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On the freshening of the northwestern Weddell Sea continental shelf

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Abstract

We analysed hydrographic data from the northwestern Weddell Sea continental shelf of three austral winters (1989, 1997 and 2006) and two summers following the last winter cruise. During summer a thermal front exists at ~64° S separating cold southern waters from warm northern waters that have similar characteristics as the deep waters of the central basin of the Bransfield Strait. In winter, the whole continental shelf exhibits southern characteristics with high Neon (Ne) concentrations, indicating a significant input of glacial melt water. The comparison of the winter data at the tip of the Antarctic Peninsula, spanning a period of 17 years, shows a salinity decrease of 0.09 for the whole water column. We interpret this freshening as a reduction in salt input to the water masses being advected northward on the western Weddell Sea continental shelf. Possible causes for the reduced winter salinification are a southward retreat of the summer sea ice edge together with more precipitation in this sector. However, the latter might have happened in conjunction with an increase in ice shelf mass loss, counteracting an enhanced salt input due to sea ice formation in coastal areas formerly occupied by Larsen A and B ice shelves.

1 Introduction

Climate change in the Southern Hemisphere is strongly evident by the atmospheric temperature rise of nearly 3 °C since 1951 at the Antarctic Peninsula (King, 1994). The decay of Wilkins Ice Shelf at the western periphery (Braun and Humpert, 2009) is supposed to be the most recent consequence of the warming. For this region, Meredith and King (2005) report a warming of 1 °C and a salinification of the surface waters for the summers 1955–1998. The warming and salinification are caused by reduced sea ice formation and, thus, decreased fresh water input due to melting as part of a surface-induced response to atmospheric (and cryospheric) changes. A similar long-term change in shelf water salinity, however of opposite sign, has been reported from the Ross Sea continental shelf (Jacobs and Giulivi, 2010). The continuous freshening since the early 1960s might have been caused remotely by increased freshwater input due to ice shelf basal melting in Amundsen and Bellingshausen Seas (Rignot and Jacobs, 2002). The freshening coincides with a positive trend of the Southern Annular Mode (SAM). The latter can be linked to a strengthening and poleward shift of the westerly winds (Thompson and Solomon, 2002), resulting in the enhanced upwelling of relatively warm Circumpolar Deep Water (CDW) onto the continental shelf (and, hence, in increased basal melting) in the Pacific sector of the Southern Ocean (Thoma et al., 2008). Other measurements from the Antarctic continental shelf, covering several decades, are rare and mostly summer biased.

Such limitation holds for the northwestern Weddell Sea. Recent observations show that this area hosts significant but intermittend sources for deep and bottom water (Schröder et al., 2002; Absy et al., 2008). The formation of deep water masses strongly depends on the availability of dense shelf water with salinities above 34.465 at a 500-m deep continental shelf break – the threshold increases for shallower shelves (Gill, 1973). The decay of Larsen A and B ice shelves (Rack and Rott, 2004) might have influenced the northwestern Weddell Sea continental shelf either due to iceberg grounding and consecutive melting or intense sea ice formation and salinification of the water column in coastal polynyas formerly covered by the ice shelves (C. Haas, personal communication, 2010). It remains speculative whether both processes balanced each other while the icebergs were stranded. However, the locations are widely separated and the continental shelf deepens towards the coast (Gilbert et al., 2003), thus, retaining dense shelf water.

During the Winter Weddell Sea Outflow Study (WWOS–ANT-XXIII/7; see Table 1 for details of all cruises used in this study) to the northwestern Weddell Sea (Lemke, 2009) hydrographic stations covered the continental shelf at the Antarctic Peninsula north of 65.1° S, revisiting a few stations of the 1989 austral winter cruise ANT-VIII/2 just northeast of the peninsula (Fig. 1). Heavy sea ice and a huge amount of grounded icebergs prevented easy manoeuvring and an exact reoccupation. However, the homogenous shelf water column in winter allows for a comparison over small horizontal distances and, therefore, the additional consideration of hydrographic data from the US-DOVETAIL cruise NBP9705 (Fig. 1b). In the following, we describe the hydrographic conditions, including the neon (Ne) and CFC distributions, on the northwestern Weddell Sea continental shelf for the austral winter of 2006. The consideration of the two winter cruises of 1989 and 1997 allows for a comparison of winter conditions over a 17-year period. In addition, hydrographic data from two consecutive austral summers 2006/07 (ANT-XXIII/8; Gutt, 2008) and 2009 (ATOS2) is described to investigate the seasonal transition of the whole shelf water column in view of the long-term changes observed on the continental shelf.

2 Data and methods

For the hydrographic measurements during ANT-XXIII/7-8 a Seabird 911+CTD (conductivity-temperature-depth) connected to a carousel (SBE 32) with 24 12-l water bottles was used. The instrument system consisted of two sensor pairs of temperature (SBE–03) and conductivity (SBE–04), a high precision pressure sensor Digiquartz, one oxygen sensor (SBE–43), a Benthos altimeter, and a Wetlabs C-Star transmissiometer. Conductivity and temperature sensor calibration was performed prior to and after the cruise at Seabird Electronics. The accuracy of the temperature sensors can be given to 2 mK. The readings for the pressure sensors are better than 2 dbar. The conductivity was corrected based on salinity measurements from water samples using a Guildline Autosal 8400 with the IAPSO Standard Seawater from the P-series P145. According to the water sample correction, salinity was measured to an accuracy of 0.002.

ATOS2 also operated with a Seabird 911 CTD-probe, equipped with oxygen and fluorescence sensors. Water samples were obtained at different depths at every station in order to measure salinity, dissolved oxygen and other biochemical parameters. Regarding salinity, a total of 90 samples were analysed onboard with a Guildline Portasal 8410A, calibrated with IAPSO Standard Seawater ampoules. The salinity of the samples ranged from 34.35 to 34.72. The linear regression between water samples and CTD values resulted in a correlation coefficient of 0.997. The mean value for the salinity residuals after the linear regression was 0.003.

During ANT-XXIII/7 a total of 46 stations were sampled in four main areas (Fig. 2):

- South Scotia Ridge with the passages to the east (South Orkney – 41° W, 61° S) and to the west (Philip – 49° W, 61° S) of the South Orkney Plateau.
- Powell Basin.
- Eastern Bransfield Strait Basin.
- Northwestern Weddell Sea continental shelf and slope.

