What controls primary production in the Arctic Ocean? 
Results from an intercomparison of five general circulation 
models with biogeochemistry

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As a part of Arctic Ocean Intercomparison Project, results from five coupled physical 
and biological ocean models were compared for the Arctic domain, defined here as north 
of 66.6°N. The global and regional (Arctic Ocean (AO)–only) models included in the 
intercomparison show similar features in terms of the distribution of present-day water 
column–integrated primary production and are broadly in agreement with in situ and 
satellite-derived data. However, the physical factors controlling this distribution differ 
between the models. The intercomparison between models finds substantial variation in the 
depth of winter mixing, one of the main mechanisms supplying inorganic nutrients over 
the majority of the AO. Although all models manifest similar level of light limitation owing 
to general agreement on the ice distribution, the amount of nutrients available for plankton 
utilization is different between models. Thus the participating models disagree on a 
fundamental question: which factor, light or nutrients, controls present-day Arctic 
productivity. These differences between models may not be detrimental in determining 
present-day AO primary production since both light and nutrient limitation are tightly 
coupled to the presence of sea ice. Essentially, as long as at least one of the two limiting 
factors is reproduced correctly, simulated total primary production will be close to that 
observed. However, if the retreat of Arctic sea ice continues into the future as expected, a 
decoupling between sea ice and nutrient limitation will occur, and the predictive capabilities 
of the models may potentially diminish unless more effort is spent on verifying the 
mechanisms of nutrient supply. Our study once again emphasizes the importance of a 
realistic representation of ocean physics, in particular vertical mixing, as a necessary 
foundation for ecosystem modeling and predictions.

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1. Introduction

Modeling of the Arctic Ocean biophysical interactions 
has a long history starting probably from the work of 
Niebauer and Smith [1989] and Smith and Niebauer [1993] 
on the impact of the mesoscale physical process on the 
phytoplankton dynamics within the framework of the two-
dimensional numerical model. Since this pioneering work, 
a number of modeling studies of various complexity were 
conducted in a variety of regions of the AO such as Chukchi 
[Walsh et al., 2004, 2005] and Barents [e.g., Wassmann et al., 2006; Ellingsen et al., 2008] seas. However, until 
recently, the Arctic Basin received little attention in either 
global- or even basin-scale ecosystem modeling studies 
because of its status as a (relatively) low-productivity area. 
Nevertheless, the recent and ongoing retreat of Arctic sea 
Ice is exposing increasingly large surface areas of the basin 
to sunlight and thus promoting increased growth of phyto-
plankton during summer months. A recent study reporting 
elevated Arctic primary production [Arrigo et al., 2008] 
greatly increased interest in modeling the present-day Arctic 
ecosystem and its possible future under continuing climate 
change. As a result, the first pan-Arctic biogeochemical 
modeling studies are now appearing [e.g., Lengaigne et al., 2009; Slagstad et al., 2011; Popova et al., 2010; Zhang et al., 2010; Jin et al., 2011; F. Dupont, Effect of sea-ice 
algae in a biophysical model of the Arctic Ocean, submitted to Journal of Geophysical Research, 2011] posing the
question as to what extent different models agree on present-day AO primary production and on the factors that control it. Assessing model performance (against observations) and agreement (against one another) will greatly increase our understanding of how much their future predictions may vary, and why.

[3] In this paper we present an intercomparison of 5 coupled physical-biological ocean models for the Arctic domain, made within the framework of the Arctic Ocean Model Intercomparison Project (AOMIP). The models examined have separate and distinct development histories for both their physics and biology, but overlap sufficiently in domain and functionality for a productive intercomparison. Since both global and regional AO models participated in the intercomparison, the Arctic Ocean domain was defined here as the area north of 66.6°N.

[4] Ecosystem model intercomparisons in any geographical area face a number of challenges. For instance, different ecosystem models vary substantially in their structure, complexity, parameterizations of ecosystem processes and their equilibration time. Furthermore, they are embedded into physical models which vary in initial and boundary conditions, geographical domains (ranging from limited regions to global), resolution, numerical methods, sub-grid-scale parameterizations, and external surface forcing. An extra challenge in the Arctic domain is the overwhelming importance of sea ice, models for which vary significantly in terms of their complexity, the processes represented and in their coupling to underlying ocean dynamics.

[5] Taking into account the various difficulties mentioned above, one may envisage two approaches for model intercomparison. One is to create a common protocol in which participating models are run under certain identical specifications such as atmospheric forcing, equilibration procedure and boundary conditions. For example, such an approach was successfully used in OCMIP (Ocean Carbon cycle Model Intercomparison Project) where, additionally, an idealized ecosystem model was a specified component of the protocols [Najjar et al., 2007]. Although such an endeavor removes many sources of incongruity between models and allows direct intercomparison of fundamental differences between models, it requires a substantial investment of resources from all participating groups since it necessitates rerunning all the models under a common protocol. This is expensive both in computational costs (especially, as in OCMIP, where equilibrium criteria were very specific), and in the effort required to accommodate the standard protocol within an existing model framework (e.g., coding, file-formatting, testing). An alternative approach is to consider existing runs with all their underlying differences and attempt to quantify the skills of the models and, as a first step, to assess if the main features of the simulated ecosystem dynamics are driven by the same physical mechanisms.

[6] The model intercomparison project described in this paper follows the latter approach of using extant simulations without a common protocol for initialization and forcing. Five models of the Arctic Ocean (both from the regional Arctic or global modeling efforts) are compared with a focus on the water column primary production, inorganic macronutrients and physical factors that are shaping them. In all five models the integration period is relatively short, and our analysis focuses on the present-day seasonal variability rather than the models’ long-term behavior that determines the large-scale pan-Arctic distribution of nutrients.

