Workshop Report

Observed and Model-Simulated Property Changes in the Deep Ocean of the Southern Hemisphere
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Workshop Organizing Committee
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OUTCOMES AND RECOMMENDATIONS

1. The most significant and consistent observed changes in the deep ocean are in the Southern Ocean and adjacent ocean basins.

2. The workshop endorsed the need for synthesis papers on the Southern Ocean Antarctic Bottom Water (AABW) and deep ocean changes. A working group, consisting of Gregory Johnson, Sarah Purkey, Steve Rintoul, and Bernadette Sloyan, was formed to explore the synthesis development and writing of the manuscripts. The carbon community is undertaking a synthesis project – RECCAP (http://www.globalcarbonproject.org/activities/RECCAP.htm)

3. It is important to link the deep ocean total carbon change to water mass formation and ocean dynamics. This link will require communication between the carbon and physical ocean synthesis working groups to ensure the most accurate message is conveyed to the rest of the climate science community.

4. The carbon community uses a number of methods to estimate anthropogenic carbon in the ocean. Currently the spread in the estimates from these methods is not converging. The workshop supports the on-going collaborations and comparison between the various methods.

5. The modeling community would greatly benefit from gridded data products in the deep ocean. The workshop endorsed the production of gridded data set.
   - Gridded temperature salinity and nutrient data are readily available (i.e. WOA, CARS2009 - http://www.marine.csiro.au/~dunn/cars2009/).
   - The carbon community have produced internally consistent carbon, nutrient and CFC data – CARINA (http://cdiac.ornl.gov/oceans/CARINA/about_carina.html) and are working on a similar data set for the Pacific Ocean (http://cdiac.ornl.gov/oceans/genInfo.html).
   - The tracer community (i.e. PMEL) are looking at spatial/temporal regressions to allow combination of CFC data collected by the repeat hydrography program for production of a gridded CFC data set.

6. Understanding the formation mechanisms and properties of AABW can be enhanced by constraining the assimilation models with the ocean tracers – analysis of temperature, salinity, and oxygen are common but we should also consider silicate, C-14, NO, PO and He-3.

7. Observed changes in the deep ocean are significant and impact the global climate. Given the signals found in the expanding deep observational record, we need to highlight deficiencies in model simulations of the deep ocean. Focusing on these deficiencies will provide the impetus to fix model physics in the next generation models. The workshop recommends that we:

- Ensure that climate model metrics developed in CLIVAR (http://www.clivar.org/organization/wgomd/reos/metrics.php) are complete and if not provide deep ocean metrics for climate model evaluation.
- Support the need for climate model freshwater flux perturbations around Antarctica (with realistic spatial input of freshwater).

8. It was agreed that we need to foster greater collaboration amongst the ocean science communities with regards to the roles of the deep ocean in climate.

9. The workshop refined the benefits of a deep ocean observing system presented in the OceanObs'09 community white paper, with particular focus on the Southern Ocean. The workshop found that all the science and societal benefits of the deep ocean observing system are strongly controlled by the Southern Ocean circulation and dynamics. It is vital that the Southern Ocean be a starting point for increased deep ocean observations.

10. Outlining the need and strategy for monitoring AABW formation sites, deep passages, and overturning circulation is a priority. This workshop endorsed the following improvements to the document presented at OceanObs'09:
    - Augmenting the global temperature and salinity observations below 2 km by building a broad-scale full-depth array of floats/gliders/moorings.
    - Observing temperature, salinity, velocity, and carbon near formation regions (add AABW locations in Ross Sea and Adelie Land to Weddell Sea monitoring).
    - Observing, temperature, salinity, and velocity downstream from these formation sites in Indian and Pacific Oceans and the Southern Ocean Choke points.
    - Observing the MOC in South Atlantic, Indian and Pacific and Southern Ocean.

11. Rigorous design studies should be undertaken to define the optimal sampling requirements of a Deep Ocean Observing System. These studies must define the goals of the observing system and consider the effectiveness and efficiency of the array given the signals that the array must detect.

12. The major change in the deep ocean is in the Southern Ocean and therefore the implementation of a deep ocean observing system must firstly target the Southern Ocean and then expand to other regions.

Introduction

Dr Bruce Mapstone, Divisional Chief CSIRO Marine and Atmospheric Research, began the workshop with a formal welcome. He highlighted the important role of the deep ocean in the global climate system – particularly the global energy, freshwater and carbon budgets. He noted that understanding the role of the deep ocean in the global climate requires a multi-disciplinary approach and lauded the workshop for gathering a cross-section of the diverse ocean science community to discuss recent results and future work. Dr. Bernadette Sloyan followed with an orientation. After that, science presentations alternated with in-depth discussions. The science presentations are summarized below, followed by summaries of and recommendations from the discussions.

Science Presentations

The workshop included 23 science presentations covering much of the breadth of current and ongoing research into the role of the southern hemisphere deep oceans in climate. A synopsis of major points of the presentations is provided.

Day 1

The morning presentation sessions were dedicated to studies of deep ocean changes observed from analyses of repeat hydrographic sections in the Pacific Ocean, south of Australia, and in Drake Passage.

The 32^{o}S transPacific ocean hydrographic section has recently been occupied for a third time (1992, 2003, and 2009; Alison Macdonald). The most recent data confirm that the deep Pacific Ocean is warming. A deep freshening is also now apparent in the most recent section. Analyses of the specific properties of the deep ocean changes suggest that the bottom water in the Tasman Sea and Southwest Pacific Basin originate from the Adelie Land and Ross Sea, respectively.

Analysis of an often repeated from Australia to Antarctica is complicated by the numerous fronts is this region (Esmee Van Wijk). Careful analysis techniques must be employed to account for frontal movement amongst the time-series section. Intermediate-depth oxygen changes are clear, but near-bottom oxygen changes are more difficult to detect.

A section across Drake Passage has been reoccupied yearly by NOC, UK (Loic Jullion). These sections provide the ability to address drivers of interannual variability of Antarctic Bottom water (AABW) formed in the Weddell Sea. Interannual bottom water variability at Drake Passage appears to be due to changes in export of AABW from Weddell Sea rather than AABW property changes. Interannual variability is strongly correlated to the zonal wind at a 5-month lag; however, this time scale is too short when considering the context of geostrophic adjustment theory. Therefore the underlying dynamics require further investigation.

