Large Multidecadal Salinity Trends near the Pacific–Antarctic Continental Margin

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ABSTRACT

Ocean temperature and salinity measurements on and near the Antarctic continental shelf in the southwest Pacific sector are evaluated for evidence of temporal change. Shelf water in the southwest Ross Sea has declined in salinity by 0.03 decade$^{-1}$ from 1958 to 2008, while its temperatures have increased in proportion to the influence of salinity on the sea surface freezing point. Modified deep-water intrusions that reach the central Ross Ice Shelf have freshened at a similar rate and cooled by $\sim$0.5°C since the late 1970s. Salinity has decreased by 0.08 decade$^{-1}$ in the westward coastal and slope front currents, consistent with increased melting of continental ice upstream in the Amundsen Sea. Overturning of those near-surface waters during winter sea ice formation and mixing across the slope front is sufficient to account for the 5-decade shelf water salinity change. A strong correlation between the freshening and change in the southern annular mode index suggests a link with the large-scale atmospheric circulation. Salinity has decreased by $\sim$0.01 decade$^{-1}$ in bottom and lower deep waters north of the continental slope between 140°E and 180°. Accompanying abyssal temperature changes are minor and variability is high, but density has declined along with salinity. Continued increases in water column stratification will modify the mode and formation rate as well as the properties of bottom and deep waters produced in this region.

1. Introduction

Salinity declined along the Antarctic continental margin during the late 20th century, more so in the Pacific sector where much of the underlying data were obtained on the Ross Sea continental shelf (Fig. 1; Jacobs and Giulivi 1998; Boyer et al. 2005). Measurements there typically show shelf water generated during winter sea ice formation, with temperatures near the sea surface freezing point and salinity gradually increasing with depth. Summer observations from 1963–2000 in a 900-m depression near Ross Island (RI) showed that the high-salinity shelf water (HSSW) in this region, formerly the saltiest water in the Southern Ocean, had freshened by $\sim$0.003 year$^{-1}$. This substantially exceeded the measurement accuracy, including seawater standard variability (Jacobs et al. 2002), and closely tracked mean salinity change along the calving front of the Ross Ice Shelf (Fig. 1) and near bottom west of the date line (Jacobs and Giulivi 1998).

Additional datasets have since been acquired in the southwest Pacific–Antarctic coastal region, providing an opportunity to update the thermohaline record. Meanwhile, ocean circulation modeling raised questions about the plausibility of a salinity trend derived from irregular observations, and we wanted to investigate the feasibility of incorporating measurements in the more frequently accessed McMurdo Sound. This study was also motivated by a desire to elaborate on a contribution to the report outlined by Convey et al. (2009) and the increasing evidence of accelerating change in the upstream Amundsen Sea. We thus recalculated HSSW salinity change over a longer period, larger depth interval, and wider area, adding associated temperature observations to the analysis. The work was extended to several other water masses and areas in and west of the Ross Sea (Fig. 1), documenting changes in waters that flow on and off the continental shelf. We then discuss potential local and external atmospheric, sea ice, and ice sheet influences, concluding that most of the salinity change results from freshwater imported to the Ross Sea and noting several related implications.
2. Observations

a. Data description and the long-term record near Ross Island

Most salinity and temperature measurements used in this study were made and processed by Lamont investigators, initially from discrete Nansen or Niskin bottles mounted with mercury-reversing thermometers accurate to 0.01–0.02 for both parameters. That range has gradually narrowed to better than 0.005 as continuous profiling starting in 1967 evolved to the use of reliable conductivity–temperature–depth (CTD) instruments calibrated before and after each cruise. From the outset, salinity data acquisition and processing has included monitoring by water sampling, with adjustments as necessary to international conductivity standards. A small fraction of the data has been obtained from other reports and the National Oceanographic Data Center, and few measurements exceed 1 standard deviation of mean fields or trends in this relatively homogeneous environment. Where the data have been gridded and averaged, that is noted in the related text or figure captions.

