-20 m of the surface. Gliders are also proving useful for navigating the continental shelf.

Observing System Simulation Experiments (OSSEs) have become an increasingly powerful tool for designing observing networks and interpreting the collected data. Participants encouraged more frequent use of OSSEs in assessing the necessary temporal and spatial scales of different ocean measurements (e.g., heat vs. carbon) and for developing regionally focused observing systems (e.g., SOCCOM).

Data management and access

Timely and public access to data is important. A non-proprietary approach to data access is encouraged internationally. Many datasets (e.g., GOSHIP, Argo) are available in near real time via the Global Telecommunication System (GTS). CLIVAR's Global Synthesis and Observations Panel, is coordinating an international framework to provide high quality subsurface data starting with temperature, and then adding salinity from XBT casts. This effort will involve data rescue, quality control, and gathering from international sources and unpublished data profiles, including metadata and uncertainties to facilitate data intercomparability.

There are multiple data management and archival entities for ocean data. With the increasing volume of regional-scale and more coastally focused glider data being generated by individual researchers and groups, participants recommended the establishment of a dedicated international repository for glider data. Formal data publication (e.g., through the Earth System Science Data open access journal) was also cited as an effective mechanism for sharing and publicizing new datasets.

2.3 Process Studies

Discussion questions:

1. What are the physical and biogeochemical processes that state-of-the-art coupled climate models do not capture/represent and may be responsible for the largest uncertainty in simulations of ocean heat and carbon uptake?
2. What are the physical and biogeochemical processes that state-of-the-art coupled climate models include but are still subject to very large biases in their representation, therefore contributing large uncertainty to simulations of ocean heat and carbon uptake?
3. What types of process studies (geography, temporal and spatial scales, etc.) would improve our understanding and representation of these physical and biogeochemical processes in models?

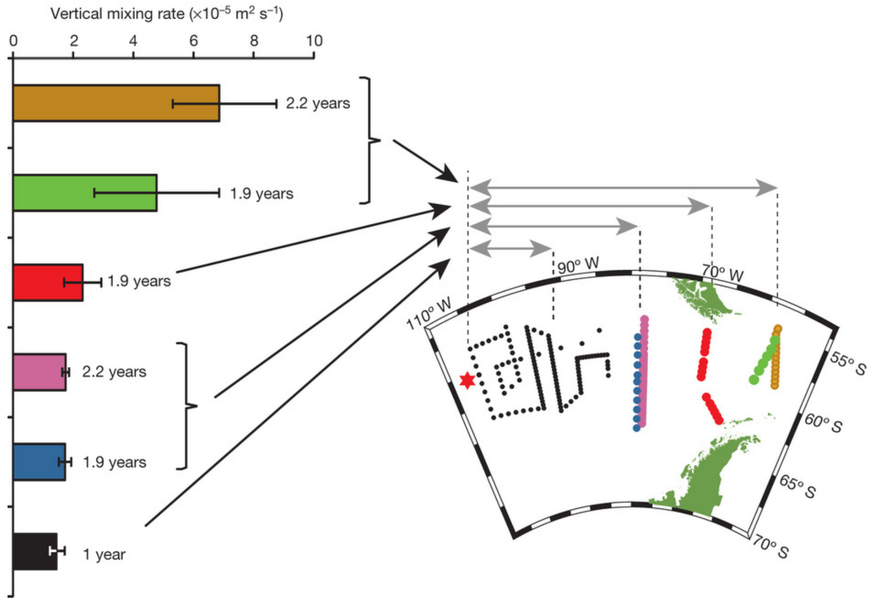
The workshop attendees identified a set of processes that would require specific studies to meet the overarching goal of improving the representation and/or parameterization of physical and biogeochemical processes in coupled climate models. It was also noted that model validation and parameterization optimization cannot be achieved by simply comparing low- and high-resolution model outputs, and that the community needs process-oriented studies in regions where observational constraints are available.

The identified processes are related to specific physical phenomena that occur in the ocean and play an important role in carbon and heat uptake. These processes link ocean physics, biology, and biogeochemistry and operate across Earth system boundaries (ocean, land, cryosphere, atmosphere):

- The role of mesoscale eddies at low- and high-latitudes;
- The dynamics in coastal upwelling zones, including the role of Eastern Boundary Currents;
- Ocean convection, overflows from marginal seas and shelf, and the interior pathways of dense water masses;
- Mechanisms of iron (Fe) input to the ocean; and
- Seasonal CO_2 fluxes.

Eddy transport and mixing

Mesoscale eddies are fundamental to ocean transport and mixing of carbon and heat at all latitudes. In the tropics, eddies are responsible for large ocean heat uptake and redistribution, but the spatial variability of their impacts is not parameterized in current global coupled models, and requires the adoption of three-dimensional and time-varying diffusivity tensors.