2. Participating Models

2.1. NEMO

[7] The Nucleus for European Modeling of the Ocean (NEMO) model is composed of an ocean general circulation model, OPA [Madec, 2008], coupled with the Louvain-la-Neuve Ice Model v2, LIM2 [Timmermann et al., 2005]. The version of NEMO used here is v3.2 and has a horizontal resolution of 1/4°, and a vertical resolution of 64 levels (6 m thickness at the surface to 250 m at 6000 m; fractional bottom grid boxes permit more realistic bathymetry). The LIM2 sea ice submodel is based upon a viscous-plastic rheology [Hibler, 1979] and three layer (two ice; one snow) thermodynamics [Semtner, 1976], and includes a number of updates to physical processes [Timmermann et al., 2005]. NEMO is forced at the surface using DFS4.1 fields developed by the European DRAKKAR collaboration [DRAKKAR Group, 2007]. This combines the CORE data set [Large and Yeager, 2004], which provides precipitation and downward short- and long-wave radiation, with the ERA40 reanalysis, from which 10 m wind and 2 m air humidity and temperature are supplied. The latter are used with the bulk formulae proposed by Large and Yeager [2004] to compute air-sea and air-ice heat and freshwater fluxes. Frequency of the forcing fields is monthly for precipitation; daily for radiation; 6 h for turbulent variables. Vertical mixing is parameterized using Turbulent Kinetic Energy (TKE) scheme [Gasparr, 1990] with subsequent modifications by Madec [2008].

[8] Biogeochemistry in NEMO is represented by the plankton ecosystem model MEDUSA (Model of ecosystem Dynamics, carbon Utilization, sequestration and Acidification) [Yool et al., 2011]. This is a size-based intermediate complexity model that divides the plankton community into “small” and “large” portions and which resolves the elemental cycles of nitrogen, silicon and iron. The “small” portion of the ecosystem is intended to represent the microbial loop of picophytoplankton and microzooplankton, while the “large” portion covers microphytoplankton (specifically diatoms) and mesozooplankton. The intention of MEDUSA is to separately represent small, fast-growing phytoplankton that are kept in check by similarly fast-growing protistan zooplankton, and large, slower-growing phytoplankton that are able to temporarily escape the control of slower-growing metazoan zooplankton. The nonliving particulate detritus pool is similarly split between small, slow-sinking particles that are simulated explicitly, and large, fast-sinking particles that are represented only implicitly. See Yool et al. [2011] for a full description of MEDUSA.

[9] The simulation of NEMO used here was originally performed to produce a high resolution, global-scale hindcast of marine biogeochemistry during the past two decades. An initial physics-only spin-up simulated the period 1978 to 1987 (10 years). The biogeochemistry was then coupled and MEDUSA was spun-up for the period 1988 to 2007 (20 years). An analysis of the Arctic region in the resulting simulation has previously been published by Popova et al. [2010]. Key properties of the model are summarized in Table 1.
Table 1. Summary of the Model Properties Directly Relevant to the Ecosystem Functioning

<table>
<thead>
<tr>
<th>Model domain</th>
<th>NEMO</th>
<th>LANL</th>
<th>UW</th>
<th>UL</th>
<th>OCCAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model minimum horizontal resolution (km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>global</td>
<td>global</td>
<td>north of 49°N</td>
<td>north of 65°N</td>
<td>global</td>
</tr>
<tr>
<td>resolution</td>
<td>≈5</td>
<td>23</td>
<td>≈5</td>
<td>55</td>
<td>111</td>
</tr>
<tr>
<td>AO maximum horizontal resolution (km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>≈15</td>
<td>62</td>
<td>≈30</td>
<td>55</td>
<td>111</td>
</tr>
<tr>
<td>resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO minimum vertical resolution (m)</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>3.4</td>
<td>5</td>
</tr>
<tr>
<td>AO maximum vertical resolution (m)</td>
<td>250</td>
<td>250</td>
<td>600</td>
<td>210</td>
<td>208</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UML depth</th>
<th>Physics + biology (years)</th>
<th>20 0 30 5188</th>
<th>10 34 50 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric forcing</td>
<td>TKE</td>
<td>DFS4.1</td>
<td>KPP Hanke and Holland [2007]</td>
</tr>
<tr>
<td>Ice physics</td>
<td>LIM2</td>
<td>CICE 4.0</td>
<td>VP-LSR, 12 thickness categories none</td>
</tr>
<tr>
<td>Ice biology</td>
<td>none</td>
<td>Deal et al. [2011]</td>
<td>Dupont (submitted manuscript, 2011)</td>
</tr>
<tr>
<td>Riverine input of nutrients</td>
<td>relaxation of N and Si toward climatology within 100 km of shoreline</td>
<td>4 mmol m⁻³ and monthly climatological river flow [see Holloway et al., 2007]</td>
<td></td>
</tr>
<tr>
<td>Number of ecosystem state variables</td>
<td>11</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>Explicit nutrient cycles</td>
<td>N, Si, Fe</td>
<td>N, Si, Fe, P,</td>
<td>N, Si</td>
</tr>
<tr>
<td>Physics only (years)</td>
<td>10</td>
<td>34</td>
<td>50</td>
</tr>
<tr>
<td>Physics + biology (years)</td>
<td>20</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

[a]OCCAM was simulated through the 1958–2004 forcing cycle four times. The first was for preindustrial spin-up, with the following three cycles representing the period 1864–2004 (inclusive), during which time anthropogenic changes to atmospheric pCO₂ were simulated. The results presented here are taken from the final forcing cycle, at which point OCCAM has undergone more than 140 years of simulation since its initial condition.