A 4DVAR data assimilation system provides a dynamically self-consistent ocean state estimation from the surface to bottom (1967-2006) that is capable of representing the recent climate changes including the bottom-water warming phenomena (Shuhei Masuda). The assimilation suggests that the deep warming in the Pacific Ocean is due to a reduction in abyssal cooling via a slow-down of the deep ocean circulation and AABW formation. This slow-down appears to originate near Adelie Land, where air-sea buoyancy fluxes over bottom water formation regions appear to have changed.

Finally, New Zealand future observational plans of the deep western boundary current adjacent New Zealand were detailed (Steve Chiswell). NIWA is seeking international collaboration to consider the minimal requirement to monitor the Pacific deep western boundary Current. This study could be carried out on their research vessel.

The afternoon presentation session covered carbon and tracer distributions and changes in deep water masses.

There are a number of methods to estimate the anthropogenic carbon inventory in the global ocean (Nicolas Metzl). While these methods show relatively good agreement in the mid- and low-latitudes, they differ significantly in the high latitudes, especially in the deep and bottom waters. The greatest discrepancy is found in the deep Southern Ocean. The carbon community is currently working to reconcile the different estimates of anthropogenic carbon in the deep Southern Ocean.

Many factors impact the ability of the Southern Ocean to absorb anthropogenic carbon; these include ocean physics, sea-ice and biological activity (Dorothee Bakker). Present day and future estimates of carbon up-take rates in the Southern Ocean rely on an improved understanding of the impact and potential change the ocean circulation, seasonal sea-ice production and melting, and biological activity.

Through the CARINA Project, the carbon community has provided a quality controlled and self-consistent of carbon, nutrients, and CFC data for the North Atlantic and Southern Ocean (Mario Hoperma). A specific focus of CARINA is the Southern Ocean; from “data mining” historical and unreported observations CARINA has significantly increased the number of carbon relevant observations in this region. These data are available to the research community. Some important questions regarding the role of the Southern Ocean in the global carbon budget currently being addressed by the research community include: What are the mechanisms that significantly affect total carbon in the Southern Ocean? What is the link between changes in air-sea carbon fluxes and changes in total carbon in the ocean's interior? What governs regional differences in carbon uptake and deep carbon transports? Is the carbon sink in the Southern Ocean really decreasing? What factors influence carbon and auxiliary variables in regions of water mass formation? What are the influences of local/regional processes on global scale carbon?

Uses of CFC and other ocean transient tracer data to determine the water mass formation rates and circulation pathways of the deep ocean were discussed (John Bullister). CFCs are often used to estimate anthropogenic carbon uptake in the ocean, and may be useful analogues for the propagation of surface flux changes (heat and freshwater) into the deep ocean. Comparison of repeated measurements of transient tracers are providing information on the propagation of Southern Ocean orgin deep ocean changes into the global ocean.

Day 2

The morning presentation session included a number of presentations that investigated the ability of climate models to simulate the deep ocean water masses, circulation and changes.

Repeat hydrographic sections in the Drake Passage, South of Africa, and the South and North Atlantic are being used to investigate changes in the lower limb of the meridional overturning circulation and transport-weighted mean temperature (Brian King).

A comparison of observed spatial and temporal trends in the deep ocean temperature and salinity against those from a suite of climate models shows that some climate models are able to reasonably reproduce the observed spatial patterns of the property trends (Bernadette Sloyan). In general those models that provided a realistic spatial pattern of trend captured the northward penetration along the western boundary of the South Pacific Ocean and Atlantic Oceans. However, the observed spatial pattern in the Indian Ocean's South Australian and Wharton Basins were poorly represented in the suite of models considered. The magnitudes of the property trends were poorly simulated in most climate models.

While some climate models may reproduce a semblance of observed trends in deep ocean physical properties, the ability of the climate models to properly simulate the Southern Ocean impact on the global carbon budget is determined by the rate at which deep ocean waters are upwelled to the mixed layer in the Southern Ocean (Joellen Russel). Currently climate models underestimate the size of the deep ocean circulation and this bias significantly impacts the total carbon and heat fluxes of the meridional overturing circulation.

Some of the deep ocean variability in particular basins of the Southern Ocean may be explained by forcing that excites a modal response (Wilbert Weijer). Normal modes have been found to play a role in the barotropic variability in the Argentine, Mascarene and Australian-Antarctic Basins. The modal response of these basins may drive decadal and longer time-scale variability of the meridional overturning circulation.

Heat content trends from assimilation of decadal repeat hydrographic sections are found in the Japanese 4DVAR assimilation model (Shinya Kouketsu). A 50-year observational record is assimilated. The assimilation model estimates the heat content change of the deep ocean in recent decades is 5-15% of the heat content increase in the upper 700 m, and that the deep ocean heat content change is largest in the Southern Ocean. The 4DVAR model shows that the signal of North Pacific bottom warming can be traced along the deep western boundary to changes off the Adelie Lands. The 40 year time-scale of the changes reaching the North Pacific strongly indicates a wave-like propagation of the signal.

Finally, the impact of the future evolution of the Southern Ocean on carbon uptake was presented (Andrew Lenton). This study considered the impact of the southward shift of the westerly wind field and changes to the heat and freshwater fluxes. This forcing resultants in increased stratification and impacts the ventilation of carbon rich deep waters and uptake of carbon by the Southern Ocean.

The afternoon presentation session considered the observed AABW changes near its formation regions and model simulation of the processes driving water mass formation.

Significant freshening of AABW of Adelie Land and Ross Sea origin has been observed (Steve Rintoul). The leading cause of the freshening in these regions is thought to be increased glacial melt in the Southeast Pacific sector of the Southern Ocean, perhaps augmented by more local sources and/or changes in the formation of sea-ice along the Adelie Coast. Time-series mooring in some of the source regions for AABW (Weddell Sea and Adelie Land) show strong seasonal outflow of bottom water off the shelf. How this variability impacts the properties of the deep ocean in the basin adjacent to AABW formation sites is still unknown.

