Circulation and water masses from current meter and T/S measurements at the Amery Ice Shelf

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Introduction

The AMISOR project, jointly conducted by the CSIRO and the Antarctic CRC, entailed a comprehensive survey of the Amery Ice Shelf, both oceanographic and glaciological in nature. This paper summarises a preliminary analysis of CTD sections, moored time series data, and borehole observations.

Figure 1 shows station and mooring locations and gives a total of instrument types attached to each mooring. Bathymetry details can be seen in *Hunter et al., 2003* ,Figure 1 (this volume).

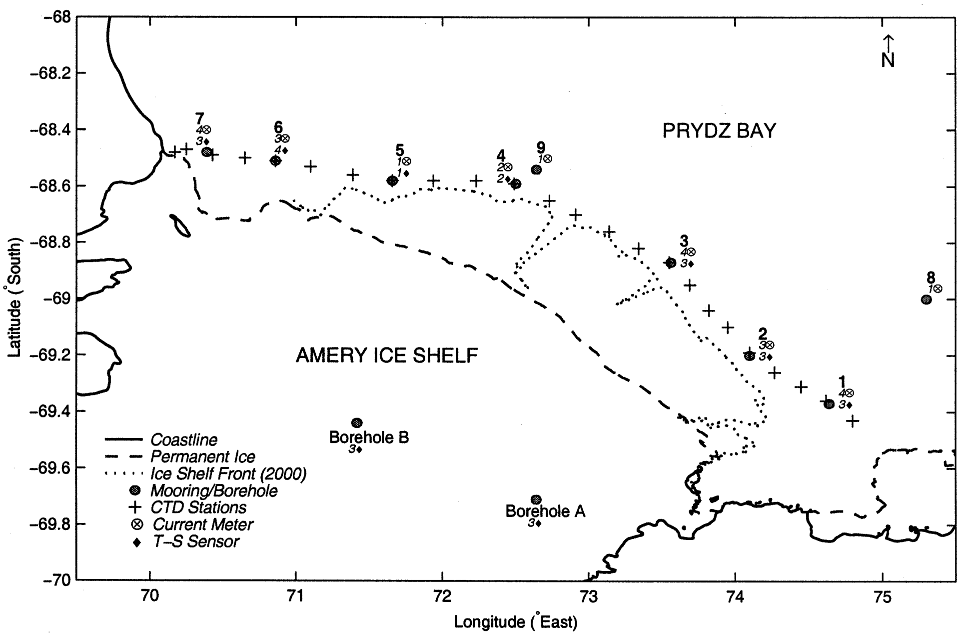

FIGURE 1
AMISOR Project: Mooring, Borehole and CTD Locations

CTD Sections

The CTD temperature profile taken during the deployment cruise in 2001 clearly shows the various water masses found in the vicinity of the Amery Ice Shelf during austral summertime (Figure 2a). Salinity profiles (not shown) also help towards classifying water types. A relatively fresh and warm water mass (between -1.8^{0}C and 2.1^{0}C) is present down to 200m (Summer Surface Water), capping a thin layer of Winter Water (34.2 to 34.5 and -1.5 to -1.9^{0}C) in a sharp transition zone to Shelf Waters which fill most of the water column from approximately 200m down with temperatures at the surface freezing point (-1.89^{0}C) and salinities of 34.4 to 34.7. Cores of Ice Shelf Water (below -2^{0}C) are seen mainly at the western end of the ice shelf (ie, the sites of moorings 4, 5, 6, and 7).

There is an interesting contrast of properties in the 2002 profile (Figure 2b) when fast ice persisted throughout the cruise and Shelf Waters occupy the whole water column, highlighting the significance of inter-annual variability in the region.

