Towards a unifying pan-Arctic perspective: A conceptual modelling toolkit[1]

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[1] We construct and construct and yet intuition still has its use. Without it we can do a lot, but not everything. When intuition is joined to exact research it speeds up the process of exact research. Paul Klee

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0. Abstract

The Arctic Ocean is forced by and interacts with the global system, and we here choose the full pan-Arctic as our focal scale for development of nested conceptual models of the Arctic Ocean ecosystem. To understand the pan-Arctic scale, however, requires that we look at the underlying scales of its major components, by considering regionality, connectivity and seasonality. Six regions are identified on the basis of hydro-morphological characteristics, which subsequently reflect ecological function and traits. Regions are static, tied to geography, but are linked by contiguous domains of shared function that facilitate material transports and share key ecological features. The pan-Arctic scale also requires attention to forcing by the seasonal light climate, wherein the maximum length of a single day varies from near 24 hours at the Arctic Circle to about 4400 hours at the North Pole. The light climate in turn forces a strong phenology in the Arctic, as reflected by periodic life cycle events of organisms and how these biotic cycles are influenced by seasonal and interannual variations in climate. Arctic Ocean ecosystems are dominated by four fundamental variables: ice cover, light climate, nutrient/food availability and advection. The conditions under which each of these variables play out in the course of a year are set by the regions and contiguous domains within which they operate and interact. In concert, the defined regions and their seasonality, the contiguous domains and their connectivity, and the four fundamental variables allow unambiguous application of scale-nested, parsimonious and adaptive, conceptual models, from which to 1) create testable hypotheses, 2) plan and then modify field campaigns, and 3) communicate essential results to managers and the general public. The

development of these nested conceptual pan-Arctic scale models creates a vital step into the future of unifying, integrative oceanographic and ecological work.

Contents

1. Introduction

The Arctic Ocean (AO; also called the Arctic Mediterranean Sea, classifying it as an estuary of the Atlantic Ocean) is located in the Arctic north polar region and operates as the functional center of the Northern Hemisphere (**Fig.1**) (for abbreviations applied throughout the text, see Table 1). It is almost completely surrounded by the vast landmasses of Eurasia and North America and almost completely covered by sea ice in winter. The ocean receives freshwater and material supplies from a vast network of rivers that drain these surrounding landmasses. It is connected to the subarctic Pacific Ocean via the Bering Strait and particularly the Atlantic Ocean by gateways at Davis Strait, Fram Strait and the Barents Sea opening. Easterly winds to the north and westerly winds to the south encircle the central AO and adjacent land masses, completing the Arctic land-sea-air system (**Fig. 1**). Thus, and importantly, the AO cannot be understood, predicted and/or managed through traditional sectorial approaches out of Europe, Asia or North America, but only through integrated, circum-Arctic and tightly interconnected, systemic approaches. Consequently, pan-Arctic integration and international cooperation in research and management are indispensable. It is essential that such cooperation crosses territorial borders, in line with the patterns of ice drift, winds, ocean currents and plankton organisms in the AO (e.g. Wassmann, 2006). Here we take as a working definition of the AO the Arctic north polar region (basins and adjacent shelves) poleward of the four gateways noted above, keeping in mind that no strict boundary will satisfy all functional and geopolitical issues.

A range of national investigations have been carried out in the AO since those of the early Arctic explorers (e.g. Nansen, 1897). Significant marine ecological work was carried out on the Siberian shelf and adjacent seas of the Sovjet Union before WWII, summarized by Zenkevich (1963). From 1937 and onwards the Soviet Union/Russia sustained an extensive sequence of ice drift stations (Ugryumov et al., 2005; Romanov et al., 2007; Belkin and Kessel, 2017) that carried out oceanographic work (for the most part physical oceanography). This work has continued up to recent times (e.g. Barneo ice camp, http://campbarneo.com/), now in a more interdisciplinary manner. Important early investigations of the AO included the US Arctic Drifting Stations in the 1950s-1960s (e.g. Cabaniss et al., 1965). Some of the large continental shelf programs in North America were carried out in the 1970s (e.g. WEBSEC, NOGAP, OCSEAP) related to the oil exploration and discovery. Already in the 1980´s Norway invested heavily in a large-scale and multi-discipline investigation of the Norwegian sector of the Barents Sea (Pro Mare; e.g. Sakshaug et al., 1991). This work continues in the ice-covered northern Barents Sea and adjacent Nansen Basin through the Nansen Legacy project (https://arvenetternansen.com/). In the eastern Bering Strait and Chuckie Sea the multidisciplinary "The Western Arctic Shelf – Basin Interactions project" (SBI) started in the late 1990´s (e.g. Grebmeier et al., 2009), followed by the «Russian-American Long-term Census of the Arctic program" (RUSALCA) between 2004 and 2015 (e.g. Hopcroft et al., 2010). Polynyas, such as the Northeast Water Polynya, the North Water Polynya/Nares Strait system and the Laptev Sea Polynia were also the subject of intensive studies (e.g. Hirche and Kwasniewski, 1997; Tremblay et al., 2006; Dimitrenko et al., 2010). The Canadian ArcticNet initiative carried out a range of overwintering expeditions to the Canadian sector of the AO (http://www.arcticnet.ulaval.ca/media/publications.php). The coastal marine

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diversity and ecosystems along the Siberian coast have been investigated and summarized by Spiridonov et al. (2011). Troughout the last decade major annual marine ecological expeditions to the Kara, Laptev and East Siberian Seas have been carried out, but little has so far been published in English (but see e.g. Arashkevich et al., 2010; Flint et al., 2015; Drits et al., 2017; Sukhanova et al., 2017).

Rather long-standing traditions are established for international cooperation in Arctic science. The first International Polar Year, for example, took place in 1882-83 and involved scientists from many countries. Subsequent International Polar Years were held in 1932-33, 1957-58 (as part of the International Geophysical Year) and 2007-2008 (Barr and Lüdeke, 2010). Interdisciplinary studies in the AO started with the Swedish icebreaker R/V Ymir´s attempt to reach the North Pole. Repetitive expeditions by R/V Polarstern of the Alfred Wegener Institute followed from 1989 and onwards, continued by R/V Oden 1991 and Arctic Ocean Section in 1994. However, the AO was excluded from the World Ocean Circulation Experiment WOCE in 1990-1998. The dominant view then was that the AO played an insignificant role for the World Ocean and was insignificant for the global climate.

In light of what is today’s accepted truth the evaluation of just 30 years ago is difficult to understand. There are four reasons, all well-known decades ago, why the AO is distinct from other oceans and critical to our planet’s survival (World Economic Forum, 2019). First, its impact on the global climate system is disproportionately large. Second, despite its small area it collects up over 10% of global river runoff. Third, owing to its complex and irregular coastline the Arctic marine domain comprises about a third of the world’s coastline. And fourth, the

AO contains one-quarter of the world's continental shelf, regions of immense socio-ecological importance. On all counts, the little AO holds a pivotal place on the global stage.

Despite notable past success involving science capable icebreakers and ice drift stations, a true collaborative spirit in the AO region remains restricted. As a consequence, our basic knowledge of the AO remains patchy. Long time series are lacking from many important regions, and our understanding of the seasonal ice cover and its associated biology is limited and often missing, in particular during winter, spring and early summer. The available literature addressing pan-Arctic integration has been edited and summarized in Wassmann (2006, 2011, 2015). One reason that research on the oceanography and ecology of the AO has lagged behind efforts elsewhere is the difficulty and harshness of year-round field sampling and that the efforts have been insufficient to cover the extent of this opening-up ocean owing to a lack of political and Earth ecosystem vision.

Events of recent years (e.g. the International Polar Year, 2007-2009) and the now accepted impact of global climate change has altered this view. An increased number of nations are becoming interested in conducting Arctic research, more ice-reinforced ships are now available and the amount of research funding that is dedicated to Arctic research is growing (e.g. the largest polar expedition in history, MOSAiC, https://mosaic-expedition.org/). Still, the lack of an adequate basic comprehension of this vast and complex system risks failing to achieve a knowledge-based understanding of the ecosystem and, consequently, a responsible resource management of the Arctic Mediterranean Sea. In addition to recent and ongoing studies providing 'puzzle pieces', we need emphasis on regions that are not investigated and on syntheses that provide the required high-level understanding. Otherwise, the outcomes of recent and ongoing studies, while possibly scientifically relevant and sound, may fall short of providing the high-level understanding required for responsible policy making and management. Continued lack of integration and conceptualization may leave us simply in worse position to manage the impacts of economic growth and industry operations in the future Arctic. In recognition of this shortcoming the Arctic Council signed an "Agreement on Enhancing International Arctic Scientific Cooperation" (Arctic Council, 2017), which intends to facilitate and promote pan-Arctic cooperation across the vastness of the AO. This agreement, which now has entered into force (Arctic Council, 2018) creates a mandate for more adequate endeavors to understand the vastness and the mediterranean nature of the AO.

Managing the imminent pressures derived from the forecasted increase in fisheries, petroleum and mineral extraction, other industrial operations and transportation in the AO requires knowledge. The cascade of effects of climate change affecting both Arctic and non-Arctic nations provides even greater challenges for sustainable ecosystem and resource management (Duarte et al., 2012; Box et al., 2019; Overland et al., 2019). As a pre-requisite an elaboration of the major research questions and programs aimed at advancing our understanding of the AO system is essential. Currently, such programs, which involve great efforts and resources, largely lack shared paradigms to help identify the key processes and levers that such programs should aim to elucidate. A need thus exists to develop community-shared theories and conceptual models that help unify our differing or lacking perspectives. Genuinely pan-Arctic perspectives and tools are required to understand, predict and manage a mediterranean-type AO now undergoing major change. One of the greatest unplanned experiments in human history is rapidly taking place before our eyes in the AO: ice-free condition during late summer, an accelerated hydrological cycle, strongly altered stratification and mixing, ocean acidification, an unprecedented change in underwater light climate and rapid warming of surface water. In summary and discussed throughout this publication the changes in the AO are based upon 4 fundamental, but highly consequence-rich and interconnected variables: ice cover (including increased stratification), light climate, nutrient/food availability and advection.

1.1. Why use a conceptual model approach?

We are motivated to begin with a system-wide perspective by the observations that: (1) global climate change is real and the Arctic is the most rapidly changing of all Earth systems, with major physical and ecological consequences (McLaughlin et al., 2011; Bhatt et al., 2014; IPCC, 2018); (2) the loss of sea-ice is the leading signal of climate change (Kwok et al., 2009; Duarte et al., 2012; Stroeve et al., 2012), with the role of the ocean in heat exchange gaining disproportionally in importance (Carmack et al., 2015; Polyakov et al., 2017); (3) the AO is coupled to and forced by the subarctic Pacific and Atlantic Oceans, with large-scale interactions affecting change in all three seas (Carmack et al., 2010; Polyakov et al., 2017; 2018; Lind et al., 2018); (4) the physical, chemical and biological components within the AO are mutually interacting, with cascading consequences throughout the system (Carmack et al., 2012; Huntington et al., 2014; Grebmeier et al., 2015); (5) the high-latitude hydrological cycle is accelerating, with substantial consequence for terrestrial and marine systems (Prowse et al., 2015; Carmack et al., 2016) .

For clarity, we here designate a conceptual model as a depiction (graphical, verbal or generic mathematical expression) of a process or a system, including its internal dynamics and its external drivers. It is a model constructed of ideas and theories to help the reader understand key processes and structural elements in the system that the model represents. The term conceptual model may be used to refer to models which are formed after a generalization of processes and linkages. Conceptual models are typically reified abstractions of things in the real world, whether physical, ecological or social, and are typically qualitative and descriptive, without attempting to formulate quantitative predictions. As such, they offer a system-wide perspective and often represent the framework around which quantitative models are built. Conceptual models advance and communicate our understanding by simplifying the complexity of multi-component systems (e.g., ecosystems) and allow us to focus on the salient processes and structural elements of such systems.

A conceptual model should be integrative, adaptive, anticipatory and succinct. Thus, in the evolution of any given scientific investigation a conceptual model is useful in: A) defining the initial scope of the problem, establishing testable hypotheses and developing experimental design; B) adapting program design during the course of the investigation as new information is acquired; and C) summarizing and communicating final results. Guidance can be applied to development of field programs, targeted experiments, numerical modelling and outreach. Such models may also be used to create scenarios to explore future consequences of management and change. A unified and pan-Arctic conceptual model for the AO, hosting a nested array of additional models addressing specific regions and processes, can thus be instrumental in providing a shared understanding that will allow improved coordination in research efforts addressing the AO in a time of change, while also minimizing the research gaps. By simplifying complex ecosystems into their core structural elements, linkages and functional processes, conceptual models provide a powerful tool to formulate hypotheses that inform scenarios of future change and evaluate intervention options.

Examples of these applications of conceptual models may illustrate why such models are, if not necessary, useful. A conceptual model forces us to identify essential features of a system with respect to a particular issue or geographic region. For example, which aspects of the ecosystem are going to affect and be affected by commercial shipping, in light of continuing climate change? A good conceptual model can help develop testable hypotheses, for example, “Shifts in the large-scale distribution of marine mammals will be affected by environmental change more than by ship traffic.” The conceptual model can then help in designing, carrying out, and as needed modifying field research to address the hypothesis (A). For example, a comparison of two areas would need to consider the characteristics of both areas to make sure the comparison was valid, and to gather additional data as needed to verify that this is indeed the case (B). In this shipping example, it is not sufficient that both areas have marine mammals. They must also be susceptible to similar influences of climate change, so that the presence of ship traffic in one region can be usefully compared with the absence of ship traffic in the other. Or that differences between the regions can be factored into the analysis of the observations from each region. On the basis of the results of the fieldwork, a new model of ship traffic can be developed, perhaps to identify times and routes that have greater or lesser effects on marine mammal distribution and behavior. The new model, of course, can be further tested and refined over time. When it comes to applying the new knowledge to the management of shipping, the conceptual model can help explain what matters and why, to help build a persuasive case for any management actions and to help show why other potential management actions are not necessary or may even be counterproductive (C). The conceptual model in this case serves as a device to focus attention and to provide a common basis for discussion and understanding, among all participants in all stages of the continuum from research to analysis to management.

1.2 Approach and goal

What do we wish to achieve here? Step by step, we wish to build up a hierarchy of unifying and comprehensive physical and ecological conceptual models for the AO. We attempt to generate shared, high-level paradigms that synthesize our understanding of the key processes and elements governing the response of the AO ecosystem in relation to current pressures and changes. We aim at doing so by summarizing existing and generating new, interdisciplinary and parsimonious conceptual models of the functioning of the AO.

We try to raise the attention of today's and the future's AO scientists and managers to prepare for a more holistic understanding of the new emerging ocean; an understanding that is required if the goals of sustainability are to be met (cf. Arctic Resilience Report, 2016; Auad et al., 2018). The interconnected ecosystem elements and concepts of the AO will then contribute to a generic understanding where new research can be placed into existing conceptual models. We finish by discussing how knowledge-based ecosystem and resource management in today’s and the future’s AO can be shaped out of an adaptive and anticipatory conceptual model approach, how it can support the integration of indigenous and local knowledge and how communication with the general public can be strengthened.

2. Global and pan-Arctic setting and basic physical function

The changes in the Arctic have already had unprecedented impacts and consequences across a range of economic (Alvarez et al., 2020), environmental(National Academy of Sciences, 2007), societal (Stephen, 2018) and geopolitical (Tingstad, 2018) realities in the lower latitudes, most notably the rising sea levels, increases in extreme weather and substantial changes in international geopolitics. The Arctic and the northern oceans drive global-scale changes that accelerate and amplify changes within the Arctic (IPCC, 2018). However, those changes in the Arctic and throughout the northern oceanic regions, in turn, drive unprecedented changes affecting the rest of planet Earth, particularly the Northern Hemisphere (AMAP, 2017). A genuine evaluation of the function of the AO demands a global context and a pan-Arctic perspective.

The AO, itself, is a mediterranean sea that is roughly half continental shelf and half basin and ridge complex. Currently, it is roughly two thirds seasonally and one third perennially ice-covered, thus now exposing an increasing portion of basin waters to sunlight and wind (Bluhm et al., 2015; Wadhams, 2017). The necessary starting point in developing a unified perspective is to recognize that the Arctic marine system is strongly coupled to the global system and that this coupling is bi-directional, with the global ocean affecting the Arctic and the Arctic strongly affecting the global ocean. Maintaining this perspective requires an internally consistent and logical use of scale, both spatial and temporal, in the development of nested and adaptive conceptual models. **Fig. 2** is a highly schematic, Sverdrup-type illustration grouping the spatial and temporal scales that encompass global, pan-Arctic and regional systems; simply starting with this perspective helps us setting research goals and efforts. The global marine scale system is represented by large spatial and time scales and is itself externally forced by even larger scales. The pan-Arctic marine system, the focus of this paper, is nested at smaller spatial and temporal scales and is coupled to the global marine system through exchanges of energy, freshwater, water masses and material properties with bordering subarctic oceans and terrestrial land masses. This system, in turn, is underlain by regional and contiguous domains, as discussed below in sections 3 and 4. Beneath the regional scale are the various mesoscale and sub-mesoscale processes that advect material properties and act to regulate biogeochemical rates and processes within specific regions. Energy and physical forcing pass from top-down from larger to smaller scales, while feedbacks and emergent properties are driven bottom-up.

The AO's thermohaline structure and circulation are forced at the global scale with freshwater delivery to the AO by the atmosphere as demanded by the climate system to transport heat (in this case as latent heat) from the low to high latitudes, and by the subsequent need to redress the resulting ocean salt balance through the meridional thermohaline circulation. The transport of heat and moisture begins with the Trade and Westerly winds which carry moisture first from the Atlantic to the Pacific and continues with the Westerly winds which carry moisture to the Arctic drainage basins (**Fig. 3A**). In contrast to the southern hemisphere, the configuration of continents in the northern hemisphere is such that they effectively capture precipitation from the storm tracks of the Westerlies and redirect in north-flowing rivers disproportionate quantities of freshwater in north-flowing rivers into the mediterranean configuration of the AO (**Fig. 1A**). The disproportionate areal coverage of lakes in high-latitude drainage basins further affects freshwater storage, modification and release timing to the ocean

(Verspoorter et al., 2014). Hence, while the AO represents only 1% (in terms of volume) and 3% (in terms of surface area) of the global ocean, it collects over 11% of the global river discharge (Dai and Tenberth, 2002; McClelland et al., 2011; Carmack et al., 2016). The freshwater budget of the AO is governed by: the delivery of fresh and low-salinity waters to the AO by river inflow, net precipitation, distillation during the freeze/thaw cycle and Pacific Ocean inflows; the disposition (e.g. sources, pathways and storage) of freshwater components within various domains of the AO (e.g. basins, shelves, coastal zone); and the release and net export of freshwater components into the bordering convective domains of the North Atlantic (Aagaard and Carmack, 1989; Carmack et al., 2016; Brown et al., 2020a).

