A NASA high-latitude salinity campaign

Kyla Drushka[1], Peter Gaube[1], Tom Armitage[2], Ivana Cerovecki[3], Ian Fenty[2], Severine Fournier[2], Chelle Gentemann[4], James Girton[1], Alexander Haumann[5], Tony Lee[2], Matt Mazloff[3], Laurie Padman[4], Luc Rainville[1], Julian Schanze[4], Scott Springer[4], Michael Steele[1], Jim Thomson[1], Earle Wilson[6]

1. Applied Physics Laboratory, University of Washington
2. NASA Jet Propulsion Laboratory
3. Scripps Institution of Oceanography, University of California San Diego
4. Earth and Space Research
5. Princeton University & British Antarctic Survey
6. Environmental Science and Engineering, Caltech

March 2020

1. Motivation for high-latitude salinity research by NASA

Climate change is rapidly reshaping high-latitude land, ice, and oceans, which has enormous consequences for climate, carbon fluxes, ecosystems, and society. There is an urgent need for better understanding and prediction of high-latitude dynamics. Ocean salinity is an important but poorly studied component of the high-latitude oceans: in both the Antarctic and Arctic salinity sets the upper ocean stratification, which is in contrast to the rest of the global ocean, where temperature determines the upper ocean stratification. In these cold oceans, salinity also plays an integral role in water mass formation, and thus the global ocean circulation and properties. In both regions, salinity is a marker of the changing water cycle, which has been significantly affected by changes in ocean temperature and circulation; weather patterns; sea ice, glaciers and ice sheets; and hydrology and river outflow. Ocean salinity can be used to understand and monitor high-latitude dynamics and water cycle changes: doing so requires better observations and models and an improved understanding of ocean-ice dynamics.

In situ observations (especially of salinity) at both poles are scarce, and satellites offer an opportunity to understand and monitor the high-latitude oceans. Though satellite salinity measurements are noisy in cold water, recent studies have shown that they can capture large-scale signals in the Arctic (e.g., Founier et al. 2019) and Antarctic (e.g., Garcia-Eidell et al. 2019). Targeted in situ measurements are needed to improve algorithms for satellite salinity and to prepare for new missions (e.g., the European Space Agency's Copernicus Imaging Microwave Radiometer (CIMR) mission, in which NASA may have some involvement). Similarly, in situ observations are necessary to better understand the dynamics produced by ocean circulation models (e.g., NASA's ECCO model). There have been recent improvements in modeling the interactions of ice shelves, sea ice, and the ocean, and efforts to assess the accuracy of these recent changes are needed. The objective of this community white paper is to present ideas about the physical processes in both the Arctic and Antarctic into which a salinity-focussed field campaign would offer major new insights.

2. Arctic Ocean

2.1 Motivation

Salinity is of fundamental importance to Arctic Ocean ice-ocean-atmosphere dynamics, as it sets the upper-ocean stratification and thus enables subsurface heat to be stored; the storage and release of heat through stratification changes has profound impacts on sea-ice formation and melt. The past decades have seen rapid changes in Arctic sea ice, permafrost, oceanic and atmospheric circulation, and the radiative heat balance. Significant changes in Arctic salinity have been observed related to sea-ice anomalies, river discharge, ocean dynamics, and deep water formation (McPhee et al., 2009; Haine et al., 2015). Salinity variations in the Arctic have a large dynamic range, especially on the shelves and in the Canada Basin. These variations are important for a number of Arctic Ocean processes, including modifications to stratification, exchanges of water between the shelves and the deeper ocean basin, and ocean-sea ice interaction. Salinity is also important for the linkages between the Arctic Ocean and the land and atmosphere, and between physical and biogeochemical processes.

The area of seasonally ice-free waters in the Arctic Ocean (the Seasonal Ice Zone, or SIZ) is growing (Steele and Ermold, 2015; Haine and Martin, 2017; Proshutinsky et al., 2019). Despite this, spatiotemporal variations of salinity in the SIZ are poorly sampled due to the paucity of in situ measurements and the relative uncertainty, low spatial resolution, and seasonal (open water) coverage of satellite sea surface salinity (SSS) measurements. As a result, the processes controlling these variations are not well understood. The knowledge gaps include horizontal and vertical variability and processes (particularly very close to the sea surface), freshwater pathways, and shelf-basin freshwater exchanges.

Some specific questions that could be addressed through an Arctic salinity field campaign are outlined below. There is significant overlap between many of these questions.

2.2 Specific science questions that could be addressed with an Arctic salinity field experiment

2.2.1. Near-surface Arctic stratification

The Arctic Ocean mixed layer separates the atmosphere and floating sea ice from the warmer, nutrient-rich waters below. Salinity stratification sets the depth of the mixed layer, which deepens and restratifies seasonally due to salinity variability arising from vertical mixing and lateral processes including ice-ocean circulation, ice melt and formation, and river runoff (Toole et al., 2010; Cole et al., 2019). In summer, melting sea ice forms a particularly strong stratified layer that traps solar radiation, forming a near-surface temperature maximum that stores significant amounts of heat (Maykut and McPhee, 1995; Jackson et al 2010). The "surface mixed layer" of the Arctic Seas is unusual in the global context: wind speeds in the Arctic can be low (especially in summer) and the upper ocean is often not mixed, but stratified right to the surface (e.g., Randelhoff et al., 2017), in both under-ice and open water areas. As a result, the understanding of mixed-layer dynamics developed in other regions thus may not apply to the Arctic. Furthermore, temperature and salinity vary in interesting and unique ways in the upper few meters of the Arctic Seas owing to saline domination of the equation of state at cold temperatures.

Strong gradients of salinity at the ocean surface will have a first-order impact on transfers of momentum, heat, and buoyancy across the air-ice-sea interface. For example, a wind event might generate strong currents limited to a thin fresh layer at the ocean surface (a “slip layer”) advecting ice (or instrument platforms) in a very different way than expected based on mixed-layer depth and drag coefficients derived from traditional models and measurements (Cole et al., 2017). A good knowledge of near-surface stratification is critical to understand when and where ice formation will occur, even if atmospheric forcing is well constrained. Moreover, use of bulk flux algorithms in the Arctic is complicated in conditions of partial sea-ice cover, as neither the COARE algorithm (developed for open ocean conditions) nor the SHEBA algorithm (developed for thick multi-year ice) are appropriate (Persson et al., 2018).

Salinity stratification also plays a complex role in sea-ice dynamics. Melting sea ice injects freshwater into the ocean, leading to strong near-surface stratification, which in turn affects atmosphere-ocean and surface-deep ocean heat exchanges (e.g., Randelhoff et al., 2017; Andreas et al 2010). Once mixed downward, salinity anomalies can also affect sea ice formation and melt: in a model study, low salinity in the upper 100 m of the Labrador Sea was shown to stabilize the water column, shielding sea ice from the entrainment of deeper warm waters and thus slowing ice melt (Fenty and Heimbach, 2013). It has been hypothesized that interannual variations in stratification are responsible in part for interannual variations in sea-ice extent via this mechanism, but this has not been explored with observations.

