Wintertime ocean conditions over the southern Weddell Sea continental shelf, Antarctica.

Keith W. Nicholls[1], Lars Boehme[2], Martin Biuw[2,3] and Michael A. Fedak[2]

---

[1] British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, U.K.

[2] Sea Mammal Research Unit, Natural Environment Research Council, Gatty Marine Laboratory, University of St Andrews, St Andrews, KY16 8LB, U.K.

[3] Norwegian Polar Research Institute, Polarmiljøsenteret, 9296 Tromsø, Norway.

Abstract

During the austral winter of 2007 a Weddell Seal tagged with a miniaturized conductivity-temperature-depth (CTD) instrument foraged over the central southern Weddell Sea continental shelf. The instrument yielded 750 CTD profiles, 250 of them to the sea floor. The data show a full depth flow of water onto the shelf via a sill at the shelf break (74°S 44°W). The warmth from the core of the flow was able to maintain the surface mixed layer above the freezing point, resulting in a band of reduced ice-production. An estimate of the on-shelf flux suggests that this flow accounts for most of the estimated 3 Sv of water draining from the southern Weddell Sea continental shelf.

Introduction

The central region of the southern Weddell Sea continental shelf is an important area for the production of High Salinity Shelf Water (HSSW), the key precursor for Antarctic Bottom Water originating in the Weddell Sea. Over the last few decades most research in the region has been concerned with the pathways of dense water leaving the continental shelf to form Weddell Sea Bottom Water (WSBW). Measurements of the drainage from the continental shelf of waters rich in glacial melt [*Foldvik et al.*, 2004], combined with tracer measurements by *Weppernig et al.* [1996], suggest a production rate of HSSW required to supply the newly formed WSBW of around 3 Sv [*Nicholls et al.*, in press].

As part of an investigation into the processes concerned with the production of HSSW, the aim of the present study is to help determine the mechanisms that control the flow on to the continental shelf of the original source waters for the HSSW, and to characterize their flow and properties. Modified Warm Deep Water (MWDW) is a relatively warm off-shelf water mass in contact with the continental slope of the southern Weddell Sea. MWDW is known to flow across the shelf-break sill formed where the Filchner Depression intersects the shelf edge (Figure 1). This core of MWDW is thought to penetrate intermittently as far south as Filchner Ice Front [*Foldvik et al.*, 1985], but summertime current meter measurements suggest that it might not be the dominant source of water for the continental shelf as a whole [*Nicholls et al.*, in press].

Summertime hydrographic sections obtained along Ronne Ice Front find a second perennial core of MWDW at a longitude of 53° West [*Rohardt*, 1984; *Foldvik et al.*, 1985; *Gammelsrød et al.*, 1994; *Nicholls et al.*, 2003]. *Foldvik et al.* [2001] describe year-round data from instruments moored at this ice-front location that show this second core to be a quasi-permanent feature, only losing its identity between September and December. *Vaughan et al.* [1995] hypothesize that this MWDW core tracks along the western flank of Berkner Bank from a second shelf break sill, at about 74°S 44° W (Figure 1).

Despite its importance in the production of HSSW, the central area of the southern Weddell Sea continental shelf has very few summertime observations, and none from winter. The reason for the lack of data is the year-round heavy sea ice. Any moorings deployed in the central area of the shelf during summer in an attempt to get winter observations would be highly vulnerable to dredging by icebergs. In an attempt to acquire wintertime data from along the hypothesized path of the MWDW inflow, four Weddell seals were equipped with tags that consisted of miniature CTD instruments and Argos transmitters. This paper describes the data from one of the seals, which traveled over the central region of the continental shelf north of Ronne Ice Shelf. We discuss the evidence the dataset provides about the wintertime structure, flux, salinity and temperature of the inflow of MWDW.

Method

The species of seal selected for the study had to meet several criteria: it must forage over the southern continental shelf, that is, not migrate north with the pack ice edge; it must dive deep enough to yield sufficient full depth profiles; and it should be present in large enough numbers in the area of the cruise to improve the chance of finding suitable animals for tagging. Based on the limited information available on the behavior of seals in the Weddell Sea, we chose the Weddell Seal (*Leptonychotes-Weddellii*). Weddell seals have the southernmost range of all seal species, remaining deep within the ice throughout the year. Weddell seals are also extremely accomplished divers [*Kooyman et al.*, 1966], and adult Weddell Seal foraging dives over the eastern Weddell Sea continental shelf have been shown to extend to 450 m [*Plötz et al.*, 2001]. In addition, helicopter seal surveys conducted by the Alfred Wegener Institute had observed Weddell Seals in the vicinity of the cruise area.

