

# STRATIFICATION IN THE CANADIAN ARCTIC ARCHIPELAGO'S KITIKMEOT SEA:

## Biological and geochemical consequences

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The Kitikmeot Sea Science Study (K3S) is being led by Fisheries and Oceans Canada, in collaboration with the Arctic Research Foundation, UiT–the Arctic University of Norway, the University of Alaska Fairbanks, the University of Manitoba, the University of Calgary, and the University of Victoria. It is supported by Polar Knowledge Canada, the Arctic Research Foundation, Fisheries and Oceans Canada, and our collaborators. The study area comprises the Kitikmeot Sea: the entire marine region of the Kitikmeot between Dolphin and Union Strait in the west and Victoria Strait and James Ross Strait in the east.

### Abstract

The Kitikmeot Sea Science Study was initiated in 2014 to provide the Canadian High Arctic Research Station a scientific basis for long-term ecological monitoring and research in the Kitikmeot Region of the southern Canadian Arctic Archipelago. The region is unique in the Arctic due to its shallow bounding sills and massive freshwater input relative to its area. Thus, three foci guide the study: (1) the Pacific-origin estuarine inflow, which sets the oceanographic structure; (2) the origin and pathways of fresh water, which influence nutrient balances and stratification; and (3) tidally influenced biological communities in narrow

passages. To investigate these themes, we apply a suite of tools deployed from the R/V Martin Bergmann.

Our results show that the Kitikmeot Sea is characterized by two-layer estuarine flow, with surface outflows and subsurface inflows across the bounding sills. River inputs along the southern boundary deliver fresh water, terrestrial nutrients, and carbon to the riverine-coastal domain, which then spread throughout the system. Strong tidal currents in narrow passages enhance vertical heat and nutrient flux to maintain ice-free conditions in winter and tight pelagic-benthic coupling in summer.

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These narrow passages have hard bottom substrate inhabited by suspension feeders, while soft sediments with deposit feeders are found in areas of weaker currents elsewhere. Our analysis reveals a dynamic ecosystem characterized by pelagic-benthic coupling modified by the physical flow field and constrained by external inputs of nutrients and fresh water.

### Résumé

L'étude scientifique de la mer de Kitikmeot a été lancée en 2014 afin de fournir à la Station canadienne de recherche dans l'Extrême-Arctique une base scientifique pour la surveillance et la recherche écologiques à long terme dans la région de Kitikmeot, dans le sud de l'archipel Arctique

canadien. La région est unique dans l'Arctique en raison de ses seuils limitrophes peu profonds et de son apport massif en eau douce par rapport à sa zone. Ainsi, trois thèmes guident l'étude : (1) l'apport estuarien d'origine pacifique, qui établit la structure océanographique; (2) l'origine et les voies d'accès de l'eau douce, qui influent sur les équilibres et la stratification des nutriments; (3) les communautés biologiques influencées par les marées dans des passages étroits. Pour étudier ces thèmes, nous utilisons une série d'outils déployés par le navire de recherche océanographique *Martin Bergmann*.

Nos résultats montrent que la mer de Kitikmeot est caractérisée par un flux estuarien à deux couches, soit des débits sortants en surface et des débits entrants