A salinity field campaign could focus on gaining a better understanding of the lateral and vertical processes that control the depth of the mixed layer and surface layers in the Arctic, under both sea ice and open water and at the ice edge (see next section). This could include quantification of the salinity structure within the upper few meters of the ocean and its relationship to fluxes of momentum, heat, and freshwater, and sea-ice. It would be particularly valuable to observe the structure and evolution of upper ocean salinity (and temperature) within the Seasonal Ice Zone. A field campaign could take place north of Alaska in the Beaufort Sea (and west from there in the Chukchi Sea), which are relatively easy to access and experience significant variability on daily/seasonal/interannual time scales.

2.2.2. Ice-edge dynamics

The Arctic sea ice edge retreats from its maximum extent in March to to its minimum in September. Sea ice retreat is governed by a combination of atmosphere-ice and ocean-ice heat fluxes (Steele et al., 2010); the details of these dynamics are complex, with retreat starting and stopping on a range of time and space scales. Ocean dynamics, SST, winds, and atmospheric heating all play a role. For instance, open water that is warmed by the atmosphere melts the floes that are blown in by winds, and thus the ice edge can appear stationary (termed "loitering"; Steele and Ermold, 2015). Ocean salinity also plays a role in the retreat, for instance through its impact on upper ocean stratification, as described above.

Observations from within the seasonal ice zone (SIZ) made during the "Seasonal Ice Zone Reconnaissance Surveys" (SIZRS) experiment showed that local sea ice melt and mixing generate a ~20-m thick fresh layer that moves with the ice edge as it retreats (Dewey et al, 2017). Recent Arctic measurements made during the ONR "Stratified Ocean Dynamics of the Arctic" (SODA) DRI have revealed very thin (1-2 m) surface layers that are much fresher than the bulk mixed layer and are ubiquitous in the marginal ice zone (MIZ). These "ice puddles"are associated with remnant/melting ice in the summer, and appear to isolate the floating sea ice from the warmer water beneath. While previous Arctic experiments including SIZRS and SODA have considered the role of stratification in the Arctic, the structure of the upper few meters of the ocean has not been a focus. Very near-surface salinity variations on scales of O(1-100) km have been observed but not well studied, and their role in coupled ocean-ice-atmosphere dynamics is poorly understood.

Salinity also plays a leading role in autumn ice-edge advance. Wind-induced mixing can release heat stored beneath the salinity-stratified surface layer, which can melt forming sea-ice and delay or temporarily reverse the advance of the ice edge, leading to thinner winter ice cover (Smith et al., 2018). On the other hand, brine rejection during sea ice formation generates strong salinity anomalies.

Dynamics at the edge of the Arctic sea ice are a particularly interesting and challenging question in the context of pushing the limits of satellite measurements near the ice edge (see below). Ultimately, refining the relationship between SSS and ice-edge dynamics could lead to a better understanding of how the ice edge's evolution affects the ocean on daily to seasonal time scales and how the ocean structure affects the advance and retreat of the ice edge.

Finally, the retreating ice edge is associated with intense, short-lived phytoplankton blooms in summer that are limited by stratification (as well as light) and hence depend on the salinity anomaly from meltwater close to the ice edge and the temperature structure away from the ice (Niebauer et al., 1990; Janout et al., 2016).

A salinity field campaign could focus on salinity anomalies near the sea-ice edge, including the vertical structure from the sea surface to below the mixed layer. It would be valuable to characterize the salinity structure on O(1-100) km horizontal scales in order to assess its relationship to sea-ice retreat (summer) or advance (winter; this would be logistically more complicated) as well as the role of near-surface salinity stratification in air/sea and surface/deep fluxes of heat and momentum. Of particular interest would be capturing the O(1-10)km scale variations that can't be accurately observed from space.

2.2.3. River runoff and Arctic freshwater balance

The Arctic Ocean is an estuary, and the numerous rivers are an enormous source of freshwater: the Arctic Ocean receives 11% of the global river runoff (Dai and Trenberth, 2002) despite representing only 1% of the global ocean in terms of volume. The 2015 update of the Arctic Report Card highlighted that, in 2014, the combined discharge of the eight largest Arctic rivers was 10% greater than their average discharge during 1980-1989. Runoff into the Arctic has been increasing in response to the accelerated global hydrologic cycle (Peterson et al., 2002), which affects salinity, stratification, ocean temperature (and hence ice melt), and biogeochemistry. However, the region between the shelves influenced by large rivers and the seasonal ice edges, where freshwater from river discharges and sea ice melt both contribute to the salinity variability, is very poorly observed. Arctic-COLORS (Arctic-COastal Land Ocean inteRactions), a proposed NASA field campaign, would focus on understanding the effects of land, ice, and future change on nearshore Arctic biogeochemistry: this could be an opportunity for collaboration between the PO and Bio programs.

A salinity field campaign could focus on low-salinity water from rivers versus from ice melt, and whether we can separate these effects (and potentially validate satellite-based efforts to do so; Matsuoka et al., 2016) and trace the waters via coastal currents, through the Arctic circulation, and eventually out of the Arctic. A particular focus could be on Russian Rivers flowing into the Kara Sea or the Mackenzie River flowing into the Beaufort Sea.

2.2.4. Improvements in salinity remote sensing

Our understanding of all of the science questions described here would greatly benefit from salinity remote sensing, and any Arctic salinity field campaign would be valuable for improving interpretation, cal/val, and algorithms for satellite salinity measurements. Understanding the salinity variability and freshwater budget of the Arctic shelves is an important observational target for salinity remote sensing. Due to the large horizontal variability, small-scale spatial gradients and the potentially significant vertical stratification (e.g., associated with so-called "ice puddles"), there could be significant sampling differences between satellite measurements of SSS (even with improved technology) and traditional in situ measurements over the water column (e.g., shipboard). The L-band radiometers used to estimate salinity from space have reduced sensitivity to salinity at cold SSTs, leading to increased error in satellite salinity at lower temperatures (Fournier et al. 2019). Understanding spatial variations and dependence on SST is needed to facilitate the calibration and validation of satellite SSS retrievals. This is the case for existing satellite missions (SMAP, SMOS) as well as for ESA's upcoming CIMR mission. CIMR is motivated by a need for better Arctic observations, and would carry a wide-swath conically-scanning multi-frequency microwave radiometer to provide observations of SST, SSS, wind speed, and sea-ice parameters (including concentration). These collocated observations have the potential to improve our understanding of ocean-ice dynamics in the Arctic, but in order to make extensive use of high-latitude CIMR data it will be necessary to develop a better understanding of the relationship between surface and subsurface properties.

