On the sensitivity of undeformed Arctic sea ice to its vertical salinity profile

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[1] The temporal evolution of sea ice salinity affects the temperature profile and vertical growth and decay of the ice cover, as well as many other important properties. Here, we use a one-dimensional thermodynamic sea ice model to explore the sensitivity to the vertical profile of ice salinity of (1) Arctic first-year and equilibrium multiyear sea ice thickness, and (2) the salt/freshwater flux at the ice/ocean interface. Results indicate that increasing the mean salinity induces a higher thermal inertia reducing summer melt and finally increasing ice thickness. The shape of the profile is also important, since low salinity at the surface must be captured to produce enough surface melt. This study gives accurate hints on what the minimum complexity of a parameterization of the temporal evolution of sea ice salinity should be. **Citation:** Vancoppenolle, M., T. Fichefet, and C. M. Bitz (2005), On the sensitivity of undeformed Arctic sea ice to its vertical salinity profile, *Geophys. Res. Lett.*, *32*, L16502, doi:10.1029/2005GL023427.

1. Introduction

[2] Improving the treatment of thermodynamics in sea ice models is motivated by the importance of sea ice to high latitude climates, which themselves have a prominent role in the global climate. Currently, most climate models include a sea ice thermodynamic component, such as the one of *Semtner* [1976] or the more recent one of *Bitz and Lipscomb* [1999] (hereafter referred to as BL99), simulating the sea ice temperature profile and thickness as main prognostic variables. Some models have considered the ice salinity as a constant, only used while computing the salt/freshwater flux at the ice bottom interface [e.g., *Fichefet and Morales Maqueda*, 1997]. The impact of salinity on the ice properties has been accounted for in models either with a vertically varying salinity profile, fixed in time [BL99], or with an isosaline profile varying in time [*Ebert and Curry*, 1993]. To improve this has frequently been reported as a next important step in future model development [*Eicken*, 2003].

[3] Sea ice haline and thermodynamic processes are interrelated, and thus are characterized by unevaluated potential feedbacks. The first aspect of their twofold relationship is that sea ice thermodynamics control the relative rate of several brine drainage mechanisms responsible for the temporal evolution of the vertical salinity profile [*Untersteiner*, 1968; *Cox and Weeks*, 1988]. The brine drainage leads, in the Arctic, to different salinity profiles for first-year (FY) and multiyear (MY) ice. The FY salinity profile is C-shaped with mean salinities often around 5‰ [*Nakawo and Sinha*, 1981]. MY ice salinity is practically zero close to the surface and increases with depth, with a mean salinity around 2‰ [*Schwarzacher*, 1959].

[4] Determining the level of complexity of a sea ice model with prognostic salinity requires a preliminary investigation of the second aspect of sea ice halo-thermodynamics (i.e., the interactions between haline and thermal processes in sea ice): the influence of sea ice salinity on the ice thermodynamics. Together with temperature, salinity controls the volume of internally trapped brine [*Frankenstein and Garner*, 1967]. Consequently, sea ice thermal properties (which regulate ice growth and melt as well as the internal vertical temperature profile) depend on salinity and temperature, particularly close to the melting point where the greatest changes in brine volume occur. Thus, an accurate knowledge of the vertical salinity profile is important for capturing the main features of Arctic MY ice, as mentioned by BL99. But, to our knowledge, no detailed study of the impact of sea ice salinity on predicting sea ice growth and melt exists.

[5] In this paper, we try to quantify the influence of the sea ice vertical salinity profile on the ice thermodynamics and on salt/freshwater exchanges in the Arctic. To do this, we use the BL99 energy-conserving one-dimensional (1D) thermodynamic sea ice model. In a forcing configuration typical of Arctic conditions, for undeformed congelation FY and MY ice, we run it with different salinity profiles, and analyse how this affects ice thickness, growth/melt rates, and, in turn, freshwater/salt flux to the ocean. We conclude by recommending directions towards the development of a halo-thermodynamic sea ice model.

