Modelling argon dynamics in first-year sea ice

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A B S T R A C T

Focusing on physical processes, we aim at constraining the dynamics of argon (Ar), a biogeochemically inert gas, within first year sea ice, using observation data and a one-dimensional halo-thermodynamic sea ice model, including parameterization of gas physics. The incorporation and transport of dissolved Ar within sea ice and its rejection via gas-enriched brine drainage to the ocean, are modeled following fluid transport equations through sea ice. Gas bubbles nucleate within sea ice when Ar is above saturation and when the total partial pressure of all three major atmospheric gases (N_2, O_2 and Ar) is above the brine hydrostatic pressure. The uplift of gas bubbles due to buoyancy is allowed when the brine network is connected with a brine volume above a given threshold. Ice-atmosphere Ar fluxes are formulated as a diffusive process proportional to the differential partial pressure of Ar between brine inclusions and the atmosphere. Two simulations corresponding to two case studies that took place at Point Barrow (Alaska, 2009) and during an ice-tank experiment (INTERICE IV, Hamburg, Germany, 2009) are presented. Basal entrapment and vertical transport due to brine motion enable a qualitatively sound representation of the vertical profile of the total Ar (i.e. the Ar dissolved in brine inclusions and contained in gas bubbles; *TAr*). Sensitivity analyses suggest that gas bubble nucleation and rise are of most importance to describe gas dynamics within sea ice. Ice-atmosphere Ar fluxes and the associated parameters do not drastically change the simulated *TAr*. Ar dynamics are dominated by uptake, transport by brine dynamics and bubble nucleation in winter and early spring; and by an intense and rapid release of gas bubbles to the atmosphere in spring. Important physical processes driving gas dynamics in sea ice are identified, pointing to the need for further field and experimental studies.

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1. Introduction

Sea ice is an important component of the Earth System. First, sea ice is a sensitive indicator of climate change, as witnessed by its rapid retreat in the Arctic (Comiso and Nishio, 2008; Lindsay and Zhang, 2005; Serreze et al., 2007) and from the waters west of the Antarctic Peninsula (Stammerjohn et al., 2008). Sea ice also influences climate due to its high albedo, its insulating effect that reduces the underlying water heat loss in winter and its influence on the water column stratification in Polar Regions, driving the global thermohaline circulation (Goosse and Fichefet, 1999; Randall et al., 2007). Sea ice may also play an important, but still mainly unresolved, role in the sequestration of greenhouse gases by the ocean. Rysgaard et al. (2011) estimated that the seasonal CO_2 uptake in the sea ice zone may equal half of the annual CO_2 uptake of ice-free polar seas. The role of sea ice on CO_2 dynamics in the Po-

lar Oceans has so far not been properly represented in global Earth System models, because in those models sea ice is considered as an impervious shield preventing ocean–atmosphere gas exchanges (Yager et al., 1995). Recently, however, active gas sources and sinks in sea ice, as well as dynamic gas transport through the sea ice brine network have been evidenced (e.g. Delille et al., 2007; Geilfus et al., 2012; Mock et al., 2002; Papadimitriou et al., 2003; Semiletov et al., 2004; Tison et al., 2010). Biogeochemical processes, including the photosynthesis and respiration of microbial assemblages thriving in sea ice actively contribute to gas dynamics (Arrigo et al., 2010; Deming, 2010; Gleitz et al., 1995), but their proper quantification has still to come.

As the observation of gas exchanges through sea ice is a real challenge, modelling can help to provide theoretical constraints on the syngenetic, epigenetic and exogenetic processes that govern gas dynamics within sea ice (Tsurikov, 1979). The processes associated with ice formation, whatever the mode of formation (wind and wave turbulence frazil ice, congelation growth of columnar ice, snow ice, superimposed ice) are referred to as *syngenetic*

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(Matsuo and Miyake, 1966). *Epigenetic* processes encompass all the phenomena that affect gas content and composition from within the sea ice. This includes the nucleation and dissolution of gas bubbles within sea ice associated with temperature changes (Tison et al., 2002); the vertical redistribution of dissolved gas associated with brine dynamics (Loose et al., 2011a; Tison et al., 2010) and the vertical uplift of buoyant gas bubbles (Zhou et al., submitted for publication); the formation of gaseous inclusions due to biogeochemical sources and sinks, such as photosynthesis (Delille et al., 2007; Mock et al., 2002). The *exogenetic* processes refer to the exchanges of gas between sea ice, the atmosphere and the ocean (Nomura et al., 2010a; Papakyriakou and Miller, 2011). For the present study, we only consider the following processes: gas entrapment and gas release from solution during freezing (syngenetic), gas bubble nucleation and rise (epigenetic), and gas exchanges between sea ice, the atmosphere and the ocean (exogenetic).

Argon (Ar) is a noble gas unaffected by biological activities such as primary production, remineralization or grazing that take place within sea ice. Hence, it is often used to understand oceanic physical processes such as deep water formation (Hamme and Severinghaus, 2007), air–sea gas exchanges (Stanley et al., 2006) or processes controlling oceanic gas saturation states (Ito et al., 2011). Ar may also be used, along with oxygen which has a similar solubility (Broecker and Peng, 1974), as a potential indicator of the net community production within environments such as seawater (Nemcek et al., 2008) and sea ice (Zhou et al., in preparation). Using the O_2/Ar ratio to estimate the net community production is an advantageous non-invasive technique compared to other methods (Arrigo et al., 2010). Hence, modelling Ar is a first step towards a better understanding of the physical controls on gas dynamics within sea ice, an estimation of primary production in sea ice, and a better understanding of gas exchanges (e.g., CO_2) in ice-covered oceans.

