

Chapter 12

Progress and Challenges in Biogeochemical Modeling of the Pacific Arctic Region

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Abstract At this early stage of modeling marine ecosystems and biogeochemical cycles in the Pacific Arctic Region (PAR), numerous challenges lie ahead. Observational data used for model development and validation remain sparse, especially across seasons and under a variety of environmental conditions. Field data are becoming more available, but at the same time PAR is rapidly changing. Biogeochemical models can provide the means to capture some of these changes. This study introduces and synthesizes ecosystem modeling in PAR by discussing differences in complexity and application of one-dimensional, regional, and global earth system models. Topics

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include the general structure of ecosystem models and specifics of the combined benthic, pelagic, and ice PAR ecosystems, the importance of model validation, model responses to climate influences (e.g. diminishing sea ice, ocean acidification), and the impacts of circulation and stratification changes on PAR ecosystems and biogeochemical cycling. Examples of modeling studies that help place the region within the context of the Pan-Arctic System are also discussed. We synthesize past and ongoing PAR biogeochemical modeling efforts and briefly touch on decision makers' use of ecosystem models and on necessary future developments.

Keywords Biogeochemical models • Ecosystem modeling • Arctic • Sea ice biogeochemistry • Carbon cycling modeling

12.1 Introduction

Rapid climate change occurring in the Pacific Arctic Region (PAR) and questions about the impact on marine ecosystems and biogeochemical cycles have led to the development of models to interpret observations and predict future changes and responses. Large uncertainties exist regarding the ways in which the biology of the Arctic, including PAR, is responding to climate change. Biogeochemical models can help elucidate these changes, synthesize observations, and guide resource-limited field campaigns. Models are particularly useful in PAR due to limited access, incomplete satellite coverage, and poor spatial resolution of field data. To comprehend the impact of climate change on the ecosystem and on biogeochemical cycling, modeling based upon measures of key processes and a range of in situ validation data is required.

The PAR ecosystem is a dynamic system. Biogeochemical models attempt to capture the dynamics and cycling of the biochemical (i.e., living) and geochemical (i.e., non-living) parts of an ecosystem. These dynamic models are formulated as a combination of a set of differential equations, some algebraic equations, and a parameter list (Box 12.1). To qualify for the term “ecosystem model”, a model must

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Box 12.1: Ecosystem Model Basics

The simplest marine ecosystem models usually represent a planktonic food web with one or more nutrient (N), phytoplankton (P), zooplankton (Z) and often detritus (D) compartments (i.e., state variables). More complex models may contain more components (e.g., bacteria, zooplankton life stages, DOM), additional biomes (e.g. sea ice, benthos), and gases, or they may extend to fish and higher trophic levels (HTLs) in order to more readily address human dimensions (e.g., fisheries, lifestyle, and habitat changes). Models that include socioeconomic interactions and responses are beginning to be introduced but are as yet unavailable for PAR and thus lie beyond the scope of this chapter.

Figure 12.1 shows a schematic of compartments and processes represented in ecosystem models with multiple layers of complexity. The basic NPZD model

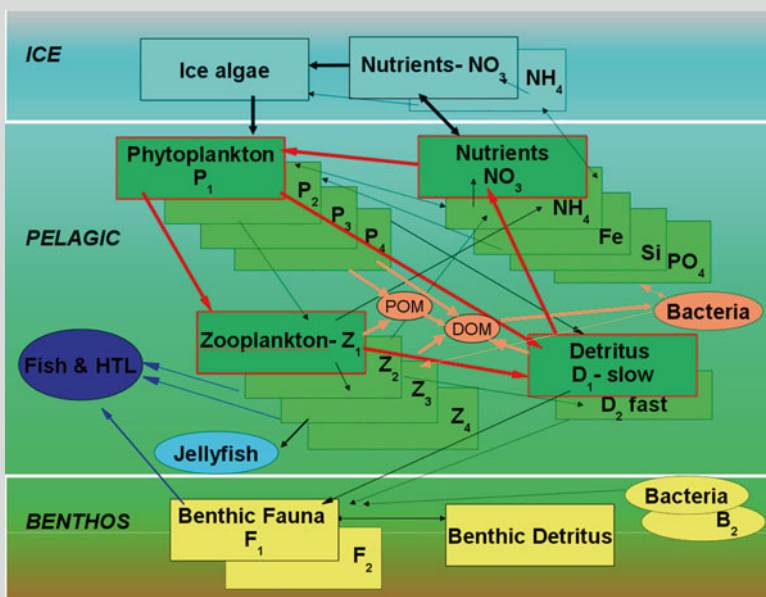


Fig. 12.1 Simplified schematic of ecosystem model components with multiple layers of complexity. The simplest NPZD (Nutrient, Phytoplankton, Zooplankton, Detritus) model as used in some ESMs; e.g., The Canadian Earth System CanESM1.5 (discussed in Sect. 12.10) is indicated by red frames and arrows which show processes linking compartments. Increased complexity is displayed by multiple nutrients (NO_3 , NH_4 , Fe, Si, PO_4), phytoplankton (P_1 , P_2 , P_3 , P_4) and zooplankton (Z_1 , Z_2 , Z_3 , Z_4) functional types, and detritus (D_1 , D_2), as well as additional components for ice algae and benthic communities, fish and higher trophic levels (HTLs), dissolved and particulate organic matter (DOM, POM), and bacteria. Links within levels of higher complexity are only drawn indicatively and do not represent the full extent necessary to model a real ecosystem

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Box 12.1: (continued)

is indicated by red frames and arrows that show processes linking compartments. Increased complexity is indicated by multiple boxes for N, P, Z, and D, as well as multiple arrows representing interactions and dependencies. (In text, subscripts are usually used to denote the number of compartments; e.g., $N_3P_2ZD_3$ denotes three N, two P, one Z, and three D compartments).

Numerically, temporal changes in model compartments are expressed by conservation equations fixed in space. There are several basic transfer functions (or processes) to consider: phytoplankton response to light, phytoplankton uptake of nutrients, zooplankton grazing, and loss terms due to death, excretion, predation, and sinking. Several functional forms for each process have been used, ranging from simple linear responses to nonlinear forms. A thorough description of modeling microbial foodwebs would extend over many pages and go beyond the scope of this chapter. Instead, we refer the reader to literature reviews that discuss different aspects and numerics of biogeochemical modeling, model components, and equations, as well as parameterizations for ecosystem processes and biogeochemical interactions (e.g. Tett 1987; Davidson 1996; Gentleman 2002; Vichi et al. 2007; Hood and Christian 2008).

Model differential equations require the definition of an initial state, which is based on available observational data. The basic model unit used is typically mmol N m^{-3} since nitrogen is limiting to PP in the oceans, and in the Arctic specifically (Tremblay and Gagnon 2009).

include explicit phytoplankton and heterotrophic organisms; the simplest such model is a nutrient-phytoplankton-zooplankton (NPZ) model. Biogeochemical models have been used for several decades in an attempt to explain, analyze, and predict what we can only sparsely measure. With their ability to extend over spatial and temporal scales far beyond what we can observe, models are useful tools in scientific research.

In this chapter, we present a synthesis of biogeochemical model development within PAR ranging from one-dimensional (1-D) and high-resolution regional, to global earth system modeling. The choice of an appropriate model is determined by the questions being asked and the data available. Validation is a large part of model development and evaluation, and is discussed in more detail in Box 12.2. With this biogeochemical model synthesis, we address the ability of dynamic modeling tools to help understand the impacts of climate change and to explore physical-chemical-biological interactions within PAR. We will discuss several examples of PAR modeling studies and will point to knowledge gaps and future research needs.

Box 12.2: Validation of Biogeochemical Models

In view of the growing human effect on the ocean and the increased interest in understanding ocean biogeochemistry (e.g., Doney 2010), the purpose of coupled biological/physical models goes beyond information synthesis and numerical experimentation. Marine system models are increasingly used to enable cost analyses, to predict outcomes of management choices, and eventually to support high-stakes decision making (e.g., Stow et al. 2009). Naturally, a model's sensitivity and skill must be tested and measured to enable us to understand model capabilities and to be confident in ecosystem projections. With the increasing complexity of physical and biogeochemical models, this is no easy task.

Model intercomparisons show that model skill is not necessarily associated with model complexity or model type, nor is it possible to identify one single model that is most skilled according to all criteria (Friedrichs et al. 2009). Different statistical quantities (i.e., skill metrics) may capture different aspects of model performance, and a thorough assessment of model skill may require use of multiple types of skill metrics simultaneously (Stow et al. 2009). The equations within a model represent hypotheses about how the system works; they might not be correct. Similarly, observations provide an approximation of the truth, limited by measurement uncertainties as well as under-sampling in space and time. Stow et al. (2009) state that a model starts to exhibit skill when the observational and predictive uncertainty halos overlap; the ideal case is a complete overlap.

More specifically for ecosystem applications, Fennel (2009) writes that the skill of physical-biogeochemical ocean models, which include truncated food webs, depends on how effectively unresolved processes are parameterized in terms of resolved processes. An important aspect is the mixture of time scales at different trophic levels of the food web. Since truncated models are still the only available choice for many biogeochemical model studies, we require a thorough understanding of potential error sources.

Stow et al. (2009) highlight several graphical techniques that are useful for assessing model skill, including simple time series plots of observations and model predictions, bivariate plots, and misfit representations as well as quantitative metrics like correlation coefficients, root mean squared error, bias, model efficiency, etc. Diagrams summarizing multiple aspects of model performance in a single figure have begun to appear, especially in the coupled model literature, as a convenient way to quantify and communicate model performance. Most common is likely the Taylor diagram, which provides summary information about how the linear correlation coefficient and the

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Box 12.2: (continued)

variance comparisons each contribute to the unbiased root mean square difference (RMSD) (Taylor 2001). Jolliff et al. (2009) point out that in certain cases the Taylor diagram provides an incomplete picture, because it often yields no information about other aspects of model performance such as the bias (the comparison of mean values) or the total RMSD (a metric for overall model and data agreement). Hence they introduce the target diagram, a Cartesian coordinate plot providing summary information about how the magnitude and sign of the bias and the pattern agreement (unbiased RMSD) each contribute to the total RMSD magnitude. While the purpose of both the Taylor and target diagrams is to compactly summarize statistical quantities to aid in model skill assessment, Jolliff et al. (2009) suggest that target diagrams may be better suited for ocean ecosystem modeling because they better summarize the overall agreement between model and data.

Since many ecosystem models are highly complex, the outputs from such models are highly multivariate. Allen and Somerfield (2009) explore multivariate approaches for skill assessment (e.g., principal component analysis or vector correlations). These allow the simultaneous examination of the ways in which numerous variables vary in relation to each other, both spatially and temporally. Doney et al. (2009) point out that the multivariate analyses of model dynamics may be particularly useful when the model data skill assessments are applied to fully-coupled climate or earth system models (e.g., Doney et al. 2006; Schneider et al. 2008; Orr et al. 2005). In global models, it is especially challenging to replicate observations from local time-series because there are many subgridscale processes and representation issues that tend to confound the comparison. Persistent physical biases in coupled models propagate into the ecological/biogeochemical mean state and seasonal cycle. Because the coupled ocean–atmosphere models generate their own internal climate variability, assessment of simulated interannual-to-decadal variability can only be done statistically, not directly (Doney et al. 2009). It has been stated repeatedly that the success of the biological and chemical simulations are highly dependent on the hydrodynamic fields and hence require a high-quality underlying physical circulation model (e.g., Matear and Holloway 1995; Doney et al. 2009; Smith et al. 2009). It is, therefore, essential to include physical model biases and errors in ecological and biogeochemical model data assessment.

Cross-validation and Monte Carlo simulation have been suggested as other options to test model skill and uncertainty or, more specifically, interpolative and extrapolative skill of marine ecosystem models (e.g., Hemmings et al. 2004; Friedrichs et al. 2007; Smith et al. 2009; Wallhead et al. 2009). These methods

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allow predictive objectives to be specified, including how much interpolation and extrapolation is required of the models. Skill assessment is then focused on estimating the skill function using skill metrics. Monte Carlo type approaches have also been used to assess ecosystem model sensitivity. Such approaches usually involve defining a domain of possible model input parameters, randomly selecting parameter inputs given the specified domain, performing deterministic computations using these inputs (running the model), and finally aggregating and analyzing the results to assess model variance and determine a statistical relationship between the model input parameters and output (e.g., Megry and Hinckley 2001; Gibson and Spitz 2011). Gibson and Spitz (2011) suggest that sensitivity analysis should be considered a prerequisite for any new marine ecosystem model. In addition to providing a measure of uncertainty to ecosystem projections, it provides helpful information during model tuning as well as insight into expected behavior of the ecosystem model under alternative physical conditions or in different regions. Sensitivity analysis can also indicate where further field and laboratory studies should be focused. This is especially true in regions where data access is limited and hence skill assessment via model data intercomparison is biased due to seasonally- or regionally-focused measurements.

In all skill assessment approaches, a major requirement is data accuracy and availability. It is essential that observations represent the true state of the system with acceptable accuracy and precision, and provide a reasonable representation of model time and space scales. Unfortunately, suitable coherent datasets are still very limited, especially in polar regions, which are within limited satellite range and frequently inaccessible for a large part of the year. We hope that the current expansion of ocean and coastal observing systems, along with improvements in satellite data product quality and advanced data management, will help to address this issue. For the PAR region, the BEST/BSIRP and the DBO (Grebmeier et al. 2010) are good examples of such improvements.

12.2 PAR Characteristics Particularly Relevant for Biogeochemical Modeling

Seasonal ice cover, wide shallow shelves, extreme environmental conditions, and extensive advection create unique biophysical relationships in the spatially and temporally dynamic PAR system. Sea ice extent can vary by hundreds of kilometers from year to year; differences of up to about 25 % have been observed based on

Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager (SSM/I) data in March and September, respectively (Frey et al. 2014, this volume). As the ice melts in spring, increased light and salinity-induced stabilization of the water column initiate the phytoplankton bloom (Sakshaug 2004) that follows the retreat of the marginal ice zone. These waters may be too cold for zooplankton to be abundant, resulting in low levels of grazing, and much of the phytoplankton biomass is left to sink to the benthos undigested (Bluhm and Gradinger 2008). Phytoplankton biomass from an open water and later-occurring bloom is more often recycled by grazers because the water column is warmer then, thus, the food source for the benthos is reduced. Recent reductions in sea ice have resulted in a shift of the subarctic pelagic-dominated ecosystem typical of the southeastern Bering Sea northward into the northern Bering Sea (Grebmeier et al. 2006, 2010). Are existing ecosystem models capable of simulating these temporal and spatial shifts that determine benthic or pelagic dominance? Capturing the timing of ice-associated and open water blooms in a model is critical for simulating the resulting food web structure.

More than half of PAR is composed of very shallow shelf seas. On these arctic shelves, sea ice, benthic, and pelagic systems are intimately linked. More than 60 % of Chukchi Sea primary production (PP) is available for local export to the benthos or offshore transport to the adjacent basin (Campbell et al. 2009). Nutrients regenerated from the benthos can fuel pelagic production when distributed upward through re-suspension processes and mixing events. A holistic modeling study of arctic warming impacts on biological productivity and biogeochemical cycling in PAR thus calls for a benthic component, including grazing by the organisms that feed on the benthos.

