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Bio-physical feedbacks in the Arctic Ocean using an Earth system model

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[1] An Earth System model with an oceanic biogeochemical component is shown to reproduce accurately the seasonal course of sea-ice and chlorophyll distribution in the Arctic region. It is argued that the phytoplankton blooms that occur concomitantly with the ice retreat along the Arctic coastal shelves in spring and summer strongly impact the Arctic climate and improve the sea-ice distribution in the model. Indeed, these blooms modify the vertical distribution of radiant heating and trap the penetrating solar heat flux at the surface in these regions. The resulting surface warming triggers a reduction of sea-ice thickness and concentration. This reduction increases the solar energy penetrating into the ocean, therefore providing a positive feedback that further amplifies the direct biological warming. The increased melting, precipitation and runoff related to these bio-physical feedbacks freshen the Arctic Ocean and the Greenland Sea, provoking a slight slowdown of the overturning circulation. **Citation:** Lengaigne, M., G. Madec, L. Bopp, C. Menkes, O. Aumont, and P. Cadule (2009), Bio-physical feedbacks in the Arctic Ocean using an Earth system model, *Geophys. Res. Lett.*, *36*, L21602, doi:10.1029/2009GL040145.

1. Introduction

[2] Chlorophyll and related pigments that strongly absorb light in the blue and red frequencies serve as vertical redistributors of radiant heating [e.g., *Ohlmann et al.*, 1996] and have therefore been suggested to feedback onto the ocean physical properties. Most of the previous studies have focused on the tropical and mid-latitude regions. In the Arabian Sea [*Sathyendranath et al.*, 1991] and in the equatorial Pacific [e.g., *Strutton and Chavez*, 2004], observational evidences support the hypothesis that chlorophyll is an important component of the upper-ocean heat budget. Modeling studies have consequently investigated the sensitivity of the tropical and mid-latitude climate system to changes in the spatial and/or temporal distribution of shortwave absorption related to chlorophyll by using ocean-only [e.g., *Nakamoto et al.*, 2001; *Murtugudde et al.*, 2002] and coupled ocean-atmosphere models [e.g., *Wetzel et al.*, 2006; *Lengaigne et al.*, 2007]. These simulations confirm the impact of chlorophyll on the tropical climate (~1°C warming of the upwelling regions, changes of the simulated characteristics of the El Niño/Southern Oscillation) and on mid-latitudes (amplification of the seasonal cycle). These changes involve a direct biological heating originating from a modification of the light attenuation by chlorophyll and feedbacks through modifications of the mixed layer depth and ocean-atmosphere interactions that lead to an amplification of the biologically induced temperature changes.

[3] Fewer studies have investigated the potential influence of the biological activity in the polar regions. These regions are characterized by intense blooms of phytoplankton along the coastal shelves during the ice retreat [*Pabi et al.*, 2008]. The direct surface biological heating generated by these blooms is likely to increase sea-ice melting along the shelves. This could allow more shortwave radiation to penetrate into the ocean and amplify the initial warming, therefore providing a new positive bio-physical feedback. Using an ocean model, *Manizza et al.* [2005] suggest that phytoplankton slightly reduces sea-ice cover in the Southern Hemisphere, with almost no impact over the Arctic Ocean. However, the prescribed atmospheric forcing in this forced study prevents ocean-atmosphere feedbacks to develop and therefore strongly constrains the sea-ice evolution, limiting the assessment of such bio-physical feedbacks on polar climate.

[4] In this study, we examine the impact of marine phytoplankton on surface ocean and sea-ice in the Arctic Ocean using a Earth System model including a state-of-the-art biological model representing space-and-time varying chlorophyll concentrations. The focus of our study onto the Artic Ocean is explained by the realistic patterns of both simulated ice concentration and chlorophyll in this region as compared to the Southern Ocean.