2. Model Description

[6] The sea ice model used here is the BL99 1D thermodynamic energy-conserving model. The internal temperature profile is computed by numerically solving the heat diffusion equation in one layer of snow and 10 layers of sea ice, characterized by their own prescribed salinity. The thermodynamic effect of salinity, through its control of brine pockets, is represented by thermal properties depending on salinity (S) and temperature (T). The specific heat (c), which depends upon the internal storage of heat, increases by more than one order of magnitude close to

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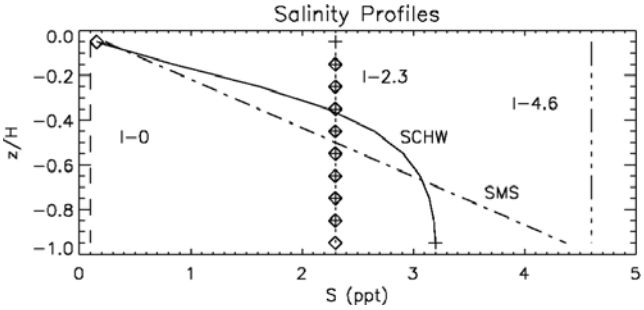

Figure 1. The different salinity profiles used in the simulations. 7-PR and L-PR are represented by squares and crosses, respectively. The remaining profiles are referenced on the plot: vertically constant profiles I-0, I-2.3 and I-4.6 (vertical dashed lines); vertically varying profile of *Schwarzacher* [1959] (SCHW, solid line); and a linear profile with the same mean salinity as SCHW (SMS, dashed-dotted line).

the melting point. The thermal conductivity (k), which regulates the heat transfer, is lowered by up to 20%. The energy of melting, which governs the ice growth/melt rate (q, defined as the energy required to melt a unit volume of sea ice) is on average 10% lower than the standard latent heat of fusion.

[7] The model is forced by classical idealized climatological atmospheric and oceanic conditions widely used in the literature. The upper surface forcing data (radiative and turbulent heat fluxes) are typical of the central Arctic [*Fletcher*, 1965]. The oceanic heat flux is set to 2 Wm^{-2} and the seasonal snow accumulation is as in *Maykut and Untersteiner* [1971]. The model was initiated with zero-thickness sea ice and run for 50 years with a one-day time step. We consider that the first and last years of the simulation represent FY and MY ice, respectively.

[8] In order to explore the sensitivity of the model to the ice salinity, different idealized salinity profiles are prescribed (see Figure 1). We use a non-linear profile, "SCHW", with salinity varying from 0‰ at the top of the ice to 3.2‰ at the bottom, and a mean salinity of 2.3‰. It is derived from the observations of *Schwarzacher* [1959]. Being the most realistic profile, it is considered as the reference for the MY ice simulations. Furthermore, we use 3 vertically constant profiles, "I-0", "I-2.3" and "I-4.6". They correspond to salinity values of 0.1‰, 2.3‰ and 4.6‰, respectively. I-4.6 is chosen as a reference for FY ice since it corresponds to the FY ice winter equilibrium value mentioned by *Kovacs* [1996]. Finally, we also use 3 profiles situated between the vertically constant I-2.3 and the vertically varying SCHW profiles. Inside the ice, "L-PR" and "7-PR" are similar to I-2.3, and at the lower and upper interfaces respectively, they have the same salinity as SCHW. "SMS" profile is a linear profile with 0‰ at the surface and the same mean salinity as SCHW.

3. Model Results

3.1. Impact of Bulk Salinity

[9] First, we only deal with vertically constant salinity profiles (i.e., isosaline ice). Figure 2a indicates that the model simulates a thicker ice for greater salinities. The MY thickness range among the different simulations is maximum in summer, reaching 144 cm. The values shown in Table 1 also indicate that, with increasing salinity, the surface melt period is shorter, as is the amplitude of the thickness seasonal cycle, and the bottom melt onset is delayed by up to two months.