Mean diapycnal diffusivities and associated timescales from the point of release (red star) through the Drake Passage. Diapycnal mixing is relatively small upstream and larger downstream of the rough topography in the Drake Passage. Data collected during the DIMES experiment. [Reprinted by permission from Macmillan Publishers Ltd: *Nature*, Watson et al. 2013]

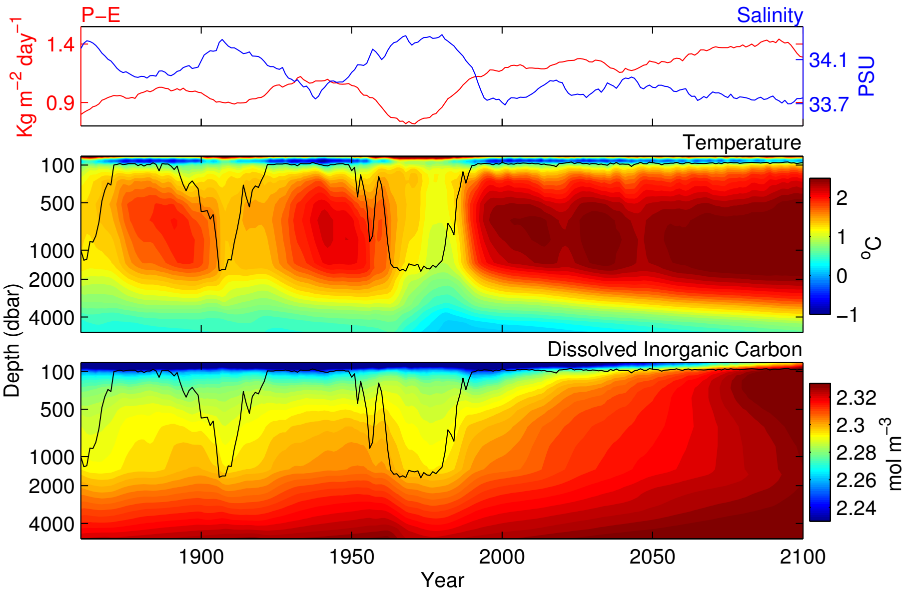
In the Southern Ocean, the interplay between wind forcing, buoyancy, and eddies has to be properly captured in climate simulations. Participants identified two high-priority questions: i) What are the effects of eddies and diapycnal mixing on water masses distributions at high latitudes; and ii) What are the impacts on the diapycnal mixing and eddy stirring of tracers into the ocean interior? Regionally and temporally focused observational efforts, such as the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) and the VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS), are providing the necessary observational constraints to address these questions, but additional process studies are needed to improve representation of eddies in models on a global basis.

Dynamics in coastal upwelling zones

Model biases in coastal upwelling zones due to inadequate spatial resolution have been a chronic problem, particularly in the eastern tropical Pacific, where upwelled waters outgas large amounts of CO_2. Participants discussed the need for higher resolution models to improve representation of coastal processes and studies to explore how these coastal processes in eastern and western boundary systems affect heat and carbon uptake, storage, and offshore transport.

Ocean convection and overturning

Model representation of convective processes also poses a challenge. In the Southern Ocean, dense bottom water is formed both by gravity currents flowing over the continental slope and by convection within the open ocean. Most models that contributed to CMIP-5 simulate only the latter, and specifically open ocean convection in the Weddell Sea, where it has not been observed since 1976. Furthermore, some models have shown that the upper ocean in this region is very close to neutral stability, making it highly sensitive to perturbations that could stimulate or shut down open ocean convection. It remains to be determined how realistic this feature is. An alternative vertical coordinate approach may be helpful in the representation of gravity currents. To further complicate the representation of deep water formation and ventilation processes in the Southern Ocean, modeled winds and consequently, heat uptake over this region, differ greatly between models. Carbon uptake, on the other hand, does not vary as much between the models, suggesting the possibility that differences in modeling the atmospheric radiative forcing, together with the momentum component, may represent the source of the discrepancies.



Simulated convection in the Weddell Sea shows collapse of convection in the model, after which remineralized carbon steadily fills the deep Weddell Sea. Panels depict modeled time series of precipitation-evaporation flux and salinity (averaged over 0-50 m), temperature and DIC (as a function of depth) averaged over the Weddell Sea region, and September mixed layer depth (black line). [Modified from Bernardello et al. 2014]

In the North Atlantic, the observational estimates of the strength of the Atlantic Meridional Overturning Circulation (AMOC) compare well with the modeled ones, but the vertical and horizontal structures and the density class distributions do not resemble observations. Discrepancies are also noteworthy in the location of modeled convection. Such mismatch, with modeled AMOC generally too shallow, is likely to impact the global representation of heat transport. It remains to be answered if those differences alter the representation of heat and carbon uptake in a consistent manner between models. Solutions proposed to improve the AMOC simulation vary from adopting isopycnal coordinates to adding the parameterization of downslope flow, as introduced by the NCAR model.

Iron transport

Iron (Fe) is an essential micronutrient for many biological functions, but the physical processes responsible for its transport from land to ocean are poorly resolved in global climate models. For example, in the Southern Ocean, Fe in glacial melt water is entrained in and then pulled offshore by eddies that form along the shelf. Numerical experiments conducted during DIMES used nested grids along the Patagonian coastline to include this process. Fe contributions from icebergs, glacial melt water, and atmospheric dust are being incorporated into some coarse-resolution models, but sediment transport is universally lacking in global climate models. The relative contributions of these and various other micronutrient sources to the ocean are poorly constrained due to sparse observational datasets.

