Weddell Sea Moorings

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1. 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 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 NOAA.

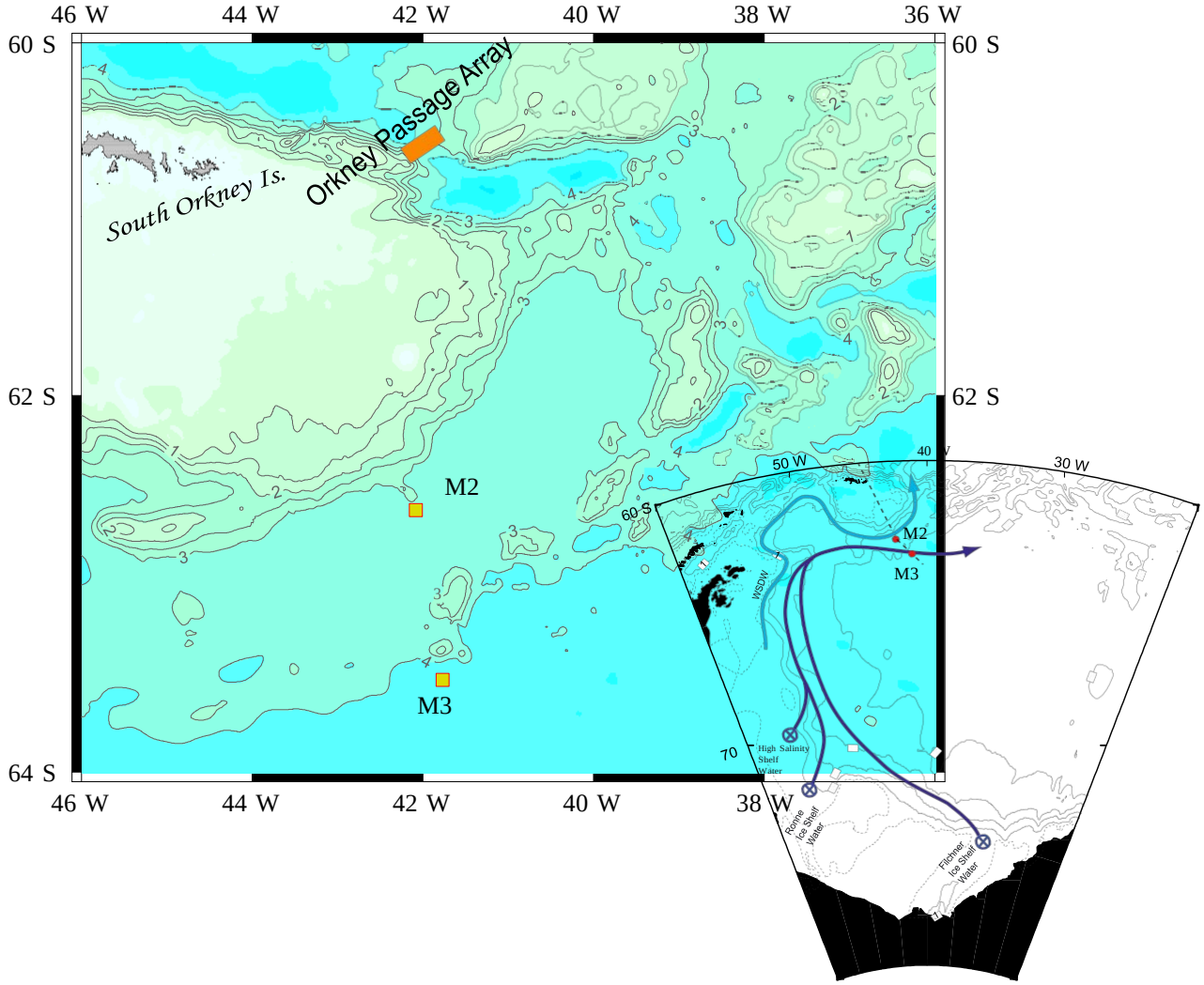

Figure 1. Weddell mooring locations, and schematic of deep and bottom water flow from source regions to the mooring array.

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 remains part of an international effort.

