Freshwater fluxes in the Weddell Gyre: Results from δ18O

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**Abstract**

Full-depth measurements of δ18O from 2008-2010 enclosing the Weddell Gyre in the Southern Ocean are used to investigate the regional freshwater budget. Using complementary salinity, nutrients and oxygen data, a four-component mass balance was applied to quantify the relative contributions of meteoric water (precipitation/glacial input), sea-ice melt and saline (oceanic) sources. Combination of freshwater fractions with velocity fields derived from a box inverse analysis enabled the estimation of gyre-scale budgets of both freshwater types, with deep water exports found to dominate the budget. Surface net sea-ice melt and meteoric contributions reach 1.8% and 3.2%, respectively, influenced by the summer sampling period, and –1.7% and +1.7% at depth, indicative of a dominance of sea-ice production over melt and a sizable contribution of shelf waters to deep water mass formation. A net meteoric water export of ~37 mSv is determined, commensurate with local estimates of ice sheet outflow and precipitation, and the Weddell Gyre is estimated to be a region of net sea-ice production. These results constitute the first synoptic benchmarking of sea ice and meteoric exports from the Weddell Gyre, against which future change associated with an accelerating hydrological cycle, ocean climate change and evolving Antarctic glacial mass balance can be determined.

Keywords: Antarctic Bottom Water; freshwater cycle; oxygen isotope; dense water export.

1. **Introduction**

The Weddell Gyre is an important region in the global climate system due to its prominent role in the formation and export of the deep and bottom waters that flood the global abyss [[1](#_ENREF_1)], and the associated sequestration of carbon, nutrients and atmospheric gases at depth on climatic time scales [[2](#_ENREF_2), [3](#_ENREF_3)]. These processes are critically sensitive to the freshwater balance of the region: at low temperatures, density (and by extension stratification, circulation and deep water formation) depends almost entirely upon salinity [[4](#_ENREF_4)] and so will be sensitive to fluctuations in the local freshwater balance caused by changes in glacial discharge, precipitation and the melting/production of sea-ice.

Model studies indicate that dramatic effects on both regional and global climate can occur on relatively short time scales if the Southern Ocean freshwater balance is altered [[5](#_ENREF_5), [6](#_ENREF_6)]. In an era of global warming, a modified hydrological cycle is expected (e.g. [[7](#_ENREF_7)] and references therein) with high latitudes strongly impacted [[8](#_ENREF_8)]. Initial evidence has shown that these effects may already be occurring, with general decreases in the salinity of the Southern Ocean identified over the last fifty years [[9](#_ENREF_9)]. Regional freshening signals have also been identified in the surface waters of the Ross Sea [[10](#_ENREF_10)], before being transferred to deep and bottom waters [[11](#_ENREF_11)].

In the Weddell Gyre, a number of trends in the freshwater system are emerging: for sea-ice, general increases in extent and area over the last 30 years have been detected [[12](#_ENREF_12), [13](#_ENREF_13)] with contrasting mechanisms being postulated, including increased upper-ocean stratification caused by accelerated glacial melt or atmospheric / oceanic warming [[14](#_ENREF_14), [15](#_ENREF_15)], and changes in wind stress [[16](#_ENREF_16)]. Net precipitation is thought to be intensifying [[17](#_ENREF_17), [18](#_ENREF_18)], although exact trends remain poorly constrained [[19](#_ENREF_19), [20](#_ENREF_20)], whilst elevated glacial discharge into the region [[21](#_ENREF_21)] has led to the freshening of both shelf waters [[22](#_ENREF_22)] and bottom waters [[23](#_ENREF_23)], primarily linked to increased ice shelf calving and the speeding up of tributary glaciers in the vicinity of the Larsen Ice Shelves [[24](#_ENREF_24), [25](#_ENREF_25)].

The response of the Weddell Gyre to these changes in freshwater forcing and their impact on deep water formation and associated biogeochemical tracers is uncertain. However, it is clear that they are affecting the formation characteristics of deep waters in the gyre [[23](#_ENREF_23)]. As the different components of the freshwater system may in principle vary independently, it is necessary to determine the behaviour of (and change in) each component individually if we are to generate predictive skill concerning how the integrated system will change overall. This is difficult to achieve over large scales in a comprehensive, internally consistent manner, and historically sparse spatio-temporal sampling has hampered an in-depth assessment of the region. Here, we investigate the freshwater composition of water masses entering and exiting the Weddell Gyre through measurements of oxygen isotopes in seawater (δ18O), obtained on three full-depth hydrographic cruises that jointly enclosed the gyre between the Antarctic Peninsula and ~30°E. At high latitudes, δ18O combined with measurements of salinity enables the partitioning and quantification of freshwater from meteoric (glacial ice melt, precipitation) and sea-ice melt sources [[26](#_ENREF_26)]. Individual box budgets and discrete transports of the different forms of freshwater are derived by solving a four-component mass balance for each water sample and combining with volume-conserving velocity fields. This enables us to quantify quasi-synoptically, for the first time, the individual exports of meteoric and sea-ice freshwater sources from the gyre into the global oceanic thermohaline circulation.

1. **Data and Methods**

2.1 δ18O as a freshwater tracer

Away from the influence of melting and freezing, δ18O, the ratio of H218O to H216O referenced to Vienna Standard Mean Ocean Water (VSMOW), behaves in a similar fashion to salinity; being increased by evaporation (E) and decreased by precipitation (P), an almost linear S / δ18O relationship emerges whose slope is dictated by regional E / P characteristics [[27](#_ENREF_27)]. Below the surface, both salinity and δ18O are conservative tracers. However, the latitudinal variability of δ18O in precipitation caused by temperature-related fractionation sets it apart: whilst salinity is unaffected, high (low) latitude precipitation is depleted (enriched) in δ18O, causing values as low as –57‰ in snow at 83°S [[28](#_ENREF_28)]. The very low δ18O values in the Antarctic Ice Sheet have been very useful in determining the contribution of glacial ice melt to Antarctic Bottom Water (AABW), the formation of which takes place around the continent’s periphery [[29-32](#_ENREF_29)]*.* In addition, the different impacts on δ18O and salinity that occur during sea-ice formation and melting can be used to investigate freshwater contributions from this source: whilst salinity responds strongly to brine rejection or freshwater addition, δ18O is only marginally affected by either process. Under equilibrium conditions, freezing produces sea ice with an isotopic signature that is only slightly heavier than the seawater from which it derives, with the fractionation factor being of order 1.0026-1.0035 [[33](#_ENREF_33), [34](#_ENREF_34)]. Accordingly, concurrent measurements of δ18O and salinity at high latitudes are useful in discerning freshwater inputs of isotopically-lighter meteoric sources from isotopically-heavier sea-ice melt sources [[30](#_ENREF_30), [35](#_ENREF_35), [36](#_ENREF_36)].

2.2 Oceanographic and Cryospheric Setting

Figure 1 shows station locations for the three ANDREX cruises forming a box around the Weddell Gyre, regional ocean fronts, and recent historical sea-ice extent at the time of each cruise from National Snow and Ice Data Center, Boulder, Co, USA, [[37](#_ENREF_37)]. The transects bounding the box extended northward along 30°E from the Antarctic continent to approximately 52°S (US CLIVAR cruise I06S on R/V *Roger Revelle* (February 2008) [[38](#_ENREF_38)]) then westward along the northern extent of the Weddell-Enderby basin and following the South Scotia Ridge (SSR) to the Antarctic Peninsula (UK Antarctic Deep Water Rates of Export (ANDREX) cruise JC30 on RRS *James Cook* (January 2009) 30°E to ~17°W [[39](#_ENREF_39)], UK ANDREX cruise JR239 on RRS *James Clark Ross* (March 2010) ~17°W to 57°W [[40](#_ENREF_40)]).

