CORC-ARCHES Southern Ocean Modern Observations

Summary

The Southern Ocean is a site of considerable water mass transformation which cools and ventilates the modern world ocean. At the polar frontal zone, formation of cold, low-salinity water sinks and spreads northward at intermediate depths. Within the seasonal sea ice zone and along the margins of Antarctica, convection injects very cold oxygenated water into the deep ocean. Of all regions within the Southern Ocean the Weddell Gyre is the largest cyclonic gyre, covering with its western part the Weddell Sea. Vigorous vertical fluxes of heat and moisture in the presence of a variable sea-ice cover couple Weddell Sea waters with the cold polar atmosphere, making the Weddell Gyre a prime source of Antarctic Bottom Water (AABW).

A suite of instrumented moorings and repeated CTD/Tracer stations were initiated in 1999 to record the characteristics of the deep and bottom water exiting the Weddell Sea just south of the South Orkney Islands. Since the Weddell Sea is a major source of deep water, changes in the outflowing deep and bottom waters formed there will in turn affect the global circulation.

1 Background

A major role of the ocean in the climate system is its ability to store heat and transport it over large distances before it is released to the atmosphere. The most powerful ocean transport mechanism is associated with its density driven overturning circulation, which is also referred to as the thermohaline circulation (THC). To first order the THC is a result of the meridional density (temperature) difference between the polar and tropical regions modified by internal mixing. In today's climate the THC consists of two large cells with sinking in the Southern Ocean and in the North Atlantic/Nordic Seas/Arctic Ocean system. Easier access to the North Atlantic Ocean has resulted in a much better understanding of the northern branch of the THC; the Southern Ocean’s role is less well documented.

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There are three processes by which this water forms:

Near shore convection:

Along the southern and western rim of the Weddell Sea convection driven by cooling and brine rejection during sea ice formation forms very cold and dense water that accumulates on the shelves and then flows into the deep Weddell Basin. In the southern and western Weddell Gyre newly formed bottom water is found in a thin (<300m), highly oxygenated benthic layer of low salinity overlying a high-salinity component south of 66 S. This benthic layer also has a high anthropogenic tracer signal and tracer-derived ages indicate it has resided on the continental shelf for about 6 years before flowing down the slope. Further to the north additional inflow from the continental margin and enhanced mixing produce the final properties of AABW.

Open ocean convection:

The seasonal ice cover in the Weddell gyre has shown dramatic variability with the occurrence of a large open ocean Polynya during 1973-1976. Presumably this was the surface manifestation of localized, deep open ocean convection as suggested by observations and related modeling studies. Currently, the water mass transformation seems to be primarily of a coastal mode, without large regions of open water being observed during the winter ice season in the Weddell Gyre. It appears that in the Weddell Sea, the air-sea-ice system is in a delicate balance between two quasi-stable modes that display substantially different sea ice distributions and deep water formation processes.

Ice shelf interaction.

A third process of water mass transformation involves melting of glacial ice within ice shelf cavities. Water residing on the continental shelf flows into the ice cavity at the bottom and melts the glacial ice from below. The resulting density decrease drives a meridional circulation within the ice cavity, which enhances the basal melting process. When the water exits the cavity, it is fresher, but also colder and forms the densest water that flows off the shelf into the deep Weddell Sea. Such flow from beneath the Filchner Ice Shelf and down the continental slope has been observed by hydrographic and current meter measurements. Isotopic signals imprinted during this process can be used to trace glacial melt water injected into the deep Weddell Sea and other regions around Antarctica by this process. It is believed that in a warming climate this basal ice melt process might lead to a retreat of the ice shelves.

The Southern Ocean in general and the Weddell Gyre in particular are regions of vigorous air-sea-ice interaction and water mass transformation. The few observations we have indicate a rich spectrum of variability of potentially large and global consequences. The processes involved are believed to be quite sensitive to small changes in the forcing and have the potential to amplify changes in the climate forcing due to dramatic ice-ocean feedback. However, the precise mechanisms of climate variability in the Southern Ocean are not well understood, nor adequately observed largely due to the difficulty in obtaining the appropriate observational data sets. Coupled models of the ocean-atmosphere-ice system do not perform well in the Southern Ocean region. Fundamental processes of water mass transformation, such as coastal shelf water formation and overflows are often poorly resolved or absent in the current generation of climate models. The stability and variability of the different deep water formation processes is poorly understood but might turn out to be crucial for the global climate system.

2 Project Description

From an observational perspective the Southern Ocean poses a significant challenge to instrumental ocean observations. First of all, portions of the basins are permanently ice covered making them difficult to access. Moreover, an enormous fraction of the Antarctic Sector is seasonally ice covered which significantly restricts the utility of standard measurement tools. It is currently not possible to make use of autonomous Lagrangian floats as a relatively inexpensive platform to obtain ocean observations because they are not able to detect the presence of sea-ice cover when surfacing. Moorings can not have surface expressions during the winter and large ice bergs limit the depth of the uppermost sensors to a minimum of 150-200m. The absence of commercial shipping activity (that can provide a platform for atmospheric and oceanographic sampling programs) has limited the data base for quantifying the air-sea-ice interaction processes and documenting their change with time. We are currently sampling the Southern Ocean (with research ships) at a frequency that is inadequate to resolve oceanic changes caused by intense monthly and seasonal variability.