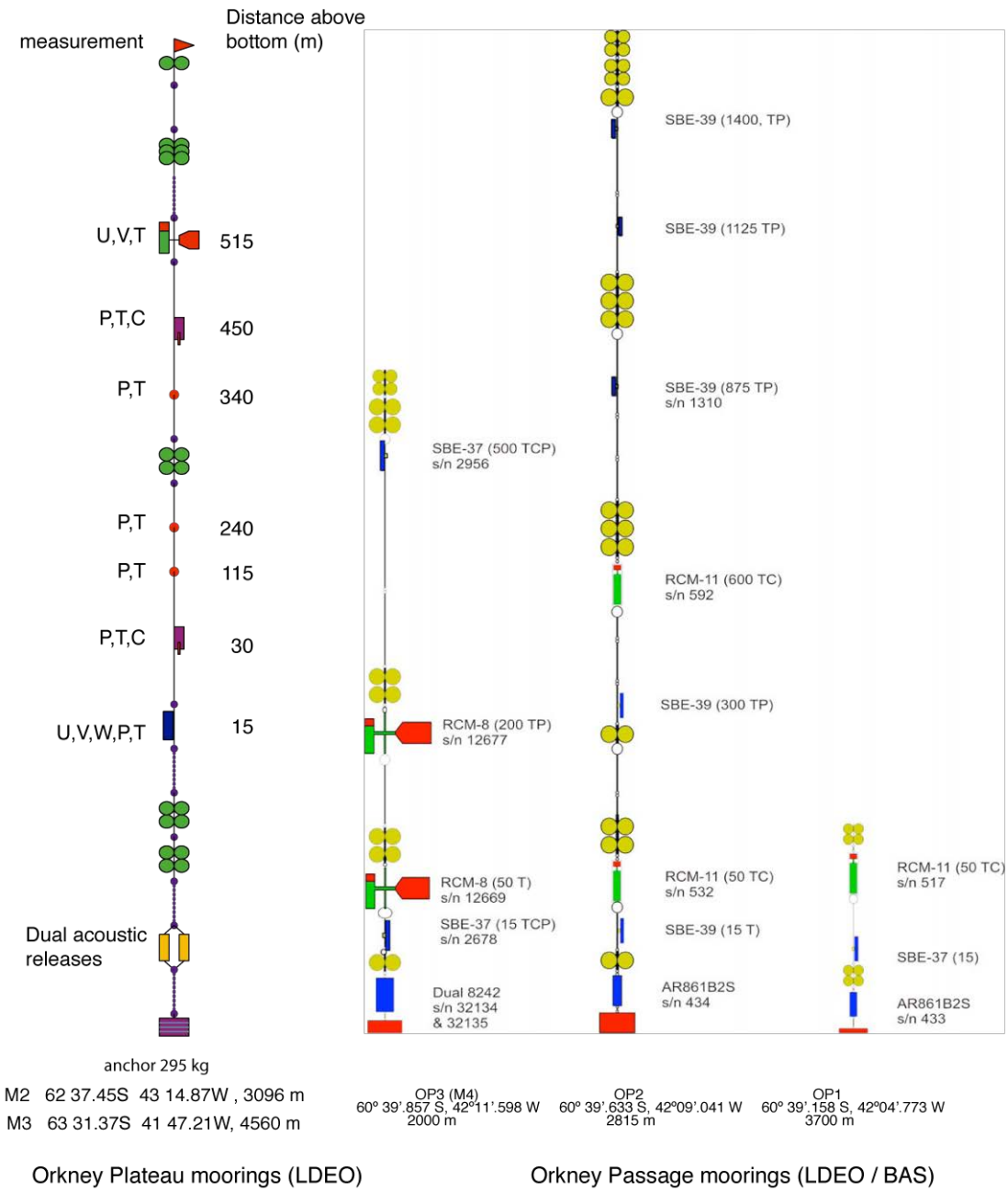

Figure 2. Weddell mooring configurations and positions. RCM current meters are being replaced with acoustic current meters as budget allows. New temperature and temperature/salinity recorders are purchased in off-field years and phased into the mooring array to allow for return and recalibration of older units.

<u>Data Collection: Frequency and Availability</u>

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 that 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 (http://www.ldeo.columbia.edu/res/div/ocp/corc-arches/data.shtml) generally within 12 months of their recovery from the moorings. Descriptions of the moorings and metadata are catalogued at OceanSITES (http://www.oceansites.org/). We are currently awaiting assignment of OceanSITES platform IDs for the moorings.

