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The changing Arctic Ocean

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The vast frozen surface of the Arctic Ocean, often referred to as the polar ice cap, separates the atmosphere from the underlying ocean, reflects incoming radiation from the sun back out to space, and provides a unique habitat for creatures ranging in size from microbes to 1500 pound (680 kg) polar bears. While the amount of Arctic sea ice has waxed and waned with the seasons for all of recorded human history, a large fraction would always persist throughout the year. This old, multiyear sea ice reached thicknesses of several meters and resisted melting, even in the polar summer (Eicken et al., 1995).

As temperatures have increased in recent decades, much of this old ice has disappeared and been replaced by thinner first-year ice that melts earlier in spring (Maslanik et al., 2011). Earlier melt has allowed the surface ocean to absorb more solar radiation, delaying the onset of freeze-up in the fall. As a result, a positive feedback has developed in which rising Arctic Ocean temperatures have been accompanied by a markedly thinner and less extensive sea ice cover and an ever-lengthening open water season, which allows the ocean to absorb more radiation, further increasing the temperature (Perovich, 2011). Estimates suggest that the volume of sea ice in the Arctic today is only 20% of that present just a few decades ago (Laxon et al., 2013). Scientists are no longer debating if the Arctic Ocean will eventually become ice-free in summer—they are debating when, with estimates ranging from 20 to 50 years from now (Wang and Overland, 2009).

For some, the loss of Arctic sea ice is a unique opportunity. Improved access to ice-free Arctic waters has sparked interest in the development of a viable Arctic commercial fishery. It has also fuelled interest from energy companies wishing to explore the shallow continental shelves for fossil hydrocarbons. Already, a more predictably ice-free Northwest Passage (Smith and Stephenson, 2013), a northern gateway between the Atlantic and Pacific oceans, has resulted in increased commercial ship traffic in Arctic waters. As all of these activities ramp up, it is essential that strategies are developed and implemented to minimize environmental degradation (Pew, 2013).

For others, the loss of Arctic sea ice looks to be a disaster in the making, particularly for indigenous populations that rely on the ocean for their food. Access to the interior ice pack for hunting is hampered as shore-fast ice diminishes and pack ice retreats further from shore. Subsistence whaling is becoming more difficult as the sea ice historically used as a reliable hunting platform disappears (Struzik, 2012). Newly ice-free waters are encouraging the northward migration of non-native animals, such as killer whales, that compete with native species and indigenous humans for food (Higdon, Hauser and Ferguson, 2012). And coastal populations are rapidly losing valuable land to erosion (Solomon, 2005; Kittel et al., 2011) caused by intense wave action from frequent and stronger storms (Hakkinen, Proshutinsky and Ashik, 2008) with more intense storm surges (Vermaire et al., 2013) in increasingly ice-free waters.

Yet the consequences of Arctic sea ice loss extend far beyond the subsistence and commercial activities of humans - there will be profound ecological implications as well. Some of these are already apparent, such as habitat reduction for large mammals like ringed seals and polar bears that require stable sea ice in spring/summer for reproduction and feeding (Stirling and Derocher, 2012). But most consequences are still playing out and our ability to either understand or predict them is limited. This is particularly true for the smallest Arctic inhabitants on which the rest of the marine ecosystem relies.

The base of the Arctic Ocean food web

All of the energy that fuels the highly productive marine ecosystems of the Arctic Ocean originates in the activity of microscopic algae that utilize the energy of the sun to make organic matter during photosynthesis. These algae live both in the sea ice and in the water column (phytoplankton). As the sun rises higher in the sky during the Arctic spring, enough light energy passes through the ice to allow algae in the ice to grow, generally attached to the bottom where nutrients are plentiful (Arrigo, Lizotte and Mock, 2010). Sea ice algae can attain population levels sufficient to color the ice with their brown pigments. Eventually, the ice warms and algae are released into the water column, where most of them sink. On the shallow continental shelves, ice algae provide some of the food early in the spring for a rich fauna of benthic invertebrates, and in turn, the animals that depend on the benthos for food, including diving ducks, walruses, and gray whales (Dunton et al., 2005; Leong et al., 2005; Grebmeier et al., 2006).