Sea ice affects satellite salinity retrievals, so sea ice concentration products are used to mask out salinity measurements near the ice edge: in the case of SMAP and Aquarius, satellite-based sea-ice concentration products are integrated over the radiometer footprint and weighted by the antenna gain to give an ice fraction; when the ice fraction is above a certain threshold value, the data are flagged. Inaccuracies in the sea ice concentration products or problems with the methodology can lead to salinity estimates that are contaminated by ice or, conversely, those that are unnecessarily flagged. Shelf seas (e.g., Kara and Beaufort Seas) may present a challenge for salinity remote sensing due to sea-ice cover; this should be taken into account when selecting the region for a field campaign. In situ measurements are needed to better inform sea ice corrections for the satellite products and to push the existing sensors to do better.

Finally, quantifying the Arctic freshwater budget (including contributions of runoff, precipitation minus evaporation, advection, and ice formation/melt/transport), and its variability and trends, requires satellite observations. This is crucially important to understand local processes as well as how recent changes in freshwater budget affect deep water convection and Atlantic overturning circulation. Recent efforts have shown that Arctic freshwater content, estimated from satellite measurements of sea surface height and ocean bottom pressure, is correlated with SSS (Fournier et al. 2020, in review), suggesting that satellite salinity could potentially be used to estimate freshwater content with a higher resolution than provided by the GRACE satellite. To develop this strategy, in situ observations are needed to link SSS to the vertically-integrated freshwater signal in the Arctic.

A salinity field campaign could focus on improving the knowledge of salinity structure near sea ice edges (including near-surface salinity stratification, sub-footprint SSS variability, and SST dependence of retrievals) and the relationship of SSS structure with sea ice concentration. The outcome of the field campaign would help improve SSS retrievals from the currently operating SMOS and SMAP satellites and for potential future missions (e.g., CIMR), for instance by improving sea ice correction in SSS retrievals. Moreover, the measurements from the field campaign would provide unprecedented in situ measurements to evaluate and constrain ocean/sea-ice interaction processes in models.

2.3 What should we aim to measure, where, on what time and space scales to address these questions?

Key components that should be measured in an Arctic salinity campaign include: vertical salinity structure including measurements up to the sea surface; horizontal scales of O(0.1-100) km; processes around the ice edge (both as it retreats in summer and as it advances in autumn). Measurements should be made within the SIZ/MIZ and in the open water south of the ice edge; measurements extending beneath the ice pack would provide information about how far north open water conditions influence the ice pack and thus the extent to which satellite-based observations represent conditions beneath the ice. It would be valuable to quantify the impacts of river runoff on salinity, stratification, and circulation, which would require measurements from the coast to the ice edge. Effectively capturing these processes and scales will require distributed measurements using autonomous platforms, along with remote sensing.

A field experiment in several different regimes would be most valuable, e.g.: (a) eastern Beaufort Sea, which opens and warms early, with relatively weak ice and ocean advection; (b) western Beaufort Sea, which opens later and has some influence from multi-year ice (less in recent years); (c) Chukchi Sea, which is strongly influenced by ocean currents moving northward from the Bering Sea into the Arctic Ocean.

2.4 Logistics and synergies with other programs

A NASA Arctic salinity campaign has much to build on scientifically, including several recent large Arctic field experiments (e.g., SODA, CODA, MOSAiC, AMOS, SIZRS, etc.). What is missing in these experiments, however, is a focus on the upper few meters of hydrographic change across the open water and into the ice pack, and the relationship of this structure with surface air/ice forcing and the deeper ocean. Although logistics in the Arctic are far from simple, technologies developed in the past decades programs provide many options for capturing the processes and scales of interest. These include ship-based measurements, ice-tethered profilers, unmanned surface vehicles (including Saildrones, which are funded to go to the Arctic through 2022), aircraft-based observations (including helicopter and unmanned aircraft) and floats deployed by aircraft, underwater gliders that can navigate under ice using acoustic arrays, wave-powered profilers, etc. However, note that sampling early in the season is very challenging: ship access is limited and deploying autonomous assets is difficult; recent deployments of Autonomous Surface Vehicles (e.g., Saildrones and Wave Gliders) have demonstrated the difficulty of sampling close to the ice. Ship-based synoptic sampling is feasible, particularly in the Beaufort Sea where smaller vessels could potentially be used to deploy autonomous assets. A complementary airborne experiment with DopperScatt to map surface currents and Passive-Active L-band and S-band Sensor (PASL) or broad L-band sensor to map SSS would be valuable.

An Arctic campaign could build synergies with other programs both within NASA (e.g., OBB, Cryosphere), with other agencies (ONR, NSF, NOAA, US Coast Guard) and internationally (e.g., Germany/AWI, Canadians). Current/upcoming Arctic experiments could potentially be leveraged (e.g., Beaufort Gyre Exploration Project, Arctic Great Rivers Observatory, Arctic-COLORS [focussed on biogeochemical and ecological processes], MOSAiC, FAMOS, SODA). A US CLIVAR workshop on “Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas” has recently been funded by NSF and NOAA Arctic Programs and will take place in mid-October 2020, providing synergy with the envisioned NASA field campaign.

3. Antarctic and Southern Ocean

3.1 Motivation

Salinity plays an important role in setting up the vertical density stratification in the high-latitude Southern Ocean (Stewart and Haine, 2016). Thereby, it affects the ocean circulation, mixing processes, the heat and carbon fluxes, as well as the sea ice and ice shelves near Antarctica (Morrow and Kestenere, 2017). However, there are significant coverage gaps in salinity observations, particularly within the seasonal ice zone around Antarctica, making it difficult to assess the temporal and spatial Southern Ocean salinity variability. Salinity governs the location of the southern-most fronts of the Antarctic Circumpolar Current (ACC; Orsi et al. 1995).The sea ice that forms and melts each year around Antarctica (with very little multi-year ice) covers a vast area and is a dominant term in the surface freshwater and buoyancy budget south of about 50°S (and hence in the global thermohaline circulation; Haumann et al. 2016; Abernathey et al., 2016). Other major contributions to the surface salinity distribution are an excess precipitation over evaporation (Durack et al., 2012) and the meltwater input from Antarctica (Depoorter et al., 2013). The freshwater fluxes from these rapidly melting glaciers, the ice shelves, and the sea ice are enormous, yet they are not well observed or modeled despite known implications for stratification and thus vertical heat exchanges (Purich et al., 2018; Haumann et al., 2020).