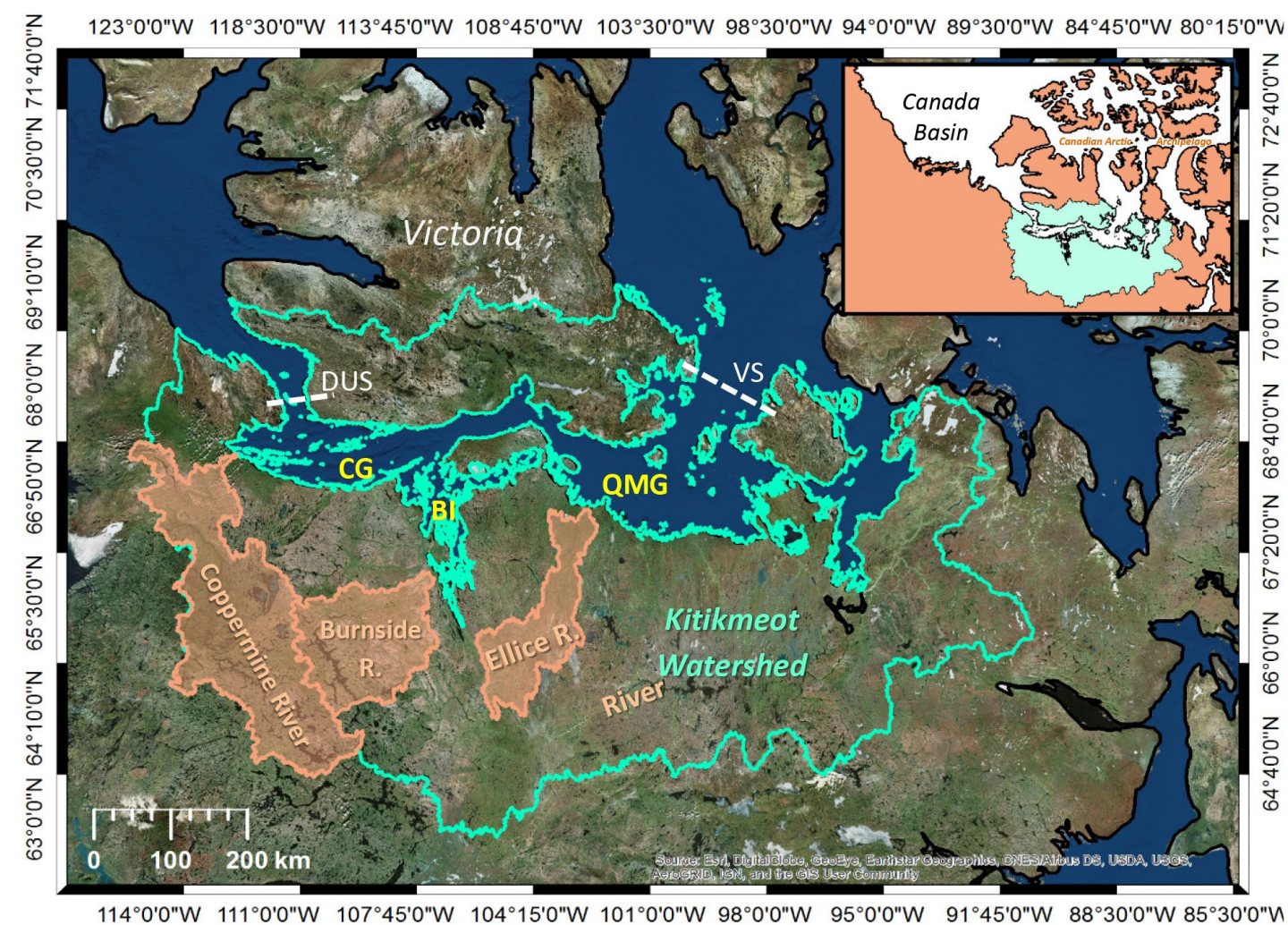


Figure 1: Kitikmeot Sea Region of the southern Canadian Arctic Archipelago. Inset plot shows the land area draining into the Kitikmeot Sea ("Kitikmeot Watershed"), shaded green in the context of the Canadian Arctic Archipelago (pink). Main plot shows the watersheds for the Coppermine, Burnside, and Ellice Rivers, shaded pink, that drain into Coronation Gulf (CG), Bathurst Inlet (BI), and Queen Maud Gulf (QMG) respectively. Shallow oceanic straits in both the west (Dolphin and Union Strait, DUS, 18 m sill) and northeast (Victoria Strait, VS, 20–30 m sill) restrict inflow of the relatively salty, nutrient-rich Pacific-origin waters that flow through the Canadian Arctic Archipelago. (From: Brown et al. 2016).



sous-marins à travers les seuils limitrophes. Les apports fluviaux le long de la limite sud apportent de l'eau douce, des nutriments terrestres et du carbone au domaine riverain-côtier, qui se propagent ensuite dans tout le réseau. Les forts courants de marée dans les passages étroits accroissent la chaleur verticale et le flux de nutriments pour maintenir des conditions sans glace en hiver et un couplage benthique-pélagique étroit en été. Ces passages étroits ont un substrat à fond dur habité par des suspensivores, tandis que des sédiments meubles et des dépositives se trouvent dans des zones de courants plus faibles ailleurs. Notre analyse révèle un écosystème dynamique caractérisé par un couplage benthique-pélagique modifié par le champ d'écoulement physique et limité par des apports externes de nutriments et d'eau douce.