Hydrographically, the region is influenced by the Antarctic Circumpolar Current (ACC), which flows unhindered around the continent from west to east and whose transport is concentrated in a number of frontal jets. The two most southerly - the Southern ACC Front (SACCF) and the Southern Boundary of the ACC - cross through the northeastern corner of the ANDREX box, and mark the furthest poleward extent of Circumpolar Deep Water (CDW). This water mass flows from the ACC into the Weddell Gyre at its eastern edge before recirculating as Warm Deep Water (WDW), and is the source of all water masses south of the Southern Boundary [[41](#_ENREF_41)]. A substantial input into the gyre occurs at the Antarctic Slope Front (ASF) at 30°E, which separates the colder, fresher continental shelf waters from the warmer, saltier waters to the north, and which flows into the gyre transporting relatively recently ventilated varieties of AABW from further east [[42-44](#_ENREF_42)]. Export from the gyre is concentrated at the Weddell Front (WF), which is roughly located at the eastern end of the SSR, and marks the northern limb of the gyre, separating colder WDW to the south from warmer CDW to the north [[45](#_ENREF_45), [46](#_ENREF_46)].

Perennial sea-ice occurs only in the southwest corner of the gyre, although almost complete coverage across the region is observed in winter. Intense air-sea interaction and sub ice-shelf processes [[47](#_ENREF_47), [48](#_ENREF_48)] result in strong densification of Antarctic shelf waters, which then mix with modified forms of WDW to create Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW) [[49](#_ENREF_49)]. Collectively, WSDW and WSBW represent the Weddell Sea contributions to the AABW that occupies the abyss of much of the Atlantic. δ18­O data from the region around the Filchner-Ronne Ice Shelf in the southern Weddell Gyre [[30](#_ENREF_30)] have shown marked influence of such ice-shelf melting on the isotopic composition of the WSDW and WSBW formed there.

2.3 The ANDREX dataset

Approximately 1200 samples for δ18O analysis were collected from 95 geographical locations during the three cruises (Figure 1). Full-depth Conductivity-Temperature-Depth (CTD) profiles were completed using 24 (UK cruises) and 36 (US cruise) Niskin bottle rosettes, with bottle samples taken for the analysis of salinity, dissolved oxygen, nutrients, and a range of other tracers. Samples for δ18O were taken on intermediate stations at 12-15 depths covering the full water column in new 50 mL glass bottles sealed with plastic stoppers and aluminium crimp seals to prevent evaporation. These were transported to the Natural Environment Research Council Isotope Geosciences Laboratory (NIGL, Keyworth, UK) and analysed for oxygen isotope ratios using an equilibration method and dual inlet mass spectrometry [[50](#_ENREF_50)], achieving a precision of better than ±0.02‰.All data are available from the British Oceanographic Data Centre (<http://www.bodc.ac.uk>). Phosphate concentrations were measured by standard colorimetric methods. On I06S, an ODF(Scripps)-modified 4-channel Technicon Autoanalyzer II was used, following [[51](#_ENREF_51)]. Calibrations were performed before and after every station using an intermdiate concentration standard from a diluted stock [[38](#_ENREF_38)], with periodic analysis of 7 different standard concentrations for linearity-response checks. On JC30 & JR239, a segmented continuous-flow Skalar San Plus autoanalyser was used, following [[52](#_ENREF_52)]. Calibrations were made daily using 5 different standard concentrations. A precision of <0.02 umol/kg was achieved [[39](#_ENREF_39), [40](#_ENREF_40)].

Oxygen measurements were performed following a standard automated Winkler titration technique with photometric end-point detection [[53](#_ENREF_53)] on I06S [[38](#_ENREF_38)], and amperometric end-point detection [[54](#_ENREF_54)] on JC30 & JR239, with a precision <0.3 umol/L [[39](#_ENREF_39), [40](#_ENREF_40)].

2.4 Determination of freshwater sources

To enable the partitioning and quantification of the different freshwater sources, we solved a four-component mass balance for each bottle location where δ18O was determined:

1. *f*CDW*+ f*SIM *+ f*MET *+ f*WW*=* 1,
2. *S*CDW·*f*CDW*+ S*SIM·*f*SIM *+ S*MET·*f*MET *+ S*WW·*f*WW*= Smeas*,
3. *δ*CDW·*f*CDW*+ δ*SIM·*f*SIM *+ δ*MET·*f*MET *+ δ*WW·*f*WW*= δmeas*,
4. *PO*CDW·*f*CDW*+ PO*SIM·*f*SIM *+ PO*MET·*f*MET *+ PO*WW·*f*WW*= POmeas*,

where *f* is the derived fraction, *S* is salinity, *δ* is δ18O and ‘*PO’* the quasi-conservative tracer ‘PO’ = [O2] + 170·[PO43-] similar to that introduced by [[55](#_ENREF_55)]. ‘PO’ is set at the surface where oxygen is assumed to be a fixed saturation and dependent on the saturation-temperature relationship, and the nutrient concentration is its preformed value. Away from the surface, respiration will change individual oxygen / phosphate concentrations but not ‘PO’ through use of a standard remineralisation ratio, thus making it a useful sub-surface tracer of water types of different surface origin. In this case, the remineralisation ratio is from [[56](#_ENREF_56)], having previously been applied in the Weddell Gyre [[57-61](#_ENREF_57)]. Surface ocean oxygen saturation can fluctuate as biological activity, upwelling and sea-ice coverage impact air-sea gas exchange and oxygen's ability to reach equilibrium with the atmosphere [[62-64](#_ENREF_62)]. Here, we follow [[57](#_ENREF_57), [64](#_ENREF_64)] in assuming full saturation of winter surface water oxygen at the point of sea-ice onset and surface capping. Whilst idealistic, any error in this estimate will apply similarly through the water column and across endmembers, and its usefulness as a tracer will not be impacted. Equations 1-4 are used to determine the contributions from CDW (Circumpolar Deep Water), SIM (sea-ice melt), MET (meteoric water) and WW (Winter Water at the Eastern Boundary). This extends the approach of a three-component inversion as applied by e.g. [[36](#_ENREF_36)]. Here, a fourth component was also utilized in order to incorporate the effect of external sources of relatively fresh oceanic waters on the Weddell Gyre box budget: Winter Water at the temperature minimum adjacent to the continental slope at the eastern boundary, with its predominant westward flow as part of the Antarctic Slope Front and clear ‘PO’ section maximum, was taken as representative of this.

