Surface salinity under transitioning ice cover in the Canada Basin: Climate model biases linked to vertical 2 distribution of freshwater

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November 26, 2022

Abstract

The Canada Basin has exhibited a significant trend toward a fresher surface layer and thus a more stratified upper ocean over the past three decades. Here, we explore the extent to which the Community Earth System Model (CESM) accurately simulates the observed surface freshening and seasonal processes that contribute to the freshening. We examine 30 simulations from CESM1 (used in the IPCC AR5), 3 simulations from CESM2 (IPCC AR6), and ocean observations from 1975 and 2006-2012. In contrast to the observations, the models simulate salinity profiles that show relatively little variation between 1975 and 2012. We demonstrate that this bias can be partly attributed to the model's tendency to mix freshwater too deep, creating a surface layer that is saltier than observed. The results provide insight for climate model improvement that could have wide-reaching implications because upper-ocean stratification influences the vertical transport of heat and nutrients.

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Key Points:

- Community Earth Systems Model versions 1.1 and 2 significantly underestimate decadal surface freshening in the Canada Basin.
- The surface freshening model bias is likely not related to seasonal freshwater input at the surface from sea ice melt or other sources.
- The models distribute freshwater over an unrealistically large depth range in recent years, which contributes to the surface salinity bias.

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Abstract

The Canada Basin has exhibited a significant trend toward a fresher surface layer and thus a more stratified upper ocean over the past three decades. Here, we explore the extent to which the Community Earth System Model (CESM) accurately simulates the observed surface freshening and seasonal processes that contribute to the freshening. We examine 30 simulations from CESM1 (used in the IPCC AR5), 3 simulations from CESM2 (IPCC AR6), and ocean observations from 1975 and 2006-2012. In contrast to the observations, the models simulate salinity profiles that show relatively little variation between 1975 and 2012. We demonstrate that this bias can be partly attributed to the model's tendency to mix freshwater too deep, creating a surface layer that is saltier than observed. The results provide insight for climate model improvement that could have wide-reaching implications because upper-ocean stratification influences the vertical transport of heat and nutrients.

Plain Language Summary

Climate models, which have been analyzed extensively to assess and predict current and future climate change and to inform policy, struggle to accurately simulate the rapid decline in Arctic sea ice. One possible source of this bias could be related to the vertical distribution of salt in the ocean, which controls the exchange of heat between the surface and deeper ocean. We compare simulations from two climate models to ocean observations collected below sea ice in the Canada Basin. In 1975, observations were collected by scientists living in ice camps, and in 2006-2012, they were obtained by automated instruments attached to sea ice. The observations indicate as much as six times greater surface freshening than the models between 1975 and 2006-2012. We show that the salt bias can be partly attributed to the models' tendency to mix freshwater from the surface deeper than in observations, resulting in a saltier ocean surface. The results may provide insight for climate model improvement that could have wide-reaching implications because the vertical distribution of salt in the ocean directly impacts the vertical transport of heat and nutrients.

1 Introduction

Rapid sea ice retreat has been extensively observed in the Canada Basin over the past several decades (F. McLaughlin et al., 2011). The increased sea ice melt and river runoff that have collected toward the center of the anticyclonic (convergent) Beaufort Gyre (Proshutinsky et al., 2009; Yamamoto-Kawai et al., 2009; F. A. McLaughlin & Carmack, 2010; E. C. Carmack et al., 2016; Wang et al., 2018; Brown et al., 2020) drive a 30-year 1.1-1.9 psu/yr trend toward a fresher surface layer (Peralta-Ferriz & Woodgate, 2015). The addition of this relatively light, freshwater at the surface has stabilized the upper ocean, altering ice-ocean processes, including wind-driven mixing, the vertical transport of heat and nutrients, and sea ice basal melt (Toole et al., 2010; Jackson et al., 2010, 2011, 2012; Steele et al., 2011; E. Carmack et al., 2015; M. L. Timmermans, 2015; M. Timmermans & Marshall, 2020).

Historically, climate models simulate a slower sea ice retreat than observed (Stroeve et al., 2007; Winton, 2011; Stroeve et al., 2012; Rosenblum & Eisenman, 2016, 2017; SIMIP, 2020). One possible source of the model bias could be related to simulated upper-ocean stratification, which tends to be less stratified than in observations (Holloway et al., 2007; Ilicak et al., 2016). The ocean stratification bias could be related to unrealistic sea ice conditions, which could result in too little freshwater input from sea ice melt each season. Alternatively, the biases could be related to unrealistic ocean processes, such as vertical diffusion (Zhang & Steele, 2007) or brine rejection schemes (Nguyen et al., 2009). Up until now, this problem has mainly been investigated with numerical experiments or by comparing simulations to annual climatologies with little to no attention paid to their

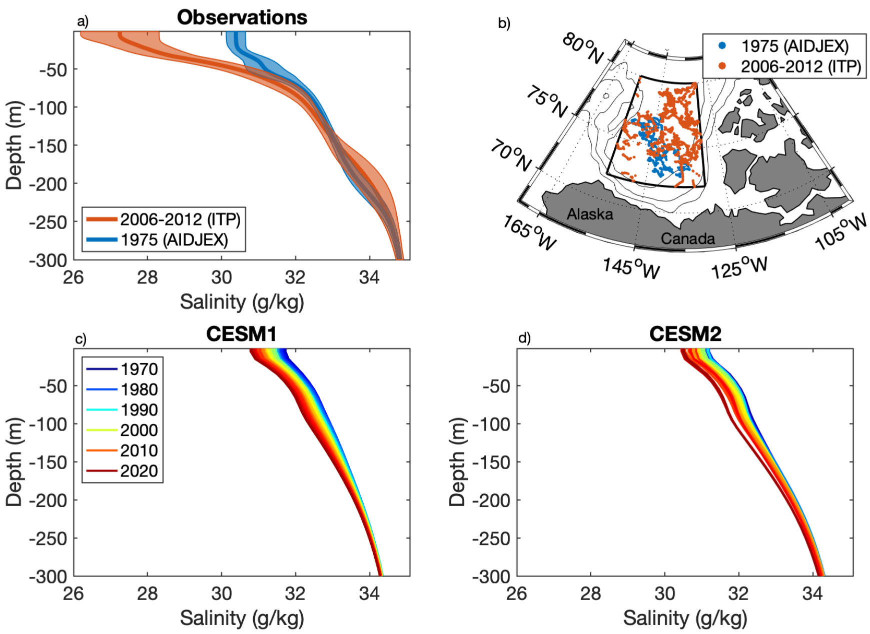

Figure 1. Observed salinity profiles from 1975 AIDJEX data (blue) and 2006-2012 ITP data (red). Solid line indicates May-December average and shading indicates one standard deviation. (b) Map showing the Canada Basin, the locations of 1975 AIDJEX data (blue) and 2006-2012 ITP data (red), and the region considered for this study (black lines). (c-d) Simulated May-December ensemble-mean basin average salinity profiles in 1970-2020 from (c) CESM1 and (d) CESM2.

seasonality (Holloway et al., 2007; Ilicak et al., 2016; Nguyen et al., 2009; Zhang & Steele, 2007; Jin et al., 2012; Barthélemy et al., 2015; Sidorenko et al., 2018).