## Introduction

The Kitikmeot Sea (Fig. 1) — which includes Coronation Gulf, Bathurst Inlet, Queen Maude Gulf, and Chancrey Inlet in the southern Canadian Arctic Archipelago — is

unique in the pan-Arctic system due to (1) its massive freshwater input relative to the area's size, (2) its primary nutrient supply delivered from the Canada Basin, and (3) its shallow bounding sills to the west and northeast ( $\leq 30$  m deep). These conditions maintain an estuarine-like circulation wherein surface outflowing fresh water of river and ice melt sources mixes with the deeper, salty oceanic waters that enter over the shallow bounding sills. Thus, strong salt stratification generally restricts vertical mixing and the upward fluxes of dissolved nutrients, resulting in overall relatively low primary production of the region. The resulting low annual biological production must affect the entire food web, and we speculate that this is a contributing factor to the lack of top predators, the larger polar bears and whales, that are found elsewhere.

Low overall biological production compels us to look for specific locations where biological production might be enhanced. Observations by residents, combined with high-resolution satellite imagery, suggest that the narrow gaps and straits between the many islands of the

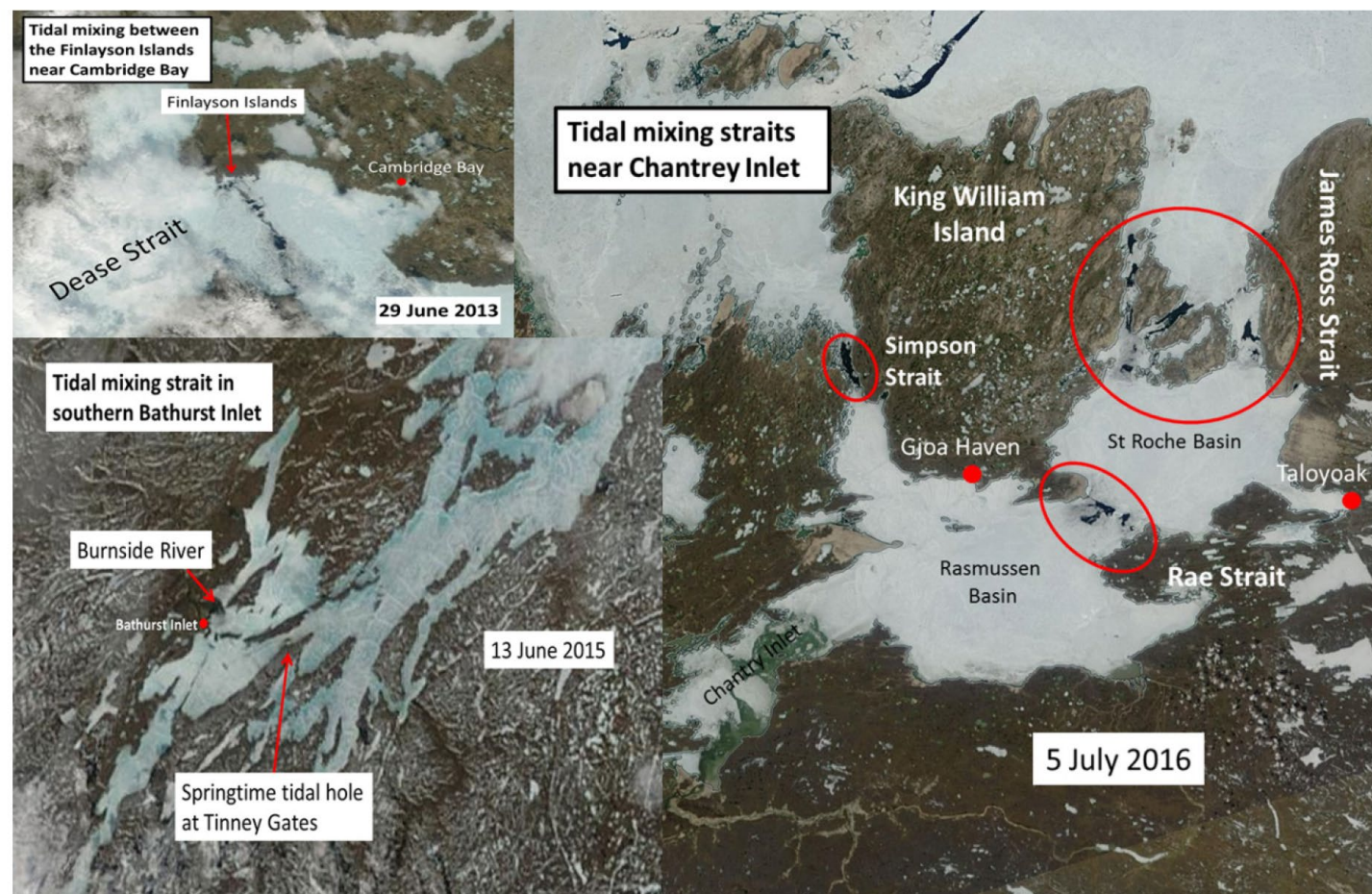


Figure 2: Satellite view of the springtime tidal mixing straits ("winter holes") in sea ice in the Finlayson Islands (upper left), Chancrey Inlet (right), and Bathurst Inlet (lower left). (From: Williams et al. 2016).