2.2. LANL

[10] The POP-CICE (Parallel Ocean Program–Sea ICE) model developed at Los Alamos National Laboratory (LANL) is coupled with an ice and ocean ecosystem model, described below. The model is discretized for a nonuniform, general curvilinear grids in which the North Pole has been moved smoothly into Greenland. For the experiments described here, we use a 320 × 384 global mesh. In the Northern Hemisphere the grid size ranges from 18 km (at high latitudes) to 85 km (at the equator). The vertical grid consists of 40 levels that vary in thickness from 10 m at the surface to 250 m below 2000 m depth. Atmospheric forcing data include six hourly air temperature, specific humidity, and wind velocity components from the Common Ocean Reference Experiments (CORE) version 2 (1958–2007) [Large and Yeager, 2009] along with monthly “normal year” precipitation from version 1 [Large and Yeager, 2004]. These data and version 2 of the Ocean Model Intercomparison Project’s cloud climatology [Röské, 2001] are used to calculate radiation fields following the AOMIP protocol, and total runoff in the Arctic also is specified following the AOMIP protocol [Hunke and Holland, 2007]. The present model run encompasses 1992–2007. The ocean component, POP 2.0 [Smith and Gent, 2002], employs the anisotropic Gent-McWilliams parameterization of Smith and Gent [2004] for lateral mixing. The K profile parameterization (KPP) [Large et al., 1994] provides vertical mixing of momentum and tracers. The sea ice component, CICE 4.0 [Hunke and Lipscomb, 2008], includes Bitz and Lipscomb [1999] thermodynamics, EVP dynamics [Hunke and Dukowicz, 1997, 2002], and horizontal transport via incremental remapping [Lipscomb and Hunke, 2004]. The thickness distribution within each grid cell is represented using five thickness categories, each with 1 layer of snow atop 4 layers ice.

[11] Biological model consists of (1) ice algal submodel in a 3 cm layer at the bottom of each sea ice thickness category [Jin et al., 2006, 2007, 2009; Deal et al., 2011] and (2) pelagic ecosystem model with 24 variables [Moore et al., 2004]: nitrate, ammonium, iron, silicate, phosphate, three types of phytoplankton (explicit C, Fe, and chlorophyll pools for each phytoplankton group, and an explicit Si pool for diatoms and CaCO₃ pool for small phytoplankton totaling 11 state variables), zooplankton, dissolved organic carbon, dissolved organic nitrogen, dissolved organic iron, dissolved organic phosphate, oxygen, dissolved inorganic carbon, and alkalinity. The two submodels were coupled through nutrient
and algal fluxes between the ice and ocean models [Jin et al., 2011].

[12] Initial conditions for ocean temperature, salinity and biological variables (NO3, Si) are from the gridded World Ocean Atlas (WOA2005) [Garcia et al., 2006]. Other ocean biological model initial conditions are taken from the global model simulation by Moore et al. [2004]. Sea ice initial conditions for the physical model are from an earlier run (1958–2006) [Hunke and Bizi, 2009] without the biological model. Initial conditions of nutrients at the bottom ice are set to sea surface values. The current version of the model does not consider riverine input of nutrients.

2.3. UW Model

[13] The UW model is the Biology/Ice/Ocean Modeling and Assimilation System (BIOMAS). BIOMAS is a coupled 3-D model consisting of three model elements: a sea ice model, an ocean circulation model, and a biological model [Zhang et al., 2010]. The sea ice model is the multicategory thickness and enthalpy distribution (TED) sea ice model [Hibler, 1980; Zhang and Rothrock, 2001, 2003]. It employs a teardrop viscous-plastic rheology [Zhang and Rothrock, 2005], a mechanical redistribution function for ice ridging [Thorndike et al., 1975; Hibler, 1980], and a LSR (Line Successive Relaxation) dynamics model to solve the ice momentum equation [Zhang and Hibler, 1997]. The ocean model is based on the Parallel Ocean Program (POP) developed at Los Alamos National Laboratory [Smith et al., 1992; Dukovicz and Smith, 1994]. The POP ocean model has been modified so that open boundary conditions can be specified [Zhang and Steele, 2000]. This modification allows the model to be nested to a global ice/ocean model of Zhang [2005]. Open boundary conditions are specified along the model’s southern boundary with sea surface height and ocean velocity, temperature, and salinity from the global model. Nitrate and silicate are restored to monthly climatology data from WOA2005 [Garcia et al., 2006] along the southern boundary. Ocean mixing follows the K profile parameterization, as discussed in the work of Zhang and Steele [2007], while ice-ocean heat flux parameterizations were discussed in the work of Hibler [1980] and Hibler and Bryan [1987].

[14] The biological model is based on the work of Zhang et al. [2010]. It incorporates two phytoplankton components (diatoms; flagellates), three zooplankton components (microzooplankton; copepods; predator zooplankton), dissolved organic nitrogen, detrital particulate organic nitrogen, particulate organic silica, nitrate, ammonium, and silicate.

[15] The model domain covers the Northern Hemisphere north of 49°N. Model grid configuration is based on a generalized curvilinear coordinate system with the “North Pole” of the model grid being displaced in Greenland by a linear orthogonal transformation. Mean horizontal resolution of both ice and ocean models is about 22 km. The ocean model’s vertical dimension has 30 levels of increasing thickness with depth, starting with six 5 m thick levels in the upper 30 m and then increasing gradually toward the bottom. Daily mean NCEP/NCAR reanalysis data are used as atmospheric forcing; that is, 10 m surface winds, 2 m surface air temperature (SAT), specific humidity, precipitation, evaporation, downwelling long-wave radiation, sea level pressure, and cloud fraction. Cloud fraction and SAT are used to calculate downwelling short-wave radiation following Parkinson and Washington [1979]. More model information can be found in the work of Zhang et al. [2010] and in Table 1.

2.4. UL Model

[16] The ocean model is an extension of the one used by Holloway and Sou [2002] and Steiner et al. [2003] and took part in the international intercomparison project for the ice-ocean models of the Arctic [Holloway et al., 2007; Hakkinen et al., 2007]. It is a z level model on a 55 km grid (rotated grid, limited to the Pan-Arctic ocean), with 40 levels down to 4350 m with the first layer being 3.4 m thick, and includes a parameterization of the “Neptune effect” [Holloway, 1987; Zou and Holloway, 1994] which represents the interactions between oceanic eddies and the bathymetry. This aims at reproducing certain aspects of the AO general circulation without resorting to eddy-resolving resolutions. The model also includes the tidal dissipation parameterization of Holloway and Proshutinsky [2007]. The atmospheric forcing comes from the NCEP/NCAR reanalysis in the form of daily 2 m air temperature, wind velocity, 2 m surface humidity and radiations, with air temperature corrections discussed in the work of Dupont (submitted manuscript, 2011).