The choice of reliable mean values for undiluted source endmembers (from which samples on the section are formed through mixing) is important in obtaining realistic representations of the freshwater contributions to a water sample. For CDW, the maximum values on the section for this water mass for salinity (34.752) and δ18­­O (+0.07‰) and the minimum value for ‘PO’ (552 μmol·kg-1) were applied. These values represent the local variety of CDW entering the Weddell Gyre, and thus will not be representative of ‘pure’ CDW further north in the ACC, but are nonetheless the appropriate values to use here. For WW at the Eastern Boundary, characteristics at the temperature minimum were applied (salinity = 34.2461, δ18O = -0.24 ‰ and ‘PO’ = 675 μmol·kg-1) and were found to be representative of other historical data in the region [[65](#_ENREF_65), [66](#_ENREF_66)]. For meteoric water, the salinity endmember was set to 0, whilst for sea-ice a salinity of 5 [[67](#_ENREF_67)] and a δ18O of +1.8‰ (taken as representative of surface waters in this region adjusted for the fractionation that occurs during freezing e.g. [[68](#_ENREF_68)]) were used. Estimates of ‘PO’ were formulated from mean phosphate and oxygen measurements taken from Antarctic snow (for the meteoric endmember, [[69-73](#_ENREF_69)] and sea-ice [[73-77](#_ENREF_73)]). The δ18O endmember for meteoric water carries the greatest uncertainty, as it must represent a combination of both local (seasonally varying) precipitation and glacial melt, which can encompass a large variability in δ18O signal depending on the exact latitude and elevation at which the precipitation accumulated. We followed a previous approach [[36](#_ENREF_36)], using an endmember of δ18O= –18‰ that combined an approximated glacial input signal around the Weddell Gyre [[32](#_ENREF_32), [78](#_ENREF_78)] and a precipitation signal from the gyre’s northern extent [[79](#_ENREF_79), [80](#_ENREF_80)].A sensitivity analysis to investigate the impact of the uncertainty in endmember selection and measurement uncertainty was conducted: endmembers were varied according to their estimation and measurement uncertainty, with both individual and combined effects on freshwater contributions and final budget assessed. Sea-ice melt and meteoric outputs were deemed most sensitive to the choice of δ18O endmembers, and least sensitive to salinity. Overall, errors in the derived freshwater contributions were calculated as being ±1% of the total volume of the fluid sampled. As effects of endmember changes on freshwater fractions were of a consistent, systematic nature, impacts on final budget estimates were small.Values adopted are detailed within each panel of Figure 4 for each water source. Due to the non-conservative nature of ‘PO’ in the surface layers caused by the air-sea flux of oxygen and highlighted by atypical proportions of CDW above the South Scotia Ridge, a standard three endmember (CDW, SIM, MET) mass balance was used for waters above the temperature minimum of Winter Water. This approach has a slight effect on calculated SIM and MET percentage contributions in these waters, which change by –0.4% and +1.0% respectively, but a negligible effect on integrated net box transports (see below).

Column inventories of integrated freshwater fractions (in metres thickness of freshwater) were also calculated by analyzing contributions on individual stations throughout the water column, before splitting into density classes and averaging across the section.

1. **Results**

The full-depth distribution of δ18­O is shown in Figure 2 and the δ18­O-salinity relationship that the data exhibit is presented in Figure 3. The highest δ18­O and salinity values are found at mid-depths in CDW, which mainly derives its properties from the North Atlantic Deep Water inflowing via the South Atlantic (δ18­O values around +0.2‰ [[35](#_ENREF_35)]). CDW circulation around the gyre is highlighted by a maximum of δ18­O ~+0.07‰ (station 97) as it enters at the east prior to conversion to WDW (maximum of –0.14‰ at station 33). Below, waters become more depleted in the heavier 18O isotope with depth, a minimum signal tracing the advection of WSDW and WSBW which acquire low δ18­O signals from the input of precipitation and glacial melt. The lowest deep water δ18­O values (–0.38‰) are found in WSBW at station 67, east of the bathymetric obstacles of the SSR. These waters are too dense to transit through the deep passages from the Weddell Gyre into the Scotia Sea [[81](#_ENREF_81)] and thus follow the cyclonic circulation of the gyre and the Weddell Front. Across the SSR, WSDW instead is the densest water mass to flow northwards out of the gyre (e.g. station 33 in Orkney Passage, the deepest gap in the ridge and location of strong volume transport [[81](#_ENREF_81)]; δ18­O = -0.33‰).

Above CDW, isotopically lighter waters are also prevalent, being primarily influenced by accumulated meteoric input (predominantly precipitation, with δ18­O –8‰ to –35‰ e.g. [[32](#_ENREF_32), [80](#_ENREF_80)]) and exhibiting the lowest δ18­O values on the section (approaching –0.45‰). Substantial regional variability exists in the surface waters, however: systematically lighter values at station 1 in Bransfield Strait reflect its proximity to glacial melt sources [[31](#_ENREF_31)]. Station 127, located on the shelf at 30°E is consistently heavier but fresher, a combination of the lower impact of local direct ice shelf melt and increased regional influence of sea-ice melt, related to recent sea-ice extent and sampling time (see Figure 1). Station 76 exhibits the freshest surface values, likely as a result of the recent retreat of sea-ice from the study area prior to sampling (Figure 1). The concurrent light δ18­O properties are caused by the addition of freshwater of meteoric provenance (most likely snow that has accumulated atop the sea-ice) accompanying the sea-ice melt.

Source distributions derived from the δ18O mass balance are shown in Figure 4. Layers below the Winter Water temperature minimum (at ~100-200 dbar) represent outputs of the four-endmember mass balance, while results from the three- endmember inversion are presented above (CDW and WW fractions above the temperature minimum are omitted for clarity). Highest percentages for the two saline sources (CDW and WW) are clearly related to the distributions of these water masses: for CDW this is between 300-1200 dbar with a maximum in the north-eastern corner of the Weddell Gyre where the ACC crosses the section twice; for WW, this is at the temperature-minimum between the surface and ~200 dbar, depending on location. In deep and bottom waters, the two sources contribute approximately equally, indicative of both being precursors to the formation of very cold and dense shelf waters involved in the formation of AABW, in line with chlorofluorocarbon-derived estimates of mixing recipes [[41](#_ENREF_41)]. For sea-ice melt, highest percentages are visible in the surface layers associated with the recent seasonal decrease in sea-ice extent (~stations 67-85, Figure 4 middle panel). This reaches a maximum of 1.8% at station 84, equivalent to 0.8 m of sea-ice derived freshwater in an 85 m thick Surface Water (neutral density γ*n* < 27.55) layer. Towards the continental boundaries of the Weddell Gyre, SIM contributions reduce, likely related to the prevailing strong sea-ice production that occurs in these areas*.* The deep and bottom waters feature entirely negative SIM percentages (mean -1.53%), caused by brine-rejection and freshwater removal that occurs during net sea-ice production and shelf water densification: for a mean WSBW thickness of 659 m and estimated surface area within the Weddell Gyre of 4x1012 m2 (from World Ocean Atlas 2009 [[82](#_ENREF_82), [83](#_ENREF_83)]) this equates to the net accumulated signal of sea ice production of ~ 4x104 m3 of freshwater for WSBW. Meteoric waters also show surface intensification up to a maximum of 3.2%, related to accumulated precipitation and equivalent to 2.9 m of freshwater. Minimal contributions are prevalent in CDW, but contributions increase with depth as glacial influence during bottom water formation increases, reaching a relative maximum percentage of 1.5%. Combined with the slight freshening provided by WW, meteoric sources dictate freshwater distributions at depth, balancing the freshwater removed through sea-ice production. The distributions presented thus strongly reflect the influence that addition/removal of freshwater through different precursor processes has on deep water formation, and trace the principal transport pathways from source locations.

