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14. ABSTRACT

This project supported Mr. Samuel Brenner, a graduate student in the University of Washington Oceanography program.

The decreasing trend in minimum sea-ice extent in the Arctic Ocean has been a topic of concern with far reaching effects. Particularly near the Marginal Ice Zone (MIZ), mix of ice and open water, combined with variations in ice surface and keel roughness, lead to a complex balance that varies over short spatial and temporal scales. Ocean properties and air-ice-ocean fluxes are therefore highly heterogeneous near the ice. This project linked several data sets and approaches from recent ONR projects, focusing on the air-sea-ice interactions near the ice edge. Sam's work involved a combination of the analysis of existing observational data and numerical modeling to study sub-mesoscale dynamics and air-ice-sea feedback processes in the Arctic Ocean.

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Early Student Support for Studies of Small-scale upper ocean variability and surface Forcing in the Arctic Ocean

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Long-term Goals

The decreasing trend in minimum sea-ice extent in the Arctic Ocean has been a topic of concern with far reaching effects. At least seasonally, there are good reasons to believe that the Arctic Ocean will become a more active ocean, with larger surface waves and larger area exposed to summer solar and wind forcing. Particularly near the Marginal Ice Zone (MIZ), mix of ice and open water, combined with variations in ice surface and keel roughness, lead to a complex balance that varies over short spatial and temporal scales. Ocean properties and air-ice-ocean fluxes are therefore highly heterogeneous near the ice. This project links several data sets and approaches from recent ONR projects, focusing on the air-sea-ice interactions near the ice edge. The fine and sub-mesoscale processes considered in our project are important for the evolution of the Arctic system, but are often poorly resolved in observations and ignored in numerical models

This project supported Mr. Samuel Brenner, a graduate student in the University of Washington Oceanography program. His work involved a combination of the analysis of existing observational data and numerical modeling to study sub-mesoscale dynamics and air-ice-sea feedback processes in the Arctic Ocean.

Accomplished

Sam Brenner defended his Ph.D on May 23rd 2022 and graduated in June 2022 (Brenner, 2022). This grant supported him through the last several years of his graduate studies. Sam is mature and well organized, and has only grown more confident, more skilled, and more curious during his tenure as a Ph.D. graduate student.

Ice edge fronts

As part of his Master's, Sam published results from a study of frontal dynamics at the ice edge. Sharp contrasts in ice cover fraction and ice properties create small-scale buoyancy, heat, and momentum forcing which have an important signature in upper ocean properties. In turn, the structure of the ocean also modulates ocean-ice-atmosphere fluxes. Similarly, small-scale currents modify the surface wave field, which should also impact the wind stress.

Highly-resolved temperature and salinity sections across the ice edge collected during recent ONR programs in the Arctic show strong fronts at the ice edge, where the warm water from ice-free regions meets the cold water found under ice. This is particularly true in late September, when ice is advancing. For example, the recovery cruise at the end of September 2014, on R/V *Norseman II,* provided us with an opportunity to conduct over two days of very high-resolution sampling of the region near the ice edge (Fig. 1). Sections of temperature and salinity extending from the ice edge roughly 15 km into open water sampled by the Underway CTD. Profile spacing ranges from about 200 m near the ice to a little under 1 km further away. A time series of sections was collected to capture the time evolution of the sharp temperature-salinity front that marks the ice edge. Fresh and cold water are found within 5 km of the ice edge, a front that persisted through the two days this region was sampled.

With direct estimates of the structure and time evolution of near-ice properties, the MIZ and SeaState observations are an important reference data set for ongoing and future observational or numerical experiments of sub-mesoscale instabilities and frontal dynamics in the Arctic (e.g., Thomas et al., 2016; Zippel and Thomson, 2016; Manucharyan and Thompson .2017).

Multiple across-drift sections show that the front rapidly evolves over an approximately 12 to 18 hour period on Oct.~03 (Fig. 2). The front steepens over a time period of a few hours with the slope reaching a maximum at approximately 10:00Z on Oct.~03, then subsequently collapses over a period of roughly 4 hours. The qualitative pattern of steepening and collapse is robust across a broad range of isopycnals, as demonstrated by the 21.65 and 21.85 isopycnal slope. The magnitude of the change in slope depends on the specific choice of isopycnal. The bulk estimate of slope (based on the ratio of lateral and vertical buoyancy gradients) generally agrees with the slope of 21.65 isopycnal.