Kitikmeot can be prone to early ice breakup, suggestive of thinner ice, which makes them dangerous places for winter travel (Fig. 2).

We hypothesize that these "winter holes" in the sea ice are caused by upward mixing of subsurface heat, induced as tidal flow accelerates over sills and through narrow passes (Fig. 2). Furthermore, as the subsurface water is likely relatively nutrient-rich, the same upward mixing will also deliver nutrients to the euphotic zone year-round. Therefore, we suggest that near these "winter holes" in sea ice there will be enhanced summertime biological productivity and a patchwork of enhanced benthic ecosystems. These "summer gardens," will

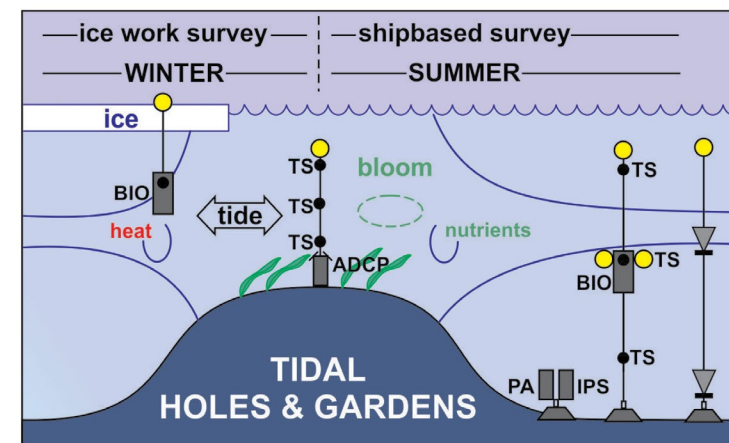


Figure 3: Schematic of the annual cycle of "tidal holes" and "gardens," showing the mechanisms by which tidally driven "winter holes" in sea ice may lead to high local biological production during the growing season ("summer gardens"). Contours represent isopycnal lines denoting stratification. Moored instrumentation measures the seasonal variation in temperature and salinity stratification (TS), profiles ocean currents (Acoustic Doppler Current Profiler, ADCP), assesses the biological response to light (Bio-optical package, BIO), listens for marine mammals (Passive Acoustics, PA), and measures ice draft (Ice Profiling Sonar, IPS). (By: Eddy Carmack, From: Williams et al. 2016).

contrast with the region's overall very low productivity (Fig. 3) and thus be biological hotspots may form critical feeding sites for the higher trophic levels.

