Supplementary Materials for

Warming of West Antarctic continental-shelf waters over the last century

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Materials and Methods

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Historical observations and associated uncertainty for the Bellingshausen Sea and Antarctic Peninsula

In this study, we utilize ocean observations obtained using various technologies that have been developed over the past 100 years. Early hydrographic surveys relied on bottle-mounted reversing thermometers to obtain discrete in situ temperature measurements and seawater samples, while salinity was determined using the silver nitrate titration method. Specifically, during the 1910 *Pourquoi Pas* cruise, protected Richter or Chabaud reversing thermometers attached to Richard bottles were deployed on hydrographic casts (*29,30*). In the 1930–1931 *RRS William Scoresby* and *RRS Discovery II* cruises, measurements were conducted using Nansen–Pettersson insulating bottles for shallow depths (generally above ~400 m) and Ekman reversing water bottles for deeper casts (*29,31-33*). The 1947–1948 *Brategg* observations similarly employed Nansen bottles equipped with reversing thermometers (*29,35*). From the 1960s onward, hydrographic observations in the Southern Ocean underwent a gradual but substantial technological transition. Improvements in thermometer manufacturing, pressure protection, and sensor development led to increased measurement precision, more standardized procedures, and more automated measurements. The introduction of conductivity–temperature–depth (CTD) profilers in the 1970s and their widespread adoption by the 1980s enabled continuous vertical profiles of temperature, salinity, and pressure with substantially higher vertical resolution than bottle-based methods.

Quality control for analyzed profiles

We applied quality control following the procedures described below. For the analyses in Boxes 1–5, we restricted the dataset to profiles that included both temperature and salinity measurements and contained more than five vertical levels. We also applied a water-mass range check, similar to the procedure in (*48*), and rejected a few profiles with unrealistic salinity values (mid-depth salinity <34.0 or Circumpolar Deep Water salinity >34.8). We chose not to apply the full traditional quality-control method of (*48*) because it requires detailed knowledge of climatological water-mass ranges, which is difficult to obtain for continental shelf regions with significant changes in mCDW properties within short distances.

In situ temperature measurements and uncertainty

In situ temperature measurements obtained from reversing thermometers are subject to several sources of uncertainty. Instrumental errors arise from calibration limitations and scale imperfections in early mercury thermometers. Additional uncertainty is introduced by pressure effects, particularly for unprotected thermometers, as hydrostatic compression alters the mercury column. Reading and transcription errors further contribute to random uncertainty. Collectively, these factors result in temperature uncertainties that are larger and less well constrained than those associated with modern electronic sensors. Following previous studies (*47,49*), we adopt an uncertainty of ±0.02 °C for bottle-based temperature measurements obtained using reversing thermometers. After the introduction of CTD profilers, temperature uncertainties are typically on the order of ~10^{-3} °C, based on manufacturer specifications.

Salinity measurements and uncertainty

During the 1930s, salinity was determined using the silver nitrate titration method, which measures the concentration of halide ions in a seawater sample, referred to as chlorinity. At the time, the relative proportions of the major dissolved ions in seawater were assumed to be globally constant. Based on this assumption, total salinity was derived from chlorinity using Knudsen's empirical relationship (*42*). This method was labor-intensive and required favorable sea conditions, as the chemist had to visually identify the colorimetric endpoint of the titration reaction. Under optimal conditions it achieved a nominal precision of approximately ±0.02 ‰, roughly an order of magnitude poorer than the precision of modern conductivity-based salinity sensors. Salinity derived from silver nitrate titration is subject to both random and systematic uncertainties. Random errors arise from uncertainties in the concentration of the silver nitrate solution, subjective endpoint detection, ship motion, operator fatigue, and sample handling issues such as contamination, evaporation, or incomplete rinsing of sample bottles, which could leave residual salt crystals and introduce sample-to-sample variability. Temperature control during titration is also important, as seawater density and reaction stoichiometry are temperature dependent; incomplete temperature equilibration can therefore introduce additional bias. Collectively, these effects imply a random measurement noise exceeding ±0.02 for individual samples. Systematic biases may also arise from the reference standards used for calibration, in particular the so-called Copenhagen Water (early IAPSO Standard Seawater). Evaluations of global hydrographic datasets have identified systematic offsets in historical salinity records associated with early standard seawater batches (*43,45,46*). In addition, historical salinity values were commonly reported on the Knudsen scale (‰), which is not strictly equivalent to modern conductivity-based definitions of salinity. Although differences between Knudsen salinity and later practical salinity scales are generally small, this tiny error (in the order of $\sim 10^{-4}$) is also added to the uncertainty.

