Cold Regions Science and Technology 119 (2015) 158–169

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Under-ice eddy covariance flux measurements of heat, salt, momentum, and dissolved oxygen in an artificial sea ice pool

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form 2 June 2015
Accepted 29 June 2015
Available online 2 August 2015

Keywords:
Sea ice
Eddy covariance
Oxygen flux
Heat flux
Salt flux
Momentum flux

ABSTRACT

Turbulent exchanges under sea ice play a controlling role in ice mass balance, ice drift, biogeochemistry, and mixed layer modification. In this study, we examined the potential to measure under-ice turbulent exchanges of heat, salt, momentum, and dissolved oxygen using eddy covariance in an experimental sea ice facility. Over a 15-day period in January 2013, an underwater eddy covariance system was deployed in a large (500 m^3) in-ground concrete pool, which was filled with artificial seawater and exposed to the ambient (-5 to -30 °C) atmosphere. Turbulent exchanges were measured continuously as ice grew from 5 to 25 cm thick. Heat, momentum, and dissolved oxygen fluxes were all successfully derived. Quantification of salt fluxes was unsuccessful due to noise in the conductivity sensor, a problem which appears to be resolved in a subsequent version of the instrument. Heat fluxes during initial ice growth were directed upward at 10 to 25 W m^{-2}. Dissolved oxygen fluxes were directed downward at rates of 5 to 50 mmol m^{-2} d^{-1} throughout the experiment, at times exceeding the expected amount of oxygen rejected with the brine during ice growth. Bubble formation and dissolution was identified as one possible cause of the high fluxes. Momentum fluxes showed interesting correlations with ice growth and melt but were generally higher than expected. We concluded that with the exception of the conductivity sensor, the eddy covariance system worked well, and that useful information about turbulent exchanges under thin ice can be obtained from an experimental sea ice facility of this size.

1. Introduction

The eddy covariance method is a means of observing surface exchanges of energy, momentum, and mass. It is based on the premise that such exchanges can be calculated from high-frequency three-dimensional velocity measurements of turbulent flow within a fluid, in conjunction with other characteristics of the turbulence (e.g., temperature, mass concentration). In the atmospheric sciences, eddy covariance has underpinned much of modern micrometeorology theory (Lee et al., 2004), has contributed to parameterizations used in weather and climate models (e.g., Beljaars and Holtslag, 1991), and has informed a wide range of topics, including greenhouse gas exchange (e.g., Baldocchi, 2003) and air–sea interactions (Smith et al., 1996).

Despite its importance in atmospheric science, the use of eddy covariance in aquatic sciences has been less prevalent, which at first glance seems a paradox; the much higher viscosity of water produces slower moving eddies, which should be easier to measure across all turbulent scales of interest. However, the environments to which aquatic eddy covariance has typically been applied – the benthic and under-ice environments – are logistically difficult to access.

In benthic research, the use of eddy covariance has been largely divided between physical oceanographers, who have a longer history of its use (Bowden and Fairbairn, 1956), and ecologists who have recently ported the technique into their field of study (Berg et al., 2003). In physical oceanography, the technique is used to characterize turbulent momentum and heat fluxes, which in turn are important for modeling currents and energy balances (Shaw and Trowbridge, 2001; Trowbridge et al., 1999). In marine ecology, the primary focus has been on applying eddy covariance to measure dissolved oxygen fluxes across the sediment-water interface, providing an

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http://dx.doi.org/10.1016/j.coldregions.2015.06.018
0165-232X/© 2015 Published by Elsevier B.V.

estimate of net ecosystem exchange. The technique has been applied to a variety of coastal (Glud et al., 2010; Hume et al., 2011; Reimers et al., 2012) and freshwater environments (Brand et al., 2008; McGinnis et al., 2008) and has also been successfully used in the deep ocean (Berg et al., 2009).

To date, the application of eddy covariance to sea ice studies has largely focused on three areas: momentum transfer between the sea ice and the ocean, which is a critical component in understanding and modeling ice drift; heat transfer, which is important in understanding the energy balance and growth/melt rates of sea ice; and salt flux, which is important for understanding ice growth and decay, mixed layer stratification, and biogeochemical cycling. Such measurements have been made under multi-year ice (McPhee, 1992, 2002; McPhee et al., 2003), landfast ice (McPhee et al., 2008; Shirasawa et al., 1997; Widell et al., 2006), leads (McPhee and Stanton, 1996), and in the marginal ice zone (McPhee et al., 1987; Sirevaag, 2009). Very recently, the oxygen eddy covariance method has been applied to sea ice (Glud et al., 2014; Long et al., 2012) for the purpose of measuring under-ice oxygen transfer.

The ability to directly measure gas exchange under sea ice is exciting because it has the potential to improve understandings of ice–ocean biogeochemical processes. Brine dynamics and algae activity in the bottom ice environment are difficult to measure, but since both can drive under-ice oxygen fluxes, both can potentially be investigated by underwater eddy covariance. Bottom ice algae are known to produce some of the most intense chlorophyll maxima in any marine environment, and they provide a concentrated food supply to higher trophic levels in the ecosystem (Cota and Horne, 1989). Unfortunately, standard techniques of measuring ice algae productivity are time intensive, destructive, and complicated by the inherent “patchiness” of ice algae (Rysgaard et al, 2001). Long et al. (2012) have shown that under-ice eddy covariance measurements of O_2 flux can be used to measure ice algae primary production, potentially avoiding some of the pitfalls of conventional techniques. Measuring under-ice fluxes of oxygen also presents an interesting avenue for investigating gas dynamics associated with sea ice brine—the concentrated seawater that becomes trapped in the sea ice structure, or is released into the water column. The release of dense brine is an important process for many reasons, one being the potential to carry gases (which are also concentrated in brine) to depth, removing them from exchange with the atmosphere. This process has been identified as a key part of the Arctic marine carbon cycle (Rysgaard et al., 2007), but many questions about the dynamics of brine rejection and gas transport remain. These dynamics are also important during the melt season, where the release of meltwater with low oxygen content appears to dominate under-ice oxygen fluxes (Glud et al., 2014).

