Freshwater Sources and Sinks for Arctic Sea Ice in Summer

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Abstract. On Arctic sea ice, the melt of snow and sea ice generate a summertime flux of fresh water to the upper ocean. The partitioning of this freshwater to storage in melt ponds and deposition in the ocean has consequences for the surface heat budget, the sea ice mass balance, and primary productivity. Synthesizing results from the SHEBA field experiment, we calculate the sources and sinks of freshwater produced during summer melt. The total freshwater input to the system from snow melt, ice melt, and precipitation from 1 June to 9 August was equivalent to a layer of water 80 cm thick over the ice-covered and open ocean. 85% of this freshwater was deposited in the ocean and only 15% of this freshwater was stored in ponds. The cumulative contributions of freshwater input to the ocean from drainage from the ice surface and bottom melting were roughly equal.

1 Introduction

During the Arctic summer melt season, copious amounts of relatively fresh water are produced due to snow and sea ice melt. Sources of freshwater are surface snow and ice melt, bottom melt, lateral melt, and rain. This freshwater can be stored in surface melt ponds, be directly deposited in the ocean, or drain from the surface to the ocean either vertically or horizontally. The amount and the fate of this freshwater have implications for the surface energy budget, the sea ice mass balance, the thermohaline structure of the upper ocean, and primary productivity in the ocean.

The amount of surface melt water stored in melt ponds influences the summer albedo of sea ice and consequently the surface heat budget. Melt ponds have been studied in field experiments (Perovich et al., 2002) and through remote sensing imagery (Rosel et al., 2012; Fetterer and Untersteiner, 1998; Webster et al., 2015; Wright et al., 2020). The morphology and evolution of ponds have been studied using surface topology (Popovic, 2018) and fractals (Hohenegger et al., 2012). Results from pond studies have been incorporated into models (Curry and Ebert, 1995; Flocco et al., 2012; Holland et al., 2012; Schroder et al., 2014). Yet, melt ponds, from a freshwater budget perspective, have received little attention.

In summer, freshwater from bottom melt, lateral melt, drainage from the surface, and rain is input to the upper ocean, freshening and stabilizing it. This freshwater can accumulate in well-defined layers under the ice when there is freshwater input to the

upper ocean, bottom topography to trap the freshwater, and calm conditions with little ocean mixing. Under these conditions, false bottoms can form under the sea ice (Untersteiner, 196_icken, 1994; Eicken et al., 1995; Notz et al., 2003). These false bottoms are below the true ice bottom and are a source of ice production during the melt season. Freshwater accumulation in leads between floes can also develop into well-defined stable layers (Richter-Menge et al., 2001).

35 The freshwater input impacts the thermohaline structure of the upper ocean, ecosystems, and biogeochemistry. The freshwater layer is a barrier for heat transfer from the ocean to the ice bottom, thus slowing bottom ablation. The upper ocean stratification affects the distribution of microbial and faunal communities and the overall productivity (Melnikov et al., 2002; Li et al., 2009). The freshwater layer can impact gas exchange between the ocean and the atmosphere and may inhibit aerosol particle production.

40 The importance of the amount and disposition of freshwater in the summer sea ice cover leads directly to several questions. How much freshwater is produced? What are the relative contributions from different sources? What fraction of surface-produced freshwater is stored in ponds? Here we address these questions by computing a freshwater budget, from a sea ice perspective, over the summer melt season by synthesizing results from the SHEBA experiment (Uttal et al., 2002). Both sources and sinks of freshwater are determined. We examine the time series of freshwater produced through surface snow and
45 ice melt, bottom melt, lateral melt, and rain, and explore the sinks of drainage to the ocean and storage in melt ponds.

2 Approach

We calculate the amount and distribution of freshwater sources and sinks during the summer melt cycle of Arctic sea ice by synthesizing results from the SHEBA program. SHEBA was a yearlong (October 1997 – October 1998) drift experiment in the Beaufort Sea. The overarching goals of SHEBA were to increase understanding of the ice albedo and cloud radiation
50 feedbacks through interdisciplinary studies of the atmosphere, ice, and ocean and use that understanding to improve models (Uttal et al., 2002). Here, data from the SHEBA field experiment are used to determine contributions from snow melt, surface melt, bottom melt, lateral melt, and rain, as well as the volume storage in melt ponds.

This work is a synthesis of existing mass balance results from the SHEBA drift experiment. The data sources for the variables needed for the study are summarized in Table 1. The underlying assumption in this study is that, by design, the SHEBA
55 ensemble of mass balance point measurements provides a statistically representative picture of the SHEBA floe (Perovich et al., 2003). The region of interest for this paper is the SHEBA measurement area of roughly 100 km^2. The focus is on the period from 1 June 1998 to 9 August 1998. This period was selected since it includes the beginning of the melt season and was the time of maximum surface melt, pond evolution, lateral melting, upper ocean stratification, and data availability.

Variable	Units	Definition	Source
$\rho_s = 0.3$	g cm^{-3}	Snow density from SHEBA snow observations	Sturm et al., 2002
$\rho_i = 0.9$	g cm^{-3}	Ice density measured from cores	Perovich et al. 1999
$\overline{m_s}(t)$	cm d^{-1}	Average snow melt rate from 135 manual thickness gauges, 77 of which operated over an entire annual cycle.	Perovich et al. 2003
$\overline{m_i}(t)$	cm d^{-1}	Average surface ice melt rate from 135 manual thickness gauges, 77 of which operated over an entire annual cycle.	Perovich et al. 2003
$\overline{m_b}(t)$	cm d^{-1}	Average bottom ice melt rate from 135 manual thickness gauges, 77 of which operated over an entire annual cycle.	Perovich et al. 2003
$P_f(t)$	None	Pond area fraction averaged over a 200-m-long survey line	Perovich et al. 2003
$\overline{P_d}(t)$	cm	Pond depth averaged over a 200-m-long survey line	Perovich et al. 2003
$C(t)$	None	Ice concentration observations from aerial photography	Perovich et al. 2002
$m_l(t)$	cm d^{-1}	Lateral melt rate measured at one site at floe edge	Perovich et al. 2003
$H_i(t)$	cm	Ice thickness measurements made at floe edge	Perovich et al. 2003
$PA(t)$	km km^{-2}	Ratio of floe perimeter to floe area from aerial photography	Perovich et al. 2002
$R(t)$	cm	Rainfall from Atmospheric Surface Flux Group measurements	Persson et al. 2002