To quantify freshwater budgets for the region, the underlying circulation of the Weddell Gyre was first diagnosed by combining all hydrographic data in a box inverse model [[45](#_ENREF_45)]. To guard against the introduction of transport biases due to differing sampling times for the three cruises, hydrographic profiles and geostrophic shear from JR239-JC30 and JC30-I6S co-located stations were compared. The former gave near-identical properties throughout the water column, so a simple joining of the transects will have a negligible effect on transport estimates. However, due to elevated mesoscale activity in the northeast corner of the box, significant variation was found on the repeated JC30 / I06S stations. In order for near-identical profiles to be sampled at both the end of JC30 and beginning of I06S, only stations south of 54°S were included for the meridional section. Although this leaves a large geographical distance between the two sections, dynamical consistency is maintained and the closure of the model domain is possible. Horizontal geostrophic velocities, diapycnal velocities, eddy fluxes, air-sea exchanges of heat and freshwater and solid sea ice transport were calculated by imposing conservation of mass, heat and salt on the thermal wind equations along the rim of the box. Velocities obtained from the inversion were then combined with the δ18O-derived freshwater fractions to obtain transports and budgets for each source. The closed volume budget allows accurate quantification of the net addition or removal of freshwater from the box. Uncertainties were investigated by performing a Monte Carlo simulation, repeating the box inversion 1000 times and applying normally distributed perturbations in the velocity field and associated unknowns with the mean of these perturbations equal to the inverse velocity and its standard deviation equal to the *a posteriori* model error. Freshwater fraction uncertainties were estimated by a similarly structured simulation, running 1000 variations of endmember properties through the model that are normally distributed and described by constituent observation uncertainties. Additional information regarding the inversion is included in the Appendix.

Cumulative full-depth freshwater transports along the length of the section and accompanying uncertainties are shown in Figure 4 (bottom panels). Sea-ice melt and meteoric transports are generally opposed, as negative SIM percentages (indicating sea-ice production has exceeded sea-ice melt) predominate across the section. In volume terms, a number of features stand out: the SACCF and Southern Boundary signals are the largest (~stations 80-95) but their effects on the total box transport are mostly balanced as they cross the northeast corner of the box. A substantial outflow located at ~station 60 is associated with the Weddell Front, whilst an opposing inflow at ~station 113 is linked to the Antarctic Slope Front. Considerable fluxes are also apparent across the SSR, with the deepest passages – particularly Orkney Passage at station 33 – hosting the strongest transports across this part of the section [[81](#_ENREF_81)]. Freshwater transport uncertainties scale with volume transport magnitude, with approximately 90% [[45](#_ENREF_45)] of the uncertainty pertaining to the circulation estimate.

Figure 5 shows total volume transports into and out of the Weddell Gyre and across major import/export regions, separated into constituent water masses and freshwater components (exact values are detailed in Table 1, where a positive (negative) sign implies flux into (out of) the box). Freshwater residuals for the ANDREX box suggest a net oceanic export of meteoric water of –36.9 ± 12.9 mSv and a net import of sea-ice melt of +50.9 ± 11.3 mSv. However, in almost all cases the transport of sea-ice melt is opposite in sign to that of the volume flux, reflective of the quantitative importance of waters with negative sea-ice melt fractions in the flux calculations (Figure 4, middle panel). The positive sea-ice melt value derived should therefore be interpreted as a net export of waters from which significant sea-ice had been produced, rather than a net import of liquid-phase sea-ice melt.

Budget residuals appear mainly to be a balance between predominantly volume-dictated opposing WDW and WSDW flows, (and to a lesser extent) Winter Water and WSBW transports. The Antarctic Slope Front and Weddell Front regions are the locations of greatest volume and freshwater import / export of these water masses, with the large uncertainties that accompany them (Figure 4) suggesting a level of sensitivity of the final budgets to the long-term mean-state of these transports. Substantial overturning and conversion of imported WDW to WSDW/WSBW/WW occurs in the region [[45](#_ENREF_45)], highlighted here through a change in relative contributions of the different freshwater types to the total volume transports entering and exiting across the Antarctic Slope and Weddell Fronts. For example, both MET (relative fraction mean of +0.60% in WSDW entering box, +0.75% leaving) and SIM (–1.18% entering, –1.43% leaving) show the imprint of high sea-ice production/melt imbalance and substantial meteoric input during deep water formation. Non-negligible freshwater transports are also observed across the SSR. The largest of these flows — WSDW through Orkney Passage — is an order of magnitude stronger than other water masses in Orkney Passage and the majority of all other passage transports (the exception being WDW in Discovery Passage, a consistent volume and meteoric import).

The closure of the Weddell Gyre freshwater budget is possible through combination of the calculated net oceanic transports with inversion-derived estimates of the other freshwater source / sink terms, namely meteoric, continental and eddy flux contributions. *A priori* estimates for these were used during generation of the circulation field (see Appendix for details), but outputs were found to be insensitive to their magnitude. Final inversion results are presented in Table 1 and compare well with *a priori* estimates: meteoric addition through precipitation and glacial input is estimated as 50 ± 3 mSv, compared with glacial input of 10 ± 5 mSv [[84](#_ENREF_84)] combined with a rough precipitation estimate from regional atmospheric analyses [[85](#_ENREF_85)] of 69 ± 35 mSv, or a more resolved estimate of 52 ± 14 mSv determined from European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim (1979-2010) P-E (Precipitation minus Evaporation) budgets) [[86](#_ENREF_86)]. For sea-ice, the inverse model estimates a net export of -13 ± 1 mSv, compared to an initial input of 14 ± 7 mSv [[45](#_ENREF_45)]. Eddy fluxes are estimated as -8.4 ± 0.4 mSv and 1.9 ± 0.3 mSv respectively for meteoric and sea-ice melt sources.

Combination of all terms gives a net meteoric divergence of +5 ± 13 mSv, suggesting that the predominant deep-water export roughly equals net local additions at the surface, and signaling a system that is in balance within the uncertainty estimates of the method. Additionally, a net accumulation of +40 ± 11 mSv of sea-ice meltwater is calculated, but due to the opposing signs of volume and sea-ice melt transports detailed above, this divergence is explained by the net export of waters from which freshwater has been removed through sea-ice formation, rather than a net import of sea-ice melt. The Weddell Gyre is thus found to be a net sea-ice production region in agreement with satellite-derived estimates that show the region near the ice shelves to dominate with production estimates of 32 mSv south of SR04 section [[87](#_ENREF_87), [88](#_ENREF_88)]. However, the oceanic export of 51 ± 11 mSv across the rim of the gyre is significantly larger than the expected balancing of the inversion-derived solid sea-ice export estimate (-13 ± 1 mSv), suggesting seasonal bias may be present. For instance, the mean sea-ice melt fraction in ANDREX summer surface waters will be higher than the annual mean, causing a positive bias in the surface SIM transport derived here. To investigate this, δ18O data from a mid-winter cruise in the centre of the Weddell Gyre in Sep-Oct 1989 (Antarctic Peninsula to Kapp Norvegia, [[89](#_ENREF_89)]) was used to adjust ANDREX surface layers to quasi-winter values and the inversion repeated. Due to the time of year of sampling, the trans-Weddell Gyre section crossed directly through sea-ice covered waters and so water mass characteristics are representative of a winter season. Using the same endmembers as used for the ANDREX data and specified in Figure 4, a three-component mass balance was performed for the 1989 bottle samples in the surface layers in order to ascertain sea-ice melt contributions. In Winter Water (γn < 28) these ranged between +0.04% and –2.41%, showing the clear impact of sea-ice production when compared to summer values (range of +1.8% to -1.3%). ANDREX Surface Water sea-ice fractions were systematically adjusted down from their summer values (mean 0.12%) by 1.8% to simulate a winter environment (leaving all other water masses unaltered) and the ocean inversion rerun using the same input data to generate a pseudo-winter transport value for the upper layers. Even with non-synoptic inputs the derived volume transports are thought to represent a long-term (decadal) mean state; the inverse model adjusts velocities to reduce the impact of short-term barotropic anomalies on the solution and thus, the circulation field should not introduce bias through its application using seasonal tracer data (see Appendix). Assumed winter sea-ice melt fractions thus gave a total winter Surface Water transport of –71 ± 1 mSv, significantly more negative than the summer-derived ANDREX transport of –15 ± 1 mSv, itself thought to be affected by a positive bias. In the context of the overall sea-ice budget, a winter Surface Water input produces a net ocean transport (freshwater volume transport and eddy flux term) of –3 mSv of sea-ice melt compared to the calculated summer value of 51 mSv, a substantial seasonal difference. The true mean annual value is likely to lie somewhere between these points: assuming that the Weddell Gyre is mostly ice-covered for 7–8 months of the year (as for 2009–2010, [[37](#_ENREF_37)]) and the winter / summer values presented here are representative of ice coverage states, an annual mean ocean SIM transport would be estimated as +15-20 mSv. This is close to balancing the net –13 mSv of freshwater estimated to be removed from the Weddell Gyre on an annual basis through sea-ice export.