Implementation of a sea ice ecosystem component is also important for PAR, especially in the Chukchi Sea, where sea ice is the prime source of production and algal biomass during the spring (Gradinger 2009). Jump-starting of the phytoplankton bloom by sea ice algae is another potential link between sea ice and pelagic systems, just as entrainment of phytoplankton into the sea ice in autumn may “seed” the spring ice algal bloom (McRoy, personal communication 2006; Werner et al. 2007). Model studies can help to elucidate these significant roles and assist us to zero in on the short window of opportunity that is available for observing these key connections.

Much of the PAR system is governed by advection (Carmack and Wassmann 2006). Circulation, currents, and flow structures (e.g., eddies, fronts) can transport and/or concentrate biomass and nutrients and cause *hot spots* for grazers at all trophic levels. For example, elevated Euphausiid abundance in the fall at Barrow, Alaska has been explained by transport from the northern Bering Sea and by southerly winds (Berline et al. 2008). Movements and other changes in flows due to changes in climate may exert a disproportionate influence on ecosystems, species distributions, and community structure. Hence, accurate high-resolution modeling of physical properties is highly important in modeling the biogeochemistry of PAR and will be addressed in Sect. 12.9.

12.3 A Brief History of PAR Biogeochemical Models

One of the first numerical modeling studies of the planktonic ecosystem in PAR focused on the Bering Strait and was performed as part of the Inner Shelf Transfer and Recycling (ISHTAR) program. The three-dimensional (3-D) ecohydrodynamic model developed at the University of Liege was adapted to the northern Bering Sea (Nihoul et al. 1993) to assess system variability in summer. Reconstructions of the first available data fields from ISHTAR by inverse modeling showed the strong influence of major circulation features on the biogeochemical cycles and ecosystems (Brasseur and Haus 1990). Nihoul et al. (1993) found seasonal patterns of primary and secondary production to be dominated by the main water mass transports, upwelling, and fronts (e.g., the strong upwelling of nutrients along the east Siberian coast was shown to sustain the biology of the region). Maxima in their simulated PP patterns appeared first along the Anadyr Stream front, and later farther north in the Chukchi Sea. The measured PP pattern is similar, although the absolute production appears to be lower in recent years compared to previous decades (Lee et al. 2007; Lee unpublished data).

Using 3-D circulation, plankton, and benthos models, Walsh et al. (2004) explored the effects of interannual changes in ice cover and water motion on carbon and nitrogen cycling within the Chukchi and Beaufort seas. Fall case studies were simulated with the analysis focusing on carbon dioxide (CO₂) cycling. Walsh et al. (2005) used the same ecological model to explore the relative roles of light and nutrients in controlling year-round production within the Chukchi and Beaufort seas. They developed seasonal carbon budgets by making use of extensive field data obtained during 2002, a year signified by the lowest ice cover in 20 years. (Since then the ice cover has decreased even further, with a minimum in 2012). Their analysis of biogeochemical processes in light-limited and nutrient-limited regimes (i.e., end of summer in open seas, and under extensive ice cover in the nutrient-poor upper waters of the Canadian Basin) provided insights into the possible consequences of future climate changes at these high latitudes. They concluded that increased light availability from future ice retreat would not benefit the shelf food web or increase carbon sequestration in the Chukchi and Beaufort seas unless additional nutrients became available.

Sea ice ecosystem models have been applied in PAR only recently. They have been used to investigate environmental controls and variability of sea ice PP and ice algal biomass. For a few western Arctic locations where sea ice algal dynamics and habitats have been rather well characterized, ice algal production has been simulated in 1-D (Lavoie et al. 2005); most often coupled to biological production models in the water column (Jin et al. 2006a, 2007, 2009; Lavoie et al. 2009, 2010; Lee et al. 2010; Pogson et al. 2011). The Jin et al. sea ice biological model has been coupled to a global dynamic sea ice model to assess large-scale variability of ice PP and algal biomass (Deal et al. 2011). All of these sea ice ecosystem models are based on the first ice algae model developed by Arrigo et al. (1993) for sea ice in Antarctica. The Arrigo et al. model contains a detailed treatment of

internal ice light and nutrient fluxes. However, ice in the Arctic is different (Dieckmann and Hellmer 2003). For example, there is more multi-year ice (MYI) and less extensive flooding in arctic ice; therefore, nutrients are more limited for algal communities close to the ice surface, while the bottom 2–3 cm are the most favorable sub-habitat for ice algal blooms (Gradinger et al. 2005 and references therein; Lee et al. 2010). The primary source of nutrients for ice algae is the mixed layer, and algae accumulation at the base of the ice will thus be greatly affected by factors that govern this nutrient exchange.

During the most recent International Polar Year (IPY March 2007 to March 2009), a large effort was expended to improve simulations of PAR ecosystem dynamics by adding ice and benthic biology, achieving higher resolution to better resolve features important to the biology, looking at longer timescales to understand long-term dynamics, examining coupling within earth system models (ESMs), and working on future projections.

12.4 Modeling PAR in 1-D: Introduction and Locations

Before proceeding to fully 3-D ecosystem models, it is often useful to first develop and test a coupled ice-ocean ecosystem model in a 1-D context. Generally, 1-D models are used for detailed diagnostic and prognostic modeling and process studies. In PAR they have been applied at specific locations to investigate the impacts of shrinking sea ice cover, increasing freshwater flux, and shifting climate regime on primary and export production. The vertical 1-D model structure simplifies analysis of model results and allows us to examine the relative importance of physical processes (i.e., water column stratification, mixing, snow melt, snow and sea ice thickness, freshwater runoff). A fast-running 1-D model can be a testing tool for developing parameterizations of complex biogeochemical or physical processes that affect ecosystem dynamics. Time series observations at specific sites allow for extensive testing and validation of 1-D models. Observations might include laboratory studies or mesocosm experiments, which are by design 1-D. Well-designed 1-D model experiments can provide a first take on addressing science questions about ecosystem responses to changes in temperature, stratification, seasonal ice zones (SIZs), and acidification associated with current environmental transitions.

Figure 12.2 includes PAR locations that have worked well for 1-D ice-ocean ecosystem modeling investigations: the outer shelf region of the Canadian Beaufort Sea (Lavoie et al. 2009, 2010), the National Oceanic and Atmospheric Administration (NOAA)/Pacific Marine Environmental Laboratory M2 mooring site in the Bering Sea SIZ (Jin et al. 2007, 2009; Gibson and Spitz 2011), the multi-year pack ice in the Canadian Basin (Lee et al. 2010), and the landfast ice zone in the Chukchi shelf (Jin et al. 2006a). Ideally, 1-D modeling sites are chosen because (1) they are representative of a particular region, (2) intensive biophysical time series measurements are available, and (3) it can be reasonably assumed that horizontal advection and diffusion effects are negligible.

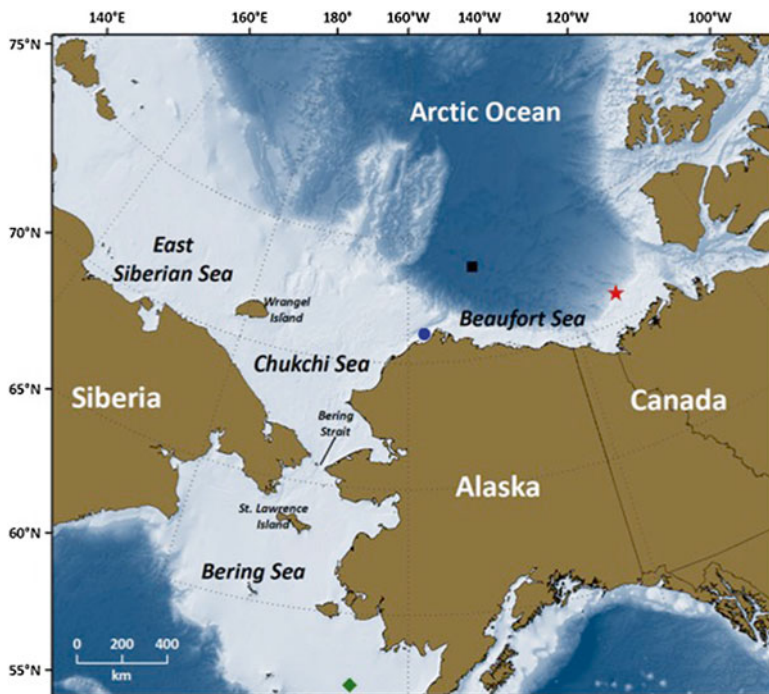


Fig. 12.2 Map of PAR, defined as the marine region extending from north of St. Matthews Island to the Beaufort Sea and the Arctic Ocean. Symbols denote locations where 1-D ice-ocean ecosystem models have been applied (*green diamond*: M2 mooring site in SI2 of the Bering Sea; *blue dot*: landfast ice zone of the Chukchi shelf; *black square*: multi-year pack ice in the Canadian Basin; *red star*: outer shelf region of the Canadian Beaufort Sea)

12.5 Results from 1-D Modeling Studies

Lavoie et al. (2005) used a detailed treatment of the boundary layer between the upper ocean and the sea ice bottom to understand the temporal patterns observed in ice algae. In the model ice algae are assumed to be limited by silicic acid. When melting occurs at the ice bottom, ice algal cells are expelled from the ice into the mixed layer at a rate proportional to the ice melt rate. Bottom ice growth and melt, which are affected by heat and salt fluxes between the ice and the ocean, were shown to be important factors for ice algae biomass accumulation at the base of the ice.

Lavoie et al. (2009) coupled the ice algae model (Lavoie et al. 2005) to a pelagic N_3PZD_3 model (see Box 12.1) to simulate the seasonal cycle and to study the physical processes controlling primary and export production on the Beaufort Shelf. In a continuing study, output from the Canadian Centre for Climate Modeling and Analysis (CCCma) coupled global climate model (CGCM2) was used to force this 1-D model to project future PP for the years 2041–2060 and 2081–2100 (Lavoie et al. 2010) (Fig. 12.3a). Their goal was to investigate the

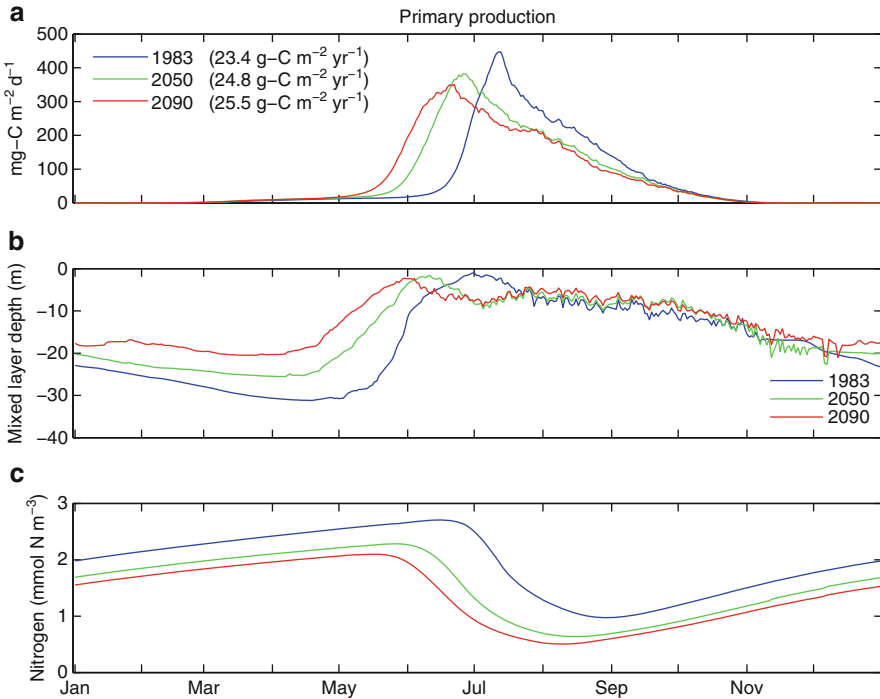


Fig. 12.3 Simulated average annual cycle for each 18-year period for the outer shelf of the Canadian Beaufort Sea: **(a)** depth-integrated primary production (phytoplankton and ice algae), **(b)** mixed layer depth, and **(c)** nitrogen concentration in the top 40 m (Figures from Lavoie et al. 2010)

impacts on PP of increased freshwater runoff and longer ice-free season. It was found that the subsurface bloom is the most important current contributor to total annual PP, although the contribution of the surface bloom can be relatively important in some years, when conditions in the previous fall lead to higher nutrient replenishment in the mixed layer by wind and winter convective mixing (Melling and Moore 1995). The simulations suggest that by mid century, the relative importance of the phytoplankton surface spring bloom compared with the subsurface bloom will have decreased further. In the model this is shown to be a result of increased stratification (due to increased runoff) that reduces the depth of winter convective mixing (Fig. 12.3b, c). Overall, the projected PP increase is modest (<10 %) by 2090 (Fig. 12.3a) and results essentially from a lengthening of the subsurface bloom. Lavoie et al. (2010) suggest that the increasing importance of the subsurface versus surface blooms could lead to a greater underestimation of chlorophyll a (chl a) concentration and PP by satellite sensors, which cannot detect subsurface chl a. Their simulations also project a decrease in the future relative importance of the ice algae contribution to total PP due to the decrease in the length of the growing season linked to earlier snow and ice melt.

The effect of stratification on the projected Beaufort Sea shelf PP could be representative of other arctic shelf seas affected by high freshwater runoff such as the Laptev and Siberian seas. However, each shelf is unique, and extrapolation of results from one shelf to another requires caution (e.g., Carmack et al. 2006). In the Bering Sea a decrease in PP is projected due to a stratification-dependent decrease in nutrient supply (see Sect. 12.9.2). However, this might not hold true for shelf seas where production is already limited more by nutrients than by light. A comparison of surface PP in the Beaufort Sea between the years 1998–2002 and 2007, a year of very low ice extent, shows little variation compared to other arctic regions (Fig. 12.2e in Arrigo et al. 2008). However, entrainment of nutrients into the surface layer through ice edge upwelling (Mundy et al. 2005), eddies (Tremblay et al. 2008), or increased wind mixing could play a more important role in the future.

Results from Jin et al. (2009) multi-species model indicate that the ecosystem in the Bering Sea SIZ responds to climate regime shifts by a switch in the dominant phytoplankton group. Their physical model was forced by sea surface wind, heat and salt fluxes, oceanic tides, and sea ice data from Hadley Center (monthly) before 1978 and SSM/I (daily) after 1979. Their sea ice algae model has four compartments, including ice algae and three nutrients, nitrate + nitrite, ammonium, and silicate. The ocean ecosystem model is $N_3P_3Z_3D$. Remotely-sensed sea ice concentration data were used to approximate the sea ice thickness in the model, as in Jin et al. (2007). Simulated dominant phytoplankton switched from ice-associated cold water species to warm water species, and zooplankton abundance increased coinciding with changes in the timing and vertical distribution of lower trophic level production after the Pacific Decadal Oscillation index reversal in 1977. Before 1977, most of the simulated annual PP was from early blooms in icy cold water. Because grazing was light, much of the assimilated carbon was transferred to the benthos. After 1977 open water phytoplankton blooms prevailed in warmer water, supporting high pelagic secondary production and zooplankton biomass.