2. Model and Experiments

[5] The model used in this study is the IPSL-CM4 model [*Marti et al.*, 2008] that couples five components of the Earth System. LMDZ-4 [*Hourdin et al.*, 2006] is the component for atmospheric dynamics and physics and has a 3.75° zonal and 2.5° meridional resolution, with 19 levels in the vertical. ORCA2 and PISCES, both described by *Aumont and Bopp* [2006], are the components for the ocean dynamics and biogeochemistry, respectively. They have a 2° zonal resolution, a meridional resolution varying from 0.5° at the equator to 2°cos(lat) poleward of 20°, and 31 vertical levels spacing of 10 m in the upper 150 m. LIM [*Timmermann et al.*, 2005] is the interactive sea-ice model with explicit thermodynamics and prognostically computed sea-ice and ORCHIDEE handles the land surface. These components have been coupled through OASIS 3 [*Valcke et al.*, 2000]. Air-sea, air-ice fluxes and SST are exchanged every day.

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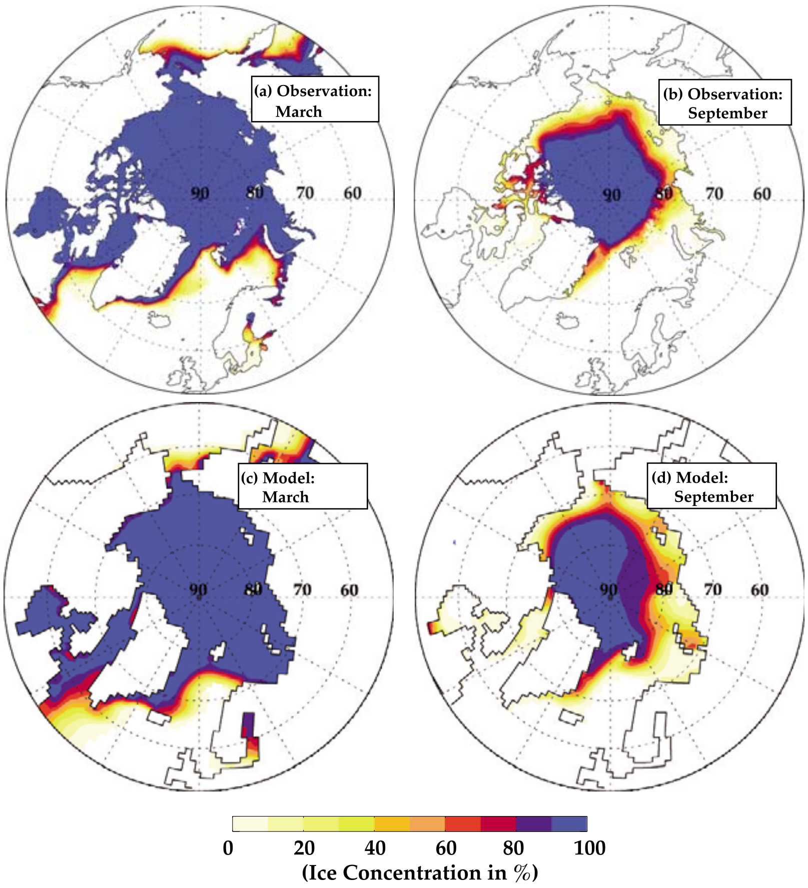


Figure 1. Observed mean 1979–2004 Sea-Ice Concentration from Nimbus-7 SMMR and DMSP SSM/I satellite data [*Comiso*, 2007] in the Arctic Ocean in (a) March and (b) September. (c and d) Same for fullBIO experiment.

[6] The twin experiments used here are identical to those described by *Lengaigne et al.* [2007]. The reference experiment (hereafter fullBIO) simulates the full biological-ocean-atmosphere interactions: the chlorophyll concentration produced by the biological component retroacts on the ocean heat budget by modulating the absorption of light via a polychromatic model that is used to calculate the phytoplankton light limitation as well as the oceanic heating rate (see *Lengaigne et al.* [2007] for a detailed description). In the sensitivity experiment (hereafter cstBIO), chlorophyll concentrations are artificially set to a constant value of 0.06 mg.m^{-3} (corresponding to an attenuation depth of 23 m, like for Jerlov 1A type water [*Jerlov*, 1968]) to simulate the absorption profile typical of oligotrophic waters. This choice of 0.06 mg.m^{-3} has been guided by the fact that a constant attenuation depth of ~20 m is commonly used in most of ocean general circulation models, and thus in most climate models. The two simulations were run for 100 years each, starting from the same initial conditions (the last time step of a previous 100-year simulation), and are compared over the last 80 years to assess the influence of biological activity on the Arctic Ocean (defined as waters north of 66°N).