[17] The biological model is a simple NPZD [Lima et al., 2002] model with four compartments for nitrate-phytoplankton-zooplankton-detritus (no further subdivision for species, size or nutrient) and was modified to the polar environment for temperature and light dependence (Dupont, submitted manuscript, 2011). It is able to capture a deep chlorophyll maximum if the phytoplankton sinking rate is fixed to ~0.1 m d−1, value retained hereafter. Another important addition was a sea-ice algae component based on the work of Lavoie et al. [2005], fit into the same 4 compartments described above. As such, the sea-ice NPZD model retains the same dynamics as for the pelagic model and assumes that all the biology occurs in a thin ice-ocean interface of 5 cm. Detritus is exported away from this interface as soon as it is produced, and nutrients are replenished via vertical turbulence flux. During ice growth, it is assumed that the phytoplankton present in the water will not be trapped in the ice matrix but will accumulate at the ice base, in the ice-ocean interface. As such it is assumed that this source of phytoplanktonic cells will give rise to the ice algae.

2.5. OCCAM

[18] OCCAM (Ocean Circulation and Climate Advanced Modeling project) is a global, primitive equation, finite difference ocean general circulation model. The version of OCCAM used here has a horizontal resolution of typically 1°, and a vertical resolution of 66 levels (5 m thickness at the surface to 200 m at depth; fractional bottom grid boxes permit more realistic bathymetry). OCCAM is organized into two horizontal grids to avoid a North Pole singularity, with grid 2 encompassing the North Atlantic and the Arctic Ocean, and grid 1 including the rest of the global ocean. The sea ice model comprises sea ice dynamics with elastic-viscous-plastic rheology (EVP) [e.g., Hunke, 2001], and ice thermodynamics derived from Semtner [1976] with 2 layers for sea ice and one for snow. The sea ice thermodynamics includes lateral and bottom ice melting and accounts for snow-ice formation. Sea ice is embedded into the upper oceanic layer conserving volume in the sea ice–ocean system. The dynamical coupling between sea ice and ocean is
done on each baroclinic oceanic time step via the quadratic drag law [McPhie, 1984]. The details of the OCCAM model are in the work of Aksenov et al. [2010]. OCCAM includes a K profile parameterization (KPP) mixed layer (see Large et al. [1997] with modifications described in the work of Popova et al. [2006]), Gent-McWilliams eddy parameterization and an advection scheme that is fourth-order accurate (a modified split-quick scheme). Surface fluxes of heat, freshwater and momentum are not specified directly, but are instead calculated using empirical formulae and NCEP-derived atmospheric boundary layer quantities (monthly for precipitation; daily for radiation; 6 h for turbulent variables). See Marsh et al. [2005] for a more complete description of OCCAM’s physics.

OCCAM’s biogeochemical model is a nitrogen-based nutrient-phytoplankton-zooplankton-detritus model; see Yool et al. [2011] for a complete description of OCCAM’s biogeochemistry. The simulation of OCCAM used here was originally performed to investigate the invasion of the ocean by anthropogenic CO2, and has been previously published in the work of Yool et al. [2009, 2010] and Saba et al. [2010]. Using multiple passes of the 1958–2004 NCEP forcing data, the simulation comprised one preindustrial spin-up cycle followed by three further cycles to represent the period 1864 to 2004. During the latter three cycles, atmospheric pCO2 was increased following the historical record. However, since the model plankton ecosystem is unaffected by changes in the carbon cycle, the output used here is drawn from the initial spin-up phase.

2.6. Summary of Participating Models

As described above, the five models participating in this intercomparison vary greatly in their numerics, parameterizations, geographical domain, grid resolution, initial/boundary conditions and in the complexity of their sea ice and ecosystem submodels. What is probably even more significant is that the models vary in the history of applications for which they were developed, and this typically determines the level of sophistication in their descriptions of particular processes. While it is outside of the scope of this paper to attempt to analyze the consequences of these differences for ecosystem dynamics, some features of particular importance for the intercomparison project are worth noting.

Three out of five participating models are global (NEMO, OCCAM and LANL) and two are regional (UL and UW), developed specifically for the Arctic Ocean. The AO is strongly coupled by advective processes to adjacent regions, and in the former cases its solution greatly depends on the quality of the simulation in the upstream regions (northern North Pacific and Atlantic), while in the latter cases the solution is significantly dictated by the quality of information at the inflow boundaries. Global models provide inflow information that is dynamically consistent with the interior of the AO. However, they tend to drift away from the observationally derived initial conditions with the increasing duration of the run. Such drift is usually most pronounced in the biogeochemical properties which have a short (annual) equilibration timescale in the upper ocean. Out of the three global models, OCCAM has the longest unconstrained run (180 years), while NEMO and LANL are both simulated for much shorter periods of about 30 years and are less likely to experience significant drift. Regional models are more heavily constrained by their observation-based boundary conditions, although in case of the UW model this constraint is imposed on the biogeochemistry only, since physical boundary conditions are taken from a lower-resolution global model.

Model resolution varies significantly from ~10 km (NEMO, UW) to ~100 km (OCCAM), with LANL and UL using an intermediate resolution of ~50 km. Although resolution significantly impacts the realism of the AO circulation features, especially advection from the upstream areas, none of the models is capable of resolving the Rossby radius of deformation which varies between ~1 km on the shelves and ~10 km in the deep AO (G. Nurser, personal communication, 2010). Thus, none of the models is capable of resolving mesoscale and other localized mechanisms of the nutrient supply such as eddy-induced, ice-edge and shelfbreak upwelling and topographic effects. Nonetheless, the significance of nutrient supply by small-scale mechanisms for large-scale biogeochemical budgets in the AO is not clear given the current state of observational and modeling understanding of AO dynamics.

