Weddell Sea Moorings

Bruce A. Huber and Arnold L. Gordon
Lamont-Doherty Earth Observatory of Columbia University, Palisades NY

Table of Contents

1. Abstract 1
2. Project Summary 1
3. Scientific Accomplishments 3
4. Education and Outreach 7
5. Publications and Reports 7
   5.1. Publications by Principal Investigators 7

1. Abstract

The Weddell Sea is a major source of Antarctic Deep and Bottom Waters. Relatively warm, saline Circumpolar Deep Water (CDW) enters the Weddell Gyre to the east of the Greenwich Meridian. As it traverses the gyre, it feeds bottom water-forming processes on the continental shelves, and interacts with floating ice shelves to produce a variety of Weddell Deep and Bottom water types. Because these formation processes include heat exchange with the atmosphere and ice shelves, the properties of the water masses formed carry an imprint of any recent changes in atmospheric and shelf ice characteristics. Three mooring sites in the northwest Weddell Sea maintained by this project sample the integrated properties of deep and bottom water leaving the Weddell Sea. The time series of observations of the lower 500 meters, begun in 1999, reveal surprisingly large variations in bottom water temperatures on interannual as well as annual time scales, which are likely related to interannual variability in the large-scale wind and sea-ice patterns over the key formation regions of the southwest and western Weddell gyre.

2. Project Summary

The world's deep oceans are filled with water masses formed at the continental margins of Antarctica. The Weddell Sea is a major source of these so-called Antarctic Deep and Bottom Waters. Relatively warm, saline Circumpolar Deep Water (CDW) enters the Weddell Gyre to the east of the Greenwich Meridian. As it traverses the gyre, it feeds bottom water-forming processes on the continental shelves, and interacts with floating ice shelves to produce a variety of Weddell Deep and Bottom water types. Because these formation processes include heat exchange with the atmosphere and ice shelves, the properties of the water masses formed carry an imprint of any recent changes in atmospheric and shelf ice characteristics, including temperature, distribution of shelf and sea ice, and shifts in large scale wind stress patterns such as those associated with the Southern Annular Mode (SAM) and ENSO.

This project maintains deep and bottom water focused oceanographic moorings south of the South Orkney Islands in the Northwest Weddell Sea to provide a time series of the combined

outflow (currents and temperature/salinity) of Antarctic Deep and Bottom Water drawn from various sites within the Weddell Sea. The observation sites were selected to monitor the integrated properties of the outflowing deep and bottom waters after they have traversed the key formation sites in the western Weddell Sea.

The moorings were initially installed and maintained as part of the NOAA-funded Consortium on Oceans Role in Climate: AbRupt climate CHangE Studies (CORC-ARCHES) Southern Ocean Modern Observations program. First installed in April 1999, the moorings have been serviced using ship time made available by other polar programs, primarily through the National Science Foundation Office of Polar Programs (OPP), and principal investigators funded by OPP who graciously allow our team to sail on their cruises. As time and resources allow during the mooring maintenance cruises, oceanographic stations to collect profiles of conductivity, temperature and tracers (CTD/tracer) are occupied at the mooring sites and at stations distributed along a line between the mooring locations (Figure 1). The cost of ship time devoted to the mooring work and associated CTD/tracer stations, typically 3 to 5 days, has been supported by funding from OCO.