The initial steepening and subsequent collapse divide the frontal evolution into a frontogenic phase followed by a frontolytic phase (as indicated in Fig. 2). A comparison of SAR images prior to the survey and at the end of the survey show a change in character of the ice edge (Fig 3). Prior to the survey (Sept.~29; Fig 3a) the ice edge was generally compact. There was considerable deformation of the ice edge during the surey, and a SAR image from late on Oct.~03 (Fig 3b) shows that this deformation resulted in a number of coherent filaments and vortical structures over a wide range of scales.Within the MIZ, sea ice is particularly mobile (Lund et al., 2018) and can act as tracer for surface ocean currents (e.g., Manucharyan and Thompson, 2017), so this deformation indicates the development of an ocean eddy field.

SODA data processing

As the core of his doctorate degree, Sam analyzed data collected from the SODA moorings. Upward looking 5-beam acoustic Doppler current profilers installed on the top float of each mooring provide measurements of ocean velocity, ice velocity, and ice draft as they evolve over an annual cycle and a wide range of ice conditions (Fig. 4).

Sam developed techniques to infer details of the surface mixed layer from the ADCPs installed on the SODA moorings. The details of the processing, and resulting mixed layer depth and temperature time series are presented in a paper in press in the *Journal of Atmospheric and Oceanic Technology* (Brenner et al. 2022).

Ice-ocean drag coefficients

Sam used the SODA measurements to calculate the ice-ocean drag coefficient using a force balance approach. The SODA moorings also provide estimates and statistics of ice geometry.

Ultimately, accurate prediction of sea ice drift requires an understanding and description of the momentum transfer at the ice-ocean interface. While many sea ice models use a constant value for the ice-ocean drag coefficient based on historical observations from ice-stations, modern observations show that the drag coefficient is highly variable with strong seasonal signals. In his work, Sam evaluated parameterization schemes variable ice-ocean drag coefficient (Fig 5). Comparison of the observed and parameterized values of the ice-ocean drag coefficient showed that parameterization schemes are generally able to reproduce both the seasonal and spatial variations.

This work has been published in Journal of Geophysical Research, Oceans (Brenner et al., 2021)

Momentum in the Surface Mixed Layer.

Finally, Sam used the observations of sea ice and the upper ocean from three SODA moorings to quantify atmosphere-ice-ocean momentum transfer, with a particular focus on the inertial-frequency response. In results available in his dissertation (Brenner 2022) and submitted to the Journal of Physical Oceanography, Sam calculates seasonal variations in the strength of mixed layer inertial oscillations and shows that sea ice damps momentum transfer from the wind to the ocean, such that the oscillation strength is minimal under sea ice cover (Fig 6).

In this work, the mooring measurements were interpreted with a simplified one-dimensional ice-ocean coupled ``slab'' model, providing insight into the drivers of the inertial seasonality: namely, that a combination of both sea ice internal stress and ocean ML depth contribute to the seasonal variability of inertial surface currents and inertial sea ice drift, while under-ice roughness does not.

Training

Nothing to report

Dissemination

Nothing to report.

Honors

Nothing to report

Tech Transfer

Nothing to report

Participants

Sam Brenner

Luc Rainville

Jim Thomson

Students

Sam Brenner started his Ph.D. in the Physical Oceanography program at UW in Sept. 2017. Sam has been working on data from the MIZ, SeaState, and SODA DRIs. He participated to the 2018 and 2019 field campaigns on USCGC Healy. He graduated in June 2022.

Products

Brenner S., L. Rainville, J. Thomson, and C.M. Lee. 2020. The evolution of a shallow front in the Arctic marginal ice zone. *Elem Sci Anth*, 8(1), p.17.
DOI: http://doi.org/10.1525/elementa.413

Brenner, S., Rainville, L., Thomson, J., Cole, S., & Lee, C. (2021). Comparing observations and parameterizations of ice-ocean drag through an annual cycle across the Beaufort Sea. Journal of Geophysical Research: Oceans, 126, e2020JC016977. https://doi.org/10.1029/2020JC016977

Brenner S., 2022. The role of sea ice in mediating atmosphere-ice-ocean momentum transfer. University of Washington Doctoral Dissertation. http://hdl.handle.net/1773/49108

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Lund B, Graber HC, Persson POG, Smith M, Doble M, et al. 2018. Arctic Sea Ice Drift Measured by Shipboard Marine Radar. J Geophys Res C: Oceans 123 (6): 4298–4321. ISSN 2169-9275. doi:10.1029/2018JC013769

Manucharyan G. E, Thompson AF. 2017. Submesoscale Sea Ice-Ocean Interactions in Marginal Ice Zones. J Geophys Res C: Oceans 122(12): 9455–9475. doi:10.1002/2017JC012895.

