



Internal melting in Antarctic sea ice: Development of “gap layers”

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Received 14 February 2008; revised 31 March 2008; accepted 24 April 2008; published 6 June 2008.

[1] An internal “gap” layer of deteriorated sea ice is co-located with a significant microbial biological community in late first year and second year Antarctic sea ice in summer. We modeled gap layer formation using a thermal flux model based on the summer reversal in thermal gradient and the thermal conductivity found in the upper ice column. The conductive model gives internal sea ice melt rates (gap layer formation rates) between 0.1 to 0.75cm/day. The cumulative melted layer thicknesses during summer computed from these rates agree with field observations. Since the processes for forming these structures act in the vertical direction only and over a significant range of expected conditions, they are commonly formed in the Antarctic sea ice zone during summer, supporting a significant contribution of gap layers to the ice mass balance and productivity on a circumpolar basis. **Citation:** Ackley, S. F., M. J. Lewis, C. H. Fritsen, and H. Xie (2008), Internal melting in Antarctic sea ice: Development of “gap layers,” *Geophys. Res. Lett.*, 35, L11503, doi:10.1029/2008GL033644.

1. Introduction

[2] The presence of perennial sea ice in Antarctica, while limited, is still of the order of 3–4 million km². Summer sea ice provides a highly important habitat for algal production and krill populations, and is used by ice-obligate seals and penguins as a haul-out area for breeding, molting, and birthing activity [Ackley *et al.*, 2003; Kooyman *et al.*, 2000; Fritsen *et al.*, 2001]. The complete absence of summer sea ice in the Antarctic therefore poses a similar ecological threat as predicted for the Arctic system’s populations due to sea ice decline. During summer, the temperatures of air, sea ice, and ocean are in near equilibrium around the freezing point of sea water. In Antarctic summer sea ice, “gap” or “freeboard” layers (herein “gap layer”) consist of a partially melted honeycomb-like ice matrix filled with sea water found below a surface layer of snow and ice [Ackley and Sullivan, 1994]. The layers are typically darkly colored because of high algal and microbial content [Kattner *et al.*, 2004]. Krill and other secondary consumers are frequently found occupying the gap layer. These features have a relatively intact snow cover and solid ice layer above them and have been observed only in the Antarctic to date. In contrast, massive surface melt, resulting in the complete loss of the snow cover, followed by melt pond formation on top of the ice is the dominant surface characteristic of Arctic

summer sea ice [Perovich *et al.*, 2002]. Melt ponds are not often observed on Antarctic sea ice and are particularly rare in summer in the Weddell, Amundsen-Bellinghousen and Eastern Ross Seas [Ackley *et al.*, 1979, 2003; Nihashi *et al.*, 2005]. Gap layers have not been widely observed in Arctic sea ice.

2. Prior Theories of Gap Layer Formation

[3] The first explanations for the presence of gap layers in Antarctic sea ice were provided by Ackley *et al.* [1979] and Ackley and Sullivan [1994]. It was suggested that a Physical-Biological Feedback (PBF) process occurs where concentrations of dark algal material accelerate melting by increasing the absorption of solar radiation within the sea ice. Algal blooms are enhanced because of brine drainage from surface layers resulting in highly saline and nutrient rich layers near sea level. In ice cores, reported by Gow *et al.* [1987], increased algal growth correlated with increased ice salinity in gap layers located 20 to 30 centimeters below the ice surface.

[4] Other mechanisms have been investigated [Fritsen *et al.*, 1998; Maksym and Jeffries, 2000; Haas *et al.*, 2001] starting with flooded snow layers. Haas *et al.* [2001], in order to explain the harder ice cover necessary over a gap layer originating as surface slush have Superimposed Ice Formation (SIF), where snow melt from above encounters the cold slush layer, and this low salinity water freezes forming a fresher ice layer. No biological interaction is necessary in this case, nor internal melting. The explanation of Fritsen *et al.* [1998] in which the gap layer is formed as a result of snow-induced flooding and partial (top-down) refreezing of flooded snow layers does result in a hard sea ice layer on top, and sea salts are rejected into the underlying gap layer slush and the underlying sea ice.