We have provided the data to many investigators and groups, summarized in Table 1. With the placement of moorings on the continental shelf and slope adjacent to the Larsen B embayment planned for early 2012 (as part of the LARISSA project funded by the US National Science Foundation), the Climate Observation Division Weddell 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.

Investigator	Affiliation	Data Application
K. Heywood	U. East Anglia	S. Ocean Meridional Overturning Circulation (SOMOC)
M. Meredith K. Nicholls	British Antarctic Survey British Antarctic Survey	Outflow of Weddell Deep and Bottom Waters to the Scotia Sea; SOMOC
S. Kern	CMAS/IOC/Inst. of Oceanography Hamburg	Impact of variations in the Ronne-Filchner polynya on bottom water characteristics
R. Kerr (student)	Laboratório de Estudos dos Oceanos e Clima Instituto de Oceanografia – FURG Brazil	Modeling the transport of Weddell Deep and Bottom waters
R. Robertson	School of Physical, Environmental, and Mathematical Sciences, Australian Defense Force Academy	Teaching; research on mixing and tides on continental shelves and slopes of Antarctica
B. Sloyan	CSIRO Marine and Atmospheric Research, Hobart, Tasmania	Assessment of CCSM4 climate model AABW formation

Table 1. Weddell Sea Moorings data distributions

2. Scientific and Observing System Accomplishments

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. 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".

Deliverables specified for this reporting period were:

- recover and redeploy the moorings at the South Orkney sites.
- continue to apply quality control to the data recovered from the moorings in early 2009, begin processing and qc on newly recovered data, and to make the entire data set collected to date available via a web portal currently under construction.
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Deliverables:

Field work

The Weddell Sea and Orkney Passage moorings were serviced in March 2011 during cruise JR252 on the BAS vessel RRS James Clark Ross. Mooring M3 was successfully recovered and redeployed. Mooring M2 was not recovered, but a replacement mooring was redeployed at the same location. The three Orkney Passage moorings were recovered and replaced with a new network of 5 moorings with higher spatial resolution across the Orkney Passage.

The failure of mooring M2 was attributed to a mechanical failure of the single release mechanism on the mooring. This release was more than ten years old and was slated for replacement. We hope to accelerate the hardware replacement schedule should additional funding become available in future years.

Data analysis, presentation and publication of results

We had three manuscripts published spanning this and the previous reporting periods. Details are provided in section 3. Highlights of the published analyses are presented below.

Antarctic Bottom Water (AABW) is approximately 70% more voluminous in the global abyssal ocean than North Atlantic Deep Water (NADW), covering more than twice the sea floor area than NADW. Observations within the Southern Ocean's Pacific sector reveal a decadal trend of decreasing salinity by increased glacial melt water, which if continued might be expected to reduce the formation rate of bottom water. Trends in the Weddell Sea are less clear, and the data set available to examine trends is limited.

The cyclonic flowing Weddell Gyre is the dominant circulation feature south of the Antarctic Circumpolar Current in the Southern Ocean's Atlantic sector. Relatively warm circumpolar deep water enters the Weddell Gyre east of the Greenwich Meridian, cooling as it proceeds westward

within the coastal current forming the gyre's poleward limb. Eventually reaching the southwestern Weddell Sea and the eastern margins of Antarctic Peninsula, it spreads onto the continental shelf. Sea-air-ice exchange over the shelf forms dense, freezing point, high salinity shelf water (HSSW). The dense shelf water is exported across the outer edge of the shelf, producing Weddell Sea Bottom Water (WSBW). The WSBW thus formed mixes with overlying water in the Weddell basin before escaping the gyre to contribute to AABW in the abyssal Southern Ocean.

Understanding the formation of AABW and observing the variability in the processes responsible for its formation motivate the continuation of the time series observations at the Orkney Plateau and Orkney Passage mooring sites.

Highlights of data delivery and analyses

With the recovery of mooring M3 and the 3 Orkney Passage moorings, the Weddell time series has been extended another 2 years. The Orkney Plateau time series is now 11 years long.

The data are presently available at the project web site 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 FY2011-12 activities.

