Freshwater input and vertical mixing in the Canada Basin's seasonal halocline: 1975 versus 2006-2012

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ABSTRACT

The Arctic seasonal halocline impacts the exchange of heat, energy, and nutrients between the surface and the deeper ocean, and it is changing in response to Arctic sea ice melt over the past several decades. Here, we assess seasonal halocline formation in 1975 and 2006-2012 by comparing daily, May to September, salinity profiles collected in the Canada Basin under sea ice. We evaluate differences between the two time periods using a one-dimensional (1D) bulk model to quantify differences in freshwater input and vertical mixing. The 1D metrics indicate that two separate factors contribute similarly to stronger stratification in 2006-2012 relative to 1975: (1) larger surface freshwater input and (2) less vertical mixing of that freshwater. The larger freshwater input is mainly important in August-September, consistent with a longer melt season in recent years. The reduced vertical mixing is mainly important from June until mid-August, when similar levels of freshwater input in 1975 and 2006-2012 are mixed over a different depth range, resulting in different stratification. These results imply that decadal changes to ice-ocean dynamics, in addition to freshwater input, significantly contribute to the stronger seasonal stratification in 2006-2012 relative to 1975. These findings highlight the need for near-surface process studies to elucidate the impact of lateral processes and ice-ocean momentum exchange on vertical mixing. Moreover, the results may provide insight for improving the representation of decadal changes to Arctic upper-ocean stratification in climate models that do not capture decadal changes to vertical mixing.

1. Introduction

The surface waters of the Arctic Ocean have changed dramatically over the past several decades as a result of the diminishing sea ice cover that once shielded much of the ocean from wind and sunlight across all seasons (Perovich 2011; Stroeve and Notz 2018; Polyakov et al. 2020), and this has important consequences for the exchange of heat and nutrients between the surface and deeper ocean (McLaughlin et al. 2011; Carmack et al. 2015; Timmermans and Marshall 2020; Brown et al. 2020). Changes in Arctic sea ice conditions are generally thought to either strengthen or weaken the underlying upper-ocean stratification depending on the competing effects of fresh-water input and of vertical mixing (Peralta-Ferriz and Woodgate 2015; Lique 2015; Nummelin et al. 2015; Davis et al. 2016). A now warmer atmosphere and ocean delays ice freeze-up, reduces winter ice growth, and can melt more sea ice each spring and summer, potentially releasing more fresh, buoyant meltwater to the surface (Stroeve et al. 2014; Carmack et al. 2016) and stabilizing the upper ocean. Conversely, the wind acts on a now more mobile ice pack (Hakkinen et al. 2008; Rampal et al. 2009; Spreen et al. 2011; Galley et al. 2013; Kwok et al. 2013; Brown et al. 2020), potentially generating greater shear that stirs and mixes the underlying ocean, and reducing the stability of the upper ocean (Lemke and Manley 1984; Polyakov et al. 2020). Increased stratification has been documented in recent decades in many regions of the Arctic, but the evolving relationship between freshwater input and upper-ocean vertical mixing in response to Arctic sea ice retreat remains an open question.

We examine this question by comparing the seasonal evolution of the upper-ocean salinity below sea ice during two time periods that are separated by approximately three decades, and that are associated with distinctly different sea ice conditions. The datasets come from the 1975 Arctic Ice Dynamics Joint Experiment (AIDJEX) program (Untersteiner et al. 2007) and from the 2004-

present Ice-Tethered Profiler (ITP) instrumentation system (Krishfield et al. 2008). Compared to the 1975 AIDJEX dataset, the ITP dataset is associated with lower sea ice concentration (Fig. 1), has less multi-year sea ice area and volume (Wadhams 2012; Kwok 2018), and is made up of smaller ice floes (Hutchings and Faber 2018) that are both thinner (Kwok and Rothrock 2009; Kwok 2018) and less deformed, with shallower ridges (Wadhams 2012; Hutchings and Faber 2018; Kwok 2018).

Both the ITP and AIDJEX data were collected in the Canada Basin (Fig. 1), where the upper-ocean hydrography evolves seasonally in response to changes in sea ice (McPhee and Smith 1976; Morison and Smith 1981; Lemke and Manley 1984; Jackson et al. 2010; Toole et al. 2010; Peralta-Ferriz and Woodgate 2015), river runoff (Macdonald et al. 1999; Yamamoto-Kawai et al. 2009), and Ekman dynamics in the Beaufort Gyre (Proshutinsky et al. 2009; Carmack et al. 2016; Meneghello et al. 2018). In the spring and summer, freshwater flux from snow and sea ice melt causes the surface mixed layer to freshen and shoal, forming a seasonal halocline. The predominant, clockwise atmospheric circulation (Beaufort High) drives convergent Ekman pumping in the Beaufort Gyre most noticeably in the fall, causing low salinity surface water to converge and the halocline to deepen within the basin (Reed and Kunkel 1960; Gudkovich 1961; Hunkins and Whitehead 1992; Proshutinsky et al. 2009; Newton et al. 2006; Jackson et al. 2010; McLaughlin and Carmack 2010; Meneghello et al. 2018). In the winter, sea ice formation results in brine rejection, which increases the surface water salinity and causes convectively-driven mixed-layer deepening that erodes the seasonal halocline.

Comparisons of single representative profiles from ITP and AIDJEX data that were collected in roughly the same location indicate a trend toward fresher surface waters, shallower mixed layers, and a more stably stratified upper ocean (Toole et al. 2010; McPhee 2012), similar to the comparison of AIDJEX and 1997 Surface HEat Budget of the Arctic (SHEBA) data (McPhee et al.

1998). June–September and November–May seasonal averages of hydrographic data across the Arctic during 1979-2012, which did not include ITP or AIDJEX data, confirmed statistically significant ∼30-year trends toward a more stably stratified upper ocean with shallower and fresher mixed layers in the Canada Basin (Peralta-Ferriz and Woodgate 2015). Decadal changes to the surface waters were primarily attributed to increased freshwater input from ice melt, river run-off, and precipitation. This freshwater has collected toward the center of an intensified anticyclonic (convergent) Beaufort Gyre (Macdonald et al. 1999; Proshutinsky et al. 2009; Jackson et al. 2010; McLaughlin and Carmack 2010; Steele et al. 2011; Peralta-Ferriz and Woodgate 2015). However, the seasonality of the freshwater input, the vertical extent of wind-driven mixing, and upper-ocean stratification was not addressed in these previous studies.

In this study, we compare seasonal processes of the upper ocean by focusing on the evolving time series from May to September in the 2006-2012 ITP data and 1975 AIDJEX data. This seasonal analysis differs from previous studies that compared two single profiles (Toole et al. 2010; McPhee et al. 1998), two 20-day average profiles (McPhee 2012), or used four- and seven-month averages (Peralta-Ferriz and Woodgate 2015). We interpret the results using a simple one-dimensional bulk model of seasonal halocline formation that allows for the comparison of the ITP and AIDJEX data in terms of seasonal freshwater input and vertical mixing. The datasets used for this study are presented in Section 2, and the one-dimensional model is presented in Section 3. In Section 4, we present results comparing the ITP and AIDJEX hydrographic data in conjunction with the one-dimensional model metrics. We discuss broad implications of the results for coupled models and mechanisms that could explain changes in the relationship between freshwater input, vertical mixing, and stratification during the two time periods in Section 5 and summarize our results in Section 6.

2. Data

This study addresses spring-to-summer halocline formation associated with two distinctly different time periods and sea ice regimes. To this end, we use observed May–September near-surface salinity profiles from the AIDJEX and ITP programs.

A major component of the AIDJEX program consisted of four occupied, drifting ice camps where oceanographic data were collected for approximately one year between May 1975 and April 1976 (Table 1). Salinity and temperature profiles between depths of 5 m and 750 m were measured daily at each camp, with a vertical resolution of 1–2 m, using a Plessey model 9040 conductivity, temperature, depth measurement system, resulting in 1279 vertical profiles. See Maykut and McPhee (1995) for a full description of the data used in this analysis.