Because of the role they play in determining upper ocean structure and the availability of light and nutrients, upper mixed layer (UML) dynamics are of key importance for the plankton ecosystem. They are modeled using a K profile parameterization (KPP) in the OCCAM, LANL and UW models, a Turbulent Kinetic Energy (TKE) scheme in the UL and NEMO models. Although various theoretical arguments have been put forward to promote the latter model, there appears to be no strong evidence that more advanced representations of turbulence, such as the TKE scheme, provide consistently better results in global or basin-scale models than simpler schemes such as KPP. For instance, in a global analysis of UML dynamics in OCCAM, Popova et al. [2006] found that the KPP scheme had a tendency to systematically overestimate winter mixing depth while estimating summer UML depths that were too shallow compared to observations. However, modifications to KPP parameters were sufficient to improve the representation of the UML for the realistic behavior of biological tracers.

The ecosystem dynamics represented in participating models varies substantially, ranging from UL’s simple, four component nutrient-phytoplankton-zooplankton-detritus (NPZD) model, to the complex, 24 component plankton functional type (PFT) model employed in LANL. However, in spite of numerous apparent differences, the hierarchy of the ecosystem models employed and the range of their applicability is clear.

The simplest model in the intercomparison is that used in the UL model, a four state variable ecosystem that is based on the nitrogen cycle only, and which includes single phytoplankton, zooplankton and detritus components.

OCCAM uses a very similar NPZD structure based around the nitrogen cycle (but with different governing equations). These allow OCCAM to directly simulate carbon cycle dynamics, and permit additional aspects such as non-Redfield stoichiometry.

The UW model separates 11 state variables and takes a significant step toward increased ecosystem complexity by adding silicate as a second nutrient and splitting phytoplankton into two functional types. The resulting model identifies diatoms (limited by nitrogen and silicon) and
3. Results

We focus our analysis here on the comparison of the total annual, vertically integrated primary production and the physical factors that regulate it in the AO. We have specifically chosen to examine year 1998 since this falls in the overlap between the runs of participating model (see Table 1), it is sufficiently forward in time from run initialization to be at least partially equilibrated and avoid strong drift, and it does not experience the (unrepresentative) low ice extent of 2006 and 2007.

3.1. Total Primary Production

Figures 1a–1e show total annual, vertically integrated primary production for year 1998 for all five models, and that estimated using satellite-derived observations (Figure 1f) [Pabi et al., 2008]. Note that model-observation comparison should be undertaken with care here for several reasons. First, satellite-derived primary production is based on an empirical model which includes a number of assumptions (e.g., the vertical structure of primary production) and which has been subject to only limited verification for the Arctic. Second, problems associated with quantifying chlorophyll-a (Chl-a) from remotely sensed ocean color are particularly acute in the Arctic relative to other parts of the World Ocean. These problems include restriction of observations to waters with sea ice concentrations of less than 10%; signal contamination by sea ice itself; the frequent occurrence of Arctic fog in areas coincident with maximum Chl-a concentrations [e.g., Perrette et al., 2010]; and signal contamination by colored dissolved organic matter (CDOM) in areas affected by riverine input. In addition, the vertical distribution of Chl-a in the AO is characterized by a strong subsurface maximum that occurs below the upper mixed layer (UML) and which cannot be detected remotely [e.g., Hill and Cota, 2005]. Pabi et al. [2008] assume an exponential decline of Chl-a below the UML which may have introduced substantial errors in the depth-integrated estimates. For comparison, the synthesis of in situ data [cf. Carmack et al., 2006, Figure 13] suggests that satellite-derived values of productivity at the Pacific and Atlantic inflows are generally underestimated, while values along the Siberian and Canadian coastline are overestimated. Nevertheless, since satellite-derived estimates of primary production remain the only source of high-resolution spatiotemporal information, we retain the Pabi et al. [2008] data here.

As can be seen from Figure 1, all models are in general agreement on the main features of the spatial distribution of primary production across the AO. The highest observed and modeled values occur in the Norwegian Sea and on the inflow shelves to the Arctic (Chukchi and Barents seas) [Carmack et al., 2006]. These regions are where the influence of the high-nutrient environments of the North Pacific and North Atlantic is the greatest. The central Arctic, with its permanent ice cover, manifests the lowest values, while productivity of the seasonally ice-free shelves shows intermediate values in good agreement with the in situ data [Carmack et al., 2006]. However, in spite of general agreement on the large-scale distribution patterns, there are substantial regional variations between the models. Thus, the Chukchi Sea, which has the highest observed productivity in the Arctic Ocean (reaching 400 g C m\(^{-2}\) yr\(^{-1}\)) [Sakshaug, 2004; Carmack et al., 2006] is only moderately productive (less than 100 g C m\(^{-2}\) yr\(^{-1}\)) in the OCCAM and UL while the rest of the models appear to reproduce this “hot spot” of productivity relatively well. Similarly, OCCAM substantially underestimates the productivity of the Norwegian and Barents Seas with values of 70–100 g C m\(^{-2}\) yr\(^{-1}\) compared...
with observed values that reach 150–200 g C m⁻² yr⁻¹. Given these patterns of observed and modeled primary production, a number of critical questions occur. What drives similarities and differences between the model estimates of Arctic production? Primary production in the AO is determined by a complex interplay between light and nutrient availability and stratification. Are similar features between models (and observations) driven by similar underlying physical processes? In sections 3.2–3.4 we investigate the main physical drivers that influence the magnitude and distribution of ocean primary production in the Arctic.