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Table 1. Summary of data sources for freshwater variables

There are two steps to this study. First, the freshwater balance on the ice surface is considered. This includes snow melt, surface ice melt, rain, storage in melt ponds, and drainage to the ocean. The second step examines the input of freshwater to the ocean. This incorporates the drainage terms as sinks in the surface freshwater budget, plus lateral ~~melt~~ and bottom melt. In this

65 component, contributions from the ice to the ocean are scaled by the ice concentration. The budgets are calculated in terms of an equivalent freshwater layer thickness. Figure 1 is a schematic visualizing the sources and sinks of freshwater during the melt season.

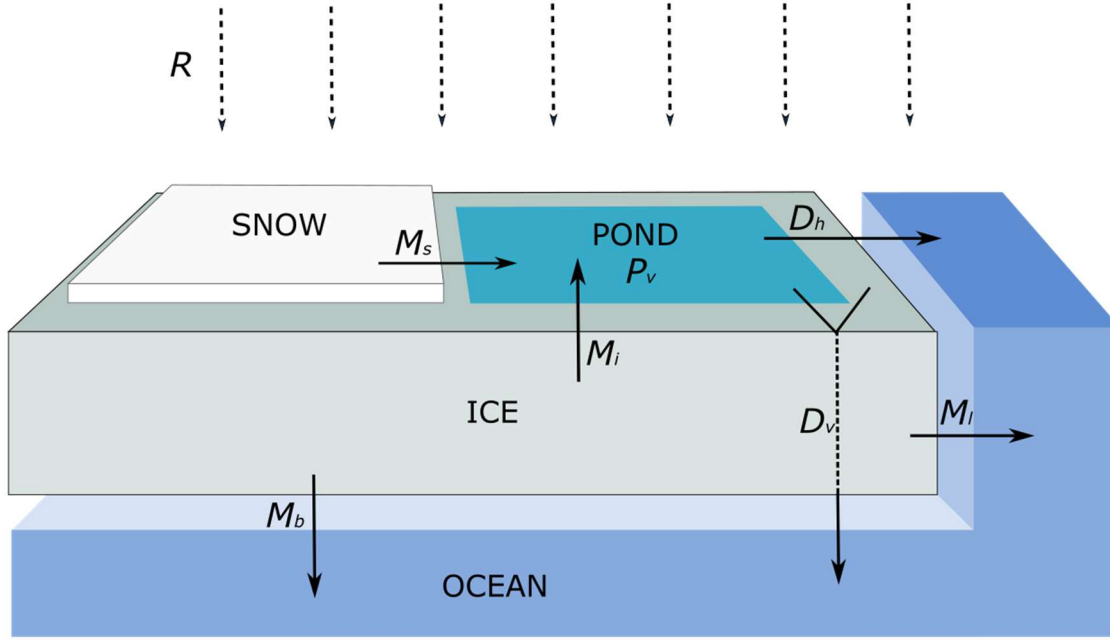



Figure 1. Schematic showing sources and sinks of meltwater used in this analysis. This includes the sources of rain (R), snow melt (M_s), surface ice melt (M_i), bottom ice melt (M_b), and lateral melt (M_l). It also has the sinks of horizontal drainage (D_h), vertical drainage (D_v), and storage in ponds (P_v)

2.1 Ice surface freshwater balance

There are four sources of freshwater on the surface of the ice: snow melt (M_s), surface ice melt (M_i), rain (R), and condensation. Condensation is small compared to the other terms and is not considered in this study. There are four sinks for freshwater on the sea ice surface: storage in ponds (P_v), drainage vertically through the ice to the ocean (D_v), drainage horizontally from the ice to leads (D_h), and evaporation. As was the case for condensation, evaporation is small and neglected in this study. For continuity, surface sources equal surface sinks giving

$$M_s(t) + M_i(t) + R(t) = P_v(t) + D_v(t) + D_h(t) \qquad (1)$$

These terms are expressed as a time series of an equivalent layer thickness of freshwater. The freshwater produced by snow melt is

$$M_s(t) = \rho_s \, \overline{m_s}(t) \qquad (2)$$

where ρ_s is the density of snow and $\overline{m_s}(t)$ is the time series of average snow melt rate on the floe. The freshwater produced by surface ice melt is

$$M_i(t) = \rho_i \, \overline{m_i}(t) \tag{3}$$

ρ_i is the density of ice and $\overline{m_i}(t)$ is the time series of average surface ice melt rate on the floe. $R(t)$ is the time series of rain during the summer. The freshwater stored in ponds is

$$P_v(t) = P_f(t) \, \overline{P_d}(t) \tag{4}$$

$P_f(t)$ is the time series of pond fraction on the floe. $\overline{P_d}(t)$ is the time series of the average pond depth.

The drainage terms are a challenge, as SHEBA had no direct measurements of drainage. As a result, vertical and horizontal drainage are combined and treated as a residual of the other terms in Equation 1. This treatment of the drainage term also accounts for simultaneous vertical and horizontal drainage, which can occur at times (Eicken et al., 2002).