Vertical profiles of temperature and salinity taken in HSSW north of Ross Island were previously averaged from 1963–78, 1982–97, and compared with a single low-salinity cast in 2000 (Jacobs et al. 2002). Here, we show 100-m means from all December–February profiles, adding earlier and more recent measurements at that site and in McMurdo Sound (Fig. 2). Two of the 18 profiles are averaged from adjacent stations, and all begin at 200 m to limit shelf water contamination by the higher variability of summer surface water. Recent deep salinities at the reoccupation site, within a 15-km radius of 77.167°S, 168.333°E, are no lower than in 2000, but the upper levels are fresher in 2004 and 2007. Salinity–depth gradients are weaker at depth on the more recent profiles, which overall span ~0.15 in salinity and 0.06°C in temperature near 500 m. More than 90% of the temperatures below 200 m are within 0.03°C (average +0.005) of the sea surface freezing point. A few colder profiles in the mid-1960s may have been more influenced by melting and freezing beneath the Ross Ice Shelf (RIS), and a warmer profile in December 1976 followed other anomalies that year (Jacobs and Giulivi 1998).
The Fig. 2 profiles generally shift in salinity from top to bottom from one year to the next. The gradual increase in salinity with depth provides only weak vertical stability in the shelf water column, making it sensitive to strong surface forcing in winter. The summer water column structure results from winter overturning in and seaward of coastal polynyas, along with subsequent lateral flow and mixing in concert with year-round freshening that decreases with depth. Weak salinity–depth gradients persist during winter in McMurdo Sound (Tressler and Ommundsen 1962), where fast ice limits new sea ice formation and freshwater is continuously

Fig. 2. Temperature and salinity profiles from 200 to 800 m, taken during summer from 1958 to 2008 in the high-salinity shelf water of the southwest Ross Sea, at locations shown on the inset, geographically located on Fig. 1. Here, MS = McMurdo Sound, where mostly shallower, dashed profiles are located. The plotted values are 100-m averages from CTD profiles or linear interpolations from earlier bottle data, with doubtful observations in parentheses. The horizontal lines at 200–565 m show salinity ranges from 6 bottle casts, 23 Dec 1960–9 Feb 1961, through a fast ice hole near 77.892°S, 166.735°E in McMurdo Sound (Tressler and Ommundsen 1962).
derived from ice shelf basal melting. The salinity range of those 1960–61 casts (Fig. 2) also provides a measure of summer shelf water variability.

b. Freshening and warming of high-salinity shelf water

Jacobs et al. (2002) reported a salinity trend of $-0.003 \text{ yr}^{-1}$ ($r = 0.92$) in the HSSW, based on 500-m values from the 1963–2000 profiles north of Ross Island. In this 1958–2008 update, we compared the 500-m-level salinity changes at that site ($-0.0026 \text{ yr}^{-1}$; $r = 0.98$) and in McMurdo Sound ($-0.0028 \text{ yr}^{-1}$; $r = 0.88$) and found the use of a 200–800-m average for all deep stations ($-0.0029 \text{ yr}^{-1}$; $r = 0.95$) in lieu of 500-m data. Figure 3 shows the salinity and temperature trends derived from the Fig. 2 profiles, with the HSSW salinity still declining by 0.03 decade$^{-1}$. The scatter could result from interannual variability in local sea ice production and brine drainage, changes in source water properties, or shifts in lateral gradients within the deep salinity field (Lewis and Perkin 1985; Fig. 4 below). Water column salinities lower than in 2000 have been reported beneath the McMurdo Ice Shelf on the south side of Ross Island in 2003 and attributed to heavy sea ice cover and large icebergs in the region just prior to their observations (Robinson et al. 2010).

The temperature of HSSW is buffered from rapid change by its formation at the sea surface freezing point but can be modified by subsurface melting and mixing. The shelf water temperatures in Fig. 3 trend slightly positive, by $-0.01^\circ \text{C}$ in 50 yr, close to the change that would be expected in the sea surface freezing point ($+0.009^\circ \text{C}$) for the observed salinity decline of 0.15 over the same period. That increase would not add to ocean freshening by greater melting under the RIS because the in situ melting point decreases with higher salinity and pressure and will rise at the same rate as the Fig. 3 temperature.

Assmann and Timmermann (2005) modeled the production of HSSW in the Ross Sea from 1958–2001 and compared the resulting temperature and salinity variability with our measurements at the reoccupation site north of Ross Island. They found smaller vertical gradients than indicated in Fig. 2, warmer temperatures, and salinity declines similar to the observations when averaged from 1963–78, 1982–97, and in 2000. However, their monthly time series showed interannual fluctuations on the order of 5–10 yr and no long-term trend. Subsampling that result at regular intervals then led to the suggestion that the strong salinity decline we reported could be attributed to aliasing by irregular sampling. That possibility can haunt any attempt to infer temporal change from seasonal, coastal data sporadically collected for other purposes. In this case, the record length has now been extended by a third fore and aft and the persistent salinity decline of 0.03 decade$^{-1}$ is statistically significant at the 99% level. Those authors also conducted sensitivity studies, one by replacing daily reanalysis 10-m winds with a mean annual cycle calculated over the 1978–96 period. That simulation resulted in overall higher shelf water salinity, but it decreased at about the same rate as the observations, suggesting greater model sensitivity than HSSW to short-term wind variability.
FIG. 4. (a), (b) Salinity sections near the Ross Ice Shelf, contoured from a grid formed at each degree of longitude and 20 dbars (~20 m) derived by interpolation following Smith and Wessel (1990) from CTD profiles within 2 km of the ice front (station numbers at top). The salinity field is overlain by temperature contours (darker shading) showing water warmer than ~1.6°C below the ice front draft (~200 m; lighter shading). Both panels use the bathymetry from 1984 station depths, with HB = Hayes Bank, RI = Ross Island, and MS = McMurdo Sound.
c. Freshening in the Antarctic Coastal Current