The tags used in this study were Satellite Relay Data Loggers (SRDLs) designed and manufactured by the Sea Mammal Research Unit (SMRU) at the University of St. Andrews. The CTD modules in the tags were manufactured by Valeport Ltd, Devon, U.K. Here we briefly describe the tags; a full description is given by *Biuw et al.* [2007]. The CTD head uses a platinum resistance temperature sensor, an inductive conductivity sensor and a strain gauge-type pressure sensor. A wet-dry sensor determines when the animal is in the water, and the pressure sensor determines when a dive is in progress. The aim is to obtain one deep profile per six-hour time window, while minimizing the number of dives for which the sensors are activated, thus maximizing battery life. Whether the tag uses the dive to obtain a profile depends on the maximum depth of the dive compared with the maximum depth of previous dives within the six-hour window, and how close the time window is to expiring. If the dive is to be used for a profile, the C, T and pressure sensors are read once per second as the seal ascends. In this application the profiles were sub-selected at 20 points at uniform pressure intervals, the salinity profile calculated, and then the T and S profiles communicated using an Argos transmitter. Data compression techniques used in the tag are discussed by *Fedak et al.* [2002]. The Argos system also stamps the messages with the transmitter position, estimated to have an accuracy of about 2 km. The tags give the transmission of temperature profiles into the Argos system a higher priority than salinity profiles, as the conductivity sensors were thought to be more prone to failure. In the event, both sensors worked well, and the reliability of the transmissions resulted in there being around nine salinity profiles for every ten temperature profiles successfully received from the tags.

The CTD heads were initially calibrated at the manufacturer's facility before being integrated into the tags at SMRU. The completed tags were re-calibrated at Valeport before being shipped. Prior to the deployment, the tags were mounted on the ship's CTD frame for a final check of the calibrations, and particularly to determine any pressure effects on the sensors. After final checks against the ship-based SeaBird Electronics CTD system, we estimate the absolute uncertainty in the tag-derived salinity and temperature data to be 0.02 and 0.005°C respectively.

The Weddell seals were located in nine to ten tenths, rotten, largely un-ridged, first year ice. For each deployment, the ship maneuvered alongside the seal's floe, typically four personnel approached the animal, placed a “head bag” over its head and lightly sedated it using an intravenous injection of a 1:1 mixture of Tiletamine and Zolasepam [Zoletil® 100 (Virbac)] at an approximate dose of 0.2–0.4 mg kg^{-1}, based on the seal’s estimated weight. The tags were glued to the fur on the head or upper neck region using two-component industrial epoxy glue according to the methods described in *Fedak et al.* [1983], and *McConnell et al.* [2002].

Results

Four tags were deployed. One stopped transmitting after about two weeks, possibly because of a failure in the tag, but more likely a result of predation. Of the three other seals tagged, one spent the winter months foraging over the continental shelf near Brunt Ice Shelf (Figure 1), another ranged over the narrow continental slope to the east, and the final animal remained over the southwestern continental shelf. It is the dataset from the last animal that is the subject of this paper. The seal spent much of the winter over the western slope of Berkner Bank and the topographic depression to the west, ideal behavior for the purposes of this study. The track is shown in Figure 1, which also highlights the region of interest. The animal entered the shelf area 25 May 2007, and the final oceanographically useful transmissions were made 26 September 2007, yielding a four-month dataset throughout the winter months.

The distribution of relative depths (the depth as a fraction of the estimated seabed depth at the dive location) of the 750 profiles obtained from within the study area is shown in Figure 2. The bathymetry in the area is poorly known; if we assume that relative dive depths of greater than ~0.9 are dives to the seafloor, then the total number of full-depth dives is ~250. Even without the assumption that the seal dives to the sea floor, any location where the seal’s maximum dive depth is greater than the present estimate of the sea floor depth improves our knowledge of the bathymetry.