The sparse historical data set makes it hard to define a climatology or mean annual cycle which then could be used as a baseline to detect climate variability as done successfully in other regions of the worlds ocean. We have only rough estimates of the current water mass transformation rates for the Southern Ocean and only a poor knowledge about their variability. The poleward heat and freshwater transports in the Southern Ocean are quite uncertain because direct observations are not adequate and the indirect methods (by using the integral air-ice-sea interaction over the basin) are uncertain because of the presence of sea ice. We can not trust heat and fresh water fluxes from numerical weather forecast models since they typically perform poorly in the Southern Ocean. Only a few stations exist which obtain real time data to initialize those models. However, we expect significant improvement during the next decade with increasing amounts of space borne remote sensing data.

Large regions of the Southern Ocean have not been sampled at all. This is particularly true for heavily ice-covered regions over the continental shelves in the Weddell Sea and at other locations around Antarctica where dense water can form. Therefore, a significant fraction of Southern Ocean research is exploratory in nature in order to develop testable hypotheses of the Southern Ocean's role in the local and global climate system.

2.1 Work Plan

2.1.1 General strategy

We continue to explore the Southern Ocean's role in the climate system by inspecting historical data sets and by maintaining our observational efforts in the Weddell Sea. The Weddell Gyre is one of the better studied regions and is a logical choice to establish a long-term observational effort. Given the limited amount of resourses we attempt to maximize the efficiency of new measurements. We also take advantage of ships of opportunity to obtain tracer and hydrographic observations in remote, sparsely sampled shelf regions around Antarctica, when opportunities become available. All of these efforts are carried out in close collaboration with other countries and US agencies to coordinate observational efforts. The existing connection with the SCOR affiliated program iAnZone (International Antarctic Zone) and the possibility to work under the CLIVAR/GOOS/GCOS umbrella is a useful framework to enhance this collaboration.

Moreover, we plan to combine the existing data sets with the regional modeling effort of our CORC-ARCHES collaborators to get a better handle on the relevance and variability of different climate processes. Ultimately, we would like to use information from both the paleo reconstructions and modeling results together with knowledge based on modern observations to derive an optimized and cost effective observing system for the Southern Ocean.

During CORC II we proposed to focus long-term observations on one basin to assess the current technology for detection and monitoring the variability of Weddell Sea Deep Water. We made good progress toward this goal with a modest amount of moored observations combined with annual hydrographic/tracer surveys. We hope to advance and explore new technologies such as profiling moorings, moored water samplers, floats and gliders that ultimately will be able to operate in such difficult environments and should be able to fill data gaps.

These studies will be augmented by interpretation of circum-Antarctic tracer data sets to study the sites, processes and rates of deep and bottom water formation (CFCs, tritium). The tracer data will also be used to gain information on the interaction between shelf waters and the glacial ice sheets (helium and oxygen isotopes).

Our efforts can be divided into five parts:

- Repeated hydrographic section
- Moored observations
- Antarctic shelf ship of opportunity observations
- Analysis of historical data sets

2.2 Results to date

In April 1999 we started the NOAA-CORC funded Weddell Sea outflow time series. NSF's Office of Polar Programs generously provides us with free access to the GOULD. We repeated the hydrographic/tracer section south of the South Orkney Plateau (Fig. 2.2.1) and deployed the first mooring array (Fig. 2.2.2). A year later in March of 2000 we went back on the GOULD and successfully recovered the mooring array and revisited all hydrographic/tracer stations. At the same time we redeployed the second mooring array with the same instrument coverage. The site was revisited in February 2001 and Dec 2001 to service the moorings and repeat the CTD/tracer stations.

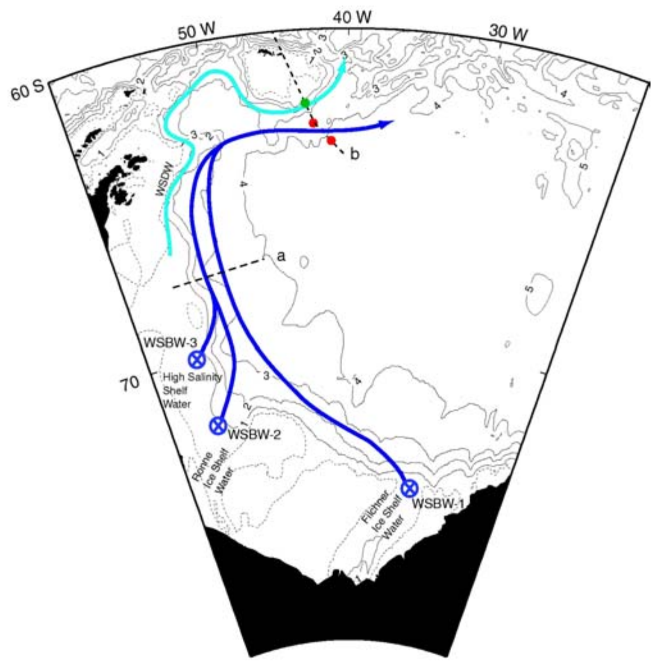

Figure 2.2.1. *Schematic of the newly ventilated bottom water pathways in the Weddell gyre. The location of the Weddell Sea time series hydrographic repeat section and mooring array are indicated.*

