Submesocale flows sustained by sea-ice meltwater in the Antarctic Marginal Ice Zone

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Introduction

Around Antarctica, sea-ice forms a thin (~1m) insulative layer over the ocean's surface, which, at its maximum, covers an area of ~19 million km^2, retreating to an area of ~3.1 million km^2 in summer (Parkinson 2014). This annual cycle is thought to play a critical role in the climate system

When the spring melt out of sea-ice occurs, a mass of freshwater (more than 15 trillion liters) is rapidly, reintroduced into the surface waters. The resulting net freshening and lightening of the mixed layer marks the beginning of summer re-stratification in the now ice-free Marginal Ice Zone.

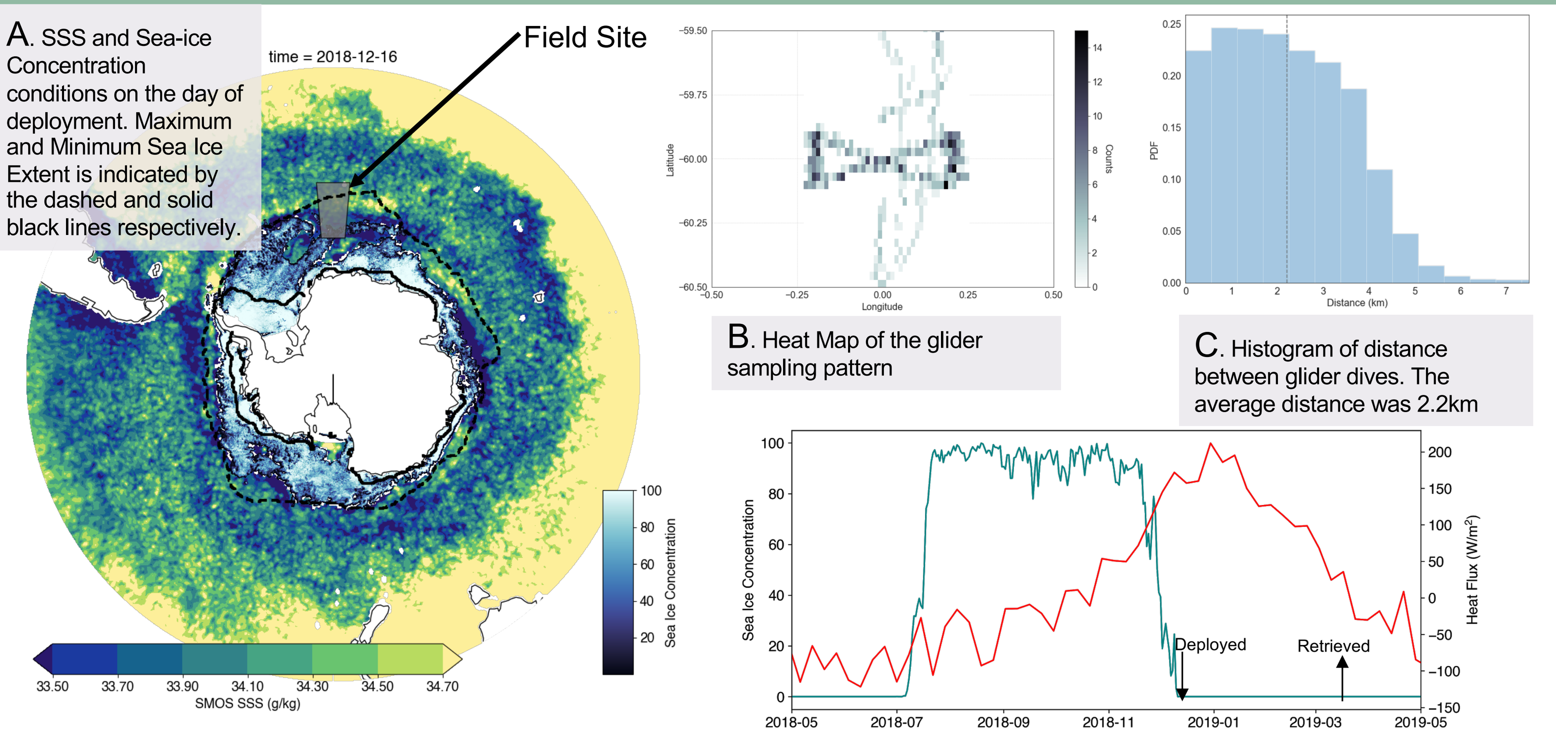
The freshwater from sea-ice melt is not only a vertical process, but the lateral gradients introduced from ,e.g., non-uniform melt and northwards Ekman transport, adds a lateral component to the mixed layer and carries the signal of melted sea-ice well beyond the marginal ice edge.