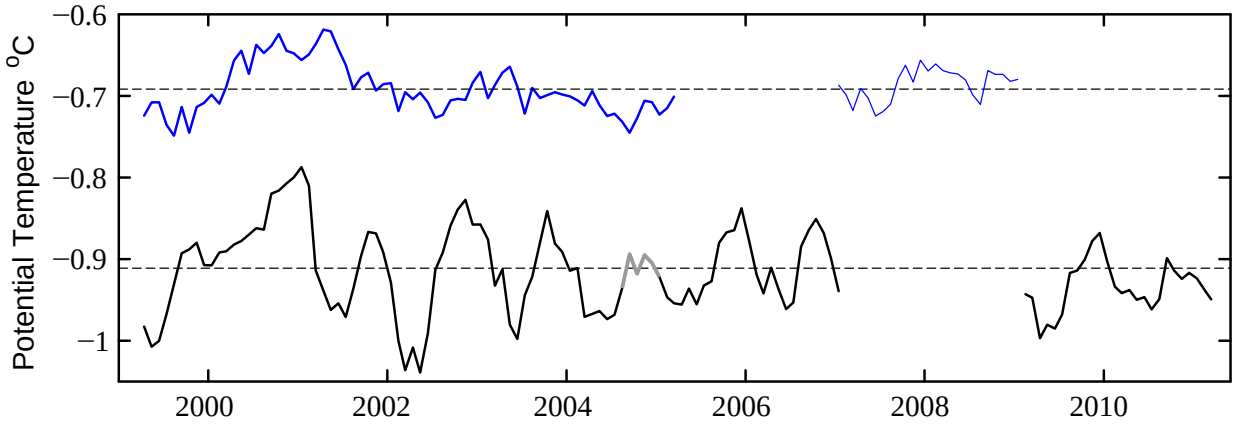

Figure 3. Time series of potential temperature at the bottom-most sensors on M2 and M3. The data from M3 2009-2011 is from the most recently recovered data set. Mooring M3 was not recoverable in 2009; M2 was not recoverable in 2011 and was not deployed in 2005 owing to combined poor weather and failure of a flotation module which caused unscheduled resurfacing of the mooring an hour after deployment.

- Deep and bottom water properties exiting the Weddell Gyre are found to exhibit significant annual cycles, the timing of which varies from year to year (Figure 4).