Although a high or equally spaced distribution was desired, the actual position of the stations was strongly influenced by local bathymetry, which often had to be determined first by means of multi-beam surveys and winter sea ice conditions. As a consequence only ten casts were conducted in the shallow waters (down to 440-m depth; Fig. 1b) off the northern coast of the Antarctic Peninsula supplemented by four stations on the continental slope at ~64.2° S down to 2500-m depth (blue square plus one in Fig. 2).

Full depth sampling for stable noble-gas isotopes and CFCs occurred at a subsample of the WWOS CTD-stations (Fig. 2). Water samples for noble-gases were tapped from the niskin bottles into copper tubes, carefully preventing contamination with air during the filling. The samples were later analysed in the IUP Bremen noble-gas mass spectrometry lab (Sültenfuß et al., 2009). The measurements achieve a precision of ±0.8% or better for helium and neon concentrations and ±0.4% for δ^3He (δ^3He = 100× ([^{3}He/^{4}He]$_{obs}$/[^{3}He/^{4}He]$_{atm}$ – 1) [%]). Water samples for CFC analysis were collected from the CTD/rosette system into 100-ml glass ampoules and sealed off after a CFC free headspace of pure nitrogen had been applied. The CFC samples were later analysed in the CFC-laboratory at the IUP Bremen (Bulsiewicz et al., 1998). The accuracy of the measurement is better than 1.5% or 0.04 pmol kg^{-1} for CFC-11 and

1.5% or 0.03 pmol kg^{-1} for CFC-12 (which ever is the greater). CFC concentrations are calibrated on the SIO98 scale (Prinn et al., 2000).

For spatial and temporal comparison we also use noble-gas and CFC data from the Ice Station Polarstern (ISPOL-ANT-XXII/2) on the slope off the Larsen C Ice Shelf in 2004/2005 (Huhn et al., 2008) as well as from ANT-IX/2 (1990), ANT-XIII/4 (1996), ANT-XV/4 (1998), and from ANT-XXIV/3 in the northwestern Weddell Sea (2008, unpublished data).

Ocean surface water is mostly in equilibrium with atmospheric helium (^{3}He and ^{4}He as well as the isotope ratio ^{3}He/^{4}He) and neon, depending on water temperature and salinity. Primordial helium (with a far higher ^{3}He/^{4}He isotope ratio) entres the deep ocean from spreading regions of the submarine ridge systems (hydrothermal vents, particularly in the Pacific Ocean), and from the melting of deep-drafted meteoric ice (leading to excess ^{4}He and Ne; Hohmann et al., 2002). Chlorofluorocarbons (CFCs) are anthropogenic trace gases entering the ocean by gas exchange with the atmosphere. The evolution of these transient tracers in the ocean interior is determined by the temporal increase in the atmosphere since the middle of the 20th century and the formation, advection and mixing processes of intermediate, deep and bottom waters. Hence, transient tracers enable the determining of transit times, i.e., the time elapsed since the water has left the surface mixed layer.

3 Observations

The northwestern Weddell Sea shelf water column ($\leq$ 500 m deep) in austral winters is characterised by a narrow range in θ/S-space (gray dots in Fig. 3) with the fresh (and warm) summer surface layer missing. The highest temperatures ($> -1.1\,^{\circ}$C) are found at stations close to the continental shelf break (Fig. 1b). Maximum temperature together with the characteristic (hook) shape in θ/S-space identifies Modified Warm Deep Water (MWDW) originating from the Warm Deep Water (WDW) of the Weddell Sea or Bransfield Strait eastern basin (Gordon et al., 2000). The cluster at lower temperature, clearly separated from the stations with strong MWDW influence, represents inner shelf stations. Here, traces of MWDW are sandwiched between Winter Water (WW), at the surface freezing point, and saltier waters, termed High Salinity Shelf Water (HSSW). These stations are also characterised by high ^{4}He (not shown) and Ne values (Fig. 4) solely caused by the presence of glacial melt water. In the western Weddell Sea the same high ^{4}He and Ne values were found so far only on the continental slope off Larsen C Ice Shelf during the ISPOL experiment in 2004/2005 (Huhn et al., 2008).

To determine the fraction and inventory of pure glacial melt water, we used an Optimum Multiparameter Analysis (Tomzcak, 1981; Tomczak and Large, 1989) similar to the approach in Huhn et al. (2008). As source waters we considered pure glacial melt water (GMW, with characteristic ^{4}He and Ne excess (Hohmann et al., 2002)), Winter Water, High Salinity Shelf Water and Warm Deep Water, and potential temperature, salinity, ^{4}He, Ne, δ^3He, and mass conservation. The source water properties are summarized in Table 2. For the four available stations in the southern WWOS area (all on the continental shelf shallower than 500 m), we determined GMW fractions up to 0.4% (Fig. 5), comparable to those at the ISPOL sites.

The θ/S-space of the consecutive austral summer of 2006/07 (ANT-XXIII/8) shows a pronounced difference in shelf water temperatures across 64° S, amounting to 0.75 °C (Fig. 6). The "thermal" difference reduces to 0.5 °C with a more southern transition (∼64.5° S) for the higher sampled austral summer of 2009 (ATOS-2). The difference might have been the same in 2006/07, since the θ/S-curve of Station 728 (yellow) follows that of Station 28 (orange) towards lower temperatures and higher salinities but in shallower waters, 283 m vs. 397 m. This demonstrates the potential of a variable (but largely unknown) shelf topography to accumulate cold and salty (= dense) shelf waters. The near-bottom θ/S tendency at Station 29 (red) towards warmer and saltier waters also exists for stations further to the east, indicating that in summer traces of MWDW extend as far as the southern entrance of the Antarctic Sound at ∼56° W. The higher bottom salinities for stations south of ∼64° S indicate the remnants of salt enrichment due to winter sea ice formation. Temperatures below the surface freezing point indicate Ice Shelf Water (ISW). During ANT-XXIII/8 the southernmost stations were occupied at ~66° S, near the northern front of Larsen C ice shelf (Fig. 1a) where Nicholls et al. (2004) already had observed the outflow of glacial melt water.