The Kitikmeot Sea Science Study (K3S) was thus initiated in 2014 to investigate the hypothesis that *narrow gaps and straits between the many islands are year-round sites of vertical mixing, which results in polynyas in winter ("winter holes") and biological hotspots in summer ("summer gardens")*.

In addition, the K3S would provide the Canadian High Arctic Research Station a scientific basis for long-term ecological monitoring and research, and facilitate a strong partnership with CHARs. Three foci guide the study: (1) the Pacific-origin estuarine inflow, which sets the oceanographic structure; (2) the origin and pathways of fresh water, which influence nutrient balances and stratification; and (3) tidally influenced biological communities in narrow passages. We apply a suite of oceanographic tools and year-round moorings deployed from the *Martin Bergmann* to investigate these themes.

The K3S carried out observational field programs within the Kitikmeot Sea aboard the *Martin Bergmann* from 2014 to 2017, gathering a suite of new and exciting observations and advancing our understanding of this region (e.g., Williams et al. 2016, 2017; Brown et al. 2016; Rotermund et al. 2017; Fredriksen 2018). To be more inclusive of the entire region being investigated (terrestrial and marine), the Kitikmeot Marine Region Science Study (KMRSS) changed its name to the Kitikmeot Sea Science Study (K3S) during the 2017 program. The following report summarizes the main findings of the K3S field program carried out over the summers of 2014 to 2017.

## Estuarine circulation and Pacific water through-flow

One of the main foci of the K3S is the investigation of the Pacific-origin inflow, which sets the oceanographic structure of the region. The sub-surface, Pacific-origin water flows from the Canada Basin through the Canadian Arctic Archipelago and is restricted from entering the Kitikmeot Sea due to the shallow oceanic straits in both the west (Dolphin and Union Strait, DUS, 18 m sill) and northeast (Victoria Strait, VS, 20–30 m sill) (Fig. 1; e.g., McLaughlin et al. 2006; Michel et al. 2015). The subsurface waters that make it into the Kitikmeot Sea across these shallow sills are the upper layers of the Pacific-origin water and are relatively salty and nutrient-rich. These Pacific inflows (Salinity = 29, Volume  $\approx 256$  km<sup>3</sup> yr<sup>-1</sup>) are expected to combine with the river inputs to the Kitikmeot Sea (Salinity = 0, Volume of river inputs  $\approx 41$  km<sup>3</sup> yr<sup>-1</sup>; Williams et al. 2016) and low-salinity sea ice melt to form the shallow surface outflow from the Kitikmeot Sea (Salinity  $\approx 25$ , Volume  $\approx 297$  km<sup>3</sup> yr<sup>-1</sup>). This describes an estuarine-like circulation in which inflowing river water mixes with the deep inflowing salty oceanic waters to produce the low-salinity surface outflow, and



yields a residence time of about 13 years for waters residing in the Kitikmeot Sea (Williams et al. 2016).

The origin and pathways of the Kitikmeot Sea's freshwater components (precipitation, river input, and sea ice melt) influence nutrient balances and stratification in the surface ocean. River inputs alone account for as much as 70 cm of fresh water added annually to the surface of the Kitikmeot Sea (Brown et al. 2016), and can be a seasonal source of terrestrial nutrients (nitrate and silicate) for the coastal marine system, providing the necessary nutrients for primary producers once mixed with deeper Pacific-origin waters, which supply ample phosphate. The confluence of terrestrial nitrate and marine phosphate in the estuaries of the Kitikmeot Sea could play an important role contributing to the productivity of the coastal region (Brown et al. 2016). For example, nutrient relationships in Coronation Gulf and Queen Maud Gulf show lower nitrate and phosphate (but similar nitrate:phosphate ratios) compared with the