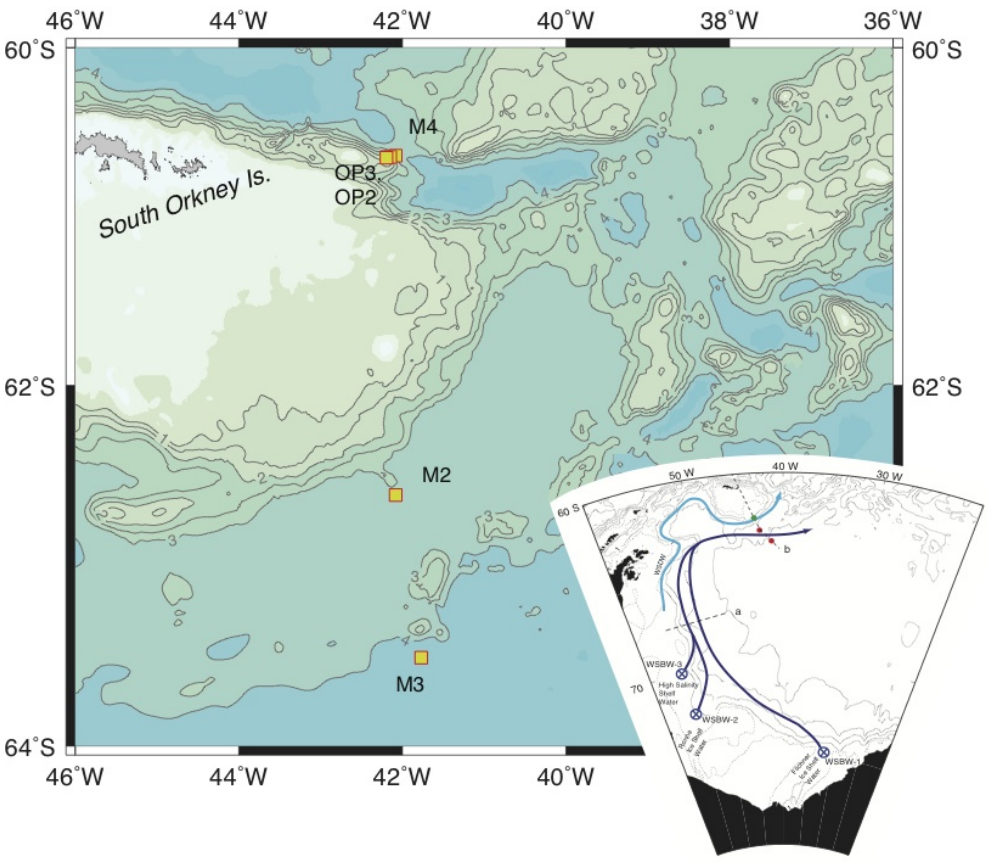


Figure 1. Weddell mooring locations, and schematic of deep and bottom water flow from source regions to the mooring array.

More recently, ship time arrangements have been made with colleagues at the British Antarctic Survey (BAS), under the auspices of an Agreement of Cooperation between Lamont-Doherty Earth Observatory of Columbia University (LDEO) and BAS. The agreement with BAS provides for sharing of equipment, personnel and data between LDEO and BAS to allow the mooring sites to be serviced at nominally two-year intervals, with BAS providing the ship time to do so. Under this agreement, by sharing material resources with BAS, we have been able to expand the mooring array to encompass the Orkney Passage to the east of the Orkney Plateau, a site of potential escape of Weddell Deep Water into the Southern Ocean. Our collaboration with BAS will continue, so this work is part of an international effort.

Data Collection: Frequency and Availability

Because the ship time required for servicing the moorings is made available on an opportunity basis, the moorings are not serviced at regularly scheduled intervals. We plan for a nominal two-year cycle, but the moorings are designed with a lifetime in excess of three years in the event that ship time is unavailable on the 2-year cycle. Moored instrument data and whatever oceanographic profile data we are able to collect are therefore available on a nominal two-year cycle. The moorings are located in regions which are seasonally covered by sea ice, so all data are recorded internally and must be recovered during the service calls. The recovered data are quality controlled, and made available via the web[1], generally within 6 months of their recovery from the moorings. Descriptions of the moorings and metadata are catalogued at OceanSITES (http://www.oceansites.org/).

