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West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability

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Supplementary Information
for
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oceanic variability

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Supplementary Table 1 | Details of datasets used.

Year	Cruise Number	Ship	Contact	E-mail	Station numbers (west to east)	Dates	Instruments
2000	NBP0001	Nathaniel B Palmer	Jacobs	sjacobs@ldeo.columbia.edu	53, 54, 55	3-4 March 2000	CTD, DO, LADCP
2006	JR141	James Clark Ross	Jenkins / Shoosmith	ajen@bas.ac.uk	18, 17, 16, 15, 14, 13	30 Jan 2006	CTD
2007	NBP0702	Nathaniel B Palmer	Jacobs	sjacobs@ldeo.columbia.edu	64, 65, 66, 67, 68, 69	22-23 Feb 2007	CTD, DO, LADCP
2009	NBP0901	Nathaniel B Palmer	Jacobs	sjacobs@ldeo.columbia.edu	119, 120, 121, 122, 123, 124	4-5 Feb 2009	CTD, DO, LADCP
2011	NBP1005	Nathaniel B Palmer	Stammerjohn	sharon.stammerjohn@colorado.edu	29, 10, 11, 9	17 Dec 2010; 2 Jan 2011	CTD, DO
2012	ANA02C	Araon	Kim / Lee	twkim@kopri.re.kr	2701, 2801, 1901, 2001, 2101	16-18 Feb 2012	CTD, DO
2014	ANA04	Araon	Kim / Lee	twkim@kopri.re.kr	1026, 1025, 1024, 1023, 1022	8-9 Jan 2014	CTD, DO, LADCP
2016	ANA06	Araon	Kim / Lee	twkim@kopri.re.kr	221, 211, 201, 191, 181, 172	19-20 Jan 2016	CTD, DO, LADCP

Instruments are Conductivity-Temperature-Depth sensors (CTD), Dissolved Oxygen sensors (DO) and Lowered Acoustic Doppler Current Profilers (LADCP).

Supplementary Table 2 | End member properties used to calculate meltwater fraction for each year.