The ITP instrument system records temperature and salinity profiles with a vertical resolution of 25 cm throughout the Arctic. The system consists of a series of surface buoys, frozen into drifting ice floes, connected to 800-m-long wires. CTD profilers move up and down the wires collecting data approximately 2-3 times per day. We use quality-controlled data, identified as level 3 in the ITP data archives, which have 1 m vertical resolution and were available for 2004-2012 at the time of the analysis. We examine all available level-3 processed data within the Canada Basin, which we define as the region bounded by 72°N, 80°N, 130°W, and 155°W (similar to the region defined by Peralta-Ferriz and Woodgate (2015); dashed lines, Fig. 1). Further, we select only ITPs that have data starting in May of a given year, similar to the data available from the AIDJEX ice camps. Lastly, profiles were removed if the shallowest observed value was deeper than 10 meters (following Jackson et al. 2010), which helps to account for the fact that ITPs often start sampling too deep to accurately measure the summer mixed layer.

In total, 517 AIDJEX profiles collected in 1975 from 4 ice camps and 2892 ITP profiles collected between 2006-2012 from 12 different ITPs satisfied these criteria (Table 1), with average shallowest measurements of ~ 6 m and ~ 7 m, respectively. All profiles were linearly interpolated onto a common 1-m vertical grid. Ice thickness measurements are not available for all ITP profiles or AIDJEX ice camps. For both datasets, we therefore assume an ice–ocean interface at 3 m, a climatological multi-year sea ice thickness in the Canada Basin (Perovich and Richter-Menge 2015), and keep the salinity and temperature constant from the shallowest measurements of each profile to $z = -3$ m, with the z-axis defined as positive up. We discuss the sensitivity of our results to missing near-surface data in Section 5.

To estimate the freshwater input from sea ice melt, we also examine 1979-2018 sea ice volume estimates provided by the Pan-arctic Ice Ocean Modeling and Assimilation System (PIOMAS, Schweiger et al. 2011). The PIOMAS sea ice volume was regridded to the 25 km Equal-Area Scalable Earth (EASE) grid and averaged over the Canada Basin (bounded by 72°N, 80°N, 130°W, and 155°W, as in the hydrographic data).

To qualitatively compare the sea ice conditions associated with the AIDJEX and ITP datasets, we examine 1975 and 2006-2012 sea ice concentrations. Daily 2006-2012 sea ice concentration observations are provided by Passive Microwave satellite data, Version 1 (Cavalieri et al. 1996), which combines data from the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (DMSP SSM/I, 2006-2007) and the Special Sensor Microwave Imager/ Sounder (SSMI/S, 2007-2012). Sea ice concentration data are co-located to each ITP observation. We note that low sea ice concentration from the passive microwave data can imply either low ice concentration or surface melt ponds (e.g., Kern et al. 2016). Since the AIDJEX data were collected in 1975, before the satellite data were available, we use the Canadian Ice Service digital archive (CISDA) chart data for the western Arctic region to determine the temporal evolution of sea ice concentration during that year in the Canada basin region (Tivy et al. 2011). Gridded datasets for each CISDA chart in June-September 1975 were analyzed to provide a weekly regional mean sea ice concentration.

3. One-Dimensional Framework

One-dimensional (1D) ice-ocean bulk models are used to provide a framework for interpreting observed seasonal mixed-layer evolution (Morison and Smith 1981; Lemke and Manley 1984; Lemke 1987; Toole et al. 2010; Petty et al. 2013; Tsamados et al. 2015; Peralta-Ferriz and Woodgate 2015; Randelhoff et al. 2017). Here, we model seasonal halocline formation starting from a homogeneous winter mixed layer in an idealized system (Fig. 2), building on conceptual models used to estimate freshwater input, vertical mixing, and upper-ocean stratification from hydrographic data in previous studies (Lemke and Manley 1984; Peralta-Ferriz and Woodgate 2015; Randelhoff et al. 2017). The resulting framework provides a suite of diagnostic, upper-ocean parameters to examine the vertical salt budget and its impact on the stratification using the observed seasonal evolution of vertical salinity profiles. This idealized model omits a range of processes, including (1) temperature effects on density, which have a less than 1% impact of the surface density in the ITP data (not shown), (2) brine-rejection driven mixing from intermittent freezing, which cannot be resolved from daily observations; (3) tidal currents, which are only expected to impact shelf waters (i.e. shallower than in the Canada Basin), (4) double-diffusion, which mainly impacts the 200-300 m depth range in this region (Timmermans et al. 2008), and a range of processes associated with horizontal advection; the impact of this will be considered in Sections 4-5.

a. Model Equations

We consider a closed, 1D ice-ocean system with an ocean of depth L that only evolves in response to thermodynamic spring-summer sea ice melt and vertical mixing with the following initial conditions ($t = t_0$): a well-mixed ocean, with vertically uniform salinity (S_0) and potential density (ρ_0), and sea ice with constant salinity (S_{ice}) and density (ρ_{ice}).

If melt water is vertically mixed to some depth, Z_{fw}, then the salinity and density below this depth remains fixed at S_0 and ρ_0 (i.e., $S(z) = S_0$ and $\rho(z) = \rho_0$ for $z \leq Z_{fw}$, where z and Z_{fw} are both negative). The conservation of salt and mass for time $t > t_0$ can then be written as:

$$\int_{Z_{fw}(t)}^{Z_{ice}} \rho(t,z)S(t,z) \cdot dz - \rho_0 S_0 (Z_{ice} - Z_{fw}(t)) = \rho_{ice} S_{ice} h_{melt}(t) \quad (1)$$

$$\int_{Z_{fw}(t)}^{Z_{ice}} \rho(t,z) \cdot dz - \rho_0 (Z_{ice} - Z_{fw}(t)) = \rho_{ice} h_{melt}(t), \quad (2)$$

where t is a seasonally evolving time variable, Z_{ice} is the ice draft, h_{melt} is the change in sea ice thickness from melt, $\rho(t,z)$ and $S(t,z)$ are the ocean potential density and salinity, respectively. The above expressions, therefore, represent the change in mass and salt in the ocean (left-hand side) in response to sea ice melt (right-hand side). These equations can be algebraically combined to estimate the sea ice melt necessary to explain the transition from the initial, well-mixed ocean (S_0, ρ_0) to the subsequent ocean profile that includes vertically mixed meltwater ($S(t,z)$, $\rho(t,z)$) at any time $t > t_0$:

$$h_{melt}(t) = \int_{Z_{fw}(t)}^{Z_{ice}} \frac{\rho(t,z)(S(t,z) - S_0)}{\rho_{ice}(S_{ice} - S_0)} \cdot dz, \quad (3)$$

where h_{melt} represents a time-evolving integral measure of seawater dilution by cumulative surface freshwater input from sea ice melt. This approach is similar to an approach used in previous studies that estimated sea ice melt from mixed-layer salinity evolution (Lemke and Manley 1984; Peralta-Ferriz and Woodgate 2015), but here the depth range is set by Z_{fw} and Z_{ice} rather than a mixed-layer depth criterion. That is, we estimate the freshwater input from sea ice melt over a well-defined volume, which avoids errors that can arise when using an arbitrary reference salinity (Schauer and Losch 2019; Rosenblum et al. 2021).

The term h_{melt} is linearly related to the vertically integrated change in salinity relative to S_0:

$$\Phi(t) = \int_{Z_{fw}(t)}^{Z_{ice}} S_0 - S(t,z) \cdot dz, \tag{4}$$

which also provides a bulk estimate of the cumulative amount of freshwater input at any time $t > t_0$. We note that Φ is closely related to the "salt deficit" or "buoyancy deficit" as defined by Martinson (1990), Martinson and Iannuzzi (1998), and Randelhoff et al. (2017).

Different salinity profiles are possible in response to the same amount of ice melt, depending on how the melt water is vertically spread or mixed through the water column (Fig. 2). For example, if the melt water were concentrated close to the surface (less vertical mixing, shallow Z_{fw}), this would result in more surface freshening and a more stably stratified water column (Fig. 2; left side). Alternatively, if the melt water were spread over a larger depth range (more vertical mixing, deep Z_{fw}), this would result in less surface freshening and a less stably stratified water column (Fig. 2; right side).