Although the profiles were obtained over a period of several months, we will assume that the hydrographic conditions in the study area were steady in order to construct a quasi-synoptic view. Such an assumption is reasonable if the on-shelf flow is strong, and the off-shelf properties have no significant seasonal variation. The similarity between CTD profiles obtained when the seal revisited an area of the sill in early September that it had originally visited in mid-June lends support to the second requirement. The absence of spatial noise in the sections is additional evidence for relatively stationary property fields. However, possible temporal evolution of the hydrographic structure of the region needs to be borne in mind.

Figure 1 shows the two boxes that we use to create the temperature and salinity sections shown in Figure 3. The approximate bedrock depth shown in the sections is from the Bedmap bathymetry [*Lythe et al.*, 2001] along the axis of the box.

The sections shown in Figure 3 indicate a substantial incursion of water from the shelfbreak, across the continental shelf, towards the ice front. The intruding water is significantly fresher in the upper layers than that to the east and west, with an increasing salinity towards the south. There is a core of MWDW at a depth of between 200 m and 350 m. Figure 4 shows the surface salinity as measured by the tag in the study area. The shallowest salinity value from each profile was used in this figure, which was always from a pressure of 8 dbar. Again, the entire dataset was regarded as synoptic. The map shows the horizontal extent of the low salinity inflow of off-shelf waters on to the continental shelf north of Ronne Ice Shelf.

Discussion

The isohalines in the vicinity of the southwestern Weddell Sea continental shelf break have been described as having a "V" shape, with high salinity to the south, over the continental shelf, and a "river" of low salinity water above the "V" flowing along the continental slope [*Gill*, 1973]. Figure 4 can be interpreted as showing isohalines outcropping at the southern side of the "V", the outcropping deviating far to the south leaving a tongue of fresher water over the continental shelf. Figure 3 shows this to take the form of a flow of off-shelf waters into the shelf region, and indicates that the incursion is a full-depth southward flow along the western flank of Berkner Bank. This represents a split in the westward continental slope front current at 44°W. *Gill* [1973] describes a similar split at 27°W where a tongue of MWDW turns to the south to traverse the eastern flank of Filchner Depression.

Examination of the 8-dbar temperatures shows that the temperature of the water in the mixed layer on the eastern side of the axis of the inflow is around 0.03°C above the surface freezing point (not visible in Figure 3), unlike the mixed layer temperatures measured to the west, which are not significantly different from the freezing point. The vertical heat flux from the warm core of MWDW must therefore cause a local reduction in the ice production rate. As the mean ice drift is across the line of the inflow, rather than along it, the reduction in the production rate is not visible in, for example, the ice concentration fields.

The fact that the inflow is in some sense strong is shown by the limited modification that the water column has undergone between the two sections in Figure 3, in an area where we expect strong wintertime atmospheric cooling, albeit through pack ice. The most notable change in the water column is the 0.05 increase in salinity of the upper 250 m of the central core of the inflow. If we assume a heat flux to the atmosphere of around 50 W m^{-2} [*Eisen and Kottmeier*, 2000], and that the central core is near the freezing point, the ice formation required to effect the necessary salinity increase would take around 17 days. Given a distance between the sections of about 180 km, the speed of flow must be on the order of 7 cm s^{-1}. The cross-sectional area of the central core (using the northern section, which is transverse to the flow) then gives a flux of about 1.6 Sv. If the remainder of the core has an average speed of half that of the central core, then the estimate of the total flow becomes at least 2.6 Sv, approaching the 3-Sv estimate of the total drainage of HSSW from the shelf. The neglect of lateral diffusion of salinity into the core means that our simple calculation is likely to underestimate the true flux, although the heat flux to the atmosphere is also poorly known.

Inspection of the isohalines from ice front sections [*Rohardt*, 1984; *Foldvik et al.*, 1985; *Gammelsrød et al.*, 1994] reveals the remnant of the lower salinity water at the depth of, and above, the MWDW core. Indeed, the ice front sections show a large-scale low salinity feature centered on the location of the core. At the ice front, *Foldvik et al.* [2001] found the direction of flow at the depth of the MWDW core to be northwestward along the ice front, with a speed of around 8 cm s^{-1}. A short section perpendicular to the ice front at 51° West was occupied in early 1980 [*Foldvik et al.*, 1985], which indicated the summertime extent of the ice front MWDW. If the current meter data were representative of the flow, then the flux northwestward along the ice front would be around 0.8 Sv. We have no evidence that the core does not split at the ice front, with a component heading southwestwards towards Berkner Island.