The AO joins the global ocean through the inflow of both Pacific-origin water (PW) through the shallow (~50 m) Bering Strait into the Canada Basin, and counter-flowing Atlantic-origin water (AW) through eastern portion of the deep (~2600 m) Fram Strait and across the relatively deep (200-400 m) Barents Sea shelf into the Nansen Basin (**Figs. 1B, 4**). Depending on pathways and mixing history the incoming AW exits the AO as a lighter (fresher) component than when it came in by mixing with freshwater than when it came in or a denser (more saline) component than when it came in by cooling and brine formation. Consequently, at the pan-Arctic scale, the system acts as both a positive and negative estuary (Carmack and Wassmann, 2006; **Fig. 4**). Modified forms of PW and AW exit through the western Fram Strait and Davis Strait gateways (**Fig. 1B**). The considerable stratification of the AO is partly shaped, entagled and driven by westerly winds that create the Polar Vortex features (**Fig. 4**).

3. Regionality: hydro-morphological features and biogeochemical cycling of shelves, the shelf break and deep basins

While the pan-Arctic system is the focal scale of this work, it is of critical significance to recognize the nested, component parts of the system. This is important to guide the selection of appropriate regional-scale applications, and not to overgeneralize findings from a particular region to the entire system (for example, see Polyakov et al., 2018). For this we follow approaches by Carmack and Wassmann (2006) and Bluhm et al. (2015) and distinguish among basic shelf, shelf break and basin regimes on the basis of topography, hydrography and biogeochemical function.

The shelf, shelf break and basin regimes are an integrated part of the physical oceanography and connected through currents. Four large-scale circulation systems can be distinguished. In the uppermost layers down to about 200 depth wef find the wind-driven circulation which forces the cyclonic Trans-Polar Drift (TPD) from interior shelves of Siberia to the export shelf of the Fram Strait and the anticyclonic Beaufort Gyre in the southern Canada Basin (**Fig. 5A**). Below therer we find the circulation of waters that comprise the halocline complex, composed largely of waters of Pacific and Atlantic origin that are modified during passage over the inflow and Siberian interior shelves (**Fig. 5B**). The topographically-trapped Arctic Circumpolar Boundary Current which carries AW cyclonically around the boundaries of the entire suite of basins (FSB and BSB are the Fram Strait and Barents Sea Branch) (**Fig.** 5C). At depth we find the slow exchange of Arctic Ocean Deep Waters that enter on the eastern and leave on the western Fram Strait (**Fig. 5D**).

3.1 Shelf types and basic biogeochemical function

The shelves of the Arctic Mediterranean are strikingly different from those of the remaining World Ocean. No other ocean comprises as much shelf area as the AO: > 50 % (Jakobsson et al., 2008). Being so dominant and increasingly exposed to sunlight, emphasis on these shallow realms, bounded by a narrow and steep shelf break and slope, is needed to understand their functional dynamics **(Fig. 5)**. In order to obtain a more adequate perspective of the pan-Arctic shelves we expand on the typology proposed by Carmack & Wassmann (2006). Inflow, interior and outflow shelves are distinguished (**Fig. 6**), which represent entirely different functional types that shape and are shaped by their biogeochemical roles (**Fig. 7**). Among the three basic shelf types we further differentiate between the shallow and deep inflow shelves (Northern Bering Sea/Chukchi Sea and Barents Sea, respectively; e.g. Hunt et al. 2013), the narrow and wide interior shelves (Beaufort Sea and Kara/Laptev/East Siberian Seas, respectively; e.g. Williams and Carmack, 2015) and the branching and longitudinal outflow shelves (Canadian Archipelago and east-Greenland shelf, respectively; e.g. Michel et al., 2015; **Fig. 7**).

3.1.1 Inflow shelves

During transit of inflowing subarctic waters along western Spitsbergen and across the Barents, Bering and Chukchi Seas the waters are strongly shaped and altered by biogeochemical and physical processes (Grebmeier et al., 2015; Vernet et al. 2019; **Fig. 7**). Transformations during transit depend on the width and depth of the shelves that, in turn, affect the water’s residence times, in particular in the biogeochemically active layers (the euphotic zone and the benthic boundary layer). These waters subsequently subduct at fronts (e.g. the Polar Front in the

Barents Sea) or along the shelf break (e.g. north of Svalbard), and thus influence property distributions within the Arctic basin (e.g. Polyakov et al. 2013, 2017). Inflow shelves also play an important role during the advection of pelagic organisms, in particular zooplankton (Kosobokova and Hirche, 2009; Wassmann et al., 2015; Ershova et al., 2015a, Hunt et al., 2016). The direct supply of freshwater from rivers to the southern Barents Sea is relatively low, and consequently stratification of surface waters is weak in the relatively deep southern Barents Sea, but relatively strong in the SIZ of the northern Barents Sea where stratification is enhanced by ice melt and inputs from the massive Siberian rivers (Smedsrud et al., 2013). The supply of relatively fresh Pacific water through the shallow Bering Strait and local ice melt support a much stronger seasonal stratification in the Chukchi Sea (Woodgate et al. 2006, 2015).

Inflow shelves have by far the highest primary production within the AO, comprising about two-thirds of the total (Sakshaug, 2004; Matrai et al., 2013). The introduction of nutrients and advection of suspended biomass is an essential feature of inflow shelves and is particularly significant in the shallow Bering Strait and adjacent Chukchi Sea where it directly fuels a biomass-rich benthic community (Grebmeier et al., 2015). Also, advection of larger zooplankton and propagules of benthic biota from sub-Arctic or boreal regions onto and over the inflow shelves is an essential aspect of their specific functionality (Wassmann et al., 2015; Ershova et al., 2015b, 2019b; Silberberger et al., 2016) (see section 4 Contiguous domains). The resulting biological community structure in both water column and at the seafloor, reflects their boreal to arctic sources (Aninisimova, 1989; Hopcroft et al., 2010; Ershova et al., 2015a; Fossheim et al., 2015).

3.1.2. Interior shelves

Interior shelves are all shallow and are characterized by the impact of major rivers, such as the Yenisei, Ob, Lena and Mackenzie Rivers, and numerous smaller rivers (Williams and Carmack, 2015). The major distinction between Eurasian and Amerasian interior shelves is that the Eurasian interior shelves are several hundred km wide while those of North America are much narrower (**Figs. 6, 7**). Interior shelves exhibit a positive estuarine circulation (river plume spreading) in summer and a negative estuarine circulation (caused by brine drainage during sea ice formation) in winter. During periods of river plume spreading the nearshore flocculation of estuarine and marine matter (both particulate and dissolved) is high but decreases offshore with distance from the river deltas. The combined effects of wind and tides can be significant and can thus enhance or reduce the dispersion of plume water towards the sea. Below the freshened surface layer, the estuarine circulation transports seawater towards the littoral zone (McClelland et al., 2011). The horizontal exchange of water masses is thus substantial and sometimes results in the formation of multiple fronts; horizontal variations in salinity are large. The load of terrigenous matter from the rivers can be large and thus turbidity and light extinction is high (Goñi et al., 2013). The innermost portion of interior shelves is characterized by land fast ice that melts during summer (Mahoney et al., 2014). Here pack ice collides against the land fast ice, and between these two ice types, bands of ridges (stamukhi) form under convergence and flaw polynyas form under divergence conditions. The presence of this stamukhi zone in the early season can also act as an ice dam, impeeding the spreading of river water over the shelf in early spring (McClelland et al., 2011).

Compared to the inflow shelves, the biogeochemical transformations taking place on interior shelves are different in that they are dominated by processing of terrestrial carbon (**Fig. 7**). The supply of terrestrial carbon into the interior shelves is transformed into usable food for marine organisms by bacteria and this comprises an increasingly important food source for Arctic biota, as already observed for freshwater systems (Dunton et al., 2012; Taipale et al., 2016). Photosynthetic primary production and the general biological activity are lower than on inflow shelves, and much of the allochthonous matter is of a refractory nature (Divine et al., 2015; Bell et al., 2016). High turbidity and export of surface waters below the ice cover, followed by nutrient limitation due to strong salt stratification are the main causes for the low primary production (Babin et al., 2015). Biomass of planktonic organisms is thus comparatively lower than on inflow shelves although hot spots may occur in certain areas (Smoot et al., 2017); biomass of benthic organisms is equally highly variable but also generally lower than on inflow shelves (Dunton et al., 2006; Ravelo et al., 2015). Some of the food for the benthic organisms is of marine origin and derives from the estuarine circulation bringing deeper waters onshore, some is locally produced, and a significant amount derives from littoral and riverine sources (Dunton et al., 2012; Stasko et al., 2018). Biological community structures in the water column and at the seafloor clearly differ from those in inflow shelves due to both the increasing influence of Arctic species and freshwater and terrestrial carbon inputs (Deubel et al., 2003; Hirche et al., 2006; Garneau et al., 2009; Ershova et al., 2019a). Sustained easterly winds promote upwelling over the shelf break, particularly when ice cover is reduced (Carmack and Chapman, 2003; Williams and Carmack, 2015; **Fig. 12**). This results in rather different nutrient upwelling scenarios on narrow and wide shelves **(Fig. 7)**. For example, along the narrow shelves of the Beaufort Sea primary production can be strongly stimulated and upwelling of off-shore nutrients may reach the innermost shelf region (Tremblay et al., 2011). On the wide shelves off Siberia upwelled nutrients are presumably limited to the vicinity of the shelf break.

3.1.3. Outflow shelves

Outflow shelves allow Arctic and Pacific halocline water back into the North Atlantic (i.e. the Nordic and Labrador Seas) via the Canadian Arctic Archipelago and along the east coast of Greenland (**Figs. 6, 7**). The outflow shelves are not simple gates or channels, but transit times of out-flow shelves are sufficiently long for thermohaline and biogeochemical changes to occur en route (Michel et al., 2015). The Canadian Arctic Archipelago in particular has long and highly variable flow-through and residence times (McLaughlin et al., 2005). On the whole, the Archipelago is a complex network of channels, sub-basins and sills, while the east Greenland shelf is less structured but deeper. The archipelago (which can be divided into a) Beaufort-Amundsen, High Arctic, c) Baffin - Labrador, d) Kitikmeot and e) Hudson-Foxe regions (Oceans North Conservation Society, World Wildlife Fund Canada, and Ducks Unlimited Canada, 2018) is currently ice-covered during most of the year with extensive, but variable, ice-melt and stratification observed during summer and early autumn. Heavy ice and pack ice cover the northern-most portions of outflow shelves. Sea ice conditions demonstrate significant declines in multi- year ice and a redistribution of ice types over the past 3 decades (Wadhams, 2018). Sea ice export strongly contributes to structuring spatially diverse productivity regimes (Michel et al., 2015).

The average current direction of the longitudinal East Greenland and Baffin Island outflow shelves is basically parallel to the ice edge, but is also influenced by a combination of tidal mixing and wind-forced up and downwelling. Also, the longitudinal outflow shelves of the western Fram Strait and eastern Greenland are, to various degrees, perpetually ice-covered by pack ice transported from the Transpolar Drift. Most of the ice produced in the AO melts along the longitudinal outflow shelves. This results in significant stratification and reduced salinity of the East Greenland Current. Primary production and associated community structure on outflow shelves are spatially variable (Ardyna et al., 2011, 2013; Mayot et al., 2018; Michel et al., 2015). In the southernmost network sections of the outflow shelf primary production can be significant (Tremblay et al., 2006). Generally, however, low nitrate concentrations in eastern Greenland and continuous ice export are thought to be responsible for comparatively low primary production (Michel et al. 2015). The contribution of ice algal production is thought to be high at least in the southern network of the outflow shelf (Matrai and Apollonio, 2013). It is highly seasonal, quickly nutrient limited and proves to be highly variable between years. The zooplankton dynamics are even more variable, probably due to irregular advection episodes through the Archipelago (Hamilton et al., 2009; Apollonio, 2013). Of all Arctic shelves, the outflow shelves have the largest area of coastal hard substrates, most high flow passages, the most abundant proximal glaciers and some of the most prominent polynyas, all resulting in – yet poorly mapped - highly variable benthic communities (Kenchinton et al., 2011; Roy et al., 2015). In contrast to most other shelves, the coastal areas include long stretches of, and increasing biomass of macroalgal primary producers (Krause-Jensen et al., 2012; Filbee-Dexter et al., 2019). Polynyas of various sizes play a role as local hot spots, with close pelagic-benthic coupling in pockets of high vertical mixing (Ambrose and Renaud, 1995; Smith and Barber, 2007).

3.2. Shelf break and slop types and basic biogeochemical function

The shelf break (submerged offshore edge of a shallow continental shelf, where the seafloor transitions to continental slope) and upper slope (seaward border of the continental shelf) form the transition zone between shelf and basins, comprising the approximate depth range of 80-1000 m in most areas (**Fig. 6**; Jakobsson et al. 2008). It is characterized by strong gradients in physical, chemical and biological properties over a narrow horizontal band (see 4.2.2). It encircles the two main basins and forms a contiguous feature stretching counter-clockwise ~ 8000 km from northwest Svalbard to northeast Greenland (**Fig. 6**). The belt is influenced by three key physical-ecological processes: i) one that is thermohaline driven and along-slope, ii) one that is wind forced and cross-slope, and iii) one that is tidally driven and promotes internal wave generation and vertical mixing.

The shelf break and slopes of the AO play a significant role for its overall physical oceanography and biogeochemical cycling. The topographically-trapped Arctic Circumpolar Boundary Current (ACBC) carries AW cyclonically along the shelf break and upper slope around the boundaries of the entire suite of AO basins (see **Fig. 5B** and section 4.2).

The recent decrease in summer ice cover on the shelf edge supports increased up-welling and has fundamentally changed the productivity and stratification along the circum-Arctic shelf break (**Fig. 12**, Williams and Carmack, 2017). Along the Eurasian and western Amerasian shelf edge, nutrient availablilty has increased, while the accumulation of ice and freshwater along the slopes of northeastern Canada and northern Greenland have contributed to increased stratification, preventing open water and upwelling (Slagstad et al., 2015). Increased solar radiation, coupled with upwelled nutrients has induced a significant increase in new production on the Eurasian and western Amerasian shelf edges to levels similar to those experienced on the adjacent shelves (Tremblay et al., 2011).

Stratification along the slope regions north of Svalbard appears to have decreased due to increased influence of AW (Polyakov et al., 2017, 2018; Lind et al., 2018), with an increasing tendency of AW (and decreasing stratification) to spread eastwards towards Siberia. These changes in ice, river inflow and ice melt may change the vertical nutrient flux may change accordingly, affecting primary production and phytoplankton size distributions (Randelhoff and Guthrie, 2017). Advection of expatriate Atlantic or Pacific origin mesozooplankton is also characteristic of the slope domain (Kosobokova, 2012; Bluhm et al., 2015, Wassmann et al., 2015; Ershova et al. 2019b).

As such, the shelf break and adjacent slopes are currently experiencing some of the greatest ecological changes in the AO. Numerical models project a doubling and tripling of primary production along the slopes on the Eurasian side and western Amerasian side (from north of Svalbard to the Beaufort Sea) (Slagstad et al., 2015), while production remains low or even declines in the central AO and the north-eastern Canada/northern Greenland shelves. While the shelf break and slope band that stretches from north of Svalbard to the Beaufort Sea has seen primary production increase; wheras it has decreased along the CAA and northern Greenland shelves.

3.3. Basin types and basic biogeochemical function

Two main basins occupy the deep central AO, the Eurasian and Amerasian basins, separated by the Lomonosov Ridge between the Greenland and Siberian shelves (**Fig. 5D)**. In turn, the Eurasian Basin is divided into the Nansen and Amundsen basins by the Nansen-Gakkel Ridge, and the Amerasian Basin into the Makarov and Canada basins by the Alpha-Mendeleev Ridge. Deep basin domains are influenced both by their deep connection to the Atlantic (~ 2600 m) and shallow connection to the Pacific (~ 50 m), and by the broad shelves around them (Jakobsson et al., 2008). The ridges that separate the deep basins form boundaries for exchange of water masses and steering of deep ocean circulation, but counterintuitively play less of a role as barriers for the dispersal of biota (Kosobokova et al., 2011; Bluhm et al., 2011; and reviewed by Bluhm et al. 2015).

Only one third of the Amerasian and Eurasian basins of the deep AO are currently perennially ice-covered, so that much of the basin area is now seasonally exposed to sunlight and wind. Within the basin domain two basic water mass assemblies are observed, the difference between them being the absence or presence of PW sandwiched between Arctic Surface Waters (ASW) above and the AW complex below; the boundary between these domains is the Atlantic/Pacific halocline front (**Figs. 4, 5**). Both domains have vertical stratification that constrains the transfer of nutrients to the surface layer (euphotic zone), thus leading to their oligotrophic state, particularly in the more strongly stratified Pacific Arctic where, despite high nutrient concentrations in the inflow, convective reset of surface layer nutrients by haline convection in winter is virtually absent. First and multi-year sea ice drastically alters albedo and insulates the underlying water column from extreme winter heat loss while its mechanical properties (thickness, concentration, roughness, etc.) greatly affect the efficiency of momentum transfer from the wind to the underlying water.

Owing to the mentioned nutrient limitation, coupled with light limitation due to snow and ice cover and extreme sun angle, primary production in sea ice and water column of the two basin domains is very low compared to the adjacent shelves (Gosselin et al., 1997). Severe nutrient limitation and complete euphotic zone drawdown in the Amerasian Basin appears to favor small phytoplankton (Li et al., 2009), a ubiquitous deep chlorophyll maximum layer (Carmack et al., 2011; Ardyna et al. 2013) and a low energy food web (Iken et al., 2010). In contrast, nutrients persist in the western Eurasian Basin, even in summer, suggesting light limitation, heavy grazing or both as the dominant controls. Further these higher stocks of nutrients in the Eurasian Basin are more conducive to marginal ice blooms which are less abundant in the Amerasian Basin. Within the basin interior the ice is now thinner and less compact, and thus more responsive to wind stress than in the pre-1970s (Gascard et al., 2008). Increased accumulation of fresh water and stratification, particularly in the Amerasian Basin constrains vertical nutrient flux and affects phytoplankton size distributions, thus limiting primary production in parts of the basins now and likely in the future (Randelhoff and Guthrie, 2017). The result of low nutrient surface waters is that vertical carbon supplies to the basin seafloor are low (Macdonald and Carmack, 1991), largely advective (horizontal) and terrestrial in origin (Fahl and Stein, 1999), and generally support low benthic and fish biomass (Bluhm et al., 2011; Mecklenburg et al., 2018; Zhulay et al., 2019), though localized islands of larger than anticipated biomass are now recognized (Vedenin et al., 2018).

4. Contiguous domains in the Arctic Ocean

The regional domains and their biogeochemical cycles discussed in section 3 are linked to each other through contiguous domains. A contiguous domain is one whose components i) share a common boundary or set of properties and functions, and ii) are connected, over defined scales, in time and space. In our pan-Arctic scale application, we seek common functional traits or phenomena that appear continuously or at least once during an annual cycle. Contiguous domains may or may not link specifically to geography as they may cross and link regional and biogeographical domains. They may further expand or contract over interannual time scales. These linkages allow material transports and share key ecological functions and causal mechanisms (Carmack and McLaughlin, 2000; Carmack and Wassmann, 2006).