After the ice melts, phytoplankton take over, growing rapidly in the surface ocean until they consume all of the available nutrients (Hill and Cota, 2005). The amount of phytoplankton usually far exceeds that of the ice algae, particularly on the nutrient-rich continental shelves (Arrigo, Lizotte and Mock, 2010). While a significant fraction of this phytoplankton biomass sinks to the sea floor, more is eaten in the water column by zooplankton such as krill and copepods, which are themselves fed upon by fish, birds, and ultimately seals and whales (Leong et al., 2005; Tremblay et al., 2012).

This regular pattern of production and consumption in Arctic waters is now being altered by the earlier retreat and overall loss of sea ice. Ice algae cannot begin to grow until the sun is high enough in the sky and sufficient radiation can penetrate the ice, so earlier sea ice retreat means a shorter growing season. Although a shorter growing season does not necessarily translate to a reduction in overall ice-algal production (nutrient supply may ultimately determine that level despite length of growing season; Gradinger, 2009; Pineault et al., 2013), where it does, the potential delivery of food to the benthos will be less. A reduction in sea ice algae may not have immediately obvious ecological implications, however, because as the window for sea ice algal growth is closing, the window for phytoplankton is opening. The amount of primary production by phytoplankton in Arctic waters is closely tied to sea ice extent and particularly the length of the open water season (Arrigo, van Dijken and Pabi, 2008; Arrigo and van Dijken, 2011). As sea ice has declined in recent decades, phytoplankton productivity has accelerated dramatically. Between 1998 and 2012, the average amount of open water area in the Arctic Ocean and total annual primary production both increased by approximately 30% as the length of the open water season increased by 45%. The largest increases in annual production (30–112%) have been in marginal seas along the Pacific side of the Arctic where the loss of sea ice and the increase in the length of the growing season is greatest (Arrigo et al., submitted; Bélanger, Babin and Tremblay, 2013).

Whether this increase in productivity will continue as sea ice declines further is not known. Models disagree as to the consequences of Arctic sea ice loss. Some predict lower production as ice melt intensifies ocean stratification, which will make it more difficult for nutrients to mix into surface waters (Walsh et al., 2005). Other models predict that reduced ice cover will expose more ocean surface to winds, thereby diminishing stratification and bringing more nutrients to the surface (Zhang et al., 2010). Observational work has confirmed that such upwelling of nutrients does stimulate primary production, yet apparently only in coastal regions of the Arctic (Tremblay et al., 2011). What the remote sensing data clearly show is that, in the short term, the loss of sea ice has resulted in a dramatic increase in Arctic productivity—a major perturbation to the Arctic marine ecosystem.

One consequence of the replacement of old, thick multiyear ice by first year ice is that conditions are now more favorable for phytoplankton to bloom beneath the ice pack (Fortier et al., 2002). Historically, thick, snow-covered sea ice transmitted too little light to the water column below and phytoplankton bloomed predominantly in open water along the retreating ice edge (Alexander and Niebauer, 1981). Now, the younger, thinner ice pack is more uniform and supports more numerous melt ponds (Polashenski Perovich and Courville, 2012), which transmit far more light than bare ice (Frey, Perovich and Light, 2011; Arrigo et al., 2012), making under-ice phytoplankton blooms possible. One example of a particularly large and well-documented under-ice phytoplankton bloom was observed in the Chukchi Sea in 2011. This bloom stretched for over 130 km beneath a continuous cover of pack ice that ranged in thickness from 0.8 to 1.3 m with a melt pond fraction of 25–50% (Arrigo et al., 2012). Phytoplankton biomass was extremely high from the sea surface down to approximately 30 m and growth rates were double those measured in nearby open water. Productivity under the ice exceeded 80 g C m^{-2} yr^{-1}, more than 10 times the value attained in the same area after the sea ice had retreated. Phytoplankton blooms beneath the ice have the potential to dramatically alter the timing and magnitude of production on the vast continental shelves of the Arctic Ocean. However, they remain virtually unexplored and an accounting of their contributions to regional energy and carbon budgets is currently missing.