Thomas, L. N., J. R. Taylor, E. A. D’Asaro, C. M. Lee, J. M. Klymak, and A. Shcherbina, 2016: Symmetric instability, inertial oscillations, and turbulence at the gulf stream front. Journal of Physical Oceanography, 46 (1), 197–217.

Zippel S, Thomson J. Air-sea interactions in the marginal ice zone. Elem Sci Anth. 2016;4:95

FIGURES

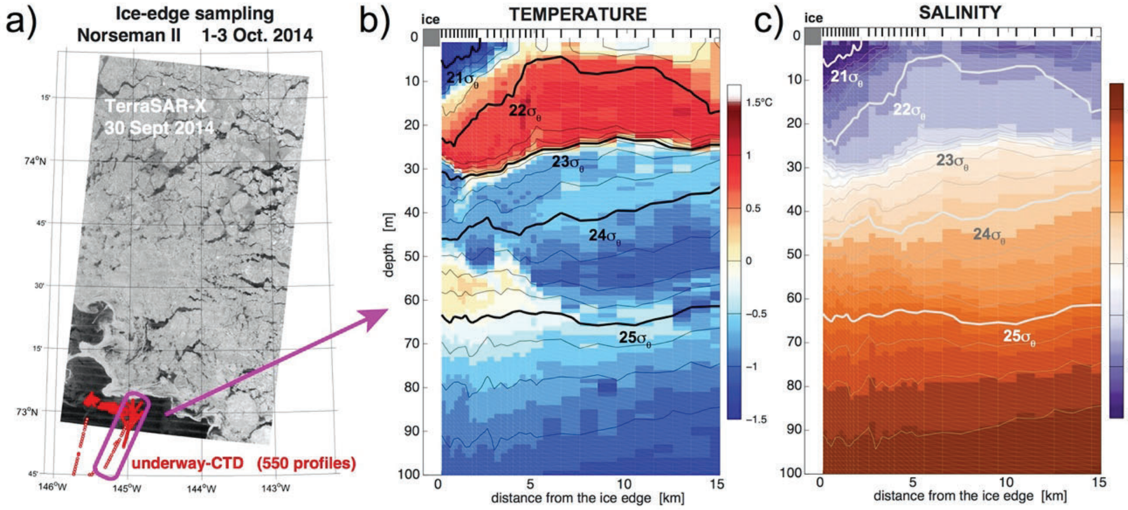

Figure 1. Temperature and salinity from the ice edge to about 15 km away, sampled by the underway CTD during the Norseman II cruise (02 Oct 2014) near the ice edge (a). Profile locations (36 casts) are indicated on the top axes. Potential density is contoured. Note the sharp temperature and salinity front near the ice edge.