Submesocale ageostrophic edies extract potential energy from strong lateral gradients (fronts) in the mixed layer which can act to rapidly shoal the mixed layer. Winds blowing up/down front along the lateral gradients further enhance or arrest the restratification by submesoscale eddies.

This study aims to observe at the submesoscale, the impact of sea-ice meltwater fronts on the mixed layer in the Marginal Ice Zone.

Study Region and Field Campaign

A Seaglider was deployed in early summer (14th December 2018), just four days after the melt of sea-ice when the surface heat flux into the ocean was almost at its maximum (Fig 1d). The glider was deployed at 60°S, 0°E and sampled in a bow-tie pattern for 102 days, following the summer progression of the mixed layer after sea-ice melt. The data analysis was supplemented with ERA5 reanalysis output.



A. SSS and Sea-ice Concentration conditions on the day of deployment. Maximum and Minimum Sea Ice Extent is indicated by the dashed and solid black lines respectively.

B. Heat Map of the glider sampling pattern

C. Histogram of distance between glider dives. The average distance was 2.2km

D. Timeseries of Sea-Ice concentration (teal) and heat flux (red) at 60°S, 0°E. The start and end of the glider deployment is indicated with arrows.

FIGURE 1

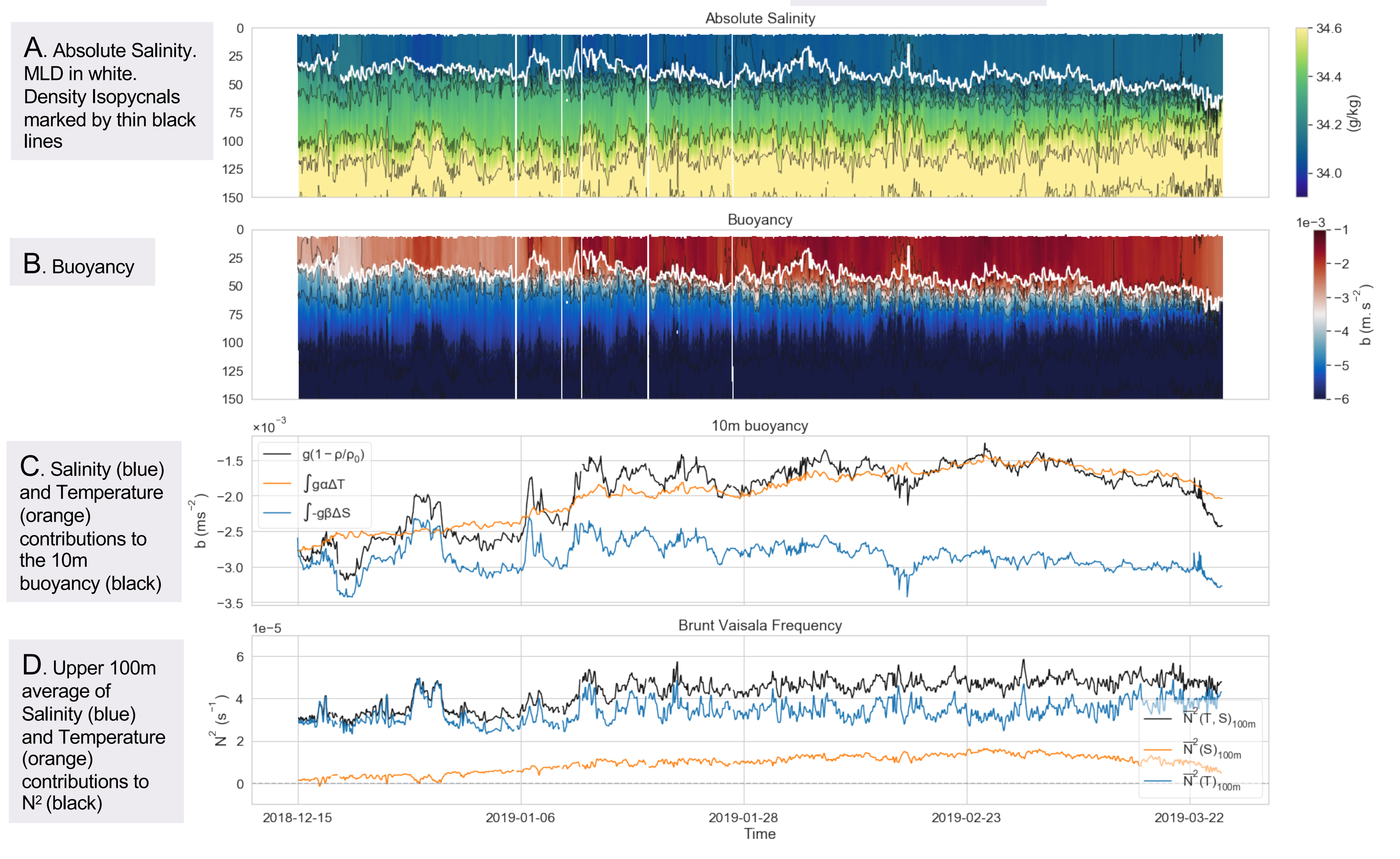
Mixed Layer Properties

Mixed layer salinity ranged from 34-34.2 g/kg over the summer season, with a range from -1.2 – 1.5 °C in mixed layer temperature. While the mixed layer thickness remained at about 40 m during early summer, a gradual deepening towards 80 m is observed in later summer. The deepening occurs concurrently with the decay of the winter water layer beneath (Fig2a,b).

Density is set by salinity both laterally and vertically throughout the season, with an increasing but not dominant role of temperature in late summer (Fig2c,d).

Lateral buoyancy fronts of up to 2e^{-7} s^{-2}, equivalent to a density front of 0.02 kg.m^{-3}.km^{-1}, and salinity front of 0.03g.kg.$^{-1}$.km^{-1} were observed (Fig2c) which are comparable to those observed in the Arctic MIZ (~0.03 kg.m-3.km-1; Timmermans and Winsor, 2013)