Seasonal CO_2 fluxes

Seasonal cycles are generally poorly represented for pCO_2, though we do get reasonable measurements for seasonal net community production (NCP), provided that no physical processes contribute significantly. Regional process-oriented studies might lend more insight into key mechanisms underlying seasonal variations. For example, an investigation in the North Atlantic, in which model simulations diverge, could address whether seasonal variations contribute to understanding trends on longer timescales. The EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) study could prove helpful for this purpose. In the Southern Ocean, which is characterized by strong winds, swells, and breaking waves, targeted follow-on studies to Southern Ocean GasEX and tracer experiments (e.g., DIMES) could help improve air-sea flux parameterizations.

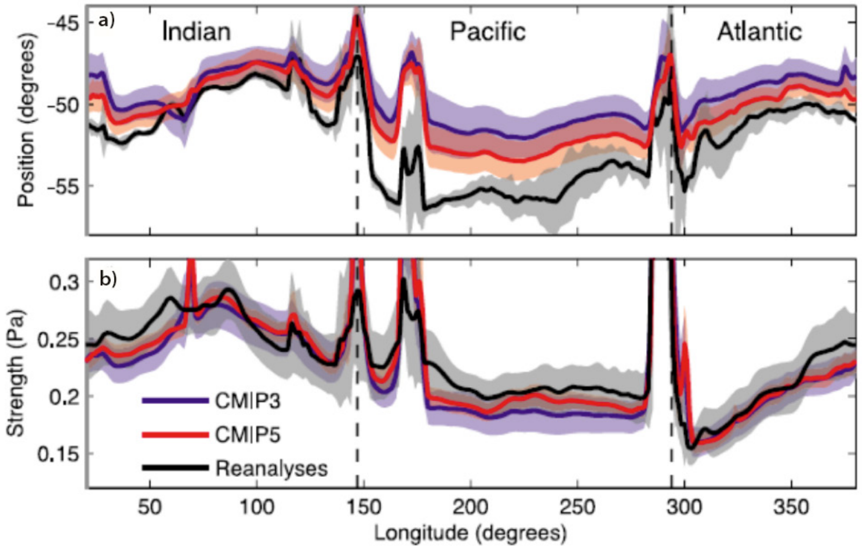
2.4 Southern Ocean – Circulation and Carbon Cycle

Discussion questions:

1. Is there motivation to continue the Drake Passage time series program for another decade?
2. What can we learn from model intercomparison in the Southern Ocean?
3. What is needed or can be done to produce a Southern Ocean surface flux dataset/reanalysis that is suitable for climate applications, including for forcing ocean-only models and for validating coupled climate models?
4. Robust simulation of the dynamics that govern Southern Ocean circulation requires resolving mesoscale eddies. This is challenging in terms of computing power and storage, typically restricting the length of simulations, especially the spin-up. Yet, reliable estimates of ocean heat and carbon uptake require well-equilibrated models. What are the best approaches to ensure adequate resolution and model equilibration given finite resources?

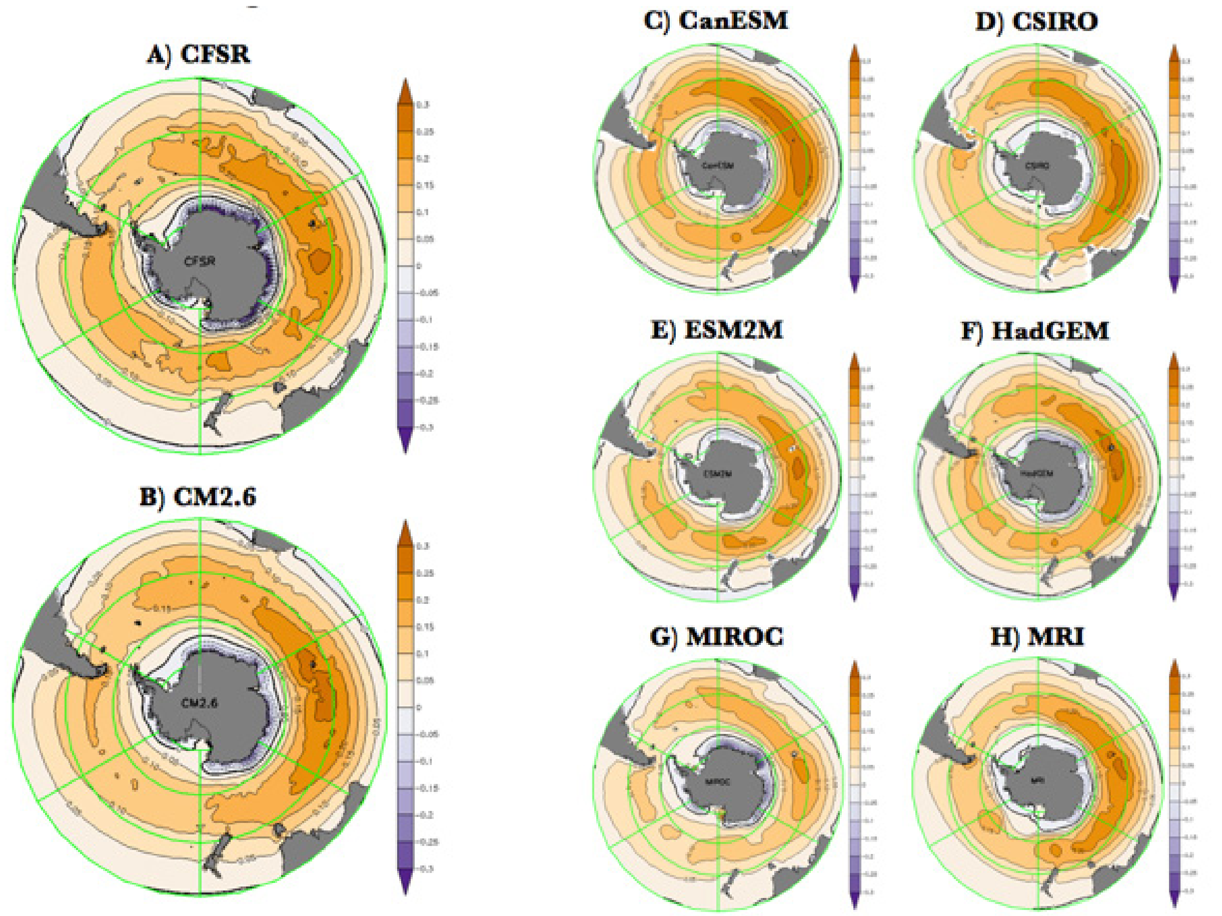
This joint session between the CLIVAR/OCB working groups and the WCRP Polar Climate Predictability Initiative (PCPI) identified several issues specific to the Southern Ocean that could increase our understanding of the Southern Ocean physics and biogeochemistry and our ability to simulate it. It was acknowledged by all that the Southern Ocean is difficult to observe, understand theoretically, and simulate, and that work can and must be done on each of these fronts, especially given the critical role that the Southern Ocean plays in the global uptake of anthropogenic heat and carbon.