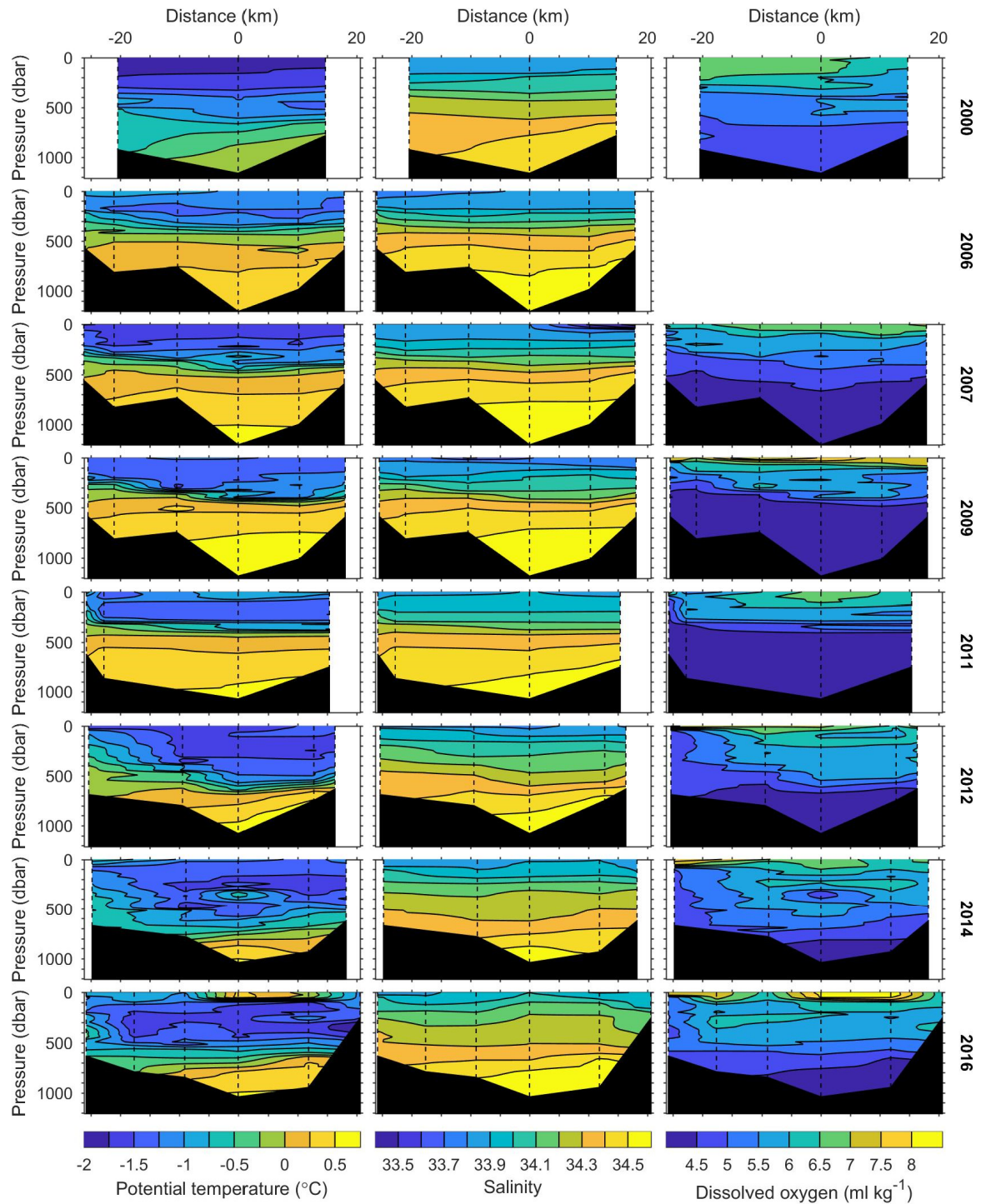
Year	Ice properties			mCDW properties			WW properties		
	T	S	DO	T	S	DO	T	S	DO
2000	-95	0	24.5	-0.3	34.43	4.75	$T_{fp}(S)$	34.22 – {0, 0.03, 0.06, 0.09}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2006	-95	0		0.75	34.63		$T_{fp}(S)$	34.07 – {0, 0.065, 0.13, 0.195}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2007	-95	0	24.5	0.8	34.62	4.36	$T_{fp}(S)$	34.18 – {0, 0.09, 0.18, 0.27}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2009	-95	0	24.5	1.0	34.65	4.225	$T_{fp}(S)$	34.1 – {0, 0.05, 0.1 0.15}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2011	-95	0	24.5	0.85	34.61	4.05	$T_{fp}(S)$	34.15 – {0, 0.06, 0.12, 0.18}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2012	-95	0	24.5	0.56	34.545	4.15	$T_{fp}(S)$	34.2 – {0, 0.035, 0.07, 0.105}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2014	-95	0	24.5	0.0	34.45	4.5	$T_{fp}(S)$	34.23 – {0, 0.02, 0.04, 0.06}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}
2016	-95	0	24.5	0.025	34.47	4.55	$T_{fp}(S)$	34.25 – {0, 0.015, 0.03, 0.045}	$DO_{sat}(S, T) -$ {0, 0.5, 1, 1.5, 2, 2.5, 3}

Properties are potential temperature (T in °C), practical salinity (S) and concentration of dissolved oxygen (DO in ml kg⁻¹). Ice properties are: an effective potential temperature that implicitly incorporates the heat loss associated with warming the ice by 15°C from its core temperature to the seawater freezing point, then melting it⁴²; a practical salinity of 0; a dissolved oxygen concentration that assumes the ice is formed from the compaction of cold firn at elevations of 1000–2000 m above sea level⁴⁷. Properties of mCDW come from observation, while those of WW are derived from an assumed salinity, with subscripts fp and sat indicating, respectively, the freezing point at atmospheric pressure as a function of salinity and the saturation concentration at atmospheric pressure as a function of salinity and potential temperature. For each year 28 realisations of WW properties are created by subtracting the values in braces from the maxima (shown graphically in Supplementary Figure 2).

