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Review

Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone

David G. Barber[a,*], Haakon Hop[b], Christopher J. Mundy[a], Brent Else[a,c], Igor A. Dmitrenko[a], Jean-Eric Tremblay[d], Jens K. Ehn[a], Philipp Assmy[b], Malin Daase[b,e], Lauren M. Candlish[a], Søren Rysgaard[a,f,g]

[a] *Centre for Earth Observation Science, Faculty of Environment, 460 Wallace Building, University of Manitoba, Winnipeg, MB R3T 2N2, Canada*
[b] *Norwegian Polar Institute, Fram Centre, N-9296 Tromsø, Norway*
[c] *Department of Geography, University of Calgary, 2500 University Dr NW, Calgary, AB T2N 1N4, Canada*
[d] *Québec-Océan and Département de biologie, Université Laval, Quebec City, QC G1V 0A6, Canada*
[e] *UiT-The Arctic University of Norway, 9037 Tromsø, Norway*
[f] *Greenland Climate Research Centre, Greenland Institute of Natural Resources, 3900 Nuuk, Greenland*
[g] *Arctic Research Centre, Aarhus University, DK-8000 Århus, Denmark*

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ABSTRACT

The Marginal Ice Zone (MIZ) of the Arctic Ocean is changing rapidly due to a warming Arctic climate with commensurate reductions in sea ice extent and thickness. This Pan-Arctic review summarizes the main changes in the Arctic ocean–sea ice–atmosphere (OSA) interface, with implications for primary- and secondary producers in the ice and the underlying water column. Changes in the Arctic MIZ were interpreted for the period 1979–2010, based on best-fit regressions for each month. Trends of increasingly open water were statistically significant for each month, with quadratic fit for August–November, illustrating particularly strong seasonal feedbacks in sea-ice formation and decay. Geographic interpretations of physical and biological changes were based on comparison of regions with significant changes in sea ice: (1) The Pacific Sector of the Arctic Ocean including the Canada Basin and the Beaufort, Chukchi and East Siberian seas; (2) The Canadian Arctic Archipelago; (3) Baffin Bay and Hudson Bay; and (4) the Barents and Kara seas. Changes in ice conditions in the Barents sea/Kara sea region appear to be primarily forced by ocean heat fluxes during winter, whereas changes in the other sectors appear to be more summer–autumn related and primarily atmospherically forced. Effects of seasonal and regional changes in OSA-system with regard to increased open water were summarized for photosynthetically available radiation, nutrient delivery to the euphotic zone, primary production of ice algae and phytoplankton, ice-associated fauna and zooplankton, and gas exchange of CO_2. Changes in the physical factors varied amongst regions, and showed direct effects on organisms linked to sea ice. Zooplankton species appear to be more flexible and likely able to adapt to variability in the onset of primary production. The major changes identified for the ice-associated ecosystem are with regard to production timing and abundance or biomass of ice flora and fauna, which are related to regional changes in sea-ice conditions.

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* Corresponding author.
E-mail address: David.Barber@umanitoba.ca (D.G. Barber).

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1. Introduction

The Arctic icescape is transforming rapidly from one dominated by a perennial to a seasonal sea-ice cover (Polyakov et al., 2012). The summer minimum extent of Arctic sea ice has declined by 50% since the earliest satellite records (daily since 1979), with a record minimum in September 2012 (National Snow & Ice Data Center, Colorado). These changes have implications throughout the Arctic ocean–sea ice–atmosphere (OSA) interface, and through teleconnections to lower latitudes of our planet (e.g., Budikova, 2009; Francis and Vavrus, 2012). The impacts of changes in the areal extent, thickness and circulation of sea ice are varied and important throughout most components of the physical, biological, and biogeochemical aspects of the Arctic marine environment. There are also many climate related issues affecting indigenous use of the icescape and safe operation of maritime industries now jockeying to develop newly accessible resources in the Arctic.