Central to our understanding of the Southern Ocean is the role of wind forcing. A rigorous assessment of the input of wind energy into the ocean and the uncertainties (spatial and seasonal) associated with the observing system is needed, as there are still basic questions about the winds that we can't answer. For example, what are the error bars associated with our satellite- and reanalysis-derived winds, and is the split in the subpolar jet real? More direct observations, as well as more validation of satellite products with radiosonde data are needed. Participants also agreed that a coordinated program to observe and model both oceanic and atmospheric biogeochemical parameters at the same place and time is needed for both improved understanding and for model validation.



Climatologies of the Southern Hemisphere surface westerly wind-stress latitudinal position by longitude (a) and strength by longitude (b) over 1979–2010 in the mean of four reanalyses, 23 CMIP-3 models and 21 CMIP-5 models. Solid lines are the ensemble means and shading shows the 95% confidence interval. Dashed black lines indicate the ocean basin boundaries. [From Swart and Fyfe 2012]

As the peak westerly wind stress over the ACC spends more time closer to the pole, we expect significant changes in the Southern Ocean's circulation and hydrography, as well as its heat and carbon uptake and storage and export. Open questions remain about the role of mesoscale eddies in the ACC momentum balance, whether the total ventilation (exposure to the atmosphere) in the Southern Ocean is increasing or decreasing, and the rate at which the Southern Ocean sink for carbon is weakening. Complicating our understanding of wind forcing over the ACC are the model-related issues with respect to the simulated winds, including: the response of the ACC to the variability in winds and the role of eddies are



Annual mean observed and simulated wind stress (Nm^{-2}) over the ocean from several of the CMIP-5 models. All of them still have their mean winds too far equatorward. [From J. Russell]

still uncertain, both in the ocean and in the models; variability in the strength and position of the simulated winds is larger than observed across models and within individual models; and carbon uptake is sensitive to the interaction between the simulated winds and the simulated (or parameterized) eddies. On this last point, several participants suggested that continued monitoring of carbon parameters in the Drake Passage time series represents an important opportunity to quantify changes in carbon uptake.