The spatial and temporal coverage of historic in situ salinity observations around Antarctica is very limited, and are particularly scarce in winter, at the subsurface, or in the sea-ice covered region (Siegelman et al., 2019; Porter et al., 2019). Over the past decade the sampling has improved thanks to the Argo and Marine Mammals Exploring the Oceans Pole to Pole (MEOP) programs (Wilson et al., 2019). Deployment of Argo floats with ice avoidance software is increasing, allowing enhanced coverage in the seasonal sea-ice zone (e.g. Campbell et al., 2019). Meanwhile MEOP is giving a first glimpse at properties along the Antarctic Margin (Narayanan et al., 2019). Autonomous surface vehicles are also increasing the coverage of SSS measurements in the region (Thomson & Girton, 2017; Schmidt 2017). Nevertheless, coverage is still sparse and mainly suitable for studying large-scale phenomena, and there is a great need for high-resolution salinity measurements in key regions like the ACC frontal zone, the sea-ice edge, and along the Antarctic continental margin. Process studies have increased our knowledge of specific locations, notably efforts in the Antarctic Peninsula via the Palmer Station Long Term Ecological Research (LTER) Network (Smith et al., 1995) and efforts in the Amundsen Sea embayment. Other specific regions are beginning to receive more attention (e.g. in Prydz Bay), but Antarctic-wide salinity observations remain insufficient. Satellites provide a potential opportunity to monitor Southern Ocean salinity and ocean-ice interaction. The dynamic range of salinity in the Southern Ocean is only about 1 psu (Pellichero et al., 2017), so, using satellites to observe Southern Ocean salinity – particularly in colder waters near the continent – is limited and challenging (Ferster et al., 2018; Garcia-Eidell et al., 2019) and will require significant effort to improve retrieval algorithms.

Although ice-ocean-atmosphere interactions are incorporated into models with increasing sophistication (e.g., the newest version ECCO; CMIP6 models), our understanding and model validation efforts remain severely limited by the dearth of observations. Better understanding and modeling the ice-ocean-atmosphere interactions in the Southern Ocean and around Antarctica, and hence predicting their impacts on circulation and climate, requires targeted field observations aimed at improving both dynamical understanding and modeling of specific processes.

3.2 Specific science questions we could gain insight into with an Antarctic salinity field experiment

3.2.1. Effects of salinity changes on vertical heat and CO_2 exchange, and ocean circulation

Southern Ocean destruction and formation of deep and bottom water masses are a fundamentally important component of the global meridional overturning circulation. Salinity plays a leading role in generating these water masses via brine rejection from sea-ice growth and ocean-ice shelf interactions, freshwater input from sea-ice and glacial ice melt, northward freshwater export from wind-driven sea-ice transport, and surface freshwater flux from precipitation minus evaporation (Abernathey et al., 2016; Haumann et al., 2016; Pellichero et al., 2018). Thus, changes in sea-ice and salinity have significant consequences for global ocean circulation. Salinity also has a direct impact on the vertical heat and CO_2 exchange and its meridional transport and thus on climate (Frölicher et al., 2015): the most buoyant waters are cold and fresh and are transported equatorward, while slightly less buoyant warm, salty and CO_2 waters are transported poleward and release both heat and CO_2 to the atmosphere.

The Southern Ocean has freshened in recent decades (Durack et al., 2012), with regional and seasonal differences arising from a complex combination of processes that are not well understood, modeled, or constrained by observations. These processes include melting and calving of ice shelves (e.g. Jacobs et al. 1992; Rignot et al., 2013); variability in sea-ice formation, advection, and melt; changing wind patterns and ocean temperatures (e.g., Haumann et al., 2016); and potentially an increasing excess precipitation over evaporation (Durack et al., 2012; Swart et al., 2018). The specific locations and details about these various processes are still poorly understood. Moreover, while most CMIP5 models are able to reproduce the salinity trends in the lower latitude Southern Ocean north of the ACC (Swart et al., 2018), they do not reproduce the observed changes in the higher latitudes. Understanding the reasons for this mismatch is a challenge because the freshwater budget is so poorly constrained by observations of salinity, precipitation and evaporation, ice formation/melt, and sea-ice export (Purich, 2018; Swart et al., 2019).

A salinity experiment could focus on quantifying key components of the freshwater balance in one or more sectors of the Southern Ocean, in particular in the seasonal sea-ice zone, including precipitation minus evaporation, advection (including advection of sea ice), sea-ice melt (summer) /formation (winter), and ice shelf melt. The role of salinity in eddy fluxes across the ACC, and setting the structure and variability of the ACC fronts, could also be quantified.

3.2.2. Sea ice

In contrast to patterns in the Arctic and expectations from a warming climate, mean Antarctic sea ice extent increased steadily from the late 1970s to its maximum extent in 2014, a trend that is not captured by CMIP5 ensembles (Swart and Fyfe, 2013). (Note that the Amundsen and Bellinghausen Seas show the opposite trend). Reasons for this increase are disputed; one hypothesis is that surface freshening has led to an increase in stratification, which is known to reduce convective mixing of warmer deep waters into the surface layer, leading to cooler SSTs and thereby an increase in sea ice formation (Lecomte et al., 2017; Wilson et al., 2019). Melting ice shelves and glaciers (Bintanja et al., 2013, 2015), an increase in precipitation over the ocean (Purich, 2018), and increased northward export of sea ice due to changing winds (Haumann et al., 2016) are all suggested mechanisms for the upper ocean freshening. September sea ice extent dropped to its lowest value in the satellite record in 2016 (Turner and Comiso, 2017) and has remained relatively low. The drivers of this abrupt change are not quite clear but preliminary work suggests that short-term atmospheric variability was a major contributor (e.g**.** Stuecker et al. 2017, Meehl et al. 2019, Wang et al. 2019**)**. Nevertheless, changes in surface salinity may have contributed to the sea ice decline in some regions. Prior to the rapid sea ice edge retreat in late 2016, a relatively large offshore winter polynya appeared in the Weddell Sea, near the Maud Rise seamount (Campbell et al. 2019). This was followed by a second, even larger polynya a year later (Cheon and Gordon 2019). Analysis of local Argo float data suggests that these events were preconditioned by abnormally high surface salinity, which weakened the local stratification and predisposed the area to deep convection (Campbell et al. 2019). Given that these events result in significant sea ice loss and massive ventilation of deep ocean and carbon, it is imperative that we understand the factors that control their initiation. However, insight into these processes is currently hindered by the limited observations of upper ocean salinity in the region. Understanding changes in Antarctic sea ice cover will require detailed observations: to understand how ocean structure affects SST and sea-ice growth, to constrain the upper ocean freshwater budget from observations, and to assess models, which will ultimately be used to predict long-term changes in sea ice cover.

Similar to in the Arctic, sea-ice formation/melt likely also generates small-scale near-surface surface salinity (and stratification) variability. Regarding stratification and water column stability, one precarious region is the Weddell Sea, where breakdown of the salinity maintained stratification can lead to giant open ocean polynyas (Campbell et al., 2019). The scales and impacts of the salinity variability, especially in regards to air-sea fluxes and vertical ocean heat fluxes, are poorly constrained.

