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Porosity of growing sea ice and potential for oil entrainment

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ABSTRACT

The pore space in the bottom-most layers of growing sea ice is directly connected to the ocean beneath, allowing for fluid exchange while providing a sheltered environment for sea-ice microbial communities. Because of its role as a habitat and its high porosity and permeability, potential entrainment of oil into this pore space is of broader concern. We estimate the ice volume that can potentially be infiltrated by oil and other buoyant pollutants in surface ocean water evaluating several years of sea ice measurements on undeformed landfast first-year sea ice at Barrow, Alaska. This ice is representative of undeformed sea ice in areas targeted for offshore oil development. The calculated ice volume is related to crude oil entrainment volumes with empirical relationships derived from field and laboratory measurements. We synthesize 12 years of sea-ice core salinity data and 6 years of quasi-continuous sea ice temperature profile measurements to derive the seasonal evolution of ice thickness and temperature gradients in sea ice. Porosity profiles are calculated from temperature and salinity profiles. Based on previous observations, an oil penetration depth is defined by a porosity threshold of 0.1 to 0.15. Ice thickness is found to increase from 0.6 m in January to its maximum of 1.5 m in May, and average temperature gradients at the ice–water interface range from −15 °C/m in January to −2 °C/m in May. Depending on ice temperature conditions, derived depths of fluid penetration range from 0.02 to 0.10 m in January to 0.12 to 0.25 m in May for a porosity threshold of 0.10. These penetration depths are approximately halved for a porosity threshold of 0.15. For average temperature conditions, expected entrainment of crude oil is less than 2 L/m^2 in January and may be as high as 5 to 10 L/m^2 in May. Accessible ice volume and entrainment potential are expected to increase during warm spells and with the opening of brine channel networks in late spring. Considering inhomogeneous spread and pooling of oil under ice, entrainment in warm sea ice is expected to add approximately 20% to previous estimates of the under-ice pooling capacity.

1. Introduction

Sea ice is a porous material that exchanges fluid with the underlying ocean during growth (e.g., Eide and Martin, 1975). This creates a small-scale marine environment that is both sheltered and connected to the ocean underneath. Thus, the bottom layers of sea ice are known to serve as a biological habitat (Cota and Smith, 1991; Gradinger et al., 2009; Krembs et al., 2000) but are also susceptible to entrainment and retention of oil spilled under the ice (e.g., Buist et al., 2008; Karlsson et al., 2011; NORCOR, 1975; Otsuka et al., 2004; Wolfe and Hoult, 1974). Most of the fluid exchange is confined to the region near the ice–water interface where the volume fraction and morphology of the pore space are challenging to quantify (e.g., Cox and Weeks, 1975; Krembs et al., 2000; Notz and Worster, 2008; Weissenberger et al., 1992). However, past field and laboratory measurements indicate that volume-averaged bulk oil entrainment is dependent on a porosity threshold that separates ice susceptible to infiltration from that that is not susceptible (e.g. Karlsson et al., 2011; NORCOR, 1975). Based on those observations and 12 years of measurements of physical properties of landfast, first-year sea ice at Barrow, Alaska, the accessible sea ice volume and potential entrainment volume of oil are estimated in this study. The focus of this study is on growing columnar ice with a lamellar ice–ocean interface, i.e. not including granular ice or thin sea ice, or ice with protruding platelets (Jeffries et al., 1995; Petrich and Eicken, 2010). Oil infiltration into this ice type has been investigated in field and laboratory experiments used in the present study (Karlsson, 2009; Karlsson et al., 2011; NORCOR, 1975).

Modes of interaction between oil and sea ice have been reviewed by Fingas and Hollebone (2003). Oil impinging on the underside of sea ice spreads laterally as a film or as discrete droplets. The lateral extent of spread is limited by the bottom topography of sea ice, which gives rise to the concept of pooling capacity (e.g., Wilkinson et al., 2007). Once the oil is stationary, a lip of sea ice will grow over the oil lens, encapsulating and immobilizing oil. Ice above the oil lens entrains oil into the connected brine pore space, such that the oil extends

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through the skeletal layer (the lowermost layer exhibiting high porosities and no mechanical strength) into the ice above and into brine channels. Dickins (1992) reviewed laboratory and field studies that investigated oil entrainment in sea ice. Summaries of more recent work were provided, among others, by Buist et al. (2008) and Dickins (2011). For the purpose of this study, the most relevant and detailed data on oil entrainment in ice are those of Martin (1979) and NORCOR (1975) for field work, and Karlsson et al. (2011) and Otsuka et al. (2004) for laboratory studies.

One of the first studies investigating the fate of oil released under sea ice from winter through spring was the NORCOR experiment in landfast first-year sea ice in the Canadian Arctic (Martin, 1979; NORCOR, 1975). It demonstrated that most of the oil spilled in fall and winter was entrained as lenses pooling under and then encapsulated in the ice. In spring, as the ice started to warm, oil began to migrate upward as brine channels increased in size. Eventually, oil reached the surface through discrete channels in May. As the ice continued to deteriorate, the oil progressively saturated the interstices within and between ice crystals. Oil continued to flow upward through the ice until surface ablation had fully exposed the level of initial oil-lens entrainment. The average concentration of oil in oil-saturated sea ice was 4.5%, with a maximum of 7% in a 4 cm section.