[10] Summer melt proves to be responsible for these differences. All along the 50 years of the simulation, total annual melt difference between I-0 and I-2.3 exceeds annual growth differences (see Figure 2b), with the major contribution from surface melt. Fresher ice melts more than higher salinity ice. Ice thickness, more than salinity, controls bottom growth, and since fresher ice is permanently thinner, it also grows more; but the difference in melt dominates the behavior. As a consequence, the equilibrium thickness is smaller for fresher ice, while the amplitude of the seasonal cycle is larger.

[11] Why does fresher ice melt more than more saline ice? Higher melt rates and longer melt periods share responsibility for this. They reflect the fundamental impact of salt on heat conduction and storage. Additional experiments (not shown here) aimed at isolating the individual effect of each of the thermal properties indicate the following. 1) Increasing salinity in the thermal conductivity $k(S,T)$ in isolation (i.e., while holding the salinity fixed in other salinity-dependent parameters) only modestly slows bottom growth through its impact on the heat conduction flux. 2) The impact of increasing salinity in the specific

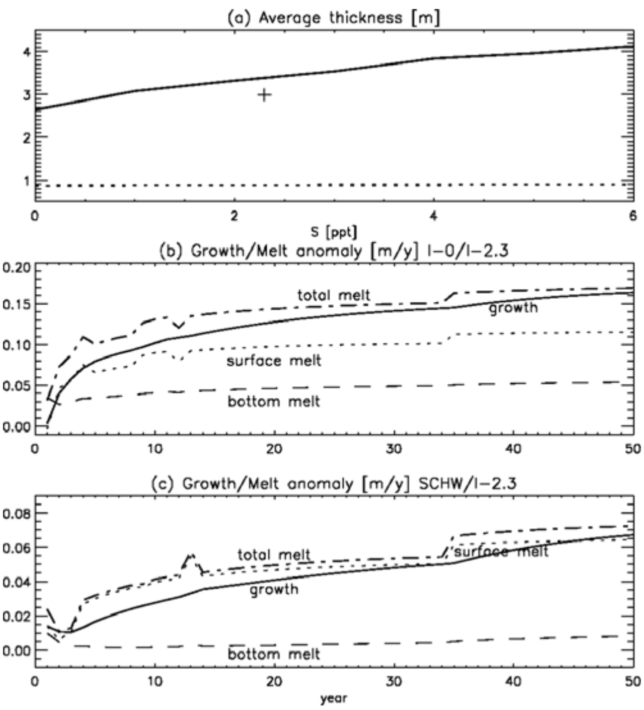

Figure 2. (a) Average MY (solid line) and FY ice thickness (dashed line) versus ice salinity, for simulations with a vertically constant salinity profile. The cross indicates the simulation with SCHW profile simulation. (b–c) 50-year evolution of differences in annual amounts of growth and total melt between simulations with (b) I-0 and I-2.3 profiles and (c) SCHW and I-2.3 profiles. Total melt is split into surface and bottom contributions.

Table 1. Summary of Results for Year 50 of the Sensitivity Experiments

Salinity Profile	Mean Ice Thickness, m	Bottom Ice Growth, m/yr	Bottom Ice Melt, m/yr	Surface Ice Melt, m/yr	Length of Surface Melt Period, days	Day of Onset of Bottom Melt	Length of Bottom Melt Period, days
SCHW	2.99	0.43	−0.06	−0.38	49	199	112
I-0	2.65	0.53	−0.11	−0.43	52	169	101
I-2.3	3.46	0.36	−0.05	−0.31	45	206	116
I-4.6	3.93	0.26	−0.01	−0.26	42	246	106
SMS	2.96	0.45	−0.07	−0.38	49	192	111
L-PR	3.45	0.37	−0.05	−0.31	45	208	117
7-PR	3.11	0.42	−0.06	−0.36	48	200	111