Here, we explore this problem by examining both sea ice conditions and ocean processes in models and observations using simulations from the two most recent generations of the Community Earth System Model (CESM1 and CESM2), both of which are extensively used in polar studies and in the Intergovernmental Panel on Climate Change (IPCC) Fifth and Sixth Assessment Reports (AR5 and AR6), and two sets of year-round ocean observations collected in the Canada Basin during 1975 and 2006-2012. Our main objective is to understand what governs the seasonal salinity evolution in the models and observations in the Canada Basin by examining seasonal surface processes related to sea ice conditions, freshwater input, and vertical mixing, all of which cumulatively contribute to decadal surface freshening. Distinguishing between atmospheric and oceanic processes that cause surface freshening in the models and observations is critical for determining if model freshening mechanisms are consistent with the natural world and helps to identify processes that might be missing or poorly simulated in the models.

2 Methods

We use year-round below-ice observations of ocean salinity collected in the Canada Basin, defined as the region enclosed by 72°N, 80°N, 130°W , and 155°W (Fig. 1b), from the 1975 Arctic Ice Dynamics Joint Experiment (AIDJEX) program (Untersteiner et al., 2007) and during 2004-present from the Ice-Tethered Profiler (ITP) instrumentation system (Krishfield et al., 2008). There were four occupied AIDJEX ice camps between May

1975 and April 1976 and 30 ITPs, which were available for 2004-2012 at the time of the analysis. The data in this study are identical to those employed by Rosenblum et al. (2021), who showed that June-September surface changes between the ITP and AIDJEX datasets are consistent with 30-year mixed-layer trends reported by Peralta-Ferriz and Woodgate (2015) in the same region. They used only quality-controlled data (level 3) in the ITP archive, screened profiles to select those that include samples above 10 m depth (as in Jackson et al., 2010) and that were collected during the period May 1 - December 31, which is common to both datasets. In total, 754 AIDJEX profiles during 1975 and 3391 ITP profiles during 2006-2012 from 12 ITPs (#1, 3-6, 8, 11, 13, 18, 33, 41, and 53) satisfied these criteria, with average shallowest measurements of ~ 6 m and ~ 7 m, respectively (Fig 1b). Profiles were linearly interpolated onto a common 1 m vertical grid, and the shallowest values were extended to $z = 0$, which we take as the ice-ocean interface, as in the models.

To examine sea ice conditions associated with the ITP dataset, we identify co-located daily sea ice concentrations, provided by the Passive Microwave satellite data, Version 1 (Cavalieri et al., 1996). Weekly, regional-mean sea ice concentrations associated with the AIDJEX data are provided by the Canadian Ice Service Digital Archive (CISDA) chart data for the western Arctic region (Tivy et al., 2011). We also examine estimates of the 1979-2018 effective sea ice thickness (sea ice volume per unit area) from the Pan Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) (Schweiger et al., 2011). PIOMAS effective sea ice thickness was regridded to the 25km Equal-Area Scalable Earth (EASE) grid, and data were collected from each grid cell residing in the Canada Basin. While several studies have shown that PIOMAS tends to underestimate sea ice thickness in regions of thicker ice and overestimate sea ice thickness in regions of thinner ice (Stroeve et al., 2014; Wang et al., 2018), the seasonality, spatial structure, distribution, and decadal trends of the sea ice thickness are realistically reproduced (Labe et al., 2018).

We use 30 simulations of 1970-2020 from CESM1 with historical and RCP8.5 forcing from the Large Ensemble project (Kay et al., 2015) and three simulations from CESM2 with historical and SSP585 forcing. CESM1 and CESM2 are run with historical forcing until 2005 and 2015, respectively. Both models use the Parallel Ocean Program Version 2 (POP2) model with a displaced pole horizontal grid, a nominal 1° resolution, 60 vertical levels, and 10 m vertical grid spacing near the surface, although some of the physical parmeterizations, including the K-profile parameterization (KPP) vertical ocean mixing scheme (Large et al., 1994), differ between the two models (Danabasoglu et al., 2020). We examine the ocean salinity, the effective sea ice thickness, the sea ice concentration in each grid box within the Canada Basin of each simulation (Table S1).

3 Results

3.1 Upper-ocean salinity

The May-December average ocean salinity over the top 300 m in the models and the observations is shown in Figure 1. The observations indicate a significantly fresher upper-ocean over the top 50 m in 2006-2012 than in 1975, with the largest differences occurring at the surface (Fig. 1a), consistent with previous studies. By contrast, the 1970-2020 ensemble mean only shows only a modest freshening from the surface down to 200 m in both models (Fig. 1c-d). This results in a simulated upper-ocean stratification that is weaker than in recent observations, similar to other ice-ocean models.

To eliminate the possibility that regional or internal variability could explain the bias, we examine the surface salinity from each observation and each grid point of each simulation during each month (Figure 2). In each dataset, we find a clear seasonal cycle where the surface becomes fresher in the summer and saltier in the fall, coinciding with seasonal sea ice evolution. In each month, we find that the models systematically

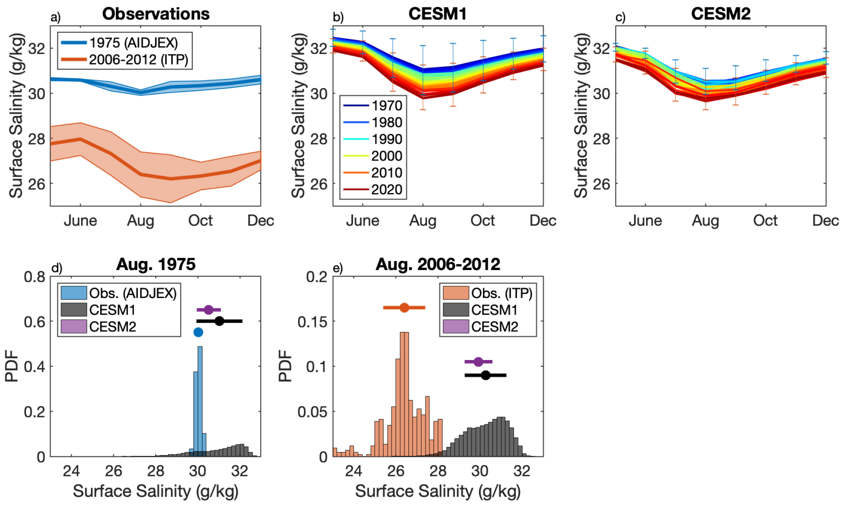

Figure 2. (a) Surface salinity from 1975 AIDJEX data (blue) and 2006-2012 ITP data (red). Solid line indicates May-December average and shading indicates standard deviation. Blue and red error bars indicate one standard deviation over all grid points and simulations in 1975 and 2006-2012, respectively. (b-c) Simulated 1970-2020 ensemble-mean surface salinity from (b) CESM1 and (c) CESM2. Distribution of August surface salinity in (d) 1975 and (e) 2006-2012 from each observation in 1975 (blue) and 2006-2012 (red), and from each grid point of each CESM1 (black) and CESM2 (purple) simulation of 1975 and 2006-2012. Solid dots and lines indicate mean and one standard deviation.

