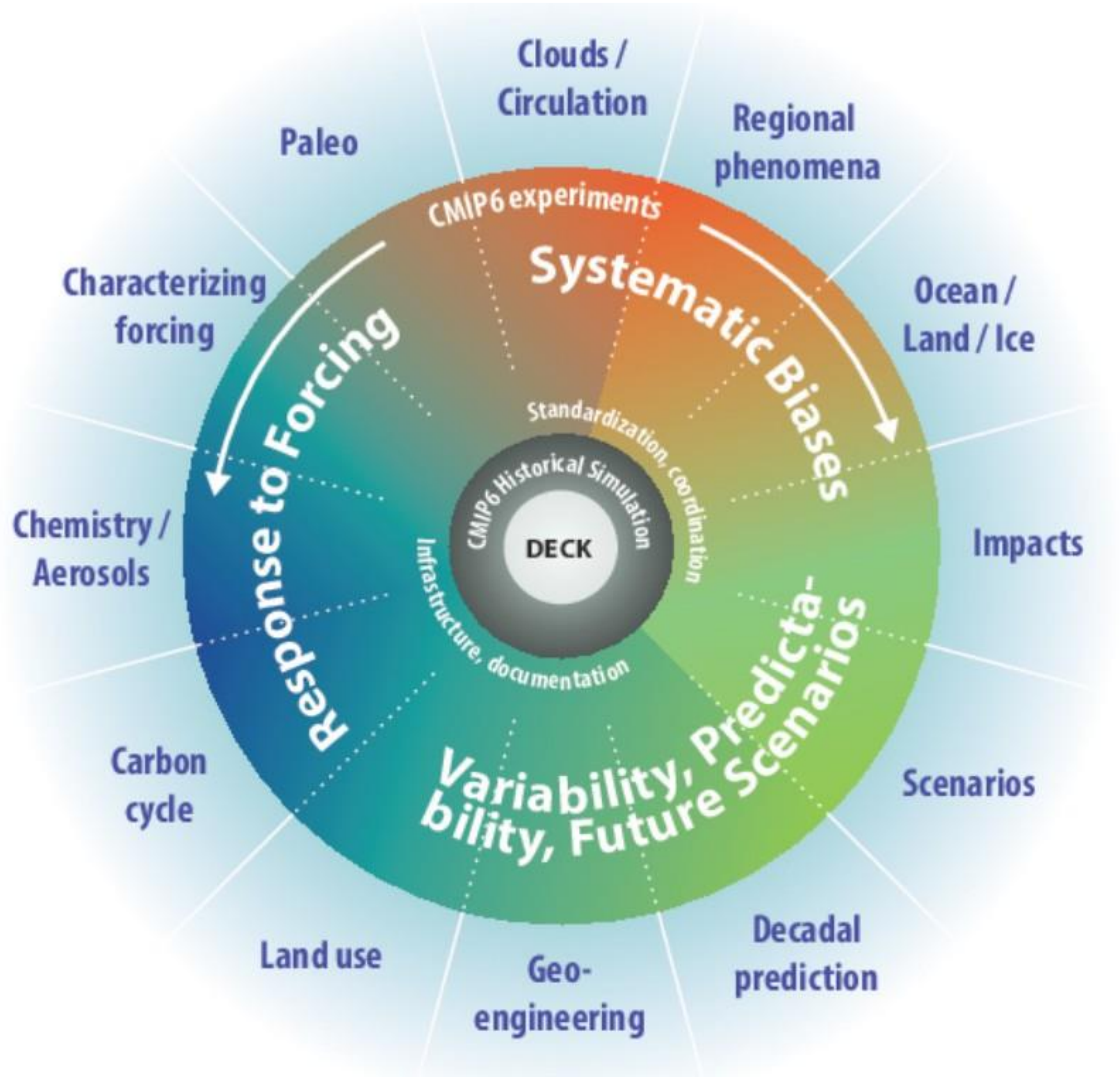

SYNTHESIS AND INTERCOMPARISON OF OCEAN CARBON UPTAKE IN CMIP6 MODELS

An Ocean Carbon and Biogeochemistry Workshop

December 8-9, 2018
Washington, DC

Synthesis And Intercomparison Of Ocean Carbon Uptake In CMIP6 Models

Workshop Report

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COVER IMAGES

Front: Figure 2 from Eyring et al., (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.*, 9, 1937–1958.