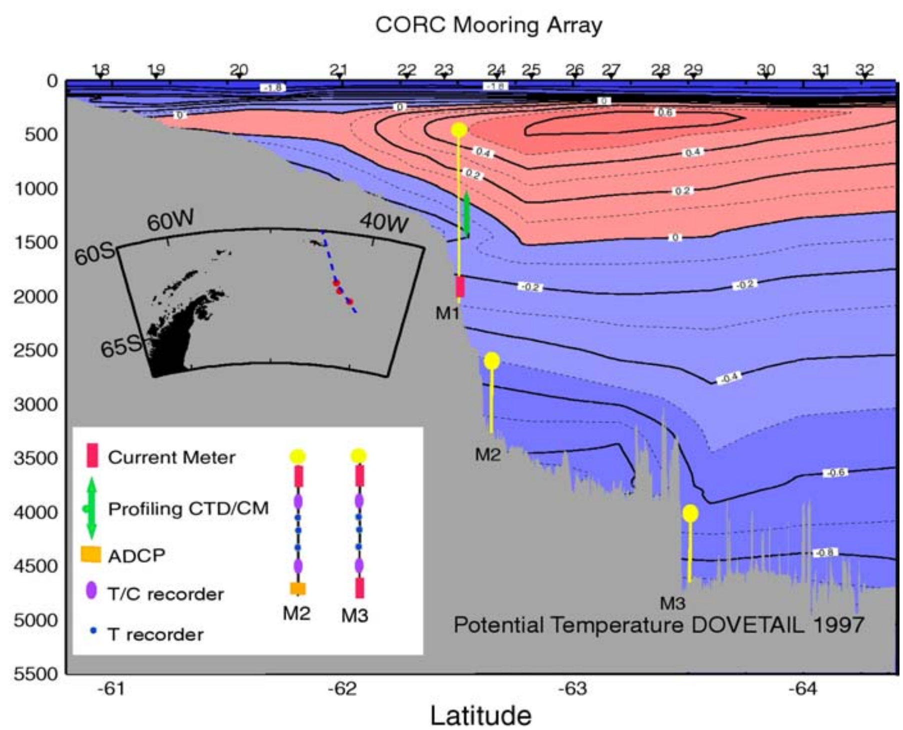

Figure 2.2.2. *Potential temperature section across the northern Weddell Sea gyre south of the South Orkney Plateau. The location of the tree moorings is indicated with a rough break up of the instruments used.*

Vertical sections of potential temperature and CFC-11 from two CORC cruises (April 1999 and 2000) and the 1997 (August) and 1998 (April) DOVETAIL cruises are shown in Figures 2.2.3 and 2.2.4. Two branches of the deep outflow from the Weddell Sea are clearly seen, a northern branch confined to a trough between the South Orkney Plateau and the Endurance Ridge and a southern branch south of the Endurance Ridge (see also Figure 2.2.1). The structure of the deep outflows is similar for the four occupations of the section with the coldest temperatures and highest CFC concentrations at the bottom in both branches. The high CFC concentrations (about half of surface water concentrations) in the core of both branches is a reflection that this water originated on the continental shelf where extensive air-sea interaction has occurred.

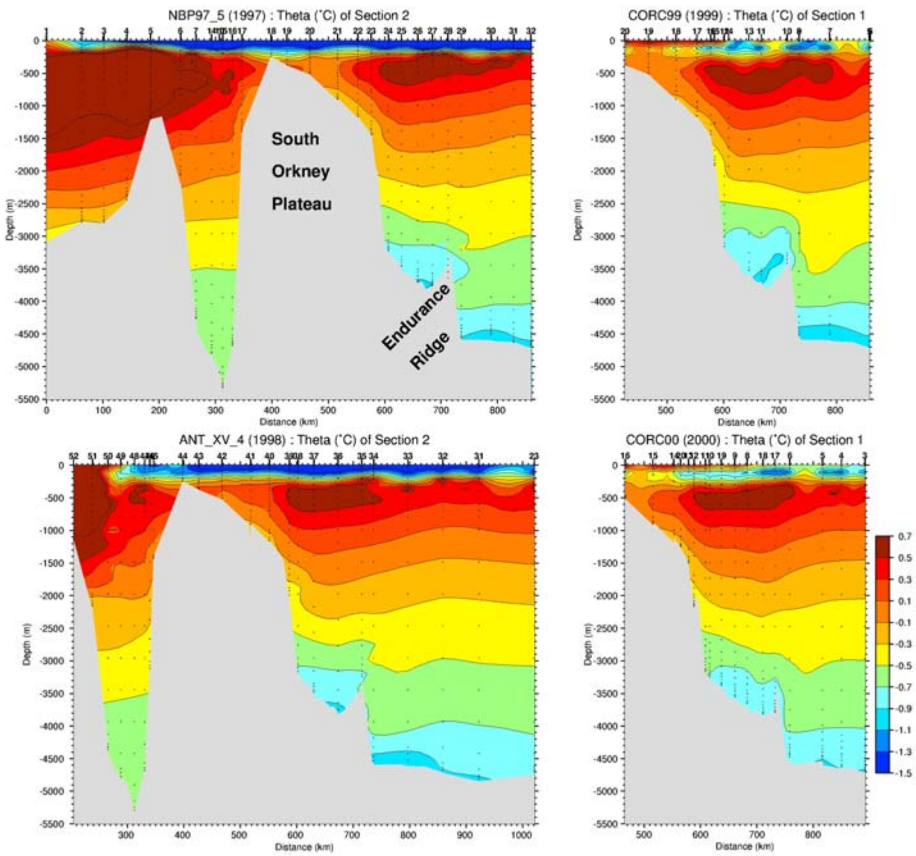

Figure 2.2.3. *Vertical sections of theta for the stations extending south of the South Orkney Plateau for the NBP97-5 cruise (Aug 1997), the ANT XV-4 cruise (Apr 1998), the CORC 99 cruise (Apr 1999) and the CORC 2000 cruise (Apr 2000). See Figure 2.2.1 for location of section. The ANT XV-4 data were kindly provided by E. Farbach.*