[5] These past interpretations are somewhat conflicting on how gap layers form and none seems sufficiently general to cover the range of observations. Ackley *et al.* [1979] conjectured a PBF mechanism because of the co-location with dark biological material in the layers. Later modeling [Zeebe *et al.*, 1996] however, concluded algal radiation absorption was insufficient to provide enough localized heat to account for the observed amount of melting, particularly early in the summer season. Haas *et al.* [2001] have suggested instead the SIF mechanism based on their observations of sea ice core data. In this model, the gap layer arises from the capping of a surface slush layer with refrozen snow melt as SIF. This mechanism is inconsistent with some observations [Gow *et al.*, 1987] which did not find SIF in many high-latitude locations, yet gap layers were frequently observed beneath a solid sea ice layer. While the mechanism of Fritsen *et al.* [1998] can form a

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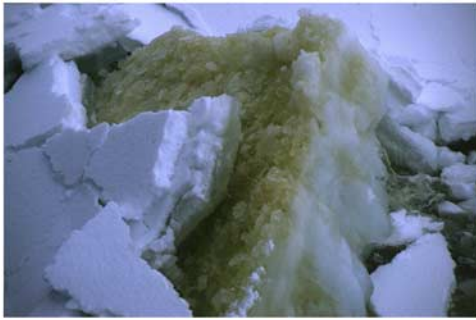


Figure 1. Photograph of a gap layer from the Weddell Sea in Antarctica (from Christian Haas). The photo shows an upturned block of sea ice with thin snow cover overlying a layer of solid ice. The layer of sea ice is stained brown from high algal content, and the porous gap layer is beneath. Thick sea ice underlying the gap layer has less algal growth.

solid sea ice layer over a slush layer, a honeycombed gap layer structure of sea ice with water-filled voids is often seen rather than unconsolidated slush beneath the top layer. Lowered seawater salinity in the gap layers [Fritsen *et al.*, 2001; Haas *et al.*, 2001] and some layers with honeycombed structure seem to support local melting in the ice interior. As well, the necessity of horizontal exchange to later widen the layers [Haas *et al.*, 2001] and provide nutrient levels to support higher biomass is somewhat in conflict with observations during summer, where well-developed gap layers with high biomass are frequently observed at hundred meter distances from floe edges [Gow *et al.*, 1987; Fritsen *et al.*, 2001] where horizontal sea water exchange is unlikely.

[6] Herein we propose a general mechanism where heat is pumped into the gap layer by the inverted summer temperature gradients and is the overriding process that commonly leads to internal melting and either forms a gap layer or widens an existing slush layer. When this thermodynamic process is coupled with the common processes of flooding and initial refreezing, or with conditions of SIF, or

initially un-flooded sea ice (no slush layer), the wide-spread gap layer phenomena can be readily explained under general summer conditions found in Antarctic pack ice.

3. Observations of Gap Layers in Antarctic Sea Ice

[7] Gap layers have been identified by several researchers [Ackley *et al.*, 1979; Ackley and Sullivan, 1994; Fritsen *et al.*, 1994, 2001; Lytle and Ackley, 1996; Haas, 1998; Haas *et al.*, 2001]. Figure 1 (courtesy Christian Haas) shows a typical cross section of summer sea ice with a gap layer consisting of a surface layer of snow, overlying a layer of solid ice. The top of the ice layer may consist of SIF but the lower portion is a solid layer of sea ice, as it is darkened by algae, which is not found in superimposed ice. Below the sea ice layer is the interstitial “gap layer” filled with saline slush or a honeycomb-like structure of sea ice and sea water. The gap layer tends to be nutrient rich and contains elevated levels of algal material [Fritsen *et al.*, 1994; Gow *et al.*, 1987]. The gap layer is typically underlain by less porous sea ice but still has extensive brine drainage channels of cm-size diameters [Ackley *et al.*, 1996].

