

Arctic Geomicrobiology and Climate Change

Project Leader

Soren Rysgaard (University of Manitoba)

Network Investigators

CJ (Christopher John) Mundy (Université du Québec à Rimouski); Tim N. Papakyriakou (University of Manitoba)

Collaborators

Jens Ehn, Ryan Galley, Casey Hubert, Zou Zou Kuzyk, Marcos Lemes, Feiyue Wang (University of Manitoba); Ronnie Glud (University of Southern Denmark); Jody Deming (University of Washington)

Post-Doctoral Fellows

Brent Else, Nicolas Geilfus, Monika Pucko (University of Manitoba)

PhD Students

Wieter Boone (Centre for Earth Observation Science (CEOS)); Karley Campbell, Odile Crabeck (University of Manitoba)

Abstract

The Anthropocene is a time of extraordinary change in the Arctic. The Arctic has experienced recent unprecedented variability in both the rates and magnitudes of change in the cryosphere, atmosphere, lithosphere, and dependent ecosystem function. At the same time, increased industrial development and the globalization of local economies has proceeded rapidly. These changes challenge our ability to respond and to develop coordinated and scientifically informed policies for Canada's Arctic. This project, aligned with the targeted achievements of the Canada Excellence Research Chair (CERC) in Arctic Geomicrobiology and Climate Change, will further our understanding of geomicrobial transformations as they occur in Arctic sea ice and sediments including the regeneration of nutrients required by primary producers, which are the basis of the health of all other inhabitants of the Arctic marine system. This project aims to observe, interpret and communicate key baseline information that Canadians can build upon to address key issues facing the Canadian Arctic as environmental stewards, stakeholders and governments sustainably develop its human and natural resources financially, socially and ecologically.

Recent evidence suggests that microbial activity and chemical transformations within sea ice greatly influence inorganic carbonate chemistry, playing a far more important role in regulating carbon dioxide (CO₂) uptake by Arctic seas than previously anticipated. Our program aims to investigate and quantify the importance of these fundamental microbial activities using state-of-the-art assessment techniques in a comprehensive three-pronged approach of ice tank micro- and mesocosms, in situ fieldwork, and modelling studies. Combining experimental ice tank and in situ studies will provide important new insight into the regulation of these processes, their seasonal and geographical distribution, and how they are coupled between surface ocean and seafloor. In 2014-2015 physical oceanographic and sea ice physical research was undertaken, along with research into sea ice biogeochemical cycling in a sea ice tanks

and during in situ studies, as well as the role of sea ice in contaminant exchange between atmosphere and ocean. Modelling activities will range from small-scale studies within sea ice and sediment compartments to local coastal regions of strategic importance and the large-scale systems of the Arctic Ocean and its peripheral seas. This project aims to produce models of coupled physical-biological processes in the Arctic marine system, increasing our predictive capacity and therefore our ability to inform future environmental conditions.

Key Messages

- Field campaigns were conducted in Nuuk (Greenland) and Cambridge Bay (Nunavut).
- A sea ice tank study was conducted at the Sea-ice Environmental Research Facility (SERF, University of Manitoba).
- Ikaite precipitation and dissolution in sea ice was found to depend largely on ice temperature.
- The dynamic formation/dissolution of ikaite throughout a seasonal cycle may have important impacts on the underlying seawater.
- Gypsum crystals were identified in sea ice for the first time, helping establish the theoretical pathway for chemical precipitates in sea ice.
- Sea ice cores were imaged using magnetic resonance, giving insight into the connectivity of the ice interior to the atmosphere and underlying ocean.

Objectives

The overall objective of the CERC program is to investigate and quantify the importance of the fundamental geomicrobial processes in the ice-covered Arctic Ocean using state-of-the-art assessment techniques in a comprehensive three-pronged approach of experimental ice tank, in situ and modeling studies. In 2013, we focused on ice tank and in situ studies, whose objectives were as follows:

1. Sea-ice Experimental Research Facility project

- Investigate controls on Ikaite formation/dissolution.
- Derive carbon mass balances through a complete sea ice growth/decay cycle.
- Investigate new techniques for measuring the content and distribution of gas bubbles in sea ice.
- Investigate the use of underwater eddy correlation to measure under-ice fluxes of heat, momentum, salt, and oxygen.