Change in the water masses in the Weddell Sea are observed throughout the water column (Mario Hoppema for Eberhard Fahrbach). The potential causes of water mass property change include: variability in the inflow to the Weddell gyre, changes in the gyre circulation, and variability in the atmosphere-ocean-ice exchange.

Ocean-ice shelf modeling studies have shown that formation rate of AABW is extremely sensitive to the glacial cavity melt (Ben Galton-Fenzi). AABW formation is overestimated in simulations without ice shelf/ocean interaction processes. These studies have also shown that coastal polynyas created in the lee of icebergs and coastal features are important features of the ice shelf-ocean interaction and dense water formation.

Finally an overview climate models and the development of the new Australian climate model was presented (Simon Marsland). Future climate model development to improve bottom water formation and properties will need to focus on parameterization of coastal polynyas, ice-shelf cavity interaction, overflows, and shelf-open water interactions.

Day 3

The final morning presentation section focused on global analyses of deep ocean circulation, contributions of deep warming to heat and sea-level budgets, and methods/climatologies.

A comparison of a mid-1990's (WOCE) and mid-2000's (revisited) Southern Ocean circulation, determined from box inverse methods, found that the deep limb of the meridional overturning circulation has slowed by approximately 5 Sv between the 1990s and 2000s (Katsmuro Katsumata). The apparent slow-down in the overturning circulation is dominated by changes in the southward transport of Pacific Deep Water. This observed slow-down of the deep circulation is also found in ocean models.

A new isopycnally averaged climatology for temperature and salinity was presented (Paul Barker. A new inverse method combining tracer equations with the traditional box inverse model to solve for along and cross isopycnal transport was described (Trevor McDougall).

Analysis of global repeat hydrographic sections has found that abyssal warming is widespread (Gregory Johnson). The largest warming is found near Antarctica and decreases with distance from Southern Ocean. The analysis has also found freshening of bottom waters in the Australian-Antarctic and Amundsen-Bellingshausen Basins. There are indications of a slowing to the deep meridional circulation in the North Pacific and North Atlantic Oceans, although these findings are based on limited observations.

The final presentation provided estimates of warming of AABW and its contribution to the global heat and sea level rise budgets (Sarah Purkey). This study found that AABW warming is a substantial fraction of the global heat imbalance and an important contributor to sea level rise. The study emphasized that there is a strong warming trend below 1000 m in the Southern Ocean. It was suggested that the global bottom water warming/cooling pattern is consistent with a retraction of AABW due to changes in formation rates.

Workshop Discussions

The workshop alternated science presentation sessions with discussion sessions. The objective of these sessions was to promote rigorous discussion expanding upon questions and/or comments raised during the science presentations, and to set priorities and directions for future work including scientific analysis and observation system development. Six discussions were held and the major outcomes are presented below.

DAY 1

Observed Ocean Change and assessment of spatial and temporal variability
Discussion leader: Steve Chiswell
Note-taker: Katsuro Katsumata
Focus: Property changes (temperature, salinity, and oxygen)

This discussion considered the spatial and temporal variability of the observed deep ocean changes. Some threads naturally lead into future discussions sessions, particularly model studies and the design of a deep ocean observing system. A question was raised regarding in the qualification of geothermal heat flux to the deep ocean and consideration of this as a component of the deep ocean heat content change. The effect of geothermal heat input on deep ocean temperature is known to be significant in certain regions of the global ocean (e.g. the North Pacific). This component of the deep ocean heat budget could be incorporated into models.

Analyses of observed warming are primarily based on data from the global repeat hydrography program (GO-SHIP, www.go-ship.org). It was noted the deep ocean warming does not significantly contribute to net meridional heat fluxes. However, the deep water heat content change is large and important in efforts to close global energy budget. In addition, deep ocean temperature and salinity observations are only one of the many scientific justifications of the repeat hydrography program, which include measurements of carbon system parameters, nutrients, oxygen, and transient tracers throughout the water column. Complementary observation of near-bottom temperature could be potentially be obtained from relatively cheap moorings that pop up at designated time period (3 to 5 yrs) and communicate data by satellite. Deep gliders and deep Argo floats are also possibilities for measuring both bottom and deep ocean properties.

Presently there are limited observations to assess the spatial and temporal variability of deep ocean change. We need to promote better communication between the modeling and observation communities. This communication would enhance feedback and initiate process studies. In general, climate models (e.g. IPCC AR4 models) do not simulate the deep ocean water masses very well. Communication between the two communities may provide the incentive to improve the representation of the deep ocean in ocean models.

It was suggested that the design of observational programs should utilize assimilation model to find low signal to noise regions or 'efficient' regions. Spatial resolution of the models limits the applicability such studies. We need to clearly define temporal and spatial scales and use the models consistently.

Observed Biogeochemical change and transient tracer distribution

Discussion leader: Bronte Tilbrook
Note-taker: Alison Macdonald
Focus: Carbon/Chemistry

Throughout the session Mario Hoppema's questions were used to stimulate the discussion, but discussion did not particularly center on them:

- What are the mechanisms that significantly affect total carbon in the Southern Ocean?
- What is the link between the air-sea carbon fluxes and changes in total carbon in the ocean's interior? Link data set of SOCAT and CARINA.
- What governs regional differences in carbon uptake and deep carbon transports?
- Is the carbon sink in the Southern Ocean really decreasing?
- What are conditions of carbon concentration and auxiliary variables in regions of water mass formation?
- What is the influence of local /regional processes on global scale ocean carbon?

At present, the total anthropogenic ocean carbon uptake during bottom water formation may be small. (It is estimated at ~1% from a back of the envelope calculation.) Thus, the deep ocean is not a huge sink for carbon, but what is sequestered in bottom waters is locked away for longer than other water masses and is therefore important to our understanding of net ocean uptake. In the long term - century scale, bottom water will be the major sink for carbon.

The carbon community uses a number of methods to estimate anthropogenic carbon in the ocean. The Tracer TrOCA (*Tr*acer combining *O*xygen, inorganic *C*arbon, and total *A*lkalinity) method assumes equilibration of carbon with the atmosphere, but studies have shown that ocean carbon is only at 35-40% equilibration in some ocean regions
There is still a large debate in the community concerning the most appropriate method to use for estimating anthropogenic carbon uptake. Currently the spread in the estimates from these methods is not converging. A difficulty in applying some of the methods is that there are now no or only a few regions in the global ocean where at least some anthropogenic carbon has not penetrated.