FIGURE 2



A. Absolute Salinity. MLD in white. Density Isopycnals marked by thin black lines

B. Buoyancy

C. Salinity (blue) and Temperature (orange) contributions to the 10m buoyancy (black)

D. Upper 100m average of Salinity (blue) and Temperature (orange) contributions to N² (black)

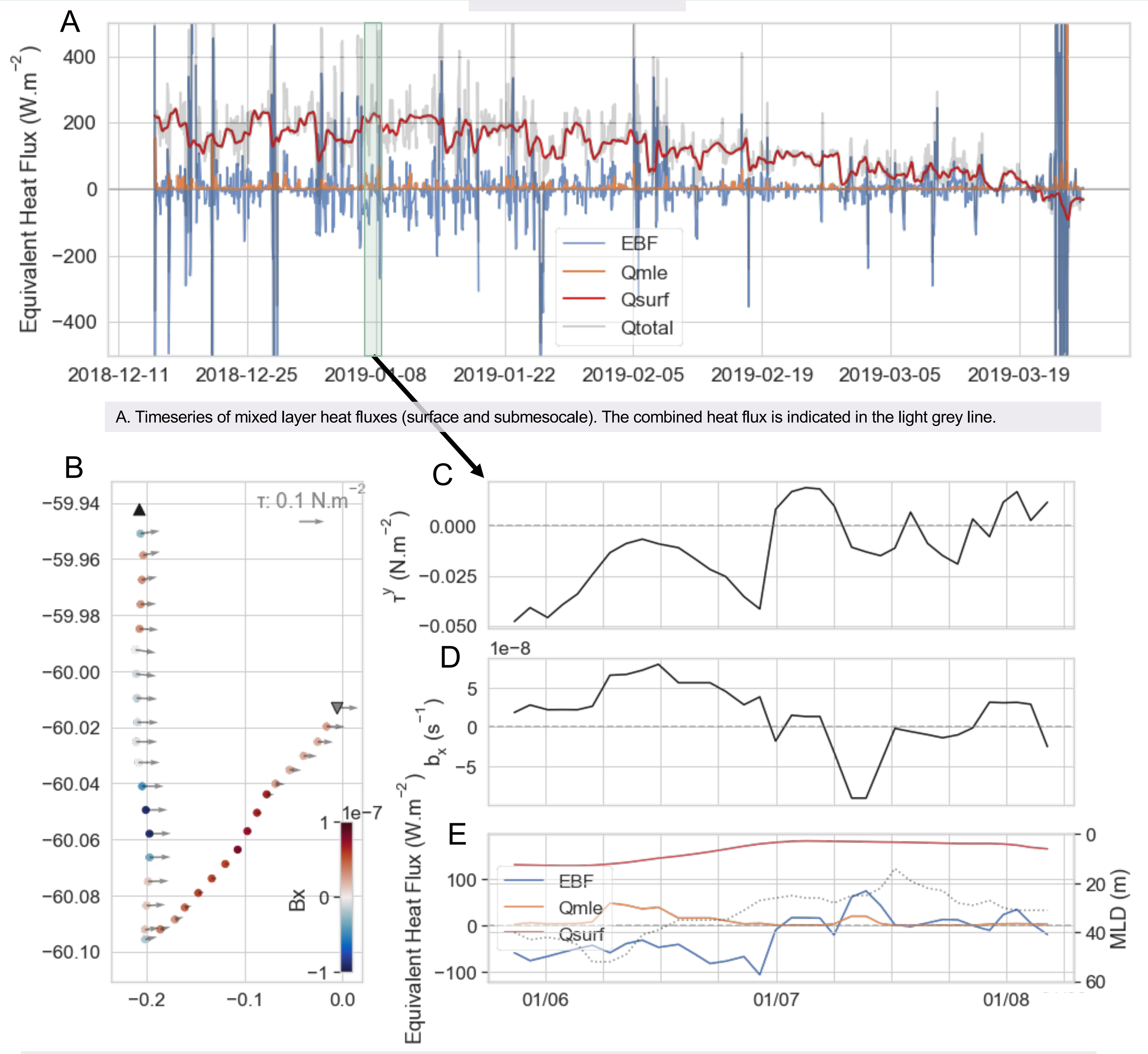
Submesoscale Fluxes

To estimate the relative role of submesocale eddies and fluxes relative to surface boundary layer fluxes (Qnet and Freshwater Fluxes), the equivalent heat flux of Mixed Layer Eddies (MLE, e.g. Mahadevan et al., 2012) and the submesocale Ekman Buoyancy Flux (EBF, e.g. Thomas and Lee, 2005; D'Asaro et al., 2011) was computed.

MLE fluxes intermittently reach up to 150 W.m^2 at their maximum before surface heat fluxes become negative**. EBF was found to be the dominant submesoscale flux reaching up to 1000 W.m², increasing variability of the total fluxes into the mixed layer (Submesoscale + Surface)** (Fig 3a). The mixed layer was also observed to react readily to EBF (Fig 3b).

The dominant role of EBF in an open-ocean Marginal Ice Zone has also recently been observed in the Arctic (Koenig et al., 2020)).