2.2 Input to the upper ocean

Freshwater drainage is important when considering freshwater input to the ocean. The total freshwater input to the ocean, $O_{fw}(t)$, is a sum of the sources: horizontal and vertical drainage, bottom melting, lateral melting $M_l(t)$, and rain falling on leads.

$$O_{fw}(t) = C(t)\big(D_h(t) + D_v(t)\big) + C(t)M_b(t) + C(t)M_l(t) + (1 - C(t))R(t) \tag{5}$$

Here, terms are scaled by the ice concentration time series, $C(t)$, to account for freshwater contributions spread over an area that includes both the ice and the leads. Bottom melting is

$$M_b(t) = \rho_i \, \overline{m_b}(t) \tag{6}$$

$\overline{m_b}(t)$ is the time series of average surface ice melt rate on the floe. Lateral melting is expressed as

$$M_l(t) = \rho_i m_l(t) \, H_i(t) PA(t) \tag{7}$$

$m_l(t)$ is the lateral melt rate and $H_i(t)$ is the ice thickness at the floe edge. $PA(t)$ is the floe perimeter per unit area of the floe (units of km km^{-2}).

3. Results

3.1 Ice surface freshwater balance

The daily freshwater input to the ice surface from snow melt, surface ice melt, and rain is plotted in Figure 2. In early June, the largest contribution comes from snow melt reaching a maximum of about 0.6 cm d^{-1}. As the snow cover melts away, the snow contribution decreases and the ice contribution begins to increase. The surface ice melt contribution increases through

June into July, reaching a peak of 2 cm d^{-1} on 20 July 1998 and rapidly decreasing afterward. It was often foggy and misting during the summer, but the amount of precipitation during these periods was small. We included the only two significant rainfall events: 2 cm of rain around 5 – 6 July 1998 and 1 cm of rain around 26 – 27 July.

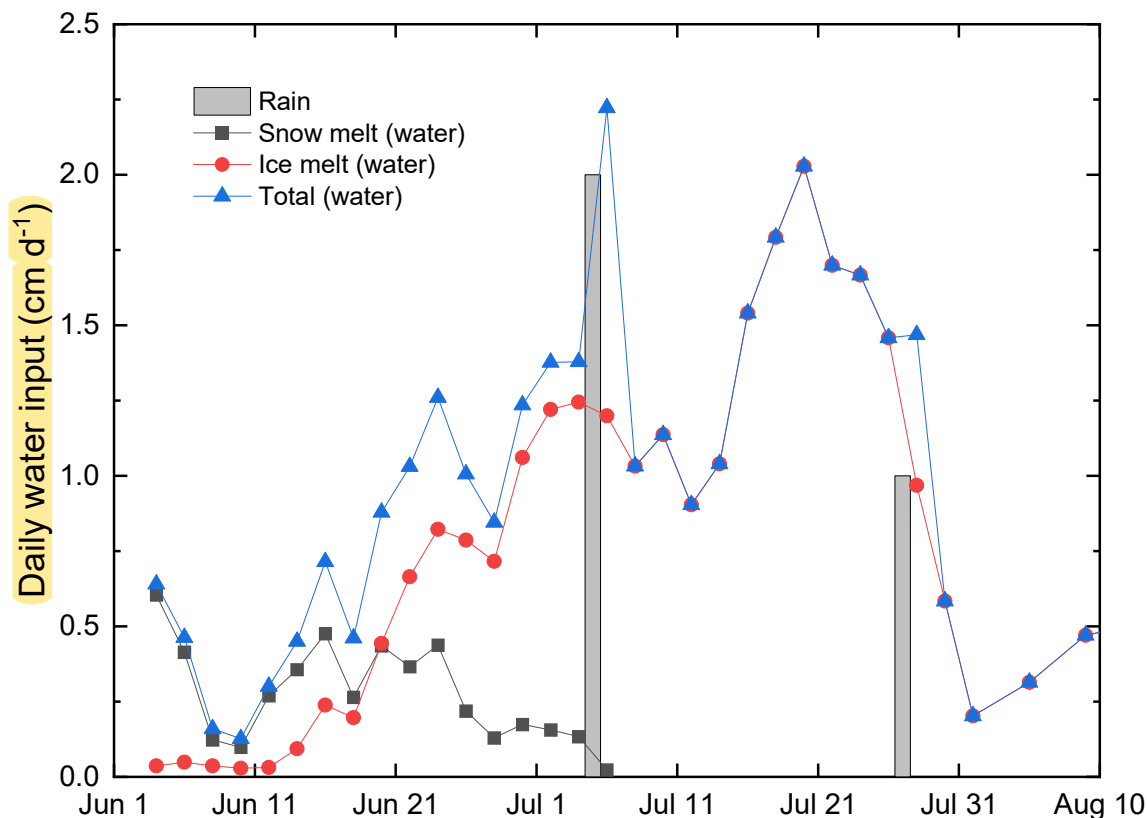



Figure 2. Time series of freshwater input from snow melt, surface ice melt, and rain.

The time series of melt pond fraction and average pond depth is shown in Figure 3. Pond measurements along the survey line started about 10 days after the initial melt pond formation. The pond survey on 20 June coincides with the first pond area maximum as observed from aerial photography (Perovich et al., 2002). The pond fraction decreased from 20 June to 25 June, due to drainage. This was primarily due to vertical drainage associated with high ice permeability (Eicken et al., 2002). Afterwards, there was a steady increase in pond fraction and depth through early August, reaching maximum values of 0.37 for fraction and 39 cm for average depth.