Cooling, freezing, and sea ice formation in and seaward of winter coastal polynyas convert large volumes of surface water to colder, saltier shelf water (e.g., Countryman and Gsell 1966; Assmann and Timmermann 2005). Shelf water properties will thus be influenced by surface water changes upstream in the westward-flowing coastal current. The changing salinity of that flow over time can be estimated from repeated ocean sections along the RIS Front, two of which are shown in Fig. 4 (see also Fig. 5 in Jacobs and Giulivi 1998). The locations of those transects have moved north and south as the RIS has advanced and retreated, but all were occupied within the narrow coastal current. From 1984 to 2007 the 34.2 isohaline deepened by ~200 m in the east and extended ~500 km westward as the underlying shelf water salinities declined. Averaged over the sector common to six sections (167.74-197.61°E), mean salinity in the upper 200 m decreased by 0.08 decade⁻¹ from 1967–2007 and more rapidly since the mid-1970s (Fig. 5a). The higher surface water freshening rate accounts for the lower rate of HSSW salinity change because the thinner surface layer is mixed downward during winter into the more voluminous shelf water, which also occupies much of the sub-RIS cavity (e.g., Smethie and Jacobs 2005). The progressively lower-salinity shelf water (LSSW) is able to replace its saltier, denser predecessors because they are steadily removed by basal ice shelf melting and bottom water formation. A closely related source of lower-salinity inflow to the continental shelf is described in the next section.

d. Freshening and cooling of modified Circumpolar Deep Water

A Circumpolar Deep-Water tracer characterized by a local temperature maximum and dissolved oxygen minimum typically appears beneath summer surface waters on the Ross Sea continental shelf. Along the RIS, this “modified” Circumpolar Deep Water (MCDW; Countryman and Gsell 1966) is usually best developed below 200 m between ~180° and 190°E. More than one temperature maximum is common when the CTD profiles are closely spaced, sometimes paired as in Fig. 4a. Where the features are more widely spaced, as in Fig. 4b, they could have separate origins near the shelf break or be discontinuous eddies that shoal westward along an isopycnal. The temperature of the primary MCDW intrusion near the central RIS Front cooled by ~0.5°C from the late 1970s to 2007, with the largest change occurring between the mid-1980s and 1994 (Fig. 6). Although that temperature range is similar to the annual cycle, it is twice the interannual summer variability recorded by instruments moored for nearly 4 yr in this region (Fig. 7 in Jacobs and Giulivi 1998).

The salinity in and around that MCDW near the RIS Front has decreased more slowly than in the coastal current but slightly faster (~0.04 decade⁻¹) than in the HSSW near Ross Island (Fig. 5a). Along with the accompanying temperature decline, this could point to rate or property changes in the MCDW inflow, alterations on the continental shelf, or both. Within the observed temperature range, a salinity decrease of 0.1 has the same impact on seawater density as a temperature rise of 2.5°C. As the shelf region density field has tracked salinity toward lower values, the MCDW has followed (Fig. 6), with the weakening temperature maximum maintaining its approximate location near the RIS in the vicinity of Hayes Bank (e.g., Fig. 4). Earlier work showed relatively widespread MCDW intrusions onto the continental shelf, with the access to and the flow across the shelf influenced by the bathymetry (Countryman and Gsell 1966; Jacobs et al. 1970, 1985; Dinniman et al. 2003). In the discussion below, we consider changes that have occurred near the shelf break source region for this particular MCDW inflow.
e. Freshening of deep and bottom waters