4 Discussion

4.1 Summer conditions

Summer conditions on the northwestern Weddell Sea continental shelf (Fig. 6) are characterised by shelf waters covering a broader (than in winter) density range with warm/fresh surface waters on top of cold/salty winter remnants. A MWDW signature, if present, only exists close to the bottom (e.g., ATOS-2: #29). Compared to the previous winter (green curve in Fig. 3) the bottom layer remains at nearly the same salinity but shifts towards higher temperatures. Such seasonal fluctuations near the bottom were also observed at a mooring site northeast of Joinville Island, recording from 05/1996 to 03/1998 in 280-m deep waters (von Gyldenfeldt et al., 2002). The missing cold "salty foot" at the warmer northern stations indicates the drainage of dense shelf waters into the fringing Weddell Sea and Bransfield Strait basins at the end of winter. It is worthy to note that for the Weddell Sea the continental slope moorings from the same experiment as above (von Gyldenfeldt et al., 2002) show a temperature decrease during summer as well as a year-by-year (1996–1998) salt reduction of 0.013 and 0.02 (Fig. 11 in Schröder et al., 2002). For Bransfield Strait a continuous freshening of waters deeper than 1000 m and colder than $-1.4\,^{\circ}$C was observed, in accordance with our observations, for the period 1980 to 2005 (Garcia and Mata, 2005). The deep temperature, however, does not show a trend and a seasonal cycle was not recorded since the data is based on hydrographic summer surveys only.

The warming of the WW in relatively shallow waters could be caused by downward mixing of surface waters resulting from enhanced storm activity during spring together with a retreating sea ice cover or from tidal action on the continental shelf (Robertson et al., 1998). Indeed, for the northwestern Weddell Sea the long-term mean sea level pressure shows the highest meridional gradient in February (NOAA, 2009). The pattern is comparable with that of the winter months, but starting in July the low-pressure centres are located more to the South. The rapid mixing of surface water to a greater depth is also evident from CFC measurements during ANT-XXIII/7, showing nearly the same values over the whole shelf water column (bold circles, squares and triangles in Fig. 7), while confined to the surface layer over the deep basin (+ in Fig. 7). All CFC surface values have a relatively low saturation in the order of 60 ± 2% due to a dense sea ice cover. Towards the north, surface water saturations increase systematically with decreasing ice coverage (x in Fig. 7). A warming of the WW due to summer surface waters, however, should be accompanied by a freshening of the water mass. Since the latter was not observed and water mass characteristics on the northwestern Weddell Sea continental shelf were similar to those in the central basin of the Bransfield Strait, we favour a southward advance of waters of Bransfield Strait origin in summer and their retreat during the winter months. The shallow moorings (#234 and #215) of von Gyldenfeldt et al. (2002) do not unconditionally support a southward advection in summer but show events of a southerly flow from October to February (their Fig. 5).

4.2 Winter conditions

Winter-2006 conditions on the northwestern Weddell Sea continental shelf (Fig. 3) are characterised by the existence of a MWDW core at its rim, mixing with shelf water at the surface freezing point. The comparison at two sites (I and II in Fig. 1b) with nearby stations, occupied in the years 1989 (ANT-VIII/2) and 1997 (NBP9705), shows a gradual freshening of 0.09 for the 17-year period (Fig. 3). The freshening is evident from top to bottom of the < 200-m deep water column (Fig. 8) and it is comparable to the salinity decrease of 0.2 over +40 years on the southern Ross Sea continental shelf (Jacobs and Giulivi, 2010). Here, an increased freshwater flux due to the enhanced melting of ice shelves fringing the Amundsen Sea was suggested as being the cause. The thinning of Larsen Ice Shelf was attributed to increased basal melting due to warmer shelf waters (Shepherd et al., 2003), although a warming on the western Weddell Sea continental shelf lacks observations (e.g., Nicholls et al., 2004). The presence of ISW at the northern front of Larsen C Ice Shelf (Fig. 6) as well as on the western Weddell Sea continental shelf (Weppernig et al., 1996; Huhn et al., 2008) and the high Ne values at the southernmost stations in winter 2006, however, indicate the input of fresh water due to ice shelf basal melting.

In the following, we estimate the amount of glacial melt water on the western Weddell Sea continental shelf for the winter of 2006. According to the bathymetry compiled by Timmermann et al. (2010), the continental shelf volume ($< 500\,\mathrm{m}$) from the northern edge of Larsen C (66° S) to the southern rim of the central basin of Bransfield Strait (~ 62°S) amounts to $4\times10^4\,\mathrm{km}^3$. With a mean GMW fraction of 0.25% (Fig. 5) the total GMW volume results to $100\,\mathrm{km}^3$. The decay of Larsen A in 1995 and Larsen B in 2002/03 reduced the total area of ice shelf base to finally $73\,000\,\mathrm{km}^2$ (Shepherd et al., 2010). Therefore, in order to account for the GMW volume in 2006 the base of Larsen C had to melt at a rate of $1.5\,\mathrm{m\,a}^{-1}$ (ice density $917\,\mathrm{kg\,m}^{-3}$), assuming that no GMW (e.g., from Ronne Ice Shelf) was advected into the region from the south. In situ observations of melting underneath Larsen Ice Shelf do not exist. However, satellite observations indicate a volume loss of $62\pm4\,\mathrm{km}^3$ per year for the period 1994–2008 (Shepherd et al., 2010) which, if solely due to basal melting, would be equivalent to a rate of $0.85\pm0.05\,\mathrm{m\,a}^{-1}$. An even smaller melt rate of $0.35\pm0.19\,\mathrm{m\,a}^{-1}$ was deduced from a tracer analysis, based on the continental shelf and slope stations occupied during the ISPOL experiment (Huhn et al., 2008). A mean melting of $1.26\,\mathrm{m\,a}^{-1}$ resulted from the application of a two-dimensional plume model to the Larsen C cavity for a “warm case”, prescribing an ambient water temperature of −1.4 °C (Holland et al., 2009). At the westernmost station (#73) of the ANT-X/7 (Bathmann et al., 1994) cross-shelf section (Fig. 1a) near-bottom temperatures were colder than −1.7 °C, but a maximum of −1.5 °C existed at 150 m depth.

The clear separation between warmer (cooler) shelf waters to the north (south) in summer (Fig. 6) and the dominance of southern characteristics on the whole northwestern continental shelf in winter indicate a northward transport of southern water masses some time in fall. The deep Weddell Sea is dominated by a cyclonic gyre circulation, but a broader continental shelf with banks and troughs, like in the southern Weddell Sea, tends to support its own circulation pattern (e.g., Grosfeld et al., 2001). Though patchy, bottom topography in the western Weddell Sea indicates the existence of banks (Luckman et al., 2009), basins, and troughs (Timmermann et al., 2010) which would allow currents without a predominant south/north orientation. Currents still need to be recorded on the western continental shelf, but observations above the slope (Muench and Gordon, 1995), remotely controlled sea ice advection (Kottmeier and Sellmann, 1996) and iceberg drift (Schodlok et al., 2006), as well as numerical model results (Hellmer et al., 2009) all indicate a northward advection of shelf waters. Assuming the western most iceberg drift of 3 km per day to be representative for advection on the western continental shelf, glacial melt water would be transported within ~110 days from the northern Larsen C front (66° S) to the tip of the Antarctic Peninsula (63° S). With the same velocity the "thermal front" would be displaced within ~30 days from its southern position beyond the northernmost hydrographic winter stations. This indicates that the shelf water in the western Weddell Sea has a residence time of less than one year.