Conclusions

We have presented data from a CTD carried by a Weddell Seal that spent the austral winter of 2007 foraging over the southern Weddell Sea continental shelf. The region surveyed by the seal included a topographic depression that guides relatively warm off-shelf water onto the continental shelf. Of the 750 profiles obtained from this area around 250 extend to the sea floor, contributing to our knowledge of both the bathymetry and hydrography of an otherwise sparsely sampled region. The data show an apparently strong, full depth inflow entering the shelf regime along the eastern flank of the depression that, at the shelf break, is centered at around 44°W.

We find that the surface mixed layer in the inflow remains above the surface freezing point as a result of vertical heat flux from the warm core of MWDW, causing a local reduction in the sea ice production rate.

Simple calculations based on the data suggest that a lower bound for the volume flux of the flow is around 2.6 Sv. This inflow could therefore account for the majority of the 3 Sv of total on-shelf transport required to balance the off-shelf flow. Historical summertime datasets collected by conventional oceanographic techniques indicate a component of this MWDW flow northwestward along the ice front with a flux of around 0.8 Sv.

The danger to instrument moorings from iceberg damage, and the difficult sea ice conditions has meant that wintertime oceanographic processes over the central southern Weddell Sea continental shelf have never before been studied. Tagged seals offer the physical oceanographer a view of a region that is virtually inaccessible in any other way.

Acknowledgements

The authors are grateful for the support of the officers and crew of *RRS Ernest Shackleton*, and to Adrian Jenkins, Ole Anders Nøst and an anonymous reviewer for their helpful comments on the manuscript.

References

Biuw, M., L. Boehme, C. Guinet, M. Hindell, D. Costa, J. B. Charrassin, F. Roquet, F. Bailleul, M. Meredith, S. Thorpe, Y. Tremblay, B. McDonald, Y. H. Park, S. R. Rintoul, N. Bindoff, M. Goebel, D. Crocker, P. Lovell, J. Nicholson, F. Monks, and M. A. Fedak (2007), Variations in behavior and condition of a Southern Ocean top predator in relation to in situ oceanographic conditions, *Proc. Natl. Acad. Sci. U.S.A.*, *104*, 13705-13710.

Eisen, O., and C. Kottmeier (2000), On the importance of leads in sea ice to the energy balance and ice formation in the Weddell Sea, *J. Geophys. Res.*, *105*, 14045-14060, doi:10.1029/12000JC900050.

Fedak, M. A., S. S. Anderson, and M. G. Curry (1983), Attachment of a Radio Tag to the Fur of Seals, *J. Zoo.*, *200*, 298-300.

Fedak, M., P. Lovell, B. McConnell, and C. Hunter (2002), Overcoming the constraints of long range radio telemetry from animals: Getting more useful data from smaller packages, *Integr. Comp. Biol.*, *42*, 3-10.

Foldvik, A., T. Gammelsrød, E. Nygaard, and S. Østerhus (2001), Current measurements near Ronne Ice Shelf: Implications for circulation and melting, *J. Geophys. Res.*, *106*, 4463-4478, doi:10.1029/2000JC000217.

Foldvik, A., T. Gammelsrød, S. Østerhus, E. Fahrbach, G. Rohardt, M. Schröder, K. W. Nicholls, L. Padman, and R. A. Woodgate (2004), Ice shelf water overflow and bottom water formation in the southern Weddell Sea, *J. Geophys. Res.*, *109*, C02015, doi:10.1029/02003JC002008.

Foldvik, A., T. Gammelsrød, and T. Tørresen (1985), Circulation and water masses on the Southern Weddell Sea Shelf, in *Oceanology of the Antarctic Continental Shelf*, edited by S. S. Jacobs, pp. 5-20, AGU, Washington D.C.

Gammelsrød, T., A. Foldvik, O. A. Nøst, Ø. Skagseth, L. G. Anderson, E. Fogelqvist, K. Olsson, T. Tanhua, E. P. Jones, and S. Østerhus (1994), Distribution of water masses on the continental shelf in the southern Weddell Sea, in *The polar oceans and their role in shaping the global environment*, edited by O. M. Johannessen, et al., pp. 159-176, AGU, Washington, D.C.

Gill, A. E. (1973), Circulation and bottom water production in the Weddell Sea, *Deep Sea Res.*, *20*, 111-140.