A new and improved Arctic?

In light of these changes, it might be easy to conclude that a more productive Arctic marine ecosystem is a beneficial consequence of climate change. However, the story is not so simple. More primary production does not necessarily mean more food for the marine ecosystem. Some or all of the increase in production measured between 1998 and 2012 may simply be recycled in the upper ocean. More research is needed to determine how much of this new production is being exported to other components of the ecosystem. Most likely the elevated primary production on the Arctic shelves will increase the flux of organic matter to the sediments, thereby increasing rates of denitrification (Ward et al., 2008; Chang and Devol, 2009; Altabet et al., 2012; Kalvelage et al., 2013), a process that converts fixed nitrogen to relatively unusable nitrogen gas. This loss of fixed nitrogen would act as a negative feedback, limiting further increases in new production in the Arctic.

Finally, while rates of Arctic productivity are increasing rapidly now, there are limits on how much production the Arctic Ocean can support. New sources of nitrogen are required to fuel additional new production, yet potential sources for these nutrients are not clear. The deep Arctic basins contain moderately high nitrate concentrations (Codispoti et al., 2013), but the strong halocline currently prevents their mixing into surface waters, except under episodic conditions of strong atmospheric forcing (Tremblay and Gagnon, 2009). Water flow from the Bering Sea through Bering Strait has increased by 50% in the last decade (Woodgate, Weingartner and Lindsay, 2012), but whether or not this increase is associated with an increased flux of nutrients is not known. In short, we lack a sufficient understanding of the ongoing physical and chemical responses to altered Arctic climate to know what the dramatic changes observed over the last few decades portend for the future.

Major pitfalls?

Sea ice in the Arctic is retreating 2.4 days earlier each year (Arrigo and Van Dijken, 2011), accelerating the blooms of open water phytoplankton (Kahru et al., 2011). Moreover, under-ice phytoplankton blooms develop even earlier and in much colder water (Arrigo et al., 2012). Together, these changes could intensify the mismatch that sometimes occurs between the life cycles of phytoplankton and their zooplankton grazers (Conover and Huntley, 1991), ultimately decreasing the food available to fish, birds, and mammals (Loeng et al., 2005), many of which time their migrations and reproduction cycle to coincide with peak Arctic productivity (Soreide et al., 2010; Wassmann et al., 2010; Wassmann, 2011). Thus, although primary production may continue to increase, its timing may shift such that an increasing fraction will become unavailable to feed the pelagic marine ecosystem, resulting in a further shift to a benthic-dominated ecosystem, in contrast to recent predictions (Grebmeier et al., 2006).

Linked to the same rise in atmospheric carbon dioxide that has resulted in Arctic warming is the acidification of the Arctic Ocean, which is likely to intensify as ice continues to disappear (Yamamoto et al., 2012). Decreasing ocean pH has reduced carbonate ion concentrations in surface waters, making it more difficult for calcifying organisms to make their shells and other supporting structures, particularly on shallow shelves (Yamamoto-Kawai et al., 2009; Bates, Mathis and Cooper, 2009). Ocean acidification in the Arctic will negatively affect pelagic organisms like pteropods (Lischka and Riebesell, 2012), but could be especially detrimental to shallow-water benthic mollusks and crustaceans (Bates, Mathis and Cooper, 2009) on which large marine mammals feed. So, while phytoplankton could fare well in a changing Arctic, the combined effects of a reduced sea ice cover and acidifying surface waters could spell disaster for both pelagic and benthic ecosystems, on which many indigenous human populations rely.