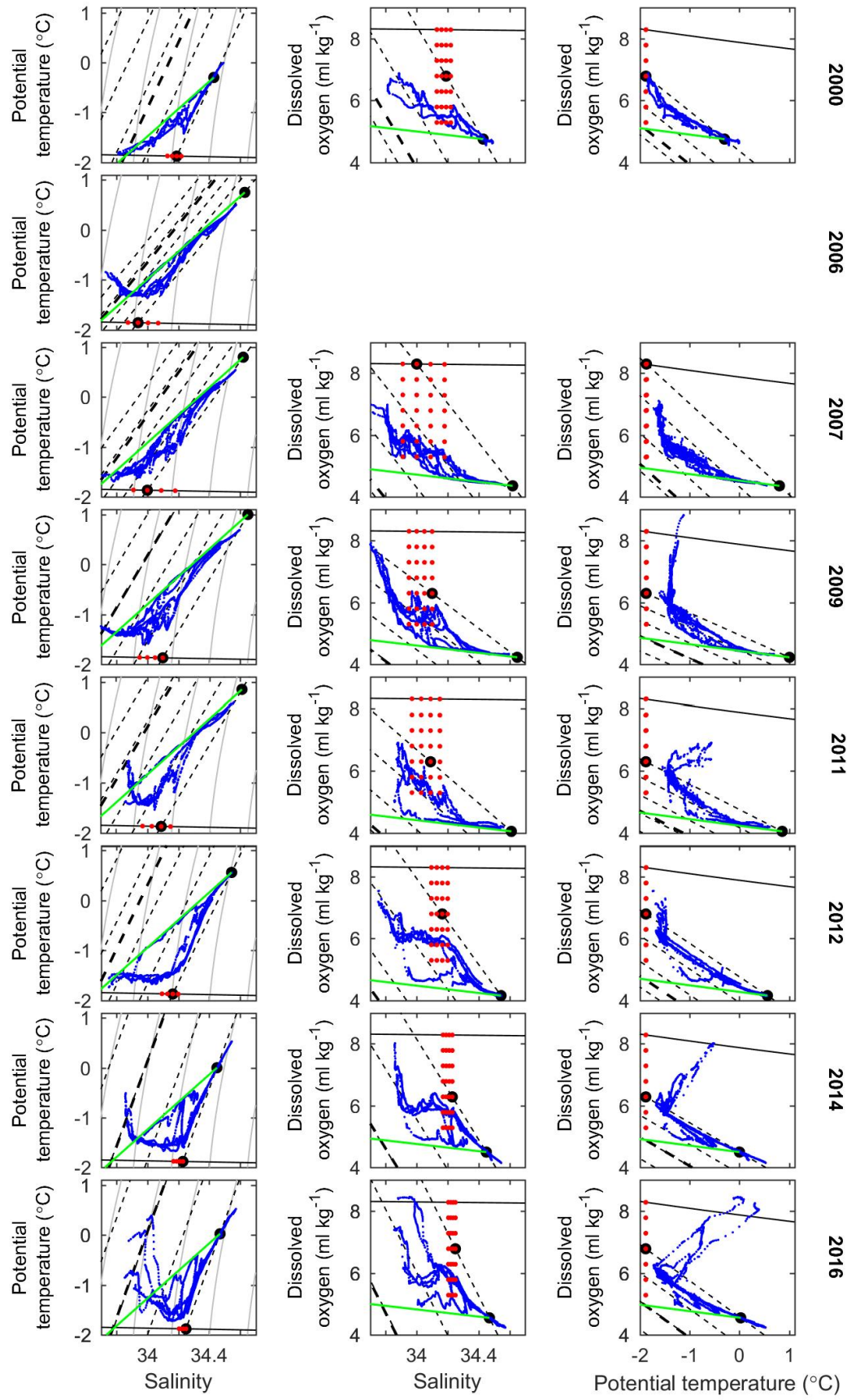
Supplementary Table 3 | Score-weighted mean and standard deviation for key diagnostics of the circulation across Dotson Ice Front in each year.