2. Nuuk Sea Ice Campaign

- Investigate the dynamics of greenhouse gases (CO₂, CH₄, N₂O) within natural sea ice, and their interactions with the seawater and atmosphere.
- Measure under-ice exchanges of salt, heat, oxygen and momentum.
- Study the evolution and distribution of pH in sea ice.
- Evaluate and compare techniques for monitoring sea ice algae primary production, and investigate the strangely low biomass/primary production in Greenland fjords.
- Study the distribution of total and methylated mercury in snow, sea ice, and seawater.

3. 2013 ArcticNet Cruise

- Investigate the ocean carbon system in Labrador Fjords, with an emphasis on air-sea CO₂ exchange.

4. 2013 R/V Martin Bergmann Cambridge Bay Cruise

- Examine the influence of sea ice melt and rivers on the freshwater budget and organic carbon cycle in coastal bays near Cambridge Bay.
- Examine the influence of physical gradients (sea ice melt and river water) on primary

production and their by-products in the vicinity of Cambridge Bay.

- Examine microbial diversity in seawater and marine sediments as it relates to in situ biogeochemical cycling and the potential microbial response to increased industrial activity, e.g., oil spills.
- Examine the surface distribution of pCO₂ in seawater as influenced by freshwater and primary production.

Introduction

Sea ice is a complex material composed of ice crystals, gas bubbles, liquid brine, solid salts and biological material. The proportions and compositions of these inclusions are not static, as physical, chemical, and biological processes create and continuously modify them. Furthermore, the distribution of gas and liquid inclusions can make sea ice permeable, permitting interaction with the underlying seawater and/or the overlying atmosphere. The study of these inclusions, their modification, and their impact on the atmosphere and seawater is a key focus of this ArcticNet project.

Within this context, major efforts were made in 2013 to better understand the formation and dissolution of solid precipitates in sea ice. As seawater freezes, salts become concentrated in brine inclusions. Theoretical work has predicted several “pathways” by which certain solid precipitates should form in these inclusions as ice temperatures decrease and brine concentration increases. Observations of natural and artificial sea ice have recently confirmed the precipitation of ikaite (CaCO₃•6H₂O) (Dieckmann et al. 2008, Dieckmann et al. 2010), an important precipitate because its formation releases CO₂, which may be transported below the ocean mixed layer with the sinking of dense brine. If this is the case, ikaite production in sea ice will act as a “carbon pump” removing CO₂ from the surface ocean to the deeper water layers (Rysgaard et al. 2009, 2011). However, the fate of CO₂ released by ikaite precipitation depends largely on the conditions and location of formation

within the sea ice as well as the physical properties of the sea ice itself. Furthermore, observations of any other chemical precipitates in sea ice did not previously exist, which means that theoretical treatments of precipitation pathways are largely unproven. The investigation of these sea ice properties prompted investigations at the Sea-ice Experimental Research Facility (SERF) over the past two years.

Also key to understanding the role of sea ice as a reactive biogeochemical medium are the processes by which fluids may be transported within the ice. Past investigations have shown that brine inclusions can form connected drainage channels that permit vertical and horizontal fluid movement (Lake and Lewis 1970; Eide and Martin 1975). These brine inclusions and their connectivity is difficult to visualize, which has led the members of this project to develop state-of-the-art magnetic resonance imagery techniques. Significant advances in the analysis of this imagery were made this year, and are discussed in this report.

Activities

Sea-ice Environmental Research Facility (SERF) Campaign

An experiment was performed at the Sea-ice Environmental Research Facility (SERF) at the University of Manitoba, Winnipeg, Canada, in an outdoor pool 18.3 m by 9.1 m in surface area and 2.6 m deep, with an approximate operating volume of 380 m³ (Fig. 1). The pool was exposed to natural ambient temperatures, winds, and solar radiation, and contained artificial seawater (ASW) similar in chemical composition to natural average seawater. Sea ice was grown in the pool from open water on 13 January (2013) and reached 20 cm in thickness on 26 January, after which the sea ice was melted by circulating heated ethylene glycol through a closed-loop hose fixed at the bottom of the pool.

Throughout the experiment, a wide range of physical, chemical, and biological measurements were made.