FIGURE 3



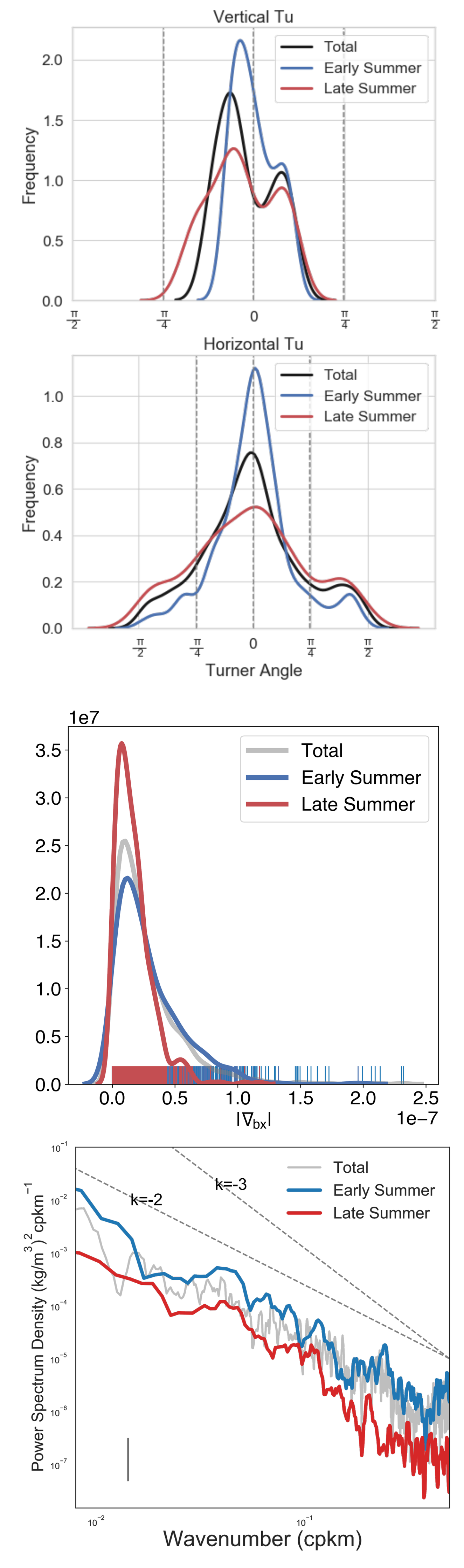
A. Timeseries of mixed layer heat fluxes (surface and submesoscale). The combined heat flux is indicated in the light grey line.

B. Subset of the timeseries in (A). The glider trajectory is plotted and colored by buoyancy gradient. Wind stress vectors are overlain. The direction of the glider in marked by the triangles, starting from the grey triangle. C. Wind stress, rotated relative to the glider path. D. Buoyancy gradient as observed by the glider. E. Submesocale equivalent heat fluxes. Net surface heat fluxes are shown in red for reference. The mixed layer depth is indicated with the dotted grey line.

The seasonal signal of sea-ice melt

The **impact of sea-ice melt water on the mixed layer at 60S is observed to decrease as the summer season progresses**. This is reflected both in lateral and vertical contribution of salinity to buoyancy (Fig 4a,b), the magnitude of lateral buoyancy gradients (Fig 4c) and the slope of the density spectra which shifts from a typical winter/ submesocale slope (k=-2) to a typical open ocean summer/mesoscale slope (k=-3). It is proposed that the submesoscale regime observed early in summer is driven by freshwater from sea-ice that is advecting northwards.

FIGURE 4



A. Histogram of the vertical Turner Angle split into early (blue line) and late summer (red line).. Values close to 0 indicate salinity driven vertical stratification. Values tending towards pi/2 indicate temperature driven vertical stratification

B. Histogram of the lateral Turner Angle split into early (blue line) and late summer (red line). Values close to 0 indicate salinity driven lateral fronts .Values tending towards pi/2 indicate temperature driven lateral fronts.

C. Histogram of the lateral Buoyancy Gradients split into early (blue line) and late summer (red line).

D. Power density spectra of mixed layer density split into early (blue line) and late summer (red line). The slopes k=-2 and k=-3 are shown in grey dashed lines.

Conclusions and future work

- **Variability in mixed layer buoyancy** is driven by **low-saline water** injected into the surface waters as the seasonal **sea-ice** retreats
- **Submesoscale** equivalent heat fluxes dominated by **wind-front interactions (EBF)** which modulate the mixed layer depth
- Signal of sea-ice melt is stronger in early summer, this is further reflected in the **increased submesoscale activity early in summer**

Further questions?

- Would a decrease in sea-ice and therefore salinity driven lateral buoyancy gradients which would decrease submesoscale overturning and vertical fluxes impact on ocean-ice feedbacks (through capping or enhancing upwelling of warm CDW) and water mass transformation (through adjusting mixed layer properties which are later subducted)?
- How do phytoplankton respond to these conditions, particularly in early summer when wind-front interactions are more prevalent? Could this play a role in explaining the late summer blooms observed in the MIZ?
- How representative is this observational dataset of the larger Antarctic MIZ conditions after sea-ice melt?