In investigating the AO through the conceptualization of contiguous domains, we take a macroecological view. In this way we examine patterns in water mass and species distribution, and in species abundance to determine relationships between abiotic and biotic factors, and further to understand and model climate change impacted ecosystems along space-and-time climate gradients (Li, 2002, 2009; Fossheim et al. 2015). Macroecology deals with the study of relationships between organisms and their environment at large spatial scales to characterize and explain patterns of abundance, distribution and diversity. The perception gained from this view will prove valuable in the design of synoptic scale research programs and the management and conservation of marine arctic resources, it is a key to understanding the ecological impacts of climate change that rely in in understanding the functions each domain provides.

When considering conceptual models for the AO it is important to recognize which biogeographical scales come closest to matching those of the climate system itself (cf. Carmack and McLaughlin, 2001). In this context it is again useful to think in terms of contiguous domains. Functions within a given contiguous domain are thus likely to share broad linkages also in response to climate forcing. Conversely, the response of different contiguous domains to climate forcing may likely be different in qualitatively and quantitatively different, and failure to recognize the interplay of scale, regionality, seasonality and contiguity may lead to over-extrapolation and misinterpretation. The contiguous nature of significant elements of the AO ecosystems implies thus a distinct pan-Arctic approach.

In defining contiguous domains, we attempt to lay the foundation for a better interpretation of previous and future investigations by placing the AO in a more realistic time/space perspective. Thereby a full set of scales linking climate to biota along entire contiguous domains may be accommodated in the future, with improved understanding of domain-wide responses to variance in climate. The AO is a beta ocean system (defined by temperature and salinity, in contrast to an alpha ocean) which defines hydrographic and ecosystem connections through the underlying cause of permanent stratification similarities; that is, salt (β) or temperature (α) stratification (Carmack, 2007). Within this system, we recognize 6 contiguous domains grouped by their reliance on seasonal processes (section 4.1) or advective processes (section 4.2). The AO is decisively connected to and forced by Pacific and Atlantic water that enter perpendicular to the AO Mediterranean through the Bering and Fram straights and the St. Anna Trough. Advection from outside, but also inside the AO is thus an overruling process that shapes all contiguous domains of the AO (section 4.2). An exception is the Seasonal Ice Zone Domain (SIZD, see 4.1) which is mainly shaped through seasonal processes, including radiation and stratification and links shelves and basins through a pulsating, expanding and shrinking area (however, in recent years incoming AW is playing an ever increasing role in the retreat of sea ice north of Svalbard and probabaly in the northern Kara Sea in the near future; see Polyalov et at 2017). With increasing thinning of the ice cover, the outer part of the central AO experiences ever more open water and greater fetch that may open up for increased vertical mixing of nutrients (Randelhoff et al. 2015; Randelhoff and Guthrie, 2016). The exact position/shape/coverage of the SIZD at any given time may also be subject to advection by wind and currents, and is thus a spatially and temporally dynamic contiguous domain.

4.1 Seasonal Ice Zone Domain

The seasonal ice zone is the area of the AO that extends from the permanent ice zone to the boundary where winter sea ice extent is at a maximum. The Seasonal Ice Zone Domain (SIZD) is now the largest contiguous domain in the AO. It comprises the cumulative area that is temporarily ice-covered at any given time within a year, i.e. basically the area between maximum and minimum ice extent in a given year. Ice and snow limit the penetration of solar radiation and thus photosynthesis of ice algae and phytoplankton. Ice and stratification by ice melt reduce the impact of wind on vertical mixing and can support an ice edge bloom where and when nutrients are available, especially on the shelves. Thirty years ago, this domain was limited in areal extent, rarely crossing the shelf break, but climate warming has greatly decreased the area of summer ice cover while only marginally decreasing winter cover, thus resulting in vast widening of the SIZD (**Fig. 8A**); it now comprises about 2/3 of the total area of the AO (similar to the size of the territory of Europe). Global climate change has and will have in decades to come have immense consequences in the SIZD. As the knowledge base for SIZD dynamics - physical and biogeochemical- - is limited, and climate change is greatest, the lack of key information is particularly discomforting. The number of time-series moorings and research platforms is small and the expanding cover of the region means the SIZD is not well represented in any conceptual mode. The past, present and future highly dynamic nature of the SIZD is exemplified in **Fig. 8B**. The shrinking and expansion of the SIZ can be compared to with the breathing of an organism. In summer the SIZD breathes in and opens up for primary production and the unfolding of seasonal and perennial Arctic life. In autumn and winter the SIZD breathes out and, along with declining radiation, spreads the sea ice cover like a lid over the AO. The seasonal exhalation and inhalation of the domain sets the rhythm for the biological carbon pump and export production to the AO benthos (see 5.3).

The seasonal ice zone is created by annual ice melt and consists of two types of ice: pack ice (that dominates by area) and land fast ice. Land fast ice attached to the coastline, to the sea floor along shoals, and to grounded icebergs in summer (Greenland) is a defining feature of Arctic coasts and can extend hundreds of kilometers offshore (Mahoney et al., 2014; Yu et al., 2014). Fast ice may either grow in place from the sea water with admixtures by river water (Eicken et al., 2005) or by freezing pieces of ice drifting to the shore or other anchor sites. In most regions the pack ice meets the fast ice during maximum ice cover. Here we find ridging, known as stamukhi; a partially-grounded accumulation of sea ice rubble that typically develops along the boundary between fast ice and the drifting pack ice, or becomes incorporated into the fast ice. In addition to stamuki we also find here polynyas, areas of open water surrounded by sea ice (Macdonald and Carmack, 1991). It is often used as a generic term for an area of unfrozen sea within the ice pack. Rapid ice melt of fast ice is also part of the seasonal ice zone, but this melt is much smaller by a factor of 3.3 by area (mean 1.84 million km^2 between 1975-2007, Yu et al., 2014) than that of the pack ice zone. Disproportionally high, however, is the use of land fast ice by horizontally or vertically migrating, feeding and/or resting marine life (Gradinger et al., 2009; Hamilton et al., 2017) and by local Arctic human communities for both travel and subsistence hunting (Eicken et al., 2009, 2014; Fox Gearheard et al., 2017).

Outside the land fast ice zone we find the SIZ of the pack ice that is free-floating, not connected to land. It expands generally north- and inwards with the AO melting season. Before climate warming accelerated in recent decades, the SIZ - assuming it was circular - had a radius of ~1,500 km in summertime. The outer rim of the SIZ is the marginal ice zone (MIZ) of more than 9,000 km (**Fig. 8B**). Previously the MIZ circumference was too long to be circumnavigated and studied synoptically during a single cruise. Soon the maximum SIZD width will only be about 500 km and the MIZ circumference less than 6,000 km, and could thus be circumnavigated in 2-3 weeks. The area of todays SIZ at a width of 500 km is > 6 million km^2 (**Fig. 8B**) renders the investigation of the SIZ an enormous challenge for the low number of available research platforms. The MIZ forms the biologically most active fringe of the pack ice SIZD. During summer the ice cover of the SIZD gets thinner and the large ice-covered SIZD supports ice algal and later phytoplankton blooms (Gradinger et al., 1999; Gradinger, 2009; Ardyna et al., 2014; Mayot et al., 2018).

To better comprehend the dynamic nature of the SIZD across the AO (the phenology and latitudinal variability is addressed in section 5.2 and **Figs. 16-18**), monthly hypothetical transects, reflecting ice over and thickness, light and plankton blooms were developed (**Fig. 9**). One such transect stretches across the AO from the wide and productive Barents Sea to the narrow Beaufort Sea shelf (**Figs. 8B, 9A**) while the other transect runs from the wide Laptev Sea shelf to the heavily ice-covered regions north of Greenland (**Figs. (B, 9B**). The distribution of SIZD phytoplankton blooms in space and time is very uneven across the AO. The phenology of ice and phytoplankton varies significantly across the AO with the largest blooms and greatest ice-melt on the Eurasian side (Arrigo and van Dijken, 2015; Slagstad et al., 2015). The maximum development of the phytoplankton bloom is encountered May through July, dictated by ice cover, light and nutrients. Climate change will influence the time window of the phytoplankton development since thinner ice and leads already after equinox will induce an early onset of thin bloom layers close to the surface (e.g. Assmy et al., 2017). Most of the thinning and reduction of ice cover takes place towards the end of the early productive season (with high new production) and thus does not immediately influence the bloom development. Recently pelagic autumn blooms, however, have increasingly been encountered (Loeng et al., 2005; Ardyna et al., 2014; Oziel et al., 2017). At high latitudes they become quickly light limited when solar radiation decreases and they depend upon increased nutrient availability through vertical mixing by winds and tides.

4.2 Contiguous domains constrained by advective processes

Within the AO at least five additional, linked, contiguous domains can be identified which, to variable degree are impacted by advection and the characteristics of water masses. The ecology of advection (c.f. Carmack and Wassmann, 2006; Wassmann et al., 2015) plays thus a fundamental role in these domains. With decreasing significance of advection these contiguous domains are:

- the Riverine Coastal Domain (RCD), which links all shelf typologies with hinterland
- the upper layer advective domains (ULAD), which connects the AO with the northern Pacific and Atlantic Oceans and the northern Barents Sea
- the Atlantic and Pacific Halocline domains (APHD), which recognize the spreading of Pacific halocline waters into the Amerasian and Eurasian basins
- the Circumpolar Boundary Current Domain (CBCD) along the shelf-break, which surrounds the basins and links shelf-basin exchanges
- the Deep Basins Domain (DBD) which is exposed to sluggish advection from the North Atlantic.

4.2.1 Riverine Coastal Domain

The riverine coastal domain (RCD) is a narrow (5-15 km wide), shallow (~10 m deep) contiguous feature that is confined by the spreading of river and glacial water discharge (**Fig. 10**). It is forced by an aggregate of continental runoff sources (**Fig. 1A)**, with diverse timing of discharge, and which extends counterclockwise around the perimeter of the coast, broken only by the major gateways at Bering and Fram straits (Carmack et al., 2015) (**Figs. 1B, 3**). Due to its riverine sources, the RCD carries a terrestrial signal from surrounding rivers, lakes and watersheds that affects light, nutrient and carbon regimes, and provides a coastal pathway for the dispersal and migration of marine biota such as anadromous fish and arctic brakish water zooplankton. The RCD acts as the initial connector between terrestrial and marine ecosystems such that physical and biogeochemical variables within the RCD yield a contiguous gradient of environmental conditions along and across the pan-Arctic coastal zone between and among shelf domains. The RCD may become even more prominent as terrestrial runoff, permafrost thaw and local ice melt are assumed to increase in the near-future climate (for estimates of permafrost carbon input into the Arctic coastal zone, see Lantuit et al., 2013). However, due to the small cross-shelf size of the RCD (~10 km) and its nearshore, shallow location that is outside the operation range of most research vessels, detailed observations of this feature are virtually missing, with probably the exception of the the Alaskan nearshore shelf and estuarine lagoons of the Beaufort Sea (e.g. Dunton et al., 2006, 2012).

The seasonally highly dynamic and physically challenging conditions of the coastal zone result in recognizably different biotic communities than are found farther offshore. Zooplankton communities are characterized by neritic and brackish taxa – especially near/in river deltas/river estuaries (Lischka et al. (2001) for the Laptev and Deubel et al. (2003) and Hirche et al. (2006) for the Kara Seas, respectively). Benthic communities including demersal marine fishes show low diversity and biomass thought to be related to a combination of seasonally low salinity, and mechanical disturbance through ice gouging (though this effect extends beyond the RCD) (Ravelo et al., 2015). Coastal migratory and forage fishes, however, can be abundant in this domain (Roux et al., 2016), and it is this narrow coastal belt where all indigenous subsistence travel and hunting activities in the marine realm take place.

4.2.2 Upper Layer Advective domains

We define the combined waters above the halocline and advected by the North Pacific, North Atlantic and the Barents Sea or transported through the Transpolar Drift as the Upper Layer Advective Domains (ULAD) (**Fig. 11**). Note that surface waters within the subarctic Atlantic and Pacific subduct upon entering the AO continue as mid-depth interflows. The advection of nutrient-, detritus- and plankton-rich waters from the Pacific and Atlantic Oceans and the northern Barents Sea into the AO plays a crucial role for the ecology and seasonality of the AO ecosystem (Wassmann et al., 2015; Hunt et al., 2016). In addition, the Siberian shelf is connected to the Fram Strait through the Transpolar Drift advection (**Fig. 11**). Such flows connect subarctic with arctic biota, supporting both primary production and higher trophic level consumers (Vernet et al 2019; Wassmann et al. 2019). By volume of water and biomass inflow, the dominant contribution to the ULAD is by the northeastern North Atlantic and the Barents Sea (**Fig. 11**). ULAD overlaps at the shelf break and upper slope with the circumpolar boundary current domain (see 4.2.3).

While the ULAD connects Arctic biota with subarctic inputs, its outflow also influences the physical, chemical and biological oceanography of adjacent subarctic waters through advective outflows, in particular through western Fram Strait, but also through the Canadian Arctic Archipelago. However, exports of biomass out of the AO into the North Atlantic Ocean are thought to be far smaller than the influx from the south (e.g. Wassmann et al., 2015). Thus, AO ecosystems are net planktonic biomass beneficiaries through advection, especially along the relatively narrow advective pathways of the ULADs: large amounts of food create the basis for fish and marine mammals feeding at the perimeter of the AO basins. Further, the transport of ice with its associated biota and conspicuous amounts of terrestrial matter that drifts across the AO with the Transpolar Drift also delivers a supply of DOC and biogenic matter from the Laptev Sea to the western Fram Strait regions (Hop and Pavlova, 2011). The biotic impact of Atlantic-, Pacific- or Arctic origin taxa being transported in the ULAD depends on their ability to survive along the transport path (Hirche and Kosobokova, 2007). Thus, advective transport can be thought of as "trail of life and death" in the AO (Wassmann et al., 2015).

We distinguish three specific ULADs based on water mass structures (**Fig. 11**): the Atlantic-Arctic (including the Barents Sea branch), the Pacific-Arctic, and the Transpolar Advective domains. The Atlantic-Arctic ULAD connects the North Norwegian shelf from the Lofoten Islands to the shelf break and upper slope domain of the western Eurasian sector of the AO. This ULAD crosses several biogeographic boundaries with impacts on species abundance and life histories. For example, the supply of the Atlantic copepod *Calanus finmarchicus* along the domain is particularly substantial (contributing 30-60% to overall zooplankton biomass, Kosobokova, 2012). The Pacific-Arctic ULAD connects the shelf of the northern Bering Sea to the Chukchi and, in particular, the western Beaufort Seas (all the way to northern Greenland), supporting pelagic and benthic biomass hotspots and higher trophic levels along the way, and facilitating biomass rich eddies beyond Point Barrow (Berline et al., 2008; Grebmeier et al., 2015; Moore et al., 2018a). The Barents Sea branch of the Atlantic-Arctic ULAD derives from the cold waters of the northern Barents Sea and connects, through the upper third of the St. Anna Trough, to the shelf break and upper slope domain along the Siberian sector of the AO. Similar to the Atlantic-Arcitc ULAD, the supply of the Arctic copepod *Calanus glacialis* along this domain is highly significant, but less investigated (Kosobokova, 2012).

The third ULAD is that of the Transpolar Drift that connects the biota (and suspended biomass) of the Laptev Sea shelf with the western Fram Strait where ice-associated biomass is released to the water column during as pack ice melts (Hop and Pavlova, 2011). The recent eastward spread of warm AW (Polyakov et al., 2017) has resulted in warming temperatures which are melting Russia's coastal "ice nurseries" faster than before. Some 80% of nursery ice now melts before it joins the open ocean, compared to 50% before 2000 (Krumpen et al., 2019). The result will be that food supplies will be reduced for those animals in in the open AO that rely on the food from sea ice will receive reduced food from TPD-transported sea ice. Further, if AW reaches the Laptev Sea in the future the Transpolar Drift may cease and disappear. Model investigations suggest that the transport of detrital carbon from the Laptev Sea to the Fram Strait by the Transpolar Drift cleased already decades ago (D. Slagstad, P. Wassmann, unpubl. res.)

The ULADs are typically characterized by net heterotrophy; i.e. consumption of biomass is greater than local production. Physical and biological forcing inside the conventional latitudinal biogeographic regions is minimized and teleconnections are created across biogeographic and production zones. They penetrate the circular nature of the AO and make them dependet upon the Pacific and Atlantic Oceans. Changes in advection through the North Atlantic (Asbjørnsen et al., 2019), the increasing spread of AW north of Svalbard (Polyakov et al., 2017) and the increasing Bering Strait throughflow driven largely by the increasing Pacific-Arctic pressure gradient (Woodgate et al., 2013) result in the ULADs, along with the SIZD, being the fastest changing contiguous domains in the AO (e.g. Vernet et al., 2019; Wassmann et al., 2019).

4.2.3 Circumpolar Boundary Current domains

At the shelf break, the Circumpolar Boundary Current Domain (CBCD) is the dominant thermohaline feature of the AO (**Fig. 5b, c,** Aagaard, 1989; Rudels et al., 1994). It is a continuation of the Atlantic-Arctic and Barents Sea ULAD (**Fig. 11**), but we list it separately because the CBC transports subducted, modified AW, that circumnavigates the entire AO shelf break and slope. Beszczynska-Möller et al. (2011) estimate that between 8 and 9 Sv (1 Sv = 10^6 m^3 s^{-1}) enter the Nordic Seas over the Greenland Scotland Ridge (sill depth ~800 m) and roughly half of this flow continues on to the AO; of the AW continuing north, about half enters the AO via Fram Strait as the Fram Strait Branch (FSB) and subducts below Arctic Surface waters (ASW) north of Svalbard (**Fig. 5C**). The other branch first crosses the Barents and the westernmost Kara Seas, subducts along the Atlantic Polar Front, continues across the eastern Barents Sea, and then drains through the St. Anna Trough as the Barents Sea Branch (BSB) (Rudels et al., 2012, 2013; Dmitrenko et al., 2014; Bluhm et al., 2015). Because the BSB water is strongly modified *en route* by mixing with local Barents Sea waters, it enters the basin with a broader density range than FSB waters and both interleaves laterally and subducts below the continuing FSB. Aagaard and Woodgate (2001) also noted that the high-latitude freezing and melting cycle can supply additional freshwater injection into the interior of the AO, resulting in a secondary salinity minimum at about 800m depth. A third water mass, formed locally on the eastern Barents and western Kara Seas also drains into the basin through St. Anna Trough (Aksenov et al., 2011). Subsequently, the three branches become the ACBC and continue cyclonically around the basin perimeter, with bifurcations occurring where ridge and slope topographies intersect. The transit is marked by slope cutting canyons and currents tend to be strongest where the slope is steep (Isachsen et al., 2003). Aksenov et al. (2011) modeled the ACBC and demonstrated that transports along the AO margins were forced by the joint effects of buoyancy loss and non-local winds which created high pressure upstream in the Barents Sea. There is still debate as to the volume transports of AW into and out of the AO, with a total amount of 4–8 Sv being generally accepted (cf. Dickson et al., 2008). What is important is that the ACBC carries a huge and varied mix of water properties and biogenic material as it travels this circuit.

The CBCD can be pictured as a long, narrow band that rapidly transports materials around the ocean perimeter, allows on slope and off slope exchange, and radiates mixing energy into the interior (**Fig. 5a, b, c**). For a description of the productivity and in particular the current ecological changes, see 3.2. Increases in primary production are expected for the Eurasian but less so in the Amerasian CBCD (Slagstad et al., 2015).