To clarify whether the salinity decrease observed in winter at the tip of the Antarctic Peninsula is related to increased melting at the base of the peninsula's glaciers and ice shelves, the shelf water characteristics at the inflow to the western continental shelf, i.e., south of Larsen C, have to be checked. Observations on the southwestern Weddell Sea continental shelf are sparse. The only CTD-section extending from the southern front of Larsen C to the continental shelf break was done in austral summer 1993 during ANT-X/7, roughly mid-time between the first two winter observations to the north. The consideration of profiles from different seasons is allowed, since model results from the continental shelf south of Larsen C (Haid et al., 2010) indicate that the water column below the summer surface layer does not experience any seasonal changes. The comparison of the observed salinity profiles shows that, at least for the years after 1993, the upper 200 m of the water column gained salt as it moved to lower latitudes on the western Weddell Sea continental shelf (Fig. 8). Therefore, based on the latter the observed winter freshening can be interpreted as a decrease in salt input related to reduced sea ice formation rather than increased basal melting.

The comparison of two SSMI/I (Cavalieri et al., 2006) derived decadal mean summer sea ice extents (1979–1988 and 1997–2006) shows that the sea ice edge moved southward on the northwestern Weddell Sea continental shelf during the 30-year period (Fig. 9). It might be just a coincidence that for the second decade the isoline of $>20\%$ concentration is located at 64° S, the position of the thermal front in the austral summers of 2006/07 and 2008/09. A more southerly sea ice edge indicates more melting of sea ice and, thus, an enhanced freshwater input to the north of it. In addition, a sea ice-free area allows for a warming of the surface layer in summer and for precipitation to directly freshen the water column without being advected with the sea ice until the ice floe decays. Both, freshening and warming of the surface layer, hamper sea ice formation in the following winter and, thus, reduce the salt input due to brine release.

The results of atmospheric analyses and re-analyses products together with a dynamic retrieval method to calculate precipitation for the period 1979 to 1999 show higher amplitudes and a higher mean precipitation for the South Atlantic sector (65°–75° S, 30°–60° W) starting in 1988 (Fig. 16 in Bromwich et al., 2004). The increase of the mean of 0.04 m/a for the 1989–1999 period applied to the surface area of 1.652×10^5 km^2, used above to calculate the water volume on the continental shelf (<500 m), corresponds to an additional freshwater input of 6.6×10^9 m^3 (6.6 km^3). Such freshwater input to the northwestern continental shelf would reduce the shelf water salinity by 0.005. However, considering the two peaks in 1989 and 1996 resulting from an increase in precipitation of 0.16 m a^{-1} and 0.12 m a^{-1}, respectively, the volume of freshwater added within one year would rise to 26×10^9 m^3 (26 km^3) and 20×10^9 m^3 (20 km^3), lowering the salinity by 0.02 and 0.017, respectively. Such fluctuations are similar to the salinity changes recorded on the continental slope to the east of the Antarctic Peninsula's tip at a depth of ~2500 m (Fig. 11 in Schröder et al., 2002). Events of high precipitation are also confirmed by the accumulation rates deduced from an ice core drilled on James Ross Island (Miles et al., 2008). Although with a decreasing trend, accumulation peaked in 1989, 1992, 1997, and 2000.

5 Conclusions

Based on the analysis of hydrographic and tracer data from the western Weddell Sea continental shelf we assume that the freshening observed at the tip of the Antarctic Peninsula for the austral winters of 1989, 1997 and 2006 was caused by a decrease of salt input due to a southward sea ice retreat and higher precipitation during the late 20th century. The latter, however, might have happened in conjunction with an increase in ice shelf mass loss, counteracting an enhanced salt input due to sea ice formation in coastal areas formerly occupied by Larsen A and B ice shelves (C. Haas, personal communication, 2010). Indeed, a time series of noble-gas observations on a repeat section covering the continental shelf and slope in the northwestern Weddell Sea (slightly north of the WWOS stations) shows austral summer Ne concentrations to increase systematically over the whole water column by roughly 0.10 nmol kg^{-1} per decade (Fig. 10). The freshening and spring-cooling observed on the continental slope (~2450-m depth) off the tip of the peninsula (von Gyldenfeldt et al., 2002) might be related to the southward progression of warmer waters of Bransfield Strait origin, diverting the shelf waters with southern characteristics towards greater depth. A meridional variability of the thermal front could also allow for Bransfield Strait waters to influence melting underneath the ice shelves fringing the western Weddell Sea. The lack of information on the salt balance calls for an enhanced investigation of the northwestern Weddell Sea continental shelf for all seasons covering hydrographic and glaciological surveys, satellite observations and numerical model studies. Our work also suggests acting with caution when relating a shelf water freshening solely to an increased contribution of glacial melt water.

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Table 1. List of details to the cruises mentioned in the text. AS = austral summer, AF = austral fall, AW = austral winter. ATOS2 was the Antarctic part of the bipolar Spanish project ATOS, standing for "Intake of Atmospheric Organic Carbon and Pollutants by the Polar Oceans".