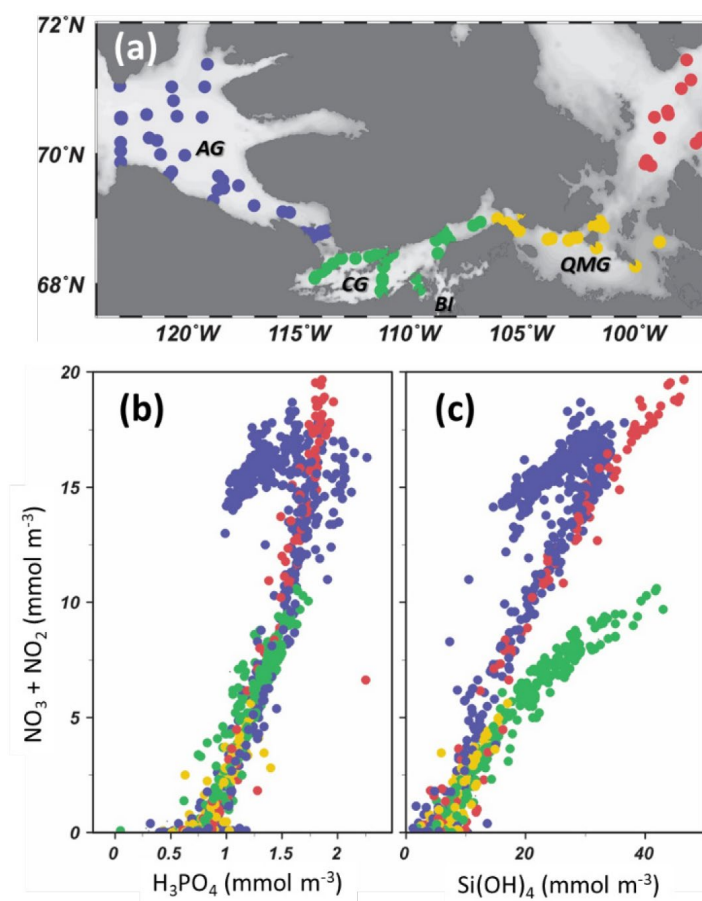


Figure 4: Nutrient relationships in Coronation Gulf (CG) and Queen Maud Gulf (QMG) show lower nitrate and phosphate (but similar nitrate/phosphate ratios) compared with the same depths in Amundsen Gulf (AG) and Larsen Sound (LS), but much higher silicate.

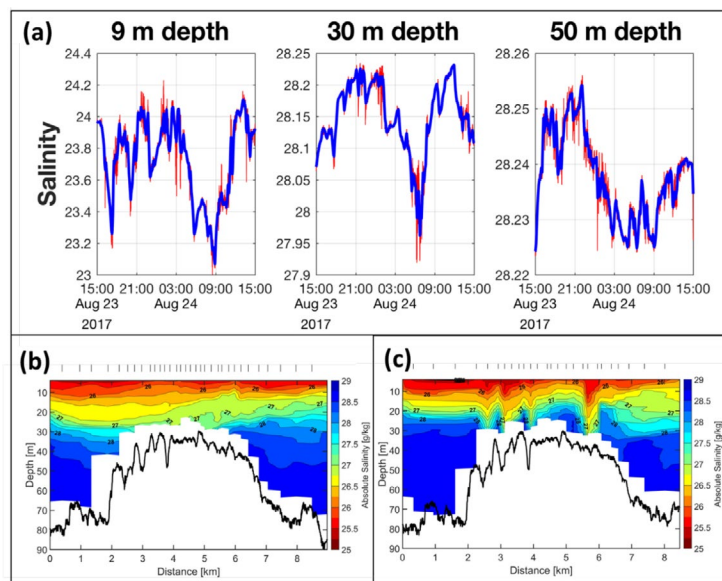


Figure 5: (a) Deployments of rapidly sampling moorings from just south of the narrow strait at Tinney Gates on Aug 23 to 24, 2017, show both slow and rapid fluctuations in salinity over 24 hrs and (b) and (c) Repeat Underway-CTD sections through the Finlayson Islands on Aug 18, 2017, (b) at 09:00 GMT and (c) 9 hrs later at 18:00 GMT. These show that as the tidal cycle progresses to peak flow, isohalines (e.g.,  $S = 27 \text{ g kg}^{-1}$ ) are brought towards the surface due to tidal mixing over the sill.

same depths in Amundsen Gulf and Larsen Sound, but much higher silicate (Fig. 4; Williams et al. 2017).