Year	2000	2006	2007	2009	2011	2012	2014	2016
Geostrophic solutions								
Number and type (F/T)	21 (F)	8 (F)	55 (F)	28 (T)	56 (T)	56 (F)	19 (T)	20 (F)
Mean inflow properties								
Transport (Sv)	1.17	0.39	0.61	0.71	0.46	0.64	0.83	0.79
STD (Sv)	0.28	0.05	0.19	0.37	0.07	0.06	0.12	0.24
Temperature (°C)	1.14	1.89	1.63	2.06	1.98	1.20	0.92	0.89
STD (°C)	0.09	0.19	0.19	0.22	0.12	0.27	0.04	0.13
Meltwater fraction (permille)	2.2	2.3	5.7	4.9	3.7	3.6	3.4	4.1
STD (permille)	1.0	0.9	1.9	1.8	1.1	2.3	1.2	1.5
Mean section properties								
Net transport (Gt yr ⁻¹)	31.0	65.6	31.0	88.2	51.5	20.9	23.1	20.5
STD (Gt yr ⁻¹)	2.5	5.1	10.8	23.4	7.0	3.3	6.9	10.8
Net melt transport (Gt yr ⁻¹)	20.8	45.9	33.8	97.2	56.2	19.7	30.6	18.5
STD (Gt yr ⁻¹)	4.4	10.1	16.7	30.8	9.8	5.1	7.8	10.9
Temperature (°C)	1.07	1.59	1.54	1.87	1.67	1.16	0.97	1.02
STD (°C)	0.09	0.10	0.20	0.20	0.15	0.14	0.02	0.03
LADCP solutions								
Number and type (F/T)	24 (F)	40 (T)		28 (T)	28 (T)			
Mean inflow properties								
Transport (Sv)	0.99	1.17		0.72	0.51			
STD (Sv)	0.46	0.49		0.18	0.09			
Temperature (°C)	1.15	1.70		2.20	1.14			
STD (°C)	0.09	0.34		0.13	0.06			
Meltwater fraction (permille)	1.7	4.9		4.2	2.0			
STD (permille)	1.2	1.6		1.0	1.2			
Mean section properties								
Net transport (Gt yr ⁻¹)	24.9	82.1		81.5	16.7			
STD (Gt yr ⁻¹)	6.1	21.9		12.7	3.3			
Net melt transport (Gt yr ⁻¹)	23.8	90.8		99.6	20.5			
STD (Gt yr ⁻¹)	8.1	37.9		17.3	2.9			
Temperature (°C)	1.12	1.64		1.85	1.02			
STD (°C)	0.10	0.25		0.18	0.08			

Number and type (F=full, T=truncated) of solutions with non-zero scores that contribute to the mean and standard deviation for each year. Geostrophic and LADCP solutions are shown separately above, but are combined in Supplementary Figure 6. Mean inflow properties are evaluated over all areas of the section where the inferred current is into the cavity, while mean section properties are evaluated over inflow and outflow regions. The near-surface layer where air-sea interactions affect properties (Supplementary Figure 3) was excluded from the calculations of circulation and property means. In cases where only a small region was excluded, calculations were repeated including the full water column from the sea surface down to the seabed, giving a maximum of 56 possible solutions for those sections. Temperatures are relative to the surface freezing point.