To quantify this effect, we will consider two bulk metrics of stratification. First, we define the surface freshening at any time $t > t_0$ as the surface salinity anomaly relative to the initial condition:

$$\delta S_{surf}(t) = S(t, Z_{ice}) - S_0. \tag{5}$$

Second, we define the stratification that occurs in response to sea ice melt at any time $t > t_0$ as the vertical derivative of salinity averaged over depth Z_{fw}:

$$S_z(t) = \frac{1}{Z_{fw}(t) - Z_{ice}} \int_{Z_{fw}(t)}^{Z_{ice}} \frac{dS(t,z)}{dz} dz. \tag{6}$$

b. Separating freshwater input and vertical mixing

We seek representations of δS_{surf} and S_z to directly compare the 1975 AIDJEX data and 2006-2012 ITP data in terms of changes to (1) the seasonal freshwater input and (2) vertical mixing. That is, for any time $t > t_0$, we seek:

$$\Delta(\delta S_{surf}(t)) = f(\Delta\Phi(t), \Delta D(t)) \tag{7}$$

$$\Delta S_z(t) = f(\Delta\Phi(t), \Delta D(t)). \tag{8}$$

Δ indicates the difference between ITP and AIDJEX data:

$$\Delta X = X_{ITP} - X_{AJX}, \tag{9}$$

where ITP indicates that the value is derived from ITP data and AJX indicates that the value is derived from AIDJEX data.

D is a bulk indicator of the vertical mixing, where we define larger and smaller mixing as mixing that leads to a deeper or shallower seasonal halocline. We choose the equivalent mixed-layer depth, an integral quantity that is closely related to the vertical extent of wind-driven mixing (similar to (Randelhoff et al. 2017)):

$$D(t) = \frac{\Phi(t)}{\delta S_{surf}(t)}, \tag{10}$$

where $D + Z_{ice}$ indicates the depth of the halocline if the meltwater were completely mixed (i.e., if the salinity were homogenized), implying that the salinity profile would have a 2-layer form and that $D + Z_{ice} = Z_{fw}$:

$$S_{bulk}(t,z) = \begin{cases} S_0 + \Phi(t)/D(t) & D(t) + Z_{ice} \le z \le Z_{ice} \\ S_0 & z < D(t) + Z_{ice} \end{cases} \tag{11}$$

(see Fig. 2 for an illustration of this 2-layer profile).

The surface freshening (δS_{surf}) and stratification (S_z) associated with this 2-layer system for any time $t \geq t_0$ is:

$$\delta S_{surf}(t) = \frac{\Phi(t)}{D(t)} \quad \text{and} \quad S_z(t) = \frac{\Phi(t)}{D(t)^2}, \tag{12}$$

respectively, following equations (5), (6), and (11). δS_{surf}, therefore, indicates the salt content changes within the mixed layer D.

Two factors determine δS_{surf} and S_z: (1) the amount of freshwater input (related to Φ and h_{melt}) and (2) the concentration or dilution of that freshwater toward or away from the surface by vertical mixing (related to D). We can, therefore, estimate how each factor contributes to $\Delta(\delta S_{surf})$ and ΔS_z (as in eqs. 7-8) by writing δS_{surf} and S_z derived from 2006-2012 ITP data in terms of the changes relative to the 1975 AIDJEX data:

$$\delta S_{surf,ITP}(t) = \frac{\Phi_{AJX}(t) + \Delta\Phi(t)}{D_{AJX}(t) + \Delta D(t)}, \tag{13}$$

$$S_{z,ITP}(t) = \frac{\Phi_{AJX}(t) + \Delta\Phi(t)}{(D_{AJX}(t) + \Delta D(t))^2}. \tag{14}$$

The difference between δS_{surf} in 1975 and 2006-2012 ($\Delta(\delta S_{surf})$) can then be re-written algebraically to isolate the relative contributions of $\Delta\Phi$ and ΔD on $\Delta(\delta S_{surf})$:

$$\Delta(\delta S_{surf}(t)) = \underbrace{\frac{\Delta\Phi(t)}{D_{AJX}(t)}}_{\substack{\text{changes to}\\ \text{freswater input}}} - \underbrace{\frac{\Phi_{AJX}(t)\Delta D(t)}{D_{AJX}(t)D_{ITP}(t)}}_{\substack{\text{changes to}\\ \text{vertical mixing}}} - \underbrace{\frac{\Delta\Phi(t)\Delta D(t)}{D_{AJX}(t)D_{ITP}(t)}}_{\text{correlated term}}. \tag{15}$$

Similarly, the difference between S_z in 1975 and 2006-2012 (ΔS_z) can be written as:

$$\Delta S_z(t) = \underbrace{\frac{\Delta\Phi(t)}{D_{AJX}(t)^2}}_{\substack{\text{changes to}\\ \text{freshwater input}}} \underbrace{- \Phi_{AJX}(t)\Delta D(t)\frac{D_{AJX}(t) + D_{ITP}(t)}{D^2_{AJX}(t)D^2_{ITP}(t)}}_{\substack{\text{changes to}\\ \text{vertical mixing}}} \underbrace{- \Delta\Phi(t)\Delta D(t)\frac{D_{AJX}(t) + D_{ITP}(t)}{D^2_{AJX}(t)D^2_{ITP}(t)}}_{\text{correlated term}}. \tag{16}$$

(See Supporting Information for full derivation.)

The three terms on the right-hand sides of (15) and (16) are estimates of the decadal changes to the stratification associated with (1) changes related to only freshening (freshwater input; $\Delta\Phi$,

Δh_{melt}), holding the vertical mixing to AIDJEX values (D_{AJX}); (2) changes related to only mixed-layer shoaling (vertical mixing; ΔD), holding the amount of freshwater input equal to AIDJEX values (Φ_{AJX}); and (3) the contribution from the correlation between $\Delta\Phi$ and ΔD.

4. Results

The observations indicate that the surface is $\sim$ 2-4 g/kg fresher in 2006-2012 relative to 1975, yet both time periods have a similar seasonal evolution (Fig. 3). At the beginning of May, both datasets indicate mixed layers that are relatively deep (thick black lines, Fig. 3a). As spring progresses, the surface freshens and the seasonal halocline forms (dashed black lines, Fig. 3a,b). Toward the end of summer, sea ice forms, the surface becomes progressively saltier, and the mixed layer deepens, eroding the seasonal halocline (compare dashed and thick black lines, Fig. 3b). Compared to 1975, 2006-2012 appears to have more seasonal freshwater stored closer to the surface, resulting in more seasonal surface freshening and a more stably stratified upper ocean for a longer time period. Qualitatively, this is consistent with the previous studies described in Section 1.

To compare the seasonal evolution of the upper ocean during 1975 and 2006-2012 using the 1D framework, we set S_0 equal to the May-average surface salinity ($S(Z_{ice})$) measured by the same ITP or AIDJEX ice camp during the same year. That is, we examine the seasonal freshwater input (Φ, h_{melt}), vertical mixing (Z_{fw}, D), and the surface freshening (δS_{surf}) relative to the May average, which marks the beginning of the melt season measured by a given ITP or AIDJEX ice camp. We present results based on alternative values of S_0 in the Supporting Information. All other constants are given in Table 2.

Figure 4 shows an example of how various quantities presented in Section 3 are computed for a single profile using observations from one AIDJEX ice camp (Fig. 4; left side) and one ITP (Fig. 4; right side). The freshwater input, indicated by h_{melt} and Φ, reflects any process that drives changes to the integrated upper-ocean salinity, including sea ice melt, river runoff, precipitation, or advection, although previous studies have demonstrated that the majority of the seasonal freshwater input during the melt season is derived from sea ice melt (e.g., Lemke and Manley 1984; Peralta-Ferriz and Woodgate 2015). Vertical mixing, indicated by Z_{fw} and D, reflects any process that vertically spreads or distributes that freshwater, including wind-driven mixing, and possibly brine-rejection from intermittent freezing, double-diffusion, or tidal currents.

a. Validation

To test the validity of our approach, we compare the cumulative seasonal freshwater input in terms of the equivalent ice melt (h_{melt}), derived from hydrographic data, to the effective ice thickness change relative to May of each year between 1979-2018 using PIOMAS. We compute h_{melt} associated with each profile in 1975 and 2006-2012. The seasonal evolution of h_{melt} and the monthly ice thickness relative to May are shown in Figure 5. Both estimates indicate cumulative sea ice melt through August. In 1975, h_{melt} begins to decrease in early September in response to sea ice formation and entrainment. In 2006-2012, h_{melt} continues to moderately increase through September in response to a later freeze up (Fig. 5a). We find similar results using different definitions of S_0 (Fig. S2).