Lee et al. (2010) applied the Jin et al. (2007) model to three sites in PAR where ice core observations were conducted (Lee et al. 2010). The sites included one clean sediment-free site (Chukchi) and one sediment-rich site (Beaufort), both in landfast sea ice offshore Barrow, plus one oceanic Ice Exercise site. Comparisons among model sites revealed that strong light attenuation by trapped sediments controlled ice PP. Thicker ice at the oceanic site also attenuated light, delaying the peak in ice algal biomass, and maximum production reached only 10 % of that at the Chukchi site because of nutrient limitation.

A 1-D version of the Bering Ecosystem Study (BEST)-NPZ ecosystem model (Sect. 12.8) was used for a sensitivity analysis to gain insights into the relative importance of biological vs. physical model parameters (Gibson and Spitz 2011). Sensitivity studies are critically important because reliable model projections require model validation, an understanding of model sensitivities, and a measure of model uncertainty. Box 12.2 introduces many of the currently applied methods. Working with the BEST-NPZ model, Gibson and Spitz (2011) used a Monte Carlo-type approach to address uncertainty in model forecasts. Their 1-D model was run iteratively with randomly selected biological inputs and environmental conditions (including temperature, salinity, ice cover, and light) that were based on triangular

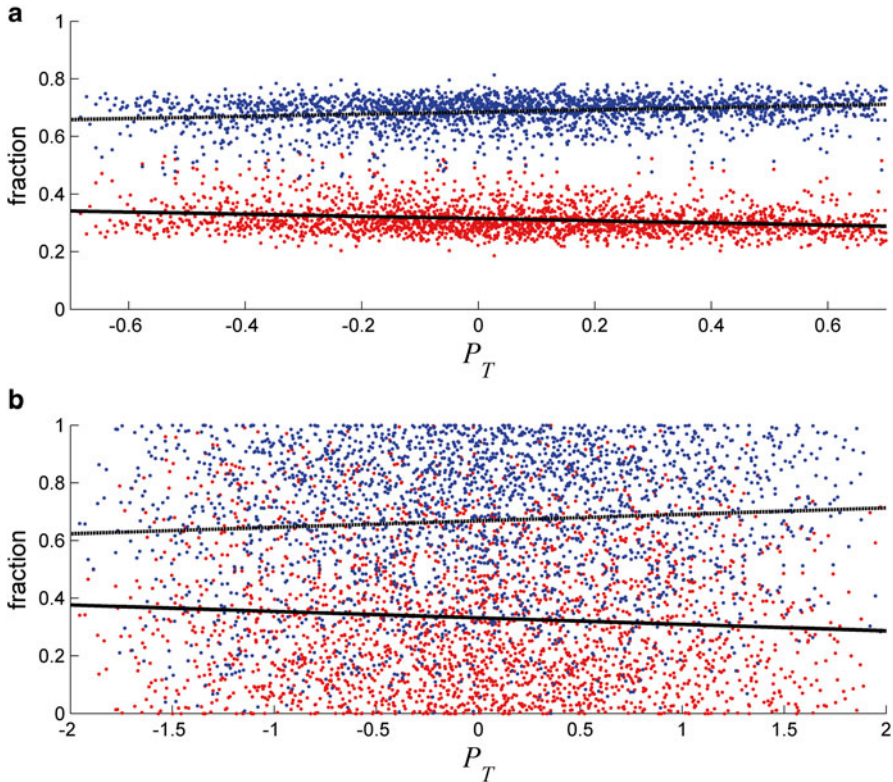


Fig. 12.4 Fraction of secondary production generated by small zooplankton (microzooplankton and small copepods; red) versus large zooplankton (large copepods and euphausiids; blue) for (a) Ex. I, in which biological parameters were varied by $\pm 10\%$ of the baseline values and physical parameters were varied within -0.7 – 1 SD and (b) Ex. IV, in which biological parameters were varied within best guesses for their actual range, and physical parameters were varied within ± 2.0 SD. P_T is temperature (Figure from Gibson and Spitz 2011)

probability distributions. Baseline values for each biological parameter were estimated based on literature reviews and on input from BEST-Bering Sea Integrated Ecosystem Research Program (BSIERP) field scientists. In their first experiment (Ex. I), the biological parameters varied within $\pm 10\%$ of the baseline values. In their fourth experiment (Ex. IV), the parameter range expanded to within their “best guess” of minimum and maximum values or, if the range was unknown, to $\pm 60\%$ of the baseline value. Physical parameters varied within -0.7 and 1.0 SD in Ex. I and within ± 2.0 SD in Ex. IV. Results suggest that the fraction of total secondary production attributable to small zooplankton (small copepods and microzooplankton) vs. large zooplankton (large copepods and euphausiids) will increase with increasing water temperature, indicating a shift to a longer pelagic food web (Fig. 12.4a). The relationship holds even with a broader range of parameter variability (Fig. 12.4b).

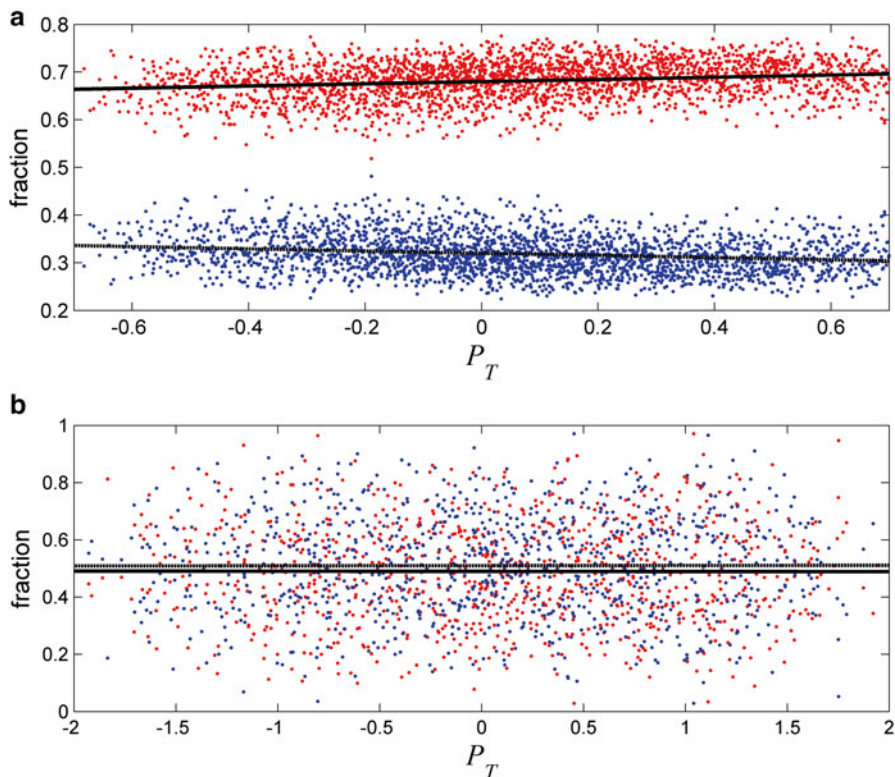


Fig. 12.5 Fraction of secondary production by mesozooplankton (small copepods and large copepods and euphausiids; *red*) versus benthic infauna (*blue*) for (a) Ex. I and (b) Ex. IV. For Ex. descriptions see Fig. 12.4 caption. P_T is temperature (Figure from Gibson and Spitz 2011)

Gibson and Spitz (2011) also ranked parameters using a least squares linearization, a multiple regression between the parameters' deviation from the mean and the model output. When they varied each parameter by only a small amount, they found that zooplankton grazing rate and efficiency, light, temperature, and ice thickness and timing were as important as benthic biomass and benthic production. But when they varied parameters within their "best guess", benthic grazing rate, benthic half saturation uptake rate, benthic assimilation efficiency, and benthic respiration rate were the most important parameters. The range implemented for the benthic parameters was relatively broad due to limited information in the literature. As a result, while benthos appears sensitive to temperature increases (Fig. 12.5a) when the parameter range is small, the relationship is not clear when the biological range is broader (Fig. 12.5b). The biological variability swamps the physical signal, highlighting the importance of narrowing down some of the benthic parameters.

12.6 Introduction to High-Resolution Regional and Pan-Arctic Models

High-resolution models provide us with tools that we can use to address science questions about biogeochemical responses to transitions in terrestrial, gateway, and shelf-to-basin fluxes, as well as to changes in ice cover. They also allow us to make first estimates of the consequences of these responses for higher trophic levels (HTLs) and socioeconomic activities. We include here models with grid cells of $\frac{1}{4}$ degree (~ 25 km) resolution or less. A 25 km resolution model barely resolves the Bering Strait, which is 50 km wide at its narrowest and provides heat, nutrients, Pacific fauna, and $\sim 40\%$ of the total freshwater input to the Arctic Ocean (Woodgate and Aagaard 2005). Arctic models that have a boundary at the Bering Strait usually prescribe boundary conditions from climatology or, if available, coarser-resolution global models. Coarse-resolution global circulation models (GCMs) usually artificially widen the strait to allow two-way flow. The main advantage of high resolution is the ability to resolve advective processes and spatial details such as smaller-scale circulation, currents, orographic features, flow structures, and ocean eddies that contribute to mixing and transport.

Below, recent high-resolution modeling studies in the PAR are presented, examining how climate-induced changes in physical forcing (e.g., temperature) and sea ice loss may alter productivity. These modeling studies usually involve evaluating mean fields, integrals, seasonal cycles, and interannual variability. In addition, sensitivity studies provide insights into ecosystem behavior in a changing climate.

12.7 Primary Productivity: Modeling the Present and Recent Past

The coupled 3-D pan-Arctic biology/sea ice/ocean model by Zhang et al. (2010) was developed to investigate the impact of declining arctic sea ice on the marine planktonic ecosystem from 1988 to 2007. Their model's horizontal resolution averages 22 km and there are 30 vertical levels of different thicknesses as small as 5 m in the top 30 m. The biological model is a modified version of the Kishi et al. (2007) 11-component lower-trophic-level model adapted to the Arctic Ocean. The physical model results are in good agreement with observed downward trends in summer sea ice extent and thickness (Rothrock et al. 1999, 2008; Stroeve et al. 2008). In the model, these changes in sea ice led to an increase in both surface and subsurface PP, mainly in the seasonally and permanently ice-covered Arctic Ocean. The general upward trend in PP was attributed to increasing photosynthetically active radiation and nutrient availability (mainly due to strengthened upwelling), and surface water temperature in the Arctic Ocean peripheral seas. Compared to in situ observations, the model was basically able to capture the timing of the spring bloom in the seasonally ice covered waters of the Chukchi/Beaufort seas. As mentioned earlier, Lavoie et al. (2010) suggest that only the subsurface bloom in the Beaufort Sea will increase due to the reduction of nutrient replenishment to the mixed layer during winter. Models often

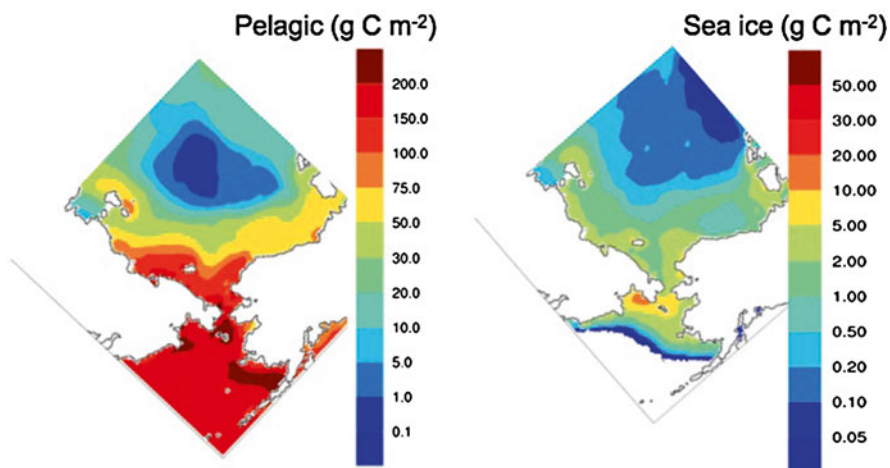


Fig. 12.6 Modeled annual primary production in the ocean upper 100 m (*top left*) and sea ice (*top right*), averaged over 1995–2006, from the study of Jin et al. (2012)

disagree and the differences (e.g., processes included, spatial domain, time period) need to be kept in mind when interpreting, contrasting, and utilizing model results.

Jin et al. (2012) coupled an ice ecosystem model to the global POP-CICE (Parallel Ocean Program-Los Alamos National Laboratory Sea Ice Model) with an open-ocean pelagic ecosystem model (Moore et al. 2004). The global domain avoids open boundary settings in the Bering Strait. Horizontal resolution ranges from 20 to 85 km, averaging 40 km north of 70°N . There are 40 vertical layers ranging from 10 m in the surface to 250 m below 2,000 m. The sea ice algal ecosystem component was coded into CICE (Hunke and Lipscomb 2008; Hunke and Bitz 2009) and first tested in CICE-standalone with a mixed-layer ocean model (Deal et al. 2011). Jin et al. (2012) examined the simulated PP in arctic sea ice and ocean waters for the model period 1992–2007 and found that annual PP increased from $305 \text{ Tg C year}^{-1}$ in 1998 to $550 \text{ Tg C year}^{-1}$ in 2007. Annual mean ice PP was highest during low ice years from 2005 to 2007. In the Zhang et al. (2010) modeling study, total PP increased by 50 %, from $456 \text{ Tg C year}^{-1}$ in 1988 to $682 \text{ Tg C year}^{-1}$ in 2007. These PP values are comparable to satellite derived estimates of $375 \text{ Tg C year}^{-1}$ in 1998 and $485 \text{ Tg C year}^{-1}$ in 2006 (Pabi et al. 2008).

Simulated annual PP in the ocean (upper 100 m) and sea ice from 1995 to 2006 in PAR by Jin et al. (2012) are shown in Fig. 12.6. The ocean production (top left) reveals high productivity in the Bering Sea ($>150 \text{ g C m}^{-2} \text{ year}^{-1}$). The Chukchi Sea production downstream of the Bering Strait ranges from $150 \text{ g C m}^{-2} \text{ year}^{-1}$ at the Bering Strait down to about $50 \text{ g C m}^{-2} \text{ year}^{-1}$ along the shelf break, similar to the range of $55\text{--}145 \text{ g C m}^{-2} \text{ year}^{-1}$ observed during 2002–2004 (Lee et al. 2007; Rho and Whitledge 2007). Arrigo et al. (2008) suggest an annual production rate (mean 1998–2002) of about $40 \text{ g C m}^{-2} \text{ year}^{-1}$ for the Chukchi Sea. The production in the perennial-ice-covered central Arctic is much lower; less than $1 \text{ g C m}^{-2} \text{ year}^{-1}$ in some regions. The modeled annual ice algal production (Fig. 12.6, top right) is

around $2 \text{ g C m}^{-2} \text{ year}^{-1}$ within the observed ranges of $0.7\text{--}5 \text{ g C m}^{-2} \text{ year}^{-1}$ offshore Barrow in the Chukchi Sea (Jin et al. 2006a). To investigate the decadal change of ocean PP from 1990s to 2007, the average annual PP in the ocean upper 100 m for low ice years (2002, 2003, 2005–2007) was subtracted from model results for high ice years (1998–2001, 2004). The differences indicate a northward shift in ocean PP with a decrease in the Bering Sea and an increase in the more northern shelf and PAR SIZ (Jin et al. 2012).