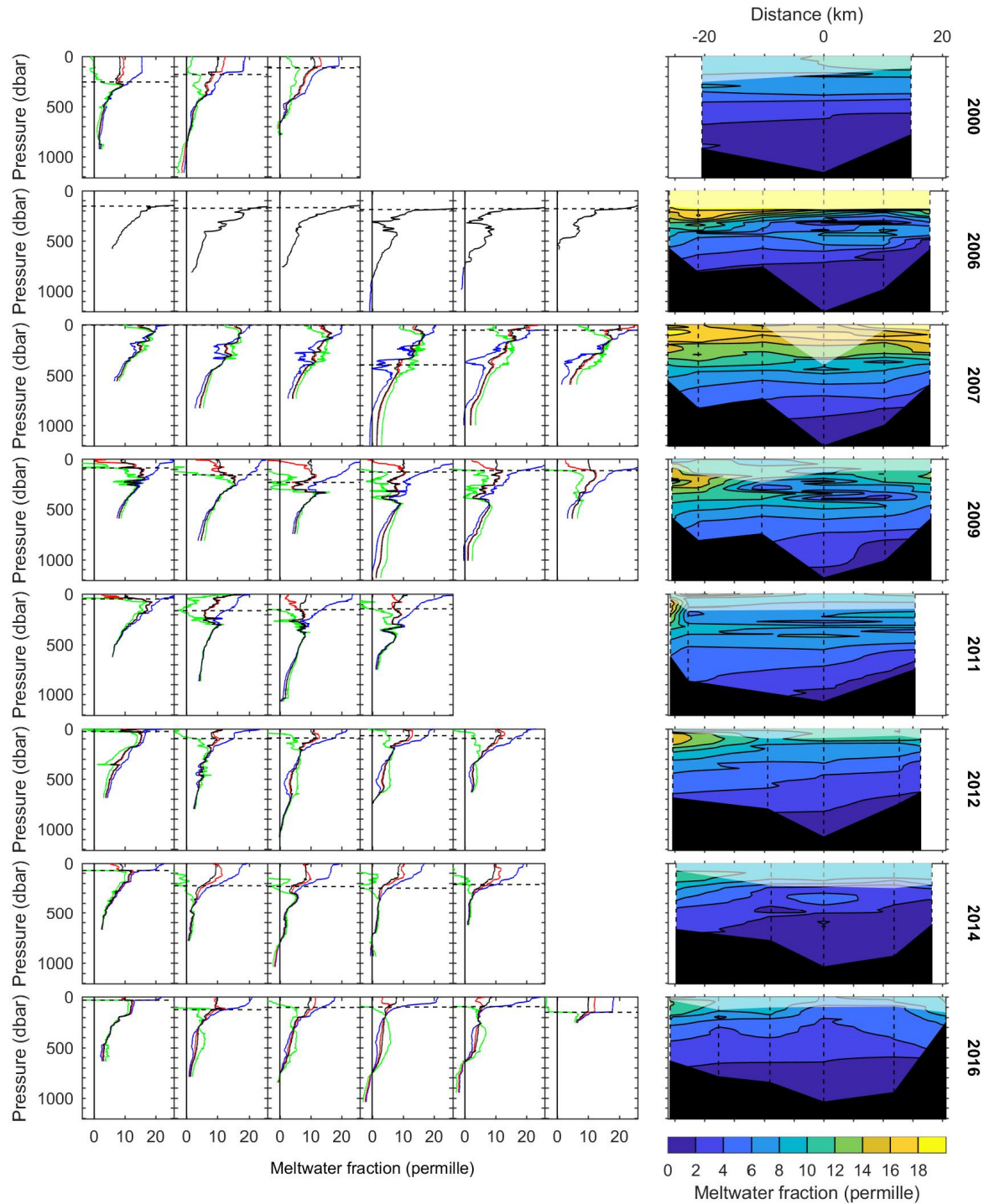


Supplementary Figure 1 | Cross-sections of potential temperature, salinity and dissolved oxygen concentration measured at Dotson Ice Front. Station locations are indicated by vertical dashed lines, with the year of observation on the right (Supplementary Table 1 has precise dates). Distance relative to the central trough station is positive eastward, and black shading shows the seabed, linearly interpolated between stations. Dissolved oxygen (right) was not measured in 2006.