Back: Photo of workshop participants taken by Galen McKinley

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INTRODUCTION

The U.S. Ocean Carbon and Biogeochemistry (OCB) Program hosted a two-day workshop December 8-9, 2018 entitled *Ocean Carbon Uptake in the World Climate Research Program's 6th Coupled Model Intercomparison project (CMIP6) Models*.

The goals of the workshop were to:

1. summarize high profile CMIP5 Ocean Carbon Uptake analyses and challenges, and discuss the planned suite of CMIP6 experiments;

2. highlight new observational constraints, including GLobal Ocean Data Analysis Project (GLODAPv2), the Surface Ocean CO_2 Atlas (SOCAT), the Surface Ocean pCO_2 Mapping Intercomparison (SOCOM), the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), community observational synthesis efforts such as Observations for Model Intercomparisons Project (Obs4MIPs), ocean carbon inversions, and atmospheric observations of CO_2 and oxygen;

3. share updated model formulations and preliminary analyses of simulated regional and global patterns in heat, carbon, and tracer uptake in CMIP6 experiments;

4. explore mechanisms of heat, carbon, and tracer uptake differences across models and observations, with an eye towards linking physical and biogeochemical drivers and their impacts; and

5. propose tools and techniques that could lower barriers to analysis.

The motivation and timeliness for the workshop is that under "sustainable" (net zero) emissions, climate services provided by land and ocean carbon cycles in a changing climate will determine "allowable" energy trajectories. These changing environmental conditions have many additional dimensions of consequence for ocean stewardship. The ocean carbon science community's challenge is to supply the best available expert information. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014) found a strong consensus across CMIP5 Earth System models that ocean warming and circulation changes will reduce the rate of carbon uptake in the Southern Ocean and North Atlantic. While CMIP5 models agreed on global ocean carbon uptake within 20%, regional carbon uptake, transport, and storage were substantially different across models. CMIP5 moved the physical climate community forward by facilitating further investigations of heat, chlorofluorocarbon (CFC), and carbon uptake, particularly in the Southern Ocean and North Atlantic. For CMIP6, several modeling centers have improved resolution from nominally 2° atmospheres and 1° oceans in CMIP5 to nominally 1° atmospheres and ¼°-1° oceans in CMIP6 and made improvements in comprehensiveness and fidelity. CMIP6 includes a standard set of Design, Evaluation, and Characterization of Klima (DECK) experiments and focused Ocean Carbon Model Intercomparison Projects: Ocean (OMIP-BGC), Coupled Climate-Carbon Cycle (C4MIP), ScenarioMIP, and Carbon Dioxide Removal (CDRMIP). These experiments will provide unparalleled comprehensiveness in publicly available model data for analysis of ocean heat, carbon and transient tracer uptake towards improving mechanistic attribution of climate- and chemistry-driven changes. Analysis and synthesis of these models will require considerable community coordination.

This workshop served as an important opportunity to improve communication between ocean carbon cycle scientists, both across sub-disciplines centering on observations, theory, models, and synthesis, and across career levels from graduate student to senior scientist. Participants shared questions, knowledge, and perceived challenges on the weaknesses of CMIP5 and CMIP6 models, potential observational constraints, and emerging theory. The workshop provided many opportunities for the development of collaborative project ideas through oral, poster, and moderated group discussion sessions, with a major emphasis on the upcoming December 2019 manuscript submission deadline to contribute to the IPCC Sixth Assessment. Participants also provided feedback to modeling centers on novel ways to push this community and the models forward, thinking beyond the currently planned suite of CMIP6 modeling activities.

RESULTS

Participants highlighted the availability of several new decadal-scale synthesis products on air-sea CO_2 flux and ocean carbon storage and the emerging need across the OCB community for more comprehensive and efficient computational tools to make optimal use of 'big data' such as the CMIP5 and CMIP6 model archives. Additionally, the group emphasized that the timeline of CMIP6 model analysis is extremely tight, between the March-June 2019 timeframe over which modeling centers are planning to supply their data and the Dec 31, 2019 manuscript submission deadline for contribution to the IPCC sixth assessment report (AR6).