We find good agreement between the PIOMAS seasonal ice thickness changes and the estimated seasonal freshwater input, represented as equivalent meters of ice melt using oceanographic observations during summer, consistent with previous studies. By the end of August, we find h_{melt} $\sim$0.5-1 m in 1975 and h_{melt} $\sim$1-2 m in 2006-2012, consistent with estimated sea ice melt during similar time periods using hydrographic data (Lemke and Manley 1984; Peralta-Ferriz and Woodgate 2015) and ice mass balance buoys (e.g., Perovich and Richter-Menge 2015). The consistency of these findings provides indirect evidence that h_{melt} is a reasonable estimate of the seasonal freshwater input. We note that in June, some data points indicate a negative h_{melt}. For the remainder of the analysis, we only consider profiles with positive values of h_{melt}.

Using each observed profile, we compare the stratification (S_z; eq. 6) to the associated 2-layer estimate (eq. 12). The seasonal evolution of each of these values in the 1975 AIDJEX and 2006-2012 ITP datasets is shown in Figure 6. We find a clear agreement between the observations and the 2-layer estimates. First, both values indicate that the seasonal halocline forms in late June of 1975 and 2006-2012, but is more stably stratified for a longer period of time in 2006-2012. Second, both values are up to five times larger in 2006-2012 relative to 1975. Toward the end of the melt season, more freshwater is stored below the mixed layer, causing the 2-layer formalism to overestimate S_z. Despite these differences, overall, we find that the 2-layer simplification captures the majority of the key features necessary to explain the differences between the upper-ocean seasonal evolution in 1975 and 2006-2012.

The equivalent mixed-layer depth (D) and the associated surface freshening (δS_{surf}) in 1975 and 2006-2012 are shown in Figure 7. These metrics indicate a number of differences between the ITP and AIDJEX datasets that are consistent with previously documented decadal trends in the Canada Basin. Specifically, Peralta-Ferriz and Woodgate (2015) found statistically significant trends of mixed-layer freshening (0.11 psu/yr) and mixed-layer shoaling (0.33 m/yr) during June–September in regions of the Canada Basin with high sea ice concentration (>15%). These rates of change would imply an average change of 3.7 psu and 11.2 m over 34 years, similar to the 3.1 g/kg and 14.5 m difference in the surface salinity ($\delta S_{surf} + S_0$) and the equivalent mixed-layer depth (D) between the 1975 AIDJEX data and the 2006-2012 ITP data over the same months. Overall, these findings suggest that a comparison of the ITP and AIDJEX datasets, in conjunction with the one-dimensional framework presented in Section 3, yields results that are consistent with Peralta-Ferriz and Woodgate (2015) using seasonal averages.

b. 1975 vs 2006-2012

The relationship between 1D bulk estimates of freshwater input from ice melt and other freshwater sources (h_{melt}; eq. 3), vertical mixing (D; eq. 10), and upper-ocean stratification (δS_{surf}, S_z; eq. 12) is shown in Figure 8, using every June-September salinity profile in 1975 and 2006-2012. During each time period, we find that the parameters exhibit relationships that are qualitatively consistent with a 1D system: Surface fluxes that result in a more buoyant surface layer cause a more stable stratification that inhibits vertical mixing (Turner 1967; Kraus and Turner 1967; Lemke and Manley 1984; Lemke 1987). That is, profiles with more freshwater input (larger h_{melt}) are associated with less vertical mixing (smaller $|D|$, where $|\cdot|$ indicates the absolute value) and a more stably stratified upper ocean (large $|\delta S_{surf}|$, S_z).

Considering differences between 1975 and 2006-2012, we find that there are more profiles in 2006-2012 with large values of h_{melt} and hence small values of $|D|$ and large values of $|\delta S_{surf}|$ and S_z, as in a 1D system. However, we also consistently find profiles with the same amount of freshwater (h_{melt}) in both time periods but with the freshwater concentrated closer to the surface (smaller $|D|$) in 2006-2012 relative to 1975 (Fig. 8a). These differences in $|D|$ are also associated with a more stable stratification (large $|\delta S_{surf}|$, S_z; Fig. 8b-c). That is, there are two separate factors causing the more stable stratification in 2006-2012 relative to 1975: (1) more freshwater input (larger h_{melt}), which mainly occurs in August and September, and (2) less vertical mixing (smaller $|D|$), which mainly occurs in June and July (Fig. 8; compare top and bottom panels).

We find similar results when examining the relationship between $\Delta(\delta S_{surf})$, ΔS_z, and Δh_{melt} during each 5-day period (Fig. 9); 5-day periods with similar levels of freshwater input in 1975 and 2006-2012 ($\Delta h_{melt} \sim 0$) have different stratification ($|\Delta(\delta S_{surf})| > 0$, $\Delta S_z > 0$) from June until mid-August. The largest difference between the two time periods occurs from mid-August through September, coinciding with the largest values of Δh_{melt}.

We can use the 1D framework (Section 3b) to estimate the relative importance of each of these factors in setting the more stable stratification in 2006-2012 relative to 1975. Figure 10b-c shows the 5-day average bulk estimates of the upper-ocean stratification (δS_{surf}, S_z) in 1975 (blue line) and 2006-2012 (red line). For each 5-day period, we compute the difference between 1975 and 2006-2012 ($\Delta(\delta S_{surf}), \Delta S_z$) in terms of (1) the larger freshwater input alone (yellow region; $\propto \Delta h_{melt}$, $\Delta\Phi$), (2) the concentration of the freshwater closer to the surface alone (purple region; $\propto \Delta D$), and (3) the contribution from the correlation between the two factors (green region; $\propto \Delta h_{melt}\Delta D$, $\Delta\Phi\Delta D$) using equations (15) and (16). The yellow region provides a rough estimate of the change in stratification that would occur if the relatively large amount of freshwater input indicated by 2006-2012 ITP data is stored within the relatively deep mixed layer measured by 1975 AIDJEX data (i.e., if $\Delta D = 0$ in eqs. (15) and (16)). Similarly, the purple region provides a rough estimate of the change in stratification that would occur if the relatively small amount of freshwater input indicated by 1975 AIDJEX data is stored within the relatively shallow mixed layer measured by 2006-2012 ITP data (i.e., if $\Delta\Phi = 0$ in eqs. (15),(16)).

Overall, the changes to the vertical mixing (ΔD), the freshwater input ($\Delta\Phi$), and the contribution from the correlation between the two terms ($\Delta\Phi\Delta D$) have similar roles in explaining the larger magnitudes of $|\Delta(\delta S_{surf})|$ and S_z in 2006-2012 relative to 1975. This implies that the concentration of freshwater closer to the surface in recent years has a similar impact on upper-ocean stratification to that caused by a larger amount of seasonal freshwater input. The seasonality of the two factors confirms our findings from Figure 9: The concentration of freshwater closer to the surface (purple region) is mainly important in June–August, while the larger amount of freshwater input and the correlated term (yellow and green regions) are mainly important in August–September. This result is also consistent with the the largest differences in h_{melt} between the two time periods occurring toward the end of the melt season (Fig. 10a).

5. Discussion

Coupled ice-ocean models and global climate models are used extensively to understand current climate change and to predict future changes, but tend to simulate an upper-ocean stratification in the Canada Basin that is weaker than observed (Holloway et al. 2007; Ilicak et al. 2016; Nguyen et al. 2009; Zhang and Steele 2007; Jin et al. 2012; Barthélemy et al. 2015; Sidorenko et al. 2018; Rosenblum et al. 2021). In a climate model, Φ is directly related to the freshwater flux at the surface due to sea ice melt, river run-off, and precipitation, while D is closely related to simulated ocean mixed-layer dynamics (Rosenblum et al. 2021). In Figure 10, the yellow region provides a rough estimate of the more stable stratification that would occur in a model that accurately simulated decadal changes to freshwater fluxes with unchanged mixed-layer dynamics. The purple region provides a rough estimate of the more stable stratification that would occur in a model that accurately simulated decadal changes to mixed-layer dynamics without simulating changes to freshwater fluxes. Climate models that do not simulate the decadal trend toward a shallower mixed layer in the Canada Basin (Rosenblum et al. 2021), therefore, do not include the contributions toward a more stratified upper-ocean that are quantified by the purple and green regions of Figure 10.