Following previous studies (*45*) and taking these factors into account, a conservative uncertainty of ±0.05 is assigned to salinity measurements derived from chemical titration. The unit conversion from between Knudsen salinity (‰) and PSS-78 practical salinity ($\leq$ O(0.01)) is negligible compared with the uncertainty of historical titration-based measurements; therefore, no unit conversion is applied to the historical data, and the uncertainty is treated conservatively. For data collected during the transitional period from approximately 1960 to 1980, when inductive and bench conductivity salinometers replaced titration but predated full standardization under PSS-78, an uncertainty is estimated to be in the order of ±0.01 (*45*). In contrast, modern salinity measurements obtained using calibrated CTD conductivity sensors and Autosal-analyzed bottle samples typically achieve uncertainties of ±0.002–0.003.

Depth measurement and uncertainty

Early hydrographic depth determinations were based on wire length, not direct pressure measurement; the actual instrument depth could be less than the wire-out length due to wire sag, ship motion, and ocean current (*44*). Because of these physical limitations, a vertical uncertainty of order ±5% of the nominal sampling depth is adopted here, consistent with practices in the handling of historical hydrographic data (e.g., *44,48-50*). Most measurements prior to—and in some cases after—the 1950s were reported at approximate discrete depths (e.g., 100 m, 200 m, 300 m). For example, at typical Circumpolar Deep Water (CDW) depths (~500 m), this corresponds to an uncertainty of approximately ±25 m.

Potential density measurements and uncertainty

Combining this information, for typical Circumpolar Deep Water conditions (temperature 1 ºC and salinity 34.7 at 500 m depth), the associated uncertainty in potential density measurements obtained from water bottles using the titration method is estimated to be approximately ±0.1 kg m^{-3}. This uncertainty decreases to less than ±0.01 kg m^{-3} for measurements obtained from water bottles when salinity is determined via conductivity, even for the period before full standardization under PSS-78. The uncertainty for the modern period is even lower and it is not considered in this study.

Historical observations in the Amundsen Sea and associated uncertainty

For the Amundsen Sea, we identified historical on-shelf observations from 1975 and 1985, collected during the USCGC Burton Island and USCGC Glacier campaigns led by the USA respectively as summarized in Table S4 (*39,40*). Both campaigns obtained only in situ temperature profiles using expendable bathythermographs (XBTs). A depth correction (*62*) was applied to these observations, and the known issue about depth bias is discussed in the main text. XBT measurements are also known to exhibit temperature biases. However, our analysis focuses on the depth of the thermocline, where strong vertical temperature gradients occur over small depth ranges; such temperature biases are unlikely to influence our conclusions. In addition, an offshore oceanographic survey of the Amundsen Sea was conducted in 1960 also by USCGC Burton Island and USCGC Glacier campaigns, during which both temperature and salinity measurements were obtained (*41*).

Modern observations for Amundsen and Bellingshausen Seas

For the modern period (post-1990) in the Amundsen and Bellingshausen Seas, we use observations from the World Ocean Database (WOD; *29*), restricting the dataset to profiles that include both salinity and dissolved-oxygen measurements. This restriction excludes some WOD records (particularly biologging data) that are not fully calibrated and can exhibit large salinity biases, while retaining sufficient data to characterize typical conditions over the past few decades. Similar issues have been reported in the Ross Sea (*54*), where observed salinities show comparable biases. In addition to the WOD data (*29*), we incorporate calibrated ship-based observations collected in the Bellingshausen Sea (*51-53*).

Along-slope geostrophic current

We calculate the along-slope baroclinic velocity from the geostrophic balance (Extended Figure 5) using, $\partial u/\partial z = -(g/(\rho_0 f))\,(\partial \rho/\partial x)$, where u is the along-slope velocity, g is gravitational acceleration, ρ is density, ρ_0 is a reference density, and f is the Coriolis parameter. The Coriolis parameter and reference density are set to $f = -1.4 \times 10^{-4}\ s^{-1}$ and $\rho_0 = 1027$ kg m^{-3}, respectively. We assume a horizontal separation of 50 km between the on-shelf and off-shelf profiles, which affects the magnitude of the inferred along-slope geostrophic velocity. However, our analysis focuses only on the vertical structure of the along-slope velocity, specifically whether eastward flow can be identified at depths below 200 m. Consequently, the assumed profile separation does not affect the conclusions of this study.