Cruise	Ship	Period	Season	Acronym
ANT-VIII/2	RV *Polarstern*	06/09/1989–31/10/1989	AW	WWGS
ANT-IX/2	RV *Polarstern*	17/11/1990–31/12/1990	AS	N/A
ANT-X/7	RV *Polarstern*	03/12/1992–22/01/1992	AS	N/A
ANT-XIII/4	RV *Polarstern*	17/03/1996–19/05/1996	AF	N/A
ANT-XV/4	RV *Polarstern*	28/03/1998–21/05/1998	AF	DOVETAIL
ANT-XXII/2	RV *Polarstern*	06/11/2004–19/01/2005	AS	ISPOL
ANT-XXIII/7	RV *Polarstern*	24/08/2006–20/10/2006	AW	WWOS
ANT-XXIII/8	RV *Polarstern*	2311/2006–30/01/2007	AS	N/A
ANT-XXIV/3	RV *Polarstern*	06/02/2008–16/04/2008	AS	GEOTRACES
ATOS2	RV *Hesperides*	24/01/2009–02/03/2009	AS	ATOS
NBP9705	RV *Nathanial B. Palmer*	31/07/1997–08/09/1997	AW	N/A

Table 2. Source water properties used for the Optimum Multiparameter Analysis (OMP). GMW = Glacial Melt Water, WW = Winter Water, HSSW = High Salinity Shelf Water, WDW = Warm Deep Water

Properties	GMW	WW	HSSW	WDW
Pot. temperature [°C]	−2.3	−1.844	−1.928	0.351
Salinity	0.00	34.378	34.817	34.667
^{4}He [nmol/kg]	25.70	1.856	1.920	1.880
Ne [nmol/kg]	89.20	8.217	8.467	8.134
δHe [%]	−1.80	−0.114	−0.806	7.148

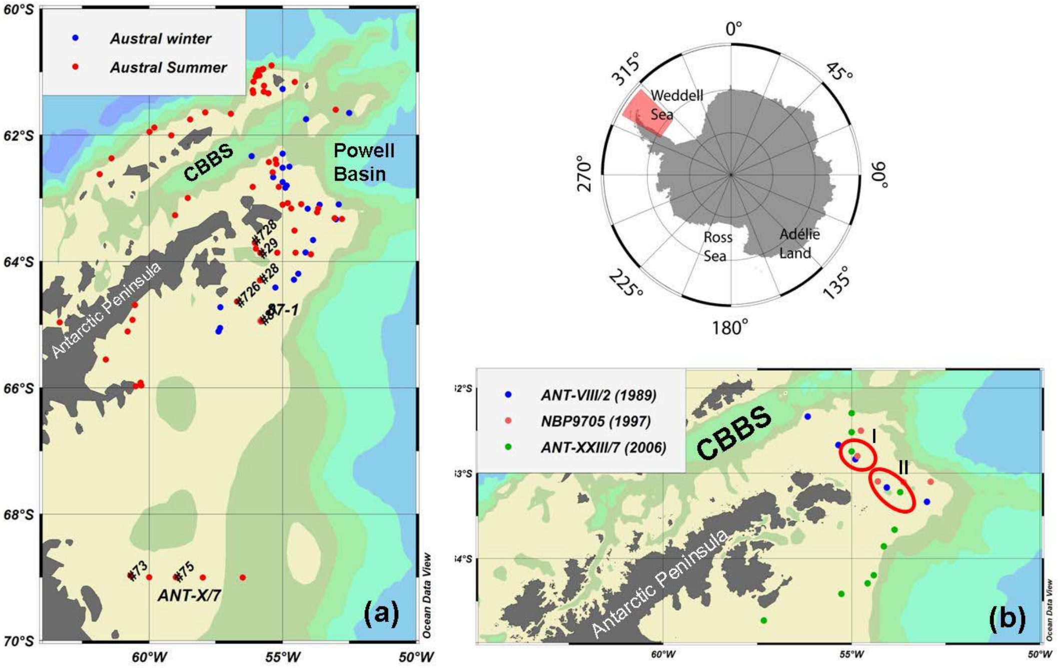

Fig. 1. **(a)** Station distribution of austral winter (blue) cruises ANT-VIII/2 (1989), NBP9705 (1997), and ANT-XXIII/7 (2006), the Winter Weddell Sea Outflow Study (WWOS), together with austral summer (red) cruises ANT-X/7 (1993), ANT-XXIII/8 (2006/07) and ATOS-2 (2009) to the shallow (< 500 m) western Weddell Sea continental shelf. Numbers refer to stations used in Fig. 6 (#28, #29, #87, #726, #728), Fig. 8 (#75), and in the text (#73). **(b)** Shallow-shelf station distribution of the three winter cruises – see insert for colour/cruise relation. Ellipse (I & II) encircles the stations providing the data for the θ/S diagrams (Fig. 3) and the profiles (Fig. 8). CBBS = Central Basin of the Bransfield Strait.

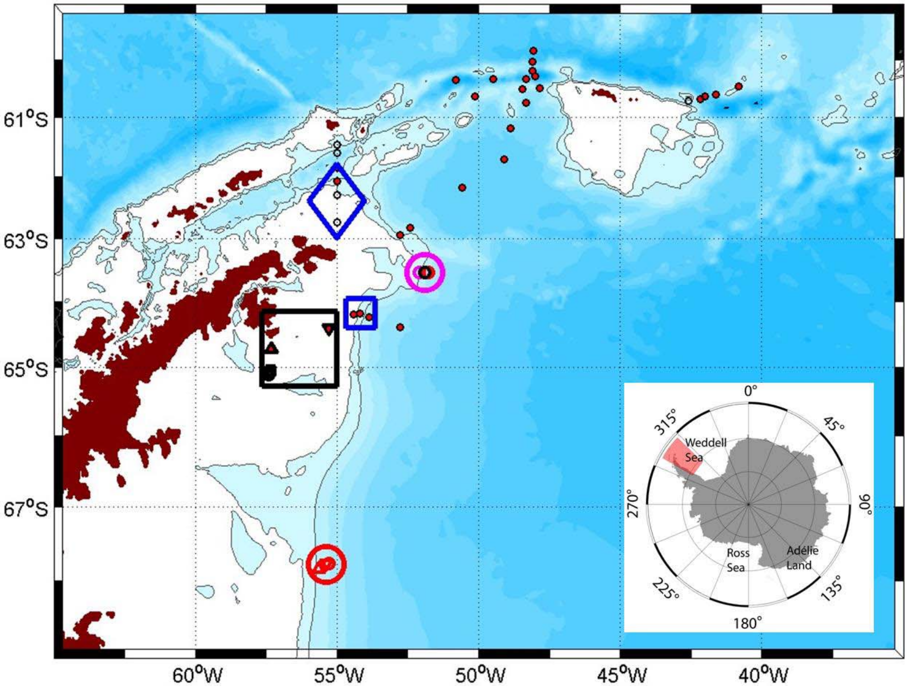

Fig. 2. Station distribution of austral winter cruise ANT-XXIII/7 (2006) to the northwestern Weddell Sea differentiated by profiles with noble-gas measurements (red dots) and CFC measurements (black open circles). The black square (with black triangles, square and circle) encloses stations which provide the neon values (Fig. 4), GMW fractions (Fig. 5) and CFC-12 values (Fig. 7). The blue diamond (blue square) borders stations which provide the CFC-12 profiles, displayed as “x” (“+”) in Fig. 7. The magenta circle surrounds stations from previous summer cruises for which the neon profiles are displayed in Fig 10. In addition, the red circle (including red triangles and circle) encloses ISPOL stations which provide the neon values added to Fig. 4. The thin grey lines represent the 500-m and 1000-m isobaths.