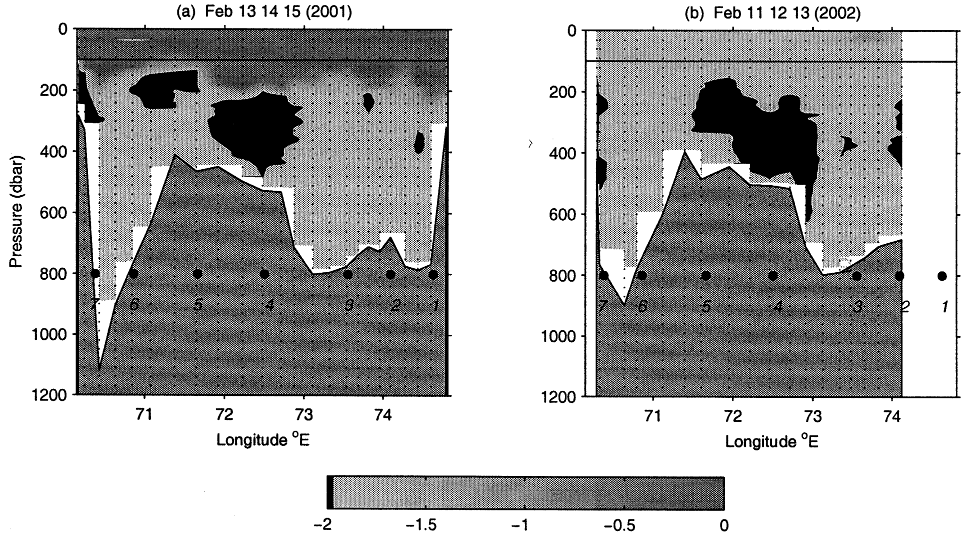

FIGURE 2
Temperature Profiles
CTD temperature profiles taken in front of the Amery Ice Shelf during the deployment and recovery cruises (austral summers 2001 and 2002 respectively). ISW (<-2^{0}C) shows as black cores within the main body of Shelf Waters (around -1.9^{0}C) with Summer Surface Waters lying above.

Mooring Data

The moored array provides one year of current, temperature and salinity time series data and consisted of seven moorings across the face of the shelf, approximately 5.5km from the ice edge, roughly 40km apart with the top instruments at 350m depth.

A basic feature of the mooring data is the disparate characteristics of water properties at the eastern side of the ice shelf when compared to the four moorings to the west (Figure 3). Both display a highly seasonal signal, but different water masses prevail. Warm and fresh HMCDW (Highly Modified Circumpolar Deep Water) appears in the east during autumn/winter at intermediate depths, but is absent at the four western moorings, where Shelf and Ice Shelf Waters are predominant.

The seasonality of Ice Shelf Water depicted in the diagrams (solid line below –2^{0}C) at moorings 4, 5, 6 and 7 is more likely a blurring of core properties as it mixes with convected Shelf Waters in late winter. This can be seen more clearly in potential density plots (not shown) where a decreasing trend in density (ISW is cold but very fresh) is interrupted by an interval of low density stability (mid-August to end of October), and then restarts. Low density stability equates to maximum convective activity and it is during this period that the most saline Shelf Waters (between 34.6 and 34.7) are produced.

A coastal polynya situated at the western end of the ice shelf is responsible for this amplified convective activity. Through analysis of sea ice concentrations derived from satellite data, *Massom et al., (1998)*, determined that this polynya is a permanent feature during winter months, with an average area of approximately 3,500 km^2.

Plots of along-shelf currents (not shown), show zonal flow is generally east to west although mooring 2 tends eastward. The seasonal signal in cross shelf flow (Figure 3 dashed line) recorded at the easterly moorings appears to be determined by the influx of different water masses. Fresher and warmer HMCDW (present during March to end August) flows mainly northward (out of shelf), while denser Shelf Waters (September to February) initiate southward flow. At the western end of the ice shelf, all currents are generally out of shelf - except for mooring 5, and except during the period of maximum convective activity (August to October) when high salinity Shelf Waters flow shelf-ward.