The recent Arctic Ocean biogeochemical model intercomparison by Popova et al. (2012) includes the Jin et al. (2012), Zhang et al. (2010), and three other coupled physical-biological models: Yool et al. (2010), Dupont (in review); and Popova et al. (2010). The study compares and contrasts the substantial variability in biogeochemical model structure and complexity, and the differences between the physical models (e.g., resolution, initial and boundary conditions, sea ice sub-model). Results show that the models broadly reproduce the present-day large-scale distribution pattern of total annual PP across the Arctic Ocean in agreement with satellite-derived (Arrigo et al. 2008) and in situ data, including the high values of observed PP in the Chukchi Sea (Carmack et al. 2006). However, the models disagree when it comes to the physical factors controlling PP. The study focuses on winter mixing as the main mechanism controlling basin-scale patterns of nutrient supply. An important conclusion is that the models' vertical mixing, in particular winter mixing, needs to be improved before they can predict future annual Arctic Ocean PP under continued sea ice retreat.

In addition to these pan-Arctic biogeochemical models, Slagstad et al. (2011) have recently extended their Barents Sea ecosystem model (Wassmann et al. 2006) to the Arctic domain. For many years, their ecosystem model consisting of 13 state variables stood out as the most validated and comprehensive physical-biological model applied within the Arctic. As with the models above, high PP in the Chukchi Sea is reproduced, but they also test the effect of retreating sea ice in the forthcoming century on primary and secondary production. One experimental outcome projects the expansion of the typical Arctic zooplankton species *C. glacialis* into the Chukchi and East Siberian Seas.

12.8 Regional Modeling Focusing on the Bering and Chukchi Seas

In the western Arctic, the most comprehensive marine ecosystem numerical modeling effort to date is part of the National Science Foundation (NSF)-supported BEST and the North Pacific Research Board-supported BSIERP. The BEST-BSIERP partnership is working to develop and implement a suite of integrated climate, physical oceanography, lower and upper trophic level ecosystem, and economic models. The ultimate objective is to produce a series of multi-year forecasts for the eastern Bering Sea ecosystem using alternate climate projections. The 15-component BEST-NPZ ecosystem model is a modified version of the Global

Ocean Ecosystems Dynamics model (Hinckley et al. 2009). Its domain includes the entire Bering Sea. The model has been designed for coupling with a HTL fish model (Forage-Euphausiid Abundance in Space and Time) under development through the BSIERP research program and has both a sea ice ecosystem (modified from Jin et al. 2006a) and a benthic component. Inclusion of the benthic submodel with explicit benthic processes, infauna, and detritus makes this model unique among PAR ecosystem models, thus enabling studies of the partitioning of organic carbon between pelagic and benthic systems.

Using the Coupled Ice Ocean Model (CIOM; Wang et al. 2009 and references therein; Hu and Wang 2010) and the Physical Ecosystem Model (PhEcoM; Wang et al. 2003; Jin et al. 2006b), a 3-D coupled CIOM-PhEcoM was developed and implemented in the Bering and Chukchi seas. Figure 12.7 shows CIOM-PhEcoM simulated chl a, and remotely-derived chl a (SeaWiifs) on April 29, 2008 and June 28, 2008. The model simulations are in general consistent with observed features, indicating that their ice-ocean-ecosystem model captures some of the important dynamics of this complex coupled system. For example, relatively high chl a concentrations (proxy for phytoplankton biomass) are apparent along the Bering Slope Current (BSC) in the daily snapshots of model results and observations. And, in the deep western Aleutian Basin, eddies or gyres (Hu and Wang 2010) entrain phytoplankton, in particular along the Kamchatka Current (Fig. 12.7a, b). Due to cloud cover, only a trace of high values is seen in the remotely-derived chl a observations along the BSC and Kamchatka Current. Chl a (Fig. 12.7c, d) and nitrate (not shown), indicate that after the sea ice has melted in late June, phytoplankton blooms in the Gulf of Anadyr and western Bering Strait are sustained by the nutrient-rich water of the Anadyr Current transiting northward into the Chukchi Sea.

12.9 Advancements in the Simulation of Physical Features

While ecosystem models are implemented in existing, usually well-established physical models, modelers are aiming for even higher resolution and more accurate representation of small-scale (<10 km horizontal) processes. So far, these kinds of improvements have mostly been achieved without a coupled ecosystem module. Even though adding ecosystem variables can help to pinpoint problems with physical parameterizations, the increase in computational resources often makes it more feasible to develop the physical model first. Eventually, the appropriateness of the physical model and its temporal and spatial scale will depend on the goal of the biogeochemical modeling effort.

A limited number of 3-D physical modeling studies have focused on the physical oceanography of the northern Bering and Chukchi seas (e.g., Overland and Roach 1987; Spaulding et al. 1987; Nihoul et al. 1993; Hermann et al. 2002; Hu and Wang 2008). These studies have proven useful in simulating the major circulation features of the region. However, they have been limited by low spatial resolution and/or small domains with lateral boundary conditions prescribed in close proximity to the

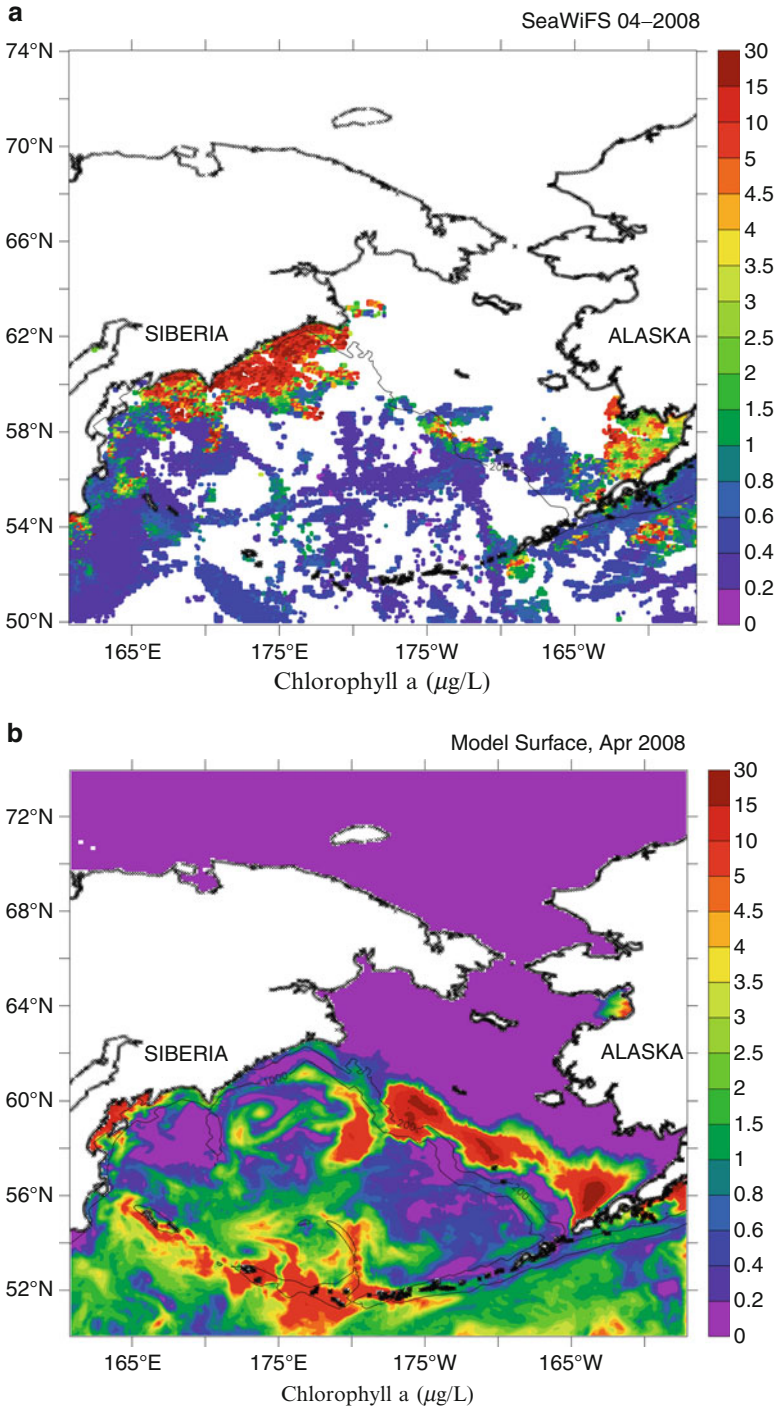


Fig. 12.7 (a) CIOM-PhEcoM simulated chl a, and (b) remotely-derived chl a (from the SeaWiFS) for April 29, 2008; and (c) CIOM-PhEcoM-simulated chl a, and (d) remotely-derived chl a for June 28, 2008. Units for chl a (color bar) are $\mu\text{g l}^{-1}$

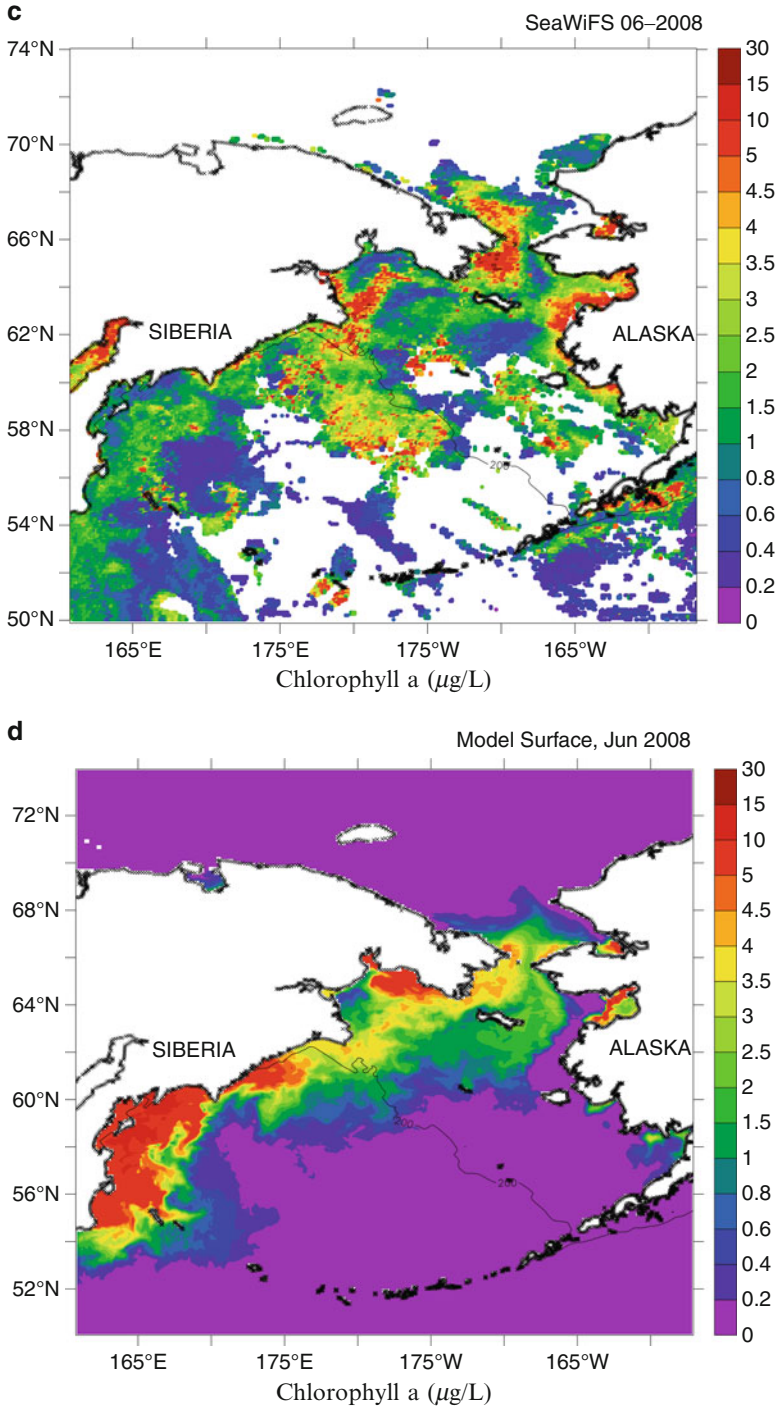


Fig. 12.7 (continued)

region of interest. In addition, these studies were integrated for only a short period of time (1 month to 1 year). Recent advancements in computing capability and updated bathymetry information have allowed the development of relatively high-resolution models, with pan-Arctic domains. In Chap. 7 of this book Clement Kinney et al. (2014) discuss volume transport and property fluxes through the Bering Strait, comparing several high-resolution models. The following subsections highlight examples from only one of these models (the Naval Postgraduate School Arctic Modeling Effort, NAME) and from an additional model for the Chukchi-Beaufort seas illustrating high-resolution capabilities related to biogeochemical modeling.

12.9.1 Gateway Fluxes

Flow through restricted passages such as the Bering Strait and in narrow currents such as the Anadyr and Alaska Coastal currents can significantly impact ecosystem dynamics, but are challenging to adequately resolve. Model resolutions on the order of kilometers are required. NAME uses a ~9 km ocean model that permits flow through the narrow straits and passages of PAR and realistically represents the coastal currents (Clement Kinney et al. 2009, 2014, this volume). NAME also resolves flow reversals that affect ice conditions in the central and eastern Bering Sea, which in turn affect nutrient and biomass transport through the Bering Strait.

The NAME 26-year (1979–2004) mean circulation in the northern Bering and Chukchi seas is shown in Fig. 12.8. Representing the narrow and shallow flow through the Shpanberg, Anadyr, and Bering straits is critical to the overall flow field and to the mass and property exchanges across this region. The strongest velocities occur within the Anadyr Current, along the coast of Siberia, and in the Bering Strait. A strong northeastward flow also exists in Barrow Canyon. This mean circulation agrees with the available observations (e.g., Stabeno et al. 1999), and it is presented primarily for reference.

Evidence of major impacts on the PAR ecosystem through the redistribution of ocean boundaries and habitats due to climate change are already observed (Grebmeier et al. 2010). A model not capable of resolving changes in gateway fluxes (also ocean fronts, currents, and general transport pathways) could easily miss changes in species transport and habitat shifts.