4.2.4 Atlantic and Pacific Halocline Domains

The AO halocline is a complex structure below the ULAD in which river inflows, ice melt, winter convection, and the insertion of Pacific and Atlantic waters - modified on their respective inflow and interior shelves - all contribute to the vertical salt stratification (**Fig. 13**). These halocline components have distinct physical, chemical and biological chracteristics according to their sources, and maintain identifiable structures both horizontally and vertically within the AO interior (Polyakov et al., 2018). The Pacific and slightly denser Atlantic components are as different from each other as are their parent oceans. Here we will describe them as the Atlantic and Pacific Halocline Domains (APHD), i. e. distinct, contiguous halocline domains that cover the entire central AO (cf. Bluhm et al., 2015, **Fig. 13).**

Waters of Pacific origin enter through Bering Strait, flow northwards across the broad Chukchi Shelf along three major branches, are modified en route on seasonal time scales, and enter the Amerasian Basin though submarine canyons at the shelf break, where they spread into the basin interior (Pickart, 2004; Weingartner, 2005; Shimada et al., 2006; Danielson et al., 2017). Pacific-origin halocline waters arrive as two main varieties, the warmer and fresher summer waters, and the colder and more saline winter waters (Coachman and Barnes, 1961; Shimada et al., 2001; Steele, 2004; McLaughlin et al., 2009). These waters are largely confined to the Canada Basin owing to the anticyclonic Beaufort High wind field, and tend to accumulate within the convergent Beaufort Gyre. The key distinction of the Pacific halocline water is that they are higher in nutrients and fresher, so that they overlie the Atlantic variety and add to the salt-stratification of the Amerasian AO.

Atlantic-origin halocline waters are largely modified and formed on Siberian shelves (Aagaard et al., 1981; Aksenov, et al., 2011; Polyakov et al., 2017). Still, as early as the mid-1980’s, arguments were presented that Atlantic-origin waters were modified by freeze/thaw processes during passage over the Barents and Siberian shelves, and subsequently entered the deep ocean (Jones and Anderson, 1986); a hypothesis also supported by numerical modelling (Killworth and Smith, 1984; Aksenov et al., 2011). An important feature of the Atlantic-origin halocline water that underlies the Pacific-origin water in the Amerasian Basin is its associated oxygen minimum.

A major front, termed the Atlantic/Pacific Halocline front blocks the spreading of Pacific water into the Eurasian Basin and allows only the lower portion of the Atlantic-origin halocline water into the Amerasian Basin (reviewed in Bluhm et al., 2015). There is debate whether this front is stationary and locked to topography, or free to shift from one stable configuration to another under climate forcing (cf. McLaughlin et al., 1996; Carmack et al., 1996).

An important aspect of the 'halocline complex' is that there is no such thing as 'a' halocline but instead there are multiple layers that comprise a staircase of increasing water density with depth that insulates the warm Atlantic layer in the basement from the Polar Mixed Layer and ice. The individual ”steps” (or layers) are formed and shaped on the shelves, and are advected into the adjacent basins, where they ‘stack themselves’ according to density. Therefore, to get from the base to the surface one has to take one step at a time. Between the 'clines' near-homogenous layers are found which is why vertical profiles of salinity in this domain actually look like a staircase. The Amerasian Basin has more 'steps' in the staircase than the Eurasian Basin (**Fig. 13**). The primary control of the APHD on biological production in the AO is its strong stratification that shapes the biogeochemical function of the central AO basins: it effectively prevents the vertical supply of nutrients and thereby hampers primary production, irrespective of increasing light levels in the changed AO. This effect is stronger in the Amerasian side where the APHD is more strongly stratified than on the Eurasian side. Further, the APHD plays a significant role in the distribution of planktonic species, as reflected in its mesozooplankton inhabitants (e.g. Bluhm et al., 2015). The domain is made up of individual layers, formed and shaped on the shelves, that are advected into the adjacent basins, where they 'stack themselves' according to density.

4.2.5 Deep Basin Domains

The Deep Basin Domain (DBD) lies below the Atlantic Layer. It is several thousand meters thick and by volume, comprises the largest – yet the least studied – contiguous domain (**Fig. 14**). The pathways, rates of spreading of AO deep waters and biological communities and processes within it are poorly known (Kosobokova, 2012), but in general there is direct deep-water exchange between the Norwegian and Greenland Seas and the Nansen Basin via Fram Strait (sill depth ~ 2600 m). From there the flow is thought to proceed from the Nansen Basin to the Amundsen Basin to the Makarov Basin and finally to the Canada Basin (MacDonald et al., 1993; Schlosser et al., 1997). From the Amundsen Basin there must be a return flow back to the Eurasian Basins, Nordic Sea and North Atlantic (Aagaard et al., 1985; Rudels et al., 2013). Indirect proof for these water exchanges between basins are (1) deep-water zooplankton communities that have higher community similarity within the DBD horizontal layers than across vertical layers in a given basin (Kosobokova, 2012); (2) generally similar zoogeographic patterns in benthic communities across basins (Bluhm et al., 2011); and (3) and the high proportion of Arcto-Atlantic affinity biota across the deep-sea floor in the DBD (Mironov et al., 2013; Zhulay et al., 2019).

The overall motion of deep water within the basins below sill depth is sluggish as clearly reflected at the deep-sea floor where animal traces are well-preserved and abundant despite low faunal densities (Zhulay et al., 2019). Schlosser et al. (1997) calculated the mean isolation age of the Eurasian Basin bottom water >2500 m to be ~250 years while that of the Amerasian Basin > 2500 m to be an additional 200 years older. Thus, the Amerasian Basin deep waters are either presently not being ventilated (Macdonald and Carmack, 1991; Macdonald et al., 1993; Aagaard and Carmack, 1994), or are being ventilated much more slowly with continuous renewal by shelf water (by freezing and brine rejection on the shelves) or influxes from the adjacent Eurasian Basins (Aagaard et al., 1985; Östlund et al., 1987; Jones et al., 1995; Rudels et al., 2000). The influxes from the adjacent Eurasian Basins would provide a mechanism to carry organic material and biota to depth. More rapid flows are expected along basin and ridge slopes, and through narrow gaps in the ridges (Bluhm et al., 2015).

Given that the organic matter flux from surface primary production to the DBD is very limited and much of the carbon is refractory in nature (Iken et al., 2005), biotic densities and biomass are generally low (Bluhm et al., 2011; Kosobokova, 2012). Extremely low concentrations, but the persistent presence of rare endemic deep-sea species of zooplankton throughout the DBD despite the presence of underwater ridges once again emphasizes the contiguous nature of DBD and the exchange of deep waters within it. In the absence of fresh algal food, feeding guilds in deep-dwelling zooplankton are dominated by carnivores, omnivores and deposit feeders (Kosobokova et al., 2002, 2011). However, the supply of biogenic matter through chemoliotrophs in the DBD, presently not adequately quantified, has also to be considered as a food source (e.g. Griffith et al., 2012; Åström et al., 2017). Benthic macrofaunal (often essentially sessile) communities tend to follow the global trend of diminishing size with increasing depth related to food limitation (Wei et al., 2010), while larger - often mobile - fauna can actively search for and surprisingly quickly find food (Premke et al., 2006; Boetius et al., 2015). Exceptions to both patterns are drop stones ubiquitously found across the DBD which consistently house biodiversity islands of hard-bottom fauna (Zhulay et al., 2019) with often unknown life cycle and feeding strategies, yet extremely low recruitment rates (Meyer-Kaiser et al., 2019).

5. Major processes forcing the biogeochemical cycles in the Arctic Ocean

Before we reach the last suite of conceptual models, those of food webs, we connect some of the most important processes to regional aspects and the functional domains. We start in the AO surface layer that is dominated by an extreme annual variability of light, freshening, stratification and warming (Agustí et al. 2010). Together both processes excerpt a strong impact on the highly seasonal productivity of and the life cycle of organisms in the AO. In turn, the phenology of autotrophs in sea- ice, the water column is connected to rocks and the seabed.

5.1 Light forcing

Light availability (or lack thereof) is a key determinant for the phenology of autotrophs and heterotrophs in the AO. Light availability is a function of available solar radiation, sun angle, presence and the character of ice, snow cover and shading (by autotrophs, colored dissolved matter and/or suspended particles). Combined, these factors set up a highly spatially and temporally variable light forcing over the expanse of the AO. For ~~astronomical~~ solar radiation during the dark season we distinguish between various types of Polar Night (**Fig. 15**), where the exact zone and type of Polar Night at a given location depends on a) latitude and b) angle between the horizon and the sun. For details, see Berge et al. 2020). Geometrically, there is one day of Polar Night at the Arctic circle (66.33°N), and the Polar Night lasts for 183 days at the North Pole. However, due to atmospheric refraction of sunlight, at sea level there will appear to be direct sunlight at noon on winter solstice up to approximately 67.4°N. For the same reason, the Polar

Night lasts “only” 177 days at the North Pole, not 183 as one would expect from geometry alone.

For the northern hemisphere, the brightest level of Polar Night is Polar Twilight which occurs ~~from 67.4°~~up to 72° N when solar elevation remains between 0° and 6° below the horizon at the winter solstice. The entire duration of Polar Night at these latitudes is limited to Polar twilight zone. Further north in a band from 72° to 78° N, Polar Night begins with a period of Polar Twilight which is followed by Civil Polar Night when solar elevation remains between 6° and 12° below the horizon at winter solstice, and then again by Polar Twilight. Still further north in a band from 78° to 84° N, Polar Night consists of Polar Twilight and Civil Polar Night followed by Nautical Polar Night when solar elevation remains between 12° and 18° below the horizon at the winter solstice, and then again by Civil Polar Night and Polar Twilight. And finally in a band from 84° to 90° N, the periods of Polar twilight, Civil Polar Night, and Nautical Polar Night are followed by Astronomical Polar Night when solar elevation remains 18° below the horizon at the winter solstice, and then again by the three lesser periods before the sun returns above the horizon. The Midnight Sun period with similar periods of permanent sun light is a mirror of the Polar Night.

Solar radiation in the Arctic is thus extremely variable with regard to latitude, ranging from roughly 6 months of direct sunlight at the North Pole to the sun being under the horizon for just minutes at the Arctic Circle. In addition, ice and snow covers modify the light reaching organisms in the ice and surface ocean. The light regime in the seasonally ice-covered Chuckie Sea is similar to that in northern Norway and the southern Barents Sea, but the latter experiences less or no ice-cover. The Bering Strait and Bering Sea, situated outside the main AO region, experience solar radiation year-round, but ice cover can still result in low light conditions for the biota. In contrast, the Nautical and Astronomically Polar Night is only experienced in the northernmost regions of the AO. Investigations during the full annual light regime have been carried out only a few places, e. g. in coastal waters off northern Svalbard, the Canadian Arctic Archipelago, northern Greenland and the White Sea (e.g. Ashjian et al., 2003; Kosobokova and Pertsova, 2018). Also, some regions encompass Arctic biota but experience a sub-Arctic light regime, and vice versa. For example, northern Norway and the southern Barents Sea experience a Polar Twilight light regime, but the biota is dominated by advected boreal forms from the south. Thus, the ~~astronomical~~ ambient light regime sets up important patterns that impact the biota, but do not necessarily determine it. Many “typical” studies in the AO have been carried out in regions that are south of the Arctic circle (66°N), outside the Arctic light/darkness regime defined in **Fig. 15** (such as southern Greenland, Hudson Bay and the Bering Sea). Ice cover and temperature are indeed not the only criteria for marine Arctic ecology, yet the annual light cycle has to be clearly defined to allow clear and unambiguous generalizations. Marine ecological investigations in the AO have to be far more rigorous in describing and considering the light climate.

In addition to light availability, ice cover is highly variable across the AO and this has obvious consequences for the phenology of auto- and heterotrophs (Kirchman et al., 2009; Leu et al., 2015; **Figs. 9, 16**). Sea ice melt is also closely connected to salt stratification, another factor dictating the biogeochemical characteristics of the AO euphotic zone. Freshening arises from ice melt which is caused by solar radiation and atmospheric warming from above (Wassmann et al., 2010; Carmack et al., 2016) and by warm water melting from below (in particular

AW; see Carmack et al., 2012a; Polyakov et al., 2017). The ice albedo, or reflectivity, also impacts heat absorption by the ice, which is further influenced by dirty ice and atmospheric deposition of black carbon (Lee et al., 2013; Goelles and Boggild 2015). The circumarctic, highly stratified band of surface water within the MIZ then shapes the development and of both the pelagic and ice associated spring blooms. These blooms, consisting of both sea ice algae and phytoplankton, come seasonally soon to an end because of nutrient depletion which is one of the most significant characteristics of todays MIZ. But the AO will also face increased stratification and nutrient limitation as the MIZ retreats increasingly to positions that are positioned over the already strongly stratified basins (Tremblay et al., 2015; Assmy et al., 2017).

5.2 Phenology and seasonal productivity variation

Within their respective envelops of hydro-morphological characteristics and contiguous domains the ecology of AO organisms appears extensive phenological cycles. The study of seasonal cyclic organismal events in algae and ~~periodic plant and~~ animal life, i.e. their phenology, is influenced by seasonal and interannual variations in climate. Phenologies are thus ~~are~~ now responding to global warming through detectable food prints of climate change (Wassmann et al., 2011). For example, changes in autotroph phenologies (e.g. Kahru et al., 2011; Rubao et al., 2012; Tedesco et al., 2019) are now affecting match and mismatch relationships between predator (including grazers) and prey (e.g. Edwards and Richardson, 2004; Post, 2016; Ramírez et al. 2017). In addition to providing a longer historical baseline than instrumental measurements, phenological observations provide high temporal resolution of ongoing changes related to climate change.

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~~Investigtions~~Investigations of phenology are thus instrumental to understand climate change.

To illustrate the principle ~~-~~and partly hypothesize patterns of geographic variability of autotrophic phenologies in ice-covered water we can use latitudinal scenarios along an imagined transect from the Barents Sea (70°N) to the North Pole (85°N) (**Fig.16**). At 70°N in the southern Barents Sea there is some indirect light (Civil Twilight) in the middle of a winter day while there are two months of Midnight sun and several months characterized by steeply increasing and decreasing daylight. At this latitude, rates of increase and decrease of daylight are about 12 minutes a day. ~~As there is~~With only open water in this region, we ~~and we~~ may find a spring bloom as early as April/May. ~~-~~However, the lack of ice-melt may result in weak stratification, hence the buildup of the bloom may be slower but the blo~~l~~om may last longer. ~~-~~Towards the beginning of the Polar Twilight Night a minor bloom may be possible in late August (e.g. Oziel et al., 2017). At 75°N and the Civil Polar Night zone we experience darkness for almost 3 months and ice cover between November and May, with an increase and decrease of daylight of about 16 minutes per day. Light penetration through ice/snow and an ice cover that is actively breaking up supports an ice algae bloom in April and a phytoplankton bloom in early June. Here ice returns often as late as December. At 80°N and northward, the Nautical Polar Night ~~zone and northward darkness~~ lasts for 4 months and ice cover may last until the end of June. The rates of increase and decrease in daylight are about 25 minutes per day. An ice algae bloom may occur in April and May (dependent on ice thickness and snow cover) and uses available nutrients, resulting in a small phytoplankton bloom based on the leftover nutrients in early July. Sea-ice often returns in November. At 85°N the light and

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dark periods last for more than 5 months each and increase and decrease rates in light are about 50 minutes per day. Most of the nutrients are used up by sea ice algae through a lengthy growth period lasting from April to August, as determined by ice thickness and snow cover (Fernández-Méndez et al., 2014). Before daylight disappears, a small phytoplankton bloom may occur (see Loeng et al., 2005; Ardyna et al., 2014; Oziel et al., 2017), but one may discuss if can be entitled an autumn bloom.

Climate change has resulted in a steady decline of nutrient concentrations in the AO inflow regions of the Northeastern North Atlantic (e.g. Rey et al., 2012; Hátún et al., 2017), the cause being the effect of climate change on subpolar gyres. Along the South to North gradient depicted in **Fig. 16** and despite of the increase in future radiation a decrease of autotrophic new production is likely in the central AO~~-~~, caused by increased stratification and reduced vertical mixing and nutrient supply (Ardyna et al., 2014; Randelhoff et al. 2019). With thinner ice at increasing latitudes stronger and more persistent ice algae blooms can be expected. In contrast and despite longer ice-free periods, phytoplankton blooms will decrease with increasing latitude caused by ice algae nutrient consumption. The post-bloom period with increased stratification and depressed nutrient supply will also be marked by a succession throughout summer of progressively smaller autotrophs (Li et al., 2009; Leu et al., 2015) and a prolonged period post bloom heterotrophy (Vaquer-Sunyer et al., 2012). Also, the timing of the phytoplankton bloom is progressively delayed from April in the south to early September in the north. The conceptual model in **Fig. 16** is neither intended to reflect the highly interannual dynamic nature of the Barents Sea and adjacent AO nor does it fully match the phenology of bloom cycles along the Pacific Arctic shelf-basin gradient.

It merely illustrates the principle patterns that define these seasonal transitions. The principles behind **Fig. 16** are also the base for **Fig. 9A, B** (left column) which depicts todays large-scale phenology of autotrophs and their dependence on light and ice-cover across the entire SIZD.

Climate change and the resulting reduction in ice cover will modify the phenology of autotrophs, but the biota cannot break out of the constraining envelope created by solar radiation and nutrient availability. For example, the bloom development at 70°N in the sector dominated by AW will move progressively northwards to 75°N and 80°N off the shelf, with phytoplankton rather than ice algae to use up the available nutrients as ice cover is reduced (**Fig. 17**). Notably, the surface water nutrient concentrations in the Arctic basins are far lower than those of the shelves, let alone those in the advected PW and AW (e.g. Tremblay et al., 2015). Modelling projects that the nutrient concentration in the central AO surface water will in fact continuously decline during this century (Slagstad et al., 2015). Larger blooms are not expected from either ice algae or phytoplankton are expected in the basins because of the limited and decreasing availability of nutrients (Slagstad et al., 2015. This is in contrast to the Eurasian shelves where pelagic primary production increases as a function of increased open water area, i.e. higher input of solar radiation (Arrigo and van Dijken, 2015; Slagstad et al., 2015) though still ultimately controlled by nutrient availability (Tremblay et al., 2015). Increased Atlantification (Polyakov et al., 2018; Randelhoff et al., 2018) and changes in vertical mixing (Randelhoff and Guthrie, 2016; Randelhoff et al., 2019) may further influence and increase the future primary production on the shelves and the shelf break.

In the Barents Sea today's bloom development in May-June at 70°N (**Fig. 17 F, left**) may be in the future be encountered at 73°N (**Fig. 17 F, right**). Similarly, the bloom scenario that today is encountered at 73°N (**Fig. 17 E, left**) may in the future be observed at 75°N (**Fig. 17 E, right**). Similary to the northward expansion of boreal species into the AO region the MIZ bloom may shift northwards, at the expense of more Arctic phenologies. This development has already resultet in the large-scale reduction of the multi year sea ice. **Fig. 17** depicts a similar process than the borealisation, i.e. the northwards displacement of both sub-Arctic water masses and boreal species. This development from today into the future can also be studied for the large-scale phenology of autotrophs and their dependence on light and ice-cover across the entire SIZD (**Fig. 9A, B** (left column: today; right column: future).