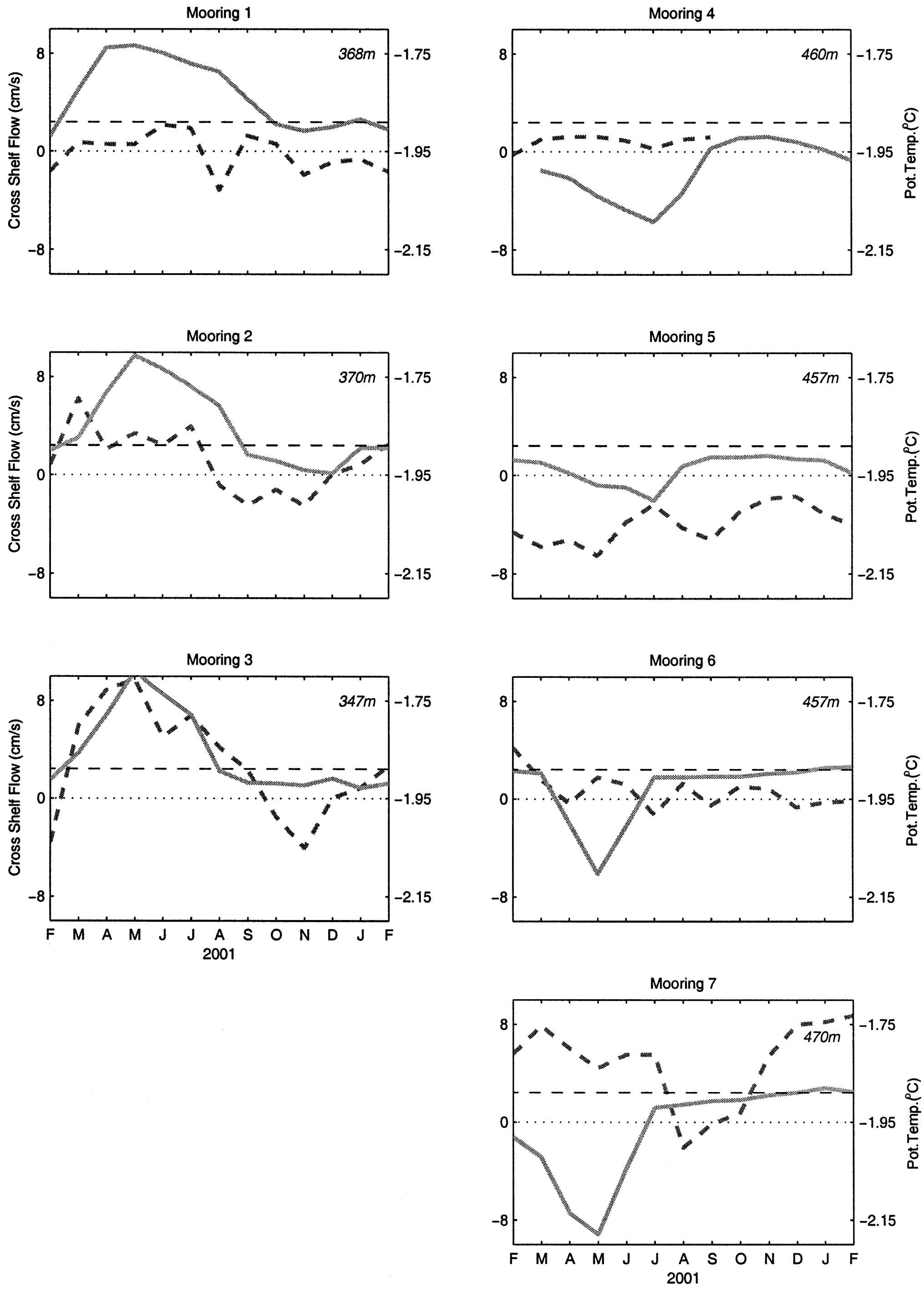

FIGURE 3
Time series of Temperature and Cross-Shelf Flow
Solid line is potential temperature, dashed line is cross shelf flow where positive values are out of shelf, and negative values are shelfward. Horizontal dashed line is the freezing point for sea water (-1.89°C).

Borehole CTD Data

Hot water boreholes were drilled in consecutive years approximately 90km south of the ice front - Borehole A is positioned over a basal melt region, and Borehole B at an ice accretion site. CTD profiles were taken at the time of drilling, plus Microcats were left suspended on a line to collect time series data of temperature and salinity.

