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Invited review article

Review: Potential catastrophic reduction of sea ice in the western Arctic Ocean: Its impact on biogeochemical cycles and marine ecosystems

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ABSTRACT

The reduction of sea ice in the Arctic Ocean, which has progressed more rapidly than previously predicted, has the potential to cause multiple environmental stresses, including warming, acidification, and strengthened stratification of the ocean. Observational studies have been undertaken to detect the impacts on biogeochemical cycles and marine ecosystems of these environmental stresses in the Arctic Ocean. Satellite analyses show that the reduction of sea ice has been especially great in the western Arctic Ocean. Observations and model simulations have both helped to clarify the impact of sea-ice reductions on the dynamics of ecosystem processes and biogeochemical cycles. In this review, I focus on the western Arctic Ocean, which has experienced the most rapid retreat of sea ice in the Arctic Ocean and, very importantly, has a higher rate of primary production than any other area of the Arctic Ocean owing to the supply of nutrient-rich Pacific water. I report the impact of the current reduction of sea ice on marine biogeochemical cycles in the western Arctic Ocean, including lower-trophic-level organisms, and identify the key mechanism of changes in the biogeochemical cycles, based on published observations and model simulations. The retreat of sea ice has enhanced primary production and has increased the frequency of appearance of mesoscale anticyclonic eddies. These eddies enhance the light environment and replenish nutrients, and they also represent a mechanism that can increase the rate of the biological pump in the Arctic Ocean. Various unresolved issues that require further investigation, such as biological responses to environmental stressors such as ocean acidification, are also discussed.

Contents

1. Introduction

The exchange of carbon with the Pacific and Atlantic oceans and internal biogeochemical cycling dominate the carbon cycle of the Arctic Ocean basin. Dissolved inorganic carbon, the largest carbon inventory in the ocean, originates from air–sea exchange, river runoff, and, to a lesser degree, dissolution of carbonate-containing minerals, decay of organic matter, and biological respiration. The carbon budget of the Arctic Ocean is thus influenced by river runoff and coastal sources of organic carbon (Anderson et al., 1998; Stein and Macdonald, 2004). However, the net Arctic Ocean air–sea flux appears to be relatively small, because of the relatively small size of the basin and because ice covers much of the sea surface. McGuire et al. (2009) have estimated the dissolved inorganic carbon stocks to be 310 petagrams (1 Pg = 1 × 10^{15} g) C and the

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dissolved organic carbon stocks to be 9 Pg C in the Arctic Ocean, including the shelf seas (Canada and Eurasian basins and Chukchi, East Siberian, Laptev, Kara, Barents, and Beaufort seas) but excluding the Nordic seas and the Bering Sea. The organic carbon stored in Arctic Ocean sediments (surface layer to 3 cm depth in the basins and to 10 cm depth on the shelves and slopes), mainly of the shelf seas, has been estimated to be 9.4 Pg C as particulate carbon (McGuire et al., 2009). Methane (CH_4) is also stored in the Arctic Ocean sediments as hydrates, from 2 to 65 Pg C on the shelves and slopes and from 30 to 170 Pg C in the basins (McGuire et al., 2009). The Arctic area plays an important role in the dynamics of the global carbon cycle; in recent decades the Arctic has been a sink for atmospheric CO_2 of 0–0.8 Pg C y^{-1}, which corresponds to 0–25% of the global net land/ocean flux during the 1990s. Furthermore, the Arctic is a substantial source of CH_4 to the atmosphere, the estimated flux being 32–112 teragrams ($1\ Tg = 1 \times 10^{12}$ g) C y^{-1} (McGuire et al., 2009). The fact that the Arctic is a sink for atmospheric CO_2 has been attributed to large phytoplankton blooms in the spring, strong cooling in the winter, and the relatively high alkalinity of the Arctic Ocean (Takahashi et al., 2009).

The Arctic climate, which modulates biogeochemical cycles in the Arctic region, was growing colder (-0.22 °C ky^{-1}) during the 2000 years prior to the 20th century, owing to a reduction of insolation, but since then it has begun to warm (Kaufman et al., 2009). In the fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC) the Arctic region was already identified as one of the areas of the world most vulnerable to global warming (IPCC, 2007). During the period 1979–2012, the annual mean Arctic sea-ice extent decreased at a rate that was very likely in the range of 3.5–4.1% per decade, and the rate of decrease of the summer sea-ice minimum (perennial sea ice) was very likely in the range of 9.4–13.6% per decade (IPCC, 2013). The magnitude of the rate of ice loss increased from 0.35×10^6 km^2 per decade during the period 1979–1993 (Comiso, 2006) to 0.9×10^6 km^2 per decade between 1993 and 2007 (Deser and Teng, 2008). According to Stroeve et al. (2012), the extent of sea-ice loss during the summer has recently become remarkable, and the area of open water in September has increased at an accelerating rate since 1999. These changes in Arctic sea-ice extent have been attributed to changes in large-scale atmospheric circulation as indicated by the status of the Arctic Dipole Anomaly (Wu et al., 2006; Overland et al., 2008), and to more variability in the phase of the winter Arctic Oscillation (Stroeve et al., 2012). A shift in the wind circulation pattern to a meridional flow that blows toward the central Arctic has caused the rate of sea-ice loss to accelerate since 2000 (Budikova, 2009, and references therein). Ocean forcing is another potential driver of the sea-ice retreat. Warming of Pacific Summer Water (PSW), which is a water mass that typically spreads out on the Chukchi Shelf, has been observed frequently since the late 1990s and is likely responsible for the rapid reductions of summer sea ice in the Chukchi and Beaufort seas of the western Arctic Ocean that have been observed since then (Shimada et al., 2006). The combined effect of these multiple processes is to warm the Arctic climate in all seasons, which leads to more open water in the summer, thereby enhancing the summer ice-albedo feedback effect. Warm ocean waters promote not only the expansion of areas that are ice free in the summer but also the further thinning of multi-year ice (Stroeve et al., 2012).