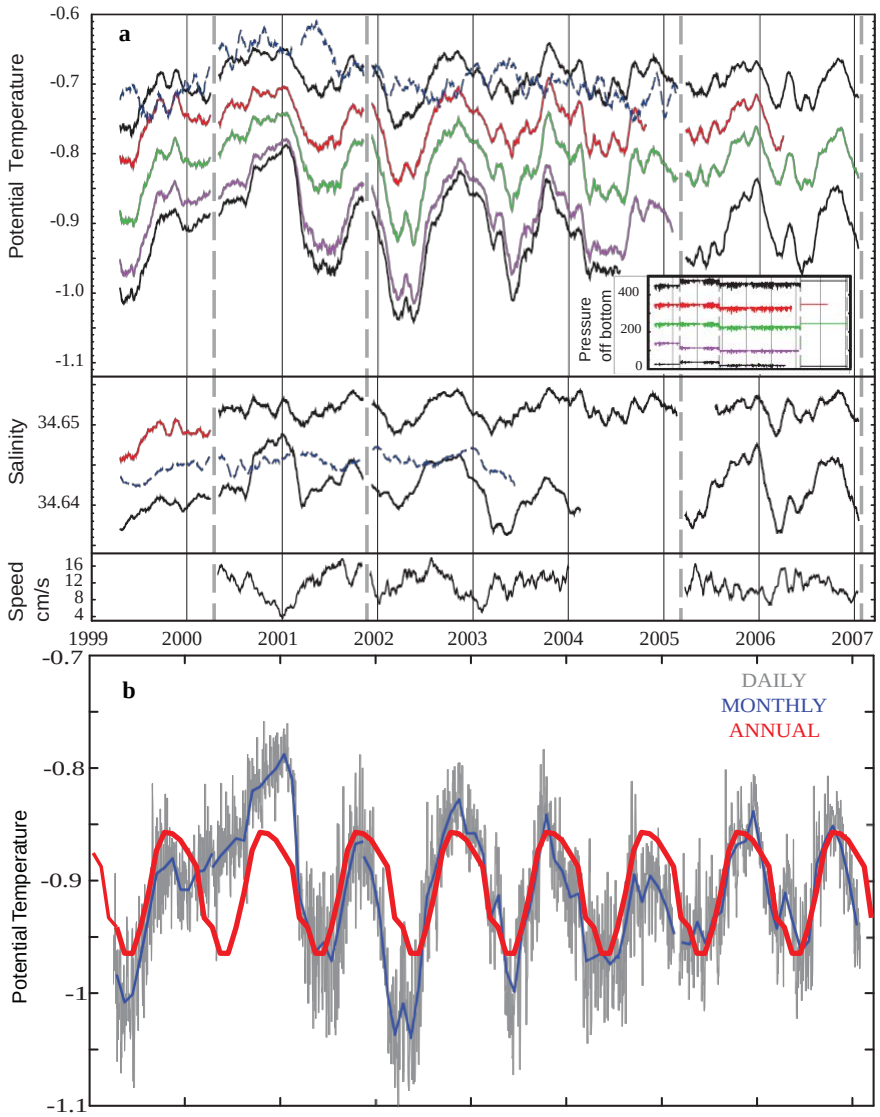

Figure 4 a-b 8-year time series at M2 and M3. 30-day running mean potential temperature, salinity and bottom speed time series at M2 and M3 (a). M3 temperature and salinity are color coded by distance from the sea floor as shown in the insert in a. M2 potential temperature and salinity time series 15 m distance from the sea floor, are shown as a dashed blue line. The vertical dashed gray lines denote mooring recovery/re-deployment times. b, the M3 bottom potential temperature daily (gray line), the monthly (blue line) and the mean seasonal cycle (red line). The 2004 gap in M3 bottom temperature is filled with data from the instrument at 4447 m, offset by the mean difference between it and the bottom temp record (-0.027°C).