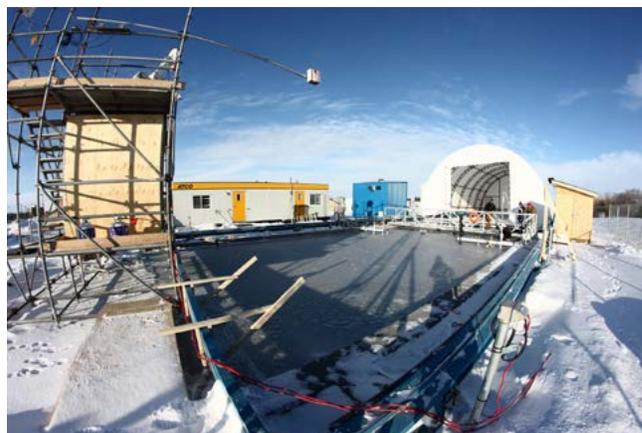


Figure 1. The Sea-ice Experimental Research Facility (SERF) during the 2013 experiment (photo by J. Sievers).

Meteorological variables and sea ice/seawater temperature were recorded continuously. Ice cores were obtained at least 3 times per day, and analyzed for ikaite content, carbon system parameters, dissolved oxygen, gas content, and contaminants. Water samples were also obtained at regular intervals, measuring carbon system parameters, salinity, and dissolved oxygen. An underwater eddy covariance system was deployed and operated continuously.

Nuuk Sea Ice Campaign

The Nuuk sea ice campaign was conducted 4 March – 17 April (2013). A sea ice site located in a small fjord adjacent to Godthåbsfjord was occupied, and re-visited on an approximately 3-day rotation. Some instruments (meteorological, oceanographic) were left at the site, but most equipment was transported back-and-forth by boat. Ice core samples were collected during site occupations, and transported back to laboratories at the Greenland Climate Research Centre for analysis. Analyzed ice core parameters included carbon system variables, gas content and distribution, microbial activity, mercury content, and brine distribution and transport. Primary production was measured under the sea ice using a variety of techniques, and underwater eddy covariance was used to measure under-ice exchanges of salt, heat, dissolved oxygen and momentum. Eight participants from four different institutions were involved in the experiment (Fig. 2).

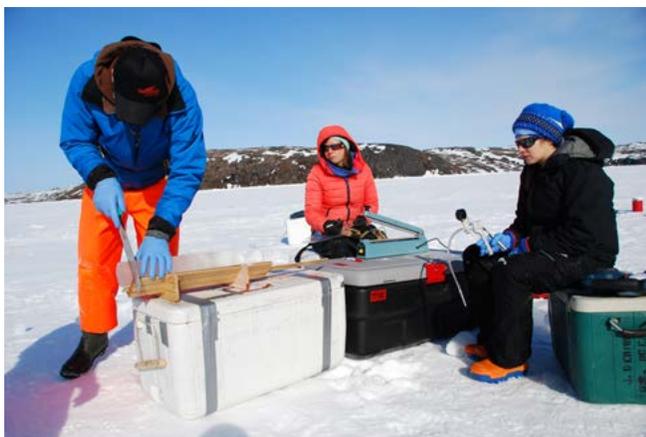


Figure 2. Collecting ice cores for sea ice chemistry and biology studies during the 2013 Nuuk campaign (photo by N. Geilfus).

2013 ArcticNet Campaign

We participated in the 2013 ArcticNet campaign, sending one researcher to study ocean carbon system parameters in sub-Arctic fjords along the Labrador coast. The study was conducted Jul. 26 – Aug. 12, and focused on the Okak and Nachvak fjords. Dissolved CO_2 concentration in the sea surface (pCO_2) was measured continuously using an on-track equilibrator, and vertical profiles of DIC and TA were collected at discrete sampling stations using the ship's rosette. Sampling for pCO_2 and other carbon system parameters was also conducted from the zodiac, accessing the inner portions of the fjords (Fig. 3).



Figure 3. The CCGS Amundsen in Nakhvak fjord, photographed during zodiac sampling (photo by B. Else).