Discussion included excellent summaries of observational constraints including SOCAT (Bakker et al., 2016; https://www.socat.info/), SOCOM (Rödenbeck et al., 2015; DeVries et al., 2017; http://www.bgc-jena.mpg.de/SOCOM/), and GLODAPv2 (Olsen et al., 2016; https://www.glodap.info/). There are several important implications of these new observational constraints, which were discussed at length during the workshop. For example, initial estimates of ocean carbon storage (Key et al., 2004; Sabine et al., 2004) in GLODAP have since been updated to 2002 with GLODAPv2 and to 2007 with extended multiple linear regression (eMLR) estimates of decadal-scale carbon uptake (Clement and Gruber, 2018). Decadal-scale variability in ocean air-sea fluxes from Landschützer et al. (2014; 2016) and Rödenbeck et al. (2014) yield estimates with a 0.5-1.0 PgC/y offset to the ocean carbon uptake estimates (building on earlier climatologies of Takahashi et al., 1997; 2002). The role of rivers and coastal areas explains about 0.7-0.8 PgC/y difference between these estimates (Resplandy et al. (2016; 2018). Participants also discussed revised estimates of Southern Ocean outgassing based on new measurements from biogeochemical profiling floats (+0.5 PgC/y relative to ship-based measurements) deployed as part of the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Program (Gray et al., 2018).

Several presentations highlighted the importance of the Global Carbon Project 2018 estimates (Le Quéré et al., 2018), which serve as a broad-scale, quasi-operational point of comparison of ongoing observationally based carbon cycle synthesis. Additional analysis efforts that have broadened our understanding of key processes driving ocean carbon uptake came up repeatedly throughout the workshop, including the inverse estimates of ocean carbon uptake from DeVries et al. (2014; 2017) and others that are largely confirming the more direct observational techniques for both long-term inventories and now decadal variability in carbon storage. It has been noted that CMIP5 models provide cumulative ocean carbon uptake estimates for 1850-1995 that are ~0-20 PgC lower than the observational uptake estimates, with strong disagreement in the Southern Ocean (Frölicher et al., 2015). Attribution of 10-30 PgC of cumulative ocean uptake to differing definitions of "preindustrial" between 1750-1850 (Bronselaer et al., 2017), over which CO_2 increased by ~10 ppm was seen as an important point of reconciliation in this regard. Workshop participants also shared recent efforts to detect and understand the processes driving decadal-scale changes in ocean carbon uptake, including the potential role of volcanoes and land carbon (McKinley et al., in prep), as well as prediction of decadal variability in air-sea fluxes (Lovenduski et al., in review. Scientists from CMIP modeling centers described core improvements to the GFDL, CESM, GISS, IPSL, and CanESM models (Table 1).

The relatively tight timeline between the availability of CMIP6 forcing fields and the deadline to contribute to IPCC AR6 presents a challenge for all modeling centers to be able to put forth the most advanced model possible, bolstered by careful evaluation of model behavior with very long simulations. Some of the specific challenges within individual centers include GFDL's struggles to control superpolyna and associated O_2, N_2 and alkalinity drift as the interior ocean warms under preindustrial forcing. CESM has been struggling with abyssal Pacific hypoxia. Overall, the broadening scope of CMIP6 with all of the various MIPs has proven a struggle for designers of models that are suited to particular purposes. We will only know as model output becomes available over the next year the degree to which modeling centers have been successful. From the modeling center presentations and associated discussions, **several key points on how to appropriately and effectively interpret CMIP models** should be communicated to the carbon cycle community:

- These experiments are designed as boundary value problems, not initial value problems.
- Models have drift – always consult a control.
- Models have systematic biases – assess whether a model is suited to the purpose at hand.
- The difference between forced variability that is associated with a particular timing (e.g., CO_2 increase; Pinatubo eruption) versus internal variability (e.g., El Niño; North Atlantic Oscillation (NAO))
- The role of scenario, structural (model), and internal variability in overall uncertainty
- Distinguishing direct response to forcing (e.g., annual ocean surface pCO_2 response in a CO_2 concentration forced run) versus emergent properties (pCO_2 seasonal cycling; ocean interior CO_2 response, particularly in CO_2 emission runs)