Kooyman, G. L. (1966), Maximum diving capacities of the Weddell seal, Leptonychotes Weddellii, *Sci.*, *151*, 1553-1554.

Lythe, M. B., and D. G. Vaughan (2001), BEDMAP: A new ice thickness and subglacial topographic model of Antarctica, *J. Geophys. Res.*, *106*, 11335-11351, doi:10.1029/12000JB900449.

McConnell, B., M. Fedak, H. R. Burton, G. H. Engelhard, and P. J. H. Reijnders (2002), Movements and foraging areas of naive, recently weaned southern elephant seal pups, *J. Anim. Ecol.*, *71*, 65-78.

Nicholls, K. W., S. Østerhus, K. Makinson, T. Gammelsrød, and E. Fahrbach (in press), Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review, *Rev. Geophys.*

Nicholls, K. W., L. Padman, M. Schröder, R. A. Woodgate, A. Jenkins, and S. Østerhus (2003), Water mass modification over the continental shelf north of Ronne Ice Shelf, Antarctica, *J. Geophys. Res.*, *108*, 3260, doi:10.1029/2002JC001713.

Plötz, J., H. Bornemann, R. Knust, A. Schröder, and M. Bester (2001), Foraging behaviour of Weddell seals, and its ecological implications, *Polar Biol.*, *24*, 901-909.

Rohardt, G. (1984), Hydrographische Untersuchungen am Rand des Filchner Shelfeises, *Ber. Zur Polarforschung*, *19*, 137-143.

Vaughan, D. G., J. Sievers, C. S. M. Doake, H. Hinze, D. R. Mantripp, V. S. Pozdeev, H. Sandhäger, H. W. Schenke, A. Solheim, and F. Thyssen (1995), Subglacial and seabed topography, ice thickness and water column thickness in the vicinity of Filchner-Ronne-Schelfeis, Antarctica, *Polarforschung*, *64*, 75-88.

Weppernig, R., P. Schlosser, S. Khatiwala, and R. G. Fairbanks (1996), Isotope data from Ice Station Weddell: Implications for deep water formation in the Weddell Sea, *J. Geophys. Res.*, *101*, 25723-25739.

Figure legends

Figure 1. Map showing the southern Weddell Sea continental shelf. The colored markers show the locations of the profiles from each of the four seals that were tagged. The box indicated by the thin black line is the region of interest for this study, and depicts the extent of the map given in Figure 4. Profiles within the red boxes were used to construct the temperature and salinity sections shown in Figure 3. Contours (every 100 m to 500 m, then every 1000 m from 1000 m) show bathymetry from the BEDMAP compilation [*Lythe et al.*, 2001], modified west of 55°W with additional cruise data.

Figure 2. Number of dives to depths (that is, maximum profile depths) relative to the seabed depth estimated from the BEDMAP compilation [*Lythe et al.*, 2001].

Figure 3. Salinity and temperature sections using the profiles from the northern (a and b) and southern (c and d) boxes shown in Figure 1. White dots show the locations of data points. The bathymetry from the BEDMAP dataset [*Lythe et al.*, 2001] is shown as a heavy black line. The dates of each profile are indicated by a colored square at the top of the sections, sharing the colorbar with the mapped parameter.

Figure 4. Surface salinity over the central continental shelf. The black dots show the locations of the data points. The area of the section is indicated in Figure 1.