heat $c(S,T)$ in isolation is to delay melt onset at the surface by increasingly resisting warming (i.e. overestimating thermal inertia) as the ice approaches melting, thus diminishing the length of the melt period. With higher salinity, the ice preferentially apportions more energy to warming and melting internally rather than melting at the interfaces. Related to this, we noted greater downward heat conduction flux in summer at the ice surface, driven by stronger temperature gradients. Thus the increase in $c(S,T)$ with S has the effect of diminishing the rates of both winter growth and summer surface melt. Overall, the experiments indicate that accounting for salinity in c is much more influential than in k, in particular during summer. 3) As shown by BL99, the effect of accounting for salinity in the energy of melting $q(S,T)$, compared to assuming a freshwater latent heat of fusion, enhances melt and growth rates – the opposite of the effect of accounting for salinity in $c(S,T)$. Because Figure 2b indicates that the melt rate decreases with increasing salinity, we know that the salinity effect on $c(S,T)$ must dominate in summer. In summary, higher salinity increases the thermal inertia of sea ice, which leads to lower melt rates, especially at the surface, and feedbacks with slower growth in winter. This finally leads to thicker ice, with a smaller amplitude seasonal cycle.

3.2. Impact of the Shape of the Salinity Profile

[12] On the one hand, FY ice thickness (see Figure 2a) and, more generally, all simulated physical FY ice characteristics, appear to be insensitive to the ice salinity, except for a slight tendency of faster growth for more saline ice, due to the dominant $q(S,T)$ effect. We expect the same behavior if salinity varies in time, since ice thickness rather than salinity controls ice growth. On the other hand, MY ice characteristics significantly depend not only on the bulk salinity (see Section 3.1) but also on the shape of the salinity profile. Figure 2a and Table 1 show the impact of progressively moving from a constant profile I-2.3 to the non-linear SCHW profile, giving differences in annual mean ice thickness (−47 cm), in the amplitude of the seasonal cycle (+7 cm) and in the summer surface melt period duration (−4 days).

[13] The importance of the low near-surface salinity is further stressed by the analysis of the transition from I-2.3 to SCHW. First, using the L-PR profile hardly changes the results, while on the contrary, decreasing the top layer salinity value to the almost-zero observed surface value (7-PR) divides nearly by a factor of five the thickness difference between the I-2.3 and SCHW cases. If we keep on getting closer to the SCHW profile, using the SMS profile, the annual mean thickness approaches the SCHW profile thickness value. The importance of surface salinity in increasing the summer surface melt is further clearly shown in Figure 2c, showing that throughout the 50 years differences between SCHW and I-2.3 cases are dominated by surface melt. In conclusion, using a constant salinity profile for Arctic multiyear ice yields an overestimation of surface thermal inertia, which results in an overestimation in thickness.

3.3. Salt/Freshwater Flux

[14] The contribution from sea ice growth and decay to the salt/freshwater flux between ice and ocean can be represented by the massive salt flux (MSF) from the ice to the ocean, proportional to the growth rate and salinity difference between ice and ocean [see, e.g., *Tartinville et al.*, 2001]. In this representation, we implicitly assume that the ice rejects some salt into the ocean (MSF positive) while it grows, and "accumulates" some salt when it melts (MSF negative). The latter assumption is somewhat unphysical, but reflects that there actually are, during the melt period, two simultaneous fluxes. The first one is a salty brine flux expelled by the ice into the ocean, while the other is a freshwater flux coming from the ice melting. The negative MSF therefore represents the combination of a salt flux and a freshwater flux, dominated by the freshwater exchange and giving a "negative" MSF. By comparing Figures 3a and 3b, we infer that the growth rate is the main factor responsible for the differences in the integrated massive salt