In summary, the workshop was highly successful in laying the groundwork for interpretation of the upcoming CMIP6 models for ocean carbon uptake. A suite of decadal snapshots of ocean carbon cycling are now emerging as fundamental constraints through observations, synthesis, and modeling. Since the modeling centers are unable to provide public data until March-June 2019 (with a December 2019 manuscript submission deadline for IPCC AR6), the community should work toward standardizing the following tools to facilitate and expedite analyses:

- Estimation of ocean biomes for regional analysis
- Explicit separation of river/coastal factors from open ocean syntheses for air-sea CO_2 flux and ocean carbon storage
- Incorporation of pre-1850 carbon cycle changes
- Improved understanding of ocean carbon cycling under reversibility and sustainability scenarios.

In addition, the development of analysis platforms, tools, guidelines, and tutorial opportunities to inform the use (and avoid potential misuse) of models represents a critical coordination and collaboration mechanism to expand community knowledge bases and maximize the impact of this emerging public database.

Table 1. Summary of updates to CMIP models since CMIP5.

Model	Updates and Improvements
GFDL ESM4	• Doubled resolution of ESM2 with improved numerics (1.25°x1° atmosphere, 0.5° ocean) • New atmosphere model - improved shortwave biases and interactive atmospheric chemistry (improved treatment of nitrogen and reduced nitrogen cycle, including interactive SO_4 and NH_3 emissions, interactive dust with dynamic vegetation, aerosol processing and deposition) • COBALTv2 ocean biogeochemistry module - explicit treatment of zooplankton biodiversity, revised physiology and remineralization as a function of bacterial colonization, temperature and oxygen, and iceberg-derived iron.
CESM-MARBL	• Improved physical ocean parameterizations and metrics • New atmospheric model • Global scaling of ocean particulate organic matter burial to balance riverine inputs • Prognostic $CaCO_3$ burial based on saturation state criterion • Time-varying riverine N and P datasets • Estuary box model handling of riverine inputs • Subgrid-scale photosynthetically active radiation (PAR) distribution under sea ice • Prognostic dust/Fe deposition, Fe-binding ligand, NH_4 emissions, carbon isotopes (^{14}C), and SF_6 • Variable P:C (after Galbraith and Martiny, 2015)

Table continues on next page

Model	Updates and Improvements
GISS-modelE-CC	• Atmosphere – clouds, aerosols, land/sea ice parameterization, 2° x 2.5° resolution with 40 vertical layers • Ocean – new grid, mesoscale dynamics and new tracers, 1° x 1.25° resolution with 40 vertical layers • Biogeochemical model – includes coastal runoff, interactive dust, prognostic alkalinity, exponential profiles for sinking and settling of particles, abiotic carbon, tracers (CFCs, SF6 etc.), new remineralization, phytoplankton maximum growth rate parameterizations, and other physiological parameters
IPSL-CM6	• New atmospheric dynamical core (DYNAMICO 0.6°) with 79 layers • Ocean with 75 layers that runs at both low (2.5° x 1.5° atm, 1° ocean) and medium (1.3° x 0.6° atm, 0.25° ocean) horizontal resolution • IPSL-CM5-AerChem with prescribed aerosols and ozone, as well as a very low resolution (3.75° x1.9° atm, 2° ocean) version with interactive chemistry and aerosols for paleoclimate studies
CanESM5	• Atmospheric model (CanAM5) updated with improved radiative transfer and land surface albedo parameterizations and updated land surface scheme, run at T63 spectral resolution (~2.8°). • New ocean model is a customized version of NEMO, using the ORCA1 configuration (1°x1° with 45 levels), and new subgridscale eddy mixing and lee wave mixing parameterizations.