A salinity field campaign could focus on understanding how ocean temperature and salinity structure affect vertical mixing and hence SST and sea-ice growth. It would be valuable to contrast different regions of the Southern Ocean, for instance the Ross Sea (strong positive sea-ice cover trend) Amundsen/Bellingshausen (negative trend). Similarly, understanding salinity-maintained stability of the Weddell Sea is vital to understanding climate due to the impacts of open ocean polynyas. An observationally-based freshwater budget would be valuable to quantify drivers of the ocean vertical structure, though in practice it may not be feasible to close the budget.

3.2.3. Quantifying ice-shelf meltwater anomalies

The Antarctic ice sheet has been losing mass for decades, predominantly from West Antarctica (Shepard et al., 2012), and ice shelves have been thinning (Paolo et al., 2015) with the fastest thinning occurring via basal melting by relatively warm circumpolar deep water at depth (Pritchard et al., 2012). The fate of the freshwater released by melting ice shelves-- from their origin in the ice-shelf cavity to their impacts on upper ocean stratification (and subsequent impacts on vertical heat fluxes; section 3.2.2) -- is not well understood (e.g. Hansen et al., 2016; Garabato et al., 2017). Ice-shelf basal melt rates are difficult to monitor, particularly as they vary on interannual, seasonal, and sub-seasonal timescales. Ice-shelf meltwater plumes have been detected using an autonomous underwater vehicle just outside an ice-shelf cavity mouth (Jenkins et al., 2010), suggesting the possibility of using salinity as a tracer for ice-shelf basal melt anomalies. Doing so would require a better understanding of the salinity signature of melting ice shelves, including the water mass transformation that takes place when meltwater mixes with the circumpolar deep water or Antarctic bottom water. On a broader scale, observations are needed to quantify the meltwater component of the Southern Ocean freshwater budget.

A salinity field campaign could focus on detecting ice-shelf meltwater export anomalies near the mouths of ice shelf cavities and matching them to ice-shelf basal melt anomalies. Ice shelf meltwater could be identified from the salinity measurements and the oxygen isotopic composition of the sea-water (e.g., Meredith et al., 2016) A freshwater budget for the shelf regions of the Amundsen or Ross Seas would be extremely valuable.

3.3 What processes should we aim to measure, where, on what time and space scales to address these questions?

A salinity campaign focusing on the freshwater budget within one or more sectors of the Southern Ocean within the Antarctic seasonal ice zone would be valuable (horizontal scales of O(10-1000) km, time scales of days-months -- e.g., using autonomous/unmanned assets including those that measure atmospheric variables, such as Saildrones, underwater and surface gliders, drifters, and profiling floats). Although closing the salinity budget is perhaps unrealistic, estimating the various budget terms in a certain location (e.g., Amundsen or Ross Seas) would nonetheless provide valuable new insight. A campaign could also focus on how the salinity structure around the ice edge affects vertical mixing, upper ocean temperature, and sea-ice formation/melt (horizontal scales of O(10-100)km, time scales of days-weeks -- e.g., a ship-based field campaign with autonomous profiling assets). Alternatively, a campaign could focus on the small-scale salinity anomalies that originate within ice-shelf cavities and form the buoyant plumes of fresh melt-water (horizontal scales of O(0.1-10)km, time scales of hours-days; e.g., ship-based measurements and autonomous vehicles).

3.4 Logistics and synergies with other programs

A Southern Ocean field experiment would be remote, costly and logistically challenging; however, because substantial data gaps exist, particularly of salinity structure near or beneath ice, such a campaign would likely produce valuable new findings.

An Antarctic campaign could build synergies with the NSF Antarctic program. A process study would be complemented by long-term projects including: the global Argo program as well as the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) project, which deploys biogeochemical Argo floats in the Southern Ocean; the MEOP project, which deploys instrumented seals; and the GO-SHIP program as well as other repeat hydrography lines. These programs are not focused on salinity but have generated a large portion of the CTD data we currently have for the Southern Ocean. As access and shiptime in the Antarctic is very limited, international collaborations would be extremely valuable (for instance with the British Antarctic Survey, National Oceanography Centre Southampton, Alfred Wegener Institute, and Commonwealth Scientific and Industrial Research Organisation). The Southern Ocean Carbon and Heat Impact on Climate (SO-CHIC) project, a European effort to understand and quantify variability of heat and carbon budgets from observations and modeling, will run for 4 years beginning in late 2019, and would also be synergistic.

4. References

Abernathey, Ryan P., Ivana Cerovecki, Paul R. Holland, Emily Newsom, Matt Mazloff, and Lynne D. Talley. “Water-Mass Transformation by Sea Ice in the Upper Branch of the Southern Ocean Overturning.” *Nature Geoscience* 9, no. 8 (2016): 596–601. https://doi.org/10.1038/ngeo2749.

Andreas, Edgar L., Thomas W. Horst, Andrey A. Grachev, P. Ola G. Persson, Christopher W. Fairall, Peter S. Guest, and Rachel E. Jordan. “Parametrizing Turbulent Exchange over Summer Sea Ice and the Marginal Ice Zone.” *Quarterly Journal of the Royal Meteorological Society* 136, no. 649 (2010): 927–43. https://doi.org/10.1002/qj.618.

Benallal, M. A., H. Moussa, F. Touratier, C. Goyet, and A. Poisson. “Ocean Salinity from Satellite-Derived Temperature in the Antarctic Ocean.” *Antarctic Science* 28, no. 2 (2016): 127–34. https://doi.org/10.1017/S0954102015000516.

Bintanja, R., G. J. van Oldenborgh, S. S. Drijfhout, B. Wouters, and C. A. Katsman. “Important Role for Ocean Warming and Increased Ice-Shelf Melt in Antarctic Sea-Ice Expansion.” *Nature Geoscience* 6, no. 5 (2013): 376–79. https://doi.org/10.1038/ngeo1767.

Bintanja, R., G. J. van Oldenborgh, and C. A. Katsman. “The Effect of Increased Fresh Water from Antarctic Ice Shelves on Future Trends in Antarctic Sea Ice.” *Annals of Glaciology* 56, no. 69 (2015): 120–26. https://doi.org/10.3189/2015AoG69A001.

Campbell, Ethan C., Earle A. Wilson, G. W. Kent Moore, Stephen C. Riser, Casey E. Brayton, Matthew R. Mazloff, and Lynne D. Talley. “Antarctic Offshore Polynyas Linked to Southern Hemisphere Climate Anomalies.” *Nature* 570, no. 7761 (2019): 319–25. https://doi.org/10.1038/s41586-019-1294-0.

Cheon, Woo Geun, and Arnold L. Gordon. “Open-Ocean Polynyas and Deep Convection in the Southern Ocean.” *Scientific Reports* 9, no. 1 (2019): 1–9. https://doi.org/10.1038/s41598-019-43466-2.

