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The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic

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ABSTRACT

The Pacific Arctic marine ecosystem extends from the northern Bering Sea, across the Chukchi and into the East Siberian and Beaufort seas. Food webs in this ecosystem are short, a simplicity that belies the biophysical complexity underlying trophic linkages from primary production to humans. Existing advective and pelagic-benthic coupling models describe processes that connect certain aspects of marine food webs, but do not offer a comprehensive approach to understanding the Pacific Arctic ecosystem. In the course of the Synthesis of Arctic Research (SOAR) project, the Arctic Marine Pulses (AMP) model was developed that depicts seasonal biophysical 'pulses' across a latitudinal gradient by linking processes in four previously-defined contiguous ecological domains, including the: (i) Pacific Arctic domain; (ii) Seasonal Ice Zone domain; (iii) the Marginal domain (i.e., the shelf break and slope); and (iv) Riverine Coastal domain. Some of the biophysical processes included in the AMP model, such as pelagic-benthic coupling on the broad shelves of the northern Bering and Chukchi seas and advection and upwelling of zooplankton along the western Beaufort shelf (i.e. the krill trap), have been the focus of long-term studies. Other aspects such as biological processes associated with shifts in seasonal sea-ice phenology and trophic responses to riverine outflow have received less attention. The AMP model provides an annual spatiotemporal framework to guide research on dynamic ecosystem processes during the recent period of rapid biophysical changes in the Pacific Arctic. The model aims to encourage integrated research to track seasonal sea-ice and current-flow dynamics, coincident with variability in nutrients, benthic and pelagic production, and upper-trophic species occurrence to provide a foundation for the development of predictive human-inclusive ecosystem models for the Pacific Arctic region. We suggest that the AMP model, with its focus on phenology, might facilitate communication between conventional science approaches to marine research and seasonal-cycle based indigenous knowledge of marine ecosystems. The goal of improving our understanding of the state and variability of the Pacific Arctic marine ecosystem is a shared one and we conclude with views on how the AMP model can support that goal while contributing to the development of a pan-Arctic ecosystem model.

1. Introduction

The Pacific Arctic region extends from the northern Bering Sea, across the Chukchi Sea to the East Siberian and Beaufort seas (Wood et al., 2015; Grebmeier and Maslowski, 2014). The northern Bering, Chukchi and East Siberian seas contain broad-shallow continental shelves, while the Beaufort Sea has a narrow shelf and steep slope culminating in the deep Canadian Basin (Fig. 1). Sea ice covers the Pacific Arctic region for 5–7 months of the year, typically reaching maximum and minimum areal extent in March and September, respectively (Frey et al., 2015). The narrow (85 km) and shallow (50 m) Bering Strait is the only gateway for Pacific water to enter the Arctic (Woodgate et al., 2015). Transport is primarily northward and comprised of three water masses, the Alaskan Coastal Water (ACW), Bering Shelf Water (BSW) and Anadyr Water (AW). Bering Strait inflow peaks in summer, providing a strong seasonal pulse (~1×10^6 m^3 s^{-1} [Sv]) of comparatively fresh water, heat, nutrients and plankton to the Chukchi-Beaufort marine ecosystem. Linking terrestrial and marine habitats are dramatic late-spring discharges from five rivers along the coastal Pacific Arctic, including the Yukon and Anadyr in the Bering Sea, the Colville and Mackenzie in the Beaufort Sea, and the Kolyma in the East Siberian Sea (Carmack et al.,

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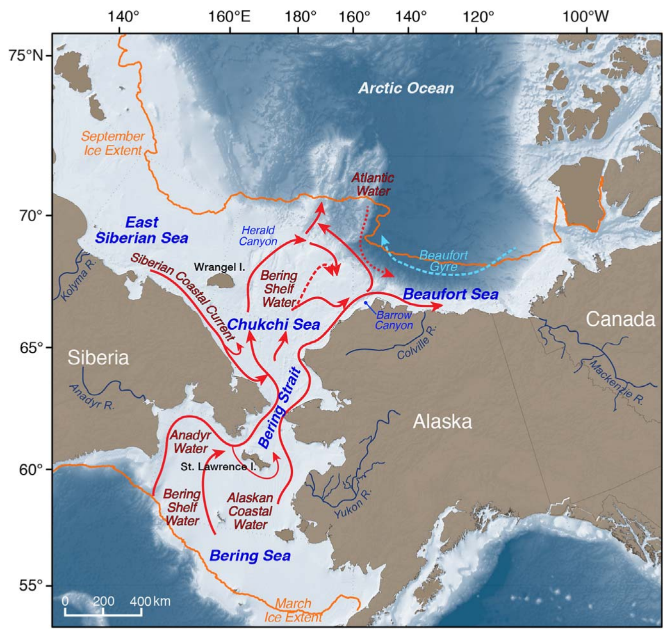

Fig. 1. Pacific Arctic marine ecosystem, as described in Grebmeier and Maslowski (2014), depicting maximum (March) and minimum (September) sea ice extent, major currents, rivers and topographic features (modified from Moore and Stabeno, 2015).

2015). The striking seasonal and inter-annual variability of sea-ice cover, Bering Strait inflow and riverine discharge provides the foundational biophysical setting for marine ecosystem processes in the Pacific Arctic, extending from primary production (ice algae and phytoplankton) to lower trophic (zooplankton, benthic invertebrates and fishes), upper trophic (marine birds and mammals) animals and humans.