3. Simulated Arctic Sea-Ice and Chlorophyll

[7] Figure 1 shows that the main spatial patterns of sea-ice concentration in March and September are accurately reproduced in fullBIO compared to observations. In particular, this experiment accurately simulates the reduction of sea-ice cover along the coast of Siberia and Alaska in summer and fall. The model closely matches the observed seasonal variation of sea-ice with a maximum area in winter (1.44 10^7 km^2 in both model and observations) and a minimum in summer (6.5 10^6 km^2 in the model vs 6.1 10^6 km^2 in observations). Aside model biases, the slight sea-ice overestimate in summer could arise from the comparison of sea-ice simulated for pre-industrial conditions to the one observed over the recent period where sea-ice area have been shown to decline. A direct comparison cannot be conducted for ice thickness due to the lack of data. However, as in most other coupled models, a too thick ice develops in the interior of the Arctic Ocean (not shown) but the modeled annual mean Arctic ice volume (2.14 × 10^4 km^3) agrees well with ocean-sea-ice hindcast estimates (2.13 × 10^4 km^3 [*Gerdes and Koeberle*, 2007]) and its interannual variability is very similar.

[8] Figure 2 summarizes the spatial and temporal chlorophyll variations in the Arctic region. During wintertime, the extended ice cover and polar night result in very low chlorophyll concentrations in the Arctic Ocean (Figure 2a). From March, the increase irradiance and a stable surface layer caused by melting create favorable conditions for phytoplankton growth behind the retreating ice edge. Surface layer chlorophyll concentrations peak in June when

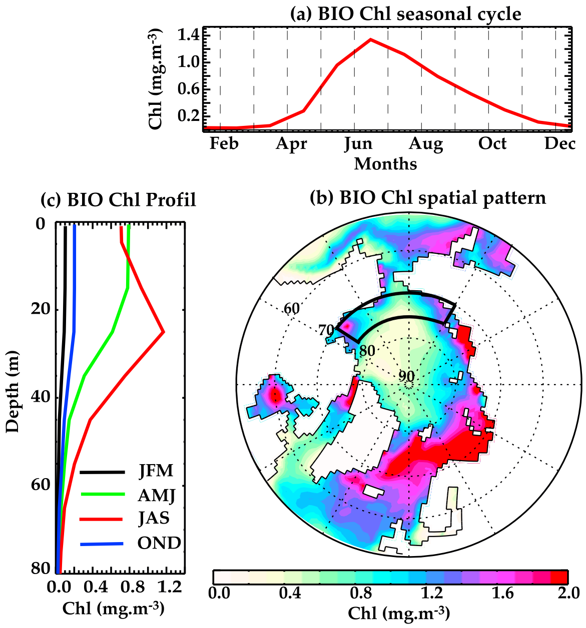


Figure 2. Mean seasonal cycle of chlorophyll concentration simulated in fullBIO experiment. (a) Averaged for latitudes north of 66°N for the top 30 m. (b) Spatial distribution in June averaged for the top 30 m. (c) Vertical profiles for each season averaged for the area, 70°−75°N, 150°E−130°W, denoted by the box shown on Figure 2b. Units are in mg.m^{-3}.

solar insolation is maximum over the Arctic region, with the highest chlorophyll concentrations simulated along the coastal regions and in the Greenland, Barents and Kara Seas (Figure 2b). Comparison with SeaWiFS ocean color data [*Pabi et al.*, 2008] indicates that the spatial and temporal chlorophyll variations are reasonably well reproduced by the model, with highest concentrations along coastal regions and a seasonal maximum in summer in both datasets [see *Pabi et al.*, 2008, Figures 7 and 12b]. The model however slightly underestimates the averaged summer surface Chl-a concentrations, with mean values inferred from satellite data exceeding 1.7 mg.m^{-3} compared to 1.3 mg.m^{-3} in fullBIO experiment (Figure 2a).