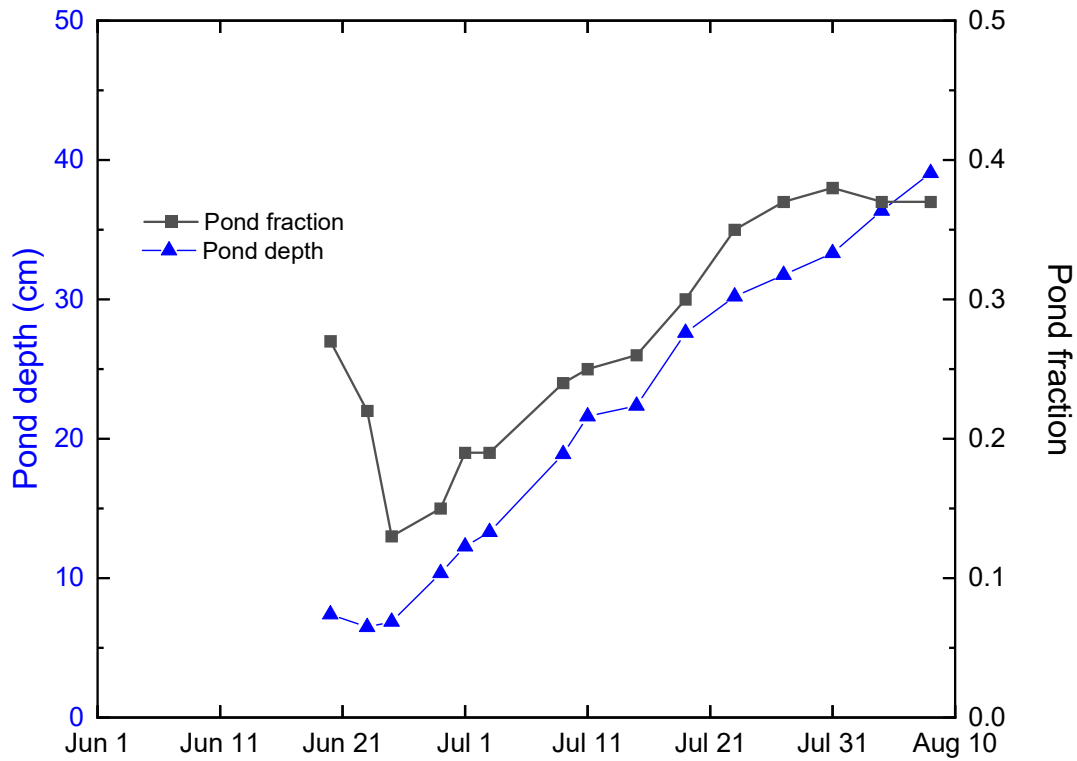



Figure 3. Time series of average pond depth ($P_d(t)$) and pond fraction ($P_f(t)$) along a 200-m-long survey line.

The time series of cumulative freshwater input to the sea ice surface and the amount stored in ponds is plotted in Figure 4. As before, the cumulative water input is presented as the equivalent depth of a layer of freshwater placed on top of the floe. Initially, the fraction of the surface freshwater stored in ponds was 0.25. It rapidly decreased to 0.07 in only 5 days as a result of vertical drainage and a reduction in pond coverage. After that, the fraction stored in ponds steadily increased to a final value of 0.23 on 8 August. Throughout the melt season, the majority of the surface freshwater is drained into the upper ocean rather than being stored in ponds. The time series of the cumulative freshwater drained both horizontally and vertically is the difference between the total cumulative input and the amount stored in ponds. By 8 August, the drained amount was equal to a 50 cm layer of freshwater on the ice surface. There was a steady increase in the amount drained from 20 June to 27 July followed by a gradual tapering to 8 August. During summer, the surface melt rates, pond depths, and pond areas were continually changing. However, even with all those changes, there was a consistency in drainage. From 20 June to 23 July, with an average increase of 1.02 cm d^{-1} and a standard deviation of 0.09 cm d^{-1}. This provided a steady influx of freshwater from the ice surface into the ocean.

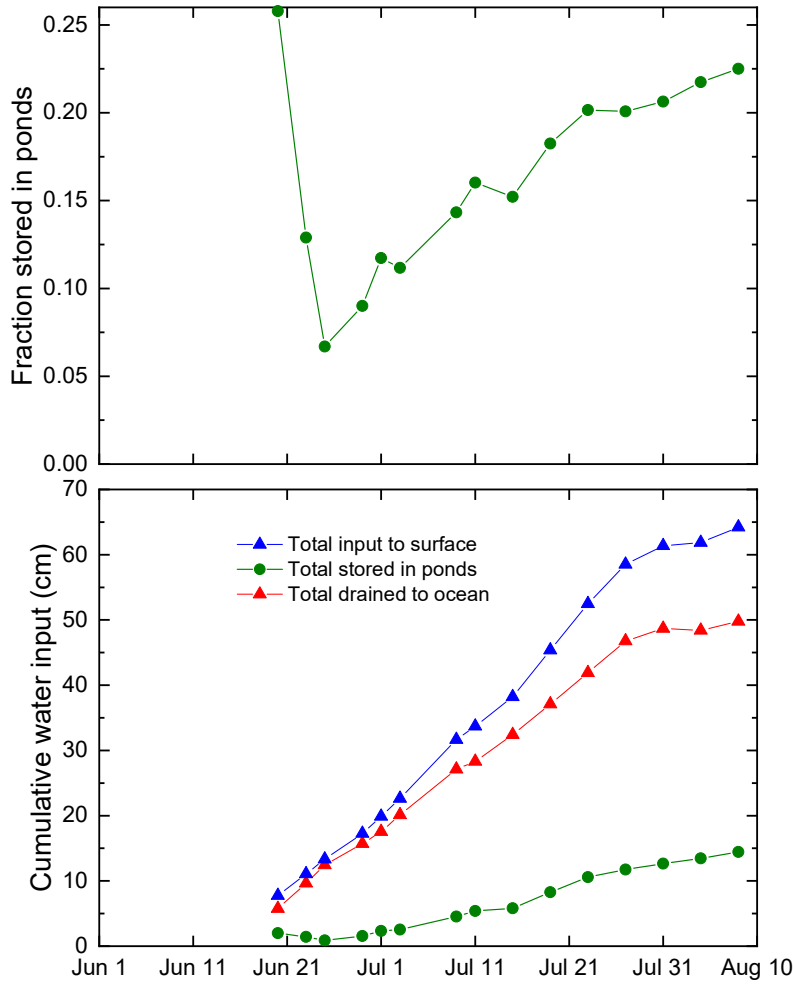



Figure 4. Time series of the fraction of surface water input stored in ponds (top), and cumulative surface water input, storage in ponds (P_v), and drained to ocean.