Freshening in the Southern Ocean extends over a much wider and deeper area than the Ross Sea continental shelf (Boyer et al. 2005), with thermohaline changes highlighted in several studies of the Antarctic continental margin and deep ocean basins south of Australia (Whitworth 2002; Jacobs 2004, 2006; Aoki et al. 2005; Rintoul 2007). Bottom waters in that region are influenced by westward flow from the Ross Sea and by lower-salinity additions from local processes (Gordon and Tchernia 1972; Rintoul 1998). Multidecadal freshening of the HSSW in Fig. 3 is thus a likely factor in the bottom water salinity decrease off the George V Coast (area 9 in Fig. 1), although sparse observations have made it difficult to document changes in bottom water properties in the northern Ross Sea. A recent increase in the number and distribution of measurements in both sectors improves the feasibility of comparative analyses, subject to the problems posed by the dynamic environment along the Ross Sea continental slope (Jacobs et al. 1970; Gordon et al. 2004; Whitworth and Orsi 2006).

Identification of change in scattered observations close to an active bottom water formation region can be complicated by large spatial and temporal variability, illustrated here by profiles north of the ~600-m Ross Sea continental shelf break (Fig. 7). Cold and fresh or salty bottom boundary layers are common and range widely in temperature, salinity, and thickness, even during a single cruise. That variability and the scarcity of repeat measurements at regular intervals can compromise comparisons of recent and older data that less often approach the sea floor. However, the newer profiles cover most of study area 7 in Fig. 1, occupy about the same thermohaline range in late spring and late summer, and suggest limited bottom boundary layer influence on salinity (Fig. 7b) below ~1900 m. That encouraged the averaging of observations within several hundred meters of

FIG. 6. Temperature vs salinity from continuous ocean profiles near the central RIS Front, 1976–2007, and from 1968 bottle data. The station locations were within a few km of the ice shelf front, depicted on the inset at a relatively southern position. Only measurements deeper than 200 m and warmer than −1.92°C are plotted, showing MCDW above −1.75°C with temperature, salinity, and density decreasing over time.
the sea floor on the deeper stations (Fig. 8). Property ranges are still large within individual cruises, but only one (1991) station was rejected (>2.5 standard deviation) and only two (2004) stations were more than 1 standard deviation from a salinity regression line of $-0.008$ decade$^{-1}$ (Fig. 8a). Similar trends were obtained by other methods, for example, by aggregating observations over pentadal intervals or averaging over other depth ranges. The salinity of bottom and lower deep water seaward of the continental slope in the northwest Ross Sea thus appears to have declined at about $1/4$ the HSSW rate in Fig. 3, roughly in agreement with estimates of the shelf water component in regional bottom water production (Orsi et al. 2002; Gordon et al. 2009).

The accompanying temperature observations do not reveal significant change (Fig. 8c), although small trends could be masked by the higher thermal variability shown in Fig. 7a. Even when averaged here over the lower 600 m of the water column, this variability is substantially larger than a long-term warming reported from individual stations nearby (Ozaki et al. 2009). Temperature change near the Antarctic continental margin will be damped by seasonal resetting of shelf waters to the surface freezing point and by year-round cooling from the melting of ice shelves and icebergs. The densities of these deep and bottom waters have declined along with salinity (Fig. 8b), but the scatter is higher and correlation lower because of the modulating effects of temperature and pressure.

Temperature and salinity measurements in 2004 from the continental rise off the George V Coast are combined in Fig. 9 with prior observations from the same area and also averaged over the lower 600 m. The salinity and density trends are higher than in the northwest
Ross Sea but with lower overall ranges and again no significant temperature change. The averaging obscures a cooling in the deepest observations (Jacobs 2006), demonstrating that evidence of change can depend upon treatment of the evidence. The larger salinity range in the more recent measurements may reflect improved areal coverage, along with increased Carmack and Killworth (1978) interleaving in the lower water column. As in Fig. 8, the long-term salinity trend is composed of irregular, stepwise changes and reversals, perhaps resulting from interannual and seasonal variability of the source components. Most salinity and temperature averages are lower than in the Ross Sea, as the westward drift of bottom water along the continental slope and rise is modified by downslope additions from the coastal and shelf-break currents, further freshened and cooled by the melting of ice shelves, glacier tongues, and numerous icebergs grounded along the Oates Coast continental shelf (Fig. 1).

3. Discussion

a. Atmospheric forcing

The atmosphere plays several roles in coastal salinity change, from direct air–sea exchanges and sea ice forcing to less obvious influences on the subsurface ocean circulation. Quantification of its effects in this data-sparse region is difficult, one example being the weak evidence for increased atmospheric moisture transport to high latitudes, which is expected to accompany a stronger hydrological cycle in a warming climate. Large-scale precipitation increases that might support the freshening of water masses originating in the Southern Ocean (Wong et al. 1999) are lacking in modeled precipitation on and near the Antarctic continent (Monaghan et al. 2006; A. Monaghan 2007, personal communication). One reanalysis product suggests an increase in precipitation over the circumpolar sea ice zone (Zhang 2007), but other analyses and satellite precipitation data show much smaller or negative trends in the Ross Sea from 1979–2007 (Cullather et al. 2008).