Comparison of CTD temperature data (Figure 4), shows a marked difference in temperature values immediately below the ice shelf: -2.25^{0}C at Borehole B compared with –2.14^{0}C at Borehole A. There is also a 100m thick layer of marine ice frozen onto the ice shelf base at Borehole B, described by the drilling operators as a slushy, porous zone *(Rosenberg et al., 2002).*

Trends are otherwise similar: minimum values are found at both sites immediately below the ice shelf base within a mixed layer of around 90m. Temperature and salinity both increase from this point to the deepest levels, where warmer denser Shelf Waters lie. Ice Shelf Water reaches down to 650m at borehole A, although not as well defined in the 500-600m range, while at borehole B it fills the water column to 750m.

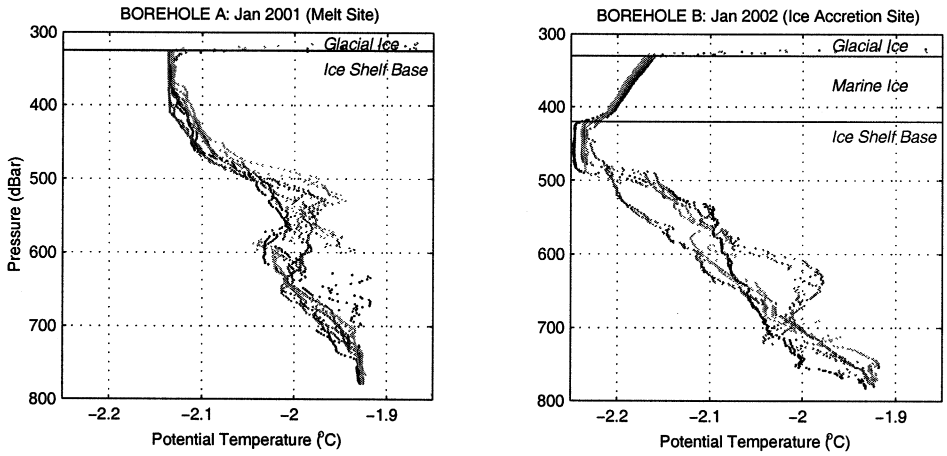

FIGURE 4
Borehole CTD Potential Temperature Profiles

Borehole T-S Time Series Data

Contrasting properties between the two boreholes can also be seen in the full year of T-S Microcat observations (not shown). Borehole A shows a large spread of data both temperature and salinity-wise with a strong seasonal signal at the uppermost level, and warmer and saltier Shelf Waters at depth. The intermediate instrument at Borehole A records mixing between top and bottom levels.

Borehole B data lie more compactly within SW to ISW gradients, with a very cold core of ISW close to the ice shelf and a layer of denser Shelf Waters detached from this process at depth.

Melt/Freeze Gradient

Melt/Freeze lines show the transformation pathway when glacial ice melts into sea water, diluting and cooling the characteristics of the original water mass. *Gade, (1979)*, was one of the first to develop a primitive model of this relationship and derived the following equation (simplified by *Nicholls et al., 2001*):

$$\frac{d\theta}{dS} = \frac{L}{S_o c_w} + \frac{(\theta_f - T_i)c_i}{S_o c_w} + \frac{(\theta_o - \theta_f)}{S_o}$$

where L is the latent heat of ice (3.35×10^5 J kg^{-1}); c_w and c_i are the specific heat capacities of water and ice (2010 and 4000 J kg^{-1} ^{0}C^{-1}, respectively); S_o and θ_o are the salinity and potential temperature of the original seawater; θ_f is the potential temperature at which ice melts at the ice shelf base (-2.15^{0}C at 350m), and T_i is the core temperature of the ice shelf (-20^{0}C).

Using S_o = 34.51 and θ_o = -1.9^{0}C, this formula gives a gradient of 2.7^{0}C/psu.

Figure 5 plots this Melt/Freeze line over a broad sample of T-S data collected from the seven moorings. As WW evolves through the same process as Shelf Waters, and comprises the same temperature range, it has not been differentiated as a separate water mass here, ie it is included within the definition of LSSW.

Results suggest that Ice Shelf Water evolves from Shelf Waters between 34.45 and 34.55, thus the HSSW generated during the intense convection period at the western end of the ice shelf does not participate in the production of ISW. The overlaid data are mooring 1 observations from below 570m, which fit nicely between the ISW bracketed by the two Melt/Freeze lines.