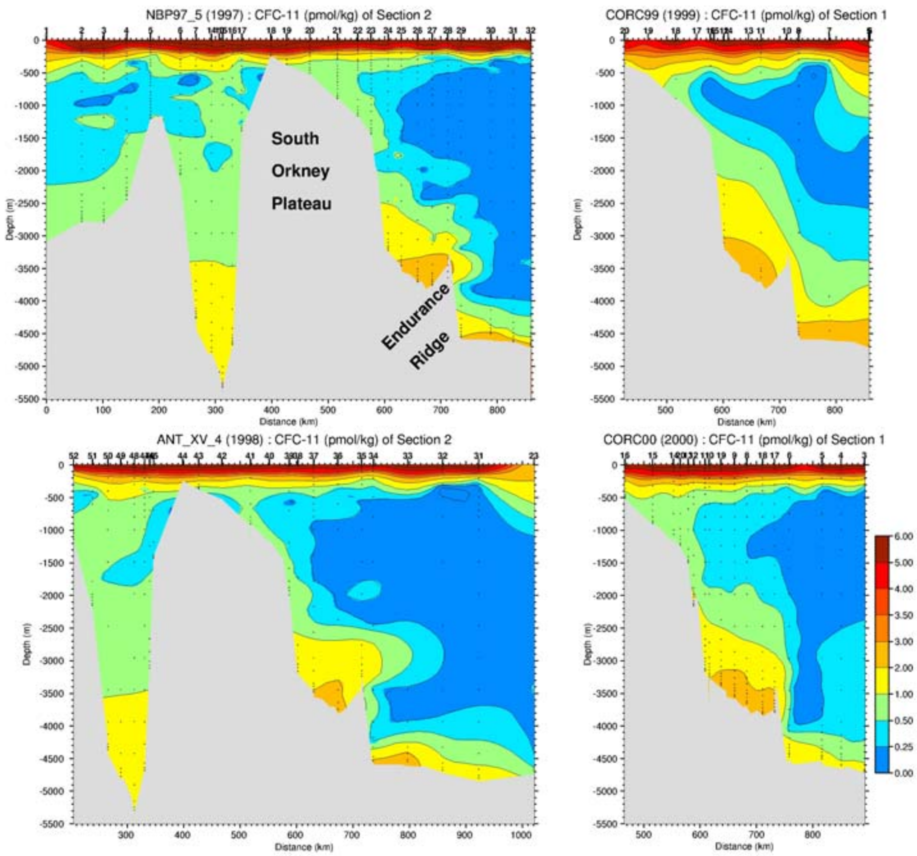

Figure 2.2.4. *Vertical sections of CFC-11 for the stations extending south of the South Orkney Plateau for the NBP97-5 cruise (Aug 1997), the ANT XV-4 cruise (Apr 1998), the CORC 99 cruise (Apr 1999) and the CORC 2000 cruise (Apr 2000). See Figure 2.2.1 for location of section. The ANT XV-4 data were kindly provided by W. Roether.*

There is a noticeable difference between the CORC 1999 and CORC 2000 cruises for the southern branch. The core is warmer and has a lower CFC concentration in 2000 than in 1999. Theta/salinity and theta/CFC-11 (Figure 2.2.5) plots reveal further differences between the cruises. For the northern branch, the salinity of the core (theta < -0.6°C) decreases by 0.01 between 1997 and 1998, then increases in 1999 and 2000 to values intermediate between the 1997 and 1998 values. The CFC concentrations with respect to theta are similar for 1997 and 1998 and for 1999 and 2000, but the 1999/2000 concentrations are about 10% higher than the 1997/1998 values. Until 1993, the CFC-11 concentrations in the troposphere and hence surface water increased continuously with time, so this may be a reflection that the water formed prior to 1993. Another explanation is that the water formed under different conditions for the different years, resulting in greater uptake of CFCs from the atmosphere for the outflow water observed in 1999 and 2000. The temporal trend for the theta/salinity plot for the core of the southern outflow is similar to that for the northern core, except for the bottom where theta is about 0.1°C warmer in 2000 than for the previous years. The CFC-11 concentrations plotted against theta are similar for the four cruises, except the concentration at the bottom is much less in 2000 (1.6 pmol/kg compared to > 2.5 pmol/kg for 1997, 1998 and 1999).