1. **Discussion and Conclusions**

Inversion-derived meteoric inputs are found to be substantially lower than the ERA-Interim reanalysis-based estimates; however, substantial variability is present in Precipitation-Evaporation fields and the proportion of precipitation that actually enters the ocean within the box is unknown, as accumulated snow could be exported from the box on top of sea-ice without melting into the ocean beneath. Similarly, export of both giant [[90](#_ENREF_90)] and small [[91](#_ENREF_91)] icebergs may contribute to lower local glacial contributions. The return flow of either melted snow advected northwards on sea-ice floes or iceberg melt will also influence the final ocean transport. Additionally, the impact of a summer sampling regime is difficult to assess; although surface waters are a net source to the box and meteoric water fractions are likely to be at a maximum, the lack of seasonal δ18O and transport data is limiting when attempting to describe mean annual behaviour.

For sea-ice, the difference between ocean-inversion-derived fluxes and sea-ice export estimates – in addition to the clear difference in sea-ice extent between mid-winter and mid-summer (Figure 1, bottom panel) – suggests that the δ18O-derived estimates are likely to be affected by sampling period seasonality, particularly shallower transports. For stations towards the Antarctic Peninsula, sea ice melt fractions are made more negative by recent sea ice growth (Figure 1 bottom, Figure 4 middle). Similarly, stations between 15°W-15°E will be reflective of the relative recent retreat of sea-ice, a matter particularly relevant for the strong transports of the Weddell Front and ACC (Figure 1 middle, Figure 4 bottom). Fractions presented here will thus capture some of the short-timescale spatial freshwater variability, as well as some interannual differences, highlighted by the variability in total regional sea-ice extents (Figure 4) - particularly at the western extent. Overall, both meteoric and sea-ice budgets are dominated by the balance between the freshwater contributions of the largest volume transports, which occur at depth. These waters contribute the most to overall budget divergence uncertainties, indicating sensitivity of the freshwater systems to the deep circulation.

Freshwater budgets for meteoric and sea-ice systems have been estimated for the Weddell Gyre region from a box inversion model combined with results from a δ18O-derived 4-endmember mass balance. Results show that ocean fluxes are currently in approximate balance with air-sea/surface inputs/outputs, although sensitive to changing ocean circulation patterns. The region is found to be a location of substantial net sea-ice production and when wintertime conditions are considered, the estimated annual oceanic sea-ice melt budget approaches previous sea-ice export estimates from the Weddell Gyre. The impact of sea ice production and meteoric water inputs are notable in the deep waters exported from the gyre; indeed, despite the surface waters having the most extreme freshwater values, it is the deep waters that dominate the freshwater budget due to their large volume fluxes. However, uncertainties remain, including those relating to the timing of the sections used here in relation to the seasonal and longer-period variability of the component freshwater inputs. Nonetheless, the freshwater compositions and budget determined here represent important benchmarks against which future changes can be determined, such as those expected due to an acceleration of the global hydrological cycle, climatic changes in sea ice production and export, and changing rates of glacial discharge from the Antarctic continent.

**Appendix: Ocean inversion of Weddell Gyre**

An estimate of the underlying circulation was diagnosed using a box inverse model [[45](#_ENREF_45)] in which the JR239, JC30 and I06S sections were combined with a fourth cruise (ANTXXII/3, 2005, [[92](#_ENREF_92)]), extending across the gyre from Joinville Island (near the Antarctic Peninsula) to Kapp Novergia (~8°W, ~70°S). This additional data was introduced to differentiate ice shelves and shelf-slope processes leading to deep water formation in the south-western corner of the box from the gyre circulation, thus improving the ability of the inversion to realistically conserve properties in the individual layers, and hence better represent the flow . Data were split into 10 neutral density layers [[45](#_ENREF_45)], selected to correspond with major regional water mass boundaries. Conservation of volume, potential temperature and salinity were then enforced within the box formed by the four sections, for both individual layers and full depth, and applied for each tracer component (*C*) as



where *m* is the number of layers; *n* is the number of station pairs; *δı* represents the direction of flow, being either +1 (into the box) or -1 (out of the box); *Lı* is the distance between successive stations; *Dıȷ* and *Vıȷ* are the layer thickness and baroclinic velocity at station pair *i* and layer *j* respectively; b*ı* is the barotropic velocity offset at the station pair *i*; *ρıȷ* is *in situ* density; *A* is the layer interface area within the box; is component *C*’s diapycnal velocity [[93](#_ENREF_93), [94](#_ENREF_94)]; *FA-S(C)* and *FSI(C)* are the air-sea and sea-ice fluxes of *C*, respectively; is the eddy-induced flux of *C* for layer *j*, consisting of advective (first) and diffusive (second) components; and denote the area-mean and time-mean operators, respectively, over a layer interface. The model was first solved to satisfy the conservation statements within *a priori* uncertainties. A second inversion was initialized using the first inverse solution in which exact conservation of full-depth volume and salt was enforced. Whilst unnecessary with regard to the velocity field (resultant changes are negligible and within uncertainty boundaries), this second step is critical for freshwater terms due to their diminished size (up to 100x smaller), and thus sensitivity to even small volume budget imbalances. *A* *priori* estimates for meteoric and solid sea-ice export terms were set: mean annual air-sea freshwater fluxes were initialized using regional atmospheric analyses estimating net precipitation of 400 ± 200 mm yr-1 for the box region, and 200 ± 100 mm yr-1 in the southeast corner [[85](#_ENREF_85)], equivalent to a total input of 70 ± 35 mSv; glacial input of 10 ± 5 mSv was estimated from radar observations of glacial grounding-line ice flux measurements [[84](#_ENREF_84)]; and a mean sea ice flux of 14 ± 7 mSv calculated from daily sea-ice concentrations combined with monthly sea-ice velocities and the climatological ASPeCT sea ice thickness for the 2005-2010 period [[45](#_ENREF_45)]. Sensitivity tests were performed using *a priori* freshwater terms of target ±50%, but final outputs were generally found to be relatively insensitive to these changes, varying by <±10%. Outputs from the Southern Ocean State Estimate (SOSE) high-resolution (1/6° grid) numerical model for the period of 2005-2010 [[95](#_ENREF_95)] were used to provide initial values for the time-varying (eddy) transport variables; time-mean quantities were calculated of 5-day means over 2 years for *in situ* station positions, and primed quantities as deviations from that time-mean. SOSE data were also used to investigate uncertainties in the barotropic velocities across the rim of the gyre box, with root mean square values of the time series of barotropic velocity offsets at each station pair deemed as representative of temporal variability in the initial solution. Subsequently, lateral transport uncertainty was calculated for the final inverse solution through the creation of 1000 random barotropic velocity offsets and perturbations in the other unknowns – with an average and standard deviation equal to the inverse model solution and final formal error, respectively – that were then run through the inverse model. The standard deviation of these 1000 independent transport estimates is used to define overall transport uncertainty. Together, these methods generate a realistic robustness estimate of the inverse model outputs, its sensitivity to initial conditions, and how representative it is of long term annual means.