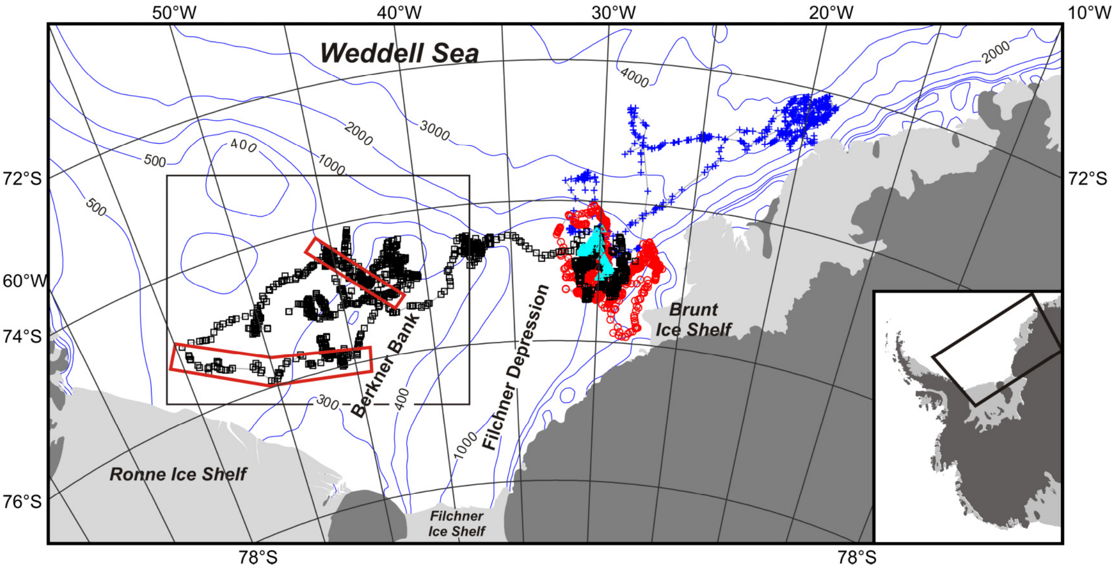

Figure 1. Map showing the southern Weddell Sea continental shelf. The colored markers show the locations of the profiles from each of the four seals that were tagged. The box indicated by the thin black line is the region of interest for this study, and depicts the extent of the map given in Figure 4. Profiles within the red boxes were used to construct the temperature and salinity sections shown in Figure 3. Contours (every 100 m to 500 m, then every 1000 m from 1000 m) show bathymetry from the BEDMAP compilation [*Lythe et al.*, 2001], modified west of 55°W with additional cruise data.

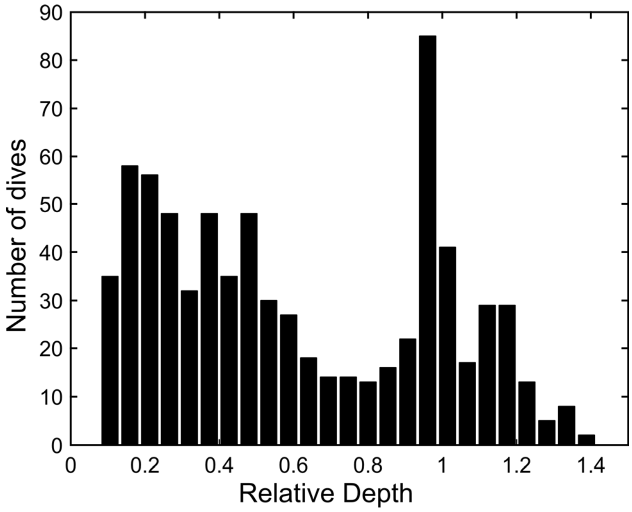

Figure 2. Number of dives to depths (that is, maximum profile depths) relative to the seabed depth estimated from the BEDMAP compilation [*Lythe et al.*, 2001].