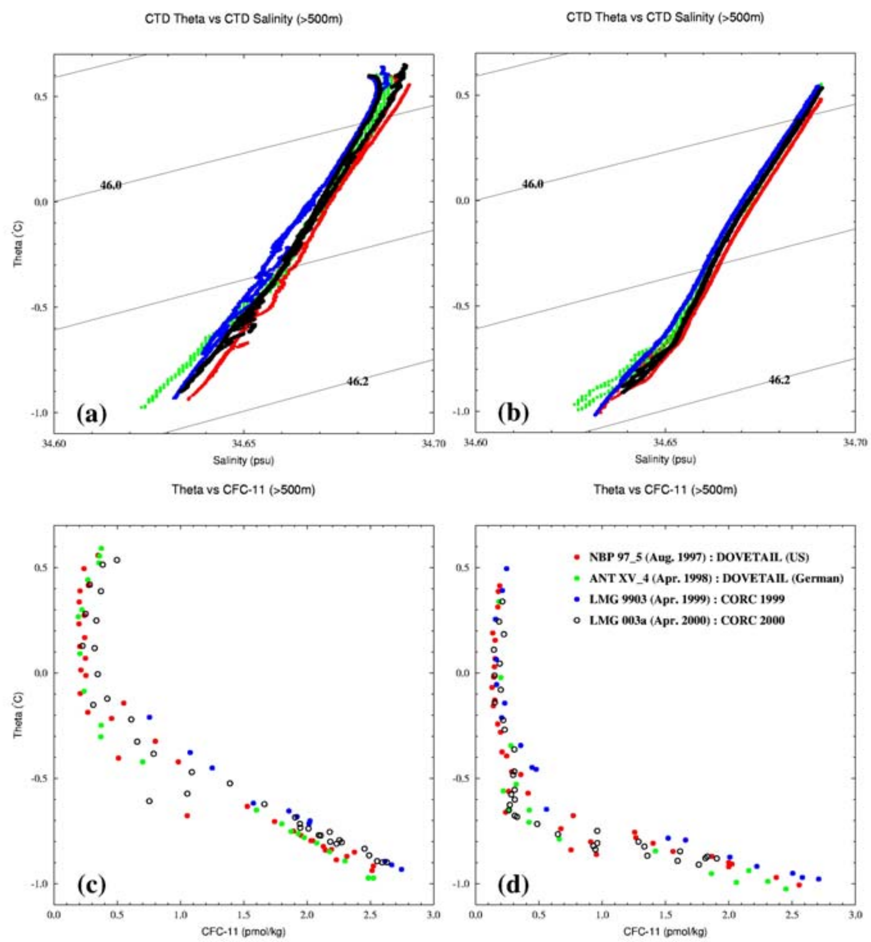

Figure 2.2.5. *Theta vs salinity for a) NBP97-5 stations 25 and 27, ANT XV-4 stations 36 and 37, CORC 99 stations 11 and 12, and CORC 00 stations 18 and 19; b) NBP97-5 stations 29 and 30, ANT XV-4 stations 33 and 34, CORC 99 stations 7, 8 and 9, and CORC 00 stations 5 and 6 and theta vs CFC-11 for c) NBP97-5 stations 25 and 27, ANT XV-4 stations 36 and 37, CORC 99 stations 11 and 12, and CORC 00 stations 18 and 19, d) NBP97-5 stations 29 and 30, ANT XV-4 stations 36 and 37, CORC 99 stations 7, 8 and 9, and CORC 00 stations 5 and 6. See Figures 2.2.1 and 2.2.3 for station locations.*

Between 1999 and 2000 the core of the southern branch has become warmer, less dense and not as well ventilated, suggesting a change in the properties of the source shelf water or a change in entrainment after the water leaves the shelf resulting in less of a shelf water component. Documenting and understanding such variability and how it impacts the inflow of newly formed deep and bottom water into the ocean is a major goal of the modern observations component of CORC. A complete interpretation of these data and more data that will be collected at this site in the future will be carried out during CORC-ARCHES.

In order to resolve the time variability between the hydrographic surveys we deployed a small mooring array. Figure 2.2.2 depicts the elements of the moorings and their location with regards to the cold cores of Weddell Sea Deep and Bottom Water. Two of the three moorings employ a combination of standard instrumentation: rotor current meter, acoustic Doppler current meter, and temperature and salinity recorder. However, one novel element of the third mooring is the Moored Profiler (MP).

The MP (Doherty et al., 1999; Toole et al., 1999) is a new instrument, recently operational, that was developed in part with previous funding from the CORC program. The device attaches to a conventional subsurface mooring and repeatedly travels along the mooring wire carrying oceanographic sensors through the water column. This system was fitted with a CTD to sample temperature and salinity as a function of depth, and a current meter that yields profiles of the ocean's absolute velocity field. The hydrographic data that are obtained are comparable to that gathered with a shipboard CTD; the velocity data are superior to Lowered Acoustic Doppler Profiler (better vertical resolution, are inherently absolute). Importantly these data are acquired autonomously; research ships are only required for deployment and recovery.

The Moored Profiler operated through the full deployment period and returned 369 high-vertical-resolution profiles of temperature, salinity and velocity between approximately 250 m depth and the bottom (about 2000 m, Figure 2.2.6). This depth interval spanned the region between the temperature extremum of the T_{max} layer (centered near 500 m depth) and the deep waters (Figure 2.2.6). Through the year-long record, the T_{max} layer's potential temperature is seen to decrease and the depth zone with potential temperatures above 0.5C narrows in vertical extent. Near the bottom there is a striking long-period variation in potential temperature with time; coldest water at the bottom was observed around August 1999 (around day 125 in Figure 2.2.6) warming thereafter to maximum values around day 350 (February 2000). The phasing of this signal is most suggestive of an annual cycle, but obviously this cannot be quantified on the basis of a single year of data. Developing a better understanding of this signal by acquiring additional data from this site is a key aspect of our present proposal.

The along- isobath velocity component exhibits a significant bottom-intensified mean flow (directed to the east north east, not shown) that is modulated on ~annual and ~20-day periods (Figure 2.2.6; bottom panel). The first question posed by these observations is: why is the boundary current flow here bottom intensified? The phasing of the low-frequency variability is such that strongest near-bottom current is associated with coldest near-bottom temperatures. This signal is consistent with a baroclinic balance in the near bottom flow: Greater vertical shear implies larger horizontal density (and temperature) gradients achieved by greater uplifting of deeper isopycnals (and isotherms) with distance towards the South Orkney Plateau. What forces this long-period variation in the bottom intensified flow is another of our research questions.