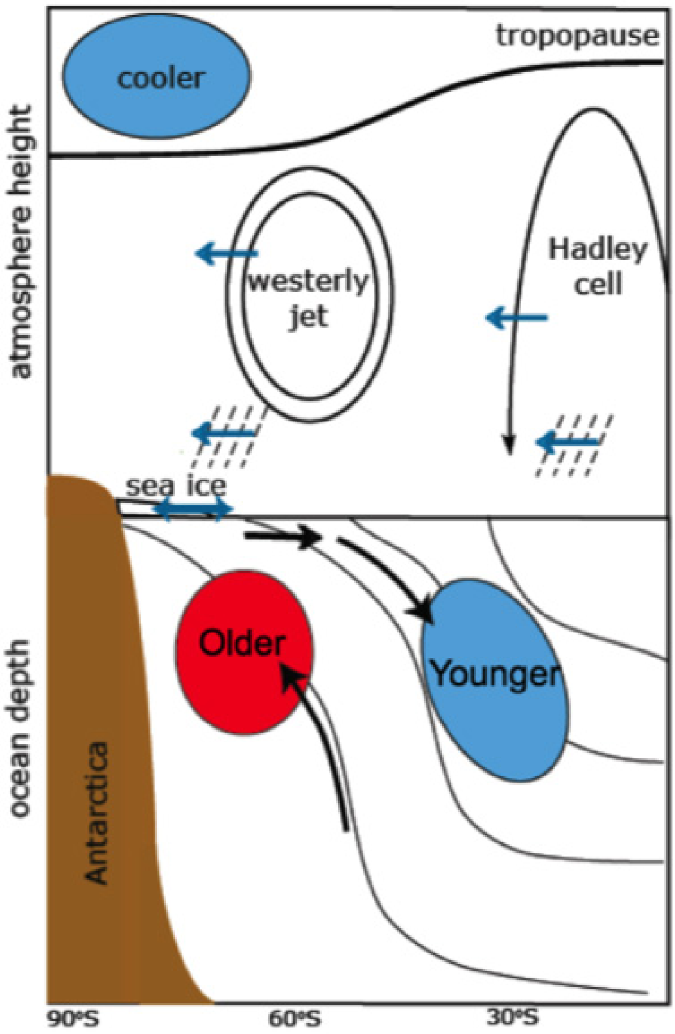
The first and foremost wind-related metric from coupled climate models and Earth system models – the strength and position of the Southern Hemisphere surface westerly winds – shows that the simulated winds are still more equatorward than the observed winds, which likely affects nearly every other metric related to the Southern Ocean.

The observed pattern of sea surface temperature trends is due in part to changes in the air-sea flux associated with changing winds, circulation, and convection. The role of convection, both in the ocean and the parameterized convection in models, needs to be explored more fully.

Some models simulate some features better than other models, and it is unrealistic to expect that any model will get all aspects of the ocean right. Model performance should be assessed on the basis of the specific goals/functions of the model. As indicated previously, models should be carefully selected for intercomparison projects, and participants stressed the need to be careful about dismissing "poorly performing" models. Model outliers can be informative and the model-model spread may be especially helpful for examining mechanisms related to the inter-model variability. The use of observationally based, standardized metrics is the best way to evaluate and compare models and to move toward reducing uncertainty in projections of future climate.

The use (and reporting) of tracers (biogeochemical and idealized) in simulations should become more routine. There is an increasing need for both top-down (e.g., CFCs) and bottom-up (e.g., radiocarbon) tracers that reveal ventilation and circulation. Several participants also felt strongly that the community needs to reexamine how the biological pump is parameterized in the models in light of new evidence suggesting that the pump might have a larger role than previously thought.

Edge processes (shelf zones, marginal seas, shelf/slope processes) and benthic processes, while not central to the global-scale uptake of heat and carbon, can provide important regional insights, as well as data for model evaluation. Bottom water formation through interactions with ice sheets and ice shelves, though difficult to assess, would also provide a valuable metric.



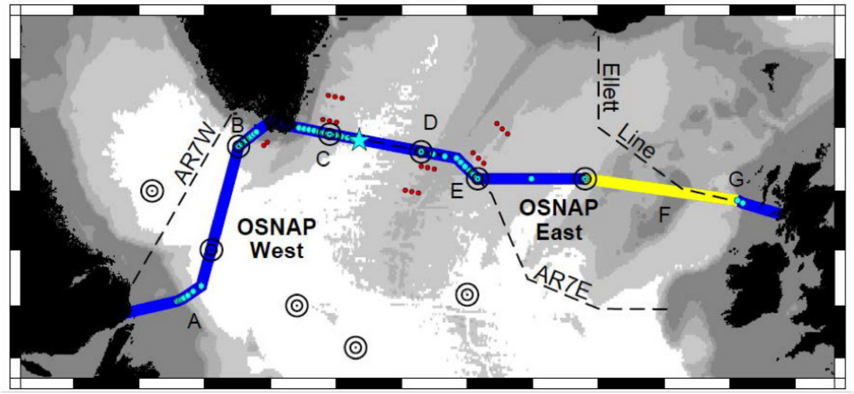
Increased wind stress over the Southern Ocean in model experiments with CFCs confirm the conventional wisdom about the overturning with increased ventilation on the equatorward side and increased upwelling to the south. The schematic also shows changes in the atmosphere connected with ozone depletion. [From Son et al. 2010; Waugh et al. 2013]

2.5 New Initiatives

Our understanding of global climate and biogeochemical cycles has advanced remarkably since the 1970s when the GEOSECS program provided global-scale biogeochemical transects that shaped our understanding of global ocean circulation and carbon pumps. In the 1990s, the WOCE and JGOFS programs produced coordinated sets of zonal and meridional transects that enabled us to estimate the three-dimensional transports of mass, heat, nutrients, and carbon. Today, we may be facing the next breakthrough in our ocean monitoring and modeling capabilities. Autonomous platforms are starting to provide continuous profiles of biogeochemical properties. And observations and models are synthesized with data assimilation techniques. Taking advantage of these advances, several new initiatives are underway to monitor and study two critical regions for ocean carbon and heat uptake: the North Atlantic and the Southern Ocean.

OSNAP

The US-led Overturning in the Subpolar North Atlantic Program (OSNAP, http://www.o-snap.org) and the Canadian-led Ventilation, Interaction and Transports in the Labrador Sea (VITALS, http://knossos.eas.ualberta.ca/vitals) Program will include a suite of shipboard and autonomous measurements to continuously monitor the fluxes of heat, mass, and freshwater in the subpolar North Atlantic.