### Evidence of mixing in tidal straits

Stratification from fresh water in the surface ocean restricts the mixing of deep Pacific-origin nutrients into the photic zone, where it could fuel primary production. The tidal flows in numerous narrow straits of the Kitikmeot Sea provide opportunities to mix deep nutrients up to the surface, breaking this strong surface stratification. Tidal currents are highest in narrow straits, and should contribute to mixing throughout the year, generating the open-water “winter holes” in springtime ice (Fig. 2). During the 2017 field season, we deployed rapid-sampling moorings to obtain a time series of temperature, salinity, and chlorophyll fluorescence data over a 24-hour period to observe the tidal cycle. Figure 5a illustrates observations from just south of the narrow strait at Tinney Gates in southern Bathurst Inlet (Fig. 2). Here, both slow and rapid fluctuations in salinity are observed at the three different depth intervals. These vertical isopycnal displacements and diapycnal mixing both have potential to deliver nutrients from deeper

Pacific-sourced waters into the photic zone at regular intervals. Further observations of tidal mixing were observed in Unahitak Narrows, a narrow strait between the Finlayson Islands in Dease Strait near Cambridge Bay (Fig. 5b, 5c; Rotermund et al. 2017). Here, repeat Underway-CTD sections illustrate that as the tidal cycle progresses to peak flow, isohalines (e.g.,  $S = 27 \text{ g kg}^{-1}$ ) are brought towards the surface by the tides over the Unahitak Narrows sill, again with the potential of bringing deeper nutrients into the photic zone.

### Increased ice algae in “winter holes” and differing benthic structure in “summer gardens”

Mixing of deep Pacific-origin nutrients up to the photic zone within the Kitikmeot Sea tidal straits creates favourable conditions for primary producers, with cascading effects into the food web. Examples of this can be found in both winter and summer studies investigating the “holes” and “gardens” potentially created by these tidal straits. Winter studies in the Finlayson Islands from 2016 indicate that ice algal biomass and current velocity were highest in the centre of the tidal straits, and decreased moving away from the straits towards the west (Fig. 6a; Dalman et al. 2017). Summertime observations of benthic communities indicate that high-flow sites, low-flow sites, and transitional sites differed in community composition (Fig. 6b; Fredriksen 2018). Suspension feeders (e.g., sea cucumbers, cnidarians, and feather stars) dominated sites with high-current velocities in the tidal straits whereas surface-deposit feeders (e.g., brittle stars) dominated in low-flow areas downstream (Fig. 6b; Fredriksen 2018). Stable isotope data reveals further information on the food web structure and indicates tight coupling of benthos to phytoplankton-based food