The southern annular mode (SAM) index has been rising (Fig. 5b) over the period that salinity has declined in the Ross Sea (Fig. 5a). The SAM is a primary mode of atmospheric variability in the Southern Hemisphere, with an index defined by the difference between mean surface pressure at several locations near 42° and 67°S (Marshall 2003). The increasingly positive annual SAM index values are anticorrelated \( r = -0.40 \) with salinities...
the following January (the month of most ocean measurements), derived from the HSSW salinity trend at the top of Fig. 5a. While shorter portions of those records are more highly correlated ($r = -0.52$ for the 1963–2000 interval), both are significant at the 99% level. A more positive SAM corresponds to stronger westerly winds and increased northward flow of surface waters, compensated in part by enhanced upwelling of deep water near the Antarctic continental margin (Hall and Visbeck 2002; Jacobs 2006). In a related modeling result, Assmann and Timmermann (2005) found that decreasing salinity of inflow to the Ross Sea continental shelf east of ~168°W derived from an upwelled thermal anomaly that lowered sea ice formation in the Amundsen Sea. Movement and deepening of the Amundsen Low (Turner et al. 2009) could enhance deep-water heat transport onto the Amundsen Sea continental shelf, as modeled by Assmann et al. (2008), increasing the melting of ice and decreasing the production of brine. These processes would freshen the Amundsen Sea (Jacobs 2006), perhaps reinforced by declining sea ice extent and season length there and in the Bellingshausen Sea (Jacobs and Comiso 2002; Jacobs et al. 2009). A more highly correlated ($r = 0.52$ for the 1963–2000 interval), both are significant at the 99% level. A more positive SAM corresponds to stronger westerly winds and increased northward flow of surface waters, compensated in part by enhanced upwelling of deep water near the Antarctic continental margin (Hall and Visbeck 2002; Jacobs 2006). In a related modeling result, Assmann and Timmermann (2005) found that decreasing salinity of inflow to the Ross Sea continental shelf east of ~168°W derived from an upwelled thermal anomaly that lowered sea ice formation in the Amundsen Sea. Movement and deepening of the Amundsen Low (Turner et al. 2009) could enhance deep-water heat transport onto the Amundsen Sea continental shelf, as modeled by Assmann et al. (2008), increasing the melting of ice and decreasing the production of brine. These processes would freshen the Amundsen Sea (Jacobs 2006), perhaps reinforced by declining sea ice extent and season length there and in the Bellingshausen Sea (Jacobs and Comiso 2002; Jacobs et al. 2009).

b. Changes in the sea ice

The formation of HSSW is a consequence of strong southerly winds off the RIS and intense katabatics in Terra Nova Bay, which remove heat and add brine to the underlying water columns while driving newly formed ice away from the coastline (Bromwich et al. 1998; Van Woert 1999). Salinization of the shelf water continues as the ice thickens by an order of magnitude from the outer polynya edges to the continental shelf break (e.g., Fig. 10 in Nicholls et al. 2009). A few decades ago, those processes generated particularly salty and dense HSSW in the western Ross Sea, leading to an atypical, high-salinity variant of Antarctic Bottom Water. Although brine from sea ice formation is not the major influence on bottom water salinity (Toggweiler and Samuels 1995), it is noteworthy that this shelf water salinity has steadily declined during a period when sea ice extent and the length of the sea ice season have increased in the Ross Sea (Comiso and Nishio 2008; Stammerjohn et al. 2008). Indeed, the ice extent increase in this sector since 1978 has been as large as in the entire Southern Ocean (Comiso and Nishio 2008), more than balancing decreases in the Bellingshausen and Amundsen Seas. The sea ice changes may be driven by the deepening Amundsen low, with increasing winds offshore along the RIS and onshore west of the Antarctic Peninsula (Turner et al. 2009).