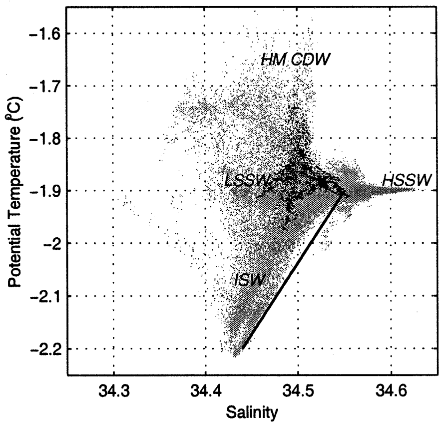

FIGURE 5
Melt/Freeze Gradient
T-S scatter plot of the time series of mooring data. Darker overlaid data is from mooring 1 below 570m. The solid black line is the melt/freeze gradient (2.7^{0}C/psu) which describes the conversion of a parent water mass to ISW.

Array/Borehole Comparison

Figure 6a compares monthly mean plots of borehole data with observations from the array moorings at similar depth levels. Borehole A at 335m exhibits the same seasonal signal as moorings 1 and 2 at 370m, even to the extent of turning slightly fresher and warmer during December to February. The Melt/Freeze gradients (solid black lines) connect the sites nicely, indicating that basal melting due to interaction with the ice shelf produces the uppermost waters at borehole A.

Borehole B at 580m reveals similar water properties to mooring 4 at 515m (Figure 6b). Analogous with the first borehole/array comparison, mooring 4 is more saline than the undershelf data, but as an outflow region, represents the reverse situation of the melt/freeze process. Supercooled ISW continues to freeze onto the base of the ice shelf as it moves towards the front, so the remaining water mass becomes more saline through brine rejection and warmer due to latent heat release. The very cold ISW in the borehole data (<-2.25^{0}C) appears at shallower levels of mooring 4 (not shown), as it would rise buoyantly when emerging from the cavity.

Figure 6c highlights the interesting relationship between the high salinity signal seen at mooring 7 (at 695m) between September and November, and similar salinity maximums at borehole B (at 740m) at around the same time. These dense waters are created during the intense convective period (discussed above) when current flow becomes strongly (and unusually) inward at mooring 7. This plot comparison suggests that very saline shelf waters drain back at least as far as borehole B (approximately 106km south-east of the deepest western moorings).

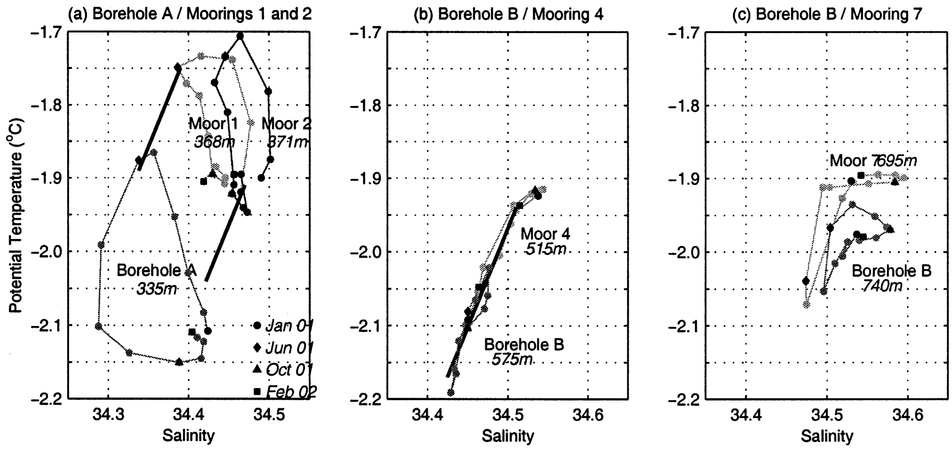

FIGURE 6
Comparison between T-S monthly means of boreholes and array instruments. Solid black line is the melt/freeze gradient.

Summary/Discussion

From the AMISOR data set, and in agreement with previous studies (eg, *Wong et al., 1998; Smith et al., 1984*), the general horizontal circulation is east to west along the front of the Amery Ice Shelf. Major flow into the shelf occurs at the eastern end (mainly from mooring 1 below 570m) and exits from the west as Ice Shelf Water. This implies that the parent water mass from which Ice Shelf Water originates is a lower salinity Shelf Water, (not HSSW which is produced mainly at the western end), and is further clarified by applying the Melt/Freeze gradient to the data.