2013 R/V Martin Bergmann Cambridge Bay Cruise

From 21-27 Jul, 2013, an exploratory study was undertaken in the vicinity of Cambridge Bay onboard the R/V Martin Bergmann (Fig. 4). The project sampled 26 stations in Dease Strait, Wellington Bay, and Queen Maude Gulf. At each location, instrument casts were made to measure vertical profiles of conductivity and temperature. At select stations (16), water samples were collected from 4 to 5 depths, and analyzed for salinity, O_{18} , nutrient concentration, total suspended solids, dissolved organic carbon, particulate organic carbon and nitrogen, pigment and mycosporine-like amino acid concentrations, particulate spectral absorption, coloured dissolved organic matter, flow cytometry, and algal taxonomy. At a subset of those stations (8), sediment samples were collected using a box core and were analyzed for radioisotopes (^{210}Pb , ^{137}Cs , ^{226}Ra), total, inorganic and organic carbon, total nitrogen, and stable carbon isotopes. We also worked in collaboration Dr. Jean-Sébastien Moore from Université Laval and Les Harris from Fisheries and Oceans Canada from Fisheries and Oceans Canada to deploy an array of acoustic receivers across Wellington Bay region as part of an acoustic telemetry project aiming to describe the marine migratory behaviour of anadromous Arctic char (*Salvelinus alpinus*) in the region.



Figure 4. The R/V Martin Bergmann conducting sampling near Cambridge Bay.

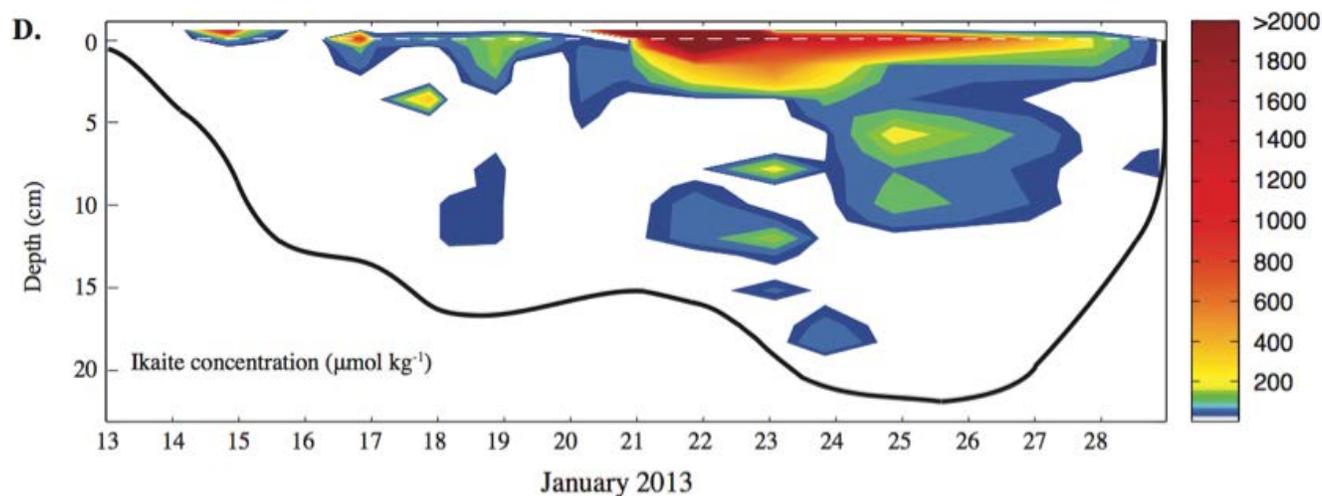


Figure 5. Ikaite concentrations in sea ice during the 2013 SERF project.

Results

Ikaite Distributions in Artificial Sea Ice

During the SERF experiment, a wide range of atmospheric conditions were encountered, which created significant variability in sea ice temperature and salinity. As a result, we observed highly dynamic ikaite precipitation and dissolution (Fig. 5). During the experiment, ikaite precipitated in sea ice with temperatures below -3°C , creating three distinct zones of ikaite concentrations: (1) a mm to cm thin surface layer containing frost flowers and brine skim with concentrations of $>2,000\ \mu\text{mol kg}^{-1}$, (2) an internal layer with concentrations of $200\text{--}400\ \mu\text{mol kg}^{-1}$ and (3) a bottom layer with concentrations of $<100\ \mu\text{mol kg}^{-1}$. Snowfall events caused the sea ice to warm, dissolving ikaite crystals under acidic ($\text{pH} \sim 5$) conditions.

Removal of the snow cover allowed the sea ice to cool and brine salinities to increase, resulting in rapid ikaite precipitation.