[8] A summary of the sea ice properties and related gap layer dimensions from two studies is compiled in Table 1. Data reported by Fritsen *et al.* [2001] from the Ross Sea in 1999 indicated the gap layer temperature averaged -1.57°C for 65 sites with an average salinity of 29.2 psu. Haas *et al.* [2001] reported a similar mean salinity of 29.3 ± 2.6 psu for 37 gap water samples in summer and early autumn in 1997. Vertical profiles through the snow layer present on sea ice during these cruises generally show a small thermal gradient in summer, with heat flow inferred in the downward direction toward the gap layer and colder ocean water. Snow/ice interface temperatures in these studies generally ranged from about 0 to -1.5°C .

[9] Percolation experiments on removed ice blocks have shown that flow of brine is confined to large brine channels in the granular ice that is typically found in the top portions of the ice cover [Golden, 2001]. Saline ice with unconnected brine pockets composes the remainder of the upper sea ice layer [Gow *et al.*, 1987]. The thermal conductivity is

Table 1. Summary of Summer/Early Autumn Sea Ice Properties^a

Location	SE Weddell	NW Weddell	SE Weddell	Ross Sea
Season	summer	summer	early autumn	summer
No. floes	11	14	8	65
Mean total ice thickness (m)	1.56 ± 0.31	1.52 ± 0.75	1.92 ± 1.39	NA
Range	1.24–1.91	0.26–2.86	0.41–4.30	NA
Mean freeboard (m)	0.07 ± 0.05	0.08 ± 0.05	0.07 ± 0.05	NA
Range	0–0.14	0–0.17	0–0.13	NA
Percentage “gap” features	73	86	38	100 ^b
Mean surface layer thickness (m)	0.07 ± 0.04	0.20 ± 0.06	0.15 ± 0.05	$0.042 \pm .035$
Range	0.02–0.15	0.10–0.29	0.10–0.16	0.0–0.13
Surface layer draft (m)	0.02 ± 0.02	0.14 ± 0.05	0.14 ± 0.01	NA
Range	0–0.07	0.08–0.23	0.13–0.15	NA
Gap thickness (m)	0.08 ± 0.09	0.04 ± 0.03	0.05 ± 0.06	0.12 ± 0.099
Range	0.01–0.27	0.01–0.09	0.01–0.09	0.0–0.51
Mean snow thickness (m)	0.24 ± 0.02	0.11 ± 0.14	0.20 ± 0.12	0.199 ± 0.161
Range	0.21–0.26	0.04–0.58	0.07–0.02	0.03–0.90

^aData from Haas *et al.* [2001] and Fritsen *et al.* [2001]; NA, not available.

^bFloes reported here are only those with gap layers.

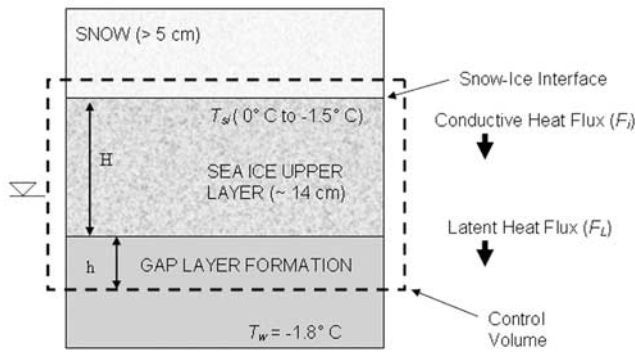


Figure 2. Block diagram of thermal diffusive flux model based on formulation by *Maykut and Untersteiner* [1971].

dependent on the sea ice salinity [*Weeks and Ackley*, 1986; *Maykut and Untersteiner*, 1971].

4. A Thermal Diffusive Flux Model for Internal Sea Ice Melt

[10] A simple thermal diffusive flux model presented here is based on *Maykut and Untersteiner* [1971] and takes into account the change in thermal properties of the upper layer of sea ice when it warms and loses salinity through brine drainage. At temperatures below the melting point for snow ($<0^{\circ}\text{C}$) but above the freezing point of sea water ($>-1.8^{\circ}\text{C}$), heat from the upper snow and sea ice can then be conducted, without melting the intermediate layer, directly to sea level, melting this saline internal ice layer.