12.9.2 Vertical Structure

The vertical structure of the water column—i.e., the depth of any permanent or seasonal pycnoclines, the strength of vertical mixing, and the stability of the water column—plays a large role in determining the access of phytoplankton to light and nutrients, and thus PP. Although not yet coupled to an ecosystem model, NAME has

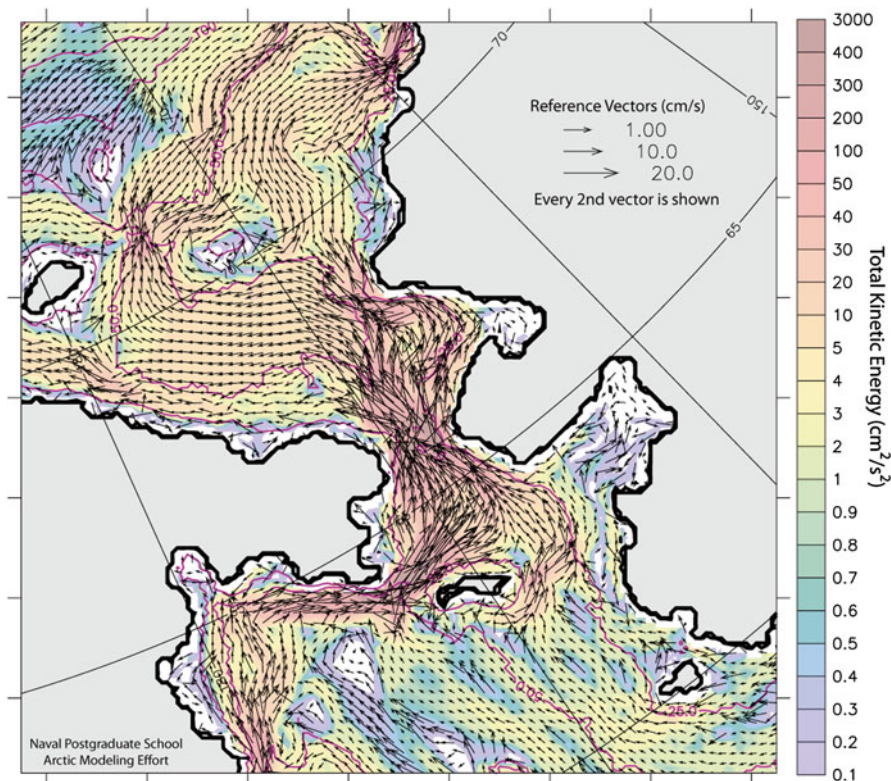


Fig. 12.8 Twenty-six-year mean (1979–2004) circulation in the upper 100 m from NAME. Every 2nd vector in each direction is shown. Shading represents total kinetic energy. *Magenta lines* denote bathymetry contours

demonstrated the ability to capture the influence on stratification of surface warming, sea-ice melt, and river discharge interacting with ocean circulation over large areas. The 2.5 m vertical resolution is currently state-of-the-art for a pan-Arctic model (Clement Kinney et al. 2014, this volume).

Eddy kinetic energy (EKE) is an important model parameter; it commonly represents regions of active mixing, including in the vertical. Vertical mixing is believed to lead to increased biological productivity in areas that become nutrient-limited in the euphotic zone. Simulated seasonally-averaged EKE in the surface layer for a typical summer and autumn is shown in Fig. 12.9. North of St. Lawrence Island, in the Chirikov Basin, and north of Bering Strait, there is a distinct decrease in EKE. Clement et al. (2005) propose that the high primary and secondary (benthic) production often found in this region (Grebmeier et al. 1988; Springer and McRoy 1993; Grebmeier and Dunton 2000) might be at least partially attributed to the high EKE and associated vertical mixing providing nutrient supply just upstream.

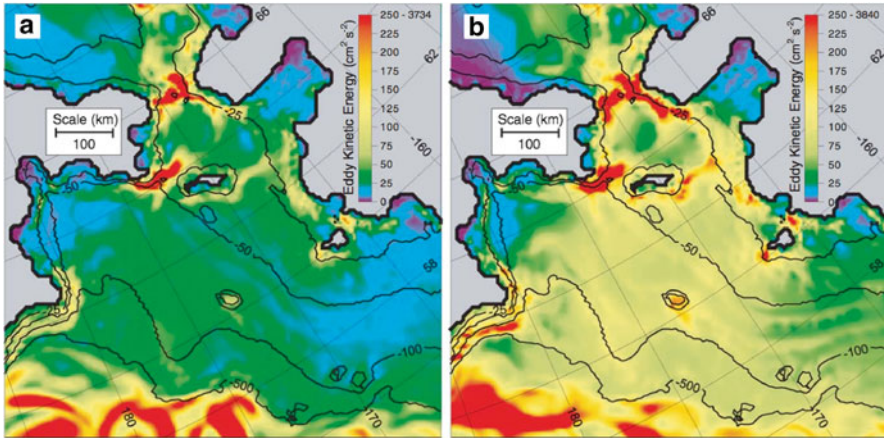


Fig. 12.9 Seasonally-averaged EKE at the surface calculated from NAME daily 1987 snapshots (a) Summer (J–A–S) average, and (b) Autumn (O–N–D) average

12.9.3 Mesoscale Eddies and Shelf-Basin Exchange

Eddies generated along the Chukchi-Beaufort shelf slope contribute to the transport of Pacific water into the basin interior and to the shelf-basin exchange of particulate organic carbon (POC), including zooplankton (e.g., Llinas et al. 2009). Zooplankton effectively link the lower and upper trophic levels, supporting large populations of mammals, seabirds, and species targeted by local fisheries (Nelson et al. 2014, this volume). Thus it is important to be able to model the impacts of the changes in these current patterns and flow structures on the ecosystem.

A number of anti-cyclonic eddies have been captured in the surface and halocline layers above 300 m depth in the Canadian Basin by in situ and drifting buoy observations (Manley and Hunkins 1985; Mathis et al. 2007). The Moderate-Resolution Imaging Spectroradiometer (MODIS) sea surface temperature has also detected a few warm-core eddies along the Beaufort shelf break (Fig. 12.10). Detailed physical and chemical properties of a cold-core eddy observed on the Chukchi Sea continental slope have been surveyed in Mathis et al. (2007) and Kadko et al. (2008). Both studies mention that the bottom-intensified shelf-edge current forms such mesoscale eddies, which play a significant role in the transport of carbon, oxygen, and nutrients associated with the Pacific winter water into the upper halocline of the Canadian Basin.

Numerical experiments using the eddy-resolving coupled sea ice-ocean Center for Climate System Research (CCSR) Ocean Component Model (COCO; Hasumi 2006), with a horizontal resolution of about 2.5 km, reveal that the interannual variations in mesoscale eddy activities and the shelf-basin exchange of Pacific water in the western Arctic Ocean depend on sea ice cover and shelf-wide surface wind conditions (Watanabe and Hasumi 2009; Watanabe 2011) (Figs. 12.10 and 12.11). Mesoscale eddies were also identified by the NAME model (Maslowski et al. 2008)

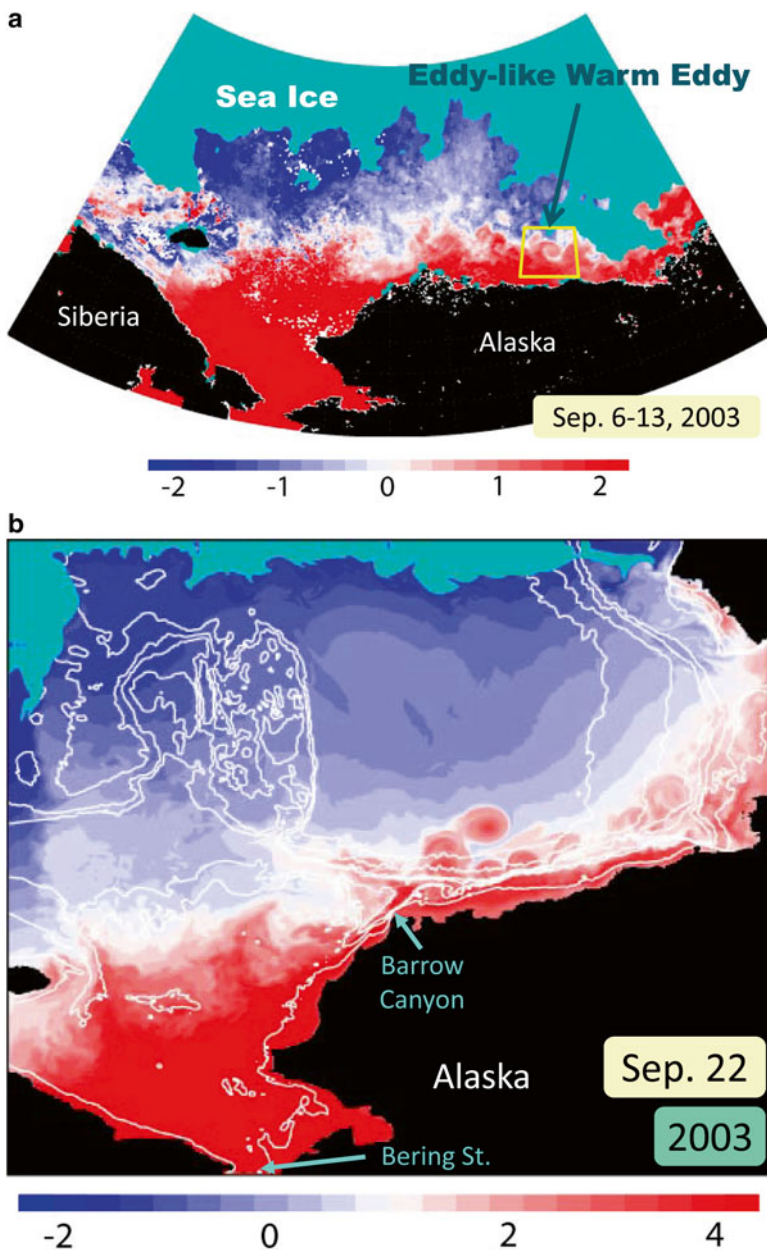


Fig. 12.10 (Top) MODIS 8-day-composite sea surface temperature during September 6th–13th, 2003 [deg C; color bar]. AMSR-E sea ice area is overlaid by sky-blue shade. (bottom) Sea surface temperature [deg C; color bar] and sea ice area in September simulated by the eddy-resolving version of the coupled sea ice-ocean model CCSR-COCO. White contours denote bottom topography (Figures from Watanabe 2011)

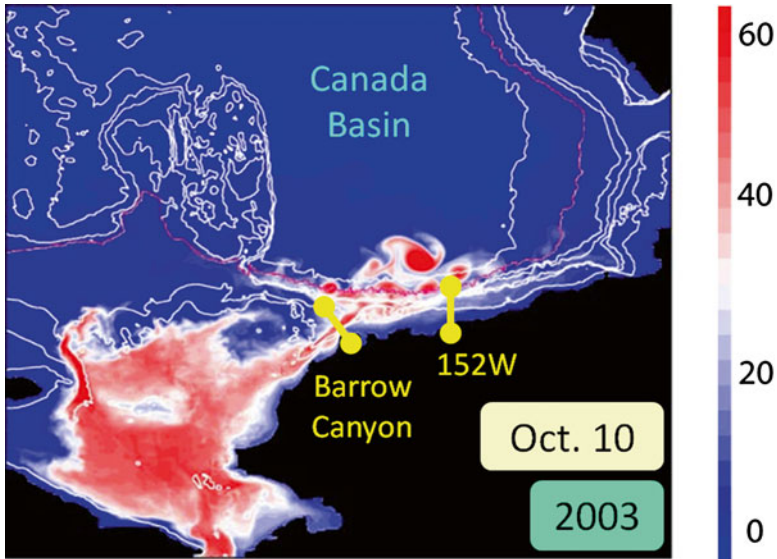


Fig. 12.11 Pacific water content in October 2003 (m), simulated by the eddy-resolving COCO with atmospheric forcing. The Pacific water content is calculated by the vertical integration of the Pacific water tracer concentration from the ocean surface to sea bottom in each grid (Figure from Watanabe 2011)

in the Beaufort Sea and Canadian Basin throughout the years. Mesoscale activity has the potential to significantly influence PP as illustrated in the northern Gulf of Alaska (Okkonen et al. 2003), where mesoscale eddies produce tongue-like features with maximum chl *a* concentrations. PP is enhanced in this region via the transport of phytoplankton and nutrients (including iron) from the outer shelf into the deep basin. In the Barents Sea, Wassmann et al. (2006) found considerably increased PP in their eddy-resolving 4-km-resolution model compared to an earlier 20-km-resolution model (Slagstad and Wassmann 1997).

High-resolution modeling is indispensable to resolve not only mesoscale eddies but also ice-edge and shelf-break upwelling. The ability of a model to simulate localized mechanisms of nutrient supply, on the order of ~ 1 km, depends on model resolution. In addition to more accurately predicting PP, high model resolution can help to clarify the underlying physical mechanisms responsible for spatial and temporal variations in marine ecosystems.

12.10 Modeling the PAR Ecosystem from an ESM Perspective

ESMs are coupled atmosphere-ocean-land-biosphere models designed to run for time periods of centuries to thousands of years and forced by changes in atmospheric CO_2 and other greenhouse gases, aerosols, solar variability, volcanism,

ozone, and land use change. Model adjustment to its forcing (spin up) is usually done in a preindustrial control mode with forcing levels fixed to preindustrial times. The spin-up time is determined by deep ocean overturning timescales, which can be thousands of years. Upon reaching a stable state, model runs can be executed in historical mode, forced by known CO₂ concentrations or emissions from preindustrial to present. Based on current states, the models are then run for future scenarios. Up to now simulations have mostly been based on the scenarios outlined in the Special Report on Emission Scenarios (SRES, Nakicenovic et al. 2000). For the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5), new scenarios known as Representative Concentration Pathways (RCPs) have been created (Moss et al. 2010).

The development of biogeochemical components in ESMs has been advanced significantly over recent years. Results from the first generation of ESMs which incorporated an interactive carbon cycle are discussed, e.g., by Friedlingstein et al. (2006) and Denman et al. (2007). The next generation of models is currently being archived for the 5th Coupled Model Intercomparison Experiment (CMIP5) in support of the IPCC AR5. This is the first CMIP to include ocean biogeochemical fields.

Generally ESMs have fairly coarse resolution, both horizontally (1–3.5°) and vertically (~50 m at the surface for earlier models and ~10 m for more recent models). This makes it difficult to resolve biological or chemical processes happening in the euphotic zone as well as small-scale physical processes, which are important for the biogeochemistry (see previous section). ESMs simulate the overall spatial and seasonal pattern with fair accuracy. However, based on the nature of those models and current data availability, it is not surprising that model skill (Box 12.2) for biogeochemical variables in global ESMs (which are usually based on limited local data sources) are rather low (e.g., Schneider et al. 2008; Steinacher et al. 2010). This is especially true in areas like the Arctic, which is characterized by few and seasonally-biased data and which includes vast shelf areas requiring high vertical model resolution.

Keeping those limitations in mind, we can focus on the uses of global ESMs and discuss their applicability for specific regions such as the PAR. ESMs provide insight into global connections and interactions between ocean basins, which might be important for the specific regions of interest. Moreover they are able to provide an estimate of changes in response to rising atmospheric CO₂ and other greenhouse gas levels and climate warming. They allow us to put recent changes into perspective with past and projected climates, and to study influences on and feedbacks from energy flows, carbon cycling, and biological productivity. More specifically, they can be used to study how biogeochemical cycling will respond to transitions in temperature, vertical stratification, SIZs, and acidification. This is a first step toward addressing consequences for socioeconomic activities. Guided by the outcomes from ESMs, we then must look to higher-resolution regional models of particular ecosystems to address more specific questions.