3.2. Short-Wave Radiation and Ice Concentration

The AO manifests extreme seasonality in light regime from permanent darkness during winter to continuous sunlight in summer, though even then solar elevation remains low. Light availability is also strongly influenced by the presence of sea ice, which (especially with snow cover) reduces the irradiance reach the ocean to a fraction of its value immediately above the ice. However, sea ice concentration is often less than 100% during the summer months, with regions experiencing coverage of 80–90% even in areas of multiannual ice [Sakshaug, 2004]. Thus, in considering impact of light on large-scale distribution of primary production, two characteristics of prime importance are: downwelling short-wave radiation at the surface of the ocean and sea ice concentration.

The modeled and observed (HadISST) [Rayner et al., 2003] monthly mean sea ice concentrations for September (the month of the minimal ice extent) are shown in Figure 2. Although the correlation between observed and modeled data is high (correlation coefficient are ~0.7 for UW, LANL and NEMO and ~0.6 for UL and OCCAM) there are substantial disagreements in respect to features of spatial variability. For instance, four models (NEMO, LANL, UW and UL) systematically underestimate sea ice concentration in the central AO by 20–30%, and by 50% in certain areas (e.g., NEMO and UL show pronounced minimum in the Laptev sector with concentrations below 50% compared to observed values of 90%). This underestimation of sea ice concentration leads to an equivalent overestimation of short-wave radiation in these regions and, therefore, also the availability of photosynthetically active radiation (PAR) for phytoplankton. The final model, OCCAM, does not follow this pattern and generally
overestimates sea ice extent and manifests much higher concentration, extending permanent cover onto the shelves of the Beaufort and Laptev Seas, and into Baffin Bay contrary to observations. Because of a number of significant differences in both the ice models and surface forcing fields, it is difficult to isolate the reason (or reasons) for the reduced Central Arctic sea ice cover simulated by the four models. At the same time an alternative algorithm [e.g., Cavalieri et al., 1996] of sea ice estimation gives much lower ice concentrations in summer (Figure 3) possibly due to retrievals of surface melt ponds looking like open water. The differences between the two algorithms are substantial and their assessment is outside of the scope of this paper. We can only comment that the bias may not be significantly detrimental for the simulation of physics in the upper and intermediate ocean, but may cause the light regime to be unrealistically favorable for primary production and that it requires further investigation.

3.3. Depth of the Upper Mixed Layer

[35] Although the impact of sea ice on productivity is most immediately evident through its control of the penetration of
solar radiation into the ocean, ice influence is not restricted to the ambient light regime. Sea ice also affects vertical stratification via salt rejection in winter and fresh water input in summer and by presenting a barrier to wind-driven mixing of the water column. In addition by contributing fresh water through melting during spring and summer time it acts to strengthen water column stratification which inhibits nutrient resupply from below and provides an additional constraint on primary production [Carmack et al., 2006].

Winter mixing is one of the two main mechanisms that supply nutrients into the photic zone of the AO and which, in doing so, set up a limit available for the consumption by phytoplankton. The second mechanism is horizontal advection of more nutrient-rich seawater, most prominently via the Pacific and Atlantic inflows to the AO. In addition, there is a number of secondary mechanisms that can influence nutrient supply and primary production on a local scale and episodically. These include severe storms and internal waves that erode the halocline, enhanced tidal mixing in the areas of rough topography, wind-driven shelf break and ice edge upwellings and the turbulent wake behind banks and cyclonic eddies. Since the horizontal resolution of the models employed in this study is insufficient to permit localized nutrient supply mechanisms, some small-scale or episodic “hot spots” of productivity are beyond our analysis and we have instead focused on winter mixing as the main mechanism controlling basin-scale patterns of nutrient supply.

The maximum depth of the UML during the year (based on monthly mean values) from the models and WOA climatology [Locarnini et al., 2006; Antonov et al., 2006] (using variable density criterion) is shown in Figure 4. Owing to the very stable stratification of the AO, deep winter mixing (in excess of 300 m) occurs only in the Atlantic inflow waters in the southeast Greenland and southwest Barents sectors (see Figure 4f). Two additional features of importance to ecosystem productivity are apparent from observational mixed layer depth: (1) winter mixing rarely exceeds 80 m outside of the Atlantic inflow, and on average is only 40 m and (2) mixing does not penetrate deeper than 20 m throughout the year on the Siberian shelves which are affected by significant riverine inputs of fresh water.
All participating models reproduce the occurrence of the deep mixing in the Atlantic inflow, although its magnitude and spatial extent vary. It is most intense (deeper than 1000 m) in the LANL and UW models, and shallower in the NEMO, UL and OCCAM models (500–700 m). As the DIN profile is relatively homogeneous in these areas below 700 m, the difference in the depth of winter convection should not have a significant effect on the winter nutrient supply in the models. However, difference in mixing in the central AO between the models is of substantial importance. Thus, NEMO and OCCAM both show good agreement with observations in confining deep mixing to Atlantic inflow waters, while LANL and UL both show overestimate mixing in the central AO with values up to 300 m over significant areas. UL also shows overestimated values although to a lesser degree than LANL and UW, generally reaching 90–110 m over the central AO. All models find mixing over the Siberian shelves to be more shallow than in other areas reflecting the influence of the freshwater input by Siberian rivers. However, this effect appears to be less pronounced in the LANL, OCCAM and UW models, where mixing in the East Siberian Sea penetrates down to the bottom (50–70 m) over large areas of the shelf.

### 3.4. Inorganic Nutrients

Nitrogen appears to be the primary limiting nutrient in the Arctic as it is the first to become exhausted in bloom events [see Tremblay and Gagnon, 2009, and references therein]. All five participating models use nitrogen as their base “currency” although NEMO, LANL and UW also include silicic acid in order to distinguish between diatom and nondiatom phytoplankton. In addition UW and LANL include ammonium as a state variable, however, as ammonium concentrations are usually small, we consider nitrate as a representative of dissolved inorganic nutrient (DIN) in all models. All models are similar in the way they initialize DIN (WOA05) [Garcia et al., 2006]; however, they vary in boundary conditions. Two regional models (UW and UL) specify monthly WOA05 on the open boundaries while three global models crucially depend on the quality of their solution in upstream areas (northern North Pacific and Atlantic) for correct representation of the nutrient supply through the Bering Strait and Atlantic inflow. Additionally, while the

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**Figure 5.** Maximum DIN concentrations (in mmol N m$^{-3}$) on the basis of monthly averaged values for (a) NEMO, (b) LANL, (c) UW, (d) UL, (e) OCCAM, and (f) WOA climatology.
rest of the models ignore riverine inputs of nutrients, NEMO includes a simplified representation in which the concentrations of N and Si are relaxed toward the WOA climatology within 100 km of shoreline. This approach aims to take account of poorly known concentrations of nutrients in rivers and their transformation in unresolved near-coastal areas.