simulate a 1970-2020 surface layer that is more consistent with observations in 1975 than in 2006-2012 (comparing Fig. 2a with Figs. 2b-c).

Focusing on August (the lowest monthly salinity in the models; Fig. 2d-e; Table S2), we find that CESM1 indicates a 2006-2012 August surface layer that is only 0.7±1.0 g/kg fresher than in 1975, similar to CESM2 (0.6±0.9 g/kg). By contrast, the observations indicate an average 3.6±1.0 g/kg change toward a fresher surface layer during the same time periods. As a consequence, we find that models are consistent with observations in 1975 but not in 2006-2012. From all simulations, only 1.4% of CESM1 grid cells and only 0.3% of CESM2 grid cells have a surface salinity that is as salty as any observation. We find similar results for other months (Fig. S1-S2).

Overall, Figures 1-2 show that the models do not simulate the 1975 to 2006-2012 surface salinity change observed in the Canada Basin and that this bias cannot be explained by regional or internal variability present within the models. In the remainder of this section, we consider three factors related to seasonal surface processes to identify sources of the surface freshening model bias.

3.2 Seasonal freshwater storage

We first examine the total amount of freshwater stored seasonally in the upper-ocean by comparing the seasonal evolution of the observed and simulated salinity profiles. Specifically, we use the upper-ocean seasonal freshwater content relative to May-average conditions (sFWC), given by:

$$\mathrm{sFWC}(t) = \int_{Z_{fw}(t)}^{0} \frac{S_{\mathrm{May}} - S(t,z)}{S_{\mathrm{May}}} \cdot dz, \tag{1}$$

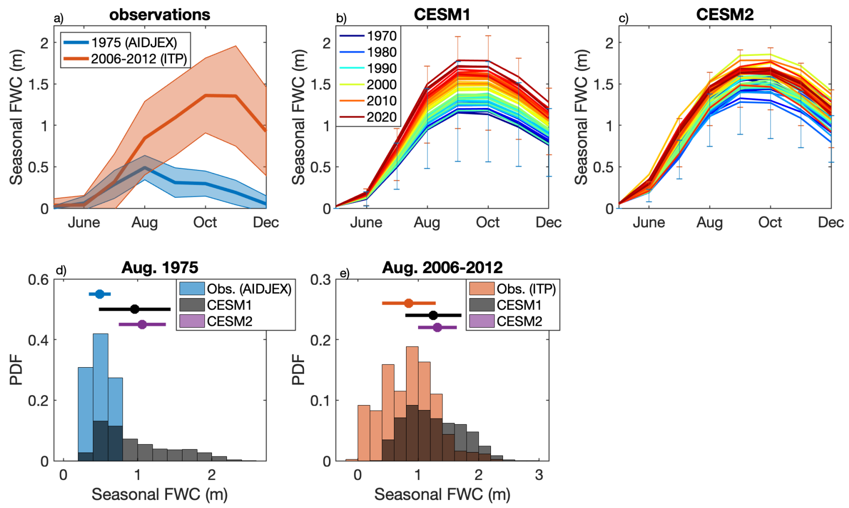

Figure 3. (a) Observed sFWC from 1975 AIDJEX data (blue) and 2006-2012 ITP data (red). Solid line indicates monthly-mean and shading indicates one standard deviation. (b-c) Simulated 1970-2020 ensemble-mean sFWC from (b) CESM1 and (c) CESM2. Blue and red error bars indicate one standard deviation over all grid points and simulations in 1975 and 2006-2012, respectively. (d-e) Distribution of August sFWC in (d) 1975 and (e) 2006-2012 from each observation in 1975 (blue) and 2006-2012 (red), and from each grid point of each CESM1 (black) and CESM2 (purple) simulation of 1975 and 2006-2012. Solid dots and lines indicate mean and one standard deviation.

where S is salinity, and Z_{fw} indicates the vertical extent of mixing defined by $S(Z_{fw}) = S_{\mathrm{May}}$, where z and Z_{fw} are both negative. S_{May} is the May-average surface salinity, which is computed separately for each grid box of each year in each model simulation and is computed separately for each ITP or AIDJEX ice camp of each year in the observations. We compute sFWC from May-December at each grid point in each simulation of 1970-2020 from each model and for each observation in 1975 and 2006-2012 (Fig. 3).

The value sFWC represents the amount of freshwater necessary to explain the transition from a well-mixed May salinity profile (S_{May}) to any subsequent profile ($S(t, z)$) for $z \geq Z_{fw}$ at a given location in the models or observations. That is, sFWC indicates the amount of freshwater contained in seasonal halocline, which reflects any process that drives changes to the upper-ocean salinity, including sea ice melt, river runoff, precipitation, or advection. Figure S3 shows examples of this calculation from single profiles.

The expression for sFWC differs from the more often used expression for freshwater content in which the reference salinity is set to 34.8 g/kg. Instead, we use a reference salinity that is set to the May-average surface salinity. This difference implies that sFWC reflects the seasonal near-surface freshwater content over a well-defined volume (see SI for full derivation of sFWC), which avoids errors that can arise when using an arbitrary reference salinity (Schauer & Losch, 2019). Furthermore, we use the same criterion for S_{May} in both the models and observations, allowing for a fair comparison.