In the present study, we attempt to identify the importance of the physical processes potentially driving gas dynamics within sea ice: gas entrapment, gas release from solution during freezing, gas bubble nucleation and rise, and gas exchanges between sea ice, the atmosphere and the ocean. To do so, a representation of the impact of those processes on Ar concentrations within first-year sea ice is implemented in a one-dimensional halo-thermodynamic sea ice model. Our analyses are based on two model simulations, run to mimic the conditions from two observation sites: Point Barrow (natural sea ice, Alaska) and INTERICE (artificial ice grown in an ice tank, HSVA, Hamburg, Germany).

2. The model

2.1. Model physics

The model presented is one-dimensional and only vertical processes are considered. We consider a horizontally uniform sea ice layer of thickness h_i and covered by a uniform layer of snow of depth h_s. The model consists of 4 components: ice halo-thermodynamics, radiative transfer, brine transport and abiotic gas dynamics. At each depth z within the ice, the brine salinity $\sigma(z)$ and brine volume fraction $e(z)$ (or brine volume) are determined from the bulk ice temperature $T(z)$ and salinity $S(z)$ (Schwerdtfeger, 1963).

In the model, sea ice forms at the ice base by congelation and melts at the surface and base of sea ice depending on interfacial heat budgets, involving atmospheric, oceanic and inner ice conductive heat fluxes (Vancoppenolle et al., 2007, 2010). Salinity and temperature control the thermal properties of sea ice (thermal conductivity, specific heat and energy of melting; see Bitz and

Lipscomb, 1999). In the model, ice may also form as snow ice when snow is deep enough to depress the ice surface below sea level. Seawater infiltrates between sea ice and the snow cover and instantaneously freezes in the snow, forming snow ice (Vancoppenolle et al., 2009). As in Vancoppenolle et al. (2010), the model halodynamics are based on advection–diffusion equations. Gravity drainage is represented using a mixing term and an effective diffusivity that involves the brine volume fraction $e(z)$ and a porous-medium Rayleigh number, Ra, (Notz and Worster, 2008). When ice melts, fresh water percolates through the brine network (i.e. flushing) given that $e \geqslant 5\%$ within the entire ice column. This process is represented as an advective flow.

2.2. Gas concentrations and dynamics

Most of the syngenetic, epigenetic and exogenetic processes that we believed to be important were introduced in the model. Considering that Ar may either be dissolved in brine inclusions or present in gas bubbles, the total concentration of Ar within each control volume of sea ice, C^{TAr}, is formulated as the sum of dissolved gas and gas bubbles:

$$C^{TAr} = C^{dAr} + C^{bAr} = e\zeta^{dAr} + C^{bAr} \tag{1}$$

where C^{dAr} is the bulk dissolved fraction of Ar, e is the brine volume fraction, ζ^{dAr} is the concentration of dissolved Ar in brine (with $e * \zeta^{dAr}$ in mmol m^{-3} of ice), and C^{bAr} is the contribution of gas bubbles to bulk concentration (in mmol m^{-3} of ice).

The total gas concentration in sea ice is in general controlled by physical and biogeochemical sources and sinks. For Ar, biological sources are nil, and therefore, we assume that the brine and bubble concentrations evolve in the following way:

$$\frac{\partial(e\zeta^{dAr})}{\partial t} = \frac{\partial}{\partial z}\left(eD\frac{\partial\zeta^{dAr}}{\partial z}\right) - Q\frac{\partial\zeta^{dAr}}{\partial z} - eS^{bub} \tag{2}$$

$$\frac{\partial C^{bAr}}{\partial t} = eS^{bub} + T^{bub} \tag{3}$$

The first two terms on the right-hand side of Eq. (2) express that the Ar dissolved in brine inclusions is transported similarly to salt. The first of these two terms represents the mixing of Ar by molecular diffusion and convection, while the second of these two terms represents the effect of flushing as in Vancoppenolle et al. (2010). D is an effective diffusivity, equal to the molecular (turbulent) diffusivity if Ra is sub (super-)critical. Q is the Darcy velocity associated with brine flushing (Vancoppenolle et al., 2010). More precisely, we consider a flux of melt water Q (of salinity 0) which enters the brine network through the uppermost layer of sea ice. With this formulation, depending on the direction of the sea ice-ocean Ar concentration gradient, Ar is either incorporated into or released from sea ice due to gravity drainage and expelled from sea ice due to percolation.

The third term on the right-hand side of Eq. (2), S^{bub}, specifies how bubble nucleation/dissolution extracts/releases dAr from/to the liquid phase. Brine volume fraction is present to ensure conservation of total Ar concentration. Gas bubbles are assumed not to follow brine dynamics; hence there are no brine transport terms in Eq. (3). The same S^{bub} term releases/extracts Ar into/from bubbles. A specific transport term T^{bub} accounts for buoyant gas bubble rise (see Section 2.4).

Finally, Ar is incorporated within sea ice through basal congelation. As in Vancoppenolle et al. (2010), the concentration of Ar in newly formed basal ice is assumed to be equal to the Ar concentration in seawater, C_wAr (see Section 2.5.1 for a description of C_wAr).