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Table 1. Summary of total freshwater transports across section and budgets, for full-depth and specific water mass types. \*Meteoric input combines both precipitation and glacial inputs.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Water mass** |  | | |  | | |  | | |  | | |  |  | | |
|  |  | **MET** | | | **SIM** | | | **CDW** | | | **WW** | | |  | **Total Volume** | | |
|  |  | **(mSv)** | | | **(mSv)** | | | **(Sv)** | | | **(Sv)** | | |  | **(Sv)** | | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *Full* |  | SW | 15.49 | ± | 11.94 | -14.99 | ± | 1.05 | -0.85 | ± | 0.20 | 1.84 | ± | 0.35 |  | 0.97 | ± | 0.22 |
| *section* |  | WW | -39.29 | ± | 10.58 | 19.89 | ± | 8.68 | -2.51 | ± | 0.58 | -3.20 | ± | 1.10 |  | -5.71 | ± | 0.58 |
|  |  | WDW | 66.49 | ± | 11.19 | -101.48 | ± | 20.39 | 6.18 | ± | 1.70 | 2.99 | ± | 1.03 |  | 9.13 | ± | 1.71 |
|  |  | WSDW | -59.34 | ± | 7.45 | 110.15 | ± | 14.23 | 0.72 | ± | 0.59 | -3.04 | ± | 0.56 |  | -2.27 | ± | 1.92 |
|  |  | WSBW | -20.20 | ± | 2.70 | 37.35 | ± | 5.40 | -0.63 | ± | 0.16 | -1.20 | ± | 0.21 |  | -1.81 | ± | 1.24 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | **Volume Total** | | **-36.85** | **±** | **12.94** | **50.92** | **±** | **11.27** | **2.91** | **±** | **0.50** | **-2.61** | **±** | **0.53** |  | **0.31** | **±** | **0.03** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | Eddy Fluxes | -8.45 | ± | 0.36 | 1.92 | ± | 0.30 | -0.17 | ± | 0.01 | -0.17 | ± | 0.01 |  | -0.34 | ± | 0.27 |
|  | Sea-ice export | | - |  | - | -13 | ± | 1 | - |  | - | - |  | - |  | -0.01 | ± | 0.00 |
|  |  | Meteoric\* | 50 | ± | 3 | - |  | - | - |  | - | - |  | - |  | 0.05 | ± | 0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | **Net budget** | | **4.70** | **±** | **13.29** | **39.84** | **±** | **11.32** | **-** |  | **-** | **-** |  | **-** |  | **0.01** | **±** | **0.28** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *South* | *Total* | SW | -3.61 | ± | 9.58 | -13.01 | ± | 0.88 | -0.33 | ± | 0.25 | 0.20 | ± | 0.19 |  | -0.14 | ± | 0.59 |
| *Scotia* |  | WW | -53.11 | ± | 9.66 | 36.53 | ± | 7.26 | -2.33 | ± | 0.42 | -4.34 | ± | 0.84 |  | -6.67 | ± | 1.25 |
| *Ridge* |  | WDW | -17.97 | ± | 15.46 | 30.65 | ± | 30.60 | -1.37 | ± | 2.20 | -1.24 | ± | 1.68 |  | -2.60 | ± | 4.83 |
|  |  | WSDW | -40.38 | ± | 1.38 | 79.71 | ± | 2.62 | -3.34 | ± | 0.10 | -3.04 | ± | 0.10 |  | -6.34 | ± | 1.95 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | **Total** | **-115.07** | **±** | **37.68** | **133.88** | **±** | **52.30** | **-7.37** | **±** | **3.48** | **-8.42** | **±** | **3.10** |  | **-15.77** | **±** | **6.56** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Phillip* | SW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  | *Passage* | WW | -7.26 | ± | 4.13 | 4.65 | ± | 2.51 | -0.13 | ± | 0.08 | -0.36 | ± | 0.20 |  | -0.49 | ± | 0.27 |
|  |  | WDW | -12.30 | ± | 9.96 | 26.28 | ± | 17.90 | -1.56 | ± | 0.94 | -1.35 | ± | 0.84 |  | -2.90 | ± | 1.77 |
|  |  | WSDW | -1.31 | ± | 0.89 | 2.28 | ± | 1.51 | -0.10 | ± | 0.06 | -0.08 | ± | 0.05 |  | -0.17 | ± | 0.65 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | *Total* | *-20.87* | ± | 18.92 | *33.21* | ± | *28.82* | *-1.79* | ± | *1.40* | *-1.79* | ± | *1.25* |  | *-3.56* | ± | *2.63* |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Orkney* | SW | 8.20 | ± | 2.90 | -3.45 | ± | 0.14 | 0.32 | ± | 0.08 | 0.09 | ± | 0.05 |  | 0.41 | ± | 0.13 |
|  | *Passage* | WW | 4.17 | ± | 2.32 | -4.92 | ± | 1.61 | 0.50 | ± | 0.09 | 0.53 | ± | 0.18 |  | 1.03 | ± | 0.27 |
|  |  | WDW | -4.80 | ± | 12.80 | 2.43 | ± | 23.45 | 1.21 | ± | 1.65 | 0.45 | ± | 1.11 |  | 1.66 | ± | 2.74 |
|  |  | WSDW | -25.68 | ± | 2.97 | 50.85 | ± | 5.99 | -2.16 | ± | 0.23 | -1.96 | ± | 0.23 |  | -4.10 | ± | 1.42 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | *Total* | *-18.11* | ± | *24.11* | *44.91* | ± | *39.49* | *-0.13* | ± | *2.44* | *-0.89* | ± | *1.79* |  | *-1.00* | ± | *4.21* |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Bruce* | SW | -1.67 | ± | 3.47 | -0.24 | ± | 0.20 | -0.05 | ± | 0.12 | -0.02 | ± | 0.06 |  | -0.08 | ± | 0.18 |
|  | *Passage* | WW | -1.08 | ± | 1.08 | 0.77 | ± | 0.97 | -0.07 | ± | 0.09 | -0.10 | ± | 0.15 |  | -0.18 | ± | 0.24 |
|  |  | WDW | -0.72 | ± | 18.54 | 0.03 | ± | 33.33 | -0.11 | ± | 2.51 | -0.01 | ± | 1.54 |  | -0.11 | ± | 4.04 |
|  |  | WSDW | -5.48 | ± | 1.08 | 10.09 | ± | 1.96 | -0.43 | ± | 0.08 | -0.35 | ± | 0.07 |  | -0.77 | ± | 1.20 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | *Total* | *-8.95* | ± | *29.96* | *10.65* | ± | *47.42* | *-0.66* | ± | *3.31* | *-0.48* | ± | *2.06* |  | *-1.14* | ± | *5.27* |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Discovery* | SW | 4.00 | ± | 1.16 | -1.00 | ± | 0.22 | 0.07 | ± | 0.02 | 0.09 | ± | 0.03 |  | 0.17 | ± | 0.05 |
|  | *Passage* | WW | 1.39 | ± | 0.41 | -0.95 | ± | 0.38 | 0.05 | ± | 0.02 | 0.10 | ± | 0.05 |  | 0.15 | ± | 0.07 |
|  |  | WDW | 13.05 | ± | 3.26 | -30.82 | ± | 8.17 | 2.28 | ± | 0.66 | 1.59 | ± | 0.52 |  | 3.84 | ± | 1.18 |
|  |  | WSDW | -8.26 | ± | 0.42 | 16.22 | ± | 0.80 | -0.61 | ± | 0.03 | -0.59 | ± | 0.03 |  | -1.19 | ± | 0.39 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | *Total* | *10.18* | ± | *6.68* | *-16.55* | ± | *12.66* | *1.79* | ± | *0.88* | *1.19* | ± | *0.71* |  | *2.97* | ± | *1.58* |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *Weddell* |  | SW | -15.81 | ± | 2.53 | 0.76 | ± | 0.10 | -0.27 | ± | 0.05 | -0.32 | ± | 0.05 |  | -0.60 | ± | 0.10 |
| *Front* |  | WW | -4.09 | ± | 0.81 | 2.75 | ± | 0.61 | -0.15 | ± | 0.03 | -0.39 | ± | 0.07 |  | -0.55 | ± | 0.10 |
|  |  | WDW | -44.26 | ± | 9.63 | 90.04 | ± | 18.31 | -5.79 | ± | 1.13 | -3.85 | ± | 0.93 |  | -9.59 | ± | 2.05 |
|  |  | WSDW | -86.09 | ± | 20.84 | 164.07 | ± | 39.30 | -5.62 | ± | 1.34 | -5.72 | ± | 1.35 |  | -11.27 | ± | 3.56 |
|  |  | WSBW | -13.93 | ± | 2.04 | 26.22 | ± | 3.88 | -0.68 | ± | 0.10 | -0.93 | ± | 0.14 |  | -1.59 | ± | 0.72 |
|  |  | **Total** | **-164.18** | ± | **41.64** | **283.84** | ± | **73.92** | **-12.51** | ± | **3.28** | **-11.21** | ± | **2.90** |  | **-23.60** | ± | **6.14** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *Antarctic* | | SW | 11.67 | ± | 5.73 | -2.21 | ± | 0.89 | 0.06 | ± | 0.03 | 0.35 | ± | 0.23 |  | 0.41 | ± | 0.26 |
| *Slope* |  | WW | 6.11 | ± | 6.51 | -7.76 | ± | 7.73 | -0.18 | ± | 0.19 | 1.08 | ± | 0.94 |  | 0.90 | ± | 1.12 |
| *Front* |  | WDW | 65.86 | ± | 8.16 | -119.28 | ± | 15.11 | 8.78 | ± | 1.14 | 5.14 | ± | 0.77 |  | 13.87 | ± | 2.08 |
|  |  | WSDW | 55.80 | ± | 2.96 | -109.43 | ± | 5.71 | 4.90 | ± | 0.25 | 4.22 | ± | 0.22 |  | 9.06 | ± | 2.00 |
|  |  | WSBW | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 | 0.00 | ± | 0.00 |  | 0.00 | ± | 0.00 |
|  |  | **Total** | **139.44** | ± | **25.86** | **-238.68** | ± | **36.07** | **13.56** | ± | **2.08** | **10.79** | ± | **2.34** |  | **24.23** | ± | **4.40** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