Fig. 17 E and F illustrate the assumed course of primary production in a scenario of continuously open water, characterized in the central and southern Barents Sea that has no major freshwater source and a weak and slow progress in surface water stratification during summer. In regions where freshwater stratification is prominent such scenarios will not be encountered. The variable production in June (**Fig. 17E**, 70°N) arises through variations in nutrient supply caused by vertical mixing events triggered by the passage of low-pressure systems after the end of the spring bloom. **Fig. 17 F** at 70°N projects future primary production after Arctic warming has resulted in increasing thermal stratification and decreased primary production, unless occurring mostly as subsurface blooms (Mayot et al., 2018). However, also late summer surface (Ardyna et al., 2014; Oziel et al. 2017) and subsurface blooms (Horvath et al., 2017) have recently been detected. These phenomena add new features to the phenology of autotrophs in the ice-free AO.

Previous and future scenarios in the phenology of the marginal ice zone are presented in **Fig. 18 A, B,** respectively. Progressing from present-day to future climate and ice conditions the principle seasonality will persist, but the timing will change. Climate warming will also result in a widening of the seasonal ice zone (**Fig. 9**) and a wider time window for primary production (**Fig. 18**). With greater incident light availability in the euphotic zone and earlier stratification a decrease in the amplitude of the spring bloom may be encountered. Without an ice edge at its current position the bloom will become less distinct and surface waters will have decreased food concentrations for grazers that have tuned their life cycle to the initiation of this bloom (Daase et al., 2013). The decreased spring bloom strength may be balanced by longer annual food availability and more detritus that would favor zooplankton species that can sustain themselves on less food and smaller food particles, i.e. smaller species (Svensen et al., 2018). The time window in which the system is dominated by heterotrophs will increase. This scenario assumes that nutrient supply will be unchanged.

The phenology of zooplankton has to face the seasonality changes in autotroph production, in particular the timing, density and time development of the spring bloom. The life cycles of common zooplankton organisms in the Arctic imply that these need more than one year for their development in contrast to boreal congeners. Biomass-dominant copepods in particular start their development during the productive season, but in the AO lower temperatures and reduced metabolism along with low food availability (in the central AO) do not permit them to complete their life cycles within the first productive season. Thus they need to overwinter to continue their development. For many species the winter at high northern latitudes implies dormancy, for others it implies reproduction and/or preparation for a new productive season, including gonad maturation and producing eggs prior to the onset of algal growth (Conover, 1988; Kosobokova, 1999; Hirche and Kosobokova, 2011; Hirche, 2013; Kosobokova and Hirche, 2016; Daase et al., 2013). For several marine mammals, the winter implies migration out of the Arctic. For lipid rich zooplankton species, for Arctic fish, and for some other invertebrates late summer and autumn are not characterized by hibernation, but by development to juvenile life stages that accumulate energy reserves, or by maturation into lipid-rich adults and preparation for overwintering at depth and in darkness (Falk-Petersen et al., 2013; Berge et al., 2015 a, b; Daase et al., 2018). In late winter and early spring, still in darkness, some commence reproduction relying on internal reserves (e.g. the key arctic oceanic copepod *Calanus hyperboreus*) or detrital food (e.g. the brackish water copepods *Drepanopus bungei, Pseudocalanus major*) and their early larvae develop (Hirche, 2013; Kosobokova and Hirche, 2016; Nahrgang et al., 2016; Darnis et al., 2017). The spring period of increasing light and the productive and full day light season is then utilized by their early offspring (new generation) for development into juvenile overwintering stages, while the overwintered late juveniles born a year ago (old generation) develop to adulthood. Towards the end of the productive season these two generations prepare to overwinter again (e.g. Fig. 18A, horizontal bars). Thus, the winter period is an important segment of the ecology of zooplankton grazers and fish in the AO which connects the preparation for overwintering and active development during spring and summer. Life cycle studies in the AO do thus demand longer time cycles than a year, in particular for a multitude of Arctic biota that are much longer-lived than boreal and tropical counterparts. Therefore, conceptual models of seasonality need to cover a minimum 18 months, such as in Fig. 18. Also, many organisms may exceed longevities of decades or centuries (Bluhm et al., 1998; Ravelo et al., 2017). The phenology timeline in the AO is thus multiannual or longer.

5.3 Cryo-pelagic-benthic coupling

Processes of cryo-pelagic-benthic coupling (CPBC) include those that connect biota in sea ice, water column and benthic habitats (Grebmeier and Barry, 1991; Carroll and Carroll, 2003; Werner, 2006). Essential processes involved in CPBC are primary production of both sea ice algae and phytoplankton, vertical export of biogenic ice-derived and pelagic matter and regeneration of deposited matter at the seafloor. Also entailed are the phenology and biological life cycles of a wide range of organism entangled in involved in CPBC which all are highly variable on both spatial and interannual scales (Wassmann et al., 2004; Grebmeier et al., 2012; Fernández-Méndez et al., 2014). The domain of CPBC action covers the entire AO where it regulates the loss of biogenic matter from sea ice and the upper layers, the retention of nutrients and biogenic matter in the water column, the supply of food to the benthos, and the regeneration of nutrients and matter at the seafloor. In particular, the CPBC connects the SIZD with the sediments of the extensive shelves, comprises thus major parts of the AO (**Figs. 8A, 9**). CPBC depends upon the new production, the accumulation and biomass of both sea ice algae and phytoplankton (Gosselin et al., 1997; Gradinger, 2009; Lalande et al., 2014), melting of sea ice from below (detachment of particulate matter; Tedesco et al., 2019), the aggregation potential of suspended matter (Engel et al., 2004; Rapp et al., 2018), grazing (Wexels Riser et al., 2002; Tamelander et al., 2012), vertical flux attenuation in the the twilight zone (Wassmann et al., 2003; Reigstad et al. 2008; Buesseler and Boyd, 2009), processes in the benthic boundary layer and benthic suspension feeding (Thomsen, 2002; Stein et al., 2004). As a consequence of this multitude of processes, the activity of CPBC is not evenly distributed, but first of all depth-depended (**Fig. 19**).

A continuum of physical and chemical forcing (ice- and snow-cover, horizontal advection, stratification/vertical mixing, nutrients, light) shapes the basic conditions for primary production, ice-attached biogenic and suspended matter accumulation in the upper layers (**Fig. 19**). This physical-chemical-biological continuum creates the base for new production and the potential standing stock of autotrophs that can be grazed, recycled, and exported vertically (advective off-set is not considered in this depiction). Because of the orders of magnitude differences between the horizontal velocity of water and the sinking speed of particulate matter vertical flux of individual particles is basically tilted to the horizontal plane. Regionally, and in particular on the shallowest AO shelves, the distance between the origin of biogenic matter and its deposition is small. In deeper regions the horizontal distance for the smaller sinking particles may be hundreds of km and advection will thus play a key role.

The maximum of the vertical organic matter flux is particularly prominent in the lower euphotic zone and the uppermost section of the twilight zone (Wassmann et al., 2003; Buesseler et al., 2007). Below the euphotic zone aggregate formation and dissolution of particulate organic matter become important constraints for vertical export (Jackson and Burd, 1998; Stemmann et al., 2012) and top-down regulation through various categories of grazing zooplankton removes biomass, destroys aggregates and produces fecal pellets (Wexels Riser et al. 2007). Along the physical-chemical-biological continuum, these processes are assumed to take the lead role for the fate of suspended and sinking biogenic matter. Food-deprived communities of heterotrophs are common in the AO because of the significant influx of long-lived zooplankton (Olli et al. 2007; Wassmann et al., 2015, 2019). Zooplankton orient themselves towards the source of food, i.e. they move upwards towards the ice-algae or the base of the euphotic zone with its associated subsurface chlorophyll maximum (**Fig. 19**). Thus, a great amount of zooplankton biomass is usually encountered just below the euphotic zone (e.g. Olli et al., 2007), regulating partly the vertical export and contributing significantly to the strength of the retention filter in the upper aphotic zone (Wexels Riser et al., 2007).

The strength of grazing, the types of grazers and the grazing efficiency determine the mode by which suspended biogenic matter is consumed, thus effecting both a slowdown (sinking particles removed) and acceleration (fecal pellets produced) of vertical export (e.g. Wassmann et al., 2003). However, fecal pellets still have some nutritious value for a number of grazers and through processes such as coprophagy and particular coprorhexy most of the rapidly sinking particles are retained in the upper layers in most areas (e.g. Wexels Riser et al., 2002; Iversen and Poulsen, 2007; Svensen et al., 2012). Sloppy feeding and microbial remineralization contribute also the retention of sinking organic matter. As a result, 20-70 % of the export production leaving the euphotic zone can be recaptured and retained in the upper 100 m (for the most in the 20-60 m depth interval) in the case of the Barents Sea (e.g. Olli et al., 2002). Hence export production is far higher on shallower (mostly <50 m) AO shelves, such as the northern Bering and Chukchi and Laptev Seas (Lalande et al., 2007, 2009a). The physical-chemical-biological continuum forces the primary production and new production in the upper layers towards greater production (**Fig. 19**; bottom-up regulation, compare scenario I with II). At shallow depths (**Fig 19** panel **A**), CPBC is highly variable, but the supply of biogenic matter is much stronger than at greater depths. With increasing depth, the physical-chemical-biological continuum (top-down regulation through grazing, mineralization and fragmentation) increasingly takes over, forcing vertical export into the opposite direction (**Fig. 19**). For example, the benthic biomass in the highly productive, shallow northern Bering Sea and southern Chukchi Sea (**Fig. 19A,** Grebmeier et la. 2015) is far higher than on deeper shelves (**Fig. 19C**; Bluhm et al. 2011b). As a consequence, the connection between new production and vertical export can be explained in a curvilinear manner (Wassmann et al., 2003) quantified as a vertical flux attenuation efficiency (Olli, 2015). In addition, planktonic heterotrophs also impose a depth-varying grazing pressure on export production by collectively developing a retention filter (Wexels Riser et al., 2001) whose vertical extent and degradation efficiency determines the vertical flux attenuation and the shape of the vertical export profiles. The potential vertical export can be low or high when the upper water column is stratified (**Fig. 19**, scenario I and II, respectively). It depends first of all upon the rate of new production and the abundance of detached ice or planktonic biogenic matter (e.g. Assmy et al., 2017; Wollenburg et al., 2018). When vertical mixing is prominent the export of suspended biogenic matter is lower (scenario III). A strong cryo-pelagic coupling and the strength of new production will move the vertical export of biogenic matter to the right (scenario I turns into scenario II, **Fig. 19**).

Grazing in the pelagic decreases the amount of vertical export and can result in strong vertical flux attenuation (Olli, 2015), which varies with the intensity and the biomass of heterotrophs and their vertical distribution and water depth (Wexels Riser et al., 2002; Svensen et al. 2012). Efficient retention filters may exist, in particular when new production is strong and the suspended biomass of large autotrophs, such as diatoms, prevail, weakening and determining pelagic-benthic coupling (Wassmann et al. 2003, Wexels Riser et al., 2007). How strong CPBC is depends not only on new production and stratification, but to a high degree on water depth and the intensity of the retention filter (Wexels Riser et al., 2007; Wiedmann et al. 2014). Grazing does not prevent that living autotrophs such as diatoms and *Phaeocystis* reach deeper water and the sediment (Wassmann et al., 1990; Boetius et al. 2013; Augustí et al., 2019). At shallow depths CPBC is highly variable, but the lack of strong retention makes it much stronger than in regions of greater depths (**Fig. 19A**). As a result, the benthic biomass in the highly productive, shallow northern Bering Sea and southern Chuckie Sea is far higher than on deeper shelves (Carroll et al., 2008; Grebmeier et al., 2015). Tightly linked to the SIZD, the CPBC is mainly a surface-driven process in areas wherein the majority of the exported biogenic matter, though depth-depended, is retained in the upper water column. On shallow shelves such as the Pacific inflow shelves, however, a much larger part of the production (can reach over 50%) settles to the seafloor either ungrazed or as fecal pellets (Lalande et al., 2007, 2009b), supporting high benthic biomass and substantial nutrient recycling (Devol et al., 1997; Cooper et al., 2009; Hardison et al., 2017).

Continuously open water at the periphery of the AO (at present for the most on the North Atlantic side of the AO but permanent open water scenarios will become more prominent due to climate change) provides possibilities for primary production between both equinoxes. Sea ice cover may become a Polar Night phenomenon. Mixing in these open water results in a delay in the spring bloom which usually does not occur before mid-April. This timing also corresponds to when ice algae start to grow in those sections of the SIZD where snow cover allows light penetration. In these regions a strong CPBC can be expected already in April (**Fig. 18**). Later in the season (after August), primary production is low, mainly due to nutrient limitation (with indications that increasingly minor autumn blooms take place Oziel et al., 2017). For the rest of the productive season both ice algae and phytoplankton will support primary production, forced by light, stratification and available nutrients. In regions of the AO that are heavily covered by sea ice the spring bloom will take place later, associated with a strong CPBC in May/June/July (**Fig. 18**). If the increasing observations of autumn blooms (Ardyna et al., 2014; Oziel et al., 2017) supports increased CPBC remains to be seen. It also results in the the principle vertical flux attenuation changes (see scenario III in Fig. 19A-C).

The timing of the cryo-pelagic-benthic coupling is highly variable in the AO. The vertical export is usually high with the timing of the spring bloom, in particular when the bloom is tense, e.g. in the MIZ (**Fig. 18A**). After the export of fresh material in connection with the spring bloom (Wassmann et al., 1990; Boetius et al. 2013; Agustí et al., 2019), degraded matter and fecal pellets take over while during post bloom and autumn scenarios detritus dominates (**Fig. 18A**). The timing of vertical flux is strongly regulated by the withdrawal of the ice edge, stratification and the availability of light. Increased vertical export of biogenic matter of variable quality can thus take place throughout the productive season in the AO, but not before April and no later than September (**Fig. 18**). In the near future todays scenario of the SIZD illustrated in **Fig. 18A** may change into longer periods with ice-free conditions (**Fig. 18B**). That will result in that vertical export of biogenicmatter starts earlier, the dampened time development of autotrophs will also result in a decreased amplitude in vertical export (**Fig. 18B**). The quality food reaching the deeper layers and the sediment will decrease and the the supply will be more even.

In summary, the intensity of CPBC is a complex relationship between production, vertical mixing, advective inputs, water depth, the intensity of the retention filter, and benthic remineralization (Lalande et al., 2014; Wiedmann et al., 2014; Grebmeier et al., 2015). Often new production or biogenic matter accumulation are used as proxies for benthic biomass and production. Neither new production nor pelagic accumulation of biogenic matter solely determine the CPBC. Nor does the supply of biogenic matter to the sediment alone indicate new production and pelagic accumulation of biogenic matter. The connection between primary and benthic production in the AO cannot be established and modelled without an detailed understanding of the complexity of the CPBC.

6. Food web models

Conceptual approaches that aim to investigate organisms and their role in biogeochemical cycling, biodiversity and ecosystem dynamics in the Arctic mediterranean must match the appropriate geography, biophysical and biogeochemical environment, seasonality and light regime, and functionality of contiguous domains (described in sections 2 to 5). Within these frameworks, organisms interact in several ways with the most prominent interaction across trophic levels. Here we follow the definition of Layman et al. (2015) of a food web as "a network of consumer-resource interactions among a group of organisms, populations, or aggregate trophic units"; an example applicable to the AO is shown in **Fig. 20**. Climate change and the increasing human use of the Arctic now demand holistic evaluations of the interdependencies of species and their interlinked response to a change or perturbation of their ecosystem. In this section we apply findings from existing regional studies to the typologies proposed in preceding sections to formulate unifying, pan-Arctic conceptualizations based on three critical questions: (1) Who eats whom, (2) how does energy flow across trophic levels, and (3) which carbon sources are most important to a given taxon or region?

6.1 Food Web Topology: Who eats whom?

The 'who eats whom' question is conceptually depicted through images of species or trophic levels (i.e. species with shared prey and predators) with arrows connecting each prey to their predator(s) (**Fig. 20**). The underlying, species-specific trophic information is traditionally derived from stomach contents studies and stable isotope studies, and where feasible, complemented by experimental work on predator-prey relationships. Diets are now generally well-documented for common, biomass-dominant Arctic species, but poorly for remaining species (**Fig. 20**, Table 2). We summarize the dominant trophic connections jointly for – simplified - shallow shelves, the Pacific inflow shelf and the basins that currently have no large-scale commercial fisheries (**Fig. 20A**), and separately for deeper shelves and those areas – the Atlantic inflow and parts of the outflow shelves - that have substantial commercial fisheries, albeit primarily on boreal species (Christiansen, 2017) (**Fig. 20B**). Moving from the base of the food web to top predators, bacteria take up DOC and support heterotrophic and mixotrophic nanoflagellates, which in turn are prey for protists (Seuthe et al., 2018; **Fig. 20A**, microbial inset (2)). These, in addition to larger, phototrophic cells such as diatoms, are then available for grazing multi-cellular zooplankton. *Calanus* spp. (e.g. *C. glacialis* and *C. hyperboreus* in Arctic water masses, advected *C. finmarchicus* in Atlantic water), krill and other zooplankton species capitalize on the spring bloom and provide food for zooplankton such as omnivorous/predatory copepods, arrow worms, jellyfishes, pelagic amphipods and pelagic snails *Clione* as well as higher trophic level taxa including various fish, seabirds, seals and whales (**Fig. 20**). Examples for dominant planktivorous at higher trophic levels include the little Auk, auklets and shearwaters, as well as bowhead whales for Arctic species (**Fig. 20A**), and minke and fin whales as boreal species (**Fig. 20B**). During ice-cover, primarily herbivorous sympagic meiofauna and herbivorous, omnivorous and carnivorous amphipods at the under-ice surface make ice-derived carbon available to young polar cod, the dominant truly Arctic fish. Adult polar cod feed primarily on copepods and other crustaceans both in the water column and near bottom and provide prey for many seabird and mammals, in particular in the areas summarized in **Fig. 20A**.

Vertical carbon flux fuels detrivorous zooplankton and the microbial loop enriches detritus pools at the seabed, supporting a variety of interstitial meiofauna (**Fig. 20A**, bottom inset), surface and sub-surface deposit-feeding invertebrates such as polychaetes and other worms, bivalves, and larger epifauna. Near-bottom currents also supply a stream of living or resuspended detritus particles to benthic suspension feeders, in particular in high flow areas or on elevations such as drop stones. In combination with the deposit-feeders, this detritus serves as prey for both invertebrate predators such as snails, sea stars, shrimps, crabs and demersal fishes as well as for benthic-feeding mammals (such as gray whales, bearded seals and walrus) and diving seabirds such as eider ducks (Planque et al., 2014; Whitehouse et al., 2014). The other small-bodied true Arctic fishes such as sculpins, and eelpouts feed primarily demersally (**Fig. 20A**). Large-bodied predators such as Atlantic cod and Greenland halibut are found in the waters of Atlantic inflow and parts of the outflow shelves (Christiansen, 2017; **Fig. 20B**), while the cold pool in the Bering Sea has so far largely kept these large predators out of the Pacific inflow shelf (but see changes in 2018, Cornwall, 2019). The spatial distribution of key players of these food webs, and with its spatial characteristics of trophic connections, has experienced shifts termed ‘borealization’ in recent decades (e.g., Fossheim et al., 2015; Frainer et al., 2018; Alabia et al., 2018; Ellingsen et al., 2020).