Cole, Sylvia T., John M. Toole, Ratnaksha Lele, Mary-Louise Timmermans, Shawn G. Gallaher, Timothy P. Stanton, William J. Shaw, et al. “Ice and Ocean Velocity in the Arctic Marginal Ice Zone: Ice Roughness and Momentum Transfer.” *Elem Sci Anth* 5, no. 0 (2017): 55. https://doi.org/10.1525/elementa.241.

Cole, Sylvia T., and James Stadler. “Deepening of the Winter Mixed Layer in the Canada Basin, Arctic Ocean Over 2006–2017.” *Journal of Geophysical Research: Oceans* 124, no. 7 (2019): 4618–30. https://doi.org/10.1029/2019JC014940.

Dai, Aiguo, and Kevin E. Trenberth. “Estimates of Freshwater Discharge from Continents: Latitudinal and Seasonal Variations.” *Journal of Hydrometeorology* 3, no. 6 (2002): 660–87. https://doi.org/10.1175/1525-7541(2002)003<0660:EOFDFC>2.0.CO;2.

Depoorter, M. A., J. L. Bamber, J. A. Griggs, J. T. M. Lenaerts, S. R. M. Ligtenberg, M. R. van den Broeke, and G. Moholdt. “Calving Fluxes and Basal Melt Rates of Antarctic Ice Shelves.” *Nature* 502, no. 7469 (2013): 89–92. https://doi.org/10.1038/nature12567.

Dewey, Sarah R., James H. Morison, and Jinlun Zhang. “An Edge-Referenced Surface Fresh Layer in the Beaufort Sea Seasonal Ice Zone.” *Journal of Physical Oceanography* 47, no. 5 (2017): 1125–44. https://doi.org/10.1175/JPO-D-16-0158.1.

Durack, Paul J., Susan E. Wijffels, and Richard J. Matear. “Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000.” *Science* 336, no. 6080 (2012): 455–58. https://doi.org/10.1126/science.1212222.

Fenty, Ian, and Patrick Heimbach. “Hydrographic Preconditioning for Seasonal Sea Ice Anomalies in the Labrador Sea.” *Journal of Physical Oceanography* 43, no. 5 (2012): 863–83. https://doi.org/10.1175/JPO-D-12-064.1.

Ferster, Brady S., and Bulusu Subrahmanyam. “A Comparison of Satellite-Derived Sea Surface Salinity and Salt Fluxes in the Southern Ocean.” *Remote Sensing in Earth Systems Sciences* 1, no. 1 (2018): 1–13. https://doi.org/10.1007/s41976-018-0001-5.

Fournier, Séverine, Tong Lee, Wenqing Tang, Michael Steele, and Estrella Olmedo. “Evaluation and Intercomparison of SMOS, Aquarius, and SMAP Sea Surface Salinity Products in the Arctic Ocean.” *Remote Sensing* 11, no. 24 (2019): 3043. https://doi.org/10.3390/rs11243043.

Fournier S., Lee T., Wang X., Armitage T.W.K., Wang O., Fukumori I., Kwok R. Sea surface salinity as a proxy for Arctic Ocean freshwater changes. *Journal of Geophysical Research: Ocean*, (2020): in review.

Frölicher, Thomas L., Jorge L. Sarmiento, David J. Paynter, John P. Dunne, John P. Krasting, and Michael Winton. “Dominance of the Southern Ocean in Anthropogenic Carbon and Heat Uptake in CMIP5 Models.” *Journal of Climate* 28, no. 2 (2014): 862–86. https://doi.org/10.1175/JCLI-D-14-00117.1.

Garabato, Alberto C. Naveira, Alexander Forryan, Pierre Dutrieux, Liam Brannigan, Louise C. Biddle, Karen J. Heywood, Adrian Jenkins, Yvonne L. Firing, and Satoshi Kimura. “Vigorous Lateral Export of the Meltwater Outflow from beneath an Antarctic Ice Shelf.” *Nature* 542, no. 7640 (February 2017): 219–22. https://doi.org/10.1038/nature20825.

Garcia-Eidell, Cynthia, Josefino C. Comiso, Emmanuel Dinnat, and Ludovic Brucker. “Sea Surface Salinity Distribution in the Southern Ocean as Observed From Space.” *Journal* *of Geophysical Research: Oceans* 124, no. 5 (2019): 3186–3205. https://doi.org/10.1029/2018JC014510.

Haine, Thomas W. N., Beth Curry, Rüdiger Gerdes, Edmond Hansen, Michael Karcher, Craig Lee, Bert Rudels, et al. "Arctic Freshwater Export: Status, Mechanisms, and Prospects." *Global and Planetary Change* 125 (2015): 13–35. https://doi.org/10.1016/j.gloplacha.2014.11.013.

Haine, Thomas W. N., and Torge Martin. "The Arctic-Subarctic Sea Ice System Is Entering a Seasonal Regime: Implications for Future Arctic Amplification." *Scientific Reports* 7, no. 1 (2017): 1–9. https://doi.org/10.1038/s41598-017-04573-0.

Hansen, James, Makiko Sato, Paul Hearty, Reto Ruedy, Maxwell Kelley, Valerie Masson-Delmotte, Gary Russell, et al. "Ice Melt, Sea Level Rise and Superstorms: Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations That 2 °C Global Warming Could Be Dangerous." *Atmospheric Chemistry and Physics* 16, no. 6 (2016): 3761–3812. https://doi.org/10.5194/acp-16-3761-2016.

Haumann, F. Alexander, Nicolas Gruber, Matthias Münnich, Ivy Frenger, and Stefan Kern. "Sea-Ice Transport Driving Southern Ocean Salinity and Its Recent Trends." *Nature* 537, no. 7618 (2016): 89–92. https://doi.org/10.1038/nature19101.

Haumann, F. A., Gruber, N., Münnich, M. (2020, in review): Sea-ice Induced Southern Ocean Subsurface Warming and Surface Cooling in a Warming Climate.Hellmer, H. H. "Impact of Antarctic Ice Shelf Basal Melting on Sea Ice and Deep Ocean Properties." *Geophysical Research Letters* 31, no. 10 (2004). https://doi.org/10.1029/2004GL019506.

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram. "Identification, Characterization, and Change of the near-Surface Temperature Maximum in the Canada Basin, 1993–2008." *Journal of Geophysical Research: Oceans* 115, no. C5 (2010). https://doi.org/10.1029/2009JC005265.

Jacobs, S. S., H. H. Helmer, C. S. M. Doake, A. Jenkins, and R. M. Frolich. "Melting of Ice Shelves and the Mass Balance of Antarctica." *Journal of Glaciology* 38, no. 130 (1992): 375–87. https://doi.org/10.3189/S0022143000002252.

Janout, Markus A., Jens Hölemann, Anya M. Waite, Thomas Krumpen, Wilken-Jon von Appen, and Fedor Martynov. "Sea-Ice Retreat Controls Timing of Summer Plankton Blooms in the Eastern Arctic Ocean." *Geophysical Research Letters* 43, no. 24 (2016): 12,493-12,501. https://doi.org/10.1002/2016GL071232.