What mechanisms caused shallower mixed layers and stronger stratification in 2006-2012 in response to the same amount of freshwater input as in 1975 (associated with the purple regions of Figure 10)? One possibility is that lateral processes are more prominent under the more mobile ice cover in recent years and cause complicated relationships between freshwater input, vertical mixing, and stratification (Randelhoff et al. 2017; Meneghello et al. 2021) or establish fronts that act to limit the effects of wind-driven vertical mixing via submesoscale instabilities (Timmermans and Winsor 2013). A second possibility is that wind-driven momentum transfer below sea ice has decreased in response to changing sea ice conditions, which can occur in regions that transitioned from multi-year to first-year ice. Specifically, modeling studies suggest that the wind-driven momentum transfer can sometimes decrease in response to the loss of ice keels and reduced sea ice roughness rather than increase in response to enhanced sea ice motion (McPhee 2012; Martin et al. 2014, 2016; Tsamados et al. 2014). A third possibility is that the shallower and more stably stratified winter halocline in 2006-2012 inhibited mixed-layer deepening to the levels seen in 1975 (Fig. 3; Toole et al. 2010; Peralta-Ferriz and Woodgate 2015). Each of these mechanisms would create a positive feedback scenario in which the same amount of melt water is concentrated closer to the surface toward the beginning of spring, setting up a more stable seasonal halocline that further inhibits vertical mixing of meltwater and further stablizes the seasonal halocline.

Another possibility is that changes to the sea ice conditions impact melt-pond drainage, which is associated with halocline formation in early summer (Gallaher et al. 2016). Unfortunately, both the ITPs and AIDJEX measurements begin at an average of ∼6–7 m depth and, therefore, do not capture important variations to the freshwater content near the surface. This surface data gap can cause mixed-layer depths to be biased too deep (Toole et al. 2010), can cause the timing of the mixed-layer shoaling to be biased several weeks too late (Gallaher et al. 2017), and can cause uncertainties in the seasonal freshwater storage. Considering results from Proshutinsky et al. (2009), we estimate that this error could cause h_{melt} to be underestimated by approximately 0.2 m during the summer months (see SI for details). More uncertainties arise because we lack measurements of the sea ice draft (Z_{ice}) for the vertical bounds of our calculations. For example, we find that $\pm$ 1 m changes to Z_{ice} result in approximately $\pm$ 0.1 m of equivalent ice melt by the end of the melt season.

Overall, the cause of the shallower vertical mixing in recent years remains an open question but one that may be essential for accurately simulating decadal changes to upper-ocean stratification in climate models (Rosenblum et al. 2021). A clear answer to this question will require shallow, near-ice hydrographic or sea ice mass balance measurements in tandem with models to disentangle the sensitivity of vertical mixing to lateral processes, ice-ocean momentum exchange, and pre-melt conditions.

6. Summary

The rapid and continuing change of summer sea ice cover in the Canada Basin has led to a fresher and more stratified upper ocean that has been primarily attributed to more freshwater input from sea ice melt, river-run off, and Ekman convergence of fresh surface waters within the Beaufort Gyre (e.g., McPhee et al. 1998; Macdonald et al. 1999; Yamamoto-Kawai et al. 2009; Jackson et al. 2010; McLaughlin and Carmack 2010; Steele et al. 2011; Peralta-Ferriz and Woodgate 2015; Carmack et al. 2015). The results presented here indicate that decadal changes to ice-ocean dynamics have a similar impact on the changing seasonal halocline as changes to the freshwater input.

We compared the seasonal evolution of the upper ocean salinity below sea ice in 1975 and 2006-2012, using data collected from the AIDJEX ice camps and ITPs (Fig. 1; Section 2). We interpret differences between the two time periods using a one-dimensional bulk model that allows for the separation of changes in terms of seasonal freshwater input and vertical mixing (Fig. 2; Section 3). While upper-ocean dynamics are significantly influenced by spatial and year-to-year variability (Fig. 1; e.g., Yamamoto-Kawai et al. 2009; Peralta-Ferriz and Woodgate 2015; Perovich and Richter-Menge 2015; Proshutinsky et al. 2019; Cole and Stadler 2019), we find that differences between the ITP and AIDJEX datasets yield results that are consistent with decadal trends in the Canada Basin reported by previous studies (Peralta-Ferriz and Woodgate (2015); Section 4a).

By examining the relationships between bulk estimates of the freshwater input (h_{melt}), vertical mixing (D), and stratification (δS_{surf}, S_z), we found that two separate factors have a similar impact on creating the stronger stratification in 2006-2012 when compared with 1975: larger freshwater input and less vertical mixing (Figs. 8, 9, 10). These results stem from the finding that profiles with the same freshwater input are often associated with less vertical mixing and a more stratified upper-ocean in 2006-2012 relative to 1975, particularly in June–July (Fig. 8). In these cases, the stronger stratification in 2006-2012 relative to 1975 appears to be unrelated to seasonal freshwater surface fluxes. These results indicate that ice-ocean dynamics, rather than freshwater input alone, play a crucial role in explaining decadal changes to the seasonal halocline in the Canada Basin.

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TABLE 1. List of AIDJEX ice camps and ITPs used in the study.

Ice Camp	Time Period Used
Blue Fox	May 10, 1975 - Sept. 31, 1975
Caribou	May 14, 1975 - Sept. 31, 1975
Snowbird	May 16, 1975 - Sept. 31, 1975
Big Bear	May 1, 1975 - Sept. 31, 1975
ITP	**Time Period Used**
1	May 1, 2006 - Sept. 31, 2006
3	May 1, 2006 - Sept. 10, 2006
4	May 1, 2007 - Aug. 17, 2007
5	May 1, 2007 - Aug. 2, 2007
6	May 1, 2007 - Sept. 31, 2007
8	May 1, 2008 - Sept. 31, 2008
11	May 1, 2009 - July 20, 2009
13	May 1, 2008 - Aug. 8, 2008
18	May 1, 2008 - Sept. 31, 2008
33	May 1, 2010 - Sept. 31, 2010
41	May 1, 2011 - Sept. 31, 2011
41	May 1, 2012 - Sept. 31, 2012
53	May 1, 2012 - Aug. 5, 2012

TABLE 2. List of constants and variable names.

Name	Description	Value/ Equation
Z_{ice}	ice-ocean interface	3 m
β	haline contraction coefficient	0.81 $kg^2/m^3/g$
ρ_{ice}	sea ice density	900 kg/m^3
S_{ice}	sea ice salinity	5 g/kg
δS_{surf}	seasonal surface freshening	eq. 15
S_z	stratification	eqs. 6,12
$S_{z,bulk}$	as in S_z but for 2-layer system	eq.12
h_{melt}	freshwater input in terms of ice melt	eq. 3
Φ	measure of freshwater input	eq. 4
Z_{fw}	penetration depth of freshwater input	eq. 3
D	equivalent mixed-layer depth	eq. 10

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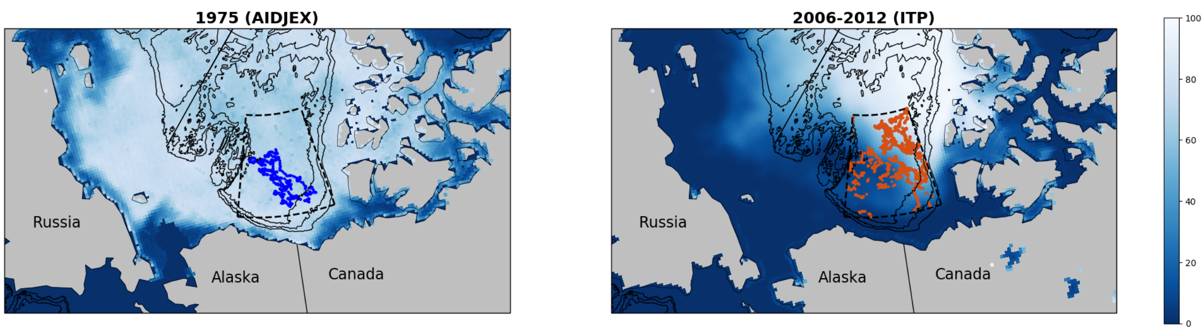


FIG. 1. Map of Canada Basin showing September sea ice concentration and location of ocean observations. (Left) September 1975 mean sea ice concentration and location of measurements from AIDJEX sea ice camps (blue dots) and (right) 2006-2012 September-mean sea ice concentration and location of ITP observations (red dots). Region indicated by dashed-lines shows the Canada Basin, which we define as the region bounded by 72°N, 80°N, 130°W, and 155°W. Solid lines indicate bathymetric contours at 1000 m, 2000 m, and 3000 m. The regional map of September 1975 sea ice concentrations are provided by Nimbus-5 ESMR Polar Gridded Sea Ice Concentrations, Version 1 (Parkinson et al. 2004)