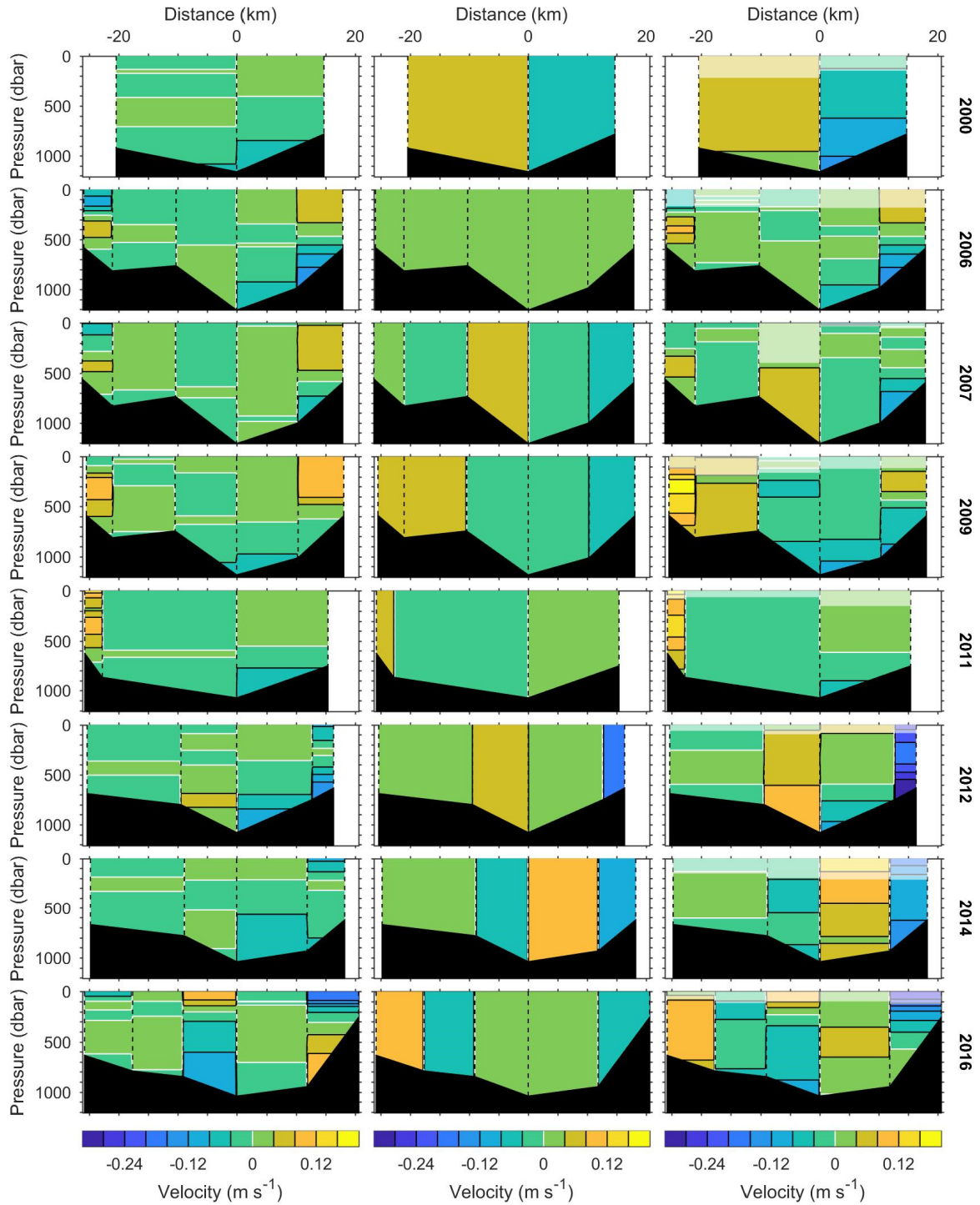


Supplementary Figure 2 | Scatter plots of potential temperature, salinity and dissolved oxygen concentration measured at Dotson Ice Front. Blue dots are 1 dbar averages from each vertical profile,

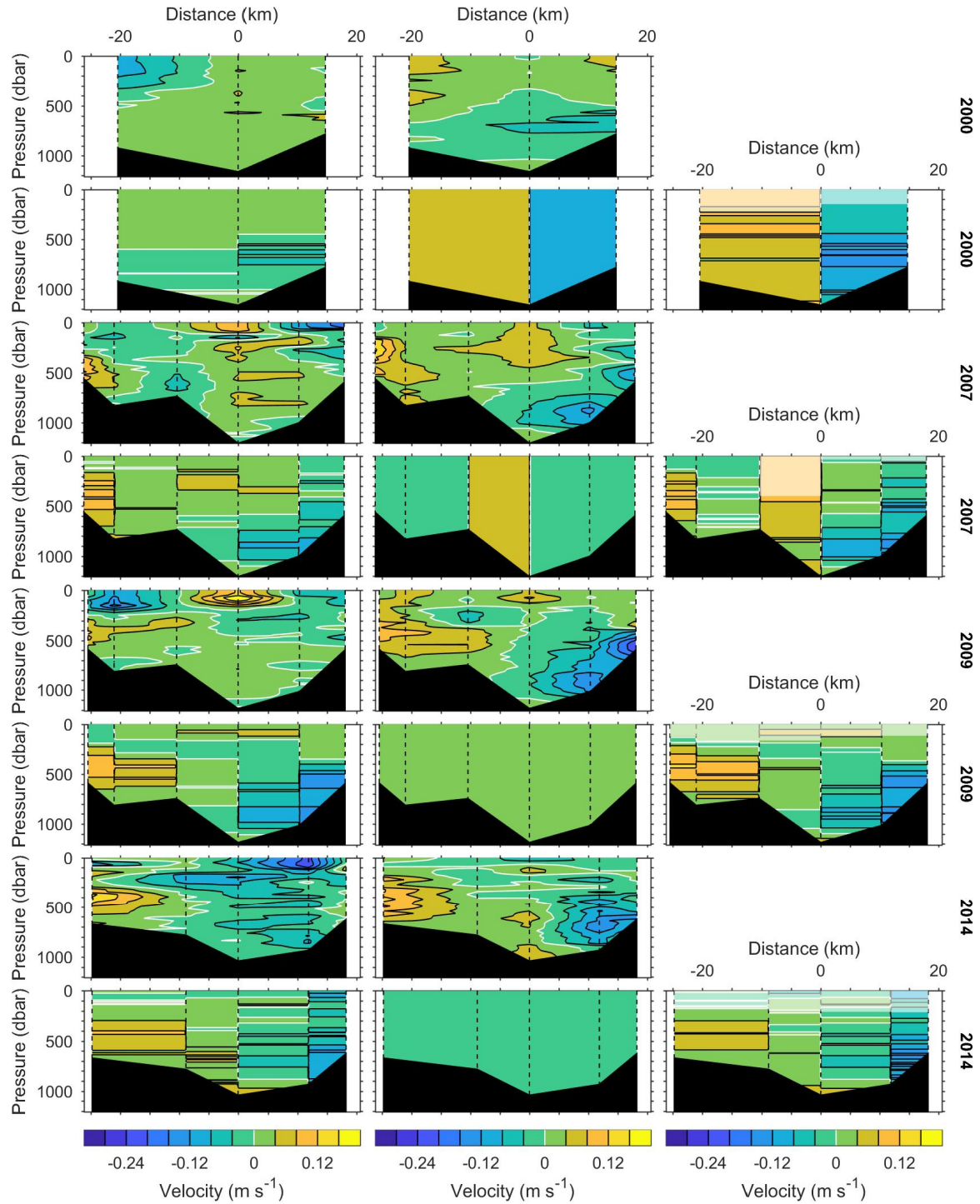
with the year of observation on the right. Dissolved oxygen was not measured in 2006. Solid black lines show the freezing point temperature (left-hand panels) and saturation concentration (centre and right-hand panels) at atmospheric pressure, while solid grey lines (left-hand panels) are contours of potential density (1027 to 1027.8 kg m^{-3} in 0.2 kg m^{-3} increments). Red dots indicate WW properties used in calculations of meltwater fraction and transport (Methods and Supplementary Table 2). Black circles are the mCDW properties (Supplementary Table 2) and the particular WW properties used to calculate contours of meltwater fraction (dashed, black lines, 0 to 40 permille in 10 permille increments) and results in Supplementary Figures 3, 4 and 5. Green lines connect mCDW properties and (assumed constant) ice properties⁴² (Supplementary Table 2). Bold, dashed, black lines are the theoretical upper bounds of meltwater fraction (intersection of green and freezing point lines)⁴².