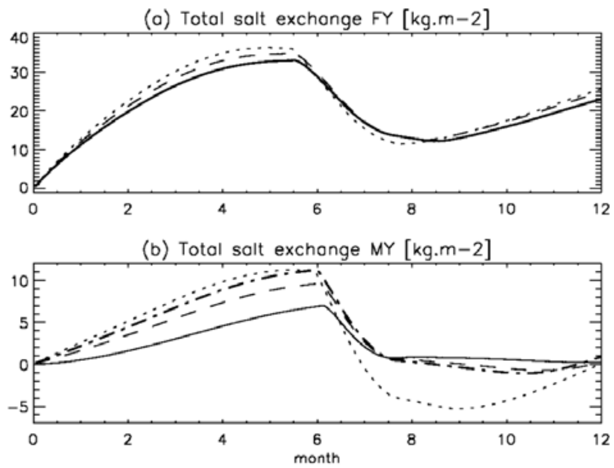

Figure 3. (a) Seasonal cycles of the integrated massive salt flux (IMSF) between ice and ocean (positive to the ocean), for FY ice and for different salinity profiles, i.e. I-4.6 (solid line), I-2.3 (dashed line) and I-0.0 (dotted line). (b) Seasonal cycles of IMSF for MY ice and for different salinity profiles, i.e. SCHW (dashed-dotted line), I-4.6 (solid line), I-2.3 (dashed line) and I-0.0 (dotted line) profiles.

flux (IMSF, defined at time t as the time-integral of the MSF calculated between the first day of the year and t).

[15] However, because the ice salinity is much smaller than the ocean salinity, the dependence of IMSF on the ice salinity for both FY and MY ice is weak. A more saline ice implies a smaller IMSF. The salinity-induced relative difference in IMSF for FY and MY ice is about 10–20% and is principally caused by different growth rates. From Figure 3b, one can also see how the IMSF looks if the SCHW profile is used. The IMSF seasonal cycle appears very similar to the I-2.3 one (see Figure 3b). Nevertheless, the SCHW profile leads to an artificial sink of salt, since the ice can melt (at the surface) at a different salinity from the one it has been formed (at the bottom), stressing the need for a salt drainage model.

3.4. Discussion on Application

[16] It is important to remember that the model we used proved to be the most sensitive in summer, when it is known to be less accurate [*Vancoppenolle and Fichefet*, 2005]. Our study further stresses the prominent importance of summer processes on the equilibrium thickness. The model uncertainties during summertime are not surprising, since melt ponds, porosity, brine drainage, meltwater flowing in the ice matrix and other processes specific to the summer are not represented. Finally, the conclusions of our study should be restricted to the Arctic, and not extended to the Southern Hemisphere, where the ice regime is different, with summer melt almost absent and a physically different sea ice [e.g., *Eicken*, 1998]. Using more layers in the snow or reducing the number of ice layers to 3 does not significantly affect the simulated ice thickness. Nevertheless, thin ice growth on synoptic timescales was not evaluated.

4. Conclusions

[17] We have shown how salinity affects the thermodynamics of Arctic sea ice and the freshwater/salt exchange between ice and ocean with an energy-conserving thermodynamic sea ice model. About the thermodynamic influence of ice salinity, our results stress that the presence of salt in the ice increases its thermal inertia, and that this thermal inertia mostly affects summer surface melt rate. Capturing the low surface thermal inertia appears to be the key aspect, since it controls – through a specific heat effect damping temperature variations – the magnitude of summer melt, which controls the equilibrium thickness of the ice. A result similar in all points [*Vancoppenolle and Fichefet.*, 2005] was obtained with high-frequency SHEBA forcing including a more realistic ocean heat flux provided by *Huwald et al.* [2005]. Regarding the salt/freshwater flux between ice and ocean, our results indicate that changing the ice salinity from 0 to 4.6‰ lowers the integrated massive salt exchange by 15% between ice and ocean in the perennial ice zone.

[18] Consequently, since the intense summer desalination by percolation of meltwater (*flushing*) drives the low surface salinity and the shape of the MY salinity profile in the Arctic [*Untersteiner*, 1968], but rarely occurs in the Antarctic [*Eicken*, 1998], a prerequisite to the development of a full halo-thermodynamic sea ice model would be to parameterize the flushing. Using a vertically constant salinity profile, even varying in time (instead of a MY ice salinity profile) would result in too thick ice through the overestimation of surface thermal inertia. The results shown here thus indicate that the simplest treatment of the temporal evolution of sea ice vertical salinity profile in thermodynamic models would be to assume a simple shape for the salinity profile, vertically constant for FY ice and linear for MY ice. An improved freshwater budget could be inferred with the time variations of the bulk salinity.

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