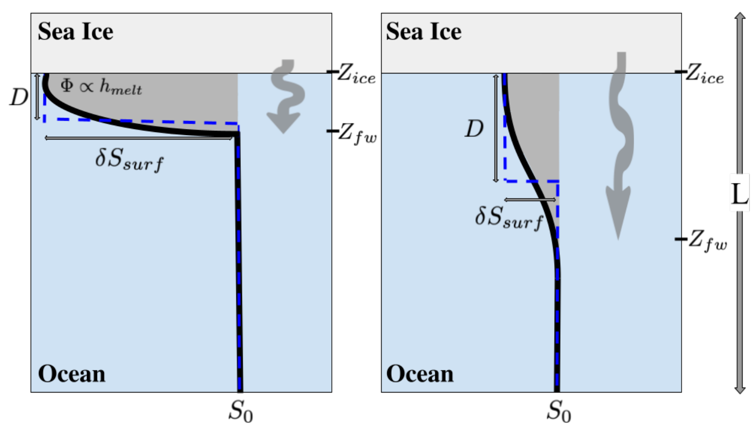


FIG. 2. Schematic of one-dimension ice-ocean model, showing an illustration of the salinity profile resulting from ice melt that is concentrated close to the surface (left) and an example where a similar amount of ice melt is mixed over a larger depth range (right). L is the depth of the ocean. D, Z_{ice}, and Z_{fw} are negative values that indicate depths. S_0 and δS_{surf} indicate the initial salinity and surface freshening, respectively. Area covered by gray shading is equal to Φ and linearly related to the equivalent sea ice melt (h_{melt}). Vertical and horizontal blue dashed lines indicate D and δS_{surf}, respectively. Grey arrows represent the vertical extent of sea-ice meltwater.

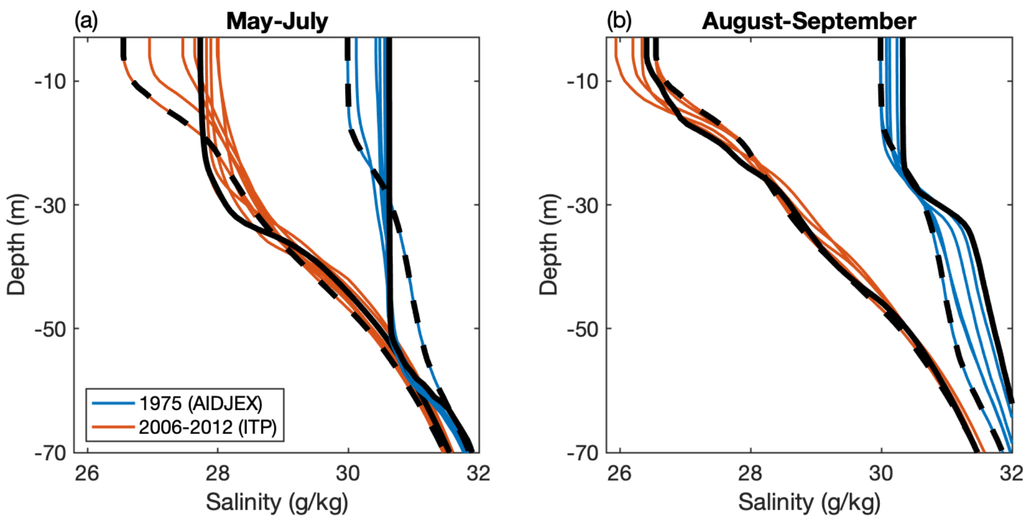


FIG. 3. 10-day mean profiles during (a) May-July and (b) August-September in 1975 (blue) and 2006-2012 (red). Solid black lines indicate 10-day mean profiles from (a) the beginning of May and (b) the end of September. Dashed lines indicate common 10-day mean profile that marks the end of July and the beginning of August, (July 30 - August 8) and are the same in panels a and b. Note that in May, when the freshwater input from sea ice melt is small, changes to the average near-surface salinity are small compared to the spatial and inter-annual variability (Fig. S1).

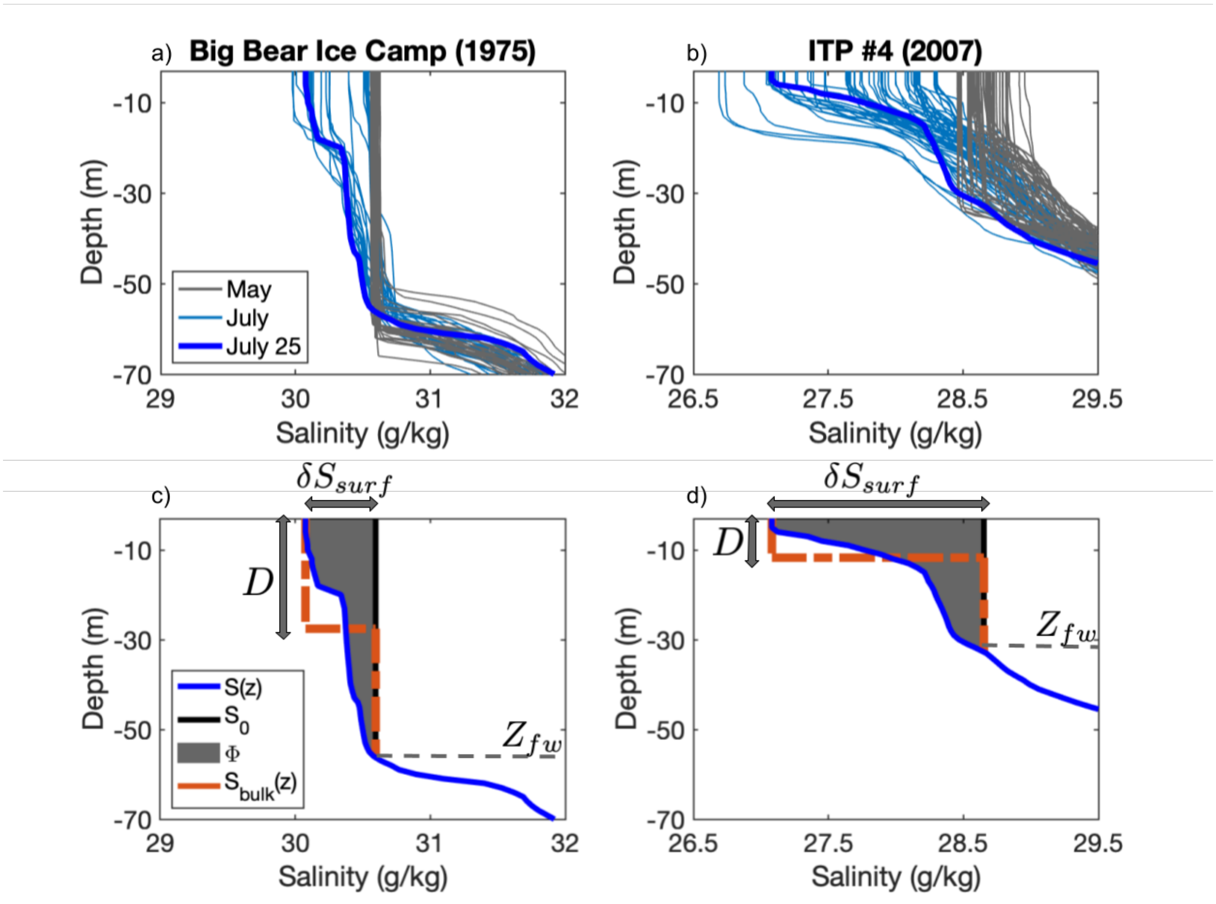


FIG. 4. Observed salinity profiles using data from (left) AIDJEX Big Bear ice camp in 1975 and (right) ITP #4 in 2007 to illustrate the methods used to estimate metrics derived in Section 3. (a-b) All observed salinity profiles measured during the month of May (gray lines) and July (blue lines), with July 25th highlighted in dark blue ($S(z)$). (c-d) Black line indicates May-average surface salinity (S_0), area covered by gray shading is the same as Φ associated with the observed July 25 profile. The associated 2-layer salinity profile (red dashed lines, $S_{bulk}(z)$), which give the surface freshening δS_{surf} and equivalent mixed-layer depth D, is shown in red. Blue lines are the same in panels (a,c) and (b,d).