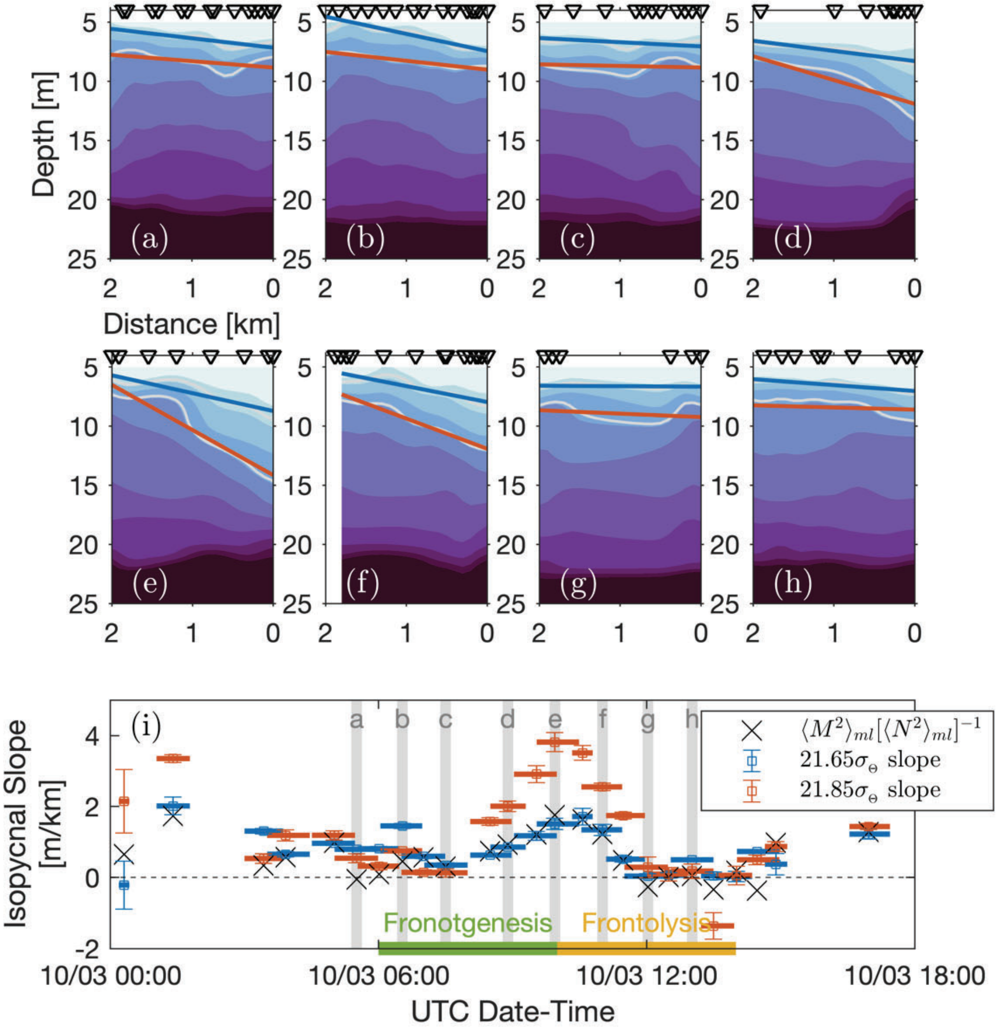

Figure 2: (a-h) Example density sections. Grey contours show the 21.65 and 21.85 contours and linear fits to those contours are shown by the blue and orange lines, respectively. Triangles at the top of each section show the locations of the uCTD casts. Distance is the across-drift distance relative to the start of each section (with 0 being nearest to the ice, and moving towards open water as distance increases). (i) Timeseries of the bulk isopycnal slope and slopes of the linear fits of 21.65 and 21.85 isopycnals for all sections. Vertical error e measures show the 95% uncertainty, horizontal bars show the range of time over which uCTD casts corresponding with each section were taken. Vertical grey bands indicate which sections are shown in (a-h), as labeled. Labeled green and yellow bands along the bottom of the figure demarcate the frontogenic and frontolyic phases of evolution.

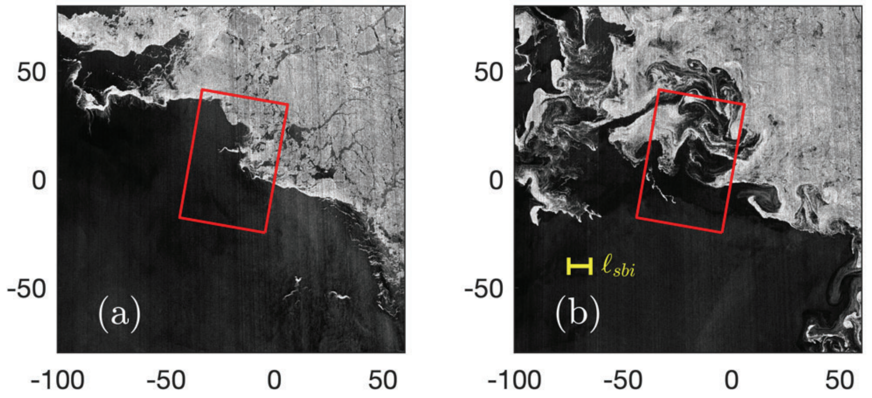

Figure 3: SAR image of the MIZ in the vicinity of the survey on (a) Sept.~29, 16:37Z and (b) Oct.~03, 16:20Z. The red rectangle represents region where the observations were collected. The yellow line shows the length of the 10-km eddy scale predicted for the MLE field