Table continues on next page

CanESM5

(continued)

- New coupler with hybrid grid cells (part land, part ocean), so coastline does not have to be based on coarser atmosphere grid.
- Canadian Model of Ocean Carbon (CMOC): identical to CanESM2 version but implemented in new ocean model.
- Additional new Canadian Ocean Ecosystem (CanOE) model - multiple phytoplankton species with flexible C/N/Fe ratios, prognostic ocean Fe cycle, distinct sinking rates for small, large, and $CaCO_3$ particles, prognostic denitrification

DISCUSSION

For the workshop's final discussion session, workshop participants divided into three groups of 12-15 people each to address the same 4 questions. Each group reported out on their discussions in plenary. Key points from these discussions are summarized below, with the hope that these actionable recommendations will improve coordination among modeling centers, increase community engagement and collaboration, and improve analyses and understanding in the coming months to years.

Question 1. What papers need to be submitted by the December 2019 IPCC AR6 deadline and who is going to write them? i.e. What are the high priority analyses in support of AR6 specifically, and the ocean carbon community in general? What are the most important science questions relating to ocean carbon uptake that we should seek to answer through CMIP6? What is the necessary level of international coordination among CMIP6 MIP leads, modeling centers, RECCAP, and others?

- **Insights from CMIP5:** The discussants concluded that key CMIP5 papers should be reviewed to identify key experiments and elements that should be repeated for CMIP6. Specific topics of interest include ecology (net primary productivity (NPP), biomass, export, phytoplankton groups); ocean acidification (pH, carbonate saturation state); CO_2 flux; O_2 and oxygen minimum zones (OMZs); inert tracers/ventilation; and characterization of the timescales of biogeochemical variability.
- **Decadal ocean carbon uptake:** An assessment seems warranted of how to make best use of the recent decadal ocean carbon uptake estimates from air-sea flux products based on sparse surface ocean pCO_2 data (Rödenbeck et al., 2014; 2015, Landschützer et al., 2014; 2016) vs. ocean carbon storage estimates from repeat hydrographic observations (WOCE-JGOFS/GO-

SHIP) and the role of internal vs. forced climate variability.

- **Modeling center coordination and data provision:** Coupled climate simulations are the priority of the modeling centers, so these will be released before ocean hindcasts (OMIP). It was also noted that coordination with the modeling centers not represented at this workshop will be important. One example of coordination is that at GFDL, a formal quality control procedure must be undertaken before data are released. Advance notice regarding high-priority variables for analysis might help GFDL get these variables QC'd and released first. Other modeling centers may have similar capacity to respond to data users.
- **Emission scenarios:** Comparison of higher emission scenarios (e.g., SSP5) vs. those with substantially lower emissions (e.g., SSP1) should provide greater contrast in the ocean climate and biogeochemical responses. More community discussion of the scenarios on which to focus would be useful.
- **Riverine and coastal carbon:** Riverine inputs and coastal fluxes and processes are both critical for balancing global carbon budgets and likely of interest to policymakers, so they should be incorporated into models.
- **Internal variability:** An assessment of how well the models capture or over/under-represent internal variability of the carbon cycle and related biogeochemical variables is needed.

Question 2. What are the essential observational constraints against which models should be confronted for fidelity assessment? i.e. What was used in OCMIP2 that remains critical? What new observational constraints should be brought to bear on our current generation of models? Can the modeling community recommend additional observations that could fill key gaps? What subset can/should be applied to control runs during development using short duration (decade to century scale) simulations vs. those that require millenial scale spun up control and associate historical simulations?

- **Observational products:** Examples of valuable observational products include SOCAT surface ocean pCO_2, GO-SHIP repeat hydrography, ocean time-series data and synthesis activities (e.g., International Group for Marine Ecological Time-Series (IGMETS)), moored CO_2 time-series (Sutton et al., 2018), and satellite data. The Obs4MIP effort should be considered.

- **Southern Ocean carbon fluxes:** Recent estimates of Southern Ocean carbon fluxes indicate substantially higher CO_2 outgassing than previous estimates. These new float-based estimates show high pCO_2, by 3.6 ± 3.4 μatm compared to ship-based data, which implies additional outgassing of 0.4 PgC/yr. It is important to be cognizant of such uncertainties when evaluating models.
- **Carbon parameter estimates via machine learning:** There are new machine learning approaches to estimating carbon parameters from Argo float temperature, salinity, and other data (LIAR, CANYON), which should be explored by the community.
- **Data treatment:** The standard approach has been to generate gridded datasets that are easy to compare to models. This was typical in CMIP5 and remains quite useful. For CMIP6, we should also consider subsampling models at the scales of the data. The grouping of data over biomes could be a useful approach in some circumstances. Uncertainty in observations and observationally-based gridded estimates needs to be accounted for in model comparisons.
- **Land masking:** For regional to global estimates, the issue of land masking can make quantitatively important differences in integrated fluxes. Models all have different masks, as well as different bathymetries so that their volumes differ. These issues need attention when models are compared to each other and/or to data.