While we are in transition from the CORC-Arches supported data collection effort to the OCO-funded data collection and distribution, we are distributing the data sets upon request[1]. To date, we have provided the data to K. Heywood (University of East Anglia) in support of their studies of outflow of Weddell waters to the Southern Ocean; to M. Meredith and K. Nicholls of BAS in support of ongoing collaborative research in the western and northwestern Weddell; and to S. Kern (Center for Marine and Atmospheric Science / Institute of Oceanography Center for Marine and Atmospheric Science / Institute of Oceanography/ Hamburg) for a joint study examining the relationship between bottom water characteristics observed at the OCO moorings and the variable extent of the Ronne-Filchner polynya in the southwestern Weddell Sea. And, with the upcoming placement of moorings on the continental shelf and slope adjacent to the Larsen B embayment (as part of the LARISSA project funded by the US National Science Foundation), the OCO mooring data will soon contribute a down-stream reference point for deep and bottom water formation processes observed in the climatically-sensitive Larsen B and C ice shelf regimes.

3. Scientific Accomplishments

Project Deliverables: Recovery and redeployment of the mooring array was the primary goal stated in our FY 2009 work plan. The mooring array was serviced during a cruise on board the

[1] Presently available at http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml and by request to bhuber@ldeo.columbia.edu. The data will be migrated to a new data portal during FY2010 activities.

British Antarctic Survey (BAS) vessel RRS ERNEST SHACKLETON (ES033), sailing from the Falkland Islands on 21 January 2009 and returning 10 March 2009. The data recovered extends the time series at mooring M2 another 2 years. Mooring M4 has been relocated and relabeled OP3, and is now part of a joint LDEO-BAS array spanning the Orkney Passage which will observe changes in the properties of Weddell waters exiting the gyre into the Scotia Sea. This project contributes directly to the observing system's program deliverable:

"Ocean Heat Content and Transport, to better understand the extent to which the ocean sequesters heat; to identify where heat enters the ocean and where it emerges to interact with the atmosphere; and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change".

Observations of the properties of deep and bottom waters exiting the Weddell Sea are an essential component of efforts to understand the links among atmosphere, sea-ice, ice shelves and deep water formation processes which contribute to the southern ocean thermohaline circulation and its variability.

During cruise ES033, moorings M2 and M4 (now identified as OP3) were recovered. M3 unfortunately could not be recovered. Neither of the paired acoustic releases on M3 responded to commands, so we presume the mooring was lost, most likely due to failure of one or more flotation bundles shortly after deployment during the 2007 cruise. This mode of failure has been experienced twice before. The first occurred during the attempted deployment of M2 in 2006, when an imploding float bundle triggered one of the paired releases and the mooring returned to the surface while we were still on site conducting a CTD station. The second implosion occurred on mooring M2 sometime during the 2007-2009 deployment. The mooring was recovered intact, but one float bundle had imploded, causing the failure of its neighboring float package. Both times, the failing buoyancy modules were McLane Research Laboratories triangular glass float packages, model G6600-2. Both had been previously deployed. We are in the process of replacing all of our McLane flotation with Benthos 17" glass sphere flotation. In addition, the two releases lost on M3 had been in service since 1999, and were slated for replacement during ES033.