In both models and observations, we find that the average sFWC increases through the summer and into the fall, coinciding with the summer melt season, river runoff, and the intensification of the convergent Beaufort Gyre circulation. In late fall and early winter, both the models and observations indicate an average decrease of sFWC, coincid-

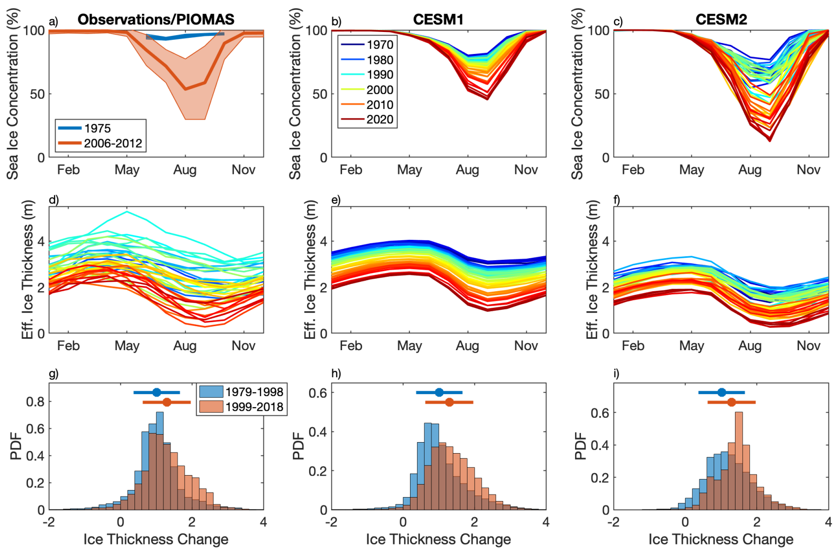

Figure 4. (a) Observed sea ice concentration co-located to 1975 AIDJEX data (blue) and 2006-2012 ITP data (red). Solid line indicates monthly mean and shading indicates standard deviation. (b-c) Simulated 1970-2020 ensemble-mean sea ice concentration from (b) CESM1 and (c) CESM2. (d-f) Effective sea ice thickness from (d) PIOMAS and (e,f) CESM1,2 ensemble mean. (g-i) Distribution of the seasonal change of the effective sea ice thickness between May and September during 1979-1998 (blue) and 1999-2018 (red) using all grid points from (g) PIOMAS, and from each (h) CESM1 and (i) CESM2 simulation. Solid dots and lines indicate the mean and standard deviation.

ing with brine rejection from freeze-up. As in Section 3.1, we consider the distribution of the sFWC from every observation and from every grid point of every simulation in August 1975 and 2006-2012 (Fig. 3d-e). We find that, on average, the August sFWC is 0.2-0.4 m larger in the models than in the observations during both time periods (Table S2). We find similar results for other months, with the bias decreasing in fall 2006-2012 and increasing in fall 1975 (Fig. 3a-c;S4-S5), suggesting a bias related to the Ekman convergence of freshwater in 1975. Together, this causes a smaller change in sFWC between 2006-2012 and 1975 in the models than in the observations.

Overall, we find that the models appear to simulate at least as much freshwater stored near the surface on seasonal timescales as the observations. This suggests that insufficient seasonal freshwater input at the surface is not the likely source of the surface freshening model bias (Figs. 1-2).

3.3 Sea ice conditions

Seasonal changes to the Arctic Ocean surface layer are primarily driven by the seasonal melting and freezing of sea ice (McPhee & Smith, 1976; Morison & Smith, 1981; Lemke & Manley, 1984; Peralta-Ferriz & Woodgate, 2015). In the models, the observations, and PIOMAS, we find a clear seasonal cycle and a considerable decline in both summer sea ice concentration (Fig. 4a-c) and effective sea ice thickness (Fig. 4d-f). To examine the decadal changes in seasonal sea ice volume evolution, which directly impacts the seasonal freshwater surface flux, we compute a seasonal change (September - May)

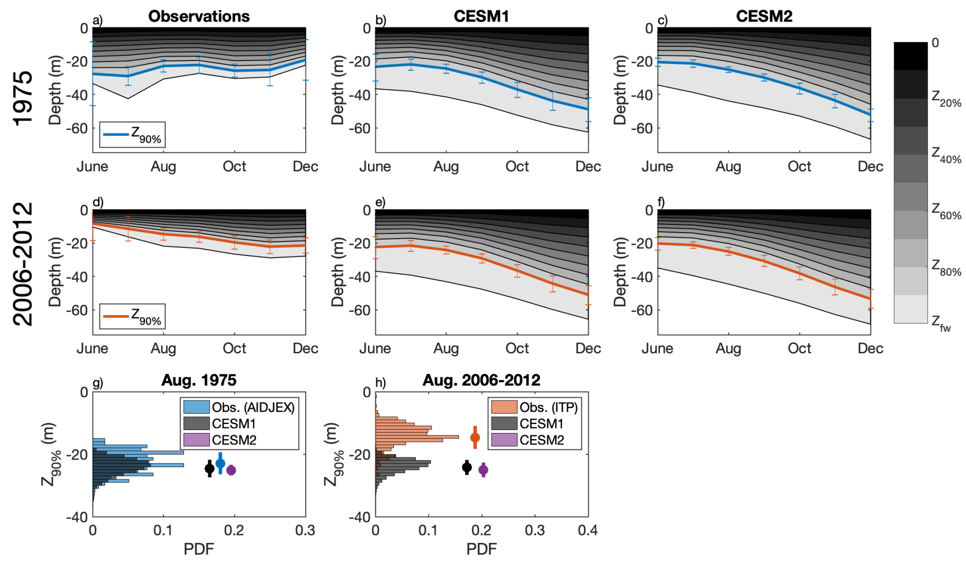

Figure 5. (a-f) Black solid lines separating each gray shading indicate the monthly-average depths of $Z_{10\%}, Z_{20\%}, ..., Z_{May}$ (eq. 2) from (a,d) observations, (b,e) CESM1 ensemble-mean, and (c,f) CESM2 ensemble mean in (a-c) 1975 and (d-f) 2006-2012. Dashed lines indicate $Z_{90\%}$ in 1975 (a-c, blue) and 2006-2012 (d-f, red). Blue and red error bars indicate one standard deviation over all grid points and simulations in 1975 and 2006-2012, respectively. (g-h) Distribution of August $Z_{90\%}$ in (g) 1975 and (h) 2006-2012 from each observation 1975 (blue) and 2006-2012 (red), and from each grid point of each CESM1 (black) and CESM2 (purple) simulation of 1975 and 2006-2012. Solid dots and lines indicate mean and one standard deviation.

in the effective ice thickness in each grid box in PIOMAS and in each simulation of CESM1 and CESM2 during 1979-2018 (Fig. 4g-i).

On average, PIOMAS, CESM1, and CESM2 indicate similar seasonal sea ice thickness changes during the melt season in 1979-1998 (0.9±0.6 m, 0.8±0.6 m, and 1.0±0.5 m, respectively) and in 1999-2018 (1.1±0.6 m, 1.1±0.6 m, and 1.3±0.5 m, respectively). These results suggest that CESM1 and CESM2 are able to realistically simulate the seasonal sea ice volume evolution in the Canada Basin, consistent with previous studies (see Methods). This suggests that, while there are differences in sea ice concentration between the models and observations (Fig. 4a-c; Table S2), seasonal sea ice volume biases are unlikely to explain the surface freshening model bias (Fig. 1-2).