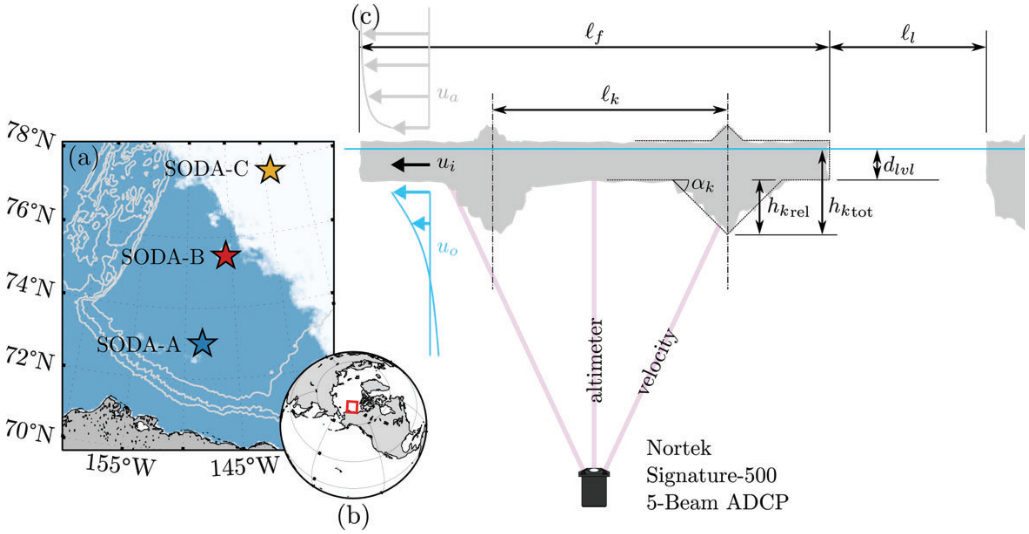

Figure 4: (a,b) Location of the three SODA moorings and (c) schematic of the instruments and ice geometry estimates.