The total anthropogenic carbon inventory is similar for many methods but the global distribution amongst the methods varies greatly. It appears that different methods work better or worse in different regions. The Transient Time Distribution (TTD) method may be most appropriate for the deep Southern Ocean.

One can also assess the total carbon change by a simple subtraction of total carbon from repeat sections. This method could be valid for estimating anthropogenic carbon change and uptake, but as with all methods this has inherent assumptions – steady state circulation and biological activity. It may be difficult to separate the natural changes from the anthropogenic changes using direct subtraction.

More accurate estimates of the carbon budget changes may be provided by methods that combine a suite of nutrient and oxygen data. The community is working on improving the quality of these data for these purposes. A brief discussion on the usefulness of co-location of carbon and nutrient observations followed. The ability to use oxygen as proxy for carbon was discussed as these two variables exhibit a tight covariance. Deep Argo floats with oxygen sensors are of significant interest and value to the carbon community. However, we to need understand the stability and accuracy of the sensors before they are routinely added to deep Argo floats.

We need a better separation of natural and anthropogenic carbon. Many groups are working towards this goal and the workshop encouraged the on-going collaborations and comparison between the various methods currently employed.

Finally, we considered potential collaborations with the modeling community. Carbon is increasingly being incorporated into models with increasing sophistication. It was suggested that it would be good to have CFC and carbon (not affected by heaving like heat) in models particularly for diagnosing changes in bottom water formation processes and rates. It was also suggested that the modeling community would greatly benefit from gridded data products. These products would help with the incorporation of carbon and CFC into models. The carbon community is producing high quality data sets of carbon, oxygen, and nutrients. The CARINA data set is available and PACIFICA should be released by late-2010. There was an apparent lack of knowledge in some parts of the model community concerning the availability of these new data sets. We need to ensure the wide advertisement and uptake of these data sets.

One of the biggest challenges is the production of a gridded CFC data set. It is a difficult task to grid these data because of the time dependant nature of this tracer. A way forward is to assume steady state circulation and then offset the data to a standard date. This would provide a means of assessing circulation connections between the formation regions to Deep Ocean and uptake of carbon. Groups (i.e. PMEL) are looking at spatial/temporal regressions to allow combination of CFC data collected by the repeat hydrography program.

To enhance the modeling community's use of observation data sets we need to engage with them. Modeling groups won't add CFCs absent a gridded product to assess the model CFC simulation. It was suggested that if models compared DIC to CFC (data) that would tell them if models are going in the right direction. A potential way forward to enhance the model use of CFC data set is the use the TTD method that provided an unbiased (time) CFC field.

Other traces considered of values are: C-13 – Distributions have been being used (signal to noise better than DIC) in models but we have limited observations. Also time lags in the terrestrial biosphere uptake and fraction in the ocean are complicated. O-18 is useful for separating the origin of water masses in bottom water. However, these data are currently not available to model community as a gridded product. O-18 is good example of an observation that can be used beyond its original intended use. Ar-39 could be used as it has a long half life, but requires large sample volumes and is difficult to measure.

DAY 2

Antarctic Bottom Water production and variability in assimilation and climate models and impact of biogeochemical response

Discussion leader: Dorothee Bakker
Note-taker: Ben Galton-Frenzi
Focus: Antarctic Bottom Water

This discussion session considered AABW production, properties and changes, and global circulation in models. Given the science presentations, this topic was also expanded to consider the mechanisms for warming of the deep ocean i.e. dynamical changes at gaps and ridges, variability of deep, and southward movement of the Antarctic Circumpolar Current (ACC).

There are a number of candidate mechanisms that can explain observed deep ocean changes. The workshop was presented with results from the Japanese 4DVAR assimilation model that found the driver of warming in the North Pacific Ocean was a topographically trapped wave that propagated from the Southern Ocean ACC region. The time scale of the propagation was approximately 40 years and it was suggested to have been driven by forcing changes off the Adelie Lands of Antarctica.

Understanding the formation mechanisms and properties of AABW can be enhanced by constraining the assimilation models with the ocean tracers – analysis of temperature, salinity, and oxygen are common but we could also consider silicate, C-14, NO, PO, and He-3.

Different classes of model have very different strengths and weakness; we need to encourage the continued use a wide spectrum of models. For example, IPCC models often show too-large carbon transports that result from a too-large shallow circulation. However, this class of model enables us to understand ocean-atmosphere coupling, i.e., that upwelling of deep water has changed with southward shift and intensification of Antarctic westerly winds.

Another great advantage of models is their temporal resolution. Combined model-observational studies may help us understand and perhaps even mitigate the extent of temporal aliasing of the deep ocean observational data sets.

It was agreed that we need to foster greater collaboration amongst our communities. We should jointly decide on important diagnostics to include in model evaluations.

Assessment of model simulation and providing input to improve the reliability of Climate Models

Discussion leader: Simon Marsland
Note-taker: Wilbert Weijer
Focus: Model simulation of deep waters properties and change

Discussion participants were asked to consider studies of the deep ocean change that will benefit from a combined model and observational approach, driven by the work currently being undertaken by both communities for the IPCC AR5. There were some concerns that adhering to the time-line of AR5 would stifle true collaboration. However, the majority of participants recognized that the AR5 time-line provides the motivation to begin common projects and that these studies will provide long term benefits to understanding global climate and variability.

We considered how models can be benchmarked against existing data sets. This includes all models – high resolution ocean only, regional limited, coupled models of varying resolution. Observations to benchmark models include short-term process studies and long-term repeat hydrography for trends. The Ocean Obs 09 strategy for deep ocean observations includes repeat hydrography sections with higher frequency repeats near source regions of dense water masses; continuous time series of overflows, gaps and constriction of deep flow along the circulation pathway. How many moorings to we need to detect change? Argo is used to resolve seasonal and longer time-scale variability in upper ocean. Boundary currents and overflows have large variability and therefore many years of data are required for robust mean transport estimates from Argo alone. As a community we need to decide what we need and have the capacity to measure. Perhaps we should focus on the low-frequency variability in the deep ocean.