12.10.1 Ocean Acidification and Primary Production (PP) Changes Projected Over the Twenty-First Century

The Arctic, encompassing PAR, is one of the regions most sensitive to recent and expected future climate changes. Climate models predict a significant retreat in sea ice cover (e.g., Holland et al. 2006; Solomon et al. 2007), signs of which are already being observed in PAR (e.g. Stroeve et al. 2011). Recently the scientific community has paid increasing attention to ocean acidification (lower pH) and the particular vulnerability of arctic ecosystems (e.g., Orr et al. 2005; Steinacher et al. 2009; Denman et al. 2011; Gattuso and Hansson 2011). Acidification can significantly affect the growth, metabolism, and life cycle of marine organisms (see Box 12.3). The ocean's acidity is affected by increased atmospheric CO₂ and increased freshwater inputs from river runoff and ice melt. The combined effect renders arctic waters especially vulnerable to decreased saturation states of calcium carbonate (CaCO₃) minerals such as aragonite and calcite (Yamamoto-Kawai et al. 2009, 2011; Denman et al. 2011). Signs of aragonite undersaturation in surface waters in the Arctic have been reported by Chierici and Fransson (2009), Bates et al. (2009) and Yamamoto-Kawai et al. (2009, 2011). The Arctic Monitoring and Assessment Programme highlighted ocean acidification as an important issue and an Arctic Ocean Acidification assessment report is now in preparation.

Steinacher et al. (2009), using the Climate System Model (CSM) 1.4-Carbon of the US National Center for Atmospheric Research (NCAR), and Denman et al. (2011), using the Canadian ESM CanESM1, report model projections of aragonite and calcite saturation, carbonate concentration, and pH, based on SRES scenarios; all project significant acidification in the Arctic over the next century. CMIP5 results are now publicly available, allowing for a more thorough analysis. As an early example we present results for the PAR from the CanESM1.5, which is a higher-resolution version of CanESM1.0 (see Arora et al. 2009 and Christian et al. 2010 for model details). CanESM1.5 is a precursor to the AR5 model version CanESM2 (e.g. Arora et al. 2011), which includes an improved ocean model and a new atmosphere but was not ready in time for this synthesis. The ocean component includes a NPZD ecosystem with simple parameterization of N₂ fixation, calcification, and iron limitation (Zahariev et al. 2008). In CanESM1.5 and 2 the ocean has more vertical levels (40) and greater vertical resolution (~10 m in the top 107 m) than in CanESM1.0 (Arora et al. 2011). The horizontal resolution is 1.41° in longitude and 0.94° in latitude. The CanESM1.5 atmosphere is the same as in CanESM1.0 but with slightly higher resolution (~2.8°). Results are presented from a historical run (1850 to 2005) and a scenario run (2006–2100). The latter is based on RCP 8.5 with aerosol optical depth as in the SRES A2 scenario. Both are carbon-intense scenarios with RCP8.5 utilizing the highest total CO₂ emission scenario that has been used in AR5 experiments.

Figure 12.12 shows annually-averaged surface pH, aragonite saturation, and depth-integrated PP simulated for the end of the century (2096–2100, left hand side) and differences (end of century minus current) projected for the next 100 years.

Box 12.3: Ecosystem Response to Acidification and Multiple Stressors: A Challenge for Ecosystem Models

In recent years, laboratory studies testing the response of certain ecosystem components to acidification have revealed signs of dissolution in existing shells (e.g., Riebesell et al. 2000; Fabry et al. 2008), altered rates of essential metabolic processes and efficiency (e.g., Dupont and Thorndyke 2009; Barcelos e Ramos et al. 2010), impaired ability to sense chemical cues from predators (Munday et al. 2010), inhibited calcification, lower growth rates, degradation of mechanical integrity (e.g., Comeau et al. 2009; Gaylord et al. 2011), and underdevelopment of essential functions (e.g., Dupont and Thorndyke 2009). The observed responses have been found to be species-specific and to affect different life stages in different ways. Melzner et al. (2009) studied the physiological basis for high CO₂ tolerance and found that species with a higher metabolic rate and a powerful ion regulatory apparatus, or with more buffer fluids (e.g., blood, egg fluid) surrounding their cells, are able to cope more easily with high CO₂. Early developmental stages that expose cells directly to the surroundings seem to be a bottleneck for species survival.

Pörtner and Farrell (2008) associate the ability to cope with climate change with an aquatic lifeform's aerobic thermal window (the temperature range within which the species is able to execute vital functions). The thermal window varies with life stages; eggs, early larvae, and spawning animals are most vulnerable because their thermal windows are narrow. This window is expected to decrease with increasing partial pressure of CO₂ (pCO₂) and decreasing oxygen (O₂; Pörtner and Farrell 2008; Pörtner 2010).

As pCO₂ rises, species distribution and abundance will change according to each organism's tolerance of and ability to adapt to the increase. The extinction of one keystone species creates an opportunity for another species with a more flexible and robust regulatory system or a different thermal window. Species that are able to do so might migrate to more suitable habitats. Hence, trophic structure and biodiversity are key to the resistance and resilience of marine ecosystems to future perturbations (e.g., Dupont and Thorndyke 2009). Cheung et al. (2011), using a bioclimatic envelope model, found that ocean acidification and reduced O₂ content lead to reduced growth performance, an increase in the rate of range shifts, and lower estimated fisheries catch potentials. Beyond the individual species response, species interaction is an important factor. Many ecological processes are synchronized; hence, the timing of processes and developmental stages is crucial.

The future cost of acidification and other climate effects (such as warming) on ecosystems (e.g., biogeographic shifts, decreases in marine harvests, loss of coastline protection, and shoreline destabilization) will depend on the marine ecosystem response and on changes in human uses of marine resources

(continued)

Box 12.3: (continued)

(Cooley et al. 2009; Sumaila and Cheung 2010) and the ability of community and infrastructure planning to adapt successfully to change. Coupled ecosystem models and bioclimatic envelope models will help to address those issues, although socioeconomic models might be required to compare probable outcomes of different management choices (Cooley et al. 2009). How can we reliably calculate species/ecosystem tipping points in coupled ecosystem models and understand how the structure and function of whole ecosystems will adapt to multi-decadal environmental change? Recommendations include studying a wide range of species, mechanisms of physiological response, complete life cycles (over several generations), organisms that are less vulnerable (to detect the physiological traits crucial for ecological success in a future ocean), species already experiencing stress (from, e.g., high $p\text{CO}_2$), and multi-stressor environments (e.g., Dupont and Thorndyke 2009; Melzner et al. 2009; Ridgwell et al. 2009; Denman et al. 2011). Lynch et al. (2009) point to the need to focus on system integration of model theory and observation as an overarching goal. Much of what is mentioned above is described in much more detail in the book on ocean acidification by Gattuso and Hansson (2011).

Surface pH in the PAR has decreased from ~ 8.2 in preindustrial times to ~ 8.0 at present. In the RCP8.5 scenario pH is projected to further decrease to ~ 7.9 by mid-century and below 7.7 by the end of the century (Fig. 12.12a), which corresponds with the results in Steinacher et al. (2009). While pH change highlights the increased ocean acidification to be expected over the next century, aragonite and calcite saturation also depend on salinity and are significantly affected by increased freshwater contributions from river inflow, precipitation, and ice melt (Yamamoto-Kawai et al. 2009; Denman et al. 2011). Hence the surface ocean north of Bering Strait, which receives higher freshwater contributions, is predicted to become undersaturated (below 1.0) in aragonite before the southern PAR (Fig. 12.12b). From now to the end of the century, CanESM1.5 results project the aragonite saturation state to change by about 0.8–1.0 in most of the PAR with somewhat smaller changes north and northeast of the Bering Strait, where surface waters have already become undersaturated. Increased PP within and north of Bering Strait (Fig. 12.12f), which acts to increase aragonite (and calcite) saturation states in the surface layer, might contribute to somewhat smaller changes in this area. Increased PP could also be responsible for rendering simulated summer surface saturations in the northern Bering Strait slightly higher than in the subsurface (not shown).

The freshwater influence at the surface can lead to a subsurface maximum in the mean saturation state, with undersaturation in the deep ocean. The switch from surface supersaturation to deeper ocean undersaturation is commonly called the saturation horizon or saturation depth. The latter has been slowly moving upward

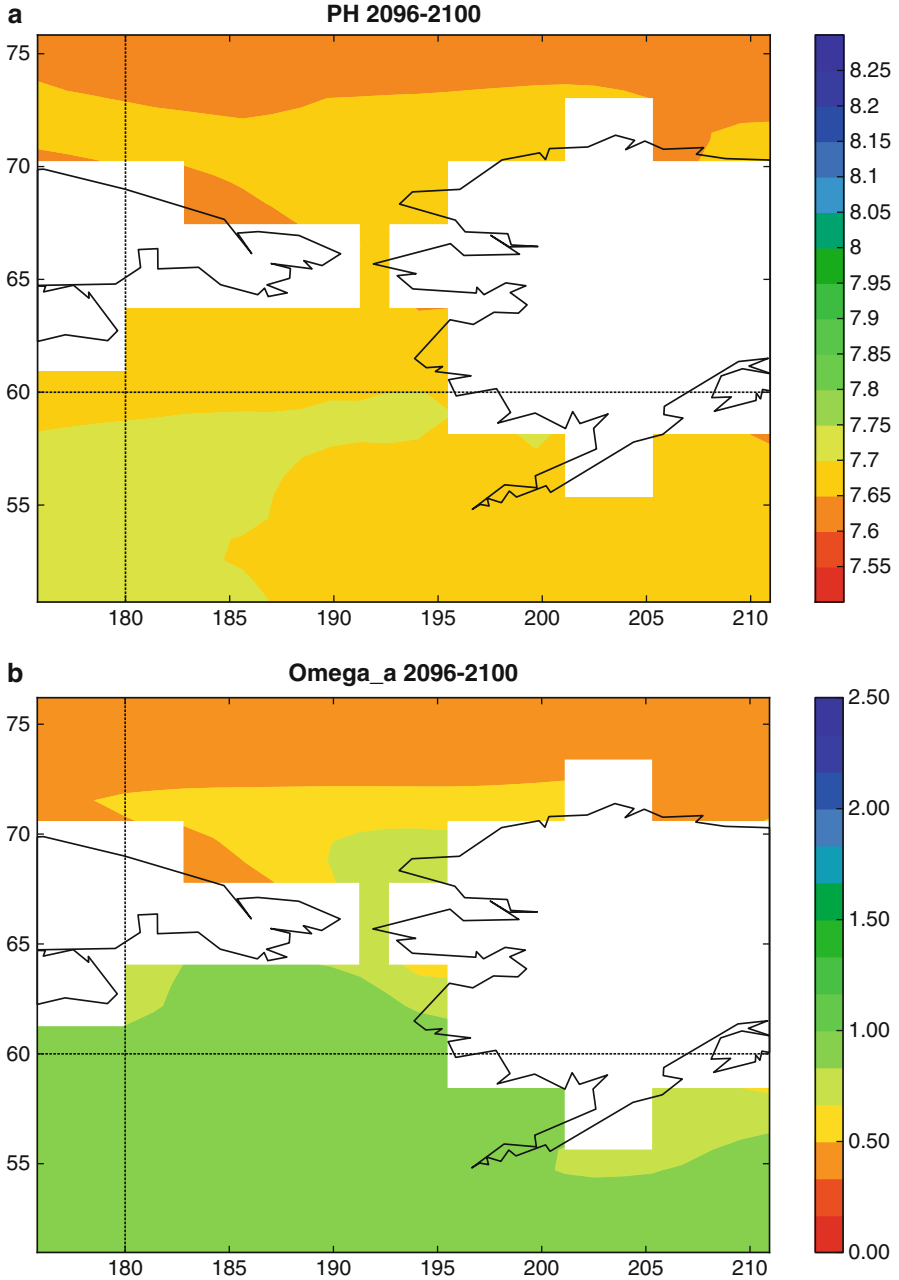


Fig. 12.12 Model predictions for the end of the century (2096–2100, **a**, **b**, **c**) and differences between the end of the century and current times (1996–2005) (**d**, **e**, **f**), simulated with CanESM1.5 and using the IPCC AR5 RCP8.5 scenario (see text). (**a**, **d**) annually-averaged pH, and (**b**, **e**) aragonite saturation state in the surface layer (top 10 m). (**c**, **f**) annually-averaged and vertically-integrated primary production in $\text{g C m}^{-2} \text{ year}^{-1}$

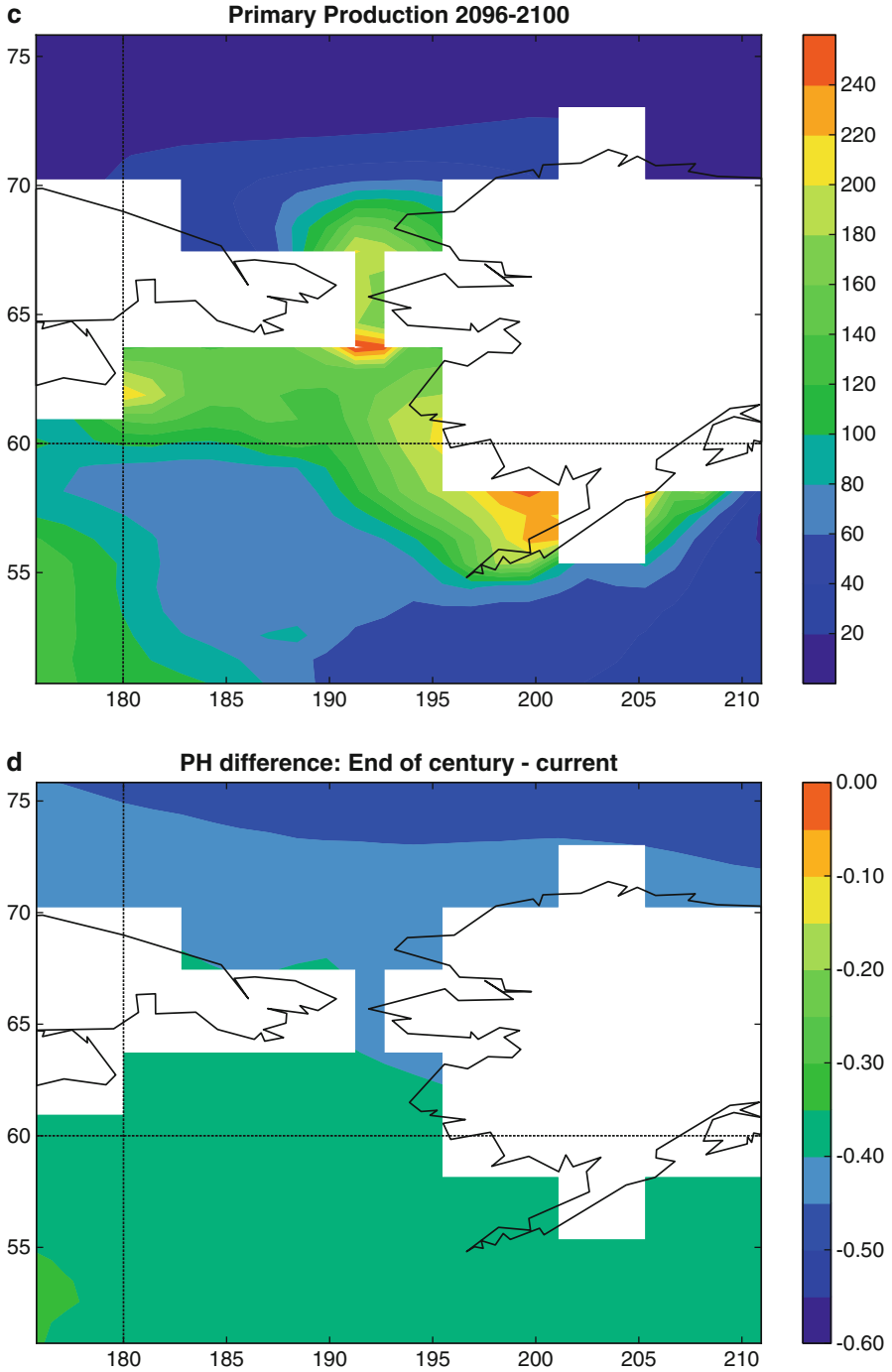


Fig. 12.12 (continued)

