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Circulation and water properties in the landfast ice zone of the Alaskan Beaufort Sea

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ABSTRACT

Moorings, hydrography, satellite-tracked drifters, and high-frequency radar data describe the annual cycle in circulation and water properties in the landfast ice zone (LIZ) of the Alaskan Beaufort Sea. Three seasons, whose duration and characteristics are controlled by landfast ice formation and ablation, define the LIZ: "winter", "break-up", and "open-water". Winter begins in October with ice formation and ends in June when rivers commence discharging. Winter LIZ ice velocities are zero, under-ice currents are weak ($\lesssim$5 cm s^{-1}), and poorly correlated with winds and local sea level. The along-shore momentum balance is between along-shore pressure gradients and bottom and ice-ocean friction. Currents at the landfast ice-edge are swift (~35 cm s^{-1}), wind-driven, with large horizontal shears, and potentially unstable. Weak cross-shore velocities (~1 cm s^{-1}) imply limited exchanges between the LIZ and the outer shelf in winter. The month-long break-up season (June) begins with the spring freshet and concludes when landfast ice detaches from the bottom. Cross-shore currents increase, and the LIZ hosts shallow (~2 m), strongly-stratified, buoyant and sediment-laden, under-ice river plumes that overlie a sharp, ~1 m thick, pycnocline across which salinity increases by ~30. The plume salt balance is between entrainment and cross-shore advection. Break-up is followed by the 3-month long open-water season when currents are swift ($\geq$20 cm s^{-1}) and predominantly wind-driven. Winter water properties are initialized by fall advection and evolve slowly due to salt rejection from ice. Fall waters and ice within the LIZ derive from local rivers, the Mackenzie and/or Chukchi shelves, and the Arctic basin.

1. Introduction

Wind stresses and buoyancy fluxes influence circulation and water property modifications on all continental shelves, particularly over the inner shelf. On arctic shelves, these influences are modulated by the annual freeze/thaw cycle, which controls the phasing and duration of river discharge and landfast ice. Landfast ice becomes bottom-fast in waters shallower than approximately 1.5 m, but typically extends offshore to about the 20 m isobath and is held in place by grounded ridges (Reimnitz, 2000; Mahoney et al., 2007a). Over the broad and gently sloping Eurasian shelf seas the width of the landfast ice zone (LIZ) can be ~100 km (Zubov, 1945; Wadhams, 1986; Morris et al., 1997; Eicken et al., 2005a), while on the narrower Beaufort Sea shelf it is more typically ~20–40 km (Reimnitz and Kempema, 1984; Barnes et al., 1984; Macdonald and Carmack, 1991; Mahoney et al., 2014). Approximately 25% of the Alaskan Beaufort Sea (ABS) shelf is covered by landfast ice for ~9 months (October – June). Landfast ice is effectively immobile and inhibits air-sea heat and momentum transfers while also providing a frictional boundary for the under-ice flow. Consequently, the ice is expected to have an important influence on the circulation characteristics of the inner shelf. For convenience, we refer to the inner shelf as where water depths are $\leq$~20 m. This definition differs from one defined by dynamic processes; i.e., that portion of the shelf over which the surface and bottom boundary layers overlap (Lentz, 1995; Li and Weisberg, 1999). A dynamically-based definition is difficult to apply in landfast ice regions where the surface and bottom boundary layers appear thin (Kasper and Weingartner, 2012) and where there is extreme seasonality in the circulation characteristics.

Frictional coupling between landfast ice and the ocean is poorly understood because it depends on the under-ice topography and current

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speed, both of which may vary considerably with space and time (Shirasawa and Ingram, 1997; McPhee, 1990; Lu et al., 2011). For example, on windward shelves, such as the ABS, the seaward boundary of the LIZ is highly deformed due to collisions with the mobile pack ice. Deformation is an integral part of the seasonal development of the LIZ (Mahoney et al., 2007a). Ridging intensity and keel depths vary alongshore and generally increase offshore and through the freezing season (Tucker et al., 1979). Ice keels can gouge the seafloor (Barnes et al., 1984) and form grounded, rubbled ice, or stamukhi (Zubov, 1945), within and at the edge of the LIZ. The stamukhi protects the inner shelf from pack ice (Reimnitz and Kempena, 1984), inhibits water exchange between the inner and outer portion of the shelf (Macdonald and Carmack, 1991), and, under appropriate wind conditions, may be bounded offshore by a flaw lead wherein new ice rapidly forms (Melling, 1993; Dmitrenko et al., 2005; Itkin et al., 2015). In addition to the seasonal changes in the LIZ, processes influencing deformation (including landfast ice breakout events) can occur on time scales of hours to days and spatial scales of a few to hundreds of kilometers (Overland and Pease, 1984; Eicken et al., 2011).

The LIZ is an important sub-region of the Arctic Ocean because it is the initial processing site for the freshwater and the dissolved and particulate loads discharged by the massive rivers emptying into the Arctic Ocean. As such the LIZ serves as the Arctic's "estuary" (Macdonald and Carmack, 1991; McClelland et al., 2012; Itkin et al., 2015). It also supports a unique biological habitat (Dunton et al., 2012, 2006), is critical to subsistence cultures, and is the site of marine industrial activities. At present, little is known about LIZ circulation processes, but a warming Arctic, and attendant changes, will affect the LIZ. Although the work reported herein was motivated to guide potential oil spill responses within the LIZ of the ABS, our measurements shed light on physical processes not only within the ABS LIZ, but perhaps on other arctic shelves as well.