Jenkins, Adrian, Pierre Dutrieux, Stanley S. Jacobs, Stephen D. McPhail, James R. Perrett, Andrew T. Webb, and David White. "Observations beneath Pine Island Glacier in West

Antarctica and Implications for Its Retreat." *Nature Geoscience* 3, no. 7 (2010): 468–72. https://doi.org/10.1038/ngeo890.

Lecomte, Olivier, Hugues Goosse, Thierry Fichefet, Casimir de Lavergne, Antoine Barthélemy, and Violette Zunz. "Vertical Ocean Heat Redistribution Sustaining Sea-Ice Concentration Trends in the Ross Sea." *Nature Communications* 8, no. 1 (2017): 1–8. https://doi.org/10.1038/s41467-017-00347-4.

Matsuoka, Atsushi, Marcel Babin, and Emmanuel C. Devred. "A New Algorithm for Discriminating Water Sources from Space: A Case Study for the Southern Beaufort Sea Using MODIS Ocean Color and SMOS Salinity Data." *Remote Sensing of Environment* 184 (2016): 124–38. https://doi.org/10.1016/j.rse.2016.05.006.

Maykut, G. A., and Miles G. McPhee. "Solar Heating of the Arctic Mixed Layer." *Journal of Geophysical Research: Oceans* 100, no. C12 (1995): 24691–703. https://doi.org/10.1029/95JC02554.

McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire. "Rapid Change in Freshwater Content of the Arctic Ocean." *Geophysical Research Letters* 36, no. 10 (2009). https://doi.org/10.1029/2009GL037525.

Meehl, Gerald A., Julie M. Arblaster, Christine T. Y. Chung, Marika M. Holland, Alice DuVivier, LuAnne Thompson, Dongxia Yang, and Cecilia M. Bitz. "Sustained Ocean Changes Contributed to Sudden Antarctic Sea Ice Retreat in Late 2016." *Nature Communications* 10, no. 1 (2019): 1–9. https://doi.org/10.1038/s41467-018-07865-9.

Meredith, Michael P., Sharon E. Stammerjohn, Hugh J. Venables, Hugh W. Ducklow, Douglas G. Martinson, Richard A. Iannuzzi, Melanie J. Leng, Jan Melchior van Wessem, Carleen H. Reijmer, and Nicholas E. Barrand. "Changing Distributions of Sea Ice Melt and Meteoric Water West of the Antarctic Peninsula." *Deep Sea Research Part II: Topical Studies in Oceanography*, Advances in understanding the marine system west of the Antarctic Peninsula, 139 (2017): 40–57. https://doi.org/10.1016/j.dsr2.2016.04.019.

Morrow, Rosemary, and Elodie Kestenare. "22-Year Surface Salinity Changes in the Seasonal Ice Zone near 140°E off Antarctica." *Journal of Marine Systems* 175 (2017): 46–62. https://doi.org/10.1016/j.jmarsys.2017.07.003.

Narayanan, Aditya, Sarah T. Gille, Matthew R. Mazloff, and K. Murali. "Water Mass Characteristics of the Antarctic Margins and the Production and Seasonality of Dense Shelf Water." *Journal of Geophysical Research: Oceans* 124, no. 12 (2019): 9277–94. https://doi.org/10.1029/2018JC014907.

Niebauer, H. J., Vera Alexander, and Susan Henrichs. "Physical and Biological Oceanographic Interaction in the Spring Bloom at the Bering Sea Marginal Ice Edge

Zone." *Journal of Geophysical Research: Oceans* 95, no. C12 (1990): 22229–41. https://doi.org/10.1029/JC095iC12p22229.

Orsi, Alejandro H., Thomas Whitworth, and Worth D. Nowlin. "On the Meridional Extent and Fronts of the Antarctic Circumpolar Current." *Deep Sea Research Part I: Oceanographic Research Papers* 42, no. 5 (1995): 641–73. https://doi.org/10.1016/0967-0637(95)00021-W.

Paolo, Fernando S., Helen A. Fricker, and Laurie Padman. "Volume Loss from Antarctic Ice Shelves Is Accelerating." *Science* 348, no. 6232 (2015): 327–31. https://doi.org/10.1126/science.aaa0940.

Parkinson, Claire L. "A 40-y Record Reveals Gradual Antarctic Sea Ice Increases Followed by Decreases at Rates Far Exceeding the Rates Seen in the Arctic." *Proceedings of the National Academy of Sciences* 116, no. 29 (2019): 14414–23. https://doi.org/10.1073/pnas.1906556116.

Pellichero, Violaine, Jean-Baptiste Sallée, Sunke Schmidtko, Fabien Roquet, and Jean-Benoît Charrassin. "The Ocean Mixed Layer under Southern Ocean Sea-Ice: Seasonal Cycle and Forcing." *Journal of Geophysical Research: Oceans* 122, no. 2 (2017): 1608–33. https://doi.org/10.1002/2016JC011970.

Persson, P. Ola G., Byron Blomquist, Peter Guest, Sharon Stammerjohn, Christopher Fairall, Luc Rainville, Björn Lund, Stephen Ackley, and Jim Thomson. "Shipboard Observations of the Meteorology and Near-Surface Environment During Autumn Freezeup in the Beaufort/Chukchi Seas." *Journal of Geophysical Research: Oceans* 123, no. 7 (2018): 4930–69. https://doi.org/10.1029/2018JC013786.

Peterson, Bruce J., Robert M. Holmes, James W. McClelland, Charles J. Vörösmarty, Richard B. Lammers, Alexander I. Shiklomanov, Igor A. Shiklomanov, and Stefan Rahmstorf. "Increasing River Discharge to the Arctic Ocean." *Science* 298, no. 5601 (2002): 2171–73. https://doi.org/10.1126/science.1077445.

Petty, Alek A. Markus. "Improving Our Understanding of Antarctic Sea Ice with NASA's Operation IceBridge and the Upcoming ICESat-2 Mission," July 26, 2017. https://ntrs.nasa.gov/search.jsp?R=20170008477.

Porter, David F., Scott R. Springer, Laurie Padman, Helen A. Fricker, Kirsty J. Tinto, Stephen C. Riser, and Robin E. Bell. "Evolution of the Seasonal Surface Mixed Layer of the Ross Sea, Antarctica, Observed With Autonomous Profiling Floats." *Journal of Geophysical Research: Oceans* (2019). https://doi.org/10.1029/2018JC014683.

Pritchard, H. D., S. R. M. Ligtenberg, H. A. Fricker, D. G. Vaughan, M. R. van den Broeke, and L. Padman. "Antarctic Ice-Sheet Loss Driven by Basal Melting of Ice Shelves." *Nature* 484, no. 7395 (2012): 502–5. https://doi.org/10.1038/nature10968.