Our global experiment

The Arctic Ocean is indeed a bellwether of change—and the Arctic marine ecosystem is changing at an alarming rate. Sea ice is declining rapidly as temperatures rise faster than anywhere else on Earth. The balance between sea ice primary production and water column production is likely shifting in favor of the phytoplankton. Over most of the Arctic Ocean, annual rates of phytoplankton production are increasing dramatically. The timing of production is shifting to earlier in the year in many areas, and in places like the Chukchi Sea, phytoplankton productivity is greatest when the ocean is still covered in ice. And the ocean is acidifying.

There is no geo-engineering solution to both increasing Arctic temperatures and decreasing ocean pH. So the only way to stabilize the Arctic Ocean is to reduce atmospheric levels of carbon dioxide and other greenhouse gases. The big questions are “does the global community have the political will to do it?” and “is it already too late?”

References

Alexander V, Niebauer HJ. 1981. Oceanography of the eastern Bering Sea ice-edge zone in spring. *Limnol Oceanogr* **26**(6): 1111–1125.

Altabet MA, Ryabenko E, Stramma L, Wallace DWR, Frank M, et al. 2012. An eddy-stimulated hotspot for fixed nitrogen-loss from the Peru oxygen minimum zone. *Biogeosci* **9**: 4897–4908

Arrigo KR, van Dijken GL, Pabi S. 2008. The impact of a shrinking Arctic ice cover on marine primary production. *Geophys Res Lett* **35**: L19603. doi:10.1029/2008GL035028

Arrigo KR, van Dijken GL. 2011. Secular trends in Arctic Ocean net primary production. *J Geophys Res* **116**: C09011.

Arrigo KR, Lizotte MP, Mock T. 2010. Primary producers and sea ice, chapter 8 in Thomas DN, Dieckmann, eds., *Sea Ice*, 2nd Edition. Oxford, UK: Blackwell Science, Ltd.: 283–326.

Arrigo KR, Perovich DK, Pickart RS, Brown ZW, van Dijken GL, et al. 2012. Massive phytoplankton blooms under Arctic sea ice. *Science* **336**: 1408.

Bates NR, Mathis T, Cooper LW. 2009. Ocean acidification and biologically induced seasonality of carbonate mineral saturation states in the western Arctic Ocean. *J Geophys Res* **114**: C11007. doi:10.1029/2008JC004862

Bélanger S, Babin M, Tremblay J-E. 2013. Increasing cloudiness in Arctic damps the increase in phytoplankton primary production due to sea ice receding. *Biogeosci* **10**(6): 4087–4101. doi:10.5194/bg-10-4087-2013

Chang BX, Devol AH. 2009. Seasonal and spatial patterns of sedimentary denitrification rates in the Chukchi Sea. *Deep-Sea Res Part II* **56**(17): 1339–1350. doi:10.1016/j.dsr2.2008.10.024

Codispoti LA, Kelly V, Thessen A, Matrai P, Suttles S, et al. 2013. Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production. *Prog Oceanogr* **110**: 107–125. doi:10.1016/j.pocean.2012.11.006

Conover RJ, Huntley M. 1991. Copepods in ice-covered seas–Distribution, adaptations to seasonally limited food, metabolism, growth patterns and life cycle strategies in polar seas. *J Mar Sys* **2**: 1–41.

Dunton KH, Goodall JL, Schonberg SV, Grebmeier JM, Maidment DR. 2005. Multi-decadal synthesis of benthic–pelagic coupling in the western arctic: Role of cross-shelf advective processes. *Deep-Sea Res Part II* **52**(24–26): 3462–3477.