The satellite sea ice record is shorter than 50 yr, with ice extent now usually tracked from 1979, following an apparent decline from the early 1970s (Zwally et al. 1983; Gloersen et al. 1992). A negative ice extent trend over several years is not uncommon, as a variety of factors cause short-term variability in the ice production and export (Kwok 2005). The underlying shelf water will also be impacted periodically by large iceberg-calving events, such as occurred several years ago in the vicinity of the HSSW study area (Lazzara et al. 1999; Martin et al. 2007; Dinniman et al. 2007; Tamura et al. 2008). Prior to its associated retreat, the RIS Front had advanced steadily northward from ~1962–2000. This reduced the open continental shelf area by several percent, which is less than the increasing ice extent from 1979–2006. Greater sea ice extent from increased production over the continental shelf would imply a stronger freeze–drift–melt cycle, with more freshwater (ice) shifted seaward or thinner ice overall. Coincidentally, a stronger wind-driven transport of surface water off the continental shelf would have been partially compensated by inflows of fresher shallow waters from the east. The differential ocean freshening rates, higher in the surface layers, would reduce upward ocean heat flux and favor thicker ice—modeled by Zhang (2007) as a response to surface warming and increased downward long wave radiation. But until we gain a better understanding of long-term variability in sea ice thickness, concentration, and transport off the continental shelf, it will be difficult to determine whether changes in local ice formation have contributed to or damped the shelf water salinity decline.

c. Changes in the continental ice

Oxygen isotope data have pointed to an increasing component of glacial melt in shelf water along the RIS (Jacobs et al. 2002), which might initially be assumed to result from faster melting of that large ice shelf. The MCDW has always had a minor impact on its average basal melt rate, however, with a shallow inflow depth relative to the overall ice shelf draft and return (northward) flow within the double-temperature maximum (Fig. 4a). More important in the present context, MCDW near the central RIS has cooled over recent decades (Fig. 6). Most of the sensible heat for basal melting is derived from the HSSW (MacAyeal 1984; Jacobs et al. 1985), the rising temperature of which would not have altered the melt rate, as noted earlier. This implies that any increase in locally generated meltwater would have to come from a stronger subice ocean circulation, if not from more common irruptions of subglacial lakes near the grounding line (Fricker et al. 2007). The salinity (density) field has shifted uniformly toward lower values along the full RIS Front (Fig. 4), implying little associated large-scale baroclinic change. Stronger offshore winds could increase upwelling and outflow near the ice front,
where observations and models suggest relatively high melt rates, but those rates and the outflow may be periodically reset by large calving events that increase the ice front thickness. The evidence is equivocal for more widespread RIS thickness change and, when dependent on an assumption of hydrostatic equilibrium, must account for changes in the underlying ocean density as well as the density of the snow, firn, and ice.

Based on the considerations outlined above, it is likely that most of the Ross Sea freshening is not generated locally but is imported from upstream, where the accelerated change includes ice shelf thinning and the increasing discharge of fast-moving ice streams (Thomas et al. 2004; Shepherd et al. 2004; Rignot et al. 2008). In the Amundsen Sea, deep grounding lines can be exposed to nearly undiluted “warm” deep-water inflows and basal melting rates are orders of magnitude higher than under the RIS (Jacobs et al. 1996; Payne et al. 2007). Much of the meltwater from thousands of decaying icebergs on and near the Amundsen continental shelf will also drift westward in the coastal and shelf break currents along the southern limb of the Ross gyre. The volume of freshwater needed to account for declining ocean salinity on the Ross Sea continental shelf can be accounted for by reported thinning rates of ice shelves in the Amundsen Sea, but that does not preclude contributions from changes in precipitation, sea ice formation, or ocean circulation.

d. Changes in MCDW inflow

The temporal changes in MCDW near the central RIS suggest its intrusion onto the continental shelf has waned over recent decades, seemingly inconsistent with the scenario of a SAM-induced strengthening of the northward Ekman flux, coupled with increased upwelling and southward transport of deep water. But change has also occurred near the Antarctic Slope Front (ASF), a strong, variable boundary between deep and shelf waters near the continental shelf break. As in the Weddell Sea, the front here is typically divided by a cold, fresh, V-shaped westward current (Gill 1973) that branches away from the coastal flow where the continental shelf widens downstream (Fig. 1). Mixing between the slope front current and deep and shelf waters near the continental shelf break. As in the Weddell Sea, the front here is typically divided by a cold, fresh, V-shaped westward current (Gill 1973) that branches away from the coastal flow where the continental shelf widens downstream (Fig. 1). Mixing between the slope front current and deep and shelf waters near the northern end of Hayes Bank leads to the MCDW on the shoreward side of the frontal zone, the properties of which vary little between the shelf break and RIS (Fig. 10). MCDW properties near the shelf break are more influenced by the shelf and slope front waters than by the deep water that provides its characteristic temperature maximum (Fig. 10, T–S insert). While that transect may not have tracked the core of the intrusion, it has appeared on more than one section (e.g., Fig. 6b in Jacobs et al. 1985).