The best observed region in the Southern Ocean is Drake Passage with approximately yearly hydrographic sections, and various moorings. It was noted that diagnostics extracted from models do not always agree well with observations. A method to overcome individual model deficiencies in multi-model ensemble analysis is to weight models according to their representation of certain metrics. Assimilation models also are valuable tools to understanding the drivers of observed variability and change.

Observed changes in the deep ocean are significant and impact the global climate. Given this evidence and the expanding deep observational record, we need to highlight deficiencies in model simulations of the deep ocean. Focusing on these deficiencies will provide the impetus to fix model physics in the next generation models.
A way forward is to asses climate model metrics was developed in CLIVAR http://www.clivar.org/organization/wgomd/reos/metrics.php ; if not complete we should interact with modeling community in this regard.

We discussed the uses of carbon, nutrients and tracers observations as modeled parameters and or validation tools of bio-geochemical models and ocean circulation models. The carbon community has published the CARINA data set. This contains quality controlled carbon, nutrient and CFC data. The Japanese 4DVAR model incorporates CFCs but this model has a relatively coarse spatial resolution. CFCs have been used off line to assess the advective circulation of this assimilation; but have not been used to constrain the velocity field. Other data sets include institutional climatologies (i.e. CARS 2009) which often include temperature, salinity, oxygen, and nutrients.

Finally there was a brief discussion on perturbation model experiments. It was suggested that more runs with freshwater flux perturbations around Antarctica could be useful.

DAY 3

Synthesis of the Deep Ocean Property Changes
Discussion leader: Joellen Russell
Note-taker: Bernadette Sloyan
Focus: Synthesis of AABW and deep ocean change

The objective of this discussion was for the workshop participants to determine the most appropriate and effective method to ensure that observed changes in the deep ocean are incorporated in IPCC AR5. The workshop was reminded of the timeline for inclusion in the report (http://cmippcmdi.llnl.gov/cmip5/docs/IPCC_AR5_Timetable.pdf);

- **July 31, 2012: By this date papers must be submitted for publication to be eligible for assessment by WG1 and;**
- **March 15. 2013: By this date papers cited by WG1 must be published o r accepted (with proof, for example, by a letter of confirmation from the editor)**

It was agreed that in some respects IPCC AR4 did not provide an adequate statement on Southern Ocean changes. However, since this report a number of studies have been published that describe the observed changes in the Southern Ocean formation of AABW and their impact on the global deep ocean. These recent studies clearly show that the Southern Ocean and global deep ocean are important components of the global energy (heat), freshwater, carbon and sea level budgets. A synthesis paper would provide a concise literature review of the published studies and strengthen our understanding of the possible dynamical processes that drive the observed change. We have some candidates – southward drift of wind forcing and/or climate mode variability. A synthesis paper would also be useful to the ocean modeling community as it would “challenge” the simulation of the deep ocean and AABW water mass properties and circulation. The carbon community is undertaking a synthesis project – RECCAP (http://www.globalcarbonproject.org/activities/RECCAP.htm) – of regional studies that will be combined into a global synthesis.

The physical and carbon communities need to be informed of the synthesis being undertaken by their communities. The carbon group will use CARINA and similar data set to determine deep ocean carbon changes. Some sections of this community expect the change of carbon will be assessed using total carbon estimates that may minimize confusion in estimating anthropogenic carbon change. It will be important to link the deep ocean total carbon change to water mass formation and ocean dynamics. This link will require communication amongst the carbon and physical ocean communities to ensure the most accurate message is conveyed to the rest of the climate science community.

In addition to the observational synthesis, we discussed comparing observations with model simulations. We now have global estimates of the deep ocean heat storage changes and sea level rise contributions. We can undertake similar analyses using the output of AR4 coupled climate models. We can use the model output to provide an indication of whether the trends we observe in the deep ocean change are long-term or dominated by shorter time-scale variability (decadal). The models may allow us to assess potential dynamical forcing that drive the observe changes at all time-scales. While this time-scale analysis is possible, we need to mindful of the model inadequacies, such as representation of ozone hole as this has an impact on the model westerly wind trends. Comparison of AR4 and AR5 models to deep observations would also simulate further investigations.

It was agreed that there was a need for synthesis papers regarding the Southern Ocean AABW and deep ocean changes. This may require both a short focused article and longer more comprehensive review article. There was a discussion about the target journal but this will depend on "new" science content of the synthesis papers. A working group, consisting of Gregory Johnson, Sarah Purkey, Steve Rintoul, and Bernadette Sloyan, was formed to explore the synthesis development and writing of the manuscripts. Other participants who indicated interest in synthesis manuscripts were Katsuro Katsumata, Wilbert Weijer, Brian King, and Alison Macdonald.

<u>Towards a Sustained Deep Ocean Observing System</u>
Discussion leader: Gregory Johnson
Note-taker: Bernadette Sloyan
Focus: Deep Ocean Observing System

Recent CLIVAR SSG and OOPC meetings requested that this workshop consider the need and requirements of a deep ocean observing system. The discussion was structured to consider the science and societal requirements, existing elements, sampling improvements, and desired technology improvements of or for an adequate deep ocean observing system. The opening point of each topic started from the results of the OceanObs'09 conference, particularly the Deep Ocean Observing and Southern Ocean Observing System (SOOS) community white papers.

SCIENCE and SOCIETAL BENEFITS
OceanObs'09 outlined the following science and societal benefits of a sustained deep ocean observing system:

Monitor and study (global) MOC

- Atlantic
- Rapid climate change
- AMO teleconnections and decadal predictability?

Deep ocean carbon sequestration and out-gassing
Upwelling of deep water and Antarctic ice sheet melt.
Deep ocean heat and freshwater uptake

- Climate sensitivity (constraining projections of global warming)
- Sea level rise (local and global)

The workshop refined the benefits, with particular focus on the Southern Ocean. We considered that the deep ocean observing system also have societal benefit on:
Ocean ecosystems

- Oxygen ventilation of the deep ocean
- Upwelling of nutrients and macro-nutrients from deep to surface ocean (the Southern Ocean dominates this circulation)
- Ocean acidification
- Upwelling of deep ocean carbon

All the science and societal benefits of the deep ocean observing system are strongly controlled by the Southern Ocean circulation and dynamics. It is vital that the Southern Ocean be a starting point for increased deep ocean observations.