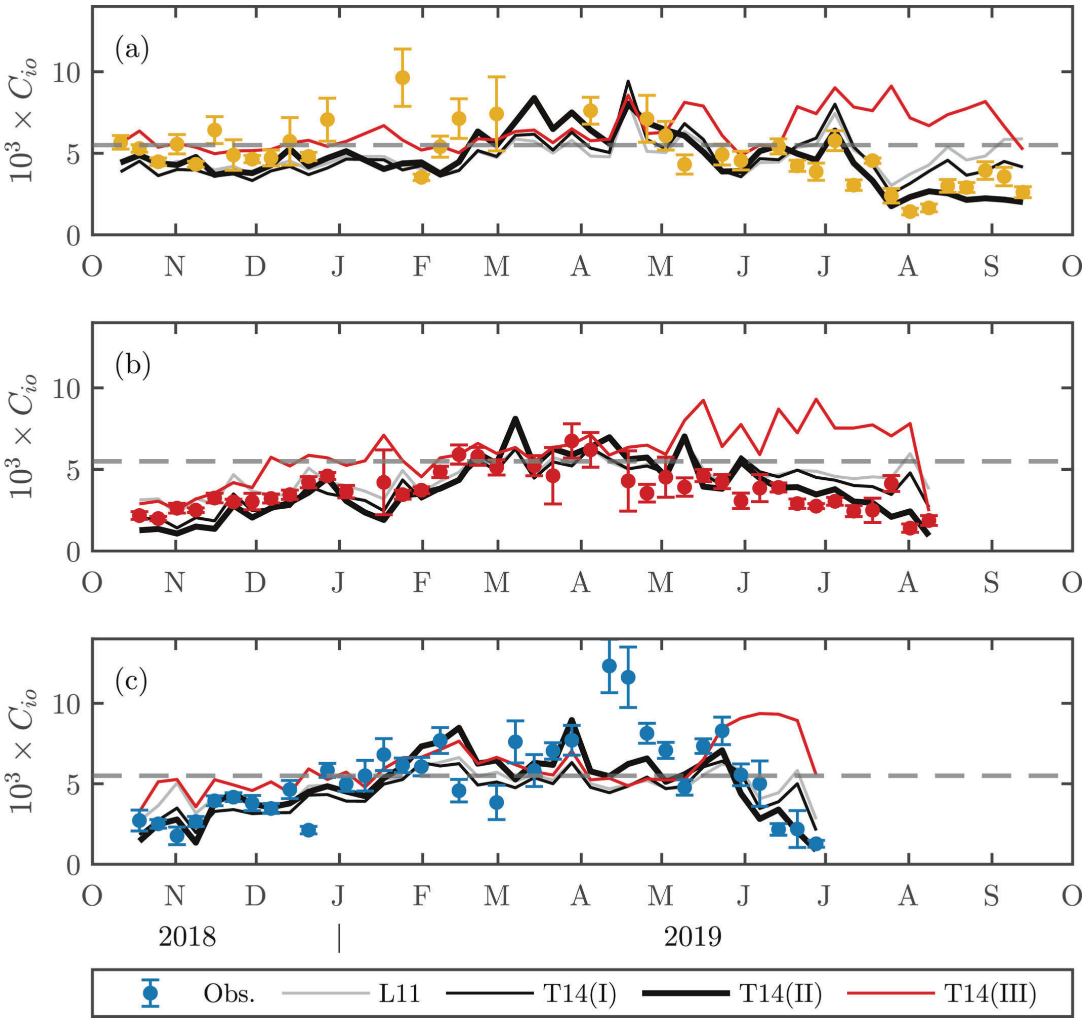

Figure 5: Timeseries of ice-ocean drag coefficients from north-to-south: (a) SODA-C, (b) SODA-B, and (c) SODA-A. In each panel, points with error-bars show the values of C_{io} calculated with the force-balance approach (labeled "Obs".), while lines correspond to the different variations of parameterization schemes

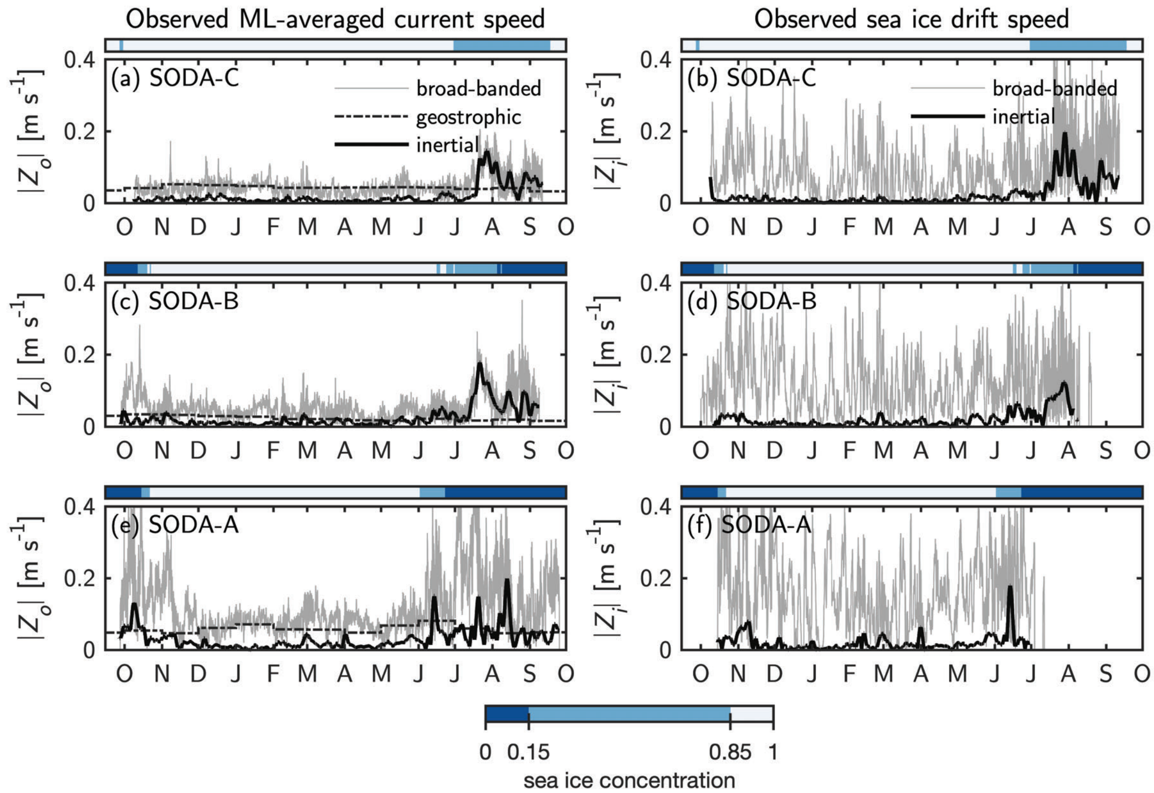

Figure 6. Timeseries of (a,c,e) observed ML-averaged current speeds, and (b,d,f) observed sea ice drift speeds, from each of the moorings: (a,b) SODA-C; (c,d) SODA-B; and (e,f) SODA-A. Lighter coloured, thin lines in all panels show the broad-banded speeds while thicker darker lines show the inertially-filtered signals. Dash-dotted lines in (a,c,e) show the gyre-scale geostrophic current speed from dynamic ocean topography. Coloured bars along the top of each panel show the sea ice concentration