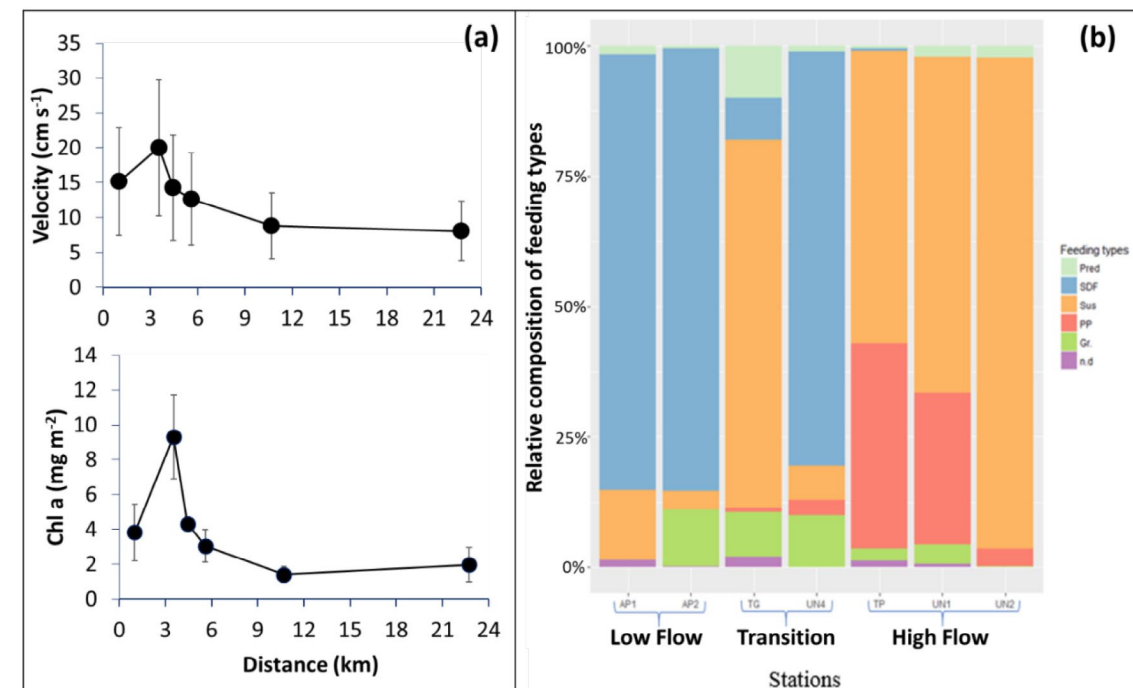


Figure 6: (a) At the Finlayson Islands, ice algal biomass (chlorophyll a, bottom) and current velocity (top) were highest in the centre of the tidal straits (at 3 km in the transect) and decreased moving east and (b) Benthic communities of suspension feeders (Sus, e.g., sea cucumbers, cnidarians, and feather stars) dominated sites with high-current velocities in the tidal straits, and surface-deposit feeders (SDF, mostly brittle stars) dominated in low-flow areas downstream (pred = predator/scavengers, PP = primary producer, Gr. = grazers, n.d. = not defined).

sources both in the tidal straits and just downstream from them (Fredriksen 2018). As well, grazers and suspension feeders in the tidal straits appear to use the freshest material, whereas surface-deposit feeders in downstream areas that accumulate sediment are slightly more isotopically enriched (Fredriksen 2018).

### Conclusions

Preliminary observations from the K3S illustrate the unique nature of the Kitikmeot Sea. Pacific-origin waters combined with freshwater input from the large terrestrial drainage basin set up the estuarine structure of the Kitikmeot Sea and further influence both its nutrient balance and stratification. Mixing within tidal straits works to break this stratification and bring Pacific nutrients into the photic zone, where they are available to primary producers. Observations of under-ice and benthic communities illustrate the effects of these physical processes on the food web, showing increased concentrations of ice algae within tidal straits and a shift in benthic communities towards suspension feeders, which can capitalize on sinking material associated with enhanced surface ocean productivity. The K3S will

continue to investigate these themes in collaboration with community partners throughout the Kitikmeot region through 2018 and beyond.

## Community considerations

Our oceanographic exploration of the Kitikmeot Sea aims to provide a description of the functioning and connectivity of the marine ecosystem that complements indigenous knowledge and is useful to northern communities. These communities depend on the marine food web for fish and seals, and on the sea ice for travel. Our results are beginning to provide a scientific basis for higher biological production and dangerous thin ice in the tidal straits of the region. Our development of the 'winter-holes-and-summer-gardens' model is based on our general understanding of coastal oceans and conversations with Canadian Rangers as part of the wintertime Canadian Rangers Ocean Watch program. We also conduct and encourage training and capacity building for oceanographic monitoring in the region via Canadian Rangers Ocean Watch, in collaboration with Ocean Networks Canada and the Arctic Research Foundation. Community-based oceanographic time series initiated in the Kitikmeot can be placed in context using the oceanographic understanding developed by the K3S.

## Acknowledgements

We would like to thank the captains and crew of the *Martin Bergmann*. Their skill and flexibility allow complex interdisciplinary oceanographic expeditions to be conducted from their small ship; without their support, the Kitikmeot Sea Science Study would not be possible. Also, this oceanographic research is only possible with the vision and support of Jim Balsillie, the founder and benefactor of the Arctic Research Foundation, which owns the Martin Bergmann research vessel. We also acknowledge the Nunavut Planning Commission, the Nunavut Impact Review Board, and the Nunavut Research Institute for granting permission for this research to be conducted in their territorial waters.

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