Eicken H, Lensu M, Lepparanta M, Tucker WB, Gow AJ, et al. 1995. Thickness, structure, and properties of level multiyear ice in the Eurasian sector of the Arctic-Ocean. *J Geophys Res* **100**(C11): 22697–22710. doi:10.1029/95JC02188

Fortier M, Fortier L, Michel C, Legendre L. 2002. Climatic and biological forcing of the vertical flux of biogenic particles under seasonal Arctic sea ice. *Mar Ecol Prog Ser* **225**: 1–16. doi:10.3354/meps225001

Frey KE, Perovich DK, Light B. 2011. The spatial distribution of solar radiation under a melting Arctic sea ice cover. *Geophys Res Lett* **38**: L22501. doi:10.1029/2011GL049421

Gradinger R. 2009. Sea-ice algae: Major contributors to primary production and algal biomass in the Chukchi and Beaufort Seas during May/June 2002. *Deep-Sea Res Part I* **56**(17): 1201–1212. doi:10.1016/j.dsr2.2008.10.016

Grebmeier JM, Cooper LW, Feder HM, Sirenko BI. 2006. Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi Seas in the Amerasian Arctic, *Prog Oceanogr* **71**(2–4): 331–361. doi:10.1016/j.pocean.2006.10.001

Hakkinen S, Proshutinsky A, Ashik I. 2008. Sea ice drift in the Arctic since the 1950s. *Geophys Res Lett* **35**(19): L19704. doi:10.1029/2008GL034791

Higdon JW, Hauser DDW, Ferguson SH. 2012. Killer whales (*Orcinus orca*) in the Canadian Arctic: Distribution, prey items, group sizes, and seasonality. *Mar Mammal Sci* **28**(2): E93–E109. doi:10.1111/j.1748-7692.2011.00489.x

Hill V, Cota G. 2005. Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in 2002. *Deep-Sea Res Part II* **52**: 3344–3354

Kahru M, Brotas V, Manzano-Sarabia M, Mitchell BG. 2011. Are phytoplankton blooms occurring earlier in the Arctic? *Glob Change Biol* **17**: 1733–1739.

Kalvelage T, Lavik G, Lam P, Contreras S, Arteaga L, et al. 2013. Nitrogen cycling driven by organic matter export in the South Pacific oxygen minimum zone. *Nature Geosci* **6**: 228–234.

Kittel TGF, Baker BB, Higgins JV, Haney JC. 2011. Climate vulnerability of ecosystems and landscapes on Alaska's North Slope. *Region Env Change* **11**(1): S249–S264. doi:10.1007/s10113-010-0180-y

Laxon SW, Giles KA, Ridout AL, Wingham DJ, Willatt R, et al. 2013. CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophys Res Lett* **40**: 732–737. doi:10.1002/grl.50193

Lischka S, Riebesell U. 2012. Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. *Glob Change Biol* **18**(12): 3517–3528. doi:10.1111/gcb.12020

Loeng H, Brander K, Carmack E, Denisenko S, Drinkwater K, et al. 2005. *Marine Systems*. (Arctic Climate Impact Assessment) Cambridge, UK: Cambridge Univ. Press: 453–538.

Maslanik J, Stroeve J, Fowler C, Emery W. 2011. Distribution and trends in Arctic sea ice age through spring 2011. *Geophys Res Lett* **38**: L13502.

Pew Charitable Trusts. 2013. Oceans North: Protecting Life in the Arctic [Internet]. Available at http://www.pewenvironment.org/campaigns/oceans-north-protecting-life-in-the-arctic/id/8589935755

Perovich DK. 2011. The changing Arctic sea ice cover. *Oceanogr* **24**(3): 162–173.

Pineault S, Tremblay J-E, Gosselin M, Thomas H, Shadwick E. 2013. The isotopic signature of particulate organic C and N in bottom ice: Key influencing factors and applications for tracing the fate of ice-algae in the Arctic Ocean. *J Geophys Res* **118**(1): 287–300. doi:10.1029/2012JC008331

Polashenski C, Perovich D, Courville Z. 2012. The mechanisms of sea ice melt pond formation and evolution. *J Geophys Res* **117**(C1): C01001. doi:10.1029/2011JC007231

Smith LC, Stephenson SR. 2013. New Trans-Arctic shipping routes navigable by midcentury. *Proc Nat Acad Sci* **110**(13): E1191–95.