SAMPLING PLAN IMPROVEMENTS

As a starting point for discussing suggested sampling plan improvements (as suggested in OceanObs'09 community white papers with additional refinement from this workshop) we first reviewed current observations of the deep ocean. Most of the current observational programs are listed on the CLIVAR Southern Ocean Panel, GO-SHIP, CDIAC and institutional web sites. These observations are a collection of process studies (not sustained) and observations with limited funding horizons but with the desire/intention to be long-term sustained observations. Separating one-time and sustained observations is complicated by the short-term funding windows (2-5 years) under which many of these programs operate. Therefore, there are serious questions concerning the different level of commitment regarding the intention for sustained observations that would be considered as a component of a sustained observation system.

A list (incomplete) of existing observations is proved below:
Repeat hydrography
RADIP/MOCHA
DWBC in North Atlantic and Weddell Sea
Inverted echo Drake Passage and South Atlantic
Prime Meridian - Germany
Pressure gauges in Atlantic
Moorings Fawn Trough – US and Australian
Moorings Cape Darnley – Japanese

Moorings Adelie Coast – Australian
Moorings Ross Sea scattered – Italian
LTER Bellingshausen Sea
CTD from Seals – Southern Elephant Seals
Array of sound sources in Weddell Sea – under-ice acoustic transmission of float profile data
South Atlantic Vema Channel
Paleo high temporal ice and sediment cores

A general consensus was that we need to preserve AABW and deep observations in the southern hemisphere oceans, and build on these observational programs.

The OceanObs'09 community white papers provide a vision for a deep ocean observing system. However it was recognized that there are considerable gaps in this vision. While the observing plan for the Weddell Sea is reasonable, the document only put a forward a plan to monitor the Atlantic MOC, not the Antarctic MOC. As a result, the vision for the Ross Sea, Adelie Land, as well as the deep Southern, Indian and Pacific Oceans is incomplete. Outlining the need and strategy for monitoring AABW formation sites, deep passages, and overturning circulation is a priority.

It was recognized that designing an observational system to monitor the MOC in the southern hemisphere is particularly difficult. The minimalist array in North Atlantic (RAPID/MOCA, MOVE) will not work in most deep southern hemisphere basins due to complicated geometry and water masses. In other words, end-points arrays are not likely to work near 30°S in southern hemisphere.

From experience, previous mooring arrays, such as the Kerguelen Plateau DWBC, are still unable to provide estimates of net northward flow as there is the potential that the array missed recirculation gyres beyond the instrument array. However, combined observations and model studies could potentially resolve these issues as the temporal information provided by the mooring array can used to assess the model simulations.

To move forward with the design of a deep ocean observing system we need to clarify the goals of the system: observations of variations in large scale properties (heat, salt, carbon, oxygen), deep circulation, and deep water formation rates, as well as boundary current volume and property transports. In determining the goal of the deep observing system we need to consider the cost effectiveness of each instrument type i.e. limited long-time (> 20 years) deep current and properties arrays versus a more distributed array of numerous point source property recorders and floats to determine large scale circulation and property distributions.

This workshop endorsed the following improvement to the document presented at OCEANOBS'09:
• Augmenting the global temperature and salinity observations below 2 km by building a broad-scale full-depth array of floats/gliders/moorings.

• Observing temperature, salinity, velocity, and carbon near formation regions (add AABW locations in Ross Sea and Adelie Land to Weddell Sea monitoring)
• Observing, temperature, salinity, and velocity downstream from these formation sites in Indian and Pacific Oceans and the Southern Ocean Choke points
• Observing the MOC in South Atlantic, Indian and Pacific and Southern Ocean.

An interesting discussion centered on the value of near bottom temperature and salinity observations. These observations would not provide the vertical information need to calculation water column inventory change. However, these near-bottom observations would provide an 'antenna' of deep ocean change and that could be enhanced if combined with models. It was also noted, that in regions of weak stratification - downstream of sills – near-bottom observation could be of considerable benefit in describing variation in the bottom km or so of the ocean.

The workshop also considered the possibility of combining the deep ocean observation array with existing program such that resources – ships, moorings – could be shared. It was suggested that we could link with the Tsunami buoy array, in term of ship coordination, but that we would require a separate mooring located nearby. There was support from JAMSTEC and Australian IMOS for their air-sea flux reference sites to be used in collaboration of a deep ocean observing platform.

Finally, this workshop highlighted that the major change in the deep ocean is in the Southern Ocean and therefore development of a deep ocean observing system must firstly target the Southern Ocean and then expand to other regions.

SAMPLING REQUIREMENTS

The sampling density and geographical distribution contained in the Deep Ocean Observing System community white paper must be viewed with extreme caution. The observing systems depicted in the figures of that white paper are stylized schematics only. The sampling requirements of the proposed observing system were not the product of an exhaustive or comprehensive study based on the scientific goals of a Deep Ocean Observing System. More rigorous design studies should determine the optimal sampling specification of a Deep Ocean Observing System; such studies should include a comprehensive review of the observed spatial and temporal changes and perhaps model simulated changes. From the global observational studies, the Southern Ocean has shown the most significant change and should be the initial focus of any development of a sustained Deep Ocean observing system.

A deep ocean observing system should consider the effectiveness and efficiency of the array given the signals that the array must detect. The design needs to consider:
• Temp difference std. dev. 0.01 – 0.04 °C @ z > 4000 m
• Decorrelation length scale below thermocline (~160 km)
• Decorrelation time scale of below thermocline (~ 30-? Days)
• Lagrangian (more cheaper) vs. Eulerian (fewer expensive) array elements.

TECHNOLOGY REQUIREMENTS

The deep ocean observing system will require improved technology to increase the reliability and cost efficiencies of the system. As proposed at OceanObs09, these advancements include:

- Development of deep floats
- Pilot use of deep gliders
- Improvements in moored systems including sensor, telemetry, and data pods
- Small, stable, low-power biogeochemical sensors

This workshop noted that many of these technology requirements are at a research and development stage in a number of institutions and partnership with private companies. For example, low powered chemical sensors (pH, O_2) are in development; JAMSTEC is working on a 3000-m float with further development to get below 3500 m; US companies and institutions are working on floats to 6000 m. Floats sensors (temperature, salinity, and pressure) are currently available, the most significant technology issue concerns the hull and pump components of the float. However, deep floats may be available in a few years.

