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Entrainment induced by near-inertial drift of sea ice and its impact on under-ice biogeochemical processes in marginal ice zones

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ABSTRACT

Mooring observation of hydrography, hydrodynamics and suspended particles distribution under a drifting sea ice revealed the mixing and entrainment pattern in the upper mixed layer (ML) of the marginal ice zone. The ice floe where the mooring system was installed drifted as near-inertial motion with approximately 12-h cycle. The mixing pattern induced by this near-inertial drift can be divided into two distinct regimes. First, simple entrainment (upward) fluxes from the seasonal pycnocline to sea ice–water boundary are induced by shear across ML and seasonal pycnocline during the period when ice floes drift toward pack ice. The entrainment speed was in the range of 0.25–2 m h^{-1}, which matches well with thickening and thinning of the ML during a near-inertial period. Turbulent wakes on the boundary between sea ice and open water occurred behind the advancing edge of ice. In the second regime, when ice floes drift toward open ocean, the turbulent wakes at the advancing edge of ice are combined with the entrainment caused by near-inertial motion, which results in a complex mixing pattern of both upward and downward fluxes in the ML. The echo intensity observed by the acoustic Doppler current profiler and beam attenuation from transmissometer revealed the elevated concentration of suspended particulate materials in the ML, which can be direct evidence visualizing the mixing pattern. Results suggest that the mixing and entrainment found in our study sustain particulate matters in suspension within upper ML for a few months. This may provide a potential mechanism to sustain abundant organic particulates in the ML and upper pycnocline for months after under-ice bloom. Under strong wind events like storms, the entrainment induced by near-inertial motion may also get enhanced, which causes elevated supply of nutrients from the deeper, permanent pycnocline to the ML.

1. Introduction

The central part of the Arctic Ocean is known to be strongly stratified during most of seasons, in particular, even stronger during spring and summer when meltwater is supplied from sea ice (Aagaard et al., 1981; Carmack and Melling, 2011). It forms an upper mixed layer (ML) with a thickness of 20 – 100 m (e.g., Rudels et al., 1996) overlying a strong pycnocline. The primary production in the ML of the Arctic Ocean is usually limited by nutrients, especially nitrogen supply, once sufficient light penetrates to the ML during early period of ice melting seasons (Lee and Whitledge, 2005; Tremblay et al., 2006, 2008; Lee et al., 2010, 2012; Wassmann and Reigstad, 2011; Popova et al., 2010, 2012, 2013). There are two main mechanisms supplying such nutrients to the ML of the Arctic Ocean: (1) horizontal advection of nutrient-rich seawater, mostly through Pacific and Atlantic inflows (Popova et al., 2012); and (2) vertical mixing caused by winter mixing (Reissmann et al., 2009), severe storms and internal waves eroding the pycnocline (McPhee et al., 2005), wind-driven upwellings near shelf breaks and sea-ice edges (Williams and Carmack, 2008; Mundy et al., 2009; Arrigo et al., 2012), and the turbulence wake following after passage of mesoscale eddies (Smith and Niebauer, 1993). In the central part of Arctic Ocean, where there exists less chances of lateral inflow, nutrients in the ML can be supplied

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mostly from layers below the pycnocline through such vertical mixing processes. Studies have shown that the dynamics of the vertical mixing directly influences on the primary production in the ML (Tremblay et al., 2006, 2008; Fer and Sundfjord, 2007). Recent intercomparison study of biophysical models also shows that the vertical mixing is one of the most fundamental factors controlling primary production in the Arctic Ocean given that sea ice concentration and thickness are similar among the models (Popova et al., 2012).

The ML is usually maintained in a turbulent state by surface wind stress and/or thermal convection. The turbulence of the ML diffuses into the underlying dense homogeneous layer, resulting in the erosion of the underlying stratification via so-called entrainment (Kato and Phillips, 1969; Kranenburg, 1984; Narimousa et al., 1986; Strang and Fernando, 2001; Nagai et al., 2005). This shear-induced entrainment mechanism drives the transport of momentum, heat and materials such as salinity and nutrients between the upper ML and lower pycnocline layer (Reissmann et al., 2009). Numerous studies show that velocity shear between the upper ML and pycnocline results in entrainment of heat and salt from below the ML in Arctic Ocean (McPhee et al., 1987; McPhee and Stanton, 1996; Skyllingstad and Denbo, 2001; Skyllingstad et al., 2003). Extensive observation and model results from Surface Heat Budget of the Arctic (SHEBA) program revealed that a significant portion (ca. 20%) of ocean-to-ice heat flux was supplied by the heat entrained from layers below the pycnocline (Holland, 2003; McPhee et al., 2005; Shaw et al., 2009). Recently, Toole et al. (2010) confirmed the importance of heat entrainment into the ML and its impacts on the variation of thermohaline stratification in the central Arctic Ocean. Most of studies have stressed on moment and heat fluxes, but very few studies have been focusing on the material transport including nutrients and organic/inorganic particulate materials via entrainment.