Borehole data also supports this flow regime, where a melting zone resulting from warmer inflowing water is found at the more easterly borehole A, and an ice accretion region at borehole B. This freezing process can only occur with the throughflow of supercooled buoyant ISW, which follows the rising ice draft towards the shelf front (and is observed at mooring 4, a strong outflow site).

There is a general trend in cross-shelf flow for dense Shelf Waters to flow inward, and the lighter and fresher water masses (ISW and HM CDW) to flow north. This accounts for the seasonal signature in the eastern moorings and southward flow during the intense convective period within the polynya. However, evidence for shelfward flow of HMCDW can be seen as a warmer signal in borehole A data, and implies that at shallower levels (say 300 to 500m) lighter waters are able to enter the cavity.

Anomalous flow directions at moorings 2 and 5 may indicate the presence of small gyres, or in the case of mooring 5, possibly a larger circulatory system operating within a separate basin which encompasses moorings 5, 6 and 7 and extends back underneath the ice shelf. This two basin concept is further substantiated by the absence of HMCDW in the western mooring data. Observations at borehole B (which is nominally located in the eastern basin), suggest there is a connection at the deepest levels to mooring 7.

Future Work

Work will continue on refining the conceptual circulation model and the seasonality of water masses and flow patterns. Quantitative analysis of the AMISOR data set will follow, including mass budgets; heat, freshwater and energy fluxes; melt rates, and tidal analysis.

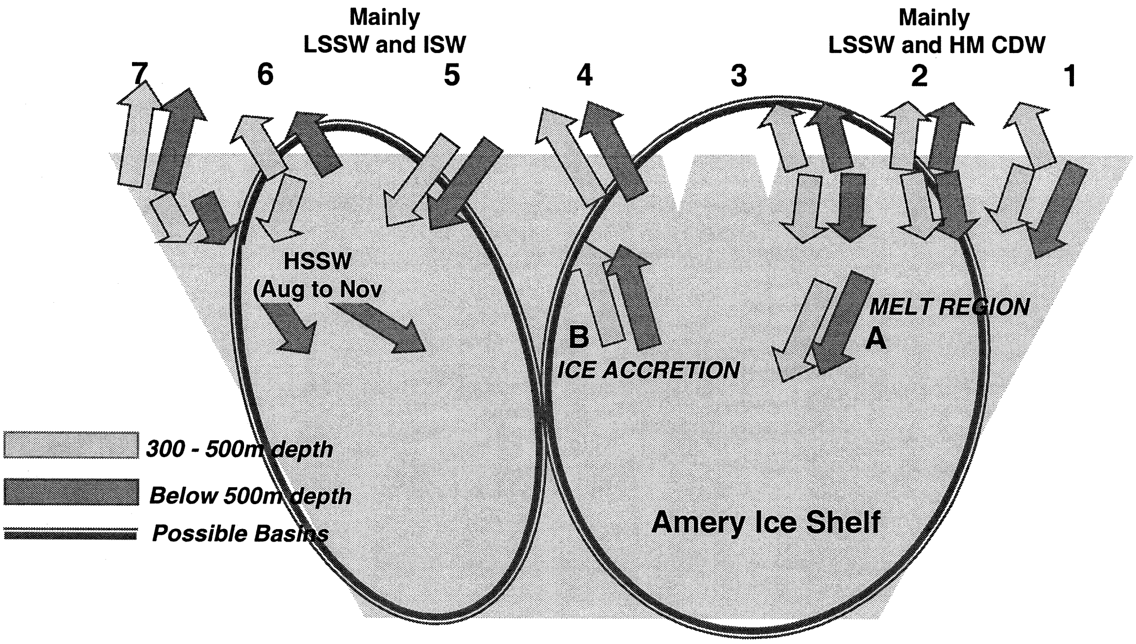

FIGURE 7
Conceptual circulation model for the region adjacent and underneath the Amery Ice Shelf, as implied by the AMISOR data set.

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