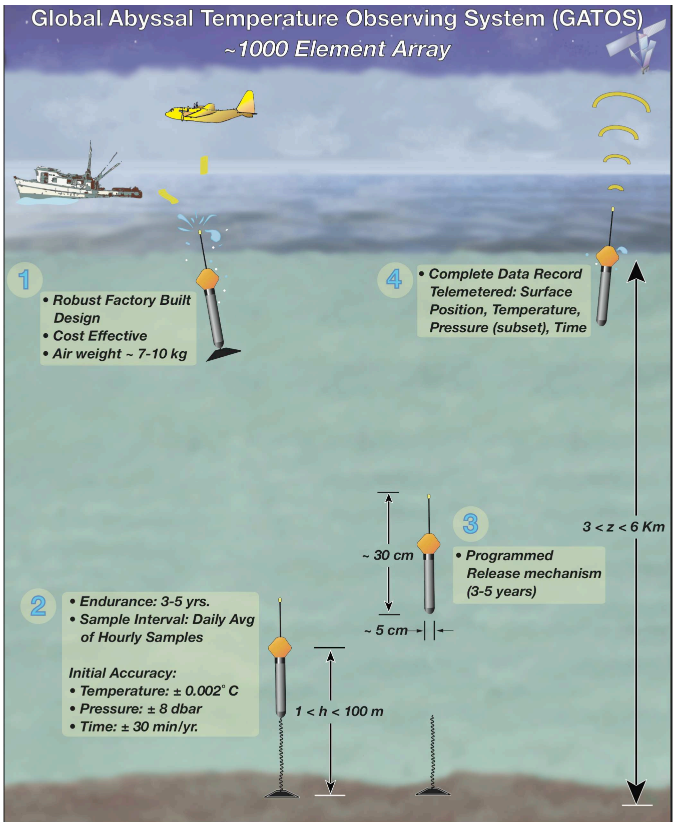
The workshop also suggested we explore the technologies employed by the deep vents community. This technology may be transferable to the deep ocean community particularly in the area of chemical sensors.

There was a brief discussion on improved efficiencies of the ship-based hydrographic program. Slide-down-the-wire rosette systems were mentioned; it was acknowledged that this change would not greatly improve the time taken to complete deep casts, being more directed at removing the noise of ship heave and pitch from CTD measurements. The time constraint of a hydrographic station can be viewed as being limited by the time needed to complete the chemical analyses (CFCs, carbon system parameters, nutrients, and oxygen).

There was a comment that the workshop should make a statement for the need of the US to maintain the current number of their global class vessels.

While improved technology for mooring systems is essential, the workshop focused on technologies that could potentially provide a large scale observing array for the deep ocean, akin to the Argo mission requirement. The instruments able to provide this type of observing system are gliders, floats, and near-bottom moorings. As mentioned deep floats are currently underdevelopment in the US and Japan, these will provide regular full depth profiles of temperature and salinity at various vertical resolution over the entire water column. There would be no post-misson calibration of sensor package without expensive deliberate recoveries, so the calibration process would likely to be similar to that currently undertaken in Argo. Thus repeat hydrographic section data would still be needed to provide the reference regional deep temperature-salinity relationships. Deep gliders provide the ability to follow a particular path (such as repeat hydrography sections), as well as pre and post-mission sensor calibration. However, gliders move slowly and are technically demanding, and (although much cheaper than ships), relatively expensive to operate in comparison to floats.

Gregory Johnson presented a disposable bottom temperature and pressure mooring that is currently in an exploratory development stage at PMEL – Global Abyssal Temperature Observing System (GATOS). The target cost per mooring is few thousand USD.



Target specifications of this system are:
- Moored for 3-5 year mission
- Then rise & telemeter data
- Cheap & feasible
- Only near-bottom values
- Target depths > 4000 m
- 1000-element global array

:

Japanese colleagues (JAMSTEC) were interested in this system and perhaps collaborating PMEL. Japanese engineers are currently working on instrument for a deep ocean observing system but have no dedicated funds at for this work at present.

Appendix A: Workshop Participants

NAME	INSTITUTION, COUNTRY	CONTACT INFORMATION
Alison McDonald	WHOI, USA	amacdonald@whoi.edu
Gregory Johnson	NOAA/PMEL, USA	Gregory.C.Johnson@noaa.gov
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Steve Rintoul	CMAR, Australia	steve.rintoul@csiro.au
Kris Paterson	CMAR, Australia	kristina.paterson@csiro.au
Helen Phillips	IMAS, Australia	H.E.Phillips@utas.edu.au

Appendix B: Workshop Agenda

Deep Ocean Workshop: Observed and Model-Simulated Property Changes in the Deep Ocean of the Southern Hemisphere
21-23 June, 2010 Hobart, Australia

Day 1 Monday 21 June

9:00 Welcome 10 min – Dr Bruce Mapstone, Chief CSIRO Marine and Atmospheric Research (CMAR)
9:10 Logistics and Introduction 20 min – Bernadette Sloyan

09:30 Alison Macdonald, WHOI, USA
Preliminary Results from CLIVAR Repeat at 30^{o}S in the Pacific Ocean
09:50 Esmee Van Wijk, CMAR, Australia
Deep Oxygen Changes Observed from SR3 Hydrographic Sections
10:10 Loic Jullion, NOC, UK
What Controls Variability of Antarctic Bottom Water in the Atlantic?

10:30 MORNING TEA

11.00 Shuhei Masuda, JAMSTEC, Japan
Abyssal Warming Through Rapid Teleconnection Between the Southern Ocean and the North Pacific
11:20 Steve Chiswell, NIWA, New Zealand
Past and Future Observations of the Deep Western Boundary Current off New Zealand

11:40 DISCUSSION: Moderator: Steve Chiswell, Note-taker: Katsuro Katsumata

Observed Ocean change and assessment of their spatial and temporal variability.