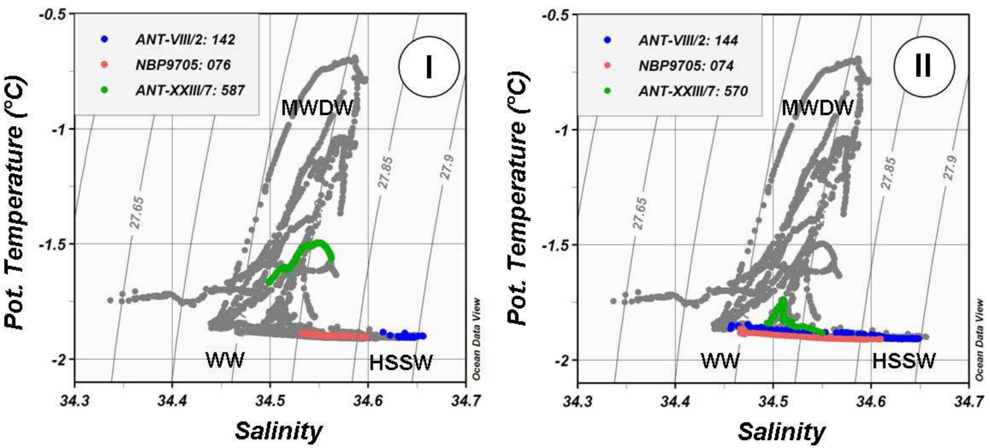

Fig. 3. Austral winter θ/S-characteristics on the shallow ($<500\,\mathrm{m}$) northwestern Weddell Sea continental shelf for cruises ANT-VIII/2 (1989), NBP9705 (1997) and ANT-XXIII/7 (2006) in gray, together with selected stations from the areas I & II (Fig. 1b), sampled during austral winters of 1989 (blue), 1997 (red), and 2006 (green). Isopycnals are drawn relative to surface pressure (σ_0). MWDW = Modified Warm Deep Water, WW = Winter Water, HSSW = High Salinity Shelf Water.

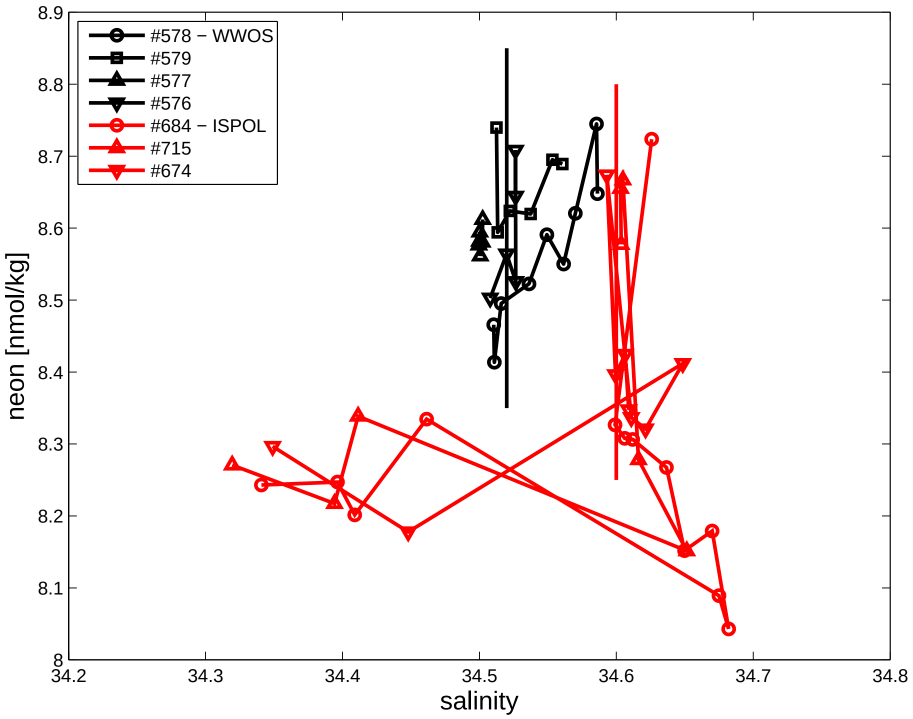

Fig. 4. Neon concentrations [nmol kg^{-1}] vs. salinity from the four southernmost ANT-XXIII/7 stations (black square in Fig. 2) and selected ISPOL stations (red circle in Fig. 2). The typical error of the Ne measurements is in the order of 0.07 nmol kg^{-1}. The solid vertical black and red lines represent the mean salinity values for the bottom layer.

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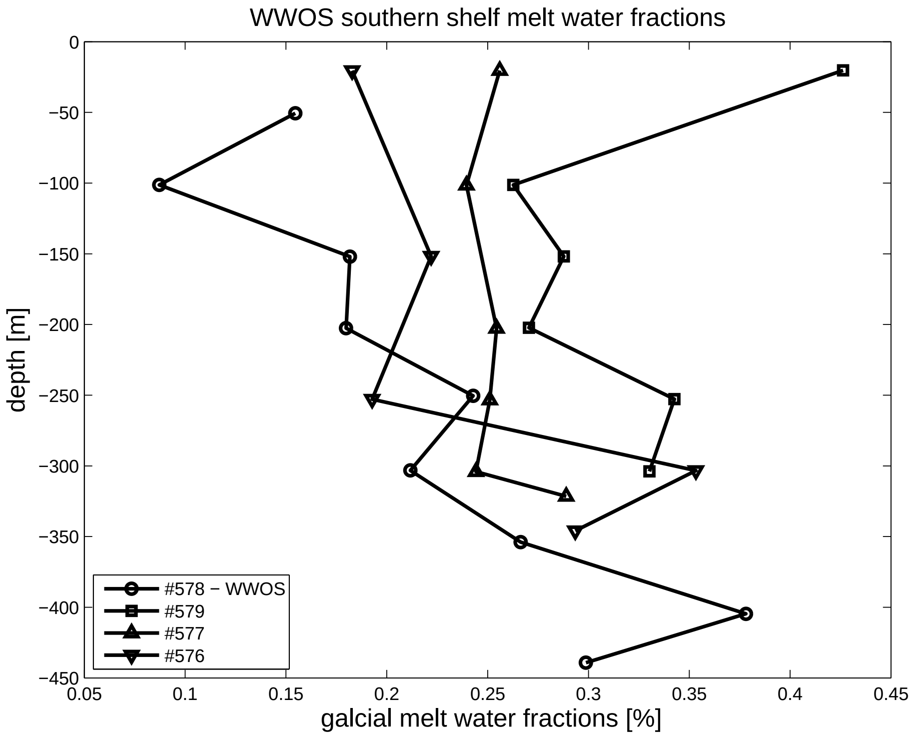

Fig. 5. Depth profiles of glacial melt water fraction [%] for the four southernmost ANT-XXIII/7 stations on the western Weddell Sea continental shelf (black square in Fig. 2). The surface sample at station # 579 might be an outlier.