[9] The seasonal vertical distribution of chlorophyll is displayed on Figure 2c within a region located along the coast of the Beaufort and east Siberian Seas, where *in situ* observations were available for comparison. The modeled vertical profiles exhibit a surface maximum during the spring bloom followed by a strong subsurface maximum at 25 m in summer, in agreement with *in situ* measurements in the Beaufort and Chucki Seas [*Hill and Cota*, 2005; *Liu et al.*, 2007]. As suggested by *Hill and Cota* [2005], this subsurface maximum in summer could result from the depletion of surface nutrients following the spring bloom, limiting the surface growth and favoring the appearance of a chlorophyll maximum at depth.

4. Bio-physical Feedbacks

[10] Comparing fullBIO to cstBIO allows assessing the influence of light attenuation due to an interactive chlorophyll on the Arctic surface ocean and sea-ice (Figure 3). Biological surface radiant heating in fullBIO is always greater or equal to the one in cstBIO in the Arctic region as during polar night no light is available and biological heating cannot operate while during spring and summer chlorophyll concentrations in fullBIO exceed the low value imposed in cstBIO (0.06 mg.m^{-3}). Our results indicate that using an interactive biology results in a warming of the ocean surface along the coastal shelves of Alaska and Siberia (Figure 3a). This warming can be explained by a direct biological heating due to changes in light attenuation enhanced by an indirect contribution originating from enhanced ice melting. The presence of chlorophyll blooms from spring occurring behind the retreating ice edge along the shelves indeed acts to directly warm the surface ocean by trapping solar heating in the ocean surface layer (15% increase due to light attenuation changes). This direct biological warming enhances ice melting (Figure 3c), thereby increasing solar heat flux penetrating into the ocean and further favoring phytoplankton growth in these regions. It results in an additional ~15% increase in surface heating that act to further amplifies the direct biological warming. Along the continental shelves of Alaska and Siberia, accounting for these bio-physical feedbacks allows to warm by ~0.5°C the surface temperature, divide by a factor of two sea-ice concentration and reduce by ~2−3 m ice thickness in late summer (Figures 3a, 3b, and 3c). The overall ice thickness decrease leads to an annual mean sea-ice volume reduction of ~17% in fullBIO. While cstBIO ovestimates sea-ice concentration along the shelves of Alaska and Siberia as well as the overall Arctic sea-ice area in summer and annual mean volume by more than 15%, including these biophysical feedbacks in fullBIO strongly reduces these biases and brings modeled sea-ice characteristics close the observed estimates (see section 3). Sea-ice thickness is not only reduced along the shelves but also in the central part of the basin where low chlorophyll concentrations and therefore low heating rate differences are found. The sea-ice thickness decrease in central Arctic is therefore unlikely to be primarily driven by local processes but more presumably by horizontal advection of ice volume anomalies from the edge to the center of the Arctic Ocean. The ocean response to these bio-physical feedbacks is maximum in late summer for SST, ice concentration and thickness (Figure 4) and therefore amplifies the sea-ice seasonal cycle, with an enhanced sea-ice loss during the melt season and ice growth during freeze-up season. However, in contrast to SST and ice concentration that are unchanged in winter, ice thickness is reduced all year long (evolving from −24% in October to −13% in April). The ice model therefore allows for a successful recovering of ice during winter, resulting in similar ice extent in the two runs, while bio-physical feedbacks permanently reduce ice thickness. Similar results have been found by *Gordon and O'Farrell* [1997] in a transient greenhouse model experiment.

[11] These bio-physical feedbacks not only warm but also freshen the Arctic Ocean surface layer by 0.15 psu (Figure 3b). This freshening is caused by an increase in all three components of the freshwater flux: 50% contribution from excess of local precipitation versus evaporation, 20% from increased runoff and 30% from direct enhanced ice melt. The increase of precipitation and runoff over the