3.4 Vertical freshwater distribution

Finally, we compare the vertical distribution of the seasonal freshwater storage in the models and observations, which we quantify by rewriting the expression for sFWC as:

$$\mathrm{sFWC} = \underbrace{\int_{Z_{10\%}}^{0} \frac{S_{\mathrm{May}} - S(z)}{S_{\mathrm{May}}} \cdot dz}_{=10\% \text{ of sFWC}} + \underbrace{\int_{Z_{20\%}}^{Z_{10\%}} \frac{S_{\mathrm{May}} - S(z)}{S_{\mathrm{May}}} \cdot dz}_{=10\% \text{ of sFWC}} + ... + \underbrace{\int_{Z_{fw}}^{Z_{90\%}} \frac{S_{\mathrm{May}} - S(z)}{S_{\mathrm{May}}} \cdot dz}_{=10\% \text{ of sFWC}}, \tag{2}$$

where $Z_{10\%}, Z_{20\%}, ..., Z_{fw}$ is the lower bound of the depth range that encompasses 10%, 20%,...,100% of the sFWC. These depths are computed at each grid point of each simulation and each observation during May-December of 1975 and 2006-2012 (Figure 5). We only include data points with positive values of sFWC, implying that some observed June profiles are not included in this portion of the analysis. As in Section 3.3, we also consider the August distribution of the $Z_{90\%}$ from every observation and from every grid point of every simulation in 1975 and 2006-2012 (5g-i; Table S2). We note that $Z_{90\%}$ is closely related to the mixed-layer depth in both the models and observations (Fig. S6).

The vertical distribution of sFWC reveals two discrepancies between the models and observations (Fig. 5). First, we find that the freshwater is spread over a deeper range in the simulations (Aug. $Z_{90\%}$ =24±2.7 m, 25±2.4 m in CESM1, CESM2) compared to the observations (Aug. $Z_{90\%}$ =14±3.7 m) in 2006-2012. Second, we find that the vertical distribution of sFWC remains relatively unchanged between 1975 and 2006-2012 in the simulations ($\sim$ 0.1 m change in Aug. $Z_{90\%}$), while the observations indicate that the freshwater is concentrated significantly closer to the surface in 2006-2012 than in 1975 ($\sim$ 8 m change). Interestingly, we find that the models do simulate a 1975 vertical distribution of sFWC consistent with the observations during the summer (Aug. $Z_{90\%}$ =23±3.5 m, 25±2.8 m, and 26±1.7 m in the observations, CESM1, and CESM2, respectively), similar to the 1975 surface salinity (Fig. 2).

Overall, we find that the 2006-2012 seasonal freshwater storage has an unrealistic vertical distribution in the models, and that the discrepancy between the models and observations cannot be explained by regional or internal variability present within the models (Fig. 5g-h). Together this suggests that simulated vertical mixing of freshwater is inconsistent with observations in recent years and that this is a likely source of the surface freshening model bias (Fig. 1,2).

4 Conclusions

State-of-the-art coupled ice-ocean models struggle to accurately simulate upper-ocean stratification in the Canada Basin, and instead tend to simulate a surface layer that is saltier and less stratified than observed (Holloway et al., 2007; Ilicak et al., 2016). The bias could be related to sea ice, atmospheric, or ocean processes and, until now, had only been examined using numerical experiments and annual climatologies (Holloway et al., 2007; Ilicak et al., 2016; Nguyen et al., 2009; Zhang & Steele, 2007; Jin et al., 2012; Barthélemy et al., 2015; Sidorenko et al., 2018).

Here, we examine this question by focusing on decadal changes to seasonal surface processes using observations from below-ice ocean measurements collected during May-December 1975 (AIDJEX) and 2006-2012 (ITPs) and in the two most recent generations of the Community Earth Systems Models (CESM1 and CESM2). We find that CESM simulates upper-ocean salinities that are fairly consistent with the observations in 1975, but it fails to capture the fresh surface layer that appears in the 2006-2012 observations (Figs. 1-2). We show that the surface freshening model bias is likely related to the unrealistically deep mixing of freshwater in the models (Fig. 5), rather than insufficient freshwater input from sea ice melt or other sources (Fig. 3 - 4). Overall, the results show that CESM1 and CESM2 simulate a mixed layer that is too salty and deep, similar to most ice-ocean models (Ilicak et al., 2016), and are not able to simulate the observed reduction in mixed-layer depth associated with increased surface freshwater fluxes. Moreover, CESM systematically simulates a mixed-layer depth consistent with observations in 1975 and a seasonal freshwater input that is similar to observations in 2006-2012. This suggests that one source of the 2006-2012 ocean stratification bias is related to missing or unrealistic summer mixed-layer dynamics in recent years, rather than sea ice or atmospheric processes, possibly due to unrealistically high vertical mixing or low vertical resolution in the models.

These results raise important questions related to the ramifications of this bias on Arctic ecosystem dynamics and on the sea ice cover because the upper-ocean stratification directly impacts the vertical exchange of heat, energy, and nutrients. For example, if the unrealistically deep transport of freshwater carries heat downwards and traps nutrients deeper, then there would be less heat available for summer sea ice melt, a weaker seasonal ice-albedo feedback, and reduced primary productivity. These results, therefore, highlight the need for improved parameterizations of upper-ocean dynamics under a rapidly changing sea ice cover.

Acknowledgments

The AIDJEX data used in this study can be found at http://lwbin-datahub.ad.umanitoba.ca/dataset/aidjex. The Ice-Tethered Profiler data were collected and made available by the Ice-Tethered Profiler Program based at the Woods Hole Oceanographic Institution (http://www.whoi.edu/itp). All sea ice concentration data created or used during this study are openly available from the NASA National Snow and Ice Data Center Distributed Active Archive Center at https://doi.org/10.5067/8GQ as cited in Cavalieri1996.

ER was supported by the National Sciences and Engineering Research Council of Canada (NSERC) PDF award. ER and JS were supported by the NSERC Canada-150 Chair. STG was supported by the US NSF (Awards PLR-1425989 and OPP-1936222) and by the US Department of Energy (DOE) (Award DE-SC0020073). This work is a contribution to the NSERC - Discovery Grant and the NSF Office of Polar Program grant # 1504023 awarded to LBT. RG was supported by the NSERC Canada Discovery Grant program. RF acknowledges funding from NSERC Canada through a CGS-D award and the US DOE (Grant DE-SC001940).

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Supporting Information for "Surface salinity under transitioning ice cover in the Canada Basin: Climate model biases linked to vertical distribution of freshwater"

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Contents of this file

1. Seasonal freshwater content
2. Figures S1 to S6
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Introduction Here we include a brief derivation of the seaonsal freshwater content (sFWC), figures as in the main text, but for different months, and tables that indicate

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the CESM variable names used in the analysis and statistics associated with histograms included in the main text.