Here we focus our analysis of modeled nutrient dynamics on two metrics: the maximum and minimum surface nutrient concentrations during the year (based on monthly mean model output). The maximum value usually occurs at the end of the winter season and is strongly driven by physical processes such as winter mixing and horizontal advection of seawater with high nutrient concentrations from the northern North Pacific and Atlantic basins. The minimum value of DIN typically occurs in summer months and reflects the local conditions for primary production. Where phytoplankton have a relatively long growing season because of early ice melt, nutrient concentrations generally fall below their half-saturation constants for uptake by phytoplankton, and nutrient limitation regulates production. Where minimum nutrient concentrations are still relatively high, this is indicative of light availability setting an upper limit on annual primary production [e.g., Popova et al., 2010]. Maximum DIN concentrations for all models and from the WOA climatology are shown in Figure 5. The WOA climatology suffers from substantial undersampling in the AO (e.g., characteristic pole-oriented pattern typical of extrapolation into unsampled areas). Figure 6, showing total number of observations used in WOA climatology for surface DIN (Figure 6a) in comparison to temperature (Figure 6b), clearly demonstrates magnitude of the undersampling. Nevertheless three main features are apparent in the spatial distribution: (1) nutrient concentrations are greatest in the areas of Pacific and Atlantic inflow; (2) typical values in the central AO are low and ~1 mmol N m\(^{-3}\); and (3) Siberian shelves show the lowest values over the AO basin which are comparable or below the typical half-saturation values for DIN uptake (0.5–1 mmol N m\(^{-3}\)). The model which is probably the closest to the observed pattern is NEMO (Figure 5a) although it underestimates the already low nutrient concentrations in the central basin by about a factor of 2. In addition it also underestimates nutrient concentration at the Pacific and Atlantic inflows by 2–3 mmol N m\(^{-3}\) (10–20%). Underestimation of nutrients in the central Arctic results in NEMO from excessive productivity under sea ice, the concentrations of which are underestimated by the model (see section 3.2 and Figure 1). We can speculate that improvement of ice concentration in NEMO will improve the agreement with observed nutrients. Slight underestimation of the DIN at the Pacific and Atlantic inflow is driven by model performance in upstream areas and will require further verification which is beyond the scope of this paper.

UW and LANL both show excellent agreement with the observed DIN at the Pacific and Atlantic inflows. However, in very similar ways, both also suffer from two problems. The first is overestimation of nutrients in the central AO (with values in excess of 10 mmol N m\(^{-3}\)), which generally follows the corresponding pattern of overestimated winter mixing (cf. Figure 4). The second problem is extremely high nutrient concentrations (in excess of 15 mmol N m\(^{-3}\)) on the Siberian shelves, and in particular in the East Siberian and Laptev seas, where observed values of DIN appear to be very low. This overestimation appears to arise from excessive mixing on the Siberian shelves. Given their shallow depth (e.g., average depth of the East Siberia Sea is only 45 m), a few mixing events during the year which penetrate to the bottom layer of the model are sufficient to provide entrainment of high deep nutrient concentrations. This is contrary to observations that show year-round stable low-salinity layer on the top of the water column which efficiently prevents entrainment of the high near-bottom nutrients [Nitishinsky et al., 2007].

The UL model shows elevated DIN concentrations at the Atlantic inflow although its pattern (which closely follows that of winter mixing; cf. Figure 4) does not agree well with the observations (Figure 5f), and is generally confined to the shelf break of the Norwegian and Greenland Seas. The model also underestimates DIN concentration north of the Bering Strait where model boundary conditions require further verification. Similarly to UW and LANL models, UL also overestimates mixing in the central AO.
leading to concomitant overestimation of nutrients, although this problem is not as pronounced as in the two former models.

[43] OCCAM’s distribution of DIN (Figure 5e) does not follow the general tendency of DIN in four other models to mimic the dynamics of the maximum winter mixing. The model shows overestimated DIN concentrations in excess of 15 mmol N m\(^{-3}\) over the majority of the AO with maximum values at the Pacific inflow despite its realistic spatial distribution of the UML depth. An explanation for this pattern lies in part in OCCAM’s overestimation of sea ice extent (see Figure 2e and section 3.2). As perennial sea ice cover in this model extends too far south onto the Canadian and Siberian shelves and leaves only small portion of the southern Chukchi Sea briefly open to the sunlight, and essentially suppresses productivity in all areas other than in the Atlantic inflow region. Thus nutrient-rich, low-salinity water penetrating from the Bering Strait and residing in the upper water column [Carmack et al., 2006] retains its high nutrient concentrations contrary to the observations which show quick nutrient utilization downstream owing to the highly productive waters of the Chukchi and Beaufort sectors. Analysis of OCCAM equilibration dynamics during the spin-up phase (not shown) finds that it takes 10 to 20 years for the nutrient-rich waters to penetrate into the AO through the Beaufort gyre up to the Lomonosov ridge and establish a persistent and high nutrient environment over the majority of the AO.