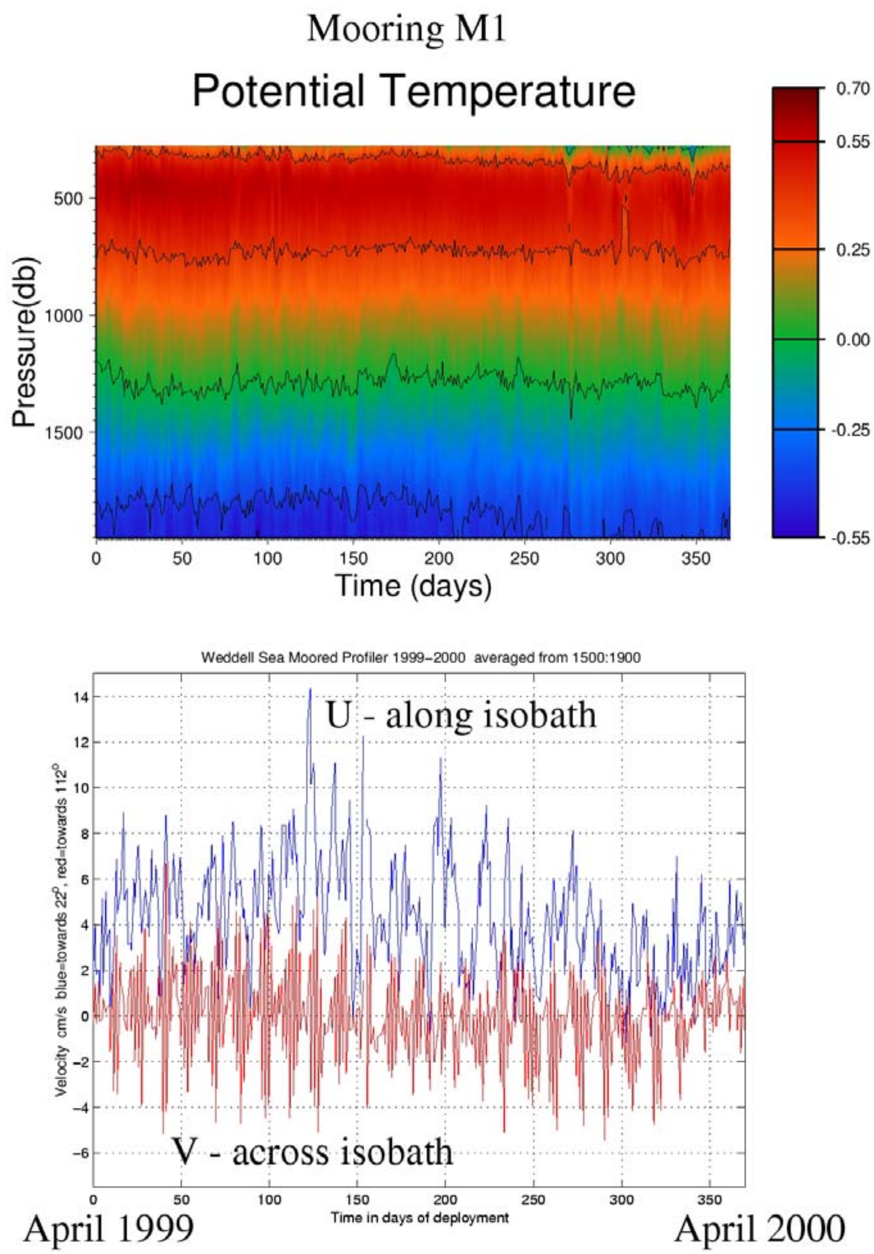

Figure 2.2.6. *Top) Depth-time contour plot of potential temperature from a Moored Profiler deployment at the 2000 m isobath south of the South Orkney Plateau from April 7, 1999 to April 10, 2000. The original two-profiles-on alternate-days, 2-dbar-binned profile data were averaged into 20 dbar bins and interpolated to a uniform 1-day grid for this figure. Bottom) Time series of depth-average velocity between 1500 and 1900 dbar from the Moored Profiler. The along-isobath component is shown in*

blue, the across-isobath in red. Note the fortnightly modulation in the across isobath component (evident in the differences between the pairs of up- and down-going profiles) and the long-period (annual?) variation in the along-isobath component, in phase with the near bottom temperatures.

Embedded in the boundary current flow are most interesting finescale velocity features. These structures with vertical wavelength of around 300 m exhibit clear phasing between the two components such that their velocity rotates clockwise with depth. This behavior is consistent with an internal wave carrying energy upwards. Curiously though, no clear phase propagation in time is seen, rather features are often found at the same depth in successive profiles and are even manifested in the year-long mean profiles. We suspect that these structures are internal lee waves forced as the near bottom current flows over small-scale bumps in the bathymetry. If so, they may play a significant role in defining the vertical structure of the boundary current. This will be explored during our analysis.

Further to the south in deeper waters a similar trend in the benthic layer temperatures was observed (Fig. 2.2.7). The coldest water vanishes over the course of the year and it appears that all isotherms are displaced downward by 100-200 m. The along shore transport decreased and seems correlated with the observed warming.