3.2 Input to the upper ocean

The time series of freshwater input to the upper ocean ($O_{fw}(t)$) is calculated using Equation 5. Here the freshwater input represents a layer over the area covered by both the ice and leads. Freshwater inputs from the ice are scaled by the ice concentration to account for the total area of ice plus leads. Helicopter-based aerial photography was used to determine the time series of ice concentration at SHEBA as shown in Figure 5 (Perovich et al., 2002). In mid-June, the ice concentration dropped to 0.8 and stayed between 0.8 and 0.85 for the remainder of the period of interest.

Rain falling on leads was a very minor component of the freshwater input to the upper ocean. After adjusting for ice concentration, the cumulative input was only 0.13 cm.

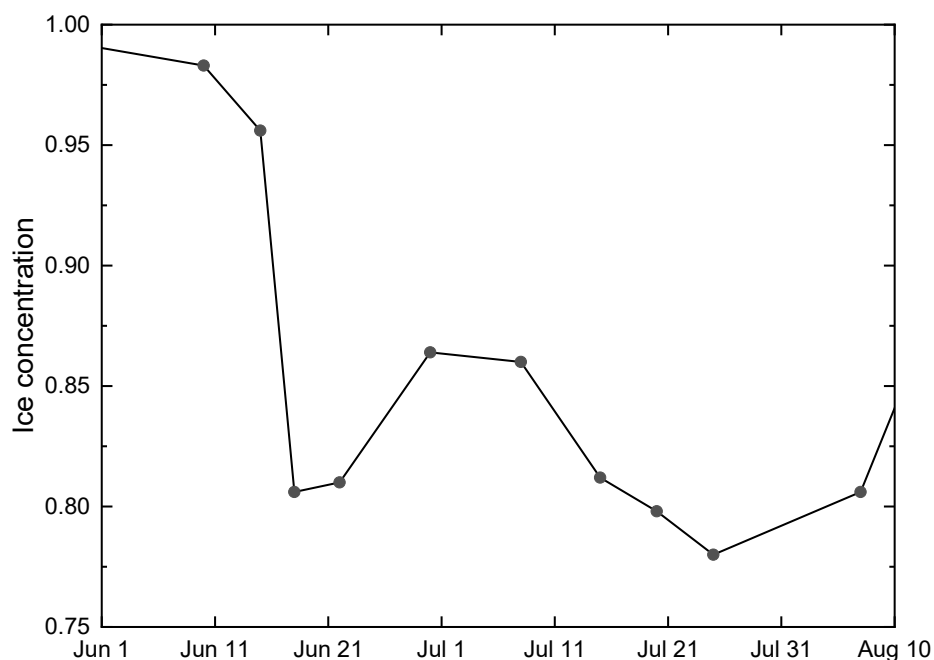



Figure 5. Time series of ice concentration determined from aerial photographs, *C(t)* (Perovich et al., 2002).

The contribution from surface drainage is simply the residual from Eq. 1, as shown in Figure 4, scaled by the ice concentration. The average bottom melt rate ($\overline{m_b}$) is computed using the same array of thickness gauges used to determine surface melt rates

150   (Perovich et al., 2003). Initially the average bottom melt rate was only about 0.2 cm d^{-1} (Figure 6). There was a gradual increase over the summer, reaching a peak of 1.1 cm d^{-1} in late July.

Determining the contribution from lateral melting is somewhat complicated. During SHEBA, there was only one site where a complete time series of lateral melting was measured. We assume that this one site is representative of the entire floe. Lateral melting can result in wall profiles with overhanging lips, shelves, and scallops (Perovich et al., 2003). Lateral melt rates were

155   determined by measuring the change in wall area and applying it to a hypothetical vertical wall generating a lateral melt rate. The ice thickness at the floe edge was measured using a thickness gauge. The ratio of floe perimeter to floe area was used to compare lateral melting to surface and bottom melting. This ratio was determined from the analysis of aerial photography where both the floe perimeter and floe area were computed.