The biophysics and marine ecology of the Pacific Arctic region represent a study in contrasts, resulting from differing processes that dominate the broad and shallow shelves of the northern Bering, Chukchi and East Siberian seas, compared to the narrow shelf, steep slope and deep basin of the Beaufort Sea (Carmack and Wassman, 2006). Food webs are generally short, a simplicity that belies the biophysical complexity underlying trophic linkages from primary production to humans (Moore and Stabeno, 2015). Because dynamic ocean processes are not depicted in most arctic food web schematics, the ecosystems appear static rather than typified by extremes in seasonal and inter-annual variability. Fortunately, the dynamic nature of arctic marine ecosystems is becoming better understood, with several peer-reviewed volumes describing biological responses to the recent extreme physical changes (e.g. Wassman et al., 2011, 2015; Moore and Stabeno, 2015; Grebmeier and Maslowski, 2014; Kulkarni et al., 2012).

The Arctic Marine Pulses (AMP) conceptual model was introduced by Moore and Stabeno (2015) and adopts four contiguous ecological domains, defined by Carmack and Wassman (2006), as a framework to link annual biophysical events, or 'pulses', in the Pacific Arctic region (Fig. 2a). Pulses are processes that occur on spatial and temporal scales extending from 1 to 1000 km over days to months during an annual cycle, as depicted on a 'Stommel' diagram of ocean dynamics (Fig. 2b). The Pacific Arctic domain is the 'focal' area for the AMP model, wherein biophysical processes associated with the Seasonal Ice Zone domain, the Marginal domain (i.e, the shelf-break and slope), and the Riverine Coastal domain act to guide ecological outcomes. The AMP model combines existing models describing (a) pelagic-benthic coupling processes (Grebmeier et al., 2012, and references therein) and (b) advective processes (Grebmeier et al., 2015c, and references therein) to capture the interconnectivity of these processes, while placing an emphasis on the annual timing of biophysical pulses in the Pacific Arctic region. This emphasis on phenology is key, given the myriad ecosystem responses already identified in this period of rapid physical alteration of the Pacific Arctic region (Grebmeier and Maslowski 2014; Frey et al., 2015; Arrigo and van Dijken, 2015; Wood et al., 2015).

Here, we further develop the AMP model by providing an overview of the phenology of biophysical pulses in the Pacific Arctic region, followed by examples of how studies including upper-trophic species provide a means to explore how the marine ecosystem responds to these events. We then suggest possible next-steps for further development of the AMP model in the Pacific Arctic and suggest that it might be a useful paradigm for other Arctic marine ecosystems. We then describe how the AMP model, with its focus on phenology, might facilitate communication between conventional science approaches to marine research and seasonal-cycle-based indigenous knowledge of marine ecosystems. The goal of improving our understanding of the state and variability of the Pacific Arctic marine ecosystem is a shared one and we conclude with views on how the AMP model can support that goal while contributing to the development of a pan-Arctic ecosystem model.

2. The Pacific Arctic Region: a realm of strong biophysical pulses

2.1. Initiating pulse of Pacific Water at Bering Strait

The Pacific Arctic domain is defined by waters entering the Arctic Ocean through Bering Strait, which circulate anticyclonically within the Beaufort Gyre at depths between 40 and 280 m, then exit via the Canadian Archipelago and Fram Strait (Carmack and Wassman, 2006). This domain is the focal area for the Pacific Arctic region, wherein the three other domains interact. The summer peak in northward transport of Pacific Water through Bering Strait, the result of the relatively invariant pressure head-driven transport dominating seasonally weak wind-driven transport (Danielson et al., 2014; Woodgate et al., 2015), is the initiating event for the Pacific Arctic advective model (Grebmeier et al., 2015c) and therefore the AMP model (Moore and Stabeno, 2015). This seasonal pulse of three water masses (ACW, BSW, AW) into the Chukchi Sea essentially 'sets the stage' for subsequent biophysical processes downstream. Specifically, sediment structure and occurrence patterns of benthic fauna and zooplankton are related to circulation and flow speed of the three water masses (Pisavera et al., 2015). In general, epi- and macrofaunal suspension feeders are associated with high-flow regimes, with deposit feeders common in weaker flow areas. Furthermore, pelagic fish and zooplankton assemblages can be linked to specific water masses, with large zooplankton taxa (e.g., copepods and euphausiids) associated with BSW and high salinity ACW (Eisner et al., 2013). Finally, the seasonal advection of nutrients and zooplankton in the cold high-salinity AW is key to the distribution and productivity of seabirds in the Chukchi Sea (Piatt and Springer et al., 2003), while also providing feeding opportunities for gray and bowhead whales in the southern Chukchi and western Beaufort seas, respectively (Bluhm et al., 2007; Ashjian et al., 2010).

Woodgate et al. (2015) provide a synthesis of transport measurements from moorings deployed in Bering Strait from 1990 to 2014 and report an overall increase from ~0.7 Sv to ~1.1 Sv in volume flux from 2001–2013, with marked inter-annual variation. The roughly 50% increase in volume flux brings corresponding changes in heat flux and freshwater, with the latter increasing from 2000–2500 $km^3 y^{-1}$ in 2001 to 3000–3500 $km^3 y^{-1}$ in 2011. The increased inflow also results in a decreased residence time of waters entering the Chukchi Sea, resulting in a "significant change in the timing of water with different properties" entering the Arctic Ocean (Woodgate et al., 2015: page 51); i.e. the advective conveyor belt is moving faster now than during the latter half of the 20th century.

While the interplay of forcing mechanisms that introduce variability in the timing and magnitude of the Pacific Water pulse through Bering Strait remains a subject of active research, Danielson et al. (2014) provide evidence that variability in northward transport is strongly