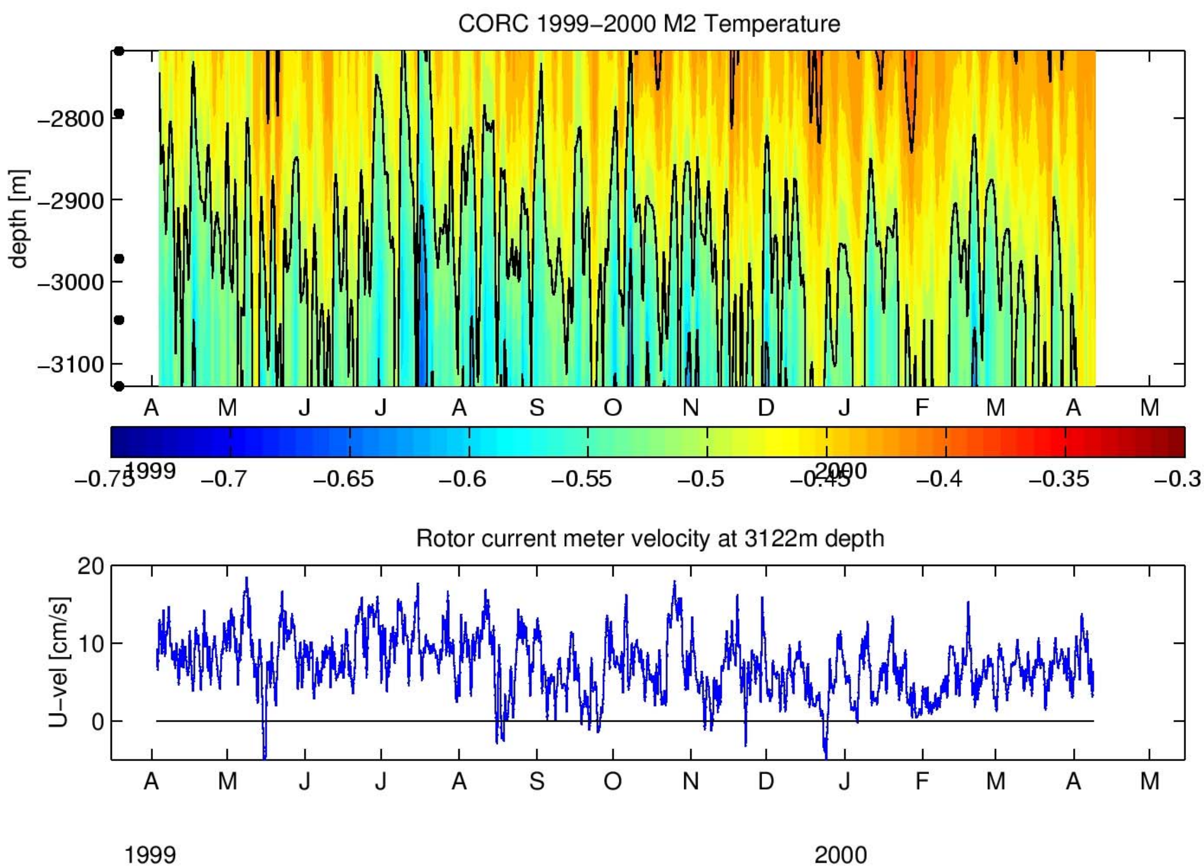

Figure 2.2.7. *Top) Depth-time contour plot of temperature from 5 sensors on the central mooring within the Jane basin deployed at about 3000m water depth. Bottom) Time series of the eastward velocity*

measured by a rotor current meter. All time series were lowpass filtered with a 40 hour cutoff time scale to remove tidal motions.

The most dramatic changes occurred at the southernmost site (Fig. 2.2.8) as discussed above in comparison of the 1999 and 2000 hydrographic/tracer sections. Weddell Sea bottom water with (in situ) temperatures below -0.65C was abundant until July of 1999. From then on a warmer water mass invaded the site and generally slower velocities were recorded by the upward looking ADCP. At this site there has been a mooring array for two years (1987-89; Barber and Crane, 1995). Since then the bottom water temperatures have slightly warmed from -0.63C during 1987-89 to -0.60C during 1999-2000.