Components of OSNAP include moored arrays (blue dots), float deployments (red dots), glider survey (yellow line), Irminger Sea global node of the Ocean Observatories Initiative (blue star), and sound sources (black concentric circles). Deployments completed during summer 2014.

SOCCOM

The Southern Ocean Carbon and Climate Observation and Modeling (SOCCOM, http://soccom.princeton.edu) project will deploy hundreds of autonomous floats across the Southern Ocean to monitor oxygen, nitrate, pH, transmission, and fluorescence in addition to physical parameters. The resulting dataset will be used to constrain an eddy-permitting ocean circulation and biogeochemistry model and produce the next generation of the Southern Ocean State Estimate. In parallel, the modeling component aims to improve our understanding of the role of winds, eddies, and stratification in regulating the uptake of carbon and heat in the Southern Ocean.

CMIP-6

The Coupled Model Inter-comparison Project phase 6 (CMIP-6, http://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6) is currently in development. The design is significantly different from the prior CMIP phases, with a limited set of simulations (atmosphere MIP, pre-industrial control, 1% per year CO_2 increase, abrupt 4xCO_2 run, historical 1850-2014 simulation) performed by all participating modeling centers, and some 20 endorsed MIPs, each focused on specific phenomena and performed by a number of centers. For these endorsed MIPs, in particular ocean MIP (OMIP) and ocean carbon MIP (OCMIP), community input is needed to formulate an experimental design that will address key scientific questions. Idealized sensitivity simulations may establish key processes aiming to achieve deeper understanding. For example, the flux anomaly forcing MIP (FAFMIP) proposes to apply heat, freshwater, and momentum flux perturbations in a controlled manner across different models. An offline discussion resolved that merging the OCMIP with the OMIP would be advantageous to both. Running the ocean and biogeochemical components simultaneously with the same core forcing would help isolate wind effects.

Climate Process Teams

Biogeochemistry and the carbon cycle are integrated into the dynamical ocean models and coupled climate models. As process-level understanding advances in biogeochemistry, there is a growing need for expediting the transfer of theoretical understanding into practical model parameterizations. Climate Process Teams (CPTs), which have played an important role in improving physical parameterizations in climate models, may serve as a viable approach for improving biogeochemical and biological parameterizations in the future.

3 Workshop Conclusions

The workshop was highly successful in helping both the Ocean Carbon Uptake and Southern Ocean Working Groups make progress towards their goals to develop metrics for evaluating biases in CMIP-5 model simulations; estimating sources of uncertainties in model projections of heat and carbon uptake; and informing future observations, model development, and analysis strategies for addressing biases and uncertainties (including protocols of CMIP-6).

Main conclusions from the workshop include:

1. Circulation and stratification biases occur primarily in mid- to high-latitudes, where subsurface water masses are formed, and these regions are critical to uptake, storage and distribution of heat, carbon and nutrients, especially the regions where mode and intermediate waters form as these supply nutrients globally. Uptake biases in the models can influence simulation of future climates. Processes with significant bias/uncertainty include convection, eddy mixing and large-scale advection, and interactions between large-scale and subgrid-scale dynamics. More high-latitude winter hydrographic observations are needed in order to better assess the models.

2. The Argo array has revolutionized the field and the next two programs – Deep Argo and BGC-Argo – are both critical to closing the budgets for heat and carbon in the ocean. "Climate quality" measurements, defined as absolute rather than relative quantities, standardized analyses, and calculated error bars associated with every measurement are needed to reduce the uncertainty in climate model projections. And funding agencies need to provide for syntheses of biogeochemical data. The highest priority new observations would be: an estimate of the total heat flux, higher resolution measurements of atmospheric gases and more wintertime observations at and under the ice edge in both hemispheres.

3. Key processes in need of further study, both for reducing model uncertainty and for a deeper theoretical understanding, include: the roles of eddies in transport and mixing, carbon exchange and storage in coastal regions, convection and water mass overflows at high-latitudes, and the seasonal cycle of exchange of $p\mathrm{CO}_2$ with the atmosphere. All of these processes could strongly affect the net uptake of anthropogenic heat and carbon and therefore the trajectory of future climate.

4. With respect to the Southern Ocean, rigorous assessment of the input of wind energy into the ocean and the uncertainties (spatial and seasonal) associated with the observing system are needed. Specifically, more direct observations and a coordinated program to observe and model both oceanic and atmospheric biogeochemical parameters at the same place and time are needed. Understanding why climate models still simulate the Southern Hemisphere westerly winds equatorward of the actual position is still a critical issue. Models should be rigorously assessed against observationally-based metrics and only high performing models for the specific process should be included in intercomparisons. Finally the use and reporting of tracers, both biogeochemical and idealized, in model simulations should become routine.

4 Acknowledgements

The working groups thank the workshop participants for their time and energy to prepare and give talks and poster presentations and to actively participate in breakout and plenary discussion sessions. We especially want to thank John Fyfe and the other members of the WCRP Polar Climate Predictability Initiative on Southern Ocean: Circulation and Carbon Cycle for their participation and assistance in the planning of this workshop. Mike Patterson and Kristan Uhlenbrock from the US CLIVAR Project Office and Heather Benway from the OCB Project Office are thanked in particular for their guidance and support in various stages of the workshop.