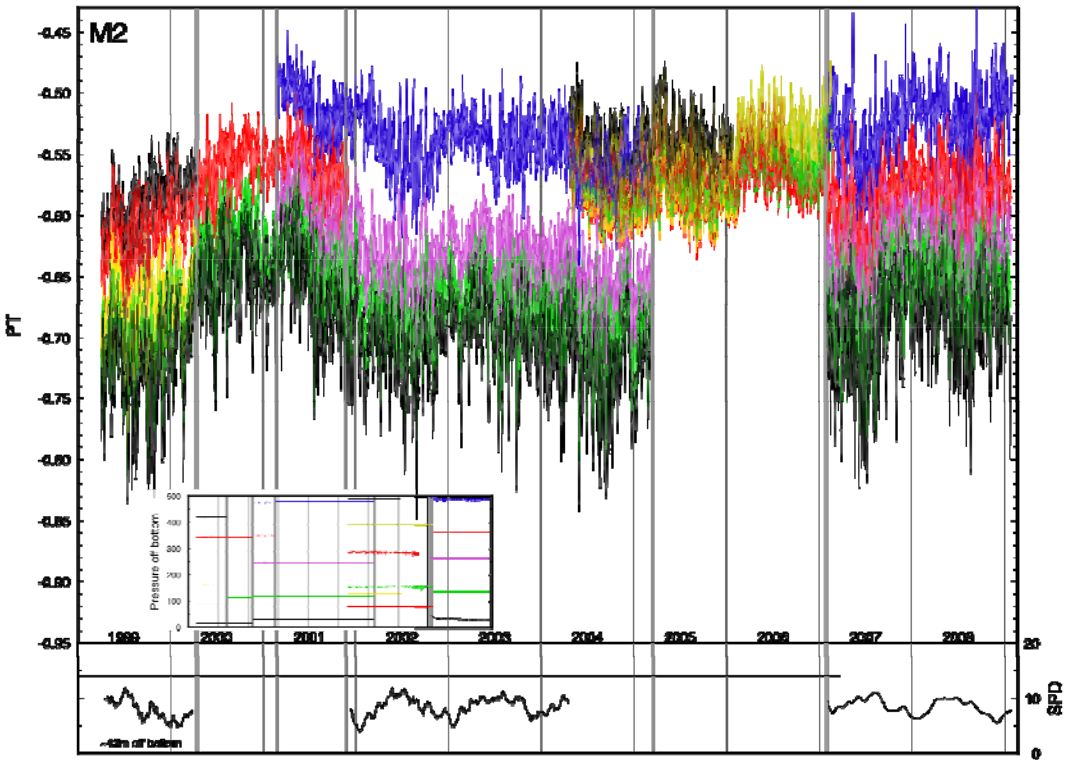
Mooring M3 was replaced with a full suite of instruments, and a mix of spare flotation and floats borrowed from other groups on board the vessel. We do not yet have enough instruments and mooring gear to sail with complete backup, so mooring M2 was redeployed in a reduced configuration, with only a single release, and instruments in the lower 250 m instead of the usual 500 m instrument string. Mooring OP3 was redeployed with the BAS Orkney Passage array.

Mooring work was accompanied by more than 200 Conductivity/ Temperature/ Depth/ profiles (CTD) including a high-resolution section across the Orkney Passage. As SHACKLETON is not a research vessel, the CTD system had to remain on deck throughout the cruise, unprotected from the weather. This resulted in large offsets in measure salinity. These will require additional effort to correct, using salinities derived from water samples collected during the cast. Thus, the data are not yet available.

Results of a preliminary analysis of the time-series data collected through 2007 were presented at the Fall AGU meeting in 2008 (see Publications and Reports below for details). These results are summarized as follows:

An 8 year record (April 1999 to February 2007) of the currents and T/S stratification within the lower ~500 m of the water column, within the outflow of dense Weddell Sea Bottom Water south of the South Orkney Islands, reveals strong T/S seasonal and interannual variability. A cold bottom water pulse is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002. (Figure 2).

At bottom temperatures <-0.8°C the salinity variability makes for a 'fan-like' appearance in T/S space suggesting a varied source of dense shelf water, with the coldest bottom water associated with the saltiest water, indicating a southwest Weddell Sea origin (Figure 3). In consideration of the isobath following distance from likely source to the mooring array, at typical bottom speed of 10-15 cm/sec, we determine that the export of the dense shelf water occurs during the austral summer (as also observed in the Ross Sea). Relationship of the behavior of the shelf water export to the strength of the Weddell Gyre and to SAM is proposed.