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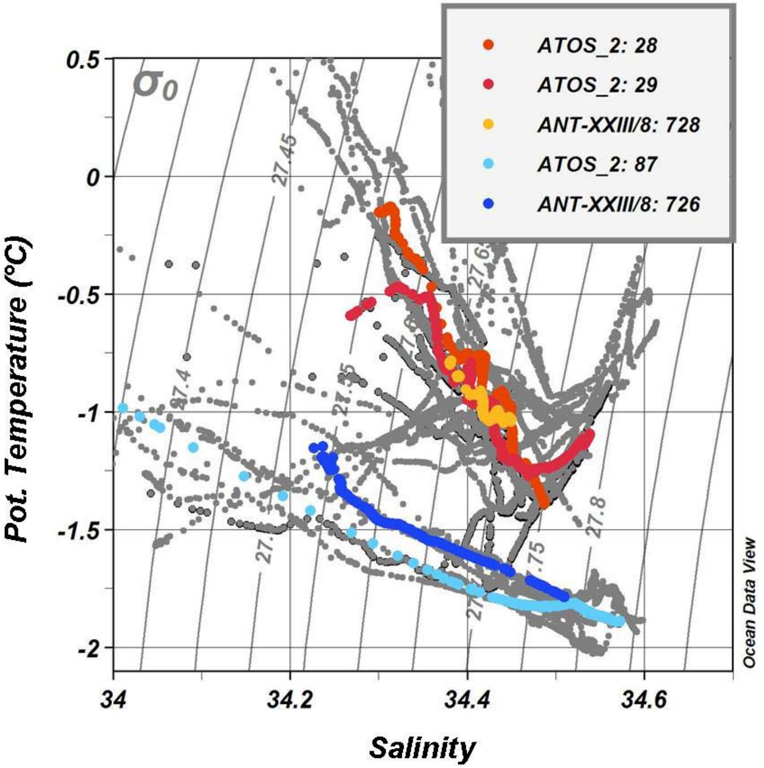

Fig. 6. Austral summer θ/S-characteristics (gray) on the shallow (<500 m) northwestern Weddell Sea continental shelf for cruises ANT-XXIII/8 (2006/07) and ATOS-2 (2009); red dots in Fig. 1a. Coloured dots depict certain stations (see insert) representing the two different "thermal" regimes on the continental shelf. Isopycnals are drawn relative to surface pressure (σ_0).

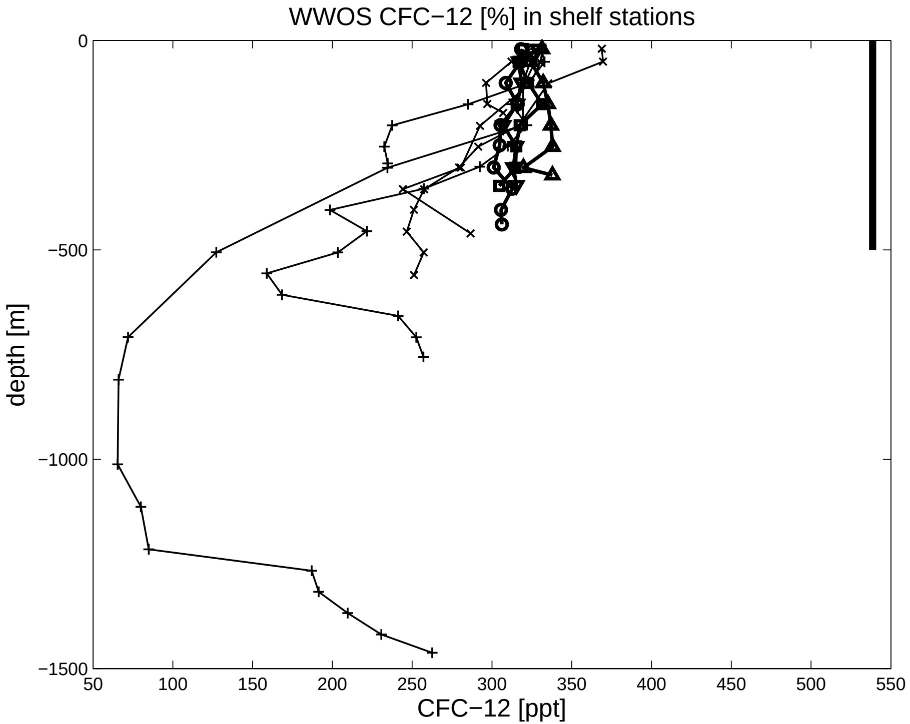

Fig. 7. CFC-12 [ppt] profiles from the northwestern Weddell Sea continental shelf (< 500 m, bold profiles from black square in Fig. 2) and the continental slope (thin profiles; "x" from northern stations – blue diamond in Fig. 2; "+" from eastern stations – blue square in Fig. 2) sampled during ANT-XXIII/7. The bold symbols (circles, squares and triangles) correspond to those in Fig. 2 and in the noble-gas vs. salinity diagram (Fig. 4). The solid line at 539 ppt depicts the atmospheric (equilibrium) partial pressure relative to the year 2006.