The conceptualization of Arctic food webs has advanced from simple predator-prey interactions and few-species chains towards highly connected webs. A formal analysis of several extensive Arctic food webs has shown that it has an unusually high number of predator species compared to basal species (de Santana et al., 2013). So instead of being represented by the classical pyramid shape, the Arctic food web is characterized rather by an inverted pyramid which is more typical of open ocean food webs (de Santana et al., 2013). However, this makes the Arctic food web more vulnerable to trophic cascade effects given the loss of a key predator species (de Santana et al., 2013). And given that many of the key predator species rely on sea ice as a habitat (Wassmann et al., 2011), it is not far-fetched to consider the fragility of several key predator species in the Arctic food web and the cascade effects this may have on the whole food web. Furthermore, the underlying studies acknowledge that: the microbial loop appears to be as active in the Arctic as elsewhere (Seuthe et al., 2018); most species eat multiple other species in the AO (Planque et al., 2014); some species can seasonally or ontogenetically shift diets (Stasko et al., 2018); great trophic diversity is recognized within most higher taxa (e.g. Jumars et al., 2015); substantial regional diet variation exists (Bluhm and Gradinger, 2008); and finally Arctic food webs are not always short, opposing the previous paradigm (Iken et al., 2005, 2010). Yet, conceptual organismal food webs obviously still need to simplify trophic and taxonomic diversity in some fashion (**Fig. 20**), depending on a given research question, area or contiguous domain.

At least four features are characteristic of the generalized Arctic predator-prey based food web concept: first, sea ice provides an additional – compared to non-polar regions - habitat and related food web for > 1000 taxa of single- and multi-cellular pro- and eukaryotes. These taxa are partly contained in the size-structured brine channel sea ice matrix (**Fig. 20A,** top inset (1)) and hence not as freely available as pelagic resources, and in addition a (now) mostly seasonal resource (Bluhm et al., 2017). Second, characteristic of biomass-dominant Arctic (but little less so of advected boreal)) zooplankton, polar cod and endemic marine mammals is their very high lipid (i.e. energy) content (Lee et al., 2006) (**Fig. 20 A**, orange color). This food web of fat is the survival strategy for many in a cold and highly seasonal habitat where metabolic rates are lower, and life cycles take longer to complete than in the boreal and sub-Arctic habitats. Third, a long dark season with low levels of primary production coincides with the habitat ranges of organisms: either migrating out of the Arctic food web for part of the year (e.g. some marine mammals), reducing or completely ceasing food intake (e.g. as cysts or through diapause), or adopting a mixotrophic or otherwise plastic feeding strategy resulting in overall higher than previously assumed polar night activity (Hirche and Kosobokova, 2011; Berge et al., 2015b; Kosobokova and Hirche, 2016). Fourth, humans in the Arctic food web are a combination of subsistence-harvesting indigenous peoples whose cultures often focus around marine mammal and migratory nearshore fish harvests (Suprenand et al., 2018, **Fig. 20A**), and commercial operators currently at the Atlantic-Arctic perimeter focusing on boreal fishes that have expanded their occurrence into Arctic waters (**Fig. 20B**). Characteristics of the Arctic regionality and contiguous domains drive differences in regional food webs through environmental forcing on biotic communities and their trophic interactions.

6.2 Energy flow and connectance in Arctic food webs

The Arctic food web concept has been expanded to depict holistic food web structural properties. One important metric describes the number and strength of interactions between compartments of the food web through the flow of energy between compartments and across trophic levels. Energy flows have been estimated based on ‘who eats who and by how much-matrices’ in combination with biomass, production, consumption and trophic efficiency rates through either energy mass balance models (e.g. Christensen and Walters, 2004) or ecological network analysis (e.g. Dunne et al., 2002) (**Fig. 21**). While Arctic and high latitude food webs in general were initially thought to be short and simple with high trophic efficiency, longer food webs and complex structure are now recognized and enter conceptual models of Arctic foods webs (e.g. Kortsch et al., 2019; Dunton et al., 2012). The linkage of the now-established microbial loop to the refined ‘classical’ food web shows that 4.5-6 trophic levels are characteristic of Arctic food webs (**Figs. 20, 21**, Table 2). Short Arctic food webs are now recognized as mostly a myth, though they exist under certain conditions and in certain places. Estimates of the number of trophic levels derived from stomach contents largely agree with those estimated from trophic markers, except detrital consumers of highly reworked material appear at higher trophic levels when estimated from ∂^{15}N values (e.g. Iken et al., 2010).

Trophic pathway analysis has documented prominent differences among Arctic regions, among Arctic and Antarctic regions, and among Arctic and non-polar regions (de Santana et al., 2013; Whitehouse et al., 2014; Kortsch et al., 2019). Differences in Arctic food webs found or confirmed by energy flow models include high system production and throughput via benthic compartments on the shallow, productive, and tightly coupled Pacific inflow shelf versus higher retention in the (deeper) pelagic system on the Atlantic inflow shelf (Whitehouse et al., 2014). Network analysis in boreal versus arctic (Barents Sea case) food webs revealed lower connectance (number of links per trophic species) and higher modularity (compartmentalization) through more specialized feeding in Arctic compared to boreal and sub-Arctic food webs. This is driven by the few biomass dominant omnivorous generalists that are major components of these highly connected the food web (Kortsch et al., 2015, 2019), a phenomenon recognized globally (Bartley et al., 2019). Such approaches should be applied to other regions of the Arctic before they can fully be generalized our pan-Arctic framework.

6.3 Carbon sources of the Arctic food web

A suit of carbon sources drives marine food webs of the AO on a pan-Arctic level thought to be primarily fueled by highly seasonal phytoplankton blooms (Oziel et al., 2017), while in coastal regions additional sources come into play (Rysgaard and Gissel Nielsen, 2006). These blooms in turn are largely fueled by advective inputs in inflow shelves, and less so in other Arctic areas (Wassmann et al., 2015). Consequently, phytoplankton is the major carbon end member in Arctic inflow shelves, mediated through a combination of advected and *in situ* production (Wassmann et al., 2015; Vernet et al., 2019). Increasingly, additional particulate carbon sources are recognized as regionally and/or seasonally contributing moderate to large proportions to total diets, especially outside the inflow shelves such as ice-algae across the basins, terrestrial carbon in the RCD, and macroalgal carbon and possibly methane seeps on the shelves (**Fig. 22**). These findings are largely based on trophic markers such as marker fatty acids biomarkers, bulk carbon and compound specific stable isotopes, the isoprenoid lipid markers such as IP_{25}, and lignin phenols (Goñi et al., 2013; Kohlbach et al., 2016) (**Fig. 22**) and mixing models estimating carbon source partitioning.

These models suggest ice algae produced in the SIZD may in certain time windows and areas contribute noteworthy or even larger proportions of carbon than phytoplankton to key Arctic organisms across trophic levels (**Fig. 22**). Biomass-dominant Arctic copepods, pelagic amphipods and krill, for example, were estimated to derive 20->90% of their carbon from ice algal organic matter in the central AO (Kohlbach et al., 2016) and in the Pacific inflow shelf (Wang et al., 2015). Ice-derived carbon supplied 30-90% of carbon to young polar (Arctic) cod, *Boreogadus saida*, in the SIZD of the central AO (Kohlbach et al., 2017) but as little as <5% in open-water interior shelf locations (Graham et al., 2014). At yet higher trophic levels, high ice-derived carbon contributions were also estimated for various seals in the Pacific inflow shelves in cold years (Wang et al., 2016). Furthermore, microphytobenthos may play an appreciable role as a carbon source in nearshore shallow shelves (McTigue et al., 2015) and also contribute to the microbial food web (Holding et al., 2017).

The role of terrestrial carbon – once thought to be unusable for marine food webs – has attracted growing attention and is now recognized as a carbon subsidy for the Arctic marine system. Conceptual models of the Arctic hydrological cycle (Vörösmarty et al., 2000) and of carbon pathways (ACIA, 2004) show this material to primarily enter from rivers that drain ponds and lakes, (thawing) permafrost, as well as glacial melt, all sources thought to increase under scenarios of climate warming (McClelland et al., 2004; Agustí et al., 2010; Carmack et al., 2016). Tracers such as trophic and lignin markers suggest terrestrial carbon covers vast areas of nearshore and shelf areas in interior shelves, slopes, and also parts of the deep basins, while it is less prominent far away from sedimentary shores and large rivers, such as in parts of the Canadian Arctic Archipelago and on the inflow shelves (Iken et al., 2010; Goñi et al., 2013). Although terrestrial carbon must necessarily undergo bacterial processing before becoming usable for marine consumers, it may contribute substantially to diets of coastal fish and subsistence-harvested whales in interior shelf (Beaufort) lagoons (Harris et al., 2018) and slope biota (Bell et al., 2016).

Along Arctic rocky shores and in fjords of primarily outflow shelves but also other arctic island groups, macroalgae provide an inter- to subtidal carbon belt that adds to the carbon source diversity and amount. Certain benthic taxa were estimated to receive over half of their carbon from macroalgal sources even at depths of several hundred meters in a fjord (Renaud et al., 2015). Given the recent increase in macroalgal biomass along Arctic rocky shores related to ice thinning and declining extent and duration, an increasing role of macroalgal carbon is envisioned for Arctic food webs (Krause-Jensen and Duarte, 2014).

Methane occurs in substantial amounts in arctic shelf sediments and water – in addition to massive stores on land (Shakova et al., 2010, 2014; Lorenson et al., 2016). Though it is open at this point whether the contribution of methane via chemosynthesis is a substantial source to Arctic food web. Locally, however, methane-derived carbon enters consumers as documented in Barents Sea cold seeps (Åström et al., 2016; Sen et al., 2018).

In summary, the proportional roles of different carbon sources that fuel Arctic food webs as well as the taxa involved in these food webs are regionally variable, strongly tied to the regionality of the Arctic, and currently changing (**Fig. 22**). Observed changes suggest that boreal taxa moving into warming seas may in the future play larger roles in the food webs than previously and change food web topology, and terrestrial and macroalgal carbon contributions and/or amounts may be increasing. And something about conceptual modelling? What role will food web models play in conceptual model development and application?

7. Complexity and nesting of conceptual models: examples combining advection and phenology

We selected the pan-Arctic as our focal scale, and then examined the key regional domains of that system and the functional mechanisms that connect these domains. The same approach can be applied - in a nested, descending scale - to specific regions and contiguous domains.

Moore et al. (2018a) selected the Pacific-Arctic domain as their focal scale, and then examined how phenology affects three contiguous domains within that Pacific-Arctic domain (the seasonal ice zone, the shelf break-slope and the riverine coastal domain), as defined earlier in Carmack and Wassmann (2006), Bluhm et al. (2015) and Carmack et al. (2015). In doing so, they bring additional detail into a nested model approach. At the pan-Arctic scale, for example, we here combined Pacific inflows into one water mass, which we have called Pacific-origin water (PW), whereas Moore at al. (2018a) recognize that the PW is further comprised of three water masses that are assembled over the Bering/Chukchi shelf: Alaska Coastal Water, Bering Shelf Water and Anadyr Water. In turn, each of these water masses has distinct phenologies for the timing and extent of the spring bloom, vertical mixing of nutrients and biogeochemical attributes. Moore at al. (2018a) further recognize, at the regional scale, the phenology of each contiguous domain; e.g. the seasonal pattern of the SIZD moving north and south, the brief freshet forcing the RCD, the timing of shelf-break upwelling in relation to SIZD behavior, and the cryo-pelagic-benthic coupling that is tied to the Pacific through flow. Moore et al. (2018a) term this complex approach the ‘Arctic Pulses’ model and argue that the same logic can be applied to other regions of the AO.

A complementary model by Grebmeier et al. (2015) expanded details of advective processes as the through flowing waters transit across the Chukchi Sea, onto the Beaufort Shelf and then into the Canada Basin. This model examined in particular the various phytoplankton, zooplankton, benthic and upper trophic biomass distributions moving into, through and out of the Chukchi Sea in association to host water masses. In another example Carmack and Melling (2011) divided the Canadian Arctic Archipelago, which we here term an outflow shelf, in five sub-regions based on freshwater supply, ice regime and water mass throughflow (Oceans North Conservation Society, World Wildlife Fund Canada, and Ducks Unlimited Canada 2018).

The situation on the Eurasian shelf and slope to the central AO creates similar challenges of comprehension: several contiguous domains overlap in space and time. The advection of AW along the Eurasian shelf break of the central AO is continuous throughout the year, but the advection of zooplankton biomass is highly pulsed, with minima in spring and maxima in August north of Svalbard (Wassmann et al., 2017). During the maximum advection period of *Calanus finmarchicus,* these copepods are already in overwintering mode and this results in a limited grazing impact upon the rich spring bloom (maximum in June) in this region. Simultaneously the SIZ domain is retreating northwards with high speed, exposing the shelf break and upper slope domain to light and potential upwelling and shelf-basin exchange (Carmack and Chapman, 2003; Randelhoff and Guthrie, 2016). Below these domains the Atlantic halocline complex is an important feature of the Eurasian basin waters, limiting the vertical supply of nutrients. Despite of the simplification that any conceptual model presents, the spatial overlapping of contiguous domains (see chapter 8 and **Fig. 24)** with distinct phenology will create a complex scenario.

Another example of nesting within a regional domain is given by Michel et al. (2015). They noted that within the general classification of outflow shelves four different conditions of nutrients and stratification exist. These specific phenologies that planktonic heterotrophs, CPBC and the benthos have to cope with. The first is the condition of high initial nutrient concentrations followed by development of strong stratification, leading to the spring bloom. These conditions are observed in Barrow Strait within the eastern Canadian Arctic Archipelago and in the MIZ off East Greenland. Here new production is determined by the initial inventory since re-supply is constrained by stratification throughout the growing season. The second condition is one of low initial nutrients and strong stratification which is found in much of the western Canadian Arctic Archipelago and on the East Greenland shelf, and which results in a weak bloom and low annual productivity. The third condition is one of high nutrients and strong mixing found in areas such as the North Water Polynya and in areas of shelf break upwelling in the Beaufort Sea where high levels of new production are sustained throughout the growing season. The fourth condition is one of variable nutrient concentrations and low light that occurs where extensive ice cover and/or extremely high latitudes limit light input regardless of nutrient inventories.

Taken together, the ‘Arctic Pulses’ model of Moore et al. (2018a), the ‘Advective’ model of Grebmeier et al. (2015), various conceptual models of the Eurasian advective shelf regime (e.g. Wassmann et al., 2019) and the Canadian Arctic Archipelago (Michel et al., 2015) illustrate the validity of the multi-scale nested approach advocated here and serve as examples for application elsewhere. They all indicate how strongly the AO is connected to the sub-arctic Pacific and

Atlantic Oceans and how powerful advection shapes the function of the entire AO (Frainer et al. 2017; Polyakov et al., 2017; Alabia et al., 2018; Ellingsen et al., 2020). Vice versa, fundamental processes in the Northern Hemisphere, first and foremost sea level rise and weather variability, are a direct consequence of climate warming in the AO region.

8. Understanding and managing Arctic Ocean systems: from “framing” and field observations to modelling, decision making and communication

Rapid decline of sea ice coverage and surface warming propels the AO into a focal point of attention, not only that of the Arctic coastal states, but the attention of many nations of the Northern Hemisphere (IPCC, 2013; Box et al., 2019). In the forthcoming decade crucial decisions regarding oil/gas exploitation, fisheries, mining, transport and tourism have to be accomplished in the AO. For most of the AO the knowledge base for sustainable resource- and ecosystem-management is inadequate to evaluate the impact on biodiversity and ecosystem sustainability. Although research efforts have strongly increased in recent years and will in times to come [e.g. ArcticNet (http://www.arcticnet.ulaval.ca/), Nansen Legacy (https://arvenetternansen.com/), MOSAIC (https://www.mosaic-expedition.org/)] the pace is not proportional with that of climate change and the knowledge demand to make well-evaluated decisions. It is thus timely to develop a strategy that provides a solid base in support of decision making that Arctic coastal nations and those interested in using the AO need to make.

Studying poorly known or unknown sea regions often starts with expeditions into the unknown and broad, but uncoordinated investigations of a range of issues, such as circulation, water column structure, chemical properties, species and organism abundance. For several, so far little investigated AO regions and the expanse of today’s SIZD this strategy is still applied. A few marine AO regions have been or are regularly investigated and adequately presented in the literature (e.g. the Chuckie, Beaufort and Barents Seas, the Bering Strait and the Canadian and Svalbard Archipelagos). They benefit from the strategy of recurrent and regular field observations that give rise to time series and a broader understanding of ecosystem function. Regretfully time series are rare in the AO (but see Cottier et al., 2010; Moore et al. 2018b). Sooner or later the question arises as to how the system in a particular region, let alone the entire AO, works and how processes or qualities within it can be understood in a pan-Arctic fashion. To address this next level of understanding one has to develop or assume theoretical approaches of the border, structure, function and population dynamics of the system. The selection of adequate conceptual models becomes now essential.

Ecosystem investigations are an essential part of conceptual models. They could be achieved by adapting a wide range of generic theoretical approaches that are not constrained to a specific ecosystem or particular regionality (**Fig. 23**). For example, one may apply the theory of adaptive cycles (**Fig. 23B**) or apply a system stability concept (**Fig. 23B**). One may approach the system by studying its trophodynamics (**Fig. 23D**) or investigate trophic cascades (**Fig. 23E**), etc. In order to study a less known system inside the frame of a specific theory one has to define what is considered “the system”, which is a segment inside a continuity. For that, one has to apply “framing”. Framing is a key component of studying nature or other systems (Trede and Higgs, 2009) and is related to agenda-setting, the process by which problems and alternative solutions gain attention. It is an integral, initial part of conveying and processing data to develop understanding. For example, out of the many functional aspects of the AO one could “place a frame” onto the marginal or seasonal ice zone and define a seasonal ice zone system (such as the SIZD, see **Figs. 8, 9**). In particular when numerical modelling is applied framing becomes an important objective: one has to identify the model domain, transport across border, nesting inside the model domain etc. Framing is an essential aspect of our scientific endeavors and is well described by Albert Einstein´s quotation that “we cannot solve our problems with the same level of thinking that created them. We have to rise above it to the next level”.