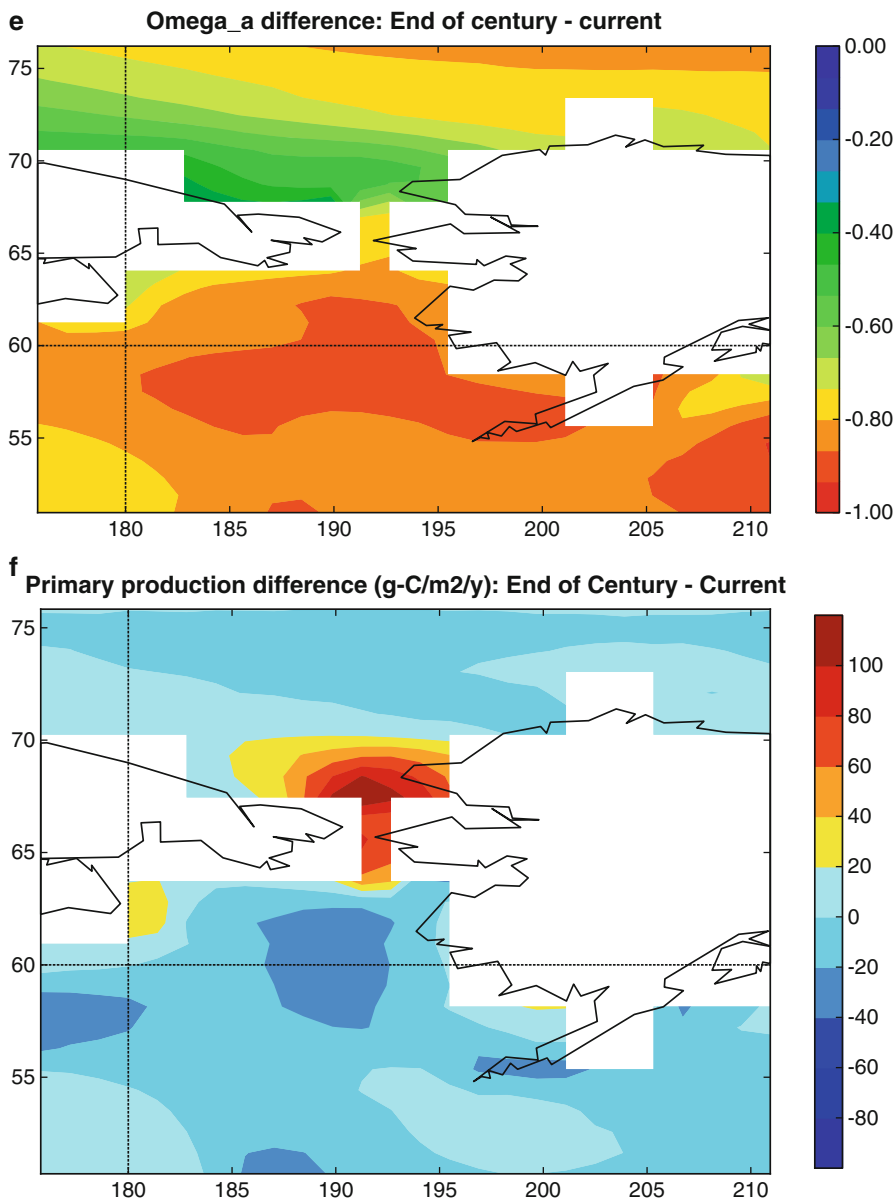


Fig. 12.12 (continued)

since preindustrial times and is projected to continue to do so in the future (e.g., Steinacher et al. 2009; Denman et al. 2011). The aragonite saturation horizon in the PAR is currently still below shelf level. CanESM1.5 projects the aragonite saturation horizon to rise to 200 m in almost all of the PAR by mid-century and the entire PAR, from surface to bottom, to be undersaturated by the end of the century. This

could have severe consequences for the pelagic and benthic communities as well as HTLs and fisheries in the area.

The simulated pattern and magnitude of PP in current times is very similar to the simulations of pelagic production by Jin et al. 2012 (Fig. 12.4, top left). Figure 12.12c shows annually-averaged depth-integrated PP projected for the end of the century with changes from current conditions in Fig. 12.12f. CanESM1.5 projects an increase in Bering Strait and Chukchi Sea PP due to the increased light and temperature that accompanies retreating sea ice. The increases range from 10 to 50 g C m⁻² year⁻¹ by mid-century and 20–110 g C m⁻² year⁻¹ by the end of the century with the highest increase within the Bering Strait. At the same time, the model shows a decrease of about 15 g C m⁻² year⁻¹ by mid-century and up to 40 g C m⁻² year⁻¹ by the end of the century in the central and southern Bering Sea. This decrease can likely be attributed to changes in stratification. A scenario discussed in Mathis et al. (2010) suggests that a decrease in sea ice causes increased availability of solar radiation and a more stratified water column. The latter would limit production through limited nutrient fluxes. A model analysis confirms that suggestion. The CanESM1.5 results show intensified warming in the area over the second part of the century leading to temperatures about 3 °C higher than current. Nutrient levels are decreased by about 30–60 % at the surface and subsurface, while nutrient levels in deeper layers are higher by about 15–40 % compared to present time values at the same depth and corresponding to reduced mixed layer depths (MLDs).

An analysis of the multimodel mean from 17 of the previous CMIP3 models (W. Merryfield, CCCma, pers. Comm.) indicated that, while the multimodel mean shows shallower MLDs under anthropogenic warming, the primary influence differs with region. In the northeast Pacific, increased near-surface stratification was most important. Steinacher et al. (2010) compare global fields of projected PP in the IPSL-CM4-LOOP model from the Institut Pierre Simon Laplace (IPSL), the COSMOS ESM from the Max Planck Institute for Meteorology (MPIM), and two versions of the NCAR Community Climate System Model (CSM1.4-Carbon and CCSM3-BEC) for the SRES A2 scenario (a high-CO₂ scenario similar to RCP8.5). A robust result from the intercomparison is a decreasing trend in global net PP. However, the magnitude differs among models and regions. Two processes are primarily responsible for changes in PP. First, a reduction in nutrient supply to the surface in a more stratified ocean leads to decreased production; second, an increase in light and temperature with retreating sea-ice and sufficient nutrients supports increased production. While the models are generally consistent in their responses, IPSL projects a decrease in Arctic PP, related to a reduced supply of macro nutrients, whereas CSM1.4, MPIM, and CCSM3 project an increase due to reduced temperature and light limitation (Note that absolute changes in the Arctic are small). In the PAR (Steinacher et al. 2010, their Fig. 12.3) all models simulate present values that are too low; the most realistic values are produced by the IPSL model. Projections show increases in PP for all models but the IPSL, which shows a decrease in the Bering Sea and an increase north of the Bering Strait, similar to the CanESM model results. In a multi-model average weighted by skill score, the IPSL model dominates in the PAR, although the skill scores are generally very low in that area (<0.2).

Discussing discrepancies between results from empirical approaches and process-based ESMs, Steinacher et al. (2010) point out the importance of a realistic representation of nutrient cycling and distribution in order to project changes in PP with some realism.

However, as stated earlier, ESMs are computationally expensive. Constant tension exists between simple grid resolution adjustments, which can improve circulation physics, and the tracer/reaction-intensive biology and chemistry. Some processes might not be resolved and parameterized adequately, especially in areas of narrow straits and shallow shelves, both of which are characteristic of the PAR. Also, ESMs so far do not account for changing carbon fluxes via rivers and coastal erosion, which can be significant (Cai et al. 2014, this volume). Fabry et al. (2009) point out that the polar seas constitute ecosystem laboratories for diverse studies in ocean acidification, including assessing potential acclimation and adaptation and modeling future impacts at population, community, and regional scales. The PAR is already an area with an intensive research program and it can serve as a test bed for developing detailed biological and biogeochemical models. It will be reasonable to perform simulations at a variety of scales ranging from local (point or column) to regional, and then to refine and transfer appropriate parameterizations to global ESMs.

12.10.2 Projections of Fisheries and Biodiversity Impacts with Bioclimatic Envelope Models

While of intense interest to managers and policy makers, projections of HTLs in the Earth system modeling framework are not yet possible. Bioclimatic envelope models are an intermediate step to allow projections of global marine biodiversity impacts (e.g. Cheung et al. 2009) and fisheries catch potential (e.g. Cheung et al. 2010, 2011) under climate change. In these models, shifts in species distribution can be predicted by evaluating changes in physical and biological conditions relative to those suitable for a given species. Suitability is determined by correlating current environmental conditions with maps of current species abundances. Future environmental conditions are provided from climate models or ESMs (e.g. Cheung et al. 2009, 2011). Cheung et al. (2009) predict numerous local species extinctions in the sub-polar regions and intense species invasion in the Arctic and southern oceans. Cheung et al. (2010) project 30–70 % increase in maximum fisheries catch potential in high-latitude regions with the largest changes in the Pacific. They note, however, that their model does not yet account for the effects of changes in ocean biogeochemistry (e.g. ocean acidification, oxygen reductions, and thermal window limitations, see Box 12.3) and phytoplankton community structure. Cheung et al. (2011) introduced a model including these new factors, but have not yet applied it to the Arctic or the Pacific oceans.

12.10.3 Marine Methane Emissions

Methane (CH₄) from subsea permafrost (Shakhova et al. 2010) and trapped in the form of clathrate hydrates is expected to leak from shallow arctic shelves, partly driven by penetration of the North Atlantic warming signal into central ocean layers (Reagan and Moridis 2008). Archer (2007) concluded that destabilizations will be particularly important around the rim of the central arctic basin because the Atlantic layer is the warmest source of water to the Arctic and both the Chukchi and Beaufort shelf zones will be directly affected.

Modeling arctic marine methane chemistry is in its infancy, and simulating methane emissions from the ocean have so far been afforded low priority in ESMs. For the most part they are represented as a constant flux equally distributed over the global ocean. The IPCC AR3 and AR4 (Prather et al. 2001; Denman et al. 2007) cite global emissions of 10–15 Tg methane year⁻¹, although the most recent measurements in the Pacific (Bates et al. 1996) and Atlantic (Rhee et al. 2009) suggest these values may constitute strong overestimates. The arctic continental shelves are believed to be a large potential source to the global atmosphere. Macdonald et al. (2009) estimate that they provide up to four times the annual flux estimated for all other coastal seas combined. New studies further suggest that aerobic marine methane production will be sensitive to changes in water-column stratification and also to the nutrient limitation likely to result from greenhouse-gas-induced warming (Karl et al. 2008). An additional source of methane may be organic carbon buried in sediments over glacial timescales and then transformed into methane under anaerobic conditions (Reeburgh 2007).

The premise of a recent modeling study by Elliott et al. (2010) is that CH₄ gas emanating from such systems will be consumed along the periphery of the PAR by methanotrophs and anaerobic oxidizers of methane (Reeburgh 2007). In the model, consumer organisms are pulled out of the sediments along with bubbles and fluids flowing into regional-scale plumes. As metabolism progresses using the new methane sources, hypoxia and nutrient depletion appear at scales of tens to hundreds of kilometers. Elliott et al. (2010) conclude that these altered water masses will form a new geochemical component of the central Arctic Ocean milieu; different regions will display distinct responses to future methane throughput.

12.10.4 Ocean Biogeochemistry-Aerosol Connections

Another important factor for consideration in modeling climate with earth system simulations is the generation of aerosols over the oceans. While current atmospheric models treat aerosols as produced mostly from sea salt and volatile reduced sulfur (Jones et al. 2001), some authors suggest a strong but poorly-quantified link between the particulate organic matter of polar surface waters and aerosol and arctic cloud

systems (e.g., Leck and Bigg 2005b, 2008; Matrai et al. 2008), and a possibly overestimated role of sea salt (e.g., Leck and Bigg 2005a; Bigg and Leck 2008).

The role of volatile dimethylsulfide (DMS) is still unclear as well. DMS is formed via a complex network of food web interactions from its precursor, dimethylsulphoniopropionate (DMSP), produced by many marine phytoplankton and sea ice algae. In the atmosphere, DMS is oxidized to sulfate aerosols, which serve as cloud condensation nuclei (CCN). Shaw (1983) was the first to suggest that biogenic sulfur gases may regulate climate through generation of sulfate aerosols that scatter sunlight back to space. However, quantitative descriptions of key processes and direct links are still lacking (e.g., Ayers and Caine 2007). The relative importance of sea salt, sulfate, and organics in determining the CCN number concentration is still unclear, as are the responses of plankton community structure and/or planktonic DMSP production to climate change. The underlying marine biogeochemistry has not yet been modeled adequately at any scale with respect to recent findings regarding the organic-to-CCN connection.

Global process models for the marine sulfur cycle constitute the first real attempt by the earth system simulation community to examine climatic effects of ocean biogeochemistry by mechanisms other than greenhouse gases (Six and Maier-Reimer 2006; Elliott 2009; Le Clainche et al. 2010). Several authors on this review are now involved in implementing generic sulfur reaction schemes into the CICE-POP-CCSM family of codes (Hunke and Lipscomb 2008; Elliott et al. 2012). Despite the development of 1-D and high-resolution regional biogeochemical models for northern high latitudes that include sea ice algae (see Sects. 12.5 and 12.6) and ocean DMS cycling (Jodwalis et al. 2000), polar biogeochemical cycling and especially the ice algae remain underdeveloped in GCMs (Elliott 2009).

12.11 Gaps and Needs: Introduction

PAR biogeochemical modelers agree that more observations are needed, specifically observations sustained throughout the year and biological process and rate measurements. For example, there is little known about the biology of marine organisms such as zooplankton at depth under the ice, and the wintertime distribution and physiological state of phytoplankton. Also, biogeochemical transfer processes within and through sea-ice have yet to be elucidated (e.g. Loose et al. 2011). Advances in modeling sea ice are critical overall: Directly and indirectly, sea ice influences nutrient availability and atmospheric composition (e.g., trace gas exchange, aerosol sources) and, along with snow cover, controls the light available to PAR ecosystems for much of the year. Many recent and on-going efforts are directed toward improving modeling of biochemical and geochemical processes, and of physical transport within the sea ice matrix. Regional downscaling from GCMs is recognized as an important tool in producing regional climate information for impact and adaptation studies. Relevant studies are at an early stage but have great potential for future research.