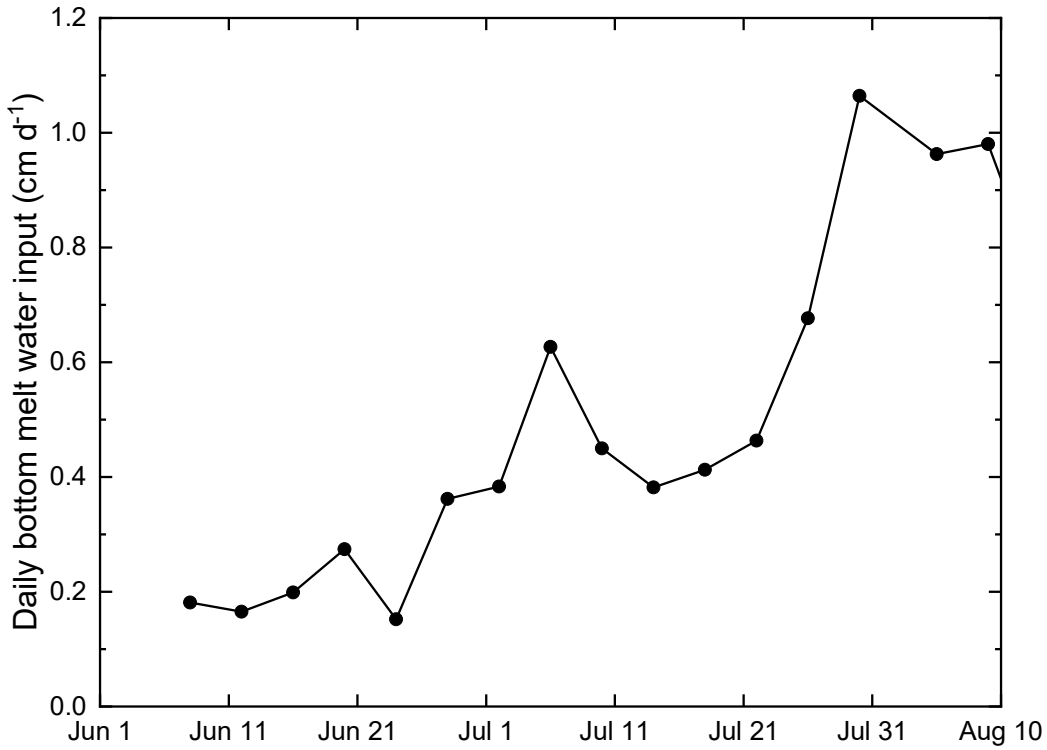
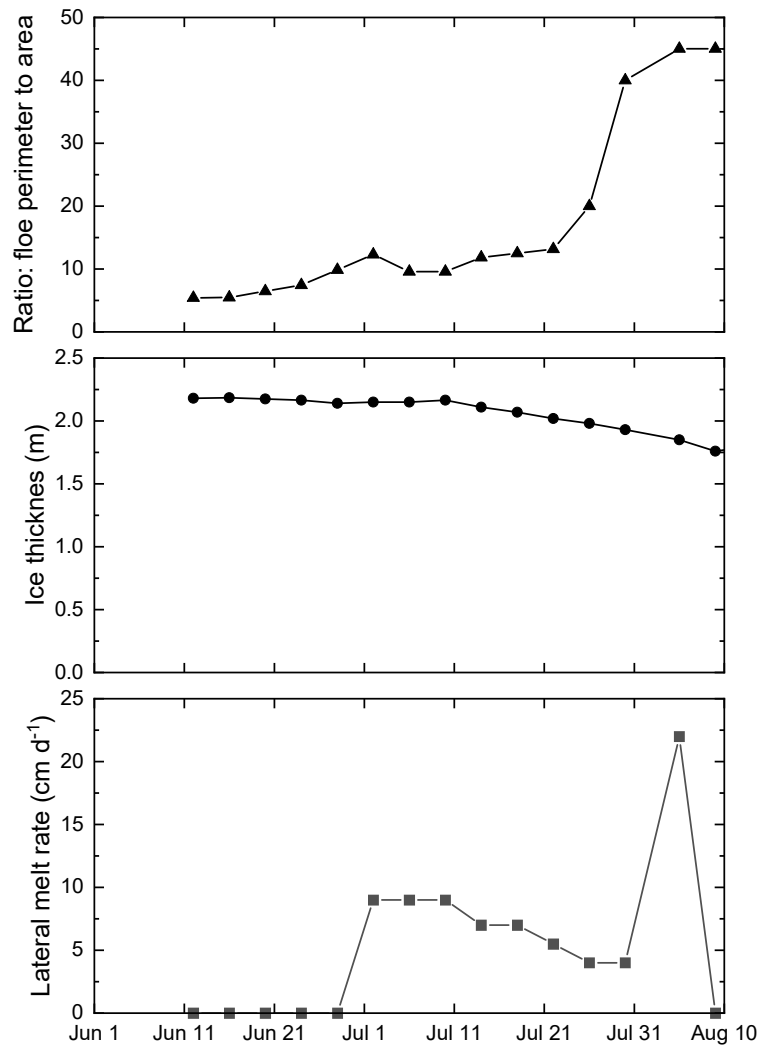



Figure 6. Time series of bottom melt rates, $M_b(t)$ (Perovich et al., 2003).

The time series of lateral melt rate, ice thickness, and the ratio of floe perimeter to area are plotted in Figure 7. There were large changes starting on 21 July. The floe perimeter to area ratio increased by roughly a factor of four, while the lateral melt increased from 4 to 22 cm d^{-1}. During this period, ice motion increased from a few cm s^{-1} to 40 cm s^{-1}, floes broke up, and heat stored in leads was transported to the ice edge, enhancing lateral melting (Richter-Menge and Perovich, 2001). The freshwater stored in the upper few meters of the lead was mixed downward.

The contributions to upper ocean freshwater input from surface drainage, bottom melt, and lateral melt are plotted in Figure 8. For most of the summer, the largest contribution was from drainage through the ice. By 9 August, though, the contributions from surface drainage and bottom melt were equal. The lateral melt contribution was the smallest. The cumulative total freshwater input increase was well represented ($R^2 = 0.999$) by a second order polynomial of the form

$$O_{fw} = 0.0105\, t'^2 + 0.432\, t' + 0.658\,, \qquad (8)$$

where t' is the number of days since 8 June.

 Figure 7. Time series of thickness at the ice edge, lateral melt rate ($M_l(t)$), and the ratio of floe perimeter to area *PA(t)*.

4. Discussion and Conclusions

From 1 June to 9 August, the total freshwater produced was equal to a layer 80 cm thick and the input to the ocean was equivalent to a layer 68 cm thick. This suggests that most of the freshwater produced over the Arctic summer was deposited in the ocean; on 9 August, only 15% of the freshwater produced was stored in ponds. This does not mean that on 9 August there was a 68 cm thick freshwater layer under the ice. The freshwater could be stored under the ice, in leads, and mixed deeper in the ocean. The fate of this freshwater depends on multiple factors including ice bottom topography, the dynamics of the ice cover, and the horizontal and vertical partitioning of drainage.