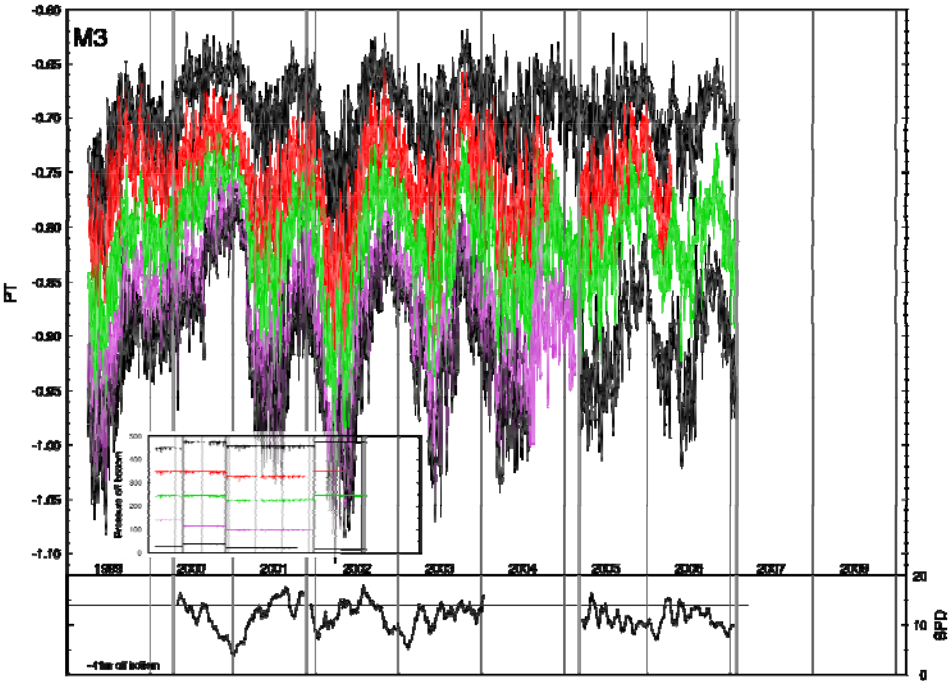
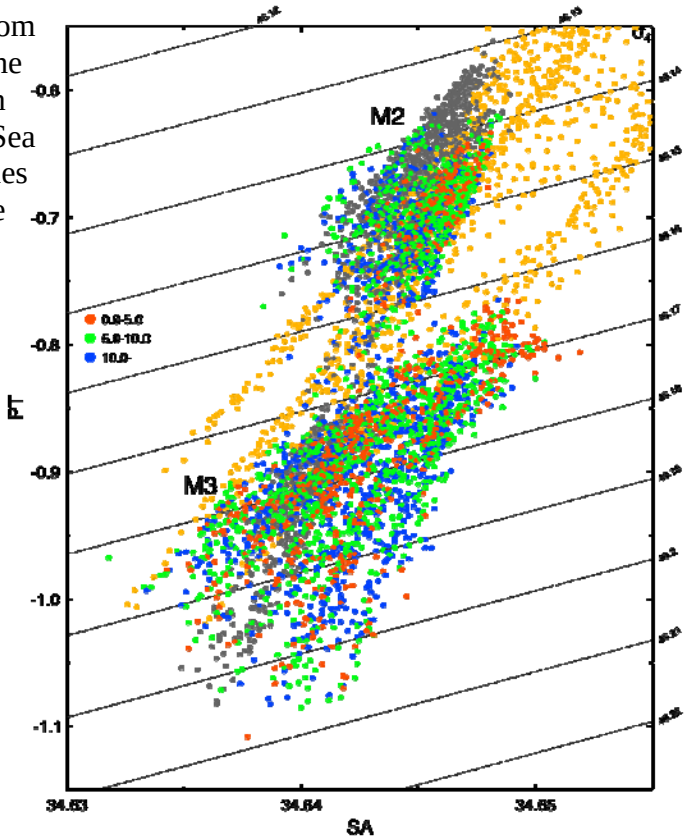


Figure 2. Time series of potential temperature, 1999 to 2009, from moorings M2/M4 (top) and M3 (bottom). Data from M4 is used to span the gap in the M2 data between 2005 and 2007. M3 was not recovered in 2009.