In order to understand systems and to study their dynamics in addition to framing conceptual models play an important role, for both scientists and mangers. “Who are the essential players, how is the energy flow regulated and what are the feed-backs of the system”? are some of the essential questions to ask. A model has to be simple, but not too simple, says Einstein, but even simple models that only comprise selected elements can be too complex to grasp, in all their simplification. Conceptual models have thus to be simple, but not too simple, and the distinction between the two options depends upon the insight and capacity of the researcher, manager or decision maker. A wide range of preferentially multidisciplinary knowledge is thus indispensable. In **Fig. 24A,** we show a highly simplified conceptual model of the topography, river run-off, and currents of the AO. This depiction is probably the simplest manner to illustrate the AO that also presents salient features, without getting too simple. Despite of the oversimplification this conceptual model will be considered complex by many. In **Fig. 24B,** we show the principle distribution of 5 upper water column contiguous domains throughout the AO. Again, the level of complexity is conspicuous despite the extreme simplification in the model. Any area in the AO will thus be impacted by a range of functional and topographic features, currents and a multitude of vertically overlapping contiguous domains. However, **Fig. 24B** illustrates what every researcher has to have in mind when doing field investigations in the AO. Which are the dominating contiguous domains at the investigation spot? And how many contiguous domains will a vertical profile involve? How is the geography of the investigation site linked to various regional and biogeographical domains, for example those from the Pacific and Atlantic Oceans? Even under extreme reduction of reality several processes will take place simultaneously that connect the investigated region in space and time to AO regions and the adjacent oceans of the Northern Hemisphere. Are conceptual models presented in **Fig. 24** as simple as possible, or too simple?

To communicate and understand the implications to all involved in AO science, management and decision making it is beneficial if we are able to grasp the complexity behind basic conceptual models. Conceptualization of reality is thus the essential *modus operandi* that addresses problem definition, selection of investigation programs and decisions that have to be made, let alone the indispensable communication of results to management authorities and the general public. As such, conceptual models represent much more than one of many facets of scientific investigations. They comprise a strategy to define, solve and communicate challenges, which combines routinely separated activities and skills into an "interdisciplinary" cooperation. Also, a good conceptual model should dare escape from earlier and more narrow concepts, but address the challenge in a more holistic, integrative manner.

An important fact, frequently forgotten by decision-makers and managers, is that we cannot manage what we do not know. It is only possible to manage an ecosystem from which we know the basics players and ecological characteristics. Regretfully many ecosystems are being managed through assumptions and extrapolations from better known regions. The precautionary principle is often not applied, and ecosystem management can, thus, imply a high degree of risk. Sustainable ecosystem and resource management must be 1) multidisciplinary, 2) systemic and 3) knowledge based. For the inadequately investigated and poorly understood regions of the AO this creates a major challenge. How can, for example, ecosystem management of the industrial use of resources and ship traffic in the central AO be administered in a sustainable manner before sufficient knowledge of the affected system and key species has accumulated? In support of an adequate system-based understanding of Arctic marine ecosystems the tool kit for conceptual models presented here may help build investigation programs that will be adapted to progress towards improved understanding and addresses management needs. An important aspect of these endeavors is pan-Arctic science publications that inform the scientific community at large of what is known from the pan-Arctic expanse (e.g. Wassmann 2006, 2011, 2015; CAFF, 2017). Further, and with similar intensity, general publications, exhibitions and videos need to be produced to inform, educate and enlighten the general public and politicians.

After many decades when research in the AO was carried out in a few shelf regions, along restricted transects, at seasonally skewed and variable times, with a limited set of scientific methods and most often in a nation's territorial waters, it has dawned on scientists that the AO is *one,* not a fractionated ocean. It is the ocean where the effects of climate warming are strongest and where despite extensive functional regionality a mediterranean nature prevails. The AO demands to be considered as a *mare nostrum*[2]. The AO is one of the world's 5 mediterranen[3] seas, mostly enclosed seas that have limited exchange of water with outer oceans and with water circulation dominated by salinity and

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[2] Mare Nostrum (our sea) was a Roman name for the Mediterranean Sea

[3] Medius = middle + terra = land, earth

temperature differences rather than winds (Günther, 1980; (see **Fig. 1**). The geographic nature of mediterranen seas implies that they can only be adequately managed through international cooperation by their coastal states (e.g. the Baltic Sea, the Mediterranean Sea). This is also the vision of the Arctic Council, but, so far, it has been most strongly advocated by scientists, resulting in attempts to contribute to a more adequate understanding of the AO as a whole (see the volumes edited by Wassmann, 2006, 2011 2015; Spiridinov et al., 2011; various CAFF, PAME and AMAP reports). A recent step towards a wise management of the AO is the legally binding *Agreement on Enhancing International Arctic Scientific Cooperation*, initiated by the Arctic Council (Showstack, 2018). It promises "to increase effectiveness and efficiency in the development of scientific knowledge about the Arctic." The agreement focuses on facilitating access to research areas, research infrastructure and facilities, and data. Lately an *Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean* was signed. It prevents fisheries in the central AO, which is based, inter alia, upon cooperation in science and research and the establishment of appropriate conservation and management measures. The agreement commits the five Arctic coastal states of Norway, Russia, the United States, Canada, and Denmark/Greenland/the Faroe Islands as well as Japan, South Korea, Iceland and the EU – which also have large fishing fleets – to abstain from any future unregulated fishing in the international waters of the AO for the foreseeable future. After the scientific endeavors to look at the AO in a holistic manner, also the political and management aspects of the AO are now beginning to be approached with increasing intensity and dedication. To achieve these goals and to plan the work an appropriate conceptual model should be developed.

Our endeavors should aim to be neither circum- (Latin prefix with the meaning “roundabout, around”) nor trans- (Latin “on the other side of”), but *pan-Arctic* [(based upon the Greek term pan (all, every, throughout)]. Such attempts should end up in a syn-Arctic comprehension (syn **=** acting or considered together; united) that translates into a comprehensive, wider-ranging and encompassing strategy, shaping local, indigenous and scientific knowledge into a pan-Arctic mental picture which unites the comprehension of the arctic coastal states. In general terms a sequence of methods, activities and institutions should be applied to the pan-AO, assuring adaptive decision making (**Fig. 25**).

In order to reach the pan-Arctic integration goal some preconditions are necessary. Despite of the progress made to establish such a unifying model, care has to be taken to omit captivating and glossy oversimplifications. *The conceptual model* of the AO does not exist and may never become a reality but may be approximated in the future through infinitesimal adaptations of existing models and the iteration of and improvement of the conceptual model of the AO (**Fig. 25**). While focusing upon our ultimate goal, an adaptive pathway has to be trodden. Our comprehension of Arctic ecosystems depends on continuous efforts to understand better and to shape the understanding inside the regionality that creates the foundation of most scientific endeavors.

The about 4 million non-indigenous and indigenous people (as defined by AMAP) that are and have been living in the Arctic for centuries and millennia, accumulating knowledge and experience, should continue to have an impact upon knowledge-based resource- and ecosystem-management. In most Arctic nations, locals have only recently been involved in AO management decisions. The knowledge of all Arctic people is clearly of interest and relevance for a sustainable, knowledge-based resource and ecosystem management of the future (**Fig. 26**). To create scenarios to safeguard the inclusion of local ecological knowledge (tied to place through experience and observation over a single lifetime or over many generations) and traditional ecological knowledge (indigenous knowledge, e.g. Berkes et al., 2000; Huntington, 2000; Drews, 2005) regarding the AO (e.g. Nichols et al., 2004; Eicken et al., 2014) is a challenge that scientist, managers and politicians need to pay attention to (Fox Gearheard et al., 2017). The selection and definition of core values has to be discussed along our pathway into our climate change- and economic opportunity-impacted future in the AO (**Fig. 26**). The journey into the future must be based upon knowledge that research and careful evaluations of the effects that transport, fisheries and industrial activities bring about. The hackneyed phrase that the AO ecosystem management must remain ecologically sustainable, i.e. take place in manners that, over time, do not alter the ecosystem carrying capacity, is still not rigorously applied. If it will be and bears fruits throughout the AO of the future remains to be seen.

9. Outlook

Alarmed by John Maynard Keynes's (1936) citation that «the difficulty lies not so much in developing new ideas as in escaping from old ones», we argue that to understand the AO in a fully pan-Arctic manner we have to consider which of the older confined and sectorial ideas have to be revised and changed. To obtain a more balanced, pan-Arctic perspective, in favor of interaction and cooperation we unified older concepts and ideas, revised them and added new ones. To provide significant elements for shared, high-level paradigm synthesis of our understanding of the key processes and elements governing the response of the Arctic ecosystem of today and the future, we thus presented a hierarchy of known and new conceptual models. We urge AO scientists and managers to undertake a holistic comprehension of a new emerging ocean that has, so far, been inadequately investigated and which now challenges our ability to understand climate change and associated the ecological response in the Northern Hemisphere. The current advancement in knowledge is already conducted at too slow a pace to address today's climate and human usage of the transformed AO. Scientist rather run after the development experienced by the AO than be the forerunner in planning how to investigate and project the future. Here we take some first steps in this direction.

The conceptual models we describe will not only support the basic understanding and management challenges of those directly working in the Arctic, but they can also serve as tools to communicate insight, understanding and support among politicians, decision makers and the general public. The latter aspect is imperative. The people of the Northern Hemisphere need to understand that the local challenges they face [e.g. sea-level rise (Dahl-Jensen, 2000; Moginot et al. 2019), weather extremes (Box et al., 2917; Waugh et al, 2917)] may need research in remote, Arctic regions where "nobody lives" (the population in the Arctic regions comprises only 0.05% of the human population). Some principal AO climate change research of generic interest is already carried out [invasion of boreal species (Frainer et al., 2018; Alabia et al., 2018), changes in biodiversity (Spiridonov et al., 2011; CAFF, 2017)] and ongoing research will pave the ground for future AO management (e.g., the Nansen Legacy project). Resource hungry nations, representing 99.95 % of humanity appear to wish to exploit the rich resource of the remote regions of the AO but may be less concerned with the ecological consequences, the requirements of the local population and the demands of long-term sustainability (Alvarez et al. 2020). It is essential to get the Global community (stakeholders, the human population at large) of the Northern Hemisphere involved in planning for a sustainable AO by communicating and communicate results, narratives, pictures and iconic graphics.

Conceptual models can strongly facilitate interdisciplinarity by providing a shared understanding of the system. Developing them involves an element of intuition which, joined to research, speeds up the process of exact science (see citation of P. Klee at the start). Working with the development of conceptual models also involves approaches relating to, involving or dealing with abstract, general or universal concepts. Once established, such models often have inertia, that can exert a profound influence on the interpretation of data and on shaping common directions, for years to come, thereby becoming essential underpinnings of new paradigms. The communities of Arctic scientists, managers, politicians and peoples of the Arctic need interdisciplinarity and shared understanding. Currently none can perceive conceptual models without taking note and reacting to the concept of climate change. Conceptual models have three basic functions: create testable hypotheses, plan and then modify field campaigns, and 3communicate essential results to managers and the general public. They have thus to be able to accommodate transience as they are not permanent and represent rather an activity than a final product.

Having in mind the transientness of all models for the AO, we wish to end with a citation from Aargaard and Carmack (1989), a visionary document that already 30 years ago encompassed many of the changes currently experienced in and adjacent to the AO. “While our scenario is highly conjectural, it is quite in keeping with the message of change that Fridjof Nansen himself preached on numerous occasions. For example, in a lecture on the Fram drift delivered in 1897 he ended with these words: *Everything is drifting, the whole ocean moves ceaselessly, a link in Nature's never-ending cycle, just as shifting and transitory as the human theories*".

Acknowledgement

We kindly recognize the invitation of IARPC (Interagency Arctic Research Policy Committee; https://www.iarpccollaborations.org/index.html) and Guillermo Auad (BOEM) to initiate the workshop *Towards a Unifying Pan-Arctic Perspective: Concepts and Theories*, in October 2016. The workshop was organized by P. Wassmann, C.M. Duarte and E. Carmack. Financial support came from NSF (National Science Foundation, award nr. 1638481), BOEM (Bureau of Ocean Energy Management; https://www.boem.gov/), ONR (Office of Naval research; https://www.onr.navy.mil/) and USARC (United States Arctic Research Commission, https://www.arctic.gov/). The organizers are grateful to H. Huntington who had the role of superb moderator and skilled discussion leader. Sara Bowden (IARPC) supported our work and we thank Jessica Rohde for her efficient and exceptional note taking and outreach activities. Ivan Gromicho, scientific illustrator at the King Abdullah University of Science and Technology, prepared illustrations for a wider audience during the meeting. Thanks also to our local host, Jacqueline Grebmeier (University of Maryland, Center for Environmental Science, Chesapeake Biological Laboratory). Thanks to the entire group turning the meeting into a model for exceptional teamwork. Patricia Kimber and Malin Daase produced and edited the figures. This publication is a contribution to IARPC, the research project ARCEx (no.228107) and the research group Arctic SIZE (http://site.uit.no/arcticsize/).

Field Code Changed

Field Code Changed

Field Code Changed

Box 1. Four elements of conceptual models that will guide the design, implementation and interpretation of field experiments and monitoring.

Scale: Scale recognizes that processes occur over wide-ranging dimensions of space and time, and often there exists an empirical relationship between space and time scales, often expressed in so-called Sverdrup diagrams. *A priori* recognition of scale, such as first identifying the focal scale together with its interacting larger and smaller scales, is useful in the design of multidisciplinary field experiments.

Pattern: Pattern can be defined, simply, as any non-random structure or process and – generally – an emergent property (bottom-up) of a complex adaptive system (i.e. rules at a lesser scale give rise to structure at a greater scale).

Seasonality: Seasonality is one of many key times scales inherent in Arctic marine systems but, owing to the phenology of biotic components, is also a critical starting point in experimental design. Seasonality in temperature, light, sea ice and the hydrological cycle all constrain the Arctic marine ecosystems.

Regionality: Regionality recognizes spatial variability (non-homogeneity) within a system and is often viewed in terms of descending dimension. At the global scale the Arctic marine system has general features such as extremes of temperature and light availability, seasonal ice cover, salt stratification, etc. But different components of this system have distinct characteristics that strongly influence internal dynamics and response to forcing, and these differences must be recognized in responsible management policy and implementation.

Table 1. Abbreviations

Water masses

ACBC	Arctic Circumpolar Boundary Current
AO	Arctic Ocean
ASW	Arctic Surface Waters
AW	Atlantic Water
NHTC	Northern Hemisphere Thermohaline Circulation
PW	Pacific Water

Domains/Processes

APH	Atlantic and Pacific Halocline domains
CBCD	Circumpolar Boundary Current Domains
CPB	Cryo-pelagic-benthic coupling
DBD	Deep Basins Domains
SIZD	Seasonal ice zone domain
RCD	Riverine Coastal Domain
ULAD	Upper layer advective domains

Table 2. Characteristics of Arctic food webs.

General concept/focus	Arctic case	Example references
Who eats whom: compartments of a food web	Sea ice as additional realms, housing >1000 species Dominant grazers: calanoid copepods Large benthic compartments: bivalves, polychaetes, crustaceans, echinoderms Key fish predator: Polar cod Abundant bird and mammal predators: alcids, gulls, ice-associated seals and whales	Planque et al., 2014; Whitehouse et al., 2014
Energy content	High lipid food web, especially in zooplankton, polar (Arctic) cod and capelin, marine mammals; high PUFA content in ice algae	Lee et al., 2006; Leu et al., 2006
Specialization versus generalism	Higher than assumed trophic plasticity, omnivory and mixotrophy; size-structured food webs	Mixotrophy: Sanders and Gast, 2012; Stasko et al., 2018; Harris et al., 2018
Food web length	Typically, 4.5-6 trophic levels: not generally different than in other seas; replacing earlier notion of short food webs	Iken et al., 2005, 2010; Whitehouse et al., 2014; Suprenand et al., 2018
Connectivity	Lower connectivity in Arctic than boreal / sub-Arctic food webs (note only Barents Sea studied); yet typically multiple trophic links per species	deSantana et al., 2013; Kortsch et al., 2015; Planque et al., 2014
Particulate Organic Carbon sources	POC: Phytoplankton, ice algae, carcasses of heterotrophic plankton, terrestrial input from large rivers, tundra and glaciers, macroalgae, microphytobenthos, (locally methane)	Iken et al., 2010; Wang et al., 2016; Renaud et al., 2015; Harris et al., 2018

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Fig. 1. Two Northern Hemisphere maps showing the encircling of the Arctic Ocean by extensive landmasses, atmospheric transports, watersheds and the connection with the Pacific and Atlantic Oceans. Figures are redrawn from Prowse et al. (2015) and Carmack et al. (2016) illustrating (A) the delivery of moisture and freshwater to the Arctic drainage basins by extra-tropical storm tracks (in the lower and higher atmosphere), and (B) oceanic pathways from the Pacific and Atlantic into and out of the Arctic Ocean and major gyres. In both maps the white shaded area denotes the Arctic drainage basins, as discussed by Prowse et al. (2015). TPD is the Transpolar Drift. The light-blue shaded area depicts surface waters influenced by fresh-water stratification.

Fig. 2. A highly schematic, Sverdrup-type diagram that shows spatial and temporal scales that couple global, pan-Arctic and regional marine systems in descending log scales of space and time. The global scale recognizes the interactions of global scale processes (thermohaline circulation, hydrological cycle, atmospheric forcing), and is externally forced by even large scales. The pan-Arctic marine system, the focus of this paper, is nested at smaller spatial and temporal space and time scales. It is fully coupled to the global marine system through exchanges of energy, freshwater, water masses and material properties including, for example, the Atlantic and Pacific through-flows and the delivery of freshwater to regional drainage basins by atmospheric transport. The pan-Arctic marine system is, in turn, underlain by regional domains, as discussed in Section 2 including inflow shelves, interior shelves, outflow shelves, the pan-Arctic shelf-break and slope, the Eurasian and Amerasian basins, and major ridge systems (see Carmack and Wassmann (2006) and Bluhm et al. (2015) for discussion). Below are the mesoscale and sub-mesoscale processes that act to regulate biogeochemical processes within specific regions. Forcing is often held to pass top-down from larger to smaller scales, while feedbacks and emergent properties are held to be driven bottom-up.

Fig. 3. Functional connection of the Arctic Ocean at the pan-Arctic scale. To the left the figure comprises the entire Northern Hemisphere, including the continents and the transportation of moisture by trade winds to the North Pacific and the westerly storm tracks (A). To the right scheme the focus is upon the functional connections of the Arctic Ocean and adjacent watershed (B). The schematic depicts the currents linking the Pacific, Arctic and Atlantic Oceans, the main pathways of moisture transport to Arctic drainage basins, the northward flow of rivers to the Arctic Ocean, the establishment of low-salinity coastal currents by river inflow, and the primary geographical domains. Redrawn from Bluhm et al. (2015) and Carmack et al. (2016).

Fig. 4. Schematic representation of the basic structure and hydrological functions of the Arctic Ocean and the coupling of Arctic and subarctic marine and atmospheric systems under Arctic warming. The 850-mbar surface is taken as representative of the Polar Vortex that was previously prominent, but which is now broken up into a multitude of vortecies, allowing in recent years for significant variability in Arctic Ocean weather. Abbreviations are: AA Arctic

amplification with tapering indicating increased poleward warming; WW Westerly wind with eddy flux convergence occurring along the Westerly wind maximum; MW meridional winds associated with Jet Stream meanders; Q ocean/atmospheric heat exchange; in the center the sea ice, fresh-water stratification and SML (Surface Mixed Layer); NSTM near surface temperature maximum forming near expanding open water areas; PW low salinity Pacific water inflow; AW high salinity Atlantic water inflow; NPIW North Pacific Intermediate water in the subarctic Pacific; DW is deep water, for which North Pacific, Arctic Ocean and North Atlantic varieties exist. Take note of the strong stratification by various water bodies in the central Arctic Ocean. See text for changes and feedbacks. Redrawn from Carmack et al. (2012).