Question 3. What new experiments or diagnostics from existing experiments should be recommended? Are there additional experiments beyond the CMIP6 DECK/OMIP/C4MIP/ScenarioMIP/CDRMIP that the modeling community should consider?

- **New experiments:** Proposals for additional experiments across the modeling centers are not feasible for the near-term, given the significant CMIP6 commitment at present. There are 23 "Model Intercomparion Projects" (MIPs) planned as part of CMIP6. Reversibility scenarios are important, and are planned in the "Reversibility" MIP.

- **Sharing scripts**: Sharing of scripts for analysis and model-data comparisons would be productive. The MOCSY resource from IPSL includes many useful functions (https://github.com/jamesorr/mocsy). Adaptation of the ESMvaltool to ocean biogeochemistry would be very useful.

- **Sharing output fields:** Shared documentation (with respect to output fields – e.g., three-dimensional monthly biogeochemical tracer fields would be useful) that is available directly from modeling centers, but not released through formal channels, could allow for greater ease of data discovery.

- **Historical forcing:** Participants discussed the need to quantify the impact of starting historical forcing at 1850 on analysis of cumulative carbon uptake, despite atmospheric pCO_2 rise having actually started in 1765 (Bronsselear et al., 2017). Runs that can assess the early era anthropogenic (1765-1850) carbon uptake would be useful.

- **Additional outputs:** Although not planned as required output from the modeling centers due to the large size of the outputs, the saving out of modeled tracer advection, diffusion, bioglocial and other tendency terms would be very useful.

Question 4. What tools might support and guide the carbon cycle community to appropriately and effectively interpret CMIP6 models?

- **Sharing model information:** Models should be inventoried and compared to each other as to their key attributes, strengths, and weaknesses. Having a repository where this information is combined with any known issues, biases, or deviations from protocols (carbonate system, flux parameterizations, spin-up strategy, etc.) would be very helpful. Including up-to-date information on the fields that each modeling center intends to provide, along with the timeline for data availability, would also be useful.

- **Anthropogenic carbon estimates:** It would be useful to document the differences between anthropogenic carbon estimates from ocean models vs. observations.
- **Comparing time frames:** Comparison of observations to models would benefit from clear guidelines on how best to compare the time-frames of synthesis datasets (e.g., GLODAP2) with model simulation years. Specific years are more useful than statements such as "late 20th century." The years of control runs that should be compared to historical runs are often not easy to determine. Clearer documentation as to why these years need to be matched up would also be useful.
- **Collaboration and training:** A workshop/hackathon on CMIP6 analyses could build community capacity, and encourage sharing of analysis tools to achieve progress on specific analyses. This and other efforts to reduce or eliminate barriers to model analysis would be welcomed by many in the community. New tools like Jupyter notebooks that were not available during previous rounds can facilitate web-based community development of analysis tools across institutions and countries.
- **Terminology:** Clarification of a variety of modeling terms (earth system model, ocean-only hindcast, internal variability, etc.) would be useful for those who are not model developers but wish to apply models to their research. The appendix to this report defines key terms discussed at the workshop and could be expanded upon as a community resource.

CONCLUSION

CMIP6 will provide a comprehensive suite of model simulations of the changing carbon cycle that will soon be available to the community for analysis. Increasingly diverse observational datasets emerging from multiple platforms span unprecedented temporal and spatial scales. The last few years have seen greater consensus and resolution of discrepancies between model and observational techniques. However, fundamental challenges remain, such as addressing discrepancies across observations and models concerning the highly dynamic Southern Ocean carbon cycle and improving our mechanistic understanding of key processes driving the ocean carbon system to build predictive capacity. As emissions trajectories and CO_2 sequestration technologies that support a transition to a stable carbon cycle continue to grow in importance, such research efforts to characterize the processes and vulnerabilities of the evolving ocean carbon cycle will be critical. Leveraging computational technologies in both forward modeling and inverse techniques, machine learning, and accessible and efficient analysis techniques will become essential tools to improve understanding and predictability in support of society.