Text S1. Here, we follow (Rosenblum et al., 2021), who considered a closed ice-ocean 1D system with an ocean that only evolved in response to sea ice melt and vertical mixing. Instead of ice melt, we consider a source of near-surface freshwater (sFWC(t)) and neglect ice draft within the ocean (as is done in the models). The system has the following initial conditions ($t = t_0$): a well-mixed ocean, with vertically uniform salinity (S_0) and potential density (ρ_0). If freshwater is vertically mixed to some depth, Z_{fw}, then the salinity below this depth remains fixed at S_0 (i.e., $S(z) = S_0$ for $z \leq Z_{fw}$, where z and Z_{fw} are both negative). The conservation of salt and mass for time $t > t_0$ over any depth $D \geq Z_{fw}$ can be written as:

$$\int_{Z_{fw}(t)}^{0} \rho(t,z)S(t,z) \cdot dz - \rho_0 S_0(-Z_{fw}(t)) = 0 \tag{1}$$

$$\int_{Z_{fw}(t)}^{0} \rho(t,z) \cdot dz - \rho_0(-Z_{fw}(t)) = \rho_{fw} \cdot sFWC(t). \tag{2}$$

ρ_{fw} is the density of the added freshwater, $\rho(t,z)$ 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 freshwater input (right-hand side). These equations can be algebraically combined to obtain an estimate for the freshwater necessary to explain the transition from the initial, well-mixed ocean (S_0, ρ_0) to the subsequent ocean profile that includes vertically mixed freshwater ($S(t,z)$, $\rho(t,z)$) at any time $t > t_0$:

$$sFWC(t) = \int_{Z_{fw}(t)}^{0} \frac{\rho(t,z)(S_0 - S(t,z))}{\rho_{fw} S_0} \cdot dz. \tag{3}$$

In the ITP and AIDJEX data, $\rho(t,z)/\rho_{fw} \sim 1.03$, where $\rho_{fw} = 1000$ kg/m^3, implying that a reasonable estimate of sFWC can be given by:

$$sFWC(t) = \int_{Z_{fw}(t)}^{0} \frac{(S_0 - S(t,z))}{S_0} \cdot dz. \tag{4}$$

We note that sFWC is closely related to sea ice melt in the observations (Rosenblum et al., 2021) and in the models. Specifically, we find that the May-December sFWC and virtual freshwater flux from sea ice melt (MELT and VSFSIT in CESM1 and CESM2, respectively) is highly correlated (R=0.88 and R=0.89 in CESM1 and CESM2 using each gridpoint of each simulation of 1970-2020). Simulated sea ice melt makes up the majority of the simulated freshwater flux in both models (VSF/VSFSIT=0.98).

References

Rosenblum, E., Stroeve, J. S., Gille, S., Tremblay, L., Carmack, E. C., Barber, D. G., ... Fajber, R. (2021). Freshwater input and vertical distribution in the Canada Basin's seasonal halocline: 1975 versus 2006-2012. *Preprint: https://doi.org/10.1002/essoar.10507192.1*.

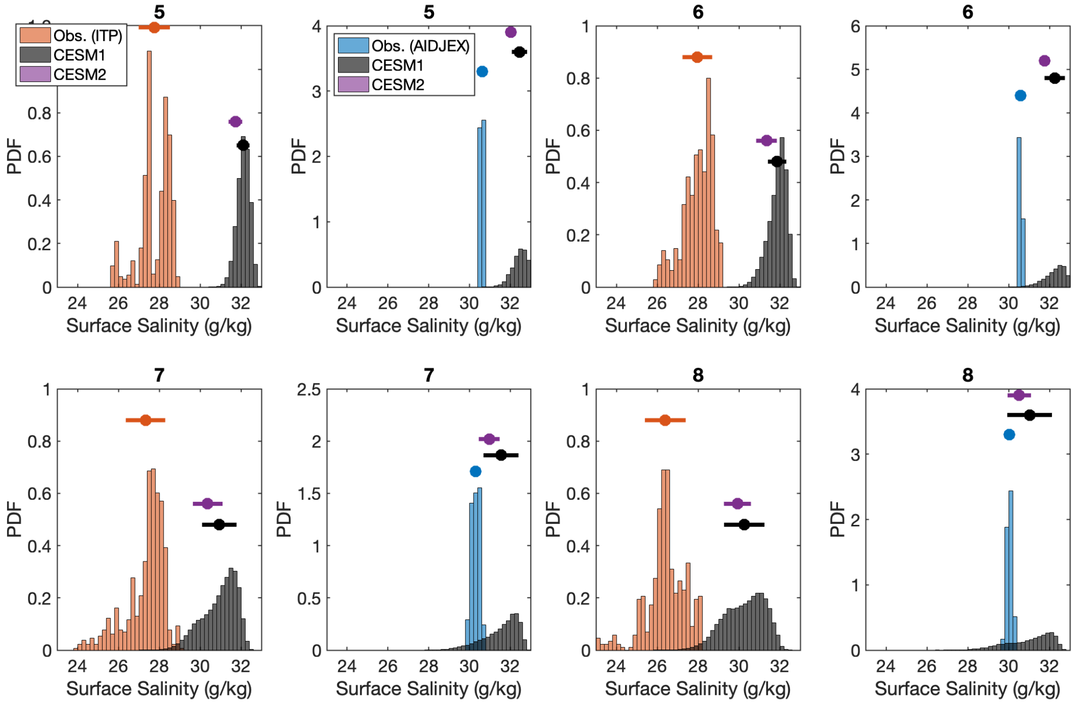

Figure S1. As in Figure 2d-e, but for May-August (5-8).

Table S1. List variable names used in the study

Description	CESM1	CESM2
Salinity	SALT	SALT
Eff. Sea Ice Thickness	hi	sivol
Sea Ice Concentration	aice	siconc

Table S2. Mean and standard deviation of histograms provided in the main text, using all observations and all grid points from each simulation.