Solomon S. 2005. Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, Northwest Territories, Canada. *Geo-Mar Lett* **25**: 127–137.

Soreide JE, Leu E, Berge J, Graeve M, Falk-Petersen S. 2010. Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. *Glob Change Biol* **16**(11): 3154–3163. doi:10.1111/j.1365-2486.2010.02175.x

Stirling I, Derocher AE. 2012. Effects of climate warming on polar bears: a review of the evidence. *Glob Change Biol* **18**(9): 2694–2706. doi:10.1111/j.1365-2486.2012.02753.x

Struzik E. 2012. As Arctic melts, Inuit face tensions with outside world [Internet]. *YaleE360*. Available at http://e360.yale.edu/feature/as_arctic_melts_inuit_face_tensions_with_outside_world/2577/

Tremblay JE, Gagnon J. 2009. The effects of irradiance and nutrient supply on the productivity of Arctic waters: a perspective on climate change. Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions, in Nihoul JCJ, Kostianoy AG, eds., *Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions*. Dordrecht, The Netherlands: Springer Netherlands (Nato Science for Peace and Security Series C: Environmental Security): 73–93.

Tremblay JE, Belanger S, Barber DG, Asplin M, Martin J, et al. 2011. Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophys Res Lett* **38**: L18604, doi:10.1029/2011GL048825

Tremblay J-E, Robert D, Varela DE, Lovejoy C, Darnis G, Nelson RJ, Sastri AR. 2012. Current state and trends in Canadian Arctic marine ecosystems: I. Primary production. *Climatic Change* **115**(1): 161–178. doi:10.1007/s10584-012-0496-3

Vermaire JC, Pisaric MFJ, Thienpont JR, Courtney Mustaphi CJ, Kokelj SV, et al. 2013. Arctic climate warming and sea ice declines lead to increased storm surge activity. *Geophys Res Lett* **40**: 1386–1390. doi:10.1002/grl.50191

Walsh JJ, Dieterle DA, Maslowski W, Grebmeier JM, Whitledge TE, et al. 2005.A numerical model of seasonal primary production within the Chukchi/Beaufort Seas. *Deep-Sea Res Part II* **52**: 3541–3576.

Wang M, Overland JE. 2009. A sea ice free summer Arctic within 30 years? *Geophys Res Lett* **36**: L07502. doi:10.1029/2009GL037820

Ward BB, Tuit CB, Jayakumar A, Rich JJ, Moffett J, et al. 2008. Organic carbon, and not copper, controls denitrification in oxygen minimum zones of the ocean. *Deep-Sea Res Part I* **55**: 1672–1683.

Wassmann P. 2011. Arctic marine ecosystems in an era of rapid climate change. *Prog Oceanogr* **90**: 1–17.

Wassmann P, Duarte CM, Agusti S, Sejr MK. 2010. Footprints of climate change in the Arctic marine Ecosystem. *Glob Change Biol* **17**: 1235–1249.

Woodgate RA, Weingartner TJ, Lindsay R. 2012. Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column. *Geophys Res Lett* **39**: L24603.

Yamamoto A, Kawamiya M, Ishida A, Yamanaka Y, Watanabe S. 2012. Impact of rapid sea-ice reduction in the Arctic Ocean on the rate of ocean acidification. *Biogeosci* **9**(6): 2365–2375. doi:10.5194/bg-9-2365-2012

Yamamoto-Kawai M, McLaughlin FA, Carmack EC, Nishino S, Shimada K. 2009. Aragonite undersaturation in the Arctic Ocean: Effects of ocean acidification and sea ice melt. *Science* **326**(5956): 1098–1100. doi:10.1126/science.1174190

Zhang J, Spitz YH, Steele M, Ashjian C, Campbell R, et al. 2010. Modeling the impact of declining sea ice on the Arctic marine planktonic ecosystem. *J Geophys Res* **115**: C10015.

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