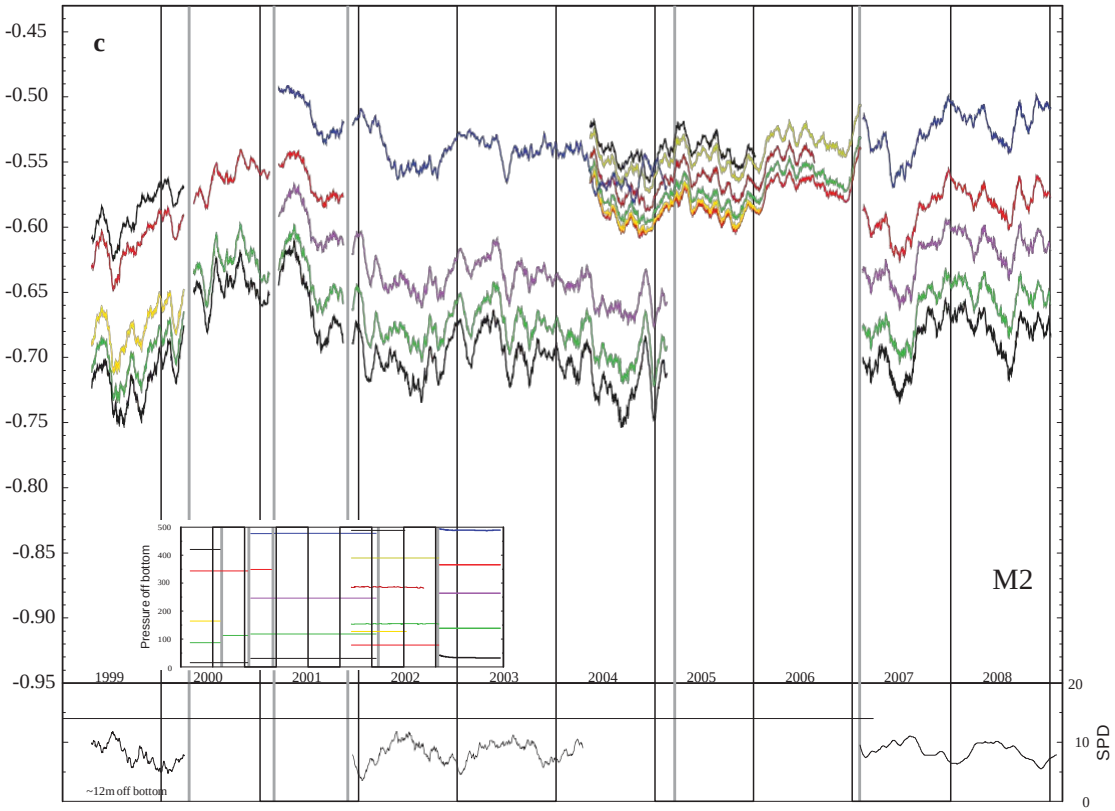

Figure 4c. Time series at mooring M2 including most recently collected data recovered in 2009. The gap 2004-2007 is overplotted with observations obtained at the Orkney Passage mooring M4 (redeployed in 2007 as OP3). M2 was unrecoverable in 2011. Note the near absence of seasonal signals, while the interannual variability is apparent, especially warming from 1999 to 2000, coinciding with the absence of a seasonal cold event at M3.

- In addition to the annual signal, interannual variability is exhibited which can be tied to processes in the southwest Weddell Sea. (Fig 5; Gordon, et al., 2010)
- The interannual variability is correlated with climate indices such as ENSO and SAM through their influence on wind patterns in the deep and bottom water formation regions of the southwest Weddell Sea. (Fig 6; McKee, et al., 2011)

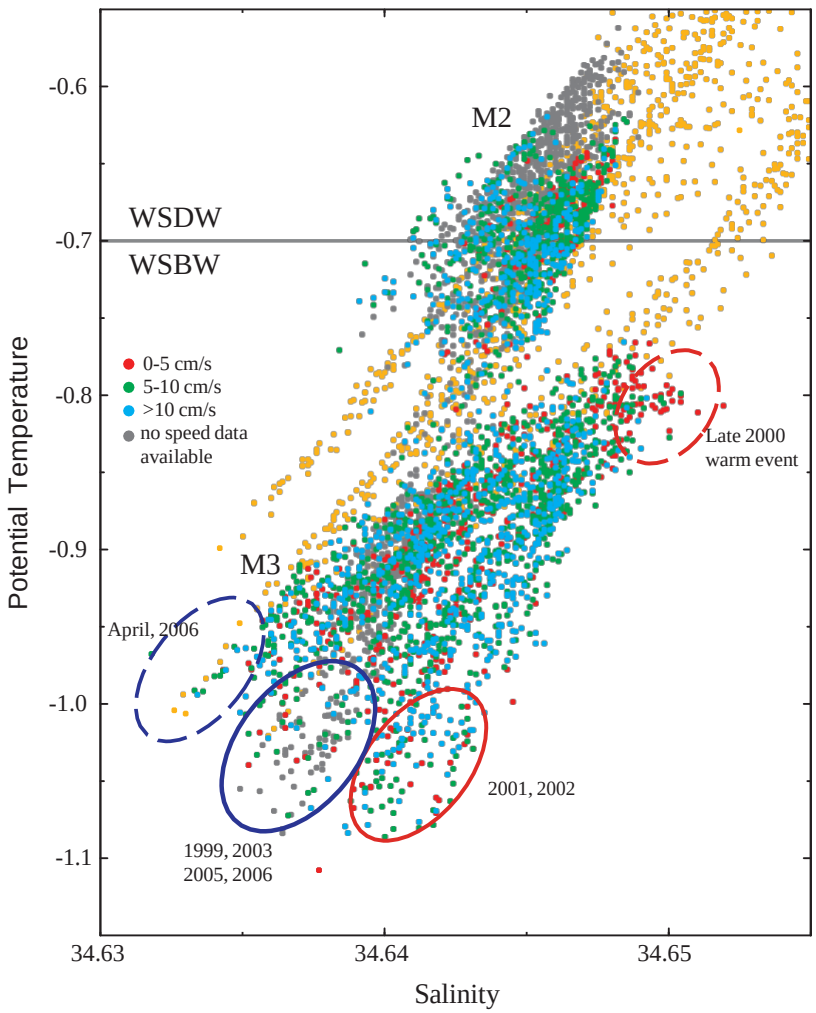

Figure 5. Potential temperature and salinity at the sea floor from M2 and M3, April 1999 to February 2007, color-coded for bottom speed [cm/sec]. The yellow dots are from the 1997 section shown in Fig. 1. The θ/S location of the cold and warm phases of the seasonal cycle for each year is identified. The bottom salinity also reveals interannual changes, with relatively salty bottom water observed in 2001 and 2002. The salinity variability at M3 forms a 'fan-like' distribution, suggesting a variable source of the shelf water end-member. The θ/S characteristics indicate a Ronne Ice Shelf HSSW origin, with the lower salinity WSBW derived from the shelf further north along the eastern margins of Antarctic Peninsula, probably associated with the Larsen ice shelves.