[11] The upper ice layer with disconnected pockets of brine is herein assumed to act as a solid layer, transferring heat by thermal diffusion without melting. The average thermal conductivity (k_i) through the upper ice layer is assumed to vary as a function of salinity [*Weeks and Ackley*, 1986]. The incorporation of changing ice layer salinity provides a range of sea ice melt rates as output from the model. In the model we assume that the ice floe is >1 meter thick with a snow cover that is sufficiently thick (>5 cm) to block most solar radiation [*Zeebe et al.*, 1996]. This value is consistent with mean snow thickness data reported in Table 1.

[12] The mean surface ice layer thickness from Antarctic field data varies from 4 to 20 centimeters depending upon the field study (Table 1). For the model we assumed a weighted mean value from the field studies (~ 14 centimeters) for the surface ice layer thickness. For model purposes the upper layer is bounded by two heat sinks, the brine at sea level is at the freezing point of sea water ($T_w = -1.8^{\circ}\text{C}$) and the snow/ice interface temperature, T_{si} varies from 0 to -1.5°C [*Haas et al.*, 2001; *Fritsen et al.*, 2001].

[13] We consider a control volume for the model (Figure 2) that contains ice above and below sea level. The rate of conductive heat transfer (flux, F_i) at the interface between the upper layer and the saline layer (no gap formed) is given by:

$$F_i = k_i(\partial T/\partial z)_H \quad (1)$$

Where k_i is the thermal conductivity of sea ice and $(\partial T/\partial z)_H$ is the temperature gradient across the ice layer of thickness

(H). The thermal conductivity of sea ice is dependent upon both temperature (T) and salinity (S). Using the equation given by *Yen* [1981] for the conductivity of pure ice:

$$k_o = 9.828 e^{(-0.0057 T)} \quad (2)$$

and the approximation for k_i given by *Maykut and Untersteiner* [1971]:

$$k_i = k_o + 0.13 (S/T) \quad (3)$$

heat flux from the upper ice layer to the gap layer at sea level is calculated using the average thermal conductivity for the ice layer for salinities between 0 and 6 psu.

[14] The heat flux into the ice below the water level is balanced by the latent heat flux (F_L) due to phase change in the gap layer. The equation for latent heat flux is given in the model as:

$$F_L = -\rho L \partial h/\partial t \quad (4)$$

Where ρ is the density of sea ice (assumed constant 920 kg/m^3) and L is the latent heat of fusion for sea ice, assumed not to vary as a function of time. The latent heat of fusion (J/kg) varies with salinity and temperature according to the formulation by *Ono* [1968]:

$$L = 333394 - 2113 T - 114.2 S + 18040(S/T) \quad (5)$$

[15] The heat flux into the gap layer results in melting of sea ice at or below sea water level and therefore, the temperature for estimating the latent heat of fusion is taken as -1.8°C . The ice melting rate ($\partial h/\partial t$) or the rate of gap layer formation may then be computed by equating the heat flux from the upper layer with the latent heat from phase change in the gap layer. The results for a range in snow-ice interface temperature (0 to -1.5°C) and range of salinity of the upper sea ice layer (0 to 6 psu) is given as daily melting rate in Figure 3.

5. Discussion

[16] Observed sea ice properties and temperature gradients from summer field studies in the Antarctic were used to develop the input and constraints for a thermal diffusive

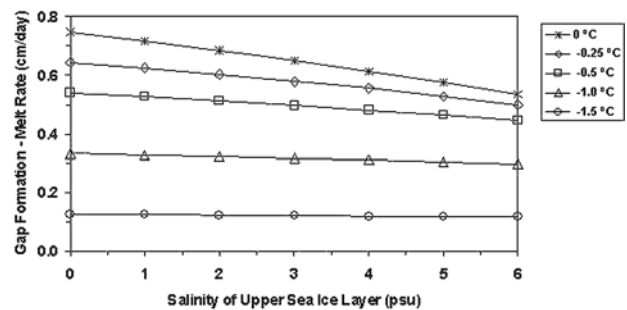


Figure 3. Gap layer formation rate (melting rate) as a function of snow-ice interface temperature ($^{\circ}\text{C}$) and salinity (psu) of the upper sea ice layer based on the thermal diffusive flux model.