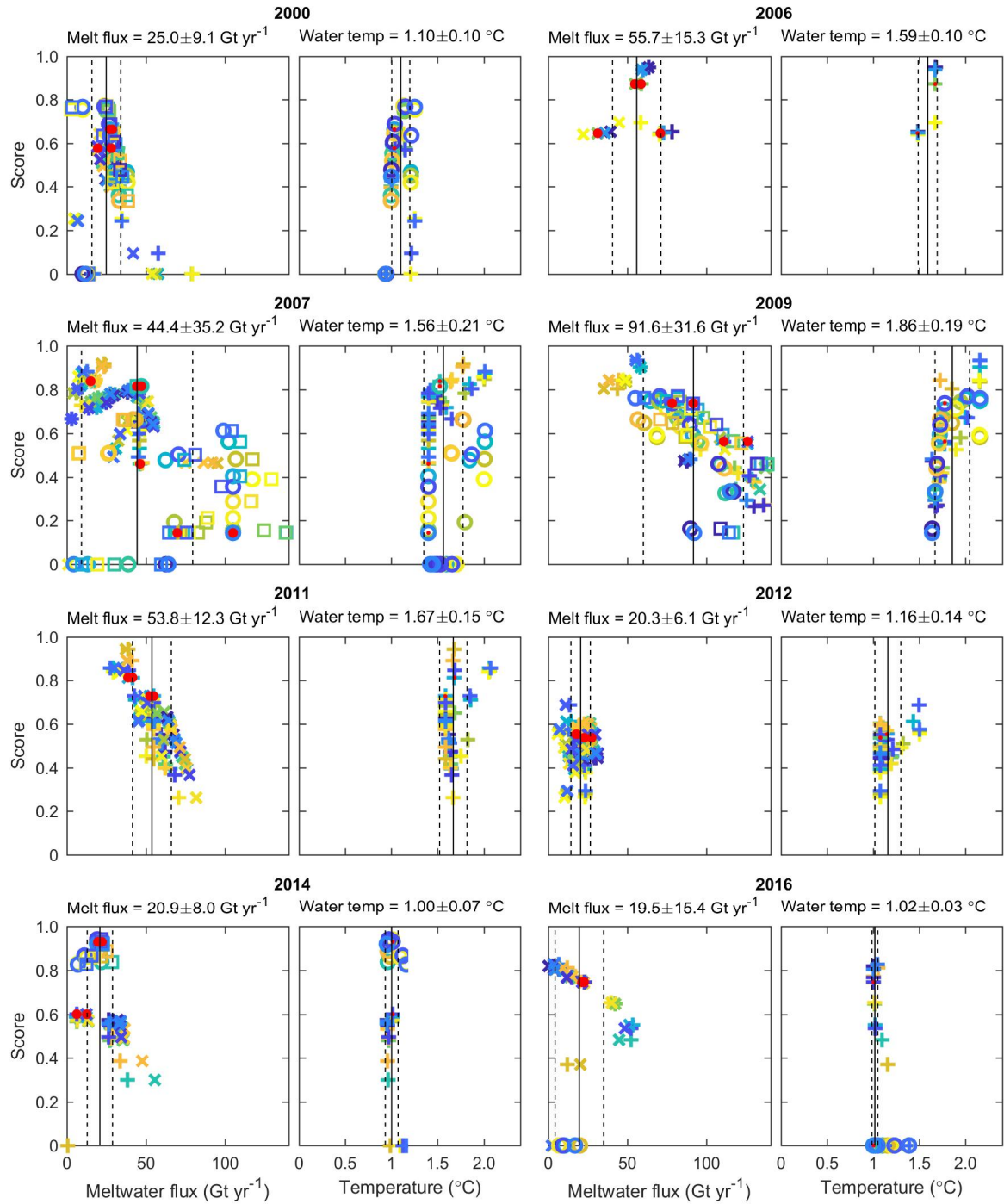
Supplementary Figure 3 | Individual station profiles and resulting cross-sections of meltwater fraction from observations at Dotson Ice Front. Three estimates of meltwater fraction (Methods and Supplementary Figure 2) are based on potential temperature and salinity (blue profiles), dissolved oxygen and salinity (red profiles) and dissolved oxygen and potential temperature (green profiles). Black profiles show the mean of those estimates (only one is possible in 2006), used to produce the contoured cross-sections (right). Dashed horizontal lines on profile plots and lighter shading on cross-sections indicate where meltwater fractions are disregarded because air-sea interactions affect near-surface properties. Horizontal distance axis origin and direction as in prior figure; individual station profiles also from west (left) to east (right).