The marginal ice zone (MIZ), the boundary between sea ice and open water, is the most active area in both physical and biogeochemical aspects (Smith and Nelson, 1985, 1986; Morison et al., 1987; Mundy et al., 2009). Arrigo et al. (2012) reported massive phytoplankton bloom under sea ice in the Arctic MIZ during 2011 summer. Their results showed that the particulate organic carbon (POC) concentration was fourfold greater in the pack ice region than in open water. They argued that nutrient upwelling to support this under-ice blooming was driven by easterly winds. However, it is rather counter-intuitive how surface wind-driven upwelling would occur in the area covered by more than 90% of thick ice. If it were not the wind-driven upwelling, then what would be the main driver for the vertical supply of nutrients in the pack ice area of the Arctic Ocean?

In this study, we propose new plausible explanation for this question. For this, we provide visual evidence that shear induced by near-inertial sea ice drift would trigger the vertical mixing and entrainment processes. We present one-day mooring data observed at the sea ice station moving along and several stationary measurements on a 550-km long transect, where vertical variability of physical and biogeochemical properties was measured. Based on the analysis of these data, we will show the direct and indirect evidences of the entrainment processes, and how they evolve over the inertial period. The entrainment speed is estimated by applying an empirical relationship between entrainment rate and Richardson number. Then, the impact of this entrainment on physical and biogeochemical processes under the ice will be discussed at the end.

2. Data collection and analysis

International Research Team led by Korea Polar Research Institute (KOPRI) conducted Arctic Ocean Research Expedition (Cruise leg: ARA02B) using IBRV *Araon*. The expedition covered deeper part of Chukchi Sea including Chukchi Plateau during July 31 – August 20, 2011 (Fig. 1). At each hydrographic station, the castings of conductivity-temperature-depth (CTD) (SeaBird, SBE 911plus) system with additional probes (e.g., transmissometer, fluorometer, oxygen sensor, etc.) were conducted to measure the profiles of temperature, salinity, and other biochemical parameters.

Water samples for chlorophyll *a* (Chl-*a*) and nutrient concentrations were collected from standard depths (0, 10, 20, 30, 50, 80,

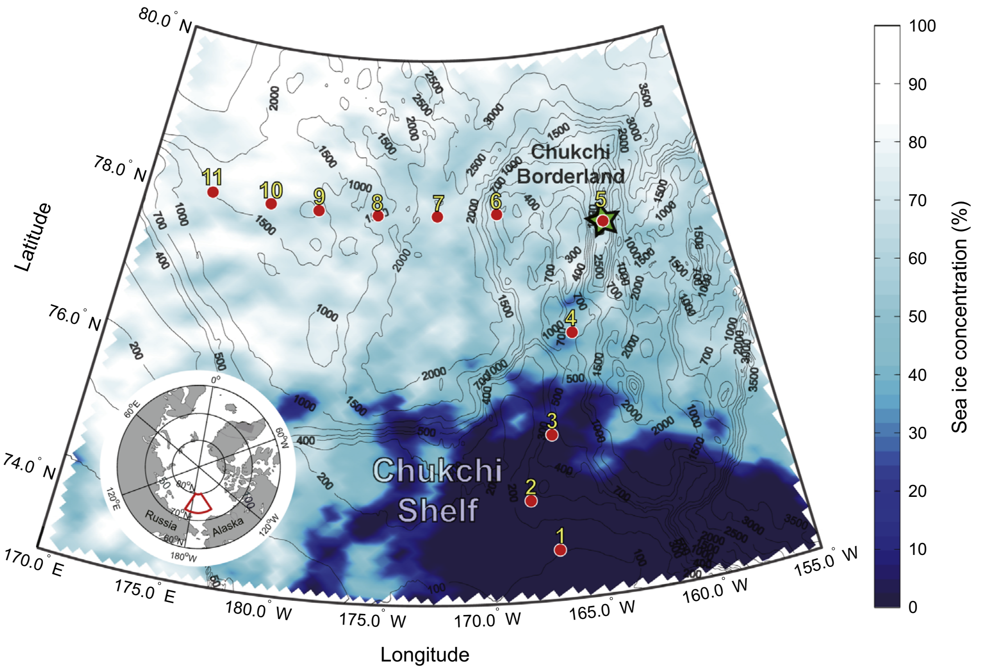

Fig. 1. Study area with bathymetry (in meter) overlain on the sea ice concentration on August 7, 2011 (Cavalieri et al., 2011). Numbers indicate the station numbers. The star indicates the initial position of sea ice experiment site.