Approximate repeat sections at 20-yr intervals across the slope front at the northern end of Fig. 10 reveal strong freshening at most levels above the deep-water salinity maximum (Fig. 11). Bergamasco et al. (2004) suggest a much larger surface and subsurface salinity rate change from 1997–2001 because of seasonal variability in a similar region in the northwest Ross Sea. Here, the waters above 200 m display the same salinity decline as surface water along the RIS (Fig. 4), with the surface values approaching 34.2 in 1984, similar to its westward progression along the ice shelf front in Fig. 4. As the salinity of westward flow along the slope front has decreased, its mixing with deep and shelf waters will have pulled the MCDW toward lower salinity and density (insert in Fig. 10). The T–S diagram also suggests warming deep water, consistent with other measurements in the southern Ross Sea gyre (Jacobs et al. 2002), whereas the MCDW is generally cooler. The latter could result from a larger component of meltwater or higher temperature variability near the frontal region, where the effects of winter surface processes can also extend deep into the water column. Assuming steady MCDW production and intrusion rates, the volumetric contribution of this external freshening source to the continental
shelf would equal that of the coastal current along the RIS, if it were similar in thickness but 5 times the width (Fig. 4a) and \( \frac{1}{5} \) the speed. Because observations and modeling indicate additional inflow locations, it remains to be determined whether the overall MCDW inflow rate has changed or mainly its properties near the central RIS.

**e. Abyssal connections**

Bottom water salinity northwest of Victoria Land (area 12, 13 in Fig. 1) decreased by 0.01–0.02 from ~1969 to 1992 (Rintoul 2007), similar to the change over that period in the longer records to its east (Fig. 8a) and west (Fig. 9a; Jacobs 2006). Adding 2003–04 measurements to this region in Fig. 12 extends the term of its salinity decline above the continental rise and reveals colder conditions south of a benthic front in the 2800–3200-m-depth range. On a \( T-S \) diagram (Fig. 13), the deep ends of most profiles bend back toward the higher-salinity bottom waters, which freshened more than 0.04 from 1967–71 to 2003–04. Most of the deepest salinities have dropped below the >34.70 criterion sometimes used to denote a Ross Sea origin, as that continuing source has freshened upstream (Fig. 8a). Projections of bottom water \( T-S \) trends to the freezing point in Fig. 13 are consistent with the larger rate of salinity change in the continental shelf component of this bottom water. While the larger salinity decrease from 1992 to 2003–04 than from 1967–71 to 1992 could support an accelerating rate of change farther west along the continental margin (Rintoul 2007), the \( T-S \) trend extensions in Fig. 13 are based on relatively few stations in a boundary current.
that may vary in speed. Tamura et al. (2008) have suggested that the downstream bottom water change resulted in part from a recent (and sudden) 30% decline in sea ice production in the Ross Sea Polynya, but most regional deep and bottom water salinity trends (Figs. 8, 9, and 13; Whitworth 2002) were ongoing during the longer period of increasing ice extent.

Shelf and near-surface waters have often provided identifying tracers for bottom water origin, although the lower deep water exerts a stronger influence on its overall characteristics (Fig. 13; Fofonoff 1956). By averaging thermohaline properties up to 600 m above the sea floor in Fig. 8, we have essentially merged the bottom and lower deep waters, which at times have been separated by the 0°C isotherm and more recently by a neutral density of 28.27 (Whitworth et al. 1998). The T–S properties above that level in Fig. 13 show that freshening of 0.01–0.02 extends well up into the lower deep water. These changes will have resulted from mixing with typically colder and fresher waters along the continental margin, some insufficiently dense to reach the abyssal sea floor. The temporal drift in near-bottom salinity in this small region over ~3.5 decades is comparable to the spatial differences between representative continental margin stations over a wider area (Fig. 3b in Orsi et al. 1999). The cause of the change seems more likely to be
The widespread freshening of near-surface components than, for example, a shifting regional influence from western to eastern Ross Sea bottom water production.