Few moored measurements have been made within the LIZ because of ice risks to shallow moorings. We know of only two reported wintertime current measurements from within the LIZ of the ABS and the results are contradictory. Aagaard (1984) concluded that current speeds within the LIZ seldom exceed 10 $cm\text{-}s^{-1}$, whereas Matthews (1981) argued from continuity considerations that speeds of up to 35 $cm\text{-}s^{-1}$ might occur occasionally. Both conclusions were tentative because they were based on short duration measurements from instruments moored close to the seabed.

Our measurements were made primarily in the vicinity of Prudhoe Bay, about midway along the ABS coast (with additional moorings in Smith and Camden Bays; Fig. 1a). The ABS shelf is ~80 km wide and extends ~600 km eastward from Barrow to the Mackenzie shelf. The bottom grades smoothly from the coast toward the shelfbreak with a bottom slope of $\sim 8 \times 10^{-4}$ shoreward of the 100 m isobath. Although ice can cover the shelf year-round, more typically the inner shelf is ice-free from mid-July to mid-October. Based on archived National Weather Service records from Barrow and the climatology of Brower et al. (1988), westward (upwelling-favorable) winds predominate in all months, and especially from September through June. In July and August upwelling-favorable winds occur only slightly more frequently than downwelling winds. There has, however, been an appreciable increase in the frequency and duration of westward wind events over the ABS over the past two decades (Schulze and Pickart, 2012; Brugler et al., 2014). A few medium-sized (1–10 $km^3\ yr^{-1}$) and numerous small arctic rivers enter the ABS along Alaska's North Slope. These drainages are entirely underlain by permafrost. Consequently, the annual river discharges, and especially the spring freshet, are brief due to rapid snowmelt and because the watersheds are completely frozen in winter, partially thawed for a brief period in summer, and do not support appreciable groundwater flow.

The purposes of this paper are to characterize and understand the processes that control the seasonal evolution of water properties and circulation over the inner shelf of the ABS with an emphasis on the landfast ice season. We also characterize the along- and cross-shore circulation and sea-level correlation scales and, where appropriate, compare these results with dynamical models of the LIZ under-ice circulation. The results should broaden our understanding of seasonality in this under-sampled portion of the Arctic Ocean and allow better insights on potential impacts on the LIZ associated with a warming Arctic. Our description is based on various data sets collected by different methods in different years as discussed in Section 2. In Section 3 we first provide an overview of the annual cycles of sea ice, currents, and water properties. We next examine several kinematic and dynamic aspects of the winter landfast ice season, explore aspects of the circulation at the landfast ice edge, and then describe features of under-ice freshwater plumes. Section 4 constitutes a discussion and summary of the results.

2. Methods

Our data derives mainly from seafloor-mounted oceanographic moorings *Dinkum*, *Reindeer*, and *Cross* deployed (Fig. 1b) in and offshore of Stefansson Sound in various years between 1999 and 2006. All moorings carried acoustic Doppler current profilers (ADCPs) and temperature/conductivity/pressure (T/C/P) recorders and some included transmissometers. Along-shore coverage was available in two years (2004–2006) from *Camden* deployed in Camden Bay (~120 km east of *Dinkum*) and in one year (2004–05) from *Smith* deployed in Smith Bay, ~235 km to the west of *Dinkum* (Fig. 1a). Deployment depths ranged from 7 to 17 m. *Dinkum* was the only mooring common to all years. The mooring positions, sensor packages, and bottom depths at each mooring used here are listed in Table 1. Sampling intervals were hourly or shorter. The moored data are supplemented with hydrographic measurements obtained during break-up in June 2001 and from late May to early June 2006, surface current measurements obtained during the open water season from a high-frequency radar (HFR) system in fall 2006, and from satellite-tracked drifters in August 2014. We also use the trajectories of several drifters deployed in the Chukchi Sea in fall 2012, which over-wintered in the LIZs of the ABS and Mackenzie shelf.

Moored instruments were mounted on compact frames constructed from fiberglass stock or Oceanscience Sea Spider stands. To limit the risk from ice keels, the top of the frames (ADCP transducers) were ~0.5–1.0 m above the seabed. Currents were measured with either a 1200 or 600 kHz Teledyne-RDI ADCP set in a gimbaled collar on the frame. The latter ensured that the ADCP remained vertical should the frame tilt from the horizontal by 20° or less (tilt sensors all indicated that the ADCPs remained level throughout their deployments except as noted). We used 0.5 or 0.25 m bin sizes on these upward-looking ADCPs. Ancillary instruments (Seabird, Inc. SBE16 SeaCats) and an acoustic release, which controlled a float and line used for recovery, were attached to the frames, each ballasted with 90 kg of lead. The design succeeded insofar as only 2 of 19 moorings deployed over the years were struck by ice (in one case with little damage to the instruments). One design problem is that the conductivity cells and acoustic release were within 20–30 cm of the seabed and thus affected by sediment re-suspension. The release mechanism was often impacted by sediments necessitating recovery by divers. Later deployments using vertically-oriented releases having the trigger mechanism held farther off the seafloor were more reliable. Bottom sediments, re-suspended by fall storms, infiltrated some of the conductivity cells rendering the salinity estimates unreliable over the remainder of the record. Finally, and in spite of the ballast, waves and currents associated with a severe storm in October 2006, inverted the *Dinkum* mooring and moved the *Cross* mooring about 200 m to the southwest of its original location. While the ADCP functioned well throughout the remainder of the *Cross* deployment, its conductivity cell was compromised by sediments.

Pre and post-calibrations of the T/C/P recorders were compared and incorporated in computing final values. Salinity was also compared with the freezing point from winter records. We estimate that the