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APPENDIX A: WORKSHOP AGENDA

SATURDAY, DECEMBER 8

8:00	Coffee/registration open
8:20	John Dunne (NOAA/GFDL) Goals, logistics and highlights of applicant responses
8:30	Matthew Long (NCAR) Introduction of community tools for model and data analysis

1) Summarize high profile CMIP5 Ocean Carbon Uptake analyses and challenges.

8:55	James Orr (IPSL) High profile summary of CMIP5/AR5 and CMIP6/AR6
9:15	Forrest Hoffman (ORNL) Nonlinear interactions between climate and CO_2 drivers of marine and terrestrial carbon cycle changes
9:40	Galen McKinley (Columbia) Forced changes and internal variability in the ocean carbon sink
10:05	Nicole Lovenduski (UC Boulder) Predicting near-term changes in ocean carbon uptake
10:30	Discussion - Make sure everybody knows the challenges and opportunities, the timeline, and can identify the resources/experts available in the room to make progress.
10:50	Coffee Break

2) Summarize new observational constraints including GLODAPv2, SOCAT, SOCCOM, GO-SHIPS, community observational synthesis efforts such as Obs4MIPs, ocean carbon inversions, and atmospheric observations of CO2 and oxygen

11:10	Nicholas Gruber (Remote - ETHZ) Observational constraints on the global ocean uptake of anthropogenic CO_2
11:35	Peter Landschützer (MPI) Observation-based estimates of the regional and global ocean carbon sink

12:00	Timothy DeVries (UC Santa Barbara) Ocean Carbon Inverse Modeling
12:25	Break for lunch
1:10	Maciej Telszewski (IOCCP) Community Ocean Carbon Observational Synthesis
1:35	Abhishek Chatterjee (NASA/GSFC) Satellite based Ocean Carbon Observations
1:50	Carolina DuFour (McGill) Air-sea CO2 fluxes in the Southern Ocean: lessons learned from the comparison between CMIP5 models and SOCCOM data
2:15	Ariane Verdy (SIO) Data assimilation of carbon and other biogeochemical constraints in the Southern Ocean State Estimate
2:40	Coffee Break
3:00	Adrienne Sutton (NOAA/PMEL) Magnitude and timing of ocean carbon uptake variability constrained by seawater pCO2 time series observations
3:25	Rik Wanninkof (NOAA/AOML) How (well) do models calculate air-sea fluxes
3:50	Discussion - Inventory of what new observational and modeling analyses can be done and are planned
4:30	Lightning talks on poster presentations
5:30-8:00	Evening Poster Reception with food

SUNDAY, DECEMBER 9TH

8:00	Coffee/registration open

3) Modeling center reports on model formulation and preliminary analysis of the CMIP6 models in their regional and global patterns in heat/carbon/tracer uptake

8:30	John Dunne (NOAA/GFDL) GFDL's Contributions to CMIP6
8:50	Matthew Long (NCAR) NCAR's Contributions to CMIP6
9:10	Anastasia Romanou (NASA/GISS) GISS Contributions to CMIP6
9:30	Jim Christian (Fisheries and Oceans Canada) Recent developments in ocean biogeochemistry in the Canadian Earth System Model

9:50	James Orr (IPSL) Progress report from IPSL for CMIP6
10:10	Discussion of CMIP6 models and experiments compared to CMIP5 models and experiments and the timeline for CMIP6/AR6
10:40	Coffee Break

4) Discuss mechanisms of heat/carbon/tracer uptake differences across models and observations towards linking physical and biogeochemical drivers and their impacts

11:00	Andrea Fassbender (MBARI) Sensitivity of the ocean carbon sink to natural and anthropogenic carbon cycle interactions
11:25	Laure Resplandy (Princeton) Systematic deficiencies in ocean transport impact land and ocean carbon sinks
11:50	John Krasting (NOAA/GFDL) Resolution-dependent patterns of heat and carbon uptake in GFDL's OMIP and OMIP-BGC simulations
12:15	Discussion and breakout group assignments
12:40	Break for Lunch
1:20	Split into three Breakout groups previously assigned with identical sets of questions for brainstorming
3:20	Coffee Break
3:40	Report back from each of the breakout groups
5:00	Conclusion/writing assignments

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APPENDIX C: KEY DEFINITIONS

Visit the living document of key definitions for the latest update **here**.