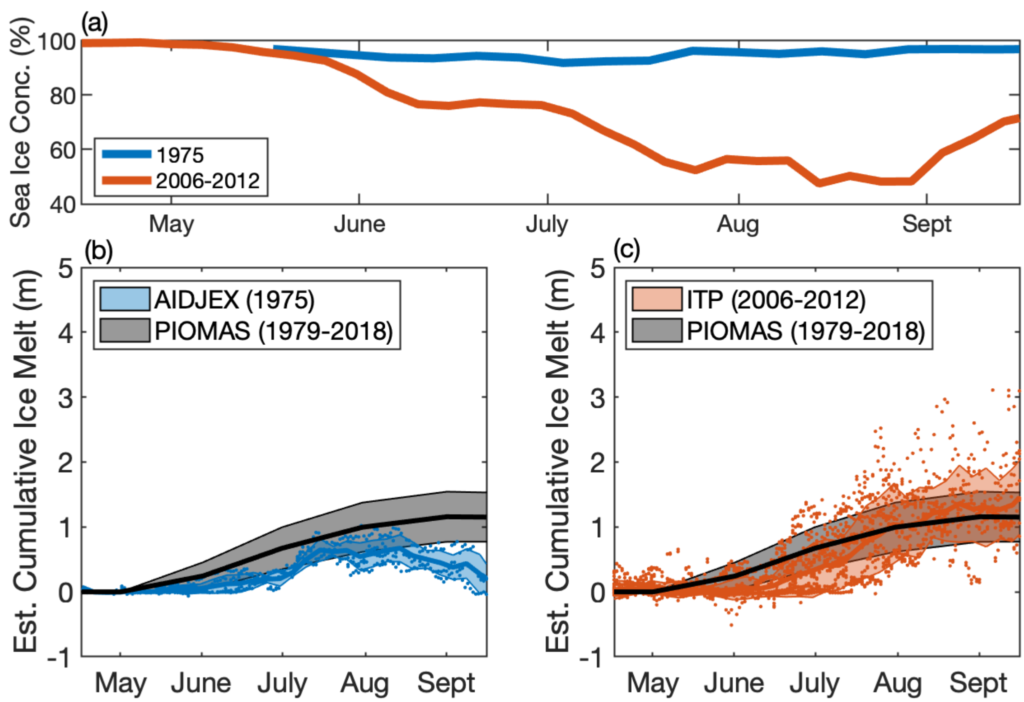


FIG. 5. (a) Sea ice concentration and (b-c) estimated freshwater input in terms of cumulative sea ice thickness changes (h_{melt}) in 1975 (blue), 2006-2012 (red). PIOMAS data provide a climatological monthly effective sea ice thickness change relative to May of each year between 1979-2018 (black). Blue and red lines indicate 5-day mean, black lines indicate monthly mean, and shadings indicate one standard deviation.

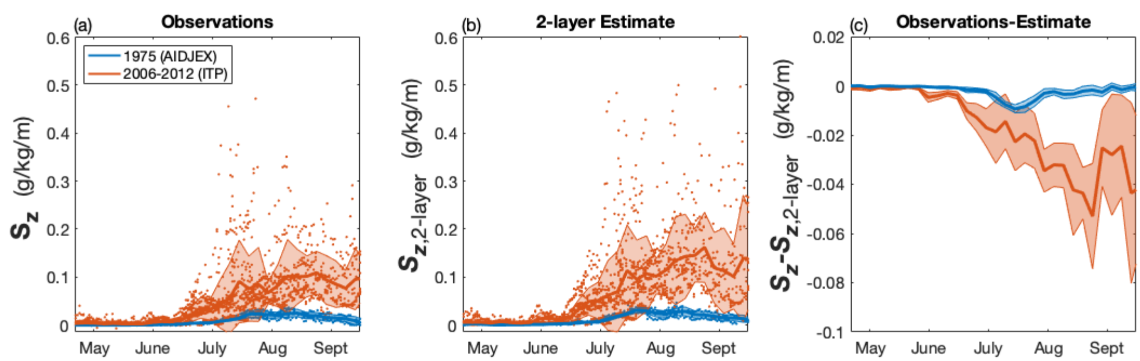
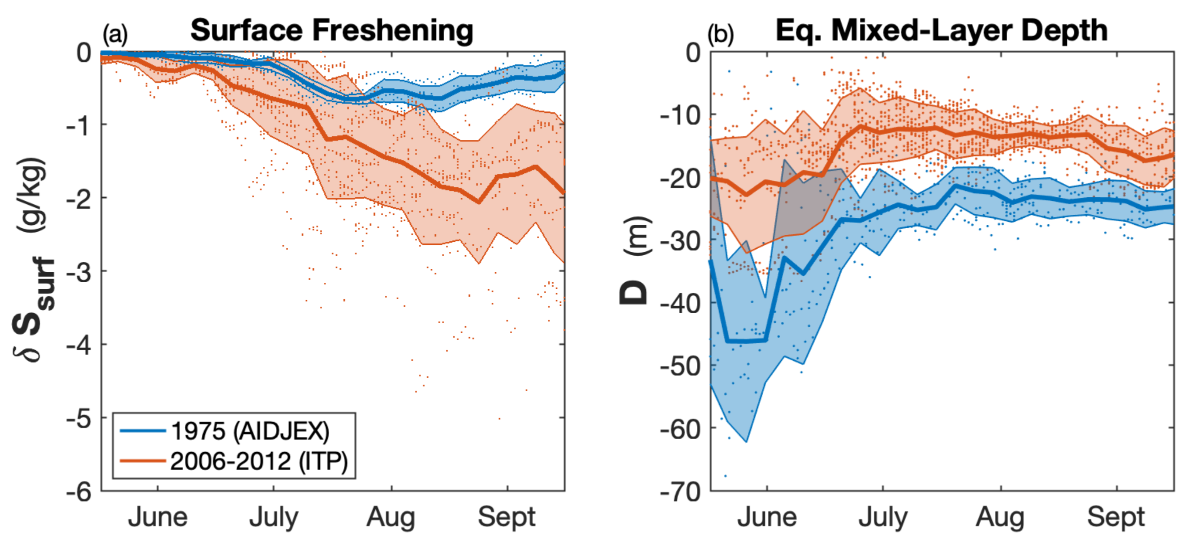
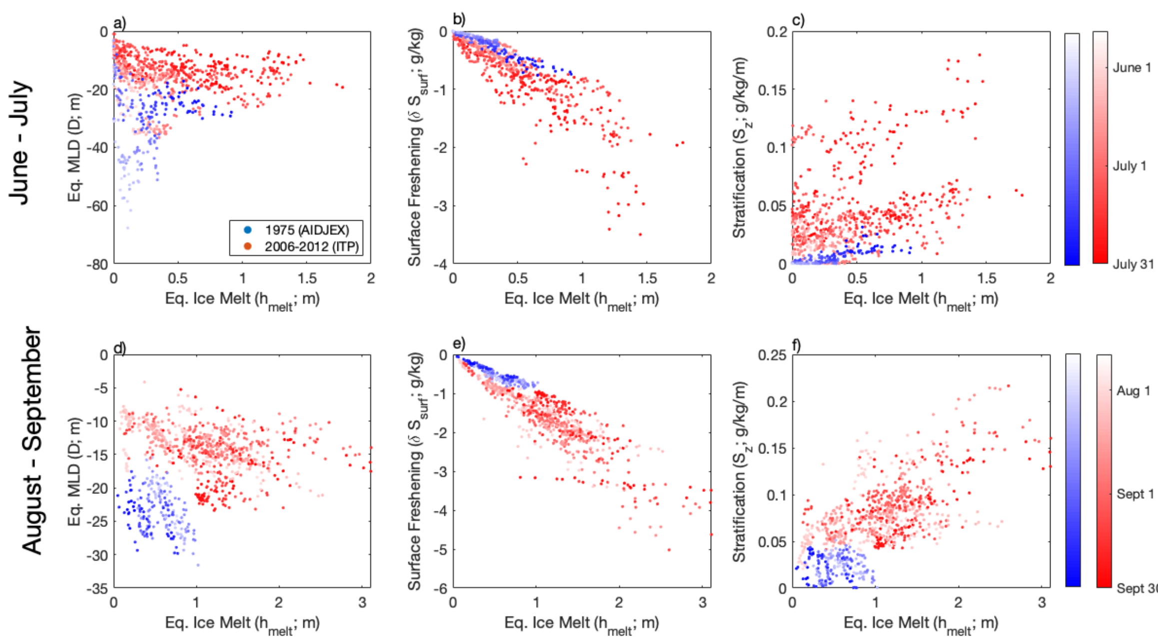


FIG. 6. Validation of the 2-layer approximation of the salinity profile by comparing the stratification (left; S_z; eq. 6) to the associated 2-layer estimate (center; eq. 12), and their difference (right) in 1975 (blue) and 2006-2012 (red). S_z is computed for each observed profile. Lines indicate 5-day means and shading indicates one standard deviation (left, center panels) or standard error (right panels).