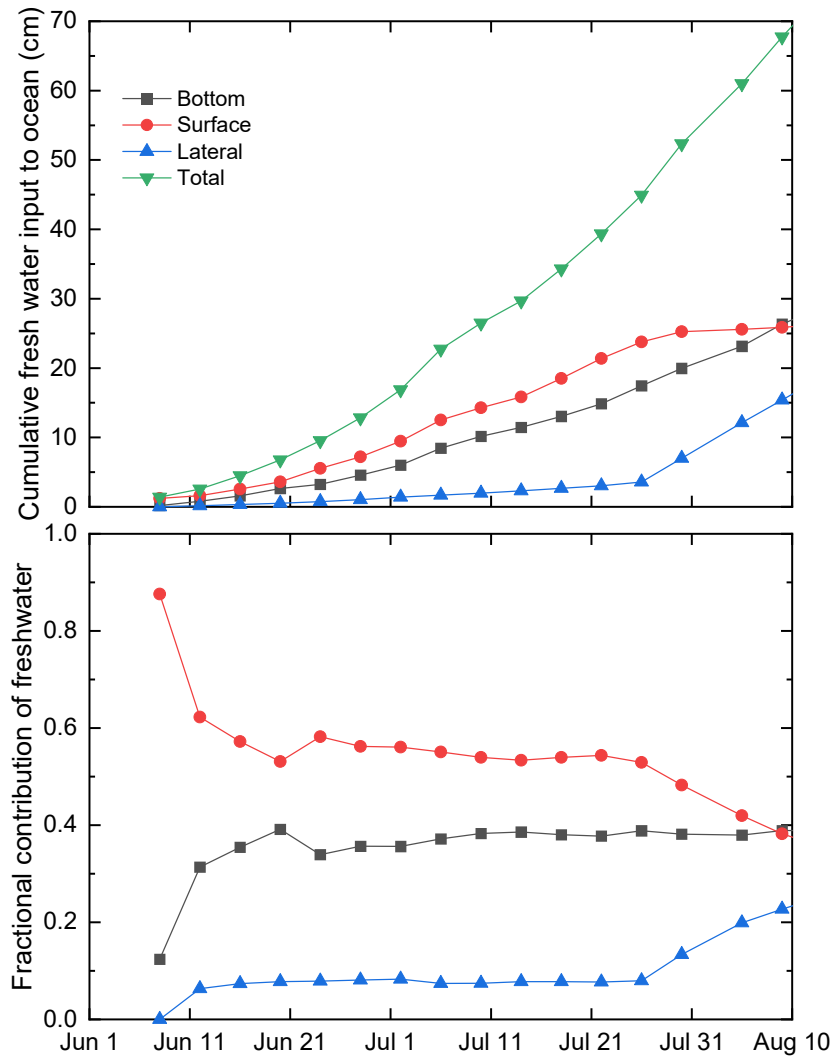



Figure 8. Upper ocean freshwater budget. Time series of fresh input to the ocean with contributions from lateral melting, bottom melting, and surface melting. The total input is also plotted. The melt contributions have been adjusted by the ice concentration.

This paper determined the amount of drainage from the ice surface to the ocean, but was unable to delineate between horizontal and vertical drainage. This misses an important distinction since freshwater input to leads or to the underside of the ice will have different behaviours and impacts. Horizontal transport will fill leads with freshwater, creating a stable surface layer that can be warmed by solar heating (Richter-Menge et al., 2001). Lateral melting also contributes directly to freshening of leads.

This results in a stable surface layer in leads affecting ocean–ice heat transfer and ocean–atmosphere gas exchange. Opening and closing of leads will mix this freshwater layer, transport heat to the ice edge, and force it under the ice. In contrast, vertical drainage can form a freshwater layer under the ice leading to the formation of false bottoms, isolate the ice from the ocean, and impact nutrient fluxes. Ice motion can mix and dissipate this layer.

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While we cannot quantitatively define the distribution of vertical to horizontal drainage, we can make some qualitative observations about the timing of when vertical vs. horizontal drainage occurred. Ponds above freeboard provide hydrostatic head to promote vertical drainage. In early June, most ponds were above freeboard. In mid-June, there was rapid drainage and a decrease in pond coverage. This occurred when the ice warmed, its brine volume increased, and it became permeable enough for vertical drainage to occur (Eicken et al., 2002). Also at this time, ponds were amorphous with no established horizontal drainage system to link ponds to the floe edge (see Figure 9).

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By early August, the situation had changed. Many of the ponds were at sea level, with no hydrostatic head. There was an elaborate melt channel network connecting melt ponds to each other and to the ice edge (Hohenegger et al., 2012) (see Figure 9). The lead fraction had increased from 0.03 to 0.18. Floes had broken, increasing the floe perimeter from 7.4 km km^{-2} (22 June) to 45.0 km km^{-2} (7 August). At this stage, horizontal drainage increased.

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It is possible to generate a rough estimate of the horizontal to vertical drainage for a brief period. During SHEBA, vertical profiles of temperature and salinity were made at a lead site. This showed the gradual buildup of freshwater and heat in the lead and how a dynamic ice event mixed this upper layer and greatly enhanced lateral melting (Richter-Menge et al., 2001). From 10 July to 20 July there was a steady deepening of the freshwater layer from 70 cm to 120 cm. This occurred during a quiescent period with little winds and little ice motion. Making a few assumptions, we use the 10-day, 50-cm increase in the freshwater layer to estimate the fraction of surface freshwater that is horizontally drained.

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We assume that i) the freshwater in leads only comes from lateral melting and horizontal drainage, ii) all lateral melting contributes to freshening of the lead, iii) no freshwater in the lead is lost under the ice or deeper in the ocean, and iv) measurements at the lead site are representative of the broader area. Using these assumptions, the increased depth of the freshwater layer in the lead from 10 July to 20 July is equal to the contribution from lateral melting and horizontal drainage. During this period, the ice concentration was 0.95, giving a concentration-adjusted lead freshening of 2.5 cm. The contribution from lateral melt during this period was 1.4 cm, giving a contribution from horizontal drainage of 1.1 cm. Adjusted by concentration, the surface freshwater production during this period was 13.8 cm, with 3.7 cm being stored in ponds and 10.1 cm drained. Thus, for this period, it is estimated that 11% of the drainage was horizontal.