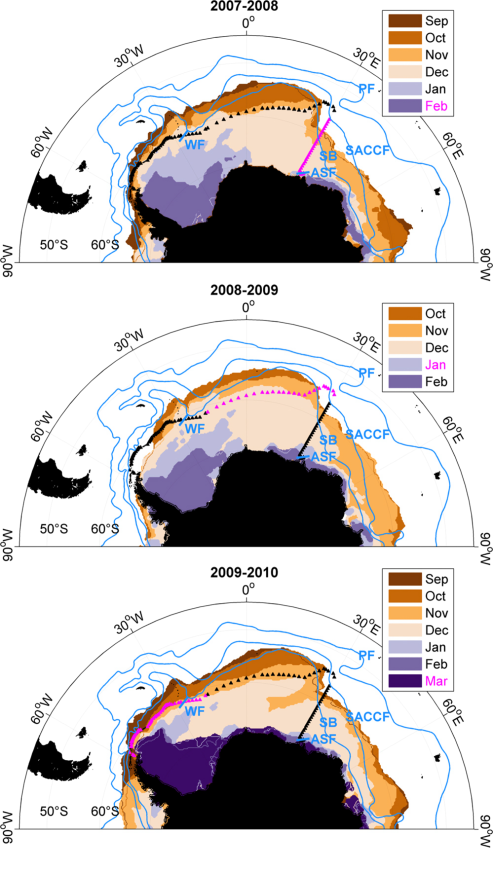


Figure 1.

Sea ice median monthly extent (>15% coverage) for Weddell Gyre region for 2007-2008 (a), 2008-2009 (b) and 2009-2010 (c) from National Snow and Ice Data Center, Boulder, Co, USA, [[37](#_ENREF_37)], ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/. These periods cover the months leading up to and including the three research cruises. Station locations for the full section are given by black triangles, stations analysed in that time period by pink triangles. The month of the analysis is indicated by pink type. The position of the Polar Front (PF), Southern ACC Front (SACCF), Southern Boundary of the ACC (SB) [[96](#_ENREF_96)] , Weddell Front (WF) and Antarctic Slope Front (ASF) are also indicated .

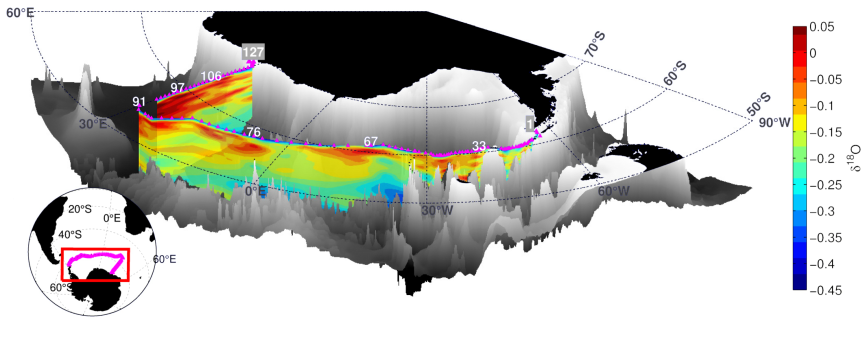


Figure 2.

δ18O field for sections encircling Weddell Gyre in Southern Ocean. Location of full-depth CTD stations are marked with pink triangles, with a limited selection of station numbers also shown (in white). Bathymetry is generated using the 5-minute TerrainBase database

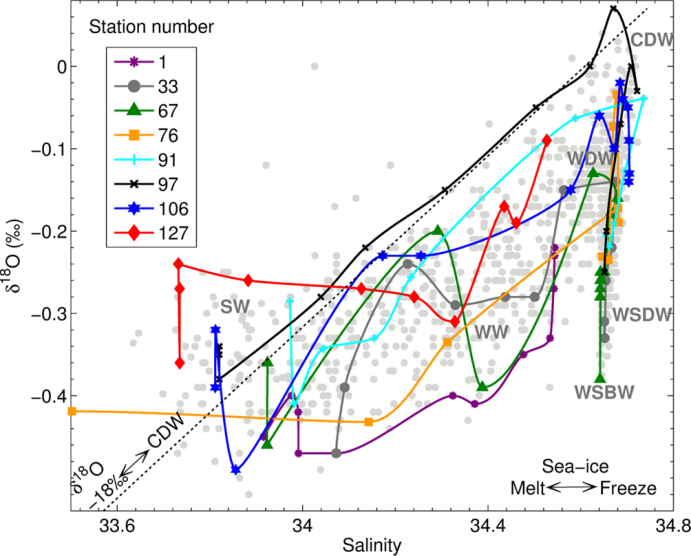


Figure 3.