Proshutinsky, A., R. Krishfield, J. M. Toole, M.-L. Timmermans, W. Williams, S. Zimmermann, M. Yamamoto-Kawai, et al. “Analysis of the Beaufort Gyre Freshwater Content in 2003–2018.” *Journal of Geophysical Research: Oceans* 124, no. 12 (2019): 9658–89. https://doi.org/10.1029/2019JC015281.

Purich, Ariaan, Matthew H. England, Wenju Cai, Arnold Sullivan, and Paul J. Durack. “Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model.” *Journal of Climate* 31, no. 7 (2018): 2613–32. https://doi.org/10.1175/JCLI-D-17-0092.1.

Randelhoff, Achim, Ilker Fer, and Arild Sundfjord. “Turbulent Upper-Ocean Mixing Affected by Meltwater Layers during Arctic Summer.” *Journal of Physical Oceanography* 47, no. 4 (2017): 835–53. https://doi.org/10.1175/JPO-D-16-0200.1.

Rignot, E., S. Jacobs, J. Mouginot, and B. Scheuchl. “Ice-Shelf Melting Around Antarctica.” *Science* 341, no. 6143 (2013): 266–70. https://doi.org/10.1126/science.1235798.

Schmidt, Kevin M., Sebastiaan Swart, Chris Reason, and Sarah-Anne Nicholson. “Evaluation of Satellite and Reanalysis Wind Products with In Situ Wave Glider Wind Observations in the Southern Ocean.” *Journal of Atmospheric and Oceanic Technology* 34, no. 12 (2017): 2551–68. https://doi.org/10.1175/JTECH-D-17-0079.1.

Shepherd, Andrew, Erik R. Ivins, Geruo A, Valentina R. Barletta, Mike J. Bentley, Srinivas Bettadpur, Kate H. Briggs, et al. “A Reconciled Estimate of Ice-Sheet Mass Balance.” *Science* 338, no. 6111 (2012): 1183–89. https://doi.org/10.1126/science.1228102.

Siegelman, Lia, Fabien Roquet, Vigan Mensah, Pascal Rivière, Etienne Pauthenet, Baptiste Picard, and Christophe Guinet. “Correction and Accuracy of High- and Low-Resolution CTD Data from Animal-Borne Instruments.” *Journal of Atmospheric and Oceanic Technology* 36, no. 5 (2019): 745–60. https://doi.org/10.1175/JTECH-D-18-0170.1.

Smith, Raymond C., Karen S. Baker, William R. Fraser, Eileen E. Hofmann, David M. Karl, John M. Klinck, Langdon B. Quetin, et al. “The Palmer LTER: A Long-Term Ecological Research Program at Palmer Station, Antarctica.” *Oceanography* 8, no. 3 (1995): 77–86.

Smith, Madison, Sharon Stammerjohn, Ola Persson, Luc Rainville, Guoqiang Liu, William Perrie, Robin Robertson, Jennifer Jackson, and Jim Thomson. “Episodic Reversal of Autumn Ice Advance Caused by Release of Ocean Heat in the Beaufort Sea.” *Journal of Geophysical Research: Oceans* 123, no. 5 (2018): 3164–85. https://doi.org/10.1002/2018JC013764.

Steele, Michael, Suzanne Dickinson, Jinlun Zhang, and Ron W. Lindsay. “Seasonal Ice Loss in the Beaufort Sea: Toward Synchrony and Prediction.” *Journal of Geophysical Research: Oceans* 120, no. 2 (2015): 1118–32. https://doi.org/10.1002/2014JC010247.

Steele, Michael, and Wendy Ermold. “Loitering of the Retreating Sea Ice Edge in the Arctic Seas.” *Journal of Geophysical Research: Oceans* 120, no. 12 (2015): 7699–7721. https://doi.org/10.1002/2015JC011182.

Steele, Michael, Jinlun Zhang, and Wendy Ermold. “Mechanisms of Summertime Upper Arctic Ocean Warming and the Effect on Sea Ice Melt.” *Journal of Geophysical Research: Oceans* 115, no. C11 (2010). https://doi.org/10.1029/2009JC005849.

Stewart, Kial D., and Thomas W. N. Haine. “Thermobaricity in the Transition Zones between Alpha and Beta Oceans.” *Journal of Physical Oceanography* 46, no. 6 (2016): 1805–21. https://doi.org/10.1175/JPO-D-16-0017.1.

Stuecker, Malte F., Cecilia M. Bitz, and Kyle C. Armour. “Conditions Leading to the Unprecedented Low Antarctic Sea Ice Extent during the 2016 Austral Spring Season.” *Geophysical Research Letters* 44, no. 17 (2017): 9008–19. https://doi.org/10.1002/2017GL074691.

Swart, N. C., and J. C. Fyfe. "The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends." *Geophysical Research Letters* 40, no. 16 (2013): 4328-4332.

Swart, Neil C., Sarah T. Gille, John C. Fyfe, and Nathan P. Gillett. “Recent Southern Ocean Warming and Freshening Driven by Greenhouse Gas Emissions and Ozone Depletion.” *Nature Geoscience* 11, no. 11 (2018): 836–41. https://doi.org/10.1038/s41561-018-0226-1.

Swart, Sebastiaan, Sarah T. Gille, Bruno Delille, Simon Josey, Matthew Mazloff, Louise Newman, Andrew F. Thompson, et al. “Constraining Southern Ocean Air-Sea-Ice Fluxes Through Enhanced Observations.” *Frontiers in Marine Science* 6 (2019). https://doi.org/10.3389/fmars.2019.00421.

Thomson, J., and J. Girton. “Sustained measurements of Southern Ocean air-sea coupling from a Wave Glider autonomous surface vehicle.” *Oceanography* 30(2):104–109 (2017). https://doi.org/10.5670/oceanog.2017.228.

Toole, J. M., M.-L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky, and J. A. Richter-Menge. “Influences of the Ocean Surface Mixed Layer and Thermohaline Stratification on Arctic Sea Ice in the Central Canada Basin.” *Journal of Geophysical Research: Oceans* 115, no. C10 (2010). https://doi.org/10.1029/2009JC005660.

Wang, Guomin, Harry H. Hendon, Julie M. Arblaster, Eun-Pa Lim, S. Abhik, and Peter van Rensch. “Compounding Tropical and Stratospheric Forcing of the Record Low Antarctic Sea-Ice in 2016.” *Nature Communications* 10, no. 1 (2019): 1–9. https://doi.org/10.1038/s41467-018-07689-7.

Wilson, Earle A., Stephen C. Riser, Ethan C. Campbell, and Annie P. S. Wong. "Winter Upper-Ocean Stability and Ice–Ocean Feedbacks in the Sea Ice–Covered Southern Ocean." *Journal of Physical Oceanography* 49, no. 4 (2019): 1099–1117. https://doi.org/10.1175/JPO-D-18-0184.1.