778 FIG. 7. (a) Surface freshening (δS_{surf}) and (b) equivalent mixed-layer depth (D) in 1975 (blue) and 2006-2012 (red). δS_{surf} and D are computed for each observed profile. Lines indicate 5-day means and shading indicates one standard deviation.



781 FIG. 8. Relationships between equivalent sea ice melt (h_{melt}) and (a,d) equivalent mixed-layer depth (D), (b,e) surface freshening (δS_{surf}), and (c,f) upper-ocean stratification (S_z) using vertical salinity profiles in 1975 (blue) and 2006-2012 (red) during June-July (a-c) and August-September (d-f). Shadings indicate date of measurement.

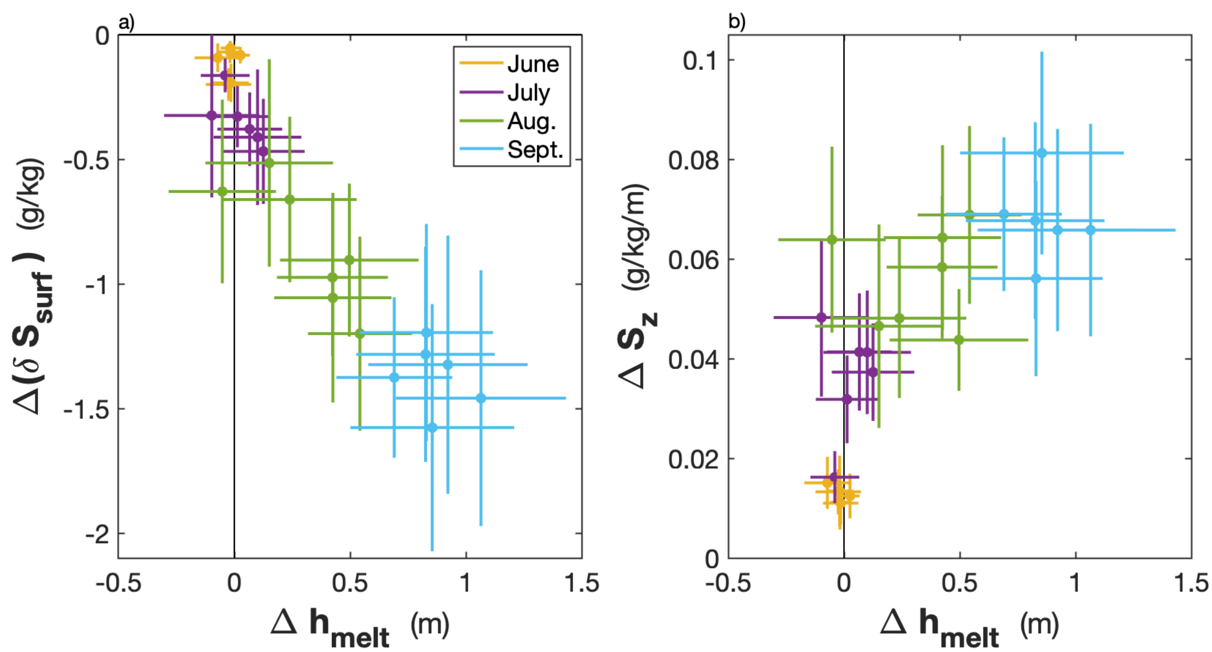


FIG. 9. Five-day average differences between 1975 and 2006-2012 using the difference between equivalent ice melt (Δh_{melt}), the surface freshening ($\Delta(\delta S_{surf})$), and stratification (ΔS_z) during the two time periods. Colors indicate month and lines indicate one standard error.

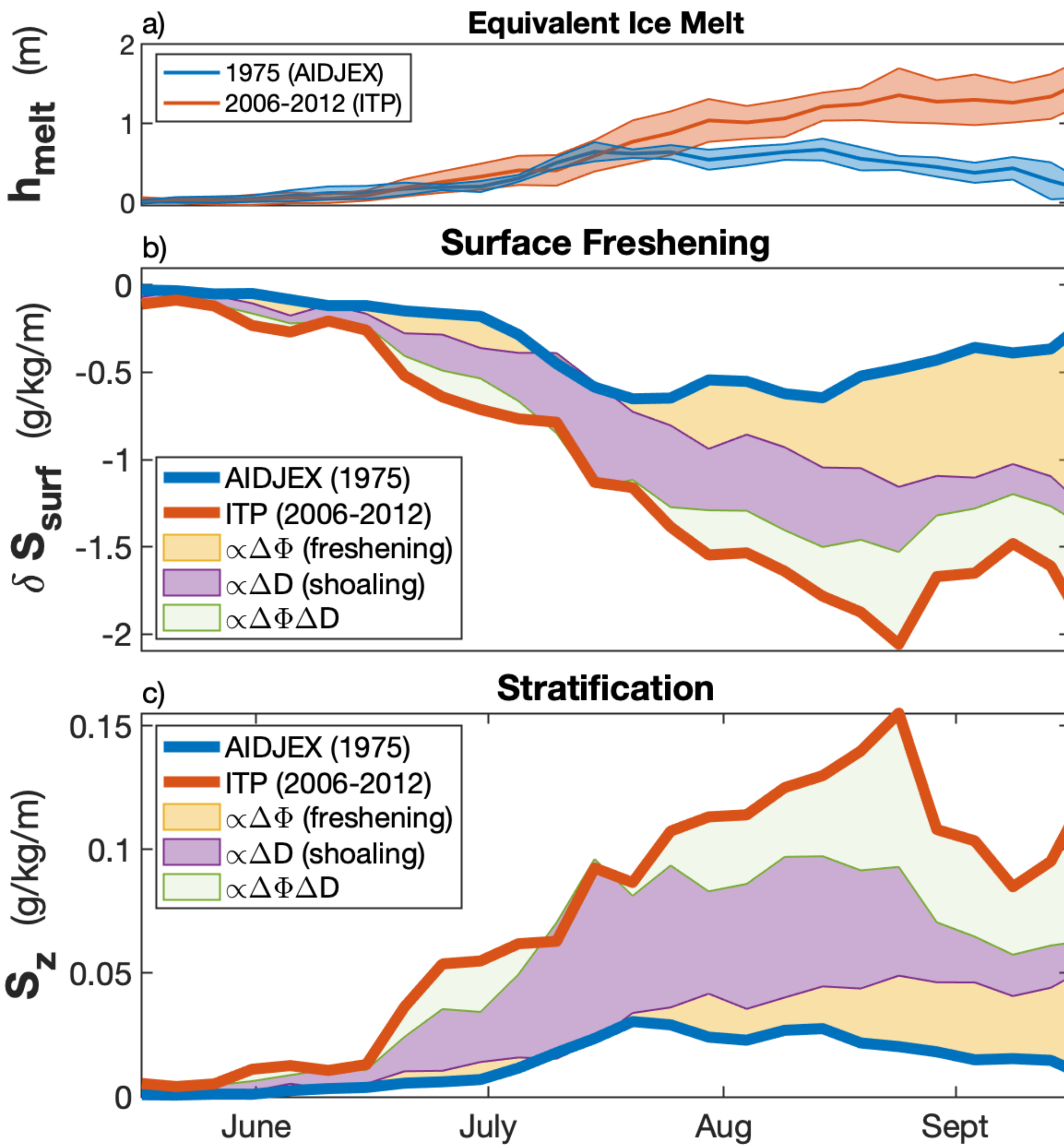


FIG. 10. Five-day mean (a) equivalent ice melt (h_{melt}), (b) surface freshening using the 2-layer estimate (ΔS_{surf}), and (c) stratification using the 2-layer estimate (S_z) in 1975 (blue) and 2006-2012 (red). (b-c) Colors are associated with three terms that contribute to the difference between 1975 and 2006-2012 ($\Delta(\delta S_{surf})$, ΔS_z).