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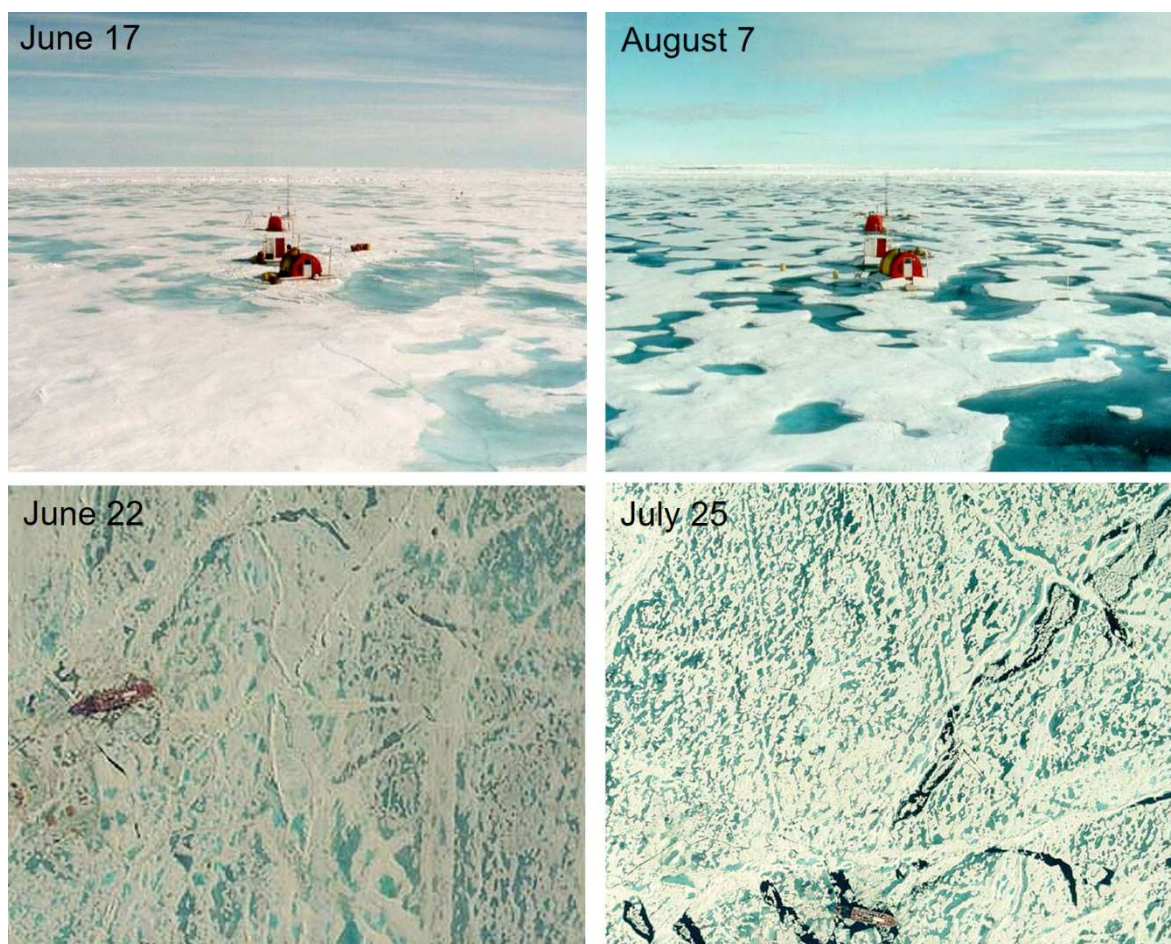
Figure 9. Surface and aerial photographs of Ice Station SHEBA at different stages of pond evolution, earlier and later in the melt season. The CCG Des Groseilliers (98 meters length) is visible in the lower photographs.

There were no measurements of the thermohaline structure of the top few meters of the upper ocean directly under the ice during SHEBA. Future studies should include routine profiles of temperature and salinity under the ice at multiple locations. This would show the buildup and erosion of the freshwater layer under the ice.

These results are from a multiyear floe in the Beaufort Sea during the summer of 1998. Future work should explore the spatial variability of the freshwater seasonal cycle and changes over time. Some information can be obtained from autonomous buoys. For example, autonomous sea ice mass balance measurements in the Beaufort Sea indicate large increases in bottom melting in recent years (Perovich and Richter-Menge, 2015). This has resulted in a larger freshwater contribution from bottom melt and a larger fraction of the freshwater production deposited in the ocean. While the contributions from surface and bottom melt are straightforward to measure autonomously, the contributions from lateral melting and the amount stored in melt ponds are more challenging. This gap could be partially filled by sensors measuring temperature and salinity profiles in the upper

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few meters of the ocean directly beneath the ice. Field experiments covering the full seasonal cycle, such as the

235 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (Shupe et al., 2020), are the optimal way to determine the evolution of the sources and sinks of freshwater in the summer.

Data availability:

The data used in this paper were from the SHEBA field experiment and can be found at the Arctic Data Center at: i) Donald Perovich, Thomas C. Grenfell, Bonnie Light, Jacqueline Richter-Menge, Walter B. "Terry" Tucker III, et al. 2007. Ice Mass

240 Balance [Perovich, D., T. Grenfell, B. Light, J. Richter-Menge, T. Tucker, H. Eicken]. Arctic Data Center. doi:10.5065/D6H130DF, version: urn:uuid:43ff491d-5383-4cdd-9595-389c8e56cf4d and ii) Donald Perovich. Aircraft Helicopter Aerial Photography [Perovich, D.]. Arctic Data Center. urn:uuid:804d4843-4ee4-4cba-86c1-e1969a161fb2.

Author contribution:

Perovich and Light contributed to the field measurements. Perovich did the initial draft preparation and the initial analysis.

245 Perovich, Smith, Light, and Webster all participated in the conceptualization, as well as the writing, review and editing.

Competing interests:

The authors declare that they have no conflict of interest.

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