Supplementary Figure 4 | Geostrophic currents perpendicular to Dotson Ice Front. Geostrophic currents between each station pair (left-hand panels) calculated using the slope of the isobars, determined from temperature and salinity profiles (Supplementary Figure 1), and an assumption of zero velocity at the lowest level in the water column with a significant meltwater fraction (Methods, Supplementary Figure 3). Depth-independent velocity adjustments (centre panels) are the minimum additions required for the resulting geostrophic circulation (right-hand panels) to satisfy integral constraints on the net transport of heat, salt and dissolved oxygen (Methods, particular solution plotted was obtained using WW properties indicated in Supplementary Figure 2). Positive values indicate flow away from the ice (northward), with lighter shading (right-hand panels) indicating the near-surface layer excluded from the calculations because of the impact of air-sea interaction.



Supplementary Figure 5 | Directly-measured currents perpendicular to Dotson Ice Front in 2000, 2007, 2009 and 2014. In each summer, zonal (left) and meridional (right) Lowered Acoustic Doppler Current Profiler components are shown in the upper two panels. The lower three panels show mean currents perpendicular to the ice front between each station pair (left) and minimum depth-independent velocity adjustments (centre) required for the resulting circulation (right) to satisfy integral constraints on the net transport of heat, salt and dissolved oxygen (Methods, particular solution plotted was obtained using WW properties indicated in Supplementary Figure 2). Positive values and lighter shading (right) as in previous figure. LADCP data in 2016 sampled a strong transient, depth-independent flow at one station, preventing any solutions with scores above zero (Methods and Supplementary Figure 6).



Supplementary Figure 6 | Meltwater flux and mean temperature above the surface freezing point across Dotson Ice Front. Results obtained for each choice of WW properties (Supplementary Table 2 and Supplementary Figure 2) are plotted (colour-coded) against the score for that solution (Methods). Solutions derived from geostrophic currents are indicated by crosses (+ and x), and those from LADCP data by circles and squares. On plots of meltwater flux, crosses (+) and circles indicate the difference between inflow and outflow, and crosses (x) and squares the net meltwater flux (Methods). Red dots denote solutions obtained with WW properties highlighted in Supplementary Figure 2 and used in Supplementary Figures 3, 4 and 5. Score-weighted means and standard deviations are indicated by vertical solid and dashed lines, respectively, and are noted numerically above each plot. Mean temperatures are averaged over the relevant section area included in the constrained budget calculation. Final score-weighted results are used in Figure 4 of the main text.