12:30 LUNCH

13:30 Nicolas Metzl, Iocean, France
Anthorpogenic CO_2 distribution in the Deep Southern Ocean
13:50 Dorothee Bakker, UEA, UK
Deep carbon inventories and transports in the Atlantic sector of the Southern Ocean – a progress report on UK ANDREX and Oceans 2025 Research
14:10 Mario Hoperma, AWI, Germany
Anthropogenic CO_2 in the Weddell Sea
14:30 John Bullister, PMEL, USA
Using Chlorofluorocarbons to Trace the Propagation of Decadal-Scale Changes in the Deep Ocean
15:00 AFTERNOON TEA

15:30 DISCUSSION Moderator: Bronte Tilbrook, Note-taker: Alison McDonald

Biogeochemical changes measured and inferred from transient tracers.

17:00 END DAY 1

Day 2 Tuesday 22 June

9:00 Daily News/Recap yesterday 10 min

09:10 Brian King, NOC, UK
Deep Water Changes in the North Atlantic at 24°N
09:30 Bernadette Sloyan, CMAR, Australia
Observed Deep Change in the Western Pacific and Climate Model Simulation of Change
09:50 Jo-Ellen Russell, University of Arizona, USA
Deep Water Production in IPCC AR4 Models
10:10 Wilbert Weijer, LANL, USA
Barotropic Variability of the Southern Ocean

10:30 MORNING TEA

11.00 Shinya Kouketsu, JAMSTEC, Japan
Bottom Water Warming in a 4DVAR Assimilation
11:20 Andrew Lenton, CMAR, Australia
The Future Evolution of the Southern Ocean and its Impact on Carbon Uptake

11:40 DISCUSSION Moderator: Dorothee Bakker, Note-taker: Ben Galton-Fenzi

AABW production and variability in models and assimilations and impact on biogeochemical response.

12:30 LUNCH

13:30 Steve Rintoul, CMAR, Australia
Freshening of AABW in the Indian and Pacific Sectors of the Southern Ocean
13:50 Mario Hoppema, AWI, Germany
Warming of the Deep and Bottom Waters in the Weddell Gyre on Decadal Time Scales
14:10 Ben Galton-Fenzi, ACE CRC, Australia
The Influence of Ice-Shelf Water on the Deep Ocean Water Masses
14:30 Simon Marsland, CMAR, Australia
Polynyas, Shelf Water and Deep Overflows in the ACCESS Model

15:00 AFTERNOON TEA

15:30 DISCUSSION Moderator: Simon Marsland, Note-taker: Wilbert Weijer

Assimilation and coupled climate model simulation and improving reliability of future climate impacts of deep ocean change.
Model simulation of observed deep change and what type of observations are needed for assimilation and model verification.
Impact of model defined variables, different mixing schemes and high latitude processes.

17:00 END DAY 2

19:00 Workshop Dinner: Boathouse Restaurant, Cornelian Bay, Hobart. Bus to and from Lenna Hotel and Boathouse Restaurant will be provided.

<u>Day 3 Wednesday 23 June</u>

9:00 Daily News/Recap yesterday 10 min

09:10 Katsuro Katsumata, JAMSTEC, Japan
Box Inverse Model of Southern Hemisphere Circulation in the 2000s
09:30 Trevor McDougall and Paul Barker, CMAR
Tools for the Analysis of Ocean Observations
09:50 Gregory Johnson, PMEL, USA
AABW Warming Between the 1990s and the 2000s
10:10 Sarah Purkey, University of Washington, USA
AABW Warming Contribution to Global Heat and Sea Level Rise Budgets

10:30 MORNING TEA

11:00 DISCUSSION Moderator: Jo-Ellen Russell, Note-taker: Bernadette Sloyan

Synthesis of the deep ocean observed changes and impacts on global climate.
What are magnitudes and spatial distributions of heat, freshwater, carbon change, and circulation pathways determined from changes in temperature, salinity, biogeochemical parameters, and transient tracers?
Establish working groups and develop time lines for submission of manuscripts.

12:30 Lunch

13:30 DISCUSSION: Moderator: Gregory Johnson, Note-taker: Bernadette Sloyan

A Sustained Deep Ocean Observation System.

What are the driving science needs? What are the temporal and spatial sampling requirements for temperature, salinity, biogeochemistry, and tracers? What new technologies are required?

15:00 Wrap-up and meeting close. Bernadette Sloyan

15:15 AFTERNOON TEA

Appendix C: Workshop Announcement

WORKSHOP DETAILS
Date: 21-23 June, 2010
Place: Hobart, CSIRO Marine and Atmospheric Research (CMAR).

Workshop Format
Day 1 and pre-lunch Day 2 will consist of short 15 - 20 minute presentations from workshop participants. These presentations will inform all participants of the individual's current and near-term research directions. These presentations will encompass the physical, chemical, and circulations changes of the Southern Hemisphere deep ocean, including changes in the formation and properties of Antarctic Bottom Water, from observation and models.

Significant discussion time will be allocated after the presentation sessions to allow for cross-cutting discussions among participants.

Afternoon Day 2 and Day 3 will be devoted to forming synthesis teams, then defining and allocating tasks needed to complete synthesis manuscripts.

The final agenda for the meeting will be determined once we have a confirmed list of workshop participants.

FUNDING
CSIRO and the Wealth from Ocean National Research Flagship have provided funds to cover accommodation and per diem for approximately 25 participants.

Cost of travel to and from Hobart will need to be covered by workshop participants. However, to enhance graduate student and junior research scientist involvement, the workshop will provide funds for airfares for approximately 5 leading young scientists. Young scientists applying for travel support should send a CV and letter explaining research interests in deep ocean change to Bernadette Sloyan. The organising committee will consider all requests for travel support and notify successful applicants by 9 April 2010.

To Attend Workshop
Email Bernadette Sloyan (Bernadette.Sloyan@csiro.au) to register as a participant of the workshop, please include the title of your presentation and research interests. Registration will close on 31 March 2010.

Workshop Organizing Committee
Bernadette Sloyan, CMAR
Bronte Tilbrook, CMAR
Gregory Johnson, PMEL
Chris Sabine, PMEL