Major support for the workshop was provided through the US Climate Variability and Predictability Research Program (US CLIVAR) and Ocean Carbon and Biogeochemistry (OCB) Program and their supporting agencies (NSF, NASA, NOAA, and DOE), with additional support from NSF's Division of Polar Programs.

5 References

Bernardello, R., I. Marinov, J. B. Palter, E. D. Galbraith, and J. L. Sarmiento, 2014: Impact of Weddell Sea deep convection on natural and anthropogenic carbon in a climate model. *Geophy. Res. Lett*., **41**, 7262-7269, doi:10.1002/2014GL061313.

Purkey, S. G., and G. C. Johnson, 2010: Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *J. Climate*, **23**, 6336–6351, doi:10.1175/2010JCLI3682.1.

Rhein, M., S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, G. C. Johnson, S. A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L. D. Talley, and F. Wang, 2013: *Observations: Ocean. Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds., Cambridge University Press, 255-310.

Son, S.-W., E.P. Gerber, J. Perlwitz, L. M. Polvani, N. Gillett, K.-H. Seo and Co-authors, 2011: The impact of stratospheric ozone on the Southern Hemisphere circulation changes: A multimodel assessment. *J. Geophys. Res.*, **115**, doi:10.1029/2010JD014271.

Swart, N. C., and J. C. Fyfe 2012: Observed and simulated changes in the Southern Hemisphere surface westerly wind-stress. *Geophys. Res. Lett.*, **39**, doi:10.1029/2012GL052810.

Watson, A. J., J. R. Ledwell, M.-J. Messias, B. A. King, N. Mackay, M. P Meredith, B. Mills, and A. C. N. Garabato, 2013: Rapid cross-density ocean mixing at mid-depths in the Drake Passage measured by tracer release. *Nature*, **501**, 408-411, doi:10.1038/nature12432.

Waugh, D.W., F. Primeau, T. Devries, and M. Holzer, 2013: Recent changes in the ventilation of the southern oceans. *Science*, **339**, 568-570, doi:10.1126/science.1225411.

Appendix A: Organizing Committee & Working Group Members

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Curtis Deutsch	University of Washington
John Fyfe	Environment Canada/ WCRP Polar Climate Predictability Initiative
Taka Ito	Georgia Tech
Igor Kamenkovich	University of Miami
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John Dunne	NOAA/GFDL
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Damon Matthews	Concordia University, Canada
Galen McKinley	University of Wisconsin
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Zanna, Laure	University of Oxford
Zickfeld, Kirsten	Simon Fraser University

Appendix C: Agenda

Friday, December 12, 2014		
18:00	Check in and working dinner	
18:30	Welcome, introductions, workshop objectives	Joellen Russell, University of Arizona
18:45	Ocean Carbon Uptake in CMIP5 Models Working Group Overview	Taka Ito, Georgia Institute of Technology
19:00	Southern Ocean Heat and Carbon Uptake Working Group Overview	Igor Kamenkovich, University of Miami
20:00	Adjourn	

Saturday, December 13, 2014 | Current State of Knowledge		
7:30	Breakfast/Check in	
Model Biases and Uncertainties in CMIP5 Models		
8:00	Role in climate: Heat/carbon uptake	Jorge Sarmiento, Princeton University
8:20	Biogeochemical models in CMIP5	John Dunne, NOAA Geophysical Fluid Dynamics Laboratory
8:40	Tropical Pacific mean climate and variability in CMIP5 models	Pedro DiNezio, University of Hawai'i
9:00	Ocean carbon uptake & climate feedbacks	Scott Doney, Woods Hole Oceanographic Institution
9:20	Southern Ocean wind and sea-ice in CMIP5: Biases and projections	Tom Bracegirdle, British Antarctic Survey
9:40	Break	

10:00	Panel discussion	
Observational Gaps and Uncertainties		
11:00	SOOS and the global data collecting system	Lynne Talley, Scripps Institution of Oceanography
11:20	Ocean/ice/air interactions	Sarah Gille, Scripps Institution of Oceanography
11:40	Lunch (on your own)	
13:00	Quantifying carbon uptake – global and regional	Galen McKinley, University of Wisconsin
13:20	Quantification of the biological pump and nutrient export	Ken Johnson, Monterey Bay Aquarium Research Institute
13:40	Deep Argo	Greg Johnson, NOAA Pacific Marine Environmental Laboratory
14:00	Panel discussion	
Process Studies: Gaps, New Measurements, and Parameterizations		
15:00	Weddell Sea convection	Jaime Palter, McGill University
15:20	Mesoscale eddies	Bob Hallberg, NOAA Geophysical Fluid Dynamics Laboratory
15:40	Break	
16:00	High resolution climate modeling	Michael Winton, NOAA Geophysical Fluid Dynamics Laboratory
16:20	Diapycnal Mixing (DIMES)	Raffaele Ferrari, Massachusetts Institute of Technology
16:40	Export Processes in the Ocean from Remote Sensing	Dave Siegel, University of California Santa Barbara
17:00	Panel discussion	
18:00	Poster session and networking event	