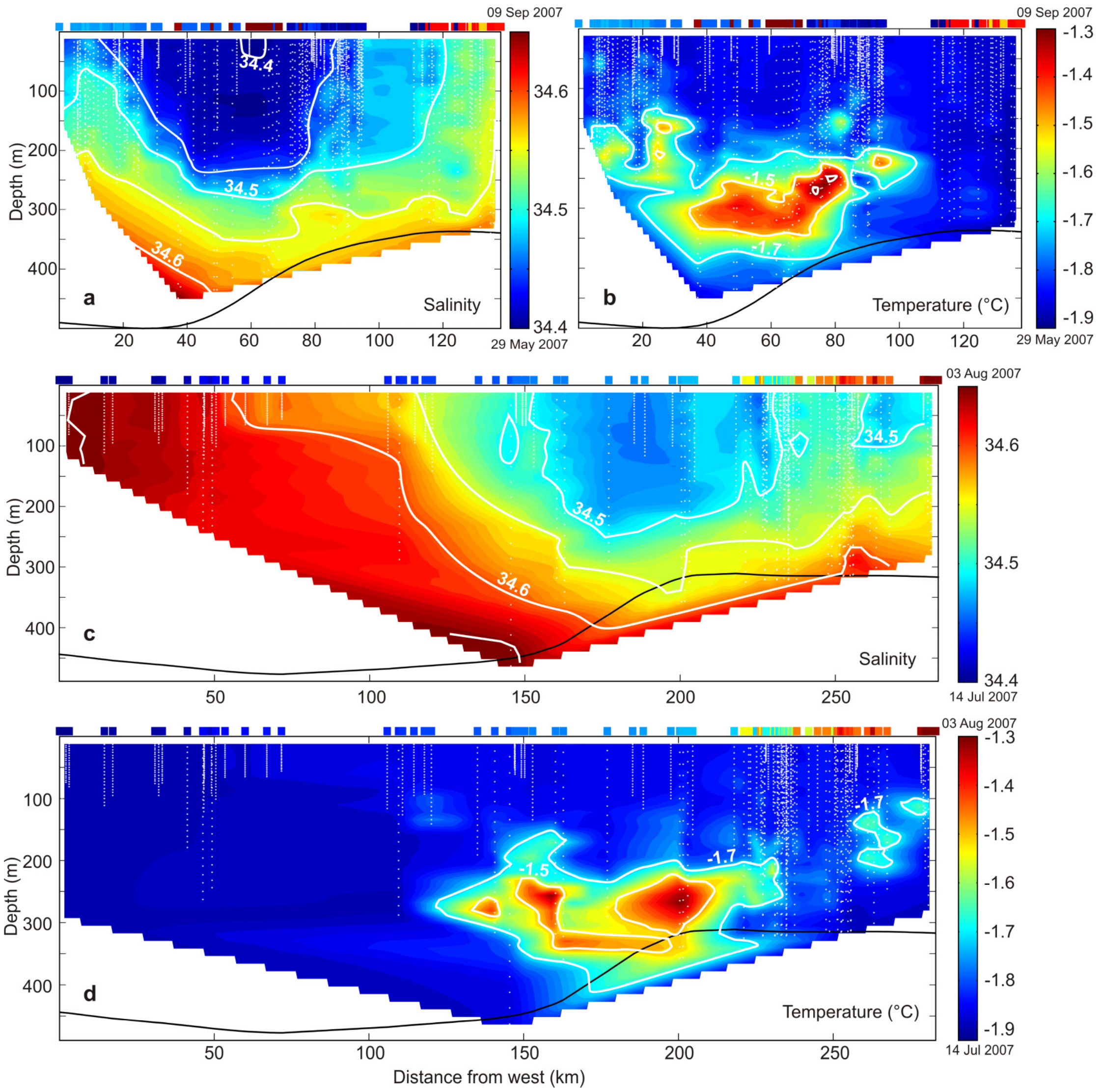

Figure 3. Salinity and temperature sections using the profiles from the northern (a and b) and southern (c and d) boxes shown in Figure 1. White dots show the locations of data points. The bathymetry from the BEDMAP dataset [*Lythe et al.*, 2001] is shown as a heavy black line. The dates of each profile are indicated by a colored square at the top of the sections, sharing the colorbar with the mapped parameter.

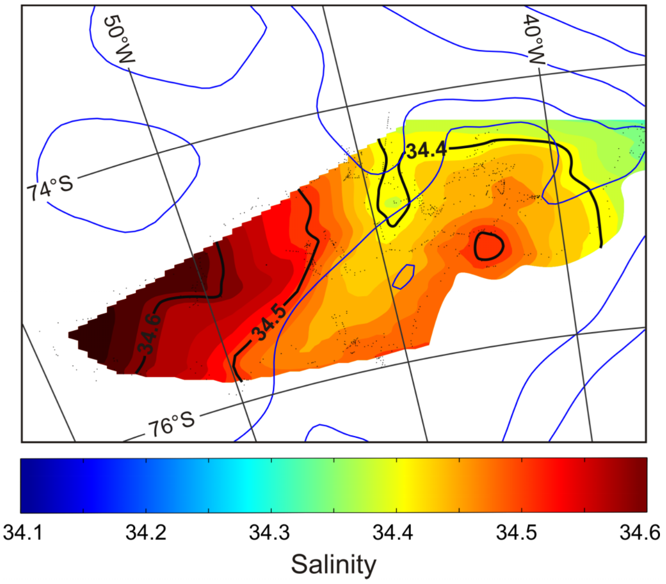

Figure 4. Surface salinity over the central continental shelf. The black dots show the locations of the data points. The area of the section is indicated in Figure 1.