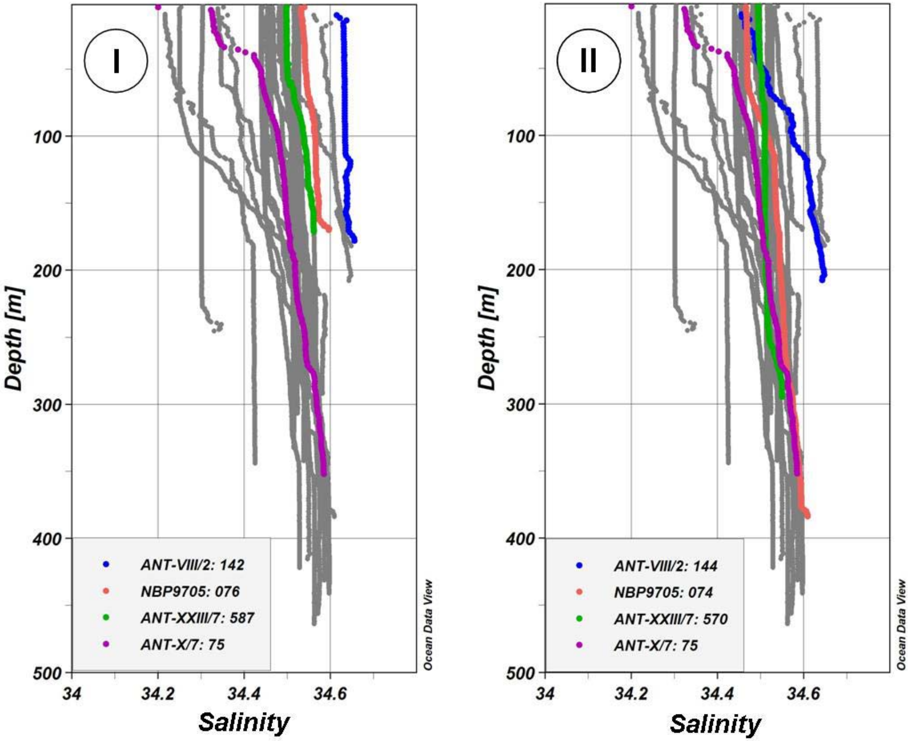

Fig. 8. Austral winter salinity profiles from the shallow (< 500 m) northwestern Weddell Sea continental shelf for cruises ANT-VIII/2 (1989), NBP97-05 (1997), and ANT-XXIII/7 (2006) in gray, together with selected stations from the areas I & II (Fig. 1b), sampled during 1989 (blue), 1997 (red) and 2006 (green). In addition, a characteristic profile from the continental shelf south of Larsen C Ice Shelf (purple) measured during austral summer cruise ANT-X/7. See (Fig. 1a) for station location.

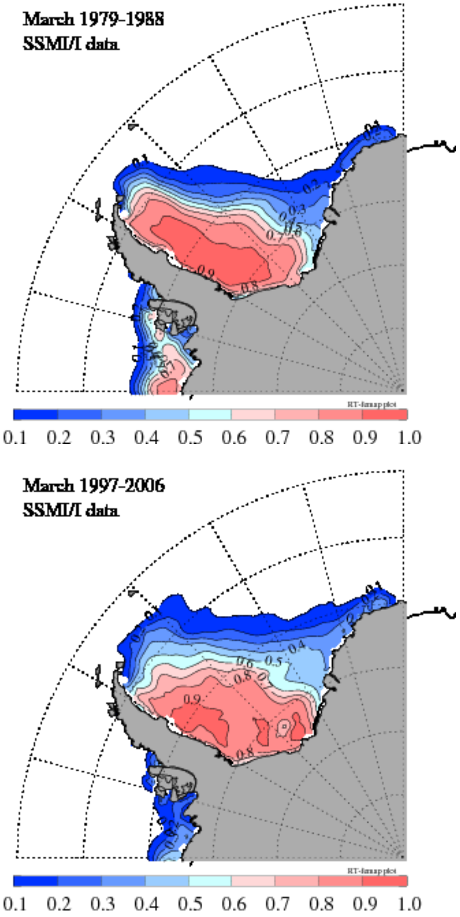

Fig. 9. SSMI/I derived decadal mean summer sea ice concentration [%] for the periods 1979–1988 and 1997–2006 for the sector 0°–90° W of the Southern Ocean showing the southward movement of the sea ice edge on the northwestern Weddell Sea continental shelf.

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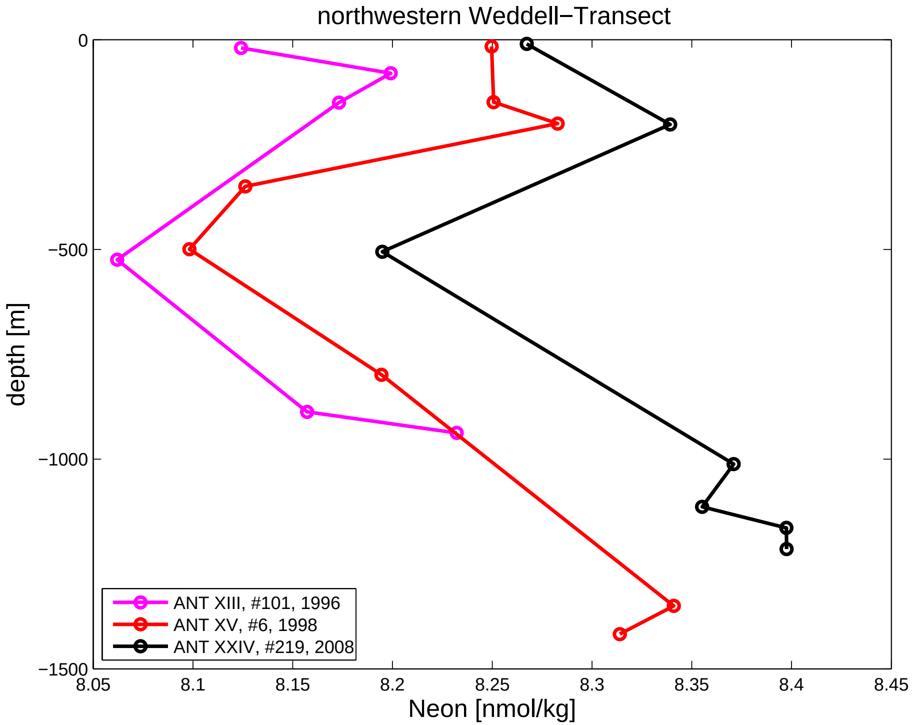

Fig. 10. Ne [nmol kg^{-1}] profiles from ADJACENT repeat stations on the continental slope (1000–1400 m depth, magenta circle in Fig. 2) in the northwestern Weddell Sea slightly north of the WWOS stations in austral summers of 1996 (purple), 1998 (red) and 2008 (black). Ne concentrations increase systematically over the whole water column by roughly 0.1 nmol kg^{-1} per decade.