In this paper, we describe the development and deployment of an underwater eddy covariance system beneath artificial sea ice. The system is novel in its ability to coincidently measure fluxes of momentum, heat, salt, and oxygen, and should therefore provide unique insights into the couplings between physical and biogeochemical processes across the ocean–sea ice interface. The use of underwater eddy covariance in an experimental sea ice facility is also novel and provides an opportunity to test the system in a controlled and heavily instrumented environment. Given the confluence of a new instrument being deployed in a new environment, the focus of this paper is primarily methodological, with the objectives to test if (1) the eddy covariance system can provide reliable measurements of momentum, heat, salt, and oxygen fluxes, and (2) if such measurements in an experimental sea ice facility have any potential to improve our understandings of turbulent exchanges under sea ice.

2. The Sea-Ice Environmental Research Facility (SERF)

The Sea-Ice Environmental Research Facility (SERF) at the University of Manitoba (Winnipeg, Canada) is an in-ground concrete pool (Figs. 1 and 2) with dimensions of 23.3 m (length) × 9.2 m (width) × 2.75 m (depth). It is filled each year with artificial seawater formulated on site to closely replicate the chemistry of Arctic surface seawater (see Hare et al., 2013, and Rysgaard et al., 2014, for exact composition). The facility is outdoors, and weather conditions in the region are conducive to sea ice growth for several months every winter. The sea ice can be melted periodically by circulating heated ethylene glycol through a closed-loop hose located on the bottom of the pool, allowing successive ice growth/melt experiments to be carried out during a sampling season. The experiment described herein was initiated from open water conditions on January 13, 2013, by turning off the heater. Sea ice was allowed to grow until January 26, when the heater was switched back on. The pool was essentially ice free on January 30, when the experiment was terminated.

SERF can be instrumented with a wide range of sensors designed to monitor the physical conditions across the seawater–sea ice–atmosphere interface. The relevant instruments deployed during the January 2013 experiment are shown in Fig. 2. Atmospheric temperature and relative humidity were measured at 2 m above the surface of the pool using a Vaisala HMP45C probe enclosed in a vented sun shield. A type-T thermocouple array measured temperatures in the sea ice and underlying seawater at 2 cm intervals for the top 0.6 m, 5 cm intervals from 0.6 to 1 m depth, and 10 cm intervals thereafter. Salinity was measured in the seawater using six Aanderaa 4319 conductivity sensors at 0.3, 0.6, 1.0, 1.75, and 2.45 m depth.

Ice samples (collected using ceramic knives or a Kovacs Mark II coring system depending on ice thickness) and water samples (using a Cole Palmer, Masterflex-Environmental sampler peristaltic pump equipped with PTFE tubing) were also obtained periodically through the experiment. Samples were only taken from a confined area located “downstream” of the eddy covariance equipment (Fig. 2) to minimize effects on the turbulence measurements. Dissolved oxygen at the ice-water interface was measured using the Winkler titration method, and bulk ice oxygen concentration was analysed by gas chromatography after extraction of the gas phase from the ice using the dry-crushing technique as developed for continental ice (Raynaud et al., 1982). Chlorophyll-*a* (Chl_a) was measured fluorometrically on bulk ice samples melted in filtered seawater (3 parts water to 1 part ice) and calculated following Parsons et al. (1984).

To induce a consistent current in the pool, four 375 W pumps were placed on the bottom at each of the corners (Fig. 2). The pumps were configured to draw water from their base and then propel it outward parallel to the bottom of the pool. For the experiment described here, the pumps were oriented successively at right angles to one another, which created a counterclockwise circulation of 2–3 cm s^{-1} near the surface. In order to establish the initial ice cover the circulation was not turned on until January 14, which effectively started the eddy covariance experiment.

3. The MicroSquid eddy covariance system

To measure turbulent exchanges beneath sea ice grown at SERF, we used a MicroSquid eddy covariance system (Fig. 3), custom-built for our purposes by Rockland Scientific International (RSI). The system is designed around a Nortek Vector acoustic Doppler velocimeter (ADV), which provides high-resolution, high-frequency measurements of current velocity in three dimensions. The system also makes high-frequency measurements of temperature using a microbead thermistor (model FP07, RSI, herein μT), conductivity using a dual needle platinized electrode cell (model SBE-7, Sea-Bird Electronics, herein μC), and dissolved oxygen (DO) using a galvanic oxygen microsensor (AMT Analysenmesstechnik GmbH, herein μDO). The analog signals of three-dimensional current velocity, temperature, conductivity, and DO are sent to a data logger, which records the signals at a frequency of 512 Hz.

The system was designed with careful attention to signal-to-noise ratio and sensor response rate. In seawater, fluctuations in vertical