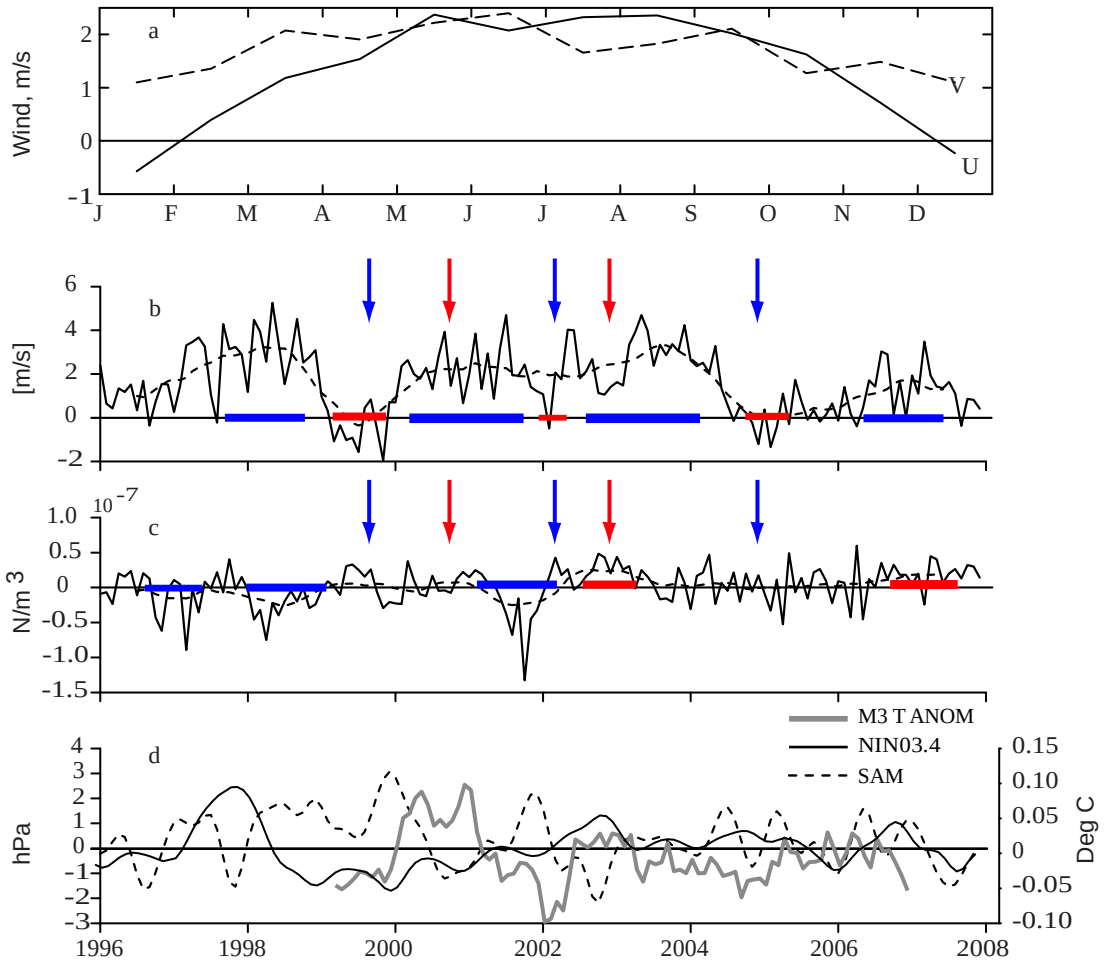

Figure 6. a) NCEP−DOE Reanalysis Climatology, 1996−2008 in 67°S to 76°S; 45°W-62°W
b) spatially averaged meridional wind speed, within the solid red domain indicated in Figure 2 map. The blue arrows mark the time of anomalous cold bottom water at M3; a red arrow marks the anomalously warm period of 2000 and a second red arrow marks a weaker warm anomaly in 2002. The blue lines denote periods of sustained strong northward winds; the red lines denote periods of near zero or reversals in the meridional winds.
c) wind stress curl anomaly within the dashed red domain indicated in the Figure 2 map. The red lines denote periods of reduced wind stress curl, and by inference diminished Weddell Gyre; while the blue lines are periods of increased wind stress curl and gyre intensity. Arrows the same as in b.
d) SAM index (dashed line), M3 bottom temperature anomaly (gray solid line) and NINO3.4 index (dotted line). The left vertical axis corresponds to the SAM index while the right vertical axis corresponds to the M3 bottom temperature anomaly. The temperature variability in NINO3.4 is scaled so as to fit on the temperature axis though it actually varies from -1.67 to 2.65 deg C.

- The Orkney Plateau time series and an overlapping time series recorded within the outflow of AABW from the Weddell Sea indicate that increased outflow temperatures are synchronous with stronger boundary current flows. These changes occur rapidly in response to changes in wind forcing. The observed synchronicity indicates that the previously detected weakening of the export of the colder forms of AABW from the Weddell Sea need not be associated with a reduction in the total flux of AABW exported via this route (Meredith, et al. 2011)

For projects involved with data collection, please address the following five questions:

a. Are your data distributed in real time on the Global Telecommunications System?
No – The moorings are covered by sea ice part of the year which so far precludes real time transmission. The data are recorded internally and must be recovered for distribution.

b. Where do your real time data reside? Are the data available online?
N/A data are delayed mode only

c. Where do your delayed mode data reside? Are the data available online? What is the date of the most recent data available publicly?

The data are available from the project web site :
http://www.ldeo.columbia.edu/res/div/ocp/corc-arches/data.shtml
The time span of the most recent publically available data via the web site is 1999 – 2007. Preliminary data for the period 2007-2009 is available upon request to the PI by email to bhbuer@ldeo.columbia.edu.