Figure 3. Potential Temperature-Salinity data from M2 and M3, color coded for current speed at the bottom. The coldest bottom water is associated with the saltiest water, indicating a southwest Weddell Sea origin. Using an average speed of 10 cm/s implies bottom water escape from the continent shelf of the southwest Weddell in October.



These preliminary findings can be encapsulated in the following points:

- The export of dense shelf water from the southwestern Weddell Sea varies seasonally and exhibits interannual fluctuations.
- A cold bottom water pulse is evident in the May-July period. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent, with slow warming since 2002.
- Southern Annular Mode [SAM] index leads the bottom water temperature features by 14-20 months. The relationship of the export of Weddell Sea Bottom Water to climate [SAM] variability is likely linked to combination production and escape rates of dense shelf water over the multiyear residence time of the shelf water.

4. Education and Outreach

We have a Columbia University undergraduate (D. McKee) engaged as a work-study student exploring the relationships between the interannual variability observed at the M2 and M3 sites, and indices of climate variability such as the Southern Annular Mode, ENSO, and direct estimates of wind stress variability over the bottom water formation sites. Mr. McKee has prepared a poster presentation on the preliminary results of our analyses for presentation at the July MOCA '09 meeting in Montreal. Mr. McKee continues to work with us in incorporating newly collected data into the analyses, and he is preparing a paper for publication planned for early 2010. His Senior Thesis will be based on his work with this project.

5. Publications and Reports

5.1. Publications by Principal Investigators

Meredith, M. P., A. C. N. Garabato, A. L. Gordon, and G. C. Johnson, 2008: Evolution of the Deep and Bottom Waters of the Scotia Sea, Southern Ocean, during 1995-2005. J. Climate, 21, 3327-3343.

A preliminary analysis of the time-series data collected through 2007 was presented at the 2008 Fall AGU meeting:

Eight Year time series of the outflow of Weddell Sea Bottom water

Arnold L. Gordon, Bruce A. Huber, Darren McKee, Xiaojun Yuan

Lamont-Doherty Earth Observatory of Columbia University

We present a nearly 8 year record [April 1999 to February 2007] of the currents and thermohaline stratification within the lower ~500 m of the water column at a mooring (M3) at 4565 m depth, south of the South Orkney Islands, positioned within the outflow of dense Weddell AABW. The time series reveals significant seasonal and interannual variability. A pulse of the coldest bottom water is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent. At bottom temperatures <-0.8°C the salinity fluctuations produce a 'fan-like' appearance in T/S space suggesting a varied source of dense shelf water. The coldest bottom water <-1.0°C is relatively salty indicating a source in the southwest Weddell Sea, about 1300 km along isobaths to the mooring site. The typical bottom speed at M3 of 10-15 cm/sec implies a shelf water export time during the austral summer. A record at a second mooring (M2) at 3059 m depth displays a much reduced annual cycle, but it too records a relatively warm period in 2000. Correlations of the

M3 time series with NINO3.4 and SAM suggest that these indices lead M3 on the order of 14-20 months, implying a likely relationship between the water mass and surface forcing. Both M3 and M2 were reinstalled in March 2007.

An oral presentation was prepared for the July MOCA ’09 Montreal meeting entitled “Seasonal and Interannual Fluctuations of Weddell Sea Bottom Water” by A. Gordon and B. Huber.

A poster presentation for MOCA ’09 was prepared as well: *“Climate Forcing of Interannual Variability of Weddell Sea Bottom Water”* by D. McKee, X. Yuan, A. Gordon, B. Huber.