OCEAN COMPONENT OF EARTH SYSTEM MODELS VS. OCEAN-ONLY HINDCAST

Global coupled ocean-ice-land-atmosphere models are commonly known as "earth system models" or "climate models". These models are typically forced only with influences external to the coupled climate system i.e. solar radiation, volcanic aerosols, and greenhouse gas concentrations. If the carbon cycle is explicitly represented, then greenhouse gas emissions would be specified and the carbon cycle will determine exchanges with the ocean and the land, and thus the model will determine the atmospheric CO2 concentration. CMIP6 models are earth system models.

In an earth system model, the state of the internal variability for the historical period is not prescribed so that it is the same as the observed. The internal variability of an earth system model is the emergent result of the coupled interactions of the system. One expects the statistics of this variability to be consistent with the historical observations, but the timing and phasing will not be. As an example, one expects the earth system model to have El Niño events occurring every 5 to 7 years, but one does not expect them to occur in 1997-98. Thus, to compare results of an earth system model to observations, one must take care that the comparisons are reasonable given the expected different states of internal variability as simulated and as observed. One rule of thumb is that averaging of 20-30 years, or 20-30 members of an ensemble of simulations is needed to get a coupled model field that can be compared to mean observations.

In order to estimate internal variability as it occurred in the historical period, the approach used is to force an ocean model with historical atmospheric reanalyses (reanalyses are atmospheric models constrained with observations so as to offer a best-estimate of the historical atmospheric state). This is an ocean-only hindcast simulation. The ocean model used may be identical to the ocean component of the earth system model, but the key difference is that the internal variability is an estimate of the actual variability. Thus, in an ocean-only hindcast simulation, one does expect El Niño to occur in 1997-98. Thus, it makes sense to make direct comparisons between observations and ocean-only hindcast simulation for the same years.

INTERNAL VARIABILITY

Ocean internal variability are deviations on all timescales from a steady repeating seasonal cycle. This is variability in circulation of all types, El Nino and other modes of climate variability, and also in ecology or biogeochemistry. In the case of an ocean-only hindcast model, the simulated internal variability is an estimate of the actual historical internal variability. Internal variability is also found in earth system models, but then its phasing is not expected to align with historical observations. Internal variability is often called "natural variability" so as to distinguish it from trends driven by external forcing.

LARGE ENSEMBLES

Large ensembles of earth system models are earth system models that are run repeatedly with small perturbations to initial conditions. These are used to estimate the full spread of potential internal variability in any represented variable and at any point in the past or future.

FORCED RESPONSE

Particularly in the context of anthropogenically-driven climate change, we are interested in separating internal variability from trends due to anthropogenic forcing. A great benefit of earth system models run in large ensemble mode is that the average response of many ensembles can be taken as an estimate of this forced response, and the remaining spread across ensemble members is an estimate of the range of potential internal variability.

ESM HISTORICAL VS. HISTORICAL

In CMIP5 and CMIP6, a coupled model forced with prescribed atmospheric CO_2 concentrations is an historical simulation. If the forcing is CO_2 emissions and there is an active carbon cycle that then determines the atmospheric CO_2 concentrations, this is called ESM historical.

PREDICTION VS. PROJECTION

Future climates are predicted on short time scales (up to 3 years) and projected on longer time scales using global coupled ocean-ice-land-atmosphere models. Short-term climate prediction works in a similar fashion to a weather forecast: Its skill depends on how well we estimate the initial state. Climate projections employ greenhouse gas emission scenarios, which are based on assumptions about future population growth and emissions per capita. Uncertainties about these projections derive firstly from the scenario uncertainty, secondly from the model uncertainty (error), and finally from internal variability, which a model never reproduces exactly. For both predictions and projections, coupled ocean-ice-land-atmosphere models are required.

For more information visit
https://www.us-ocb.org/cmip6-wg/

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