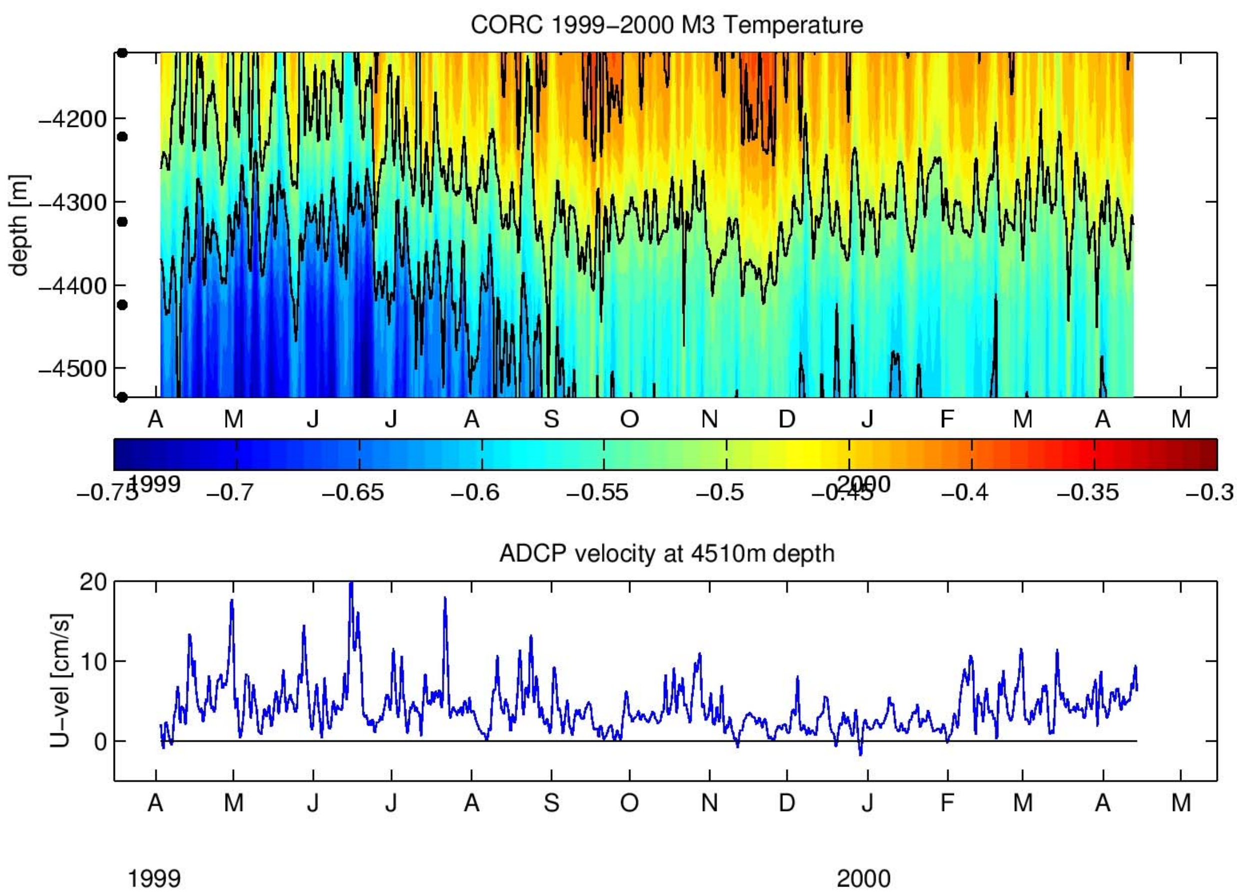

Figure 2.2.8. *Top) Depth-time contour plot of temperature from 5 sensors on the southern most mooring just south of the Endurance ridge deployed at about 4500m water depth. Bottom) Time series of the eastward velocity measured by an upward looking ADCP. All time series were lowpass filtered with a 40 hour cutoff time scale to remove tidal motions.*

Is this recent warming part of a long term trend? Or are we just seeing variability on interannual time scales? We have begun to evaluate the long term variability of the Warm Deep Water (T_{max} layer by assembling all historical data and computed annual averages of the T_{max} layer for two regions, the inflow and outflow regions (boxes in inset in Figure 2.2.9). The coldest T_{max} for the inflow region occurred in 1973 and for the outflow region in 1974-1976 (Fig. 2.2.9). These years coincide with the presence of the Weddell Polynya, which began in 1973 and continued until 1976. Unfortunately, there is no data for the inflow region during the Weddell Polynya years and no data for the outflow region for the years prior or subsequent to it. Consequently, we cannot determine the exact extent of the cooling during the time of the Weddell Polynya. Subsequent to the Weddell Polynya years, a general warming trend occurs in both the inflow and outflow regions. This warming trend has fluctuations superimposed on it, with the predominant period of the fluctuations being about 4 years. Overall, the slopes for both transects are similar and indicate a warming of ~0.007C/yr since 1970. We propose to extend this line of work by looking at the deeper layers, however, the time resolution is not as good and inter cruise calibration is challenging.

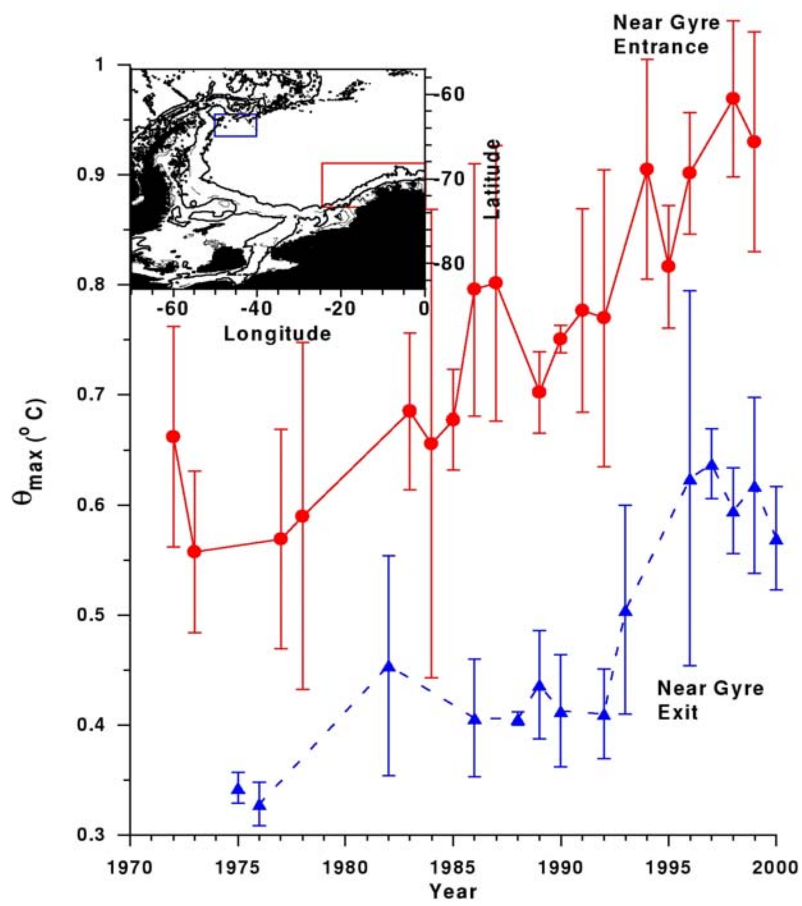

Figure 2.2.9. *The average T_{MAX} for the inflow region (circles) and the outflow region (triangles) from 3000-4500 m water depth. The error bars represent one standard deviation of the values. The inset indicates the locations of the inflow and outflow regions.*

3 References

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