Fig. 5. Schematic showing four large-scale circulation systems (with L > 1000 km); these are: (A) the large scale wind-driven circulation which forces the cyclonic Trans-Polar Drift (TPD) from interior shelves of Siberia to the export shelf of the Fram Strait and the anticyclonic Beaufort Gyre in the southern Canada Basin (BG): also shown are the Icelandic and Greenlandic Gyres (IG and GG, respectively) and the North Atlantic Current (NAC); (B) the circulation of waters that comprise the halocline complex, composed largely of waters of Pacific (blue) and Atlantic (red) origin that are modified during passage over the inflow and Siberian interior shelves, respectively; (C) the topographically-trapped Arctic Circumpolar Boundary Current which carries AW cyclonically around the boundaries of the entire suite of basins (FSB and BSB are the Fram Strait and Barents Sea Branch), and (D) the very slow exchange of Arctic Ocean Deep Waters that enter on the eastern and leave on the western Fram Strait. Redrawn from Bluhm et al. (2015).

Fig. 6. Three shelf types exist in the Arctic Ocean: inflow (tourquoise-gray), interior (blue) and outflow (pink) shelfs. Also shown (turquoise) is the shelf break and upper slope region that surrounds the outer shelves and the deep Canadian and Eurasian basins (gray). Redrawn from Carmack and Wassmann (2006).

Fig. 7. Typology of distinct shelf types in the Arctic Ocean: inflow (top), interior (middle) and outflow (bottom) shelves. Among these categories one may separate deep (left) and shallow (right) inflow shelves, wide (left) and narrow (right) interior shelves, and linear (left) and branched/topography-rich (right) outflow shelves. Following this, the Barents Sea is a deep and the Chukchi Sea is a shallow inflow shelf. The Kara, Laptev and East Siberian Seas are wide interior shelves, while the Beaufort Sea is a narrow inflow shelf. The East Greenland shelf has banks and troughs but is a "linear" while the Canadian Arctic Archipelago has a branched and topographically complex shelf. The basic biogeochemical cycling features of the three shelf types are presented to the right. Redrawn and updated from Carmack and Wassmann (2006).

Fig. 8. Seasonal ice zone domain. A) Illustrates the maximum sea ice extent 30 years ago (dark orange) and at present (light orange). The white area depicts todays minimum ice extent. Also shown are the transect lines illustrated in Figs. 9A (black) and 9B (green). (B) The relationship between the marginal ice zone (MIZ – outer rim of seasonal ice zone) circumference (km) and the seasonal ice zone (SIZ – zone between minimum and maximum ice extent) radii (km) in an

assumed circular, ice-covered ocean. While the MIZ length decreases in a linear manner when the SIZ declines, the SIZ area (km^2) increases in curvilinear manner.

Fig. 9. Hypothetical, annual variability of ice (white), light (blue) and plankton and ice algae blooms (green) across the Arctic Ocean, now (left) and in the future (2050 right). The annual variability of sea ice thickness, light and plankton blooms for every month (Jan to Dec) across the Arctic Ocean are shown: now (to the left) and 2050 (to the right). The figure depicts a transect from the Barents Sea to the Beaufort Sea shelf (A) while a transect from the north of Greenland to the Laptev Sea shelf is shown in (B). The figure shows that the phytoplankton blooms in the Arctic Ocean are not smooth circles that shrink unevenly from the periphery on the shelf towards the center (basins). The blooms have a variable phenology with regard to timing, strength and width, and biomass may shift in depth location in the water column seasonally. The greatest changes in the future take place in the most productive months.

Fig. 10. Highly schematic representation of potential buoyancy-boundary flows driven by continental discharge along northern coastlines around North America and Eurasia. The flow is not continuous, and the schematic represents the merging of multiple sources of freshwater discharge from northern North America and northern Eurasia. Hundreds of rivers and glacial ice melt, which have a propensity for the formation of an aggregate or contiguous domain along the coastline are here termed the Riverine Coastal Domain (RCD), shown with a red line. Redrawn from Carmack et al. (2015).

Fig. 11. The Upper Layers Advective Domain of the Arctic Ocean. Within this domain, we distinguish among 4 sub-domains: the Atlantic (red), the Pacific (pink), the Arctic (light red) and the Transpolar (light purple) advective domains. All have lengths of several thousand km and pass through several biogeographic regions. Redrawn from Wassmann et al. (2015).

Fig. 12. Circumpolar Boundary Current Domains during times when sea ice cover withdraws, to various degrees withdraws from the shelf into the deep Arctic Ocean basins and thus is exposed to easterly winds. The cartoon depicts the two-dimensional upwelling circulation, when ice is leaving the shelf break, (A), and when the ice has left the shelf break a shelf-break jet can develop that can give rise to upwelling (B). Upwelling provides the exposed shelves and shelf breaks with additional nutrients that may reach into the surface waters. If stratification is strong upwelling may cause subsurface blooms (e.g. Martin et al., 2010).

Fig. 13. Changes in the distribution of the Atlantic and Pacific Halocline Domains as related to the predominant wind fields (H and L for atmospheric high and low pressure, respectively). The change from earlier (left) towards recent windfields (right) and increased supply of advected Pacific and Atlantic inflows (PI, AI) result in important changes in the position of the halocline. Take note of the recent increase in sea level height and depth of the surface water (SW), in particular in the Amerasian Basin. Take also note how the dominating Atlantic Water (AW) spreads in recent times further into the Arctic Ocean, in particular in the surface. The Cold Halocline Water (CHL), however decreased in recent years. AO (Atlantic

Outflow); PHW (Pacific Halocline Water); LHW (Lower Halocline Water). Redrawn from Polyakov et al. (2018).

Fig. 14. Deep Basin Domain (DBD, deeper than 1000 m). This domain is physically characterized by low current flows, water exchange between basins being limited by ridges/sills, old age of the water, low and stable temperature, and high salinity. The age of the deep water is about 200 years in the Nansen and Amundsen basins, but about 500 years in the Canadian Basin. Biochemically, the DBD receives highly diminished vertical carbon input, but horizontal carbon input can be important. This results in low biotic densities and biomass, dominance of soft sediments dotted with glacial drop stones. The DBD is intersected by ridges, with local outflows of chemical-rich fluids and (largely unmapped) seamounts. Today's biotic connectivity to the north Atlantic and the global deep-sea is high while that to the Pacific is essentially absent. AWin (Atlantic Water inflow); AODWout (Atlantic Ocean Deep Water outflow); GSDWin (Greenland Sea Deep Water inflow); BD (Brine Drainage); NB (Nansen Basin), NGR (Nansen-Gakkel Ridge); AB (Amundsen Basin); LR (Lomonosov Ridge); MB (Makarov Basin); AMR (Alpha-Mendeleev Ridge); CB (Canada Basin). The dashed vertical lines and circle arrows indicate bottom water mixing. Sb (salinity); Θb (potential temperature)

Fig. 15. The Polar Night north of the Arctic Circle. Between 67.4 and 72°N the sun is below the horizon from 1-72 days per year. Between 72 to 78°N the sun is below the horizon between 72-112 days per year. Between 78 to 84°N the sun is below the horizon for 112-144 days per year. Above 84°N the sun is below the horizon for 144-177 days per year. The period of midnight sun is a geometrically mirror of the polar night, but due to atmospheric refraction of the sun, the period of midnight sun is up to 14 days longer than the Polar Night. Take note how the light regimes vary between regions were marine Arctic research has been and is carried out (not shown). Investigations north of Svalbard, in the Barents Sea, the Beaufort shelf or the Chukchi Sea take place under widely different light regimes and are thus difficult to compare.

Fig. 16. Hypothetical phenology of ice algae and phytoplankton blooms as a function of latitude. Light, ice and stratification determine the environmental envelope that regulates the timing of ice algae and phytoplankton bloom development along a latitudinal axis of open water-Seasonal Ice Zone Domain (ranging from 75–85°N). There are long to short productive periods in open water (70–75°N) and heavily ice-covered regions (> 73–75°N) in the European Arctic corridor, respectively. Inside each longitudinal light window with its variable ice cover the timing and extent of the ice and phytoplankton and ice algae phenology changes from April in the south towards late summer at high latitudes. A recent feature is the tendency for autumn blooms that has been observed in the Polar Twilight zone, but these blooms will have no light base in the Nautical Polar Night zone (see Fig. 15).

Fig. 17. Climate change alters the phenology of the ice algae and phytoplankton blooms. Present-day scenario (left) and predicted future scenario with a warmer climate (right) along similar latitudes. The hypothetical timing of the ice algae and phytoplankton bloom development in the Eurasian Arctic corridor along a

latitudinal axis is indicated: from the open water-seasonal ice zone region (ranging from 75–85°N) with long to short productive periods in open water (70–75°N) to heavily ice-covered regions (> 73–75°N). Notice how today's bloom development scenario A disappears for good while the new scenario F enters at the southern section of the latitudinal gradient in the future. Panels E and F exemplify the course of primary production in the scenario of continuously open water in the central/southern Barents Sea, characterized by no major freshwater source and weak and slow development of surface water stratification. The variable production in June (panel E) arises through variations in nutrient supply caused by vertical mixing events triggered by low-pressure passage after the end of the spring bloom. Panel F projects future primary production at 70°N after Arctic warming leads to increasing thermal stratification and decreased primary production. Modified from Leu et al. (2011) and Wassmann and Reigstad (2012).

Fig. 18. Phenology of the bloom development and in downward carbon export at about 78°N in the Barents Sea over a two-year period. The present-day climate is depicted in panel A and the consequences of a warmer climate with thinner ice in winter and more melting of summer ic) is displayed in panel B. A thinning of sea ice, variable snow cover, supports a) more intense and earlier ice algae blooms and b) a greater annual extent of the seasonal ice zone. The green-to-red gradient indicates the balance of suspended biomass from autotrophic (green) to heterotrophic (red) sources. The annual new and export production in both scenarios is assumed similar because stratification (induced by sea-ice melt and increased surface warming) limit nutrient availability. Greater wind stress may though increase the vertical contribution of nutrients. The width and color of the vertical arrows illustrate the semi-quantitative magnitude and composition (autotroph, fecal pellet and detritus (green, red, brown, respectively) of vertical export.
In an adaption to the short productive period and cold temperature many organisms at Civil Polar Night and Nautical Polar Night latitudes expand their annual life cycle to more than year. Some of the involved processes that organisms such as Polar cod apply during the Polar Night are indicated in panel A (see white vertical bars). To understand the marine ecology at high latitudes in the AO we must have to change our traditional attention to spring and summer, but pay increasingly attention to the a) autumn and overwintering and b) multiannual time spans. Winter seems to play an essential role for the marine ecology of the AO. Redrawn from Wassmann and Reigstad (2011).

Fig. 19. Hypothetical graph explaining the principles of cryo-pelagic-benthic coupling (CPBD) for shallow (A), moderate (B) and deep ocean (C) regions. The thin vertical lines (grey) illustrate the subsurface contribution of ice-derived biogenic matter. The level of new production (based upon nutrient availability and supply) and light availability increases amount of the suspended biomass that can sink. Scenario I (red) illustrates the CPBD for less productive, scenario II (green) the high productive and stratified regions. Depth and the intensity of the of the pelagic retention, in particular in the upper twilight zone, plays a major role for the intensity of cryo- pelagic-benthic coupling. Benthic organisms in shallow regions, such as the Chukchi Sea (see panel A) enjoy a far higher supply and quality of biogenic matter than deeper shelves (such as the deeper Barents Sea, see panel

C)). In the AO basins the CPBD is assumed to be weak (not shown). Vertical mixing in non-ice-covered regions that will become more frequent in the future results in a dilution of suspended biomass in the upper layers and a change vertical flux retention (scenario III, blue). Shallow shelves have far greater resuspension and contribute substantially more to remineralization than those in the deeper ones. Resuspension of particulate matter from the sediment surface, being most intensive on shallow shelves, contributes to the horizontal export of carbon into the deep basins.

Fig. 20. Conceptual Arctic food web showing dominant taxa and their trophic position and indicating trophic links among species through arrows. This depiction overlays a vertically structured concept of the Arctic Ocean's compartments including sea ice, water column and seabed. A shallow shelf and more Arctic influence is indicated by characteristic biota, subsistence populations and more sea ice (A, Bering Strait region, Chukchi Sea). The semi-transparent fishing vessel indicates (potential) fisheries moving north. A deep shelf and one with more Atlantic influence is indicated by characteristic biota including commercial species, less sea ice and fishing effort (B). The basin conditions are not shown in detail. Circular insets illustrate the ice brine channel system biota (1), the microbial food web (2) and the meiofaunal sediment community (3). Primary producers are colored in green, consumers in black (and light blue in deeper waters), and orange indicates particularly lipid-rich biota with high energetic value for their consumers. For more detail, see text section 6.1.

Fig. 21. Conceptual depiction of energy flow in Atlantic (A) and Pacific (B) inflow shelves. Dominant functional and/or taxonomic groups are shown as rectangles and trapezoids and are vertically arranged along a trophic level axis, starting from the base of the food web at the bottom. A given group may extend across several trophic levels; box size indicates the relative biomass of a given group. Trapezoids indicate increasing or decreasing relative importance along a south (lower side)-to-north (upper side) gradient (only shown where very prominent). Brown shades indicate benthic-dominated, blue shades pelagic-dominated flows. Lines between boxes show (only particularly prominent) energy flows with green lines denoting energy transfers from the lowest trophic levels and detritus and black lines denoting energy flow between consumer levels. Dark gray outlines marks groups with particularly high connectance (i.e. many trophic links). Modified from Whitehouse et al. (2014) and informed by Carroll and Carroll (2003), Dommasnes et al. (2010), Iken et al. (2010), de Santana et al. (2013), Hunt et al. (2013), Kortsch et al. (2015, 2019), Skaret and Pitcher (2016), Pedersen et al. (2018), Suprenand et al. (2018). D = demersal, gelat. zoop. = gelatinous zooplankton, M = marine mammals, S = seabirds.

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Fig. 22. Particulate carbon sources supporting the (eukaryotic) Arctic food web. Substantial methane sources (blue ovals, CH_4) are documented in sub-sea surface sediments, and early evidence suggests methane uptake into the food web. Carbon sources playing strong roles in a given region of the Arctic Ocean are shown: Pelagic particulate organic matter (pPOM) is the primary (particulate) carbon end member, and overwhelmingly so in the inflow shelves (dark green). In the central basin, ice-derived POM (iPOM, light green) can contribute about half to

primary production. Interior shelves in particular receive substantial amounts of terrestrial organic matter (tPOM, light brown) from permafrost and rivers (brown arrows), though glaciers also contribute. Rocky shores of Greenland, the Canadian Arctic Archipelago (gray trapezoids), Svalbard and Russian shelf island groups (gray circles) provide increasing amounts of macroalgal carbon (MA and brown outlines). Notably, dissolved organic carbon (DOC; not shown in this figure) contributes most carbon to the entire carbon pool, but must be taken up through the microbial loop, namely bacteria, before entering the eukaryotic food web.

Fig. 23. The figure illustrates icons for established approaches to complex systems level modeling. Panel A illustrates C.S. Holling's so-called *rule of hand* which states that most complex adaptive system will be governed by the interactions among a small number (say 5 ± 2) internal parameters; changes to any of these internal parameters will alter the behavior and equilibrium state of the overall system and its response to external forcing (drivers) (Holling, Pers. Comm.). Panel B illustrates the *complex adaptive cycle* which states that a given social-ecological system will undergo a natural cycle of 1) growth, 2) collapse, 3) release and 4) reorganization (Gunderson and Holling, 2002). Panel C illustrates the *ball-in-basin* which conveys the ability (resilience) of a system to return to its equilibrium state (K1) when perturbed; As resilience is decreased the K1 basin depth shoals; at some point a given external shock may force the system beyond its threshold (tipping point; Wassmann and Lenton, 2012; Duarte et al., 2012) into a new stable equilibrium (Walker and Salt, 2006). Ongoing changes in sea ice dynamics may illustrate this process (Duarte et al., 2012). Panel D illustrates the concept of *trophodynamics* (e.g. phasing, match-mismatch, etc.) in which the joint phenologies of prey and predator influence the efficiency carbon transfer up a given food web (Parsons, 1988). Typically, a well-matched phase will result in a robust pelagic food web, while mismatched phasing will strengthen pelagic benthic coupling (Wassmann, 1998). Panel E illustrates the concept of *trophic cascade*, a top-down process in which reduction (enhancement) at one trophic level may result in enhancement (reduction) at the underlying level, followed by reverse effects at successive levels (Carpenter and Kitchell, 1993). Examples include removing a planktivorous fish from a system which results in reduced grazing of zooplankton which results in a greater number of phytoplankton, and so on; cascade effects will spill over into nutrient and water quality effect as well. Panel F illustrates the process of *system cascade*, wherein an external driver (e.g. climate warming) may directly affect one system (e.g. sea ice cover) which in turn affects another system (e.g. increased ocean stratification) which affects yet another system (e.g. nutrient availability), and so on through the food web (Carmack et al., 2014). The main feature here is not that the initial driver affects succeeding systems in the chain directly, but rather through the cascade links. In addition, each succeeding system will have different tipping points and feedback processes. Panel G illustrates a mapping approach to following a system´s cascade in which links between a given drivers are followed through linked systems. Panel H illustrates the process of *synchronous failure*, a conceptual framework that shows how multiple stresses can interact within a single social-ecological system to cause a shift in that system's behavior based on identifies the pattern's causes, intermediate processes, and ultimate outcomes (Homer-Dixon et al., 2015). Synchronous failure can often be characterized by a pattern of expanding scale

and magnitude. Panel I illustrates the importance of scale, into which each of the above concepts must be mapped (Carmack and McLaughlin, 2000).

Fig. 24. Two hypothetical figures that illustrate how one may move from observations over abstraction to the ultimate simplified "template"-type conceptual model. A) illustrates continents, shelfs and basins, major currents freshwater run-off and connectivity to the Atlantic- and Pacific Oceans. B) illustrates all of the contiguous domains that are plotted into this hypothetical depiction of the Arctic Ocean. For each region in the Arctic Ocean researchers need to have the basic knowledge, illustrated in A and B, in mind.

Fig. 25. Schematic sequence of methods, activities and institutions that assure adaptive decision making. Starting with a hypothesis that results in predictions observations and a sampling design are formed. After quality control of the data the updated knowledge gives rise to an update of the hypothesis (prediction) and eventually to the formulation of a model that then provides the base for a new round of investigations. Also, the needs of the management come into play here. They use the model results and contribute to management measures that become part of the new observation regime, the research design and management features. For every sequence of activities result are published scientifically while communication with decisions makers, politicians and the general public (consisting in our case first of all the people living in the Arctic) is mandatory. In concert this creates the strategy for adaptive decision making which ultimately also improves the conceptual model of the Arctic Ocean.

Fig. 26. A schematic that illustrates how knowledge (our history and culture) is transferred, created and shaped (current system and core values), transformed and impacted (pathway) to create the base for our future. In our present, humanity´s core values (here summarized in the term sustainability without which there will be no justifiable future) play a crucial role. We are forced by climate change and economic drivers. During the time between now and the future (pathway) discussions and debates are indispensable and the public has to distinguish between the institutions and ideas that block or hinder a sustainable future.

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