[44] Minimum nutrient concentrations in the models and observations (WOA2005) are shown in Figure 7. Here, again, we must take care in interpreting details of the spatial distribution from climatological data in the heavily undersampled AO (Figure 6). Nevertheless the climatology unambiguously points toward the fact that, over the majority of the AO, DIN is drawn down to concentrations below its half-saturation level at some stage during the summer, with the exception of areas immediately north of the Bering Strait and Atlantic inflow. As seen previously, NEMO is the only model which shows nutrient exhaustion over the majority of the AO. Nevertheless, it underestimates residual nutrients at the Atlantic inflow implying that total AO regime is more oligotrophic than is actually observed. The rest of the models overestimate unutilized nutrients to a various degree (especially OCCAM), although LANL, UW and UL model

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**Figure 7.** Minimum DIN concentration (in mmol N m\(^{-3}\)) on the basis of monthly averaged values for (a) NEMO, (b) LANL, (c) UW, (d) UL, (e) OCCAM, and (f) WOA climatology.
agree on summer oligotrophic conditions on the Beaufort shelves.

[45] Model skill in reproducing annual minimum nutrient concentrations in the AO is probably the most crucial test to demonstrate if the realistic distribution of the primary production is achieved for the right reasons and driven by the right physical mechanisms. In the AO, where both nutrient and light limitation of primary production is tightly controlled by the distribution of ice, it is easy to fall into a trap of correctly modeling only one of two factors with a satisfactory consequence for the distribution of the total productivity. Thus, in our intercomparison experiment: OCCAM finds that the present-day (1998) AO is totally limited by light; LANL and UL generally agree on about 2/3 of the total area being limited by light (minimum DIN concentration above half-saturation level) and 1/3 by the nutrients; UW points toward 1/3 of the total OA area being limited by light; and NEMO finds nutrient limitation of the entire ocean except a small area immediately adjacent to the Bering Strait.

4. Potential Role of the Ice Algae

[46] One immediate caveat to our analysis is that it has focused on total annual AO primary production, which is dominated by water column primary production in the seasonally ice-free AO where productivity is highest. This approach ignores the role played by attached ice algae. These have the ability to grow at low-light levels [Kirst and Wiencke, 1995] and provide food in autumn and spring, when phytoplankton in the water column are scarce [Bluhm and Gradinger, 2008; Schnack-Schiel, 2003]. Further, both observations and model results indicate that upon ice melt, release of substantial amounts of ice algae biomass can contribute to phytoplankton seeding and nutrition of zooplankton and benthos [see Gradinger, 2009, and references therein; Jin et al., 2007, 2009]. On the basis of estimates from observations, more than 50% of primary production in the central AO covered by perennial ice where water column production is low is attributed to ice algae [Gosselin et al., 1997], while on Arctic shelf seas, the percentage of marine production by ice algae is estimated to be between 4 and 25%, depending upon location [Legendre et al., 1992]. Only the LANL and UL models in this intercomparison study includes ice algae and ice algal production. Pan-Arctic results for simulated primary production within sea ice from these models can be found in the work of Jin et al. [2011] and Dupont (submitted manuscript, 2011). Although importance of ice algae as an early and concentrated food source for higher trophic levels is clear, assessment of the necessity of their inclusion in large-scale models aimed at lower trophic levels is outside of the scope of this paper.

5. Discussion and Conclusions

[47] In this study we have compared Arctic Ocean (AO) primary production, and the physical factors controlling it, in five general circulation models with coupled biogeochemistry. All participating model reproduce broadly similar patterns of total annual AO primary production with the highest values at the Atlantic and Pacific inflows and low values in the central Arctic, in agreement with both satellite-derived and in situ data. Nevertheless, the physical factors controlling this distribution in the five models are different.

[48] Production in the Arctic Ocean is known to be colimited by availability of light and nutrients. Our analysis finds that sea ice extent and concentration are broadly similar among the models, and provide comparable levels of light limitation. However, substantial differences in the depth of winter mixing between the participating models provide significantly different amounts of nutrients available for the phytoplankton to utilize during the spring and summer productive season. The nutrient climatology from the World Ocean Atlas shows that nitrate concentrations fall below the half-saturation level over at least 70% of the area of the AO.

[49] The annual minimum nutrient concentration varies substantially between the participating models from near-complete utilization across the AO in some models to year-round nutrient replete conditions in others. A root cause of the unrealistically high nutrient concentrations found in some of the models is excessive vertical mixing, and this shifts the balance between the relative importance of nutrient and light limitation in the AO. These differences between models might not be detrimental in determining present-day AO primary production since both light and nutrient limitation are tightly coupled to the presence of ice. Essentially, as long as at least one of the two limiting factors is reproduced correctly, simulated total primary production will be close to that observed. However, if the retreat of the Arctic sea ice continues into the future as expected, a decoupling between sea ice and nutrient limitation will occur and the future predictive capabilities of the models will potentially diminish.

[50] Consequently, in finding a high sensitivity of the Arctic Ocean primary production to vertical mixing, and echoing earlier studies for other regions of the World Ocean, our study emphasizes the importance of its realistic representation in ocean GCMs.

6. Recommendation for Future AO Modeling Studies

[51] 1. Our study represents only a first step toward AO ecosystem model intercomparison and as such, it has only focused on total water column primary production. However, it is “export” rather than total primary production that controls removal of the organic carbon into the deep ocean and out of the contact with the atmosphere [e.g., Eppley and Peterson, 1979]. Thus, ecosystem model intercomparison experiments should in future address a split between new and regenerated fractions of primary production and their potential future changes as a way to assess model uncertainty in predicting AO impact on the atmospheric CO₂.

[52] 2. This study focuses on the magnitude of AO primary production in the pelagic plankton ecosystem and largely ignores the role of attached sea ice algae. These occur on the underside of sea ice, and provide a concentrated food source for metazoan grazers that in turn feed fish, seabirds and marine mammals [Bluhm and Gradinger, 2008; Schnack-Schiel, 2003]. Because sea ice algae are adapted for growth at the low-light levels that occur under sea ice [Kirst and Wiencke, 1995], they bloom earlier in the year than phytoplankton, and serve as a food source for both pelagic and benthic communities [Gradinger, 2009]. Furthermore, ice algae are released into the water column upon sea ice melt.
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References


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