	Years	Observations/PIOMAS	CESM1	CESM2
August Surface Salinity (g/kg)	1975	30.0±0.1	31.0±1.1	30.5±0.6
	2006-2012	26.4±1.0	30.3±1.0	29.9±0.7
Seasonal Sea Ice Change (m)	1979-1998	0.9±0.6	0.8±0.6	1.0±0.5
	1999-2018	1.1±0.6	1.1±0.6	1.3±0.5
August sFWC (m)	1975	0.5±0.2	1.0±0.5	1.1±0.3
	2006-2012	0.9±0.4	1.3±0.5	1.3±0.3
August $Z_{90\%}$ (m)	1975	22.9±3.5	24.6±2.8	25.1±1.7
	2006-2012	14.6±3.7	24.2±2.4	25.1±2.4

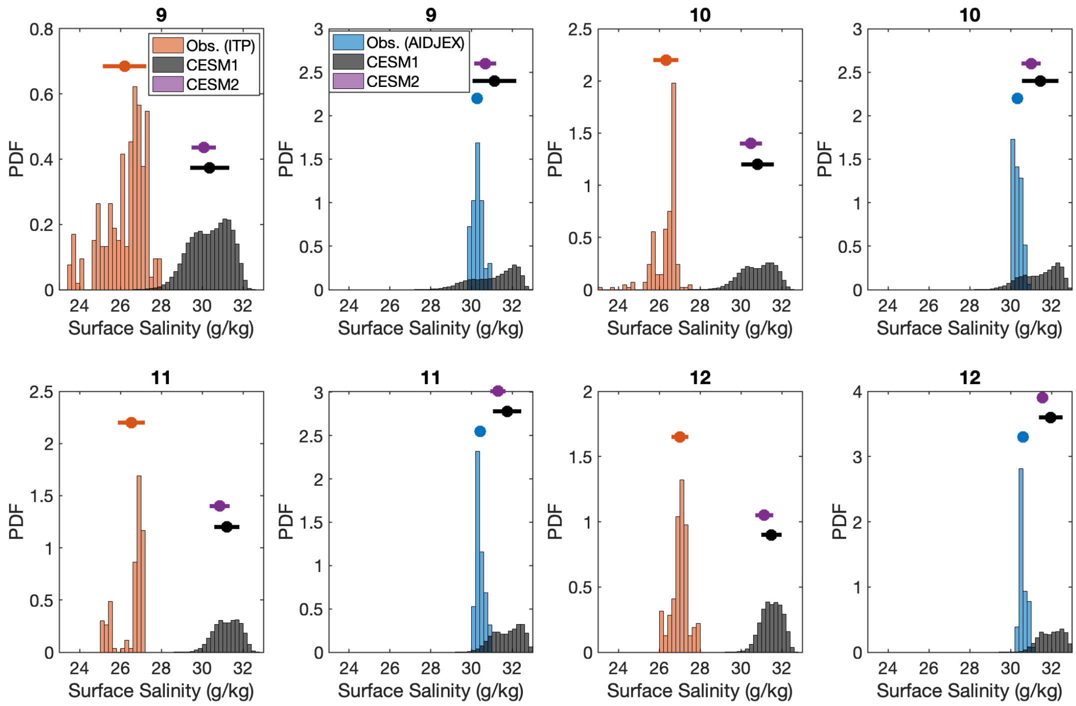

Figure S2. As in Figure S1, but for September-December (9-12).

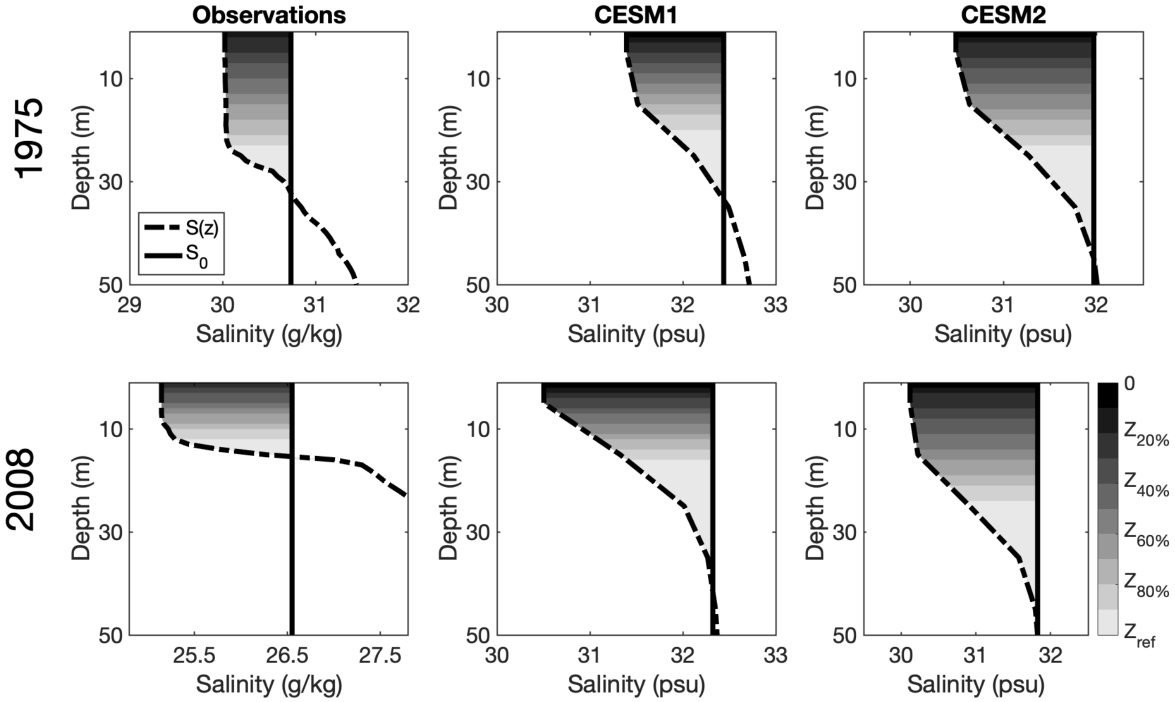

Figure S3. Examples of how sFWC and $Z_{10\%}, Z_{20\%}, ..., Z_{fw}$ are computed in the observations (left column), CESM1 (middle column), and CESM2 (right column) using data from 1975 (top row) and 2008 (bottom row).