Recently, Karlsson et al. (2011) reported on results of laboratory experiments on oil entrainment in sea ice. They grew ice to approximately 0.15 m thickness, injected oil under the ice, allowed the oil lens to become encapsulated, raised the ambient temperature in some experiments, and then determined vertical profiles of oil concentration and ice properties. Including similar measurements of Otsuka et al. (2004), they found that samples with porosity above 0.1 contained oil, and that oil concentration maintained a maximum of approximately 5% by mass for porosities above 0.15. Results did not reveal differences between the 3 different crude oils used, or dependence on warming of the ice prior to excavation. Based on this prior work, we estimate bulk oil entrainment as a constant 4.5% by mass for ice of a porosity above a threshold that we consider to vary between 0.1 and 0.15. Hence, the present study explores the question as to how much oil may be retained in columnar (i.e., congelation) sea ice as a function of the distance of this porosity threshold from the ice–ocean interface. A further motivation for this study derives from the fact that recent work by Wilkinson et al. (2007) has led to improved estimates of oil pooling under sea ice but does not consider the entrainment and immobilization of oil into the high-porosity bottom sea ice layers. A comprehensive model of oil–ice interaction such as those reviewed by Reed et al. (1999), however, requires better estimates and parameterizations of immobilization of oil in the bottom layers. Such processes are also of importance in assessing the impact of oil on sea-ice microbial communities, which are typically concentrated in the very same subvolume of the ice cover.

2. Methods

To achieve the goals of this study, field measurements of sea ice bulk salinity and temperature profiles were used to calculate porosity profiles under different boundary conditions relevant in the context of oil release under sea ice. These profiles were interpreted in the context of previous work, relating the porosity profile to potential oil entrainment. Salinity data were available for 12 years while temperature profile time series were available for only 6 years. In order to obtain temperature profiles applicable for all cores and to aid in the development of parameterization schemes we devised three temperature scenarios for each day of the year (cold, average, and warm) and determined three corresponding porosity profiles for each of the salinity cores.

Ice sampling and characterization were carried out in level landfast sea ice in the Chukchi Sea at Barrow, Alaska, between Ukpeagvik Iñupiat Corporation Naval Arctic Research Lab (UIC-NARL) and Point Barrow. The landfast ice at this location is representative of undeformed level ice common in many of the regions targeted for offshore oil and gas development, in particular in the Chukchi and Beaufort Seas. Each year, a location approximately 0.5 to 2 km offshore near Barrow was chosen for repeat measurements. The investigated ice was level first-year ice that started to form between November and December and continued to increase in thickness until the end of May. Water depth was approximately 6 m. In general, a limited amount of snow melt took place in May and meltpond formation began in June (Petrich et al., 2012).

Sea ice cores for salinity determination were taken with a fiberglass core barrel (10 cm diameter) and immediately sectioned into vertical segments on site to minimize loss of brine from the ice (Eicken, 2010). 55 cores used in this study had a vertical sampling size at the bottom of approximately 0.05 m or less and were taken between 2000 and 2011. Of these cores, 8 cores were sampled at a vertical section thickness of 0.03 m or less.

Starting in the winter of 2005/6, an automated probe was used to record profiles of water and ice temperature in vertical intervals of 0.1 m (Druckenmiller et al., 2009). Measurements were performed at intervals of 5 to 30 min from January or February until June. In order to determine porosity profiles, the ice temperature profile is needed at the ice–water interface. We determined this profile by determining a best fit curve for adjacent thermistors as described below.

The complete set of salinity and temperature measurements is archived as part of the Seasonal Ice Zone Observing Network (SIZONet) and is available through the Advanced Cooperative Arctic Data and Information Service (ACADIS, http://www.aoncadis.org/; Eicken et al., 2008).

For the ice considered here, the temperature follows an approximately linear profile above the ice–water interface and is depth-independent below the ice–water interface (Petrich and Eicken, 2010). Deviations from the linear profile are most pronounced close to the ice surface where ice temperature responds quickly to air temperature variations and seasonal warming. Since this region is not of interest, the fitting algorithm was restricted to temperature data at least 0.4 m below the ice–snow interface, and no more than 1.0 m above the ice–water interface. For each temperature profile, least-square optimization was used to find the parameters T_w, z_{IF}, dT/dz, and d^2T/dz^2 of the equation

$$T(z) = \begin{cases} T_w & \text{for} \quad z - z_{IF} < 0 \\ T_w + \dfrac{dT}{dz}(z - z_{IF}) + \dfrac{d^2T}{dz^2}(z - z_{IF})^2 & \text{for} \quad z - z_{IF} \geq 0 \end{cases}, \tag{1}$$

where T is temperature, z is vertical position, $z - z_{IF}$ is the vertical position above the ice–water interface, T_w is the depth-independent water temperature, dT/dz is the temperature gradient above the ice–water interface ($dT/dz < 0$), and d^2T/dz^2 is the curvature of the ice temperature profile. Visual inspection showed that the second-order fit produces unrealistic results in the presence of strong temperature gradients early in the season. As a result, we performed a linear fit prior to day-of-year 65, i.e. $d^2T/dz^2 = 0$ was prescribed in Eq. (1). The time series of temperature measurements are available through ACADIS.

Temperature and salinity were used to calculate profiles of porosity, φ, from phase relationships given by Cox and Weeks (1983) and Leppäranta and Manninen (1988) (cf. Petrich and Eicken, 2010). An air content of 0 was assumed since the ice under consideration was below the freeboard line and we are only considering the pore space connected to seawater. Porosity profiles were calculated at 1 mm increments based on a linear temperature profile and bulk salinity measured at the corresponding depth.

Sea ice data from Barrow, Alaska, were related to oil-in-ice experiments in the Canadian Arctic and laboratory studies, all performed on structurally similar, columnar ice. Laboratory tank experiments were performed under quiescent conditions, and sea ice had a lamellar ice–ocean interface and crystal structure representative of undeformed