flux model based on the *Maykut and Untersteiner* [1971] formulation. The results of the model give a melting rate for gap layer formation ranging from 0.12 to 0.75 cm/day for the cases shown in Figure 3. Changing the surface layer thickness in the model affects the thermal gradient and therefore, the results of the model output. The values for these cases give a range of gap layer thickness, assuming 20 to 30 days of available heat flux in the austral summer, of approximately 2 to 22 centimeters. This range of values falls within the observed range of data from Antarctic field studies (Table 1). The mean gap layer thickness values relate more closely with the cumulative melt rates on the lower curves, indicating that the average temperature gradient is on the low side of the reported range (i.e. $T_{si} < 0^{\circ}\text{C}$). The upper curve represents the special case of SIF ($T_{si} = 0^{\circ}\text{C}$), so the results of this model indicate that most gap layer formation can occur without relying on that special condition, but does predict it as well.

[17] Actual field conditions in Antarctic sea ice are more dynamic, resulting in frequent changes in thermal gradient, freeboard, snow thickness, and salinity rather than the constant values assumed here. However, even in simplified form, the physics of the model explain the formation of internal gap layers in Antarctic sea ice and do not necessarily rely on special conditions assumed in previous models of PBF in the first case, and of both flooding and snowmelt in the second. The thermal model is therefore more generally applicable to the widespread observation of gap layers in Antarctic sea ice. A crucial element necessary for the development of gap layers is the fluid and thermal transport properties of sea ice [Golden *et al.*, 2007], where seasonal warming initially causes brine drainage from the upper layer until the layer freshens, then allowing diffusive heat flux into the ice layer at sea level where the melting takes place. The melting layer is separated from the top surface of the ice since the freshened top layer is below its melting point, so melting takes place at the “hydraulic minimum” (sea level) where the temperature is at the melting point for sea ice. The sea ice at this level then melts as heat is added from above.

[18] Observations indicate gap layer temperatures and salinities are at the equilibrium values for the sea water freezing point (-1.57°C) and gap water salinity (29.2 psu) [Haas *et al.*, 2001; Fritsen *et al.*, 2001]. Local ice melting in the gap layer is also suggested by the difference between these salinities and surface sea water salinities (>33 psu) typically observed in leads near the ice [Ackley *et al.*, 2003]. Using salinity values for surface sea water intruding into the gap layer of 31 to 35 psu and diluting to 29 psu with sea ice melt at 6 psu, yields a melted ice layer thickness range between 8 and 15 cm. This estimate is consistent with the melting rates modeled here and observed totals for gap layer thicknesses, respectively.

6. Conclusions

[19] We show that gap layers can develop under general seasonal warming conditions and are not limited in occurrence by special circumstances. Their development can now be quantified and the model tested against future observations. The generality applies in all areas of summer sea ice in Antarctica, confirming the potential for a large-scale

contribution of gap layers to structuring pack ice biological processes. Gap layers had previously been estimated, if widespread, to make a significant contribution to sea ice associated biological production during the Antarctic summer [Legendre *et al.*, 1992; Arrigo *et al.*, 1997, 1998]. A localized study at Ice Station Weddell [Lytle and Ackley, 1996] estimated about half of the autumn-winter ice accumulation is accounted for by the freezing of gap layers and surface slush, about equal to the contribution of new ice growth in leads locally. The cycle of internal melting, gap layer formation and freeze-back is therefore an important component of Antarctic sea ice mass balance. Inclusion of this process in both air-ice-ocean interaction and biogeochemical models should therefore improve model fidelity for sea ice response to climate forcing and lend confidence to their predictions in Antarctic sea ice regions.

[20] **Acknowledgments.** Supported by NSF Grant ANT 0703682-Sea Ice Mass Balance in the Antarctic to UTSA, S. F. Ackley, and NSF-Grant ANT 0529666 to DRI, C. H. Fritsen. M. J. Lewis acknowledges the support of Southwest Research Institute. The authors wish to acknowledge Christian Haas for his comments and the use of Figure 1 and the anonymous reviewer's remarks, both of which improved the paper.

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