Salinity - δ18O field for full sections (grey dots). Individual stations are highlighted in colour. Black dotted line indicates mixing line between Circumpolar Deep Water endmember (S 34.68, δ18O 0.07‰) and meteoric (S 0, δ18O -18‰) endmembers. General characteristics of main water masses are highlighted. Sea-ice processes move sample points almost horizontally on this plot, whilst mixing with meteoric (CDW) water would move points diagonally downwards (upwards).

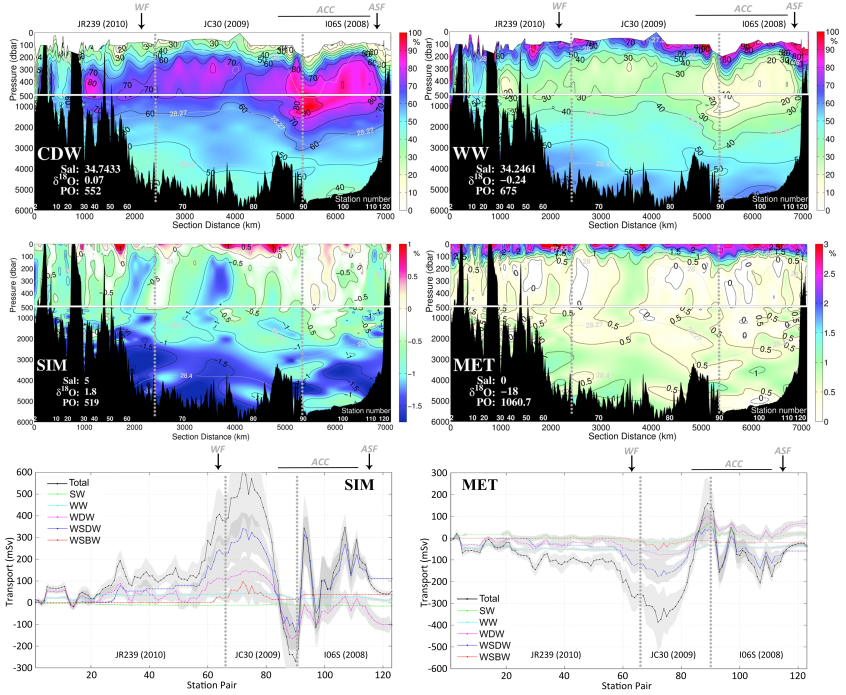


Figure 4.

Contributions of source water masses and freshwater types across section for Circumpolar Deep Water (CDW), Winter Water (WW), Sea-Ice Melt (SIM) and Meteoric (MET) sources. For CDW and WW, white shaded area in surface layers indicates region of water column where a three-endmember 18O inversion was applied. For SIM, negative fractions imply the removal of freshwater through sea-ice formation. Grey contours indicate neutral density isopycnals separating SW, WW, CDW, WSDW and WSBW. Vertical dashed lines separate beginning and ends of individual cruises. Text inserts indicate water mass endmembers for 18O inversion. Boxes bottom left and right show the full depth cumulative transport (with shaded uncertainties) and transports for a number of water mass classifications for SIM and MET respectively. Positive (negative) indicate transports into (out of) the Weddell Gyre box.

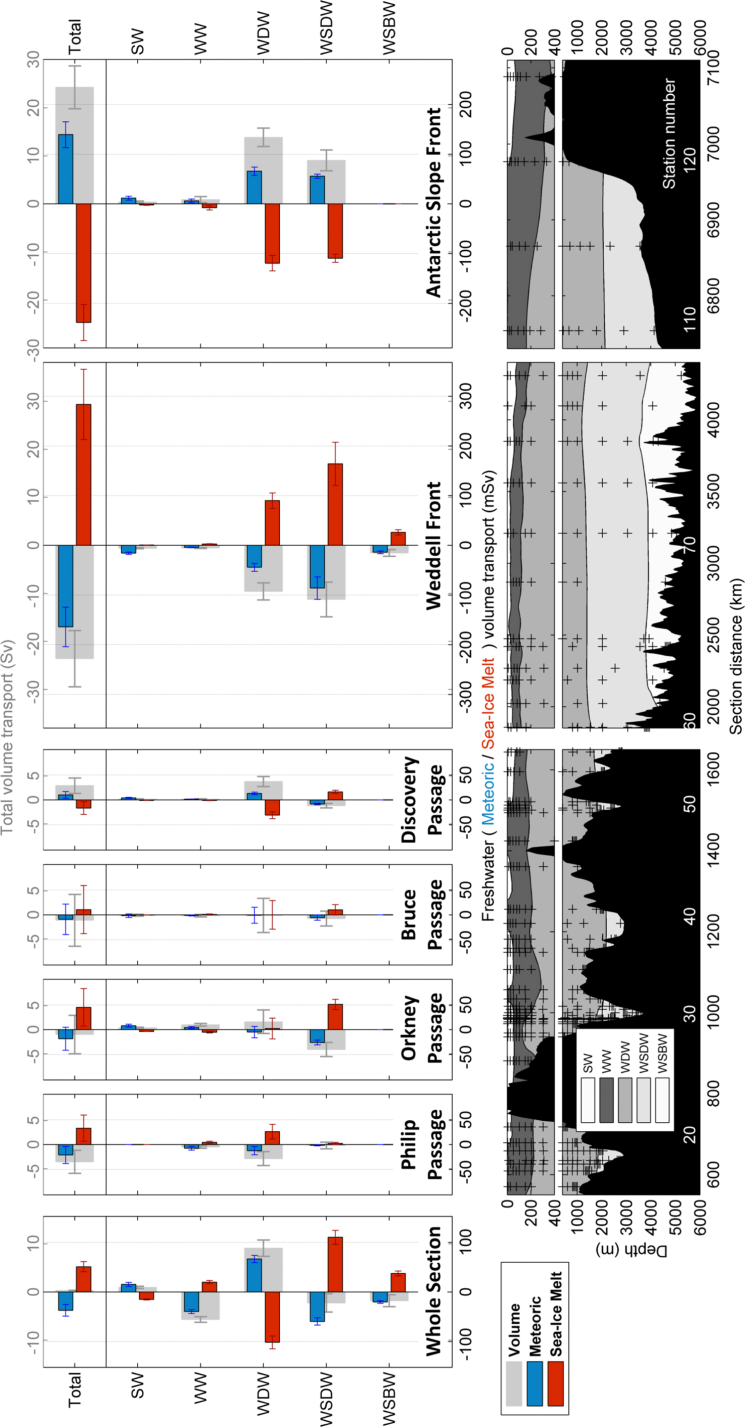


Figure 5.

Total volume and freshwater transports for the full water column and separated into constituent water masses. Also shown are a breakdown of these water movements for the main import/export regions of the gyre, namely the deep passages of the South Scotia Ridge and the Weddell Front and Antarctic Slope Front. Fine errorbars indicate transport uncertainties. Positive values imply transport into the Weddell Gyre region, negative values imply export from the region. Bottom panel shows the distribution of water masses for these regions of the section. Crosses indicate locations where bottle samples for taken for δ18O. Bathymetry from ETOPO2 2-minute global bathymetry database.