Sea-ice reduction (melting) may adversely affect marine organisms. Ocean acidification, another effect, in addition to global warming, of increases of atmospheric carbon dioxide (CO_2) concentrations, is likely to have a serious impact on organisms in the Arctic Ocean, because ocean acidification is expected to proceed most rapidly in polar regions (Orr et al., 2005). In the Canada Basin of the western Arctic Ocean, the area in which the saturation index of aragonite was less than 1 ($\Omega < 1$), indicating undersaturation, expanded from 1997 to 2008 as a result of the dilution effect of sea-ice melting. Thus, sea-ice melting associated with warming can accelerate the impact of ocean acidification in the Arctic Ocean (Yamamoto-Kawai et al., 2009). In contrast, a reduction of sea ice will bring improved light conditions to the ocean surface and might thereby enhance phytoplankton photosynthesis and the supply of food for higher trophic level organisms. In the western Canada Basin, diatom productivity was greater in 2004 than in 1994, the implication being that the biological pump was enhanced during 1994–2004 because of the reduction of sea ice (Nishino et al., 2009). This result suggests that the accelerated reduction of sea ice in the Arctic Ocean means that it will continue to be a sink for atmospheric carbon dioxide in the near future (Nishino et al., 2011a). For these reasons, the Arctic Ocean is set to undergo one of the most serious, potentially catastrophic changes in environmental status of any ecosystem in the world. Understanding the impact of warming, freshening, and increases of pCO_2 in the water column associated with this rapid sea-ice reduction on the organisms in the Arctic region is an urgent issue. Predicting the changes in productivity at each trophic level and within pelagic and benthic food webs in the near future is important, not only for improving scientific knowledge but also for anticipating societal impacts, including impacts on local communities.

A number of descriptive reviews have summarized important knowledge about primary production, the biological pump, and marine ecosystems in the Arctic Ocean and pan-Arctic region (e.g., Grebmeier et al., 2006; Carmack and Wassmann, 2006: Grebmeier, 2012; Arrigo, 2014). Carmack and Wassmann (2006), for example, have summarized existing knowledge about pan-Arctic marine food webs and have developed some unifying concepts. They have used semi-quantitative diagrams to show the relationship between the production and vertical export of biogenic matter during the productive season as a function of the physical–biological continuum. Their model is based primarily on data from the Barents Sea shelf collected at depths greater than 200 m. This paper complements these earlier reviews by summarizing recently published and otherwise available yearlong or nearly yearlong datasets for the fluxes of sinking particles and lower trophic level organisms, collected mainly in sediment traps on the Northwind Abyssal Plain and shelves along the margins of the Chukchi Sea, Canada Basin, and Beaufort Sea in the western Arctic Ocean. The aim is to improve our understanding of the physical processes that potentially control biogenic particle fluxes, the dynamics of production and the biological pump, and the response of the functionality of lower trophic level organisms to the dramatic environmental changes in the western Arctic Ocean associated with sea-ice reduction. I will also make some predictions based on a novel ecosystem model developed specifically for the Arctic Ocean.

2. Chukchi and Beaufort seas in the western Arctic Ocean

In this paper, the western Arctic Ocean (Figs. 1a and b) refers to the area encompassing the Chukchi Sea, the northern Bering Strait, and the Beaufort Sea. The Chukchi Sea (area 620×10^3 km^2), together with the northern Bering Strait and the Beaufort Sea (area 178×10^3 km^2), occupies only 13% of the total shelf area and 9% of the total shelf volume of the Arctic Ocean (Jakobbson et al., 2004, 2008, 2012). Pacific-origin water comprises two water masses, each associated with a different season, PSW and Pacific Winter Water (PWW), which spread into the northern Bering Strait and the Chukchi Sea. Both PSW and PWW appear in the upper halocline of the western Arctic Ocean (depth $< \sim 200$ m); PSW is characterized by a temperature maximum and a salinity of 31–32 at less than ~80 m depth, and PWW is characterized by a temperature minimum and a salinity of ~33 at 100–150 m depth (Coachman and Barnes, 1961). The PSW is further divided into Eastern Chukchi Summer Water (ECSW), which originates from Alaskan Coastal Water and has a relatively high temperature and low salinity, and Western Chukchi Summer Water (WCSW), which originates from Bering Sea Water and has a relatively low temperature and high salinity (Shimada et al., 2001). ECSW flows into the Canada Basin via the Beaufort Gyre, where it forms a temperature maximum at a salinity of 31–32 east of the Chukchi Plateau, and WCSW flows across the Chukchi Abyssal Plain west of the Chukchi Plateau, where it forms a temperature maximum at a salinity of ~32.5 (Shimada et al., 2001; Steele et al.,