d. Where are your data archived and with what frequency?
The data are archived on secure storage at Columbia University/LDEO in all forms as soon as they are recovered from the moorings. We are working with OceanSITES for archival in OceanSITES netcdf format and are currently awaiting the assignment of platform IDs to complete the process.

e. What is the web site where the data for your program can be accessed?
The data are available from the project web site :
http://www.ldeo.columbia.edu/res/div/ocp/corc-arches/data.shtml

f. Have you successfully retrieved your program's data from the website or Data Assembly Center where your data reside, just to ensure the accessibility of the data?
Yes – every 6 months

2.1. Outreach and Education

Undergraduate/Graduate education

1. We have a former Columbia University undergraduate (D. McKee) continuing his engagement in 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 is first author on a publication on this topic (see section 3.). Mr. McKee anticipates continuing his education in climate studies as a graduate student

2. In June 2011, we hosted a visit of 14 undergraduate students from The City College of the City University of New York (CCNY). These students, enrolled in a summer Biological Oceanography course at CCNY (3 credits), spent 5 hours at LDEO meeting with and attending informal lectures by 5 researchers on a variety of topics, including the NOAA-funded research in the Weddell Sea. CCNY is the oldest 4 year public college in the United States, and is recognized as a Minority Institution under Federal Guidelines.

Public Outreach

Lamont-Doherty Earth Observatory hosts an annual Open House which draws between 2000 and 3000 visitors from the metropolitan New York region. Visitors are encouraged to stroll the Observatory grounds, visiting hands-on earth science exhibits, lectures and demonstrations. Our NOAA-funded research is prominently highlighted during the Open House.

3. Publications and Reports

3.1. Publications by Principal Investigators

McKee, D. C., X. Yuan, A. L. Gordon, B. A. Huber, and Z. Dong, 2011: Climate impact on interannual variability of Weddell Sea Bottom Water. *J. Geophys. Res.*, **116**.

Meredith, M. P., A. L. Gordon, A. C. Naveira Garabato, E. P. Abrahamsen, B. A. Huber, L. Jullion, and H. J. Venables, 2011: Synchronous intensification and warming of Antarctic Bottom Water outflow from the Weddell Gyre. *Geophys. Res. Let.*, **38**.

3.2. Other Relevant Publications

Published during the preceding reporting period but cited above:

Gordon, A. L., B. Huber, D. McKee, and M. Visbeck, 2010: A seasonal cycle in the export of bottom water from the Weddell Sea. *Nature Geosci*, **3,** 551-556.