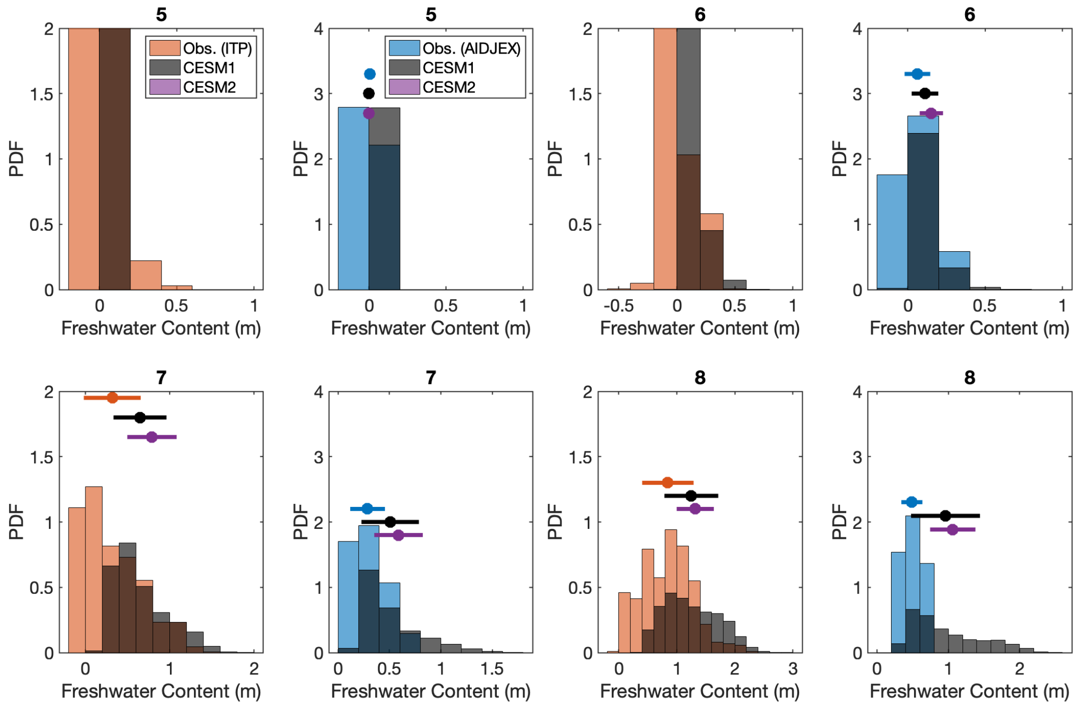

Figure S4. As in Figure 4d-e, but for May-August (5-8). Only the mean and standard deviation are included for CESM2 (purple).

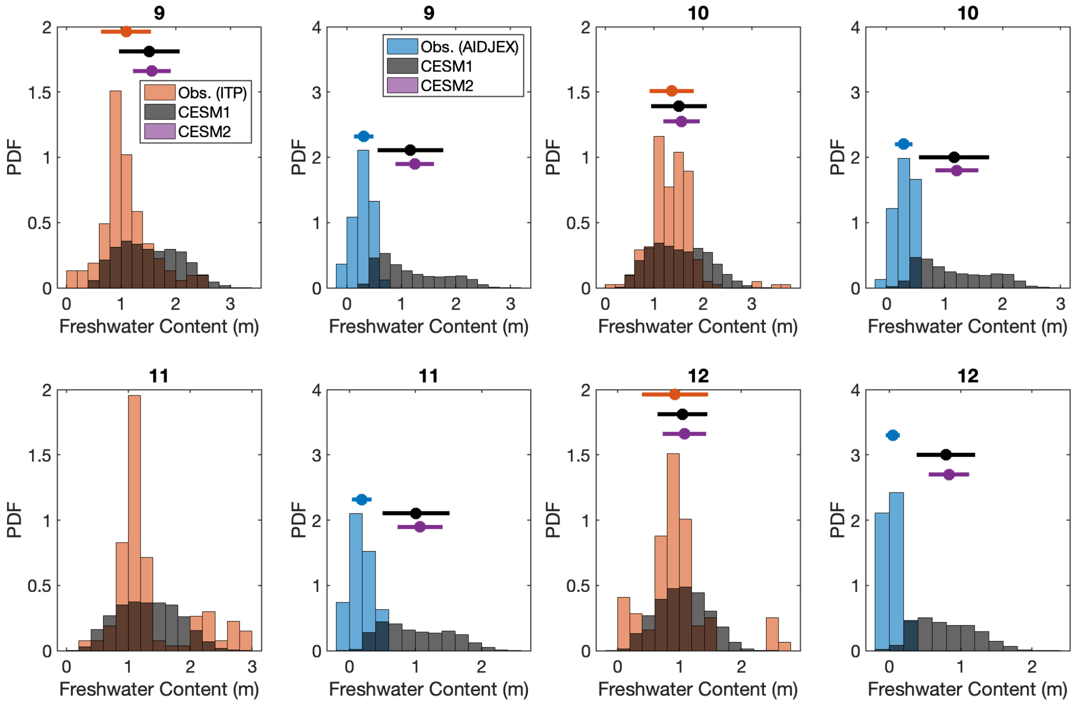

Figure S5. As in Figure S5, but for September-December (9-12).

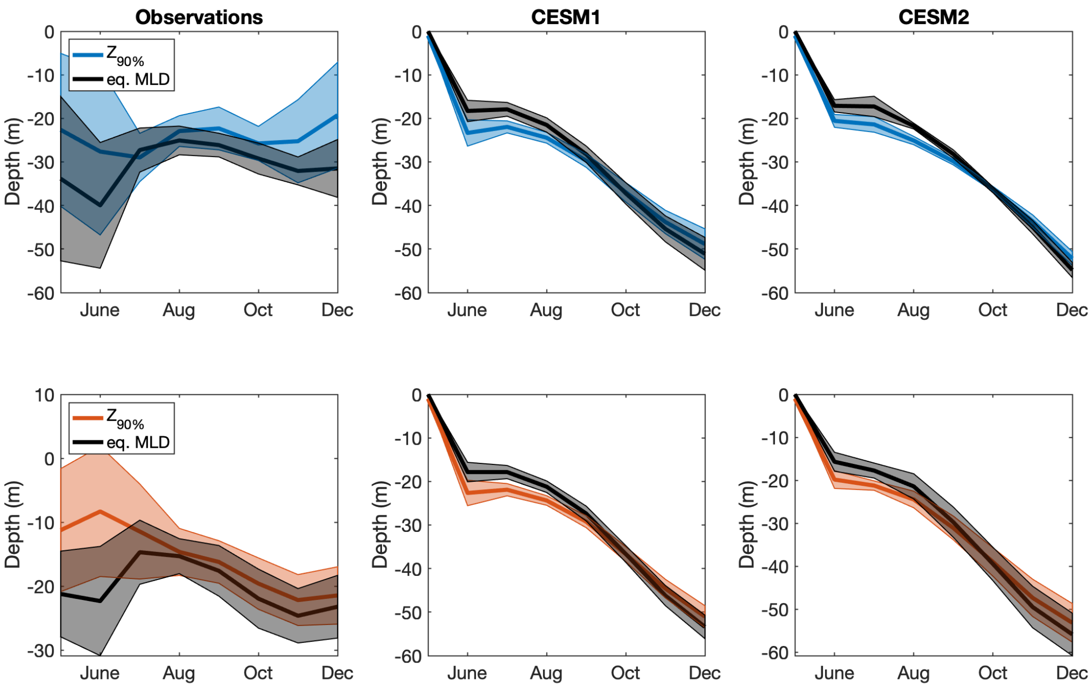

Figure S6. $Z_{90\%}$ (blue, red) and equivalent mixed-layer depth (black) in 1975 (top row), 2006-2012 (bottom row). Solid line indicates basin ensemble mean, and shading indicates the spread across the ensemble members using one standard deviation.