12.12 Availability of Observations

Wassmann et al. (2011) studied footprints of climate change in the Arctic ecosystem and point out the significant lack of reliable baseline data from which change can be identified, particularly for planktonic and benthic systems. The sparseness and heterogeneity of the available biological and biogeochemical observations, for instance seawater nutrient concentrations and plankton biomass, also creates problems for 3-D model initialization and validation. An ideal dataset would cover all seasons and most of the model domain. The World Ocean Atlas (WOA) monthly climatology http://www.nodc.noaa.gov/OC5WOA05/pr_woa05.html is the only gridded dataset available for model initialization of seawater nutrient concentrations in PAR. However, a few new arctic databases are being developed with the goal of improved understanding of Arctic Ocean PP and its changing physical controls such as light, nutrients, and stratification. The NSF Arctic Primary Productivity Observational Synthesis Project has perhaps the largest nutrient database as a result of this effort. A merged-calibrated file for the Arctic is now also available from the Carbon dioxide in the Atlantic Ocean (CARINA) data synthesis project, which is accessible via the Carbon Dioxide Information Analysis Center (CDIAC, http://cdiac.esd.ornl.gov/oceans/CARINA/Carina_inv.html). The quality of the data in this merged product is significantly higher than data in the WOA, but the measurements are patchily distributed and insufficient to grid, especially by season and in shallow water. Carbon data from the Pacific Ocean are being synthesized in the North Pacific Marine Science Organization effort. Additional datasets from large arctic projects exist that have not yet been added to the WOA, such as the NSF Shelf Basin Interactions (SBI) and the NOAA IPY project: Russian American Long-Term Census of the Arctic (RUSALCA). Observationally-driven IPY projects, such as Canada's Three Oceans, measured spatial variability along ship transects and recorded temporal variability using year-round moorings. Many of the recent measurement programs within the Pacific Arctic are part of the Pacific Arctic Group's (PAG) Distributed Biological Observatory (DBO) which aims at linking physics and biology (Grebmeier et al. 2010). Efforts for data management and sharing of DBO data, e.g. within The Advanced Cooperative Arctic Data and Information Service (ACADIS) of the Arctic Observing Network (AON), are underway. ACADIS provides data management support for all projects funded by NSF's Arctic Science Program.

Long-term observational networks that address spatial scaling issues (e.g., fine-scale observations vs. coarse scale models) and link observations to processes influencing biogeochemical dynamics are needed for modeling efforts. Time series observations over very broad spatial domains will aid in validating 3-D biogeochemical models. Synthesis products from IPY efforts, such as maps of benthic biomass, provide models with more realistic initial conditions across the model domain. Remote-sensing data provide synoptic biological information, but these are snapshots of the surface ocean layer under clear sky conditions and are not indicative of the hydrography below the surface. Biological rate measurement and process-oriented datasets needed for parameterizing models are rare for PAR.

New modeling approaches and data assimilation procedures that directly incorporate observations from a wide range of measurement systems including biological and biogeochemical observations are yet to be developed. The demand for marine system models to support policy and management decisions is on the rise. The focus needs to be set on better enabling diagnostic modeling of the present-day and more accurate modeling for real-time forecasts and management projects. For now PAR models could be designed to take advantage of ocean color products that are routinely produced and distributed, and expand from there as arctic biological databases emerge. To build up these databases, sufficient support and effort needs to be invested in comprehensive sampling of the Arctic.

12.13 Modeling Brine Processes and Tracer Transport in Sea Ice

Current ice algae models usually apply simple parameterizations for nutrient supply, salt, and material release. Oceanic emissions are essentially prohibited because sea ice forms a barrier to gas exchange in models. However, laboratory and field studies show that sea ice can be highly permeable to CO₂ (Gosink et al. 1976; Kelley and Gosink 1979; Golden et al. 1998) and that it controls and contributes to air-sea flux of climatically-active trace gases, such as CO₂ and DMS (Semiletov et al. 2004; Delille et al. 2007; Zemmeling et al. 2008; Miller et al. 2011). A simplification helpful for modelers is the “rule of fives”: At temperatures below about -5°C , corresponding to a brine volume fraction of about 5 % and a typical bulk sea ice salinity of 5 parts per thousand, brine inclusions are mostly disconnected, and sea ice is effectively impermeable to fluid flow. For temperatures above -5°C , the brine inclusions become connected over larger scales, allowing fluid and gas transport through the sea ice (e.g. Golden et al. 1998; Petrich and Eicken 2009). Modelers are now looking into more accurate representations of brine dynamics to describe permeability and salinity profiles within ice, which affect physical properties like heat transport and melting (e.g., Golden et al. 2007; Petrich and Eicken 2009; Vancoppenolle et al. 2009) as well as gas fluxes and nutrient and material cycling (Vancoppenolle et al. 2010). Notz and Worster (2009) revisited sea ice desalination processes and concluded that gravity drainage in winter and flushing during summer are the only significant contributors to salt loss from sea ice. They point out that while models of flushing are fairly realistic, the lack of a physically-based quantitative description of gravity drainage is a significant shortcoming of sea ice models. From the biogeochemical perspective, improved brine process modeling will allow us to assess the importance of nitrate versus silicic acid or other nutrient limitations, the production of dissolved organic carbon (DOC) and extracellular polymeric substances (EPS) by ice algae, and their subsequent recycling by bacteria. The latter appears to play an important role in organic carbon cycling within the sea ice (Krembs et al. 2002; Riedel et al. 2008). EPS are sticky and play an important role in cell aggregation and

sinking. Although ice algae do not represent a major fraction of annual PP, their actual influence on the export of organic carbon could be strong.

Improved knowledge of gas exchange through sea ice has the potential to alter our understanding of the seasonal amplitude, and localized sources and sinks of atmospheric CO₂ and other gases in PAR. However, little is known about the complex dynamic processes involved. Rysgaard et al. (2007) suggest that CaCO₃ precipitation in sea ice might act as a sink for CO₂. Recent observations confirm the presence of the mineral ikaite likely caused by the precipitation of CaCO₃ within brine channels in the Arctic (Dieckmann et al. 2010). CO₂ is pumped in and out of central ice layers through processes that are partly dominated by chemical thermodynamics but that also involve complex brine dynamics that affect alkalinity and pH within the bulk ice structure.

12.14 Snow Component

While most Arctic snow melts completely by Spring, it has a significant effect on physical and biological processes within the sea ice matrix and below. Snow remains one of the most important variables needing improvement in sea ice models as well as ice ecosystem models. Snow cover controls ice growth rate and the amount and timing of light availability at the underside of the ice, which in turn regulate ice algal bloom onset, biomass accumulation, and termination of the ice algal bloom (Lavoie et al. 2005, 2009; Mundy et al. 2005; Jin et al. 2006a). Snow cover also affects the onset and magnitude of the phytoplankton spring bloom, through its effect on ice melt, timing of ice disappearance and release of nutrients and ice algae. The highly variable processes in the evolution of the snow (and ice) cover, especially during the melting season (e.g., formation of melt ponds, snow-ice formation during flooding), which affect both light conditions and habitat for sea-ice ecosystems, are still insufficiently described in models and will need further attention in future model development.

12.15 Microbial Loop

Heterotrophic bacteria as well as the rest of the microbial loop need attention in PAR biogeochemical models. Contributions of the microbial loop to carbon cycling (e.g., PP and export production) are substantial and are discussed in a previous chapter (Mathis et al. 2014, this volume). Important bacterial processes such as decomposition of organic matter and remineralization of nutrients are typically included in PAR biogeochemical models through implicit representation of bacteria. In this way, Lavoie et al. (2009) were able to simulate detrital flux comparable to the mean annual POC flux estimated from sequential sediment traps, although microplankton, dissolved organic matter (DOM), ammonium, and

bacteria compartments would have enhanced the model. DOM concentrations in arctic rivers are among the highest in the world (Dittmar and Kattner 2003). Cai et al. (2014, this volume) summarize riverine DOC fluxes from many studies in the Pacific region of the Arctic Ocean. DOC supplied by these rivers has traditionally been considered refractory, but new studies question this assumption and suggest that DOC delivered by rivers during the spring freshet is labile (Holmes et al. 2008, and references therein). Similarly, Garneau et al. (2008) found that some areas of the Mackenzie shelf environment could be a source of CO₂ due to high bacterial production, and they suggest that the bacterial-to-PP ratio could increase in the future due to the increase in allochthonous substrate supplied by rivers. To represent these processes realistically in biogeochemical models, an explicit description of bacteria and/or related compounds need to be included.

12.16 Modeling Adaptation and Synergistic Effects

At this point most ecosystem models, especially those incorporated into global ESMs, are fairly simple with either constant or temperature-dependent parameterizations. However, to adequately simulate both functional and structural ecosystem changes in a changing climate, this might not be sufficient. It is not known how Arctic ecosystems will adapt to the drastic changes happening in such short time spans. Laboratory studies show significant impact of, for example, ocean acidification and other stressors on marine life (Box 12.3); however, they also show that, while some species will fail to survive, others will thrive under the same conditions. Many open questions wait to be resolved: Will the less fortunate simply be replaced by more suitable species? Do community structures stay the same and just shift their location? Or, if creating longer-term projections, do species adapt genetically and/or behaviorally or die out? How do timings of migration, growth and reproduction patterns and predator–prey interactions change?

From a modeling perspective, we ask: Are our coarsely-grouped phytoplankton and zooplankton compartments representative of those found in today's climate, and will they still be representative tomorrow? Do current parameterizations provide accurate predictions because better adapted species will simply replace less competitive/poorly adapted species? Or do we need to think about genetically or physiologically adaptive processes occurring over generations represented on timescales of global ESMs? While species replacement and migration might not necessarily require changes in parameterizations, evolutionary adaptation will. How can this be achieved if the adaptation potential for individual species varies? Laboratory studies show that for some species one generation is enough to cope with the environmental changes like e.g. impacts of ocean acidification (Dupont and Thorndyke 2008), however many more generations might be needed for genetic mutations to manifest. The synergism of effects is an important factor. Organisms might be able to adjust to one effect, but perhaps not to multiple stressors including warming, ocean acidification, hypoxia, habitat destruction, overfishing, introduced species, etc. One type

of modeling that would allow projections on how these changes might occur requires a complex adaptive systems approach (e.g. Norberg 2004). In the approach of Norberg, the ability of the ecosystem to evolve with a changing environment/climate is a function of the existing biodiversity within species or functional groups of species. In a related approach, Pahlow et al. (2008) allow the parameters within the model to change or adapt in response to changes in environmental variables, but the essential structure of the ecosystem remains unchanged.

12.17 Dynamical Downscaling

Dynamical downscaling, where the output from one (or more) GCM is used to force a finer-resolution regional climate model (e.g., Liang et al. 2008) could be applied to PAR. The statistical downscaling method used in Lavoie et al. (2010) to provide forcing for future projections is limited by the ability of the GCM to represent important mesoscale features and processes. Regional climate downscaling (RCD) techniques are increasingly being utilized to produce regional climate information for impact and adaptation studies. Hence it is critical that the potentials, limitations, and uncertainties of RCD-based information are well understood by the modeling and user communities. The World Climate Research Program has formed a Task Force on Regional Climate Downscaling (TFRCD) to address those issues and foster international collaboration between global climate modelers, the downscaling community, and end-users to better support impact and adaptation activities. The TFRCD initiated a framework called the Coordinated Regional Climate Downscaling Experiment (CORDEX), which among other integrative approaches defines a common set of Regional Climate Model domains for dynamical downscaling (http://copes.ipsl.jussieu.fr/RCD_CORDEX.html). The CORDEX domains include a setup for the Arctic, however so far the program has been limited to the atmosphere. To further advance modeling of arctic marine biogeochemistry Arctic System Models are needed (Roberts et al. 2010) and are now starting to become feasible (e.g., Maslowski et al. 2012). Both dynamical and statistical downscaling methods will benefit from the continuously improving presentation of the Arctic Ocean in GCMs. Marine biogeochemical modeling has received a significant boost in recent years and will provide an important addition to RCD models, especially with respect to future fisheries management.

12.18 Summary

Models are useful and necessary tools for studying the impact of climate related changes on the complex interactions that influence PAR ecosystems. We expect that continuing advances in computing power and resources combined with increasing attention to this sensitive region will rapidly advance PAR biogeochemical modeling

in coming years. The goal of this model synthesis is to provide an overview, to evaluate the ability of current PAR ecosystem models to address interactions within the ecosystem and between physical and biogeochemical properties, and to discuss model suitability to simulate ecosystem changes in a changing climate. The specifics of PAR with its seasonal sea ice zone and shallow shelves call for coupled ecosystem models including benthic, pelagic, and ice communities. Some models already incorporate all three components and are able to represent observed shifts from a benthic-dominated system to a pelagic-dominated system in response to sea ice retreat, as well as seeding of spring algae blooms by ice algae. Existing models can (1) simulate annual ice algal and pelagic production within the ranges of the observations, (2) represent hot spots in production and differences in regional distribution of biomass, (3) explore the effects of interannual changes in ice cover and water motion on carbon and nitrogen cycling, (4) analyze biogeochemical processes under alternate light- and nutrient-limited regimes, and (5) study seasonal cycles and the physical processes controlling primary and export production under both current conditions and future scenarios. These results provide valuable insights into possible future ecosystem dynamics in a changing Arctic, enabling first estimates of consequences for HTLs and socioeconomic activities.

The subsurface phytoplankton bloom is a major contributor of fixed carbon, and we caution that satellite-derived estimates of phytoplankton production, which are not able to track subsurface blooms, might underestimate actual concentrations. This shortcoming must be taken into account when validating ecosystem models, which provide vertical structure and depth-integrated PP. Light attenuation is a major factor limiting PP, and factors like ice-entrapped sediments, thicker ice, and/or snow depth have been shown to affect the amount of light available to marine algae. We point out that ecosystem structures and physical environments in different regions are quite specific and that ecosystem models from other regions (e.g., the southern ocean or even the Barents Sea) cannot readily be applied to PAR.

We highlight the importance of capturing the timing and location of the ice edge and open water blooms for simulating the food web structure that follows. An accurate representation thereof requires high-resolution modeling. Since much of the PAR system is governed by advection, proper representation of currents, circulation, frontal systems, and vertical stratification as well as potential future changes in those systems is important. The very-high-resolution physical models that exist are able to represent relevant features (e.g., eddies). However, these models are not yet coupled to a marine ecosystem component.

Both 1-D and regional models forced by climate model output as well as climate models themselves provide first estimates of future and current PAR changes. Model results suggest not only a PP increase in the northern PAR due to the ice retreat, but also some reduction in the southern PAR attributed to changes in the upper ocean stratification. They also show a reduction in the importance of the ice algae contribution due to the earlier snow and ice melt, while other models suggest even more ice algal production in low ice years. Models also suggest switches in the dominant phytoplankton groups due to changes in sea ice cover (i.e., timing of sea ice retreat), which might support either pelagic- or benthic-dominated systems.

Projections with ESMs highlight imminent acidification, which renders PAR waters undersaturated in aragonite and calcite from top to bottom by the end of the century. This acidification could carry severe consequences for pelagic and benthic communities. It is important to note that ESMs do not yet incorporate any physiological or behavioral changes beyond regional shifts due to acidification or other environmental influences. Many of the possible physiological and behavioral changes are not yet understood and must be explored in laboratory and field studies.

We emphasize model validation as a procedure of major importance in developing model parameterizations, highlighting the need for observational data from within PAR. Consistent and continuous interaction between modelers and field scientists, preferably starting in the planning stage of a project, is essential. These interactions have proven beneficial from an observational standpoint as well. While data are essential for validating models, models in turn can be used to interpret and extrapolate data, identify hot spots for observations, test hypotheses, and guide the design of field programs.

In closing, biogeochemical modeling in PAR has advanced significantly over recent years. Limitations still exist due partly to the lack of gridded datasets and the limited understanding of links between individual ecosystem components and possible adaptation processes in a changing climate. We expect integrated observing and modeling approaches for PAR to increase over the coming years, advancing our understanding of the underlying systems and our ability to accurately represent those systems in model equations.

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