Sunday, December 14, 2014 | Future Directions		
7:30	Breakfast/Check in	
Southern Ocean: Circulation and Carbon Cycle *Sponsored by WCRP Polar Climate Predictability Initiative*		
8:00	The door to the deep Southern Ocean: An update	Joellen Russell, University of Arizona
8:20	Role of the Southern Ocean in heat uptake	Kyle Armour, Massachusetts Institute of Technology
8:40	Changes in the ventilation of the Southern Ocean	Darryn Waugh, John Hopkins University
9:00	Wind driven changes in the Southern Ocean carbon sink	Neil Swart, Environment Canada
9:20	Observational strategies for detecting weakening of Southern Ocean carbon sink	Nikki Lovenduski, University of Colorado
9:40	Break	
10:00	Panel discussion	
New Initiatives		
11:00	CMIP6 and future Climate Process Teams	Gokhan Danabasoglu, National Center for Atmospheric Research
11:35	Forcing ocean models with flux anomalies (FAFMIP)	Anastasia Romanou, Columbia University
11:55	VITALS/OSNAP	Jaime Palter, McGill University
12:15	SOCCOM	Jorge Sarmiento, Princeton University
12:50	Lunch (on your own)	
13:00	Student/Early Career Scientists Lunch Event (invite only)	
14:00	Final discussion	
15:00	Workshop adjourns	

Poster Session	
Dissolved organic carbon accumulation, export and removal in the North Atlantic: Insights gained from ocean transects	Craig Carlson, University of California Santa Barbara
Metrics for validating water mass formation and distribution in the Southern Ocean model solution	Ivana Cerovecki, Scripps Institute of Oceanography
Evolution of ocean acidification in CMIP5 models	James Christian, Fisheries and Oceans Canada
Exploring the role of ocean heat and carbon uptake in determining the linear relationship between global warming and cumulative	Dana Ehlert, Simon Fraser University
Southern Ocean carbon trends: Sensitivity to methods	Amanda Fay, University of Wisconsin-Madison
Effect of the mesoscale on Southern Ocean watermass structure	Ivy Frenger, Princeton University
Recovery of deep ocean ventilation with global warming	Thomas Froelicher, ETH Zurich
Antarctic Bottom Water temperature changes in the western South Atlantic from 1989–2014	Gregory Johnson, NOAA/Pacific Marine Environmental Laboratory
On the role of mesoscale eddies in ventilation of the Southern Ocean	Igor Kamenkovich, University of Miami
Why carbon emission rates matter for TCRE and oceanic heat and carbon uptake	John Krastin, NOAA/Geophysical Fluid Dynamics Laboratory
Vertical redistribution of oceanic heat content	Xingfeng Liang, MIT
Southern Ocean convection and tropical teleconnections	Irina Marinov, University of Pennsylvania
A validation procedure for a Southern Ocean model solution	Matthew Mazloff, Scripps Institution of Oceanography

Organic carbon export rates from transient tracer data in the Indian Ocean	Sabine Mecking, University of Washington
Validation and analysis of ocean model simulations using satellite ocean color fields	Avichal Mehra, NOAA National Centers for Environmental Prediction
Recent change in the Southern Ocean carbon system based on time series observations in the Drake Passage	David Munro, University of Colorado, Boulder
Timescales and magnitude of internal variability in surface ocean pCO2: 1975-2036	Darren Pilcher, University of Wisconsin-Madison
Warming, freshening, and contraction of Antarctic Bottom Water between the1990s and 2000s	Sarah Purkey, Lamont-Doherty Earth Observatory
Export Processes in the Ocean from RemoTe Sensing (EXPORTS): Science Plan for a NASA Field Campaign in Ocean Carbon Cycling	David Siegel, University of California Santa Barbara
Deep ocean warming and its sensitivity to surface heat flux and Greenland melting waters	Y. Tony Song, NASA Jet Propulsion Laboratory
Contrasting drivers of CO2 sink locations in the Northern and Southern Hemisphere oceans	Peter Strutton, University of Tasmania
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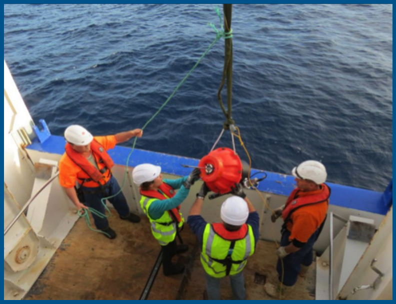

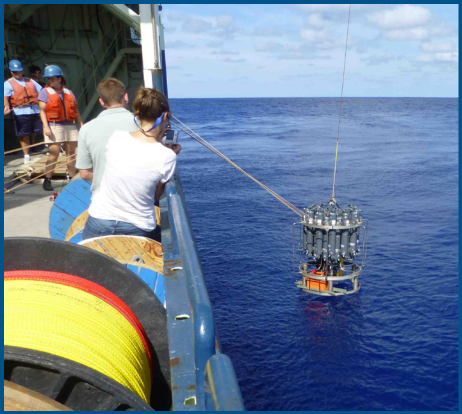

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