First Observations of Gypsum in Natural and Artificial Sea Ice

To investigate the occurrence of chemical precipitates in sea ice, we examined samples from a 2012 SERF experiment, and a 2012 expedition to Young Sound (Greenland). In frost flowers, brine skim, and thin sea

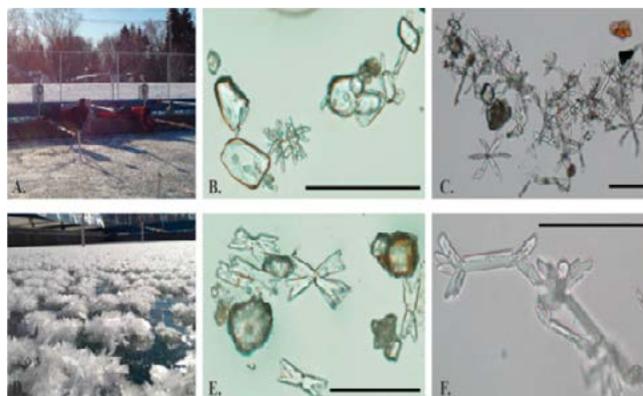


Figure 6. A) SERF pool covered with frost flowers; (B) mixture of ikaite and gypsum crystals found in SERF ice; (C) mixture of ikaite and gypsum crystals found in SERF frost flowers; (D) closer view of frost flowers; (E) gypsum crystals from sea ice samples, (F) gypsum crystals from brine skim samples.

ice from both locations we found crystals with two distinct morphologies (Fig. 6). Rhombic single crystals that dissolved rapidly at room temperature were confirmed to be ikaite crystals by x-ray diffraction analysis. Euhedral crystals that did not dissolve at room temperature, and were typically intergrown with each other were confirmed to be gypsum crystals by x-ray diffraction analysis. These are the first observations of gypsum precipitation in sea ice.

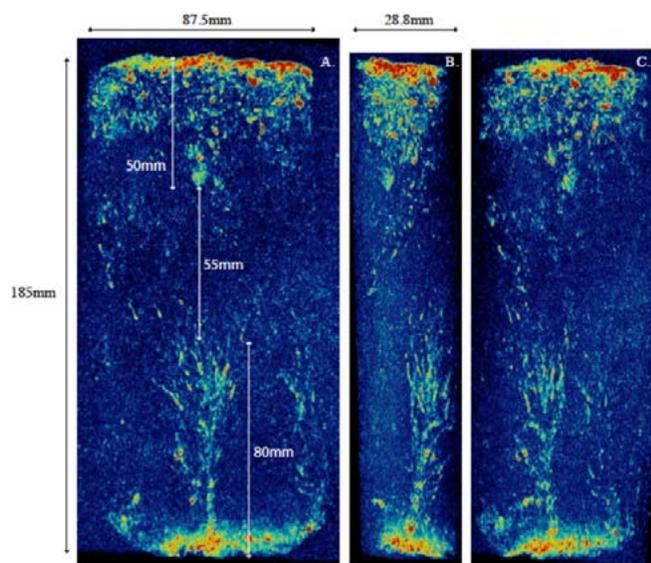


Figure 7. Magnetic resonance images in 3-dimensional maximum intensity projection. Viewed from front (LEFT), side (MIDDLE) and rotated obliquely (RIGHT).

Observations of Brine Drainage Channels in Young Sea Ice

Magnetic resonance imagery of sea ice cores obtained from SERF in 2012 showed that three-dimensional reconstruction of a brine drainage channel can be performed rapidly using this technique (Fig. 7). The ice that we sampled was very young, but already had a well-established brine drainage system. The imagery was used to identify the amount and location of liquid inclusions in sea ice, and to elucidate horizontal and vertical fluid permeability. A simple analysis to derive vertical profiles of liquid fractions from the magnetic resonance imagery compared well to existing models of liquid fraction based on temperature and salinity.

Discussion

Ikaite Distributions in Artificial Sea Ice

The ikaite concentrations that we measured at SERF in 2013 are the highest ever reported in sea ice. Concentrations were particularly high at the surface of the sea ice, in frost flowers and in the brine skim. This is interesting, since any CO_2 liberated by CaCO_3

formation in these portions of the ice would be lost to the atmosphere; however, an equal amount of CO_2 should be taken up again upon dissolution of the ikaite crystals during melt. Another interesting aspect of this study is the observed relationship between ikaite concentration and ice temperature. The relationship itself is not surprising, however we were able to show that the form of the temperature/ikaite relationship follows that predicted by FREZCHEM (Marion et al. 2010), a model for chemical precipitation in sea ice. A key implication of this relationship is that storage and transport of cores for ikaite analysis should be done very carefully. Another key observation of this study is that ikaite precipitation and dissolution may occur multiple times between fall freeze-up and summer melt. Since ikaite formation is associated with dense brine with high CO_2 concentration, and ikaite dissolution is associated with lighter brine with low CO_2 concentration, this may create a pumping mechanism that keeps pCO_2 low in ice-covered surface waters even in wintertime.

First Observations of Gypsum in Natural and Artificial Sea Ice

The discovery of gypsum crystals in sea ice was somewhat surprising, given that researchers have now been looking for chemical precipitates in sea ice for several years. However, we were able to show (using the FREZCHEM model) that gypsum crystals likely exist in a narrow temperature window between -6.2 and -7.1°C . It is very possible that past studies have not sampled ice within this window, or that core storage at low temperatures caused the absence of gypsum crystals. The discovery of these crystals is important, because it helps confirm theoretical precipitation pathways for sea ice brines. Furthermore, gypsum crystals are not common in the marine environment; therefore, if they can be identified in marine sediments at high latitudes, they may provide a proxy record for past sea ice conditions.

Observations of Brine Drainage Channels in Young Sea Ice

The ability to image brine drainage channels in sea ice has several important implications. First, it allows for

characterization of the permeability of sea ice. In the core that we imaged, the upper layers had spherical, unconnected brine pockets, which were clearly impermeable to fluid transport. This suggests that the ice volume is not readily able to exchange material with the atmosphere. On the other hand, the lower layers were connected, indicating that convective exchange with the underlying seawater could occur. Second, the morphology of the brine channels is important. The fact that brine drainage channels are connected both vertically and horizontally has some bearing on brine collection techniques that rely on drainage through these channels. Finally, the imaging of brine channels helps confirm work relating sea ice desalinization to mushy layer theory (e.g. Feltham et al. 2006).

Conclusion

This ArcticNet project has made important strides this year towards better understanding chemical precipitates in sea ice. Ikaite production and dissolution in sea ice was shown to be very dynamic, and strongly related to ice temperature. This suggests that controls on ice temperature (e.g. ice thickness, snow depth, atmospheric temperature) may be very important in determining the quantity and location of ikaite in sea ice. Temporal variations in temperature may drive repeated ikaite formation and dissolution over an annual cycle, which may have important impacts on the underlying water column. The discovery of gypsum crystals in sea ice further extends our knowledge of precipitates in sea ice, and is useful in confirming existing theoretical understandings of precipitates. Increased confidence in these models may ultimately lead us towards discoveries of other precipitates in sea ice. Finally, the development of magnetic resonance imaging techniques to observe the connectivity of brine channels helps us understand how material may be transported in sea ice. Combining this technique with our knowledge of precipitates should help us understand how chemical reactions occurring within sea ice impact the underlying seawater and overlying atmosphere.

Acknowledgements

We thank the Canada Excellence Research Chairs (CERC) program, and ArcticNet for financial support. We also acknowledge the financial and logistical support of the Arctic Science Partnership.

References

- Dieckmann, G. S., Nehrke, G., Papadimitriou, S., Göttlicher, J., Steininger, R., Kennedy, H., Wolf-Gladrow, D., and Thomas, S. N.: Calcium carbonate as ikaite crystals in Antarctic sea ice, *Geophys. Res. Lett.*, 35, L08501, doi:10.1029/2008GL033540, 2008.
- Dieckmann, G. S., Nehrke, G., Uhlig, C., Göttlicher, J., Gerland, S., Granskog, M. A., and Thomas, D. N.: Brief Communication: Ikaite (CaCO₃·6H₂O) discovered in Arctic sea ice, *The Cryosphere*, 4, 227–230, doi:10.5194/tc-4-227-2010, 2010.
- Eide, L. I. and Martin, S.: 1975. The formation of brine drainage features in young sea ice, *Journal of Glaciology*, 14(70): 137-154).
- Feltham, D. L., Untersteiner, N., Wettlaufer, J. S., and Worster, M. G.: 2006. Sea ice is a mushy layer, *Geophysical Research Letters*, 33, L14501, doi: 10.1029/2006GL026290.
- Lake, R. A. and Lewis, E. L.: 1970. Salt rejection by sea ice during growth, *Journal of Geophysical Research*, 75(3): 583-597.
- Marion, G.M., Mironenko, M.V., Roberts, M.W.,: FREZCHEM: a geochemical model for cold aqueous solutions. *Comput. Geosci.*, 36, 10–15, 2010.
- Rysgaard, S., J. Bendtsen, L. T. Pedersen, H. Ramløv, and R. N. Glud (2009), Increased CO₂ uptake due to sea ice growth and decay in the Nordic Seas, *J. Geophys. Res.*, 114, C09011, doi:10.1029/2008JC005088.
- Rysgaard, S., Bendtsen, J., Delille, B., Dieckmann, G., Glud, R. N., Kennedy, H., Mortensen, J.,

Papadimitriou, S., Thomas, D., and Tison, J.-L. (2011): Sea ice contribution to air-sea CO₂ exchange in the Arctic and Southern Oceans, *Tellus B*, 63, 823–830, doi:10.1111/j.1600-0889.2011.00571.x, 2011.

Publications

(All ArcticNet refereed publications are available on the ASTIS website (<http://www.aina.ucalgary.ca/arcticnet/>).

Barber, D.G., Hop, H., Mundy, C.J., Else, B., Dmitrenko, I., Tremblay, J.-E., Ehn, J.K., Assmy, P., Daase, M., Candlish, L., Rysgaard, S., 2013, Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Sea Ice Zone, *Progress in Oceanography*,

Campbell, K.L., Mundy, C.J., Barber, D.G., Gosselin, M., 2013, Time series measurements of ice algae biomass using transmitted irradiance and assessment of influential physical variables over the spring melt period, *Arctic*,

Campbell, K.L., Mundy, C.J., Barber, D.G., Gosselin, M., 2013, Characterizing the ice algae biomass-snow depth relationship over spring melt using transmitted irradiance, *Journal of Marine Systems*,

Crabeck, O., Delille, B., Rysgaard, S., Thomas, D.N., Geilfus, N.-X. and J.-L. Tison, 2014, CO₂ and CH₄ in sea ice from a subarctic fjord, *Biogeosciences*,

Crabeck, O., Delille, B., Rysgaard, S., Thomas, D.N., Geilfus, N.-X., Else, B.G.T., and J.-L. Tison, 2014, First 'in situ' determination of gas transport coefficients (DO₂, DAr and DN₂) from bulk gas concentration measurements (O₂, N₂, Ar) in natural sea ice, *Journal of Geophysical Research*,

Else, B.G.T., Galley, R.J., Lansard, B., Barber, D.G., Brown, K., Mucci, A., Papakyriakou, T.N., Tremblay, J.-E., and S. Rysgaard, 2013, Further observations of a decreasing atmospheric CO₂ uptake capacity in the Canada Basin (Arctic Ocean) due to sea ice loss, *Geophysical Research Letters*, v.40, 1132-1137, doi:10.1002/grl.50268

Else, B.G.T., Papakyriakou, T.N., Asplin, M.G., Barber, D.G., Galley, R.J., Miller, L.A., and A. Mucci, 2013, Annual cycle of air-sea CO₂ exchange in an Arctic polynya region, *Global Biogeochemical Cycles*, v.27, no.2, 388-398, doi:10.1002/gbc20016

Else, B.G.T., Papakyriakou, T.N., Raddatz, R., Galley, R.J., Mundy, C.-J., Barber, D.G., Sywstun, K., and S. Rysgaard, 2013, Surface energy budget of landfast sea ice during the transitions from winter to snowmelt and melt pond onset: The importance of net long wave radiation and cyclone forcings, *Journal of Geophysical Research*,

Galindo, V., Levasseur, M., Mundy, C.J., Gosselin, M., Tremblay, J.-E., Scarratt, M., Gratton, Y., Papakiriakou, T., Lizotte, M., 2013, Influence of brine drainage on sea ice and under-ice dimethylsulfoniopropionate in the Canadian Arctic Archipelago in spring, *Journal of Geophysical Research*,

Galley, R.J., Else, B.G.T., Geilfus, N.-X., Hare, A.A., Isleifson, D., Ryner, L., Barber, D.G., and S. Rysgaard, 2013, Morphology and distribution of liquid inclusions in young sea ice as imaged by magnetic resonance, *The Cryosphere Discussions*, v.7,, 4977-5006, doi: 10.5194/tcd-7-4977-2013

Galley, R.J., Else, B.G.T., Prinsenberg, S.J., and D. Barber, 2013, Summer sea ice concentration, motion and thickness near areas of proposed offshore oil and gas development in the Canadian Beaufort Sea - 2009, *Arctic*, v.66, no.1, 105-116

Geilfus, N.-X., G. Carnat, G. S. Dieckmann, N. Halden, G. Nehrke, T. Papakyriakou, J.-L. Tison, and B. Delille, 2013, First Estimates of the Contribution of CaCO₃ Precipitation to the Release of CO₂ to the Atmosphere During Young Sea Ice Growth, *Journal of Geophysical Research*, v.118, no.1, 244-255

Geilfus, N.-X., R. J. Galley, M. Cooper, N. Halden, A. Hare, F. Wang, D. H. Søgaard, and S. Rysgaard, 2013, Gypsum crystals observed in experimental and natural sea ice, *Geophysical Research Letters*, v.40,, doi:10.1002/2013GL058479

- Hare, A.A., F. Wang, D. Barber, N.-X. Geilfus, R.J. Galley, and S. Rysgaard, 2013, pH Evolution in Sea Ice Grown at an Outdoor Experimental Facility, *Marine Chemistry*, v.154, 46-54
- Kuzyk, Z.Z., Gobeil, A.C. and R. Macdonald, 2013, 210Pb and 137Cs in Margin Sediments of the Arctic Ocean: Controls on Boundary Scavenging, *Global Biogeochemical Cycles*, doi:10.1002/gbc.20041
- Leu, E., Mundy, C.J., Assmy, P., Campbell, K., Gabrielsen, T.M., Gosselin, M., Juul-Pedersen, T., Gradinger, R., 2013, Arctic spring awakening – steering principles behind the phenology of vernal ice algae blooms, *Progress in Oceanography*,
- McDonald, S., Koulis, T., Ehn, J., Campbell, K., Gosselin, M., Mundy, C.J., 2013, Functional regression: Estimating optical depth and attenuation coefficients for sea ice covers in Resolute Passage, Canada, *Annals of Glaciology*,
- Mundy, C.J., Gosselin, M., Gratton, Y., Brown, K., Galindo, V., Campbell, K., Levasseur, M., Barber, D.G., Papakyriakou, T., Bélanger, S., 2014, Role of environmental factors on phytoplankton bloom initiation under landfast sea ice in Resolute Passage, Canada, *Marine Ecology Progress Series*, doi:10.3354/meps10587
- Puko M., Burt A., Walkusz W., Wang F., Macdonald R.W., Rysgaard S., Barber D.G., Tremblay J-E., and Stern G.A., 2014, Transformation of mercury at the bottom of the Arctic food web: an overlooked puzzle in the mercury exposure narrative, *Environmental Science and Technology*,
- Puko M., Walkusz W., Macdonald R.W., Barber D.G., Fuchs C., and Stern G.A., 2013, Importance of Arctic zooplankton seasonal migrations for α -hexachlorocyclohexane (α -HCH) bioaccumulation dynamics, *Environmental Science and Technology*, v.47, 4155-4163
- Rysgaard, S., D. H. Sogaard, M. Cooper, M. Puko, K. Lennert, T. N. Papakyriakou, F. Wang, 2013, Ikaite Crystal Distribution in Winter Sea Ice and Implications for CO2 System Dynamics, *The Cryosphere*, v.7, no.2, 707–718. doi:10.5194/tc-7-707-2013
- Rysgaard, S.R., Wang, F., Galley, R.J., Grimm, R., Lemes, M., Geilfus, N.-X., Chaulk, A., Hare, A.A., Crabeck, O., Else, B.G.T., Campbell, K., Papakyriakou, T., Sorensen, L.L., Sieverts, J., and D. Notz, 2013, Dynamic ikaite production and dissolution in sea ice – control by temperature, salinity and pCO2 conditions, *The Cryosphere Discussions*, v.7, 6075-6099, doi:10.5194/tcd-7-6075-2013