The Marginal Ice Zone (MIZ) is defined here as the area along the edge of the ice pack that is affected by open ocean processes (Wadhams, 1986). Often, but not exclusively, the MIZ is thought of as the area of smaller ice floes that have been affected by ocean waves, and is thus highly variable in space and time in terms of location, size and ice characteristics (Sundfjord et al., 2007; Barber et al., 2009). Recent observations suggest that the influence of ocean waves can extend over hundreds of kilometres into the ice-pack during the summer season when the melting pack-ice is increasingly weakened (Barber et al., 2009). Squire and Moore (1980) identified three zones within the MIZ that exhibit a distinct character: (1) the edge zone (closest to the open ocean), (2) transition zone, and (3) interior zone. The MIZ is usually characterized by short and intense phytoplankton blooms (e.g., Engelsen et al., 2002; Arrigo et al., 2012), which develop in the shallow mixed layer near the ice edge during melting due to favourable photosynthetically available radiation (PAR) levels and winter-accumulated nutrients. However, ice edge blooms are not the rule in summer (Falk-Petersen et al., 2000), when depletion of nutrients in the shallow surface layer limits primary production, unless nutrients are introduced into the surface layer by upwelling-favourable winds coincident with a retreat of the ice edge beyond the shelf break (Carmack and Chapman, 2003). Annual production is typically low in ice-covered areas (e.g., 60 g C m^{-2} y^{-1} in the northern Barents Sea), but higher in the outer part of the MIZ (100 g C m^{-2} y^{-1}; Wassmann et al., 2006). This production is transferred to the deep ocean and benthos by sinking organic matter (Wassmann et al., 1991; Renaud et al., 2008), or converted to lipids by zooplankton and higher trophic levels (Falk-Petersen et al., 2009a,b; Wold et al., 2011; Søreide et al., 2013), which typically contain few species in large populations (Welch et al., 1992; Bluhm and Gradinger, 2008).

Physical processes in the MIZ are strongly influenced by spatial and temporal variability of the ice to open water fraction. Important physical processes in the MIZ are: momentum exchange across the air–sea boundary (Claussen, 1991; Perrie and Hu, 1996; Birnbaum and Lupkes, 2002), wave interaction (Wadhams et al., 1988; Squire et al., 1995), heat (Perovich et al., 1989) and salt fluxes (McPhee et al., 2008), turbulence at the sea-ice edge (Johannessen et al., 1987; Drue and Heinemann, 2002) and floe size dynamics (Lu et al., 2008). These processes occur at various spatial and temporal scales within the MIZ and affect the adjacent ocean or sea-ice area. Each of these processes can lead to increased open water fraction. In particular wave generation is able to penetrate further into the MIZ and, by affecting surface mixing and ice floe sizes, can cause rapid decay of sea ice.

Biological processes in the MIZ are governed by the thermodynamic and dynamic interactions within the sea ice and open water, which control the euphotic depth and nutrient levels. The availability of light and nutrients for primary production is controlled by the areal fraction and recent history of distribution of ice vs open water in the MIZ and also the thickness of the ice, melt ponds on the ice, and overlying snow layer, and the stability of the underlying water masses (Engelsen et al., 2004; Ehn et al., 2011; Mundy et al., 2011). Ice algae initiate primary production during late winter–early spring as they grow on the underside of the ice at low light transmission (Hegseth, 1998), and represent an early food source for zooplankton and ice fauna (Søreide et al., 2010, 2013; Leu et al., 2015). Ice algae also exist inside the ice and in brine channels together with an interior community of microbes, meio- and macrofauna (Horner et al., 1988; Gradinger and Ikävalko, 1998; Gradinger et al., 1999, 2005). Deformation of ice in the MIZ can create complex ridge habitats for organisms inhabiting the ice–ocean interface (e.g., ice amphipods and polar cod [*Boreogadus saida*], Hop et al., 2000; Gradinger and Bluhm, 2004; Fortier et al., 2006; Gradinger et al., 2010; Hop and Gjøsæter, 2013) and the ice–atmosphere interface (e.g., seabirds, seals and polar bears, Smith, 1987; Smith and Lydersen, 1991; Lønne and Gabrielsen, 1992; Stirling and Derocher, 2012). The response of the marine ecosystem is controlled not only by the mix of ice and open water in the MIZ, but also by the seasonal timing of this mix (Søreide et al., 2010; Leu et al., 2011). The zone of biological production has significantly extended into the pack ice interior (Legendre et al., 1992; Arrigo et al., 2012).

The air–sea CO_2 exchange varies regionally within the Arctic, mainly because of variations in sea-ice cover, but also because of regional differences in primary production. Since these processes are intrinsically variable within MIZs, air–sea CO_2 exchange in these regions is expected to be complex and very sensitive to perturbations driven by climate change.

The objectives of this review are to describe the changing nature of Arctic MIZs and to examine the key biological and biogeochemical consequences of the current rapid change in the MIZ seasonality and extent. This is intended to be a Pan-Arctic review contrasting areas of change and variability and consequences for the associated ecosystem, with a particular emphasis on assessing our current state of knowledge across regions. To focus this review we address the following interrelated research questions:

(1) How much open water do we have within the Arctic Ocean including the MIZ and how does this vary spatially and temporally?
(2) What effect does this open water have on the availability of photosynthetically available radiation to the ocean surface mixed layer?
(3) Given the changes in 1 and 2, what is the response of ocean energetics and nutrient delivery to the euphotic zone within the MIZ and how does this change in space and time?