The shelf water salinity decrease has lowered its density, which in turn has lowered the salinity and density of deep and bottom waters downstream (Figs. 8, 9, and 13). Analogous to a Toggweiler and Samuels (1995) mixing hypothesis, the growing dominance of freshening over brining has rendered shelf water incapable of maintaining the former density of newly formed bottom water. Although buoyancy is also influenced by nonlinearities in the seawater equation of state, associated thermobaric effects have not compensated for the large salinity change. The rate of bottom water formation and/or ventilation of the abyssal Southern Ocean are not well established in this region, or elsewhere, with different methods, definitions, and assumptions leading to substantially different estimates (Broecker et al. 1998; Orsi et al. 2002; Jacobs 2004). A lack of bottom water formation in the eastern Weddell Sea was attributed by Fahrbach et al. (1994) to a narrow continental shelf that inhibits brine accumulation, in combination with a deep-water heat source capable of melting sufficient glacial ice to negate both that brine and the deep-water salt flux. Shallow salinities there were below a 34.465 threshold that may limit shelf and deep-water mixtures in the Weddell Sea from forming bottom water (Gill 1973). By that measure, adjusted for local deep-water properties, bottom water formation would cease in this area if the Fig. 13 thermohaline change rates were to persist for several more decades. On the other hand, Richardson et al. (2005) modeled a mere 5% decrease in the Antarctic Bottom Water overturning cell 10 yr after an instantaneous 1.0 psu freshwater pulse was applied to the upper several hundred meters everywhere south of 65°S.

It might also be conjectured that the observed salinity trends from 1958–2008 are only one limb of a longer cycle, particularly if linked to the southern annular mode. For example, SAM indices appear to vary on several time scales and were positive but trending lower in 1936 (Visbeck 2009). A January 1936 salinity profile taken from Discovery II ranged from 34.62 at 200 m to 34.87 at 800 m at 77.22°S, 170.1°E, which is about 50 km southeast of our reoccupation site (Fig. 2). Shelf water is often more stratified in that direction than in the Fig. 2 profiles, however, and inferences from a single cast could be suspect. To the extent that atmospheric circulation near the sea surface has been influenced by the ozone hole, projections several decades into the future enter the time frame when recovery of that perturbation is anticipated (Son et al. 2009). In the interim,
sectors with declining shelf water density seem likely to retain more of the ongoing freshening in the near-surface layers, experience more isopycnal modifications of deep water by large-scale interleaving, and produce less of the classical Antarctic Bottom Water.

4. Conclusions

An earlier record of high-salinity shelf water (HSSW) freshening in the southwest Ross Sea from 1963–2000, recalculated and extended here from 1958–2008, continues to show a salinity decline of 0.03 decade$^{-1}$. Associated shelf water temperatures have increased in proportion to the rise in sea surface freezing point that would accompany the observed salinity decrease. Modified circumpolar deep water (MCDW) near the Ross Ice Shelf has declined in salinity by $\sim0.04$ decade$^{-1}$ from 1967–2007, while its temperature has cooled by $\sim0.5\,^\circ$C, suggesting a lessening deep water and rising surface water influence on shelf water properties. From 1964–2007, salinity in the westward currents along the ice shelf and slope front decreased at a rate of 0.08 decade$^{-1}$. The more rapid freshening of these near-surface currents, subsequently entrained in the formation of MCDW and shelf waters, is sufficient to account for the HSSW salinity decline. The salinity trend is anticorrelated with the rising annual SAM index, indicative of a link to large-scale atmospheric change.

Bottom and lower deep waters seaward of the continental slopes in the northwest Ross Sea and George V Coast (140°E–180°) have declined in salinity by $\sim0.01$ decade$^{-1}$ over similar periods, consistent with independent estimates of shelf water involvement in the formation of abyssal waters. There has been no significant change in average temperatures within 600 m of the sea floor in those areas, but seawater density has decreased along with the salinity. North of Victoria Land, lower deep-water salinity has declined by about half the near-bottom rate from $\sim1969$–2004. Continued persistence of recent freshening rates in and west of the Ross Sea would favor deep-water modification over bottom water formation in this region. The rapidly changing salinities also have implications for studies that set specific limits on bottom water properties.

The shelf water salinity near Ross Island can serve as an index for processes occurring over a wider region, manifested by greater freshening in shallower waters upstream (to the east) and lesser freshening in deeper waters downstream. The larger salinity change in the coastal currents has increased the buoyancy of surface waters relative to the underlying shelf waters. This will have reduced upward ocean heat flux, a potential factor in increased sea ice extent in the Ross sector over the past 3 decades. The salinity decreases will also have contributed to global sea level rise, mainly by the role of freshening in the halosteric expansion of seawater (Munk 2003). Although the apparent freshwater volume needed to account for persistent freshening in the Ross Sea is less than reported from accelerated continental ice discharge and melting upstream, changes in precipitation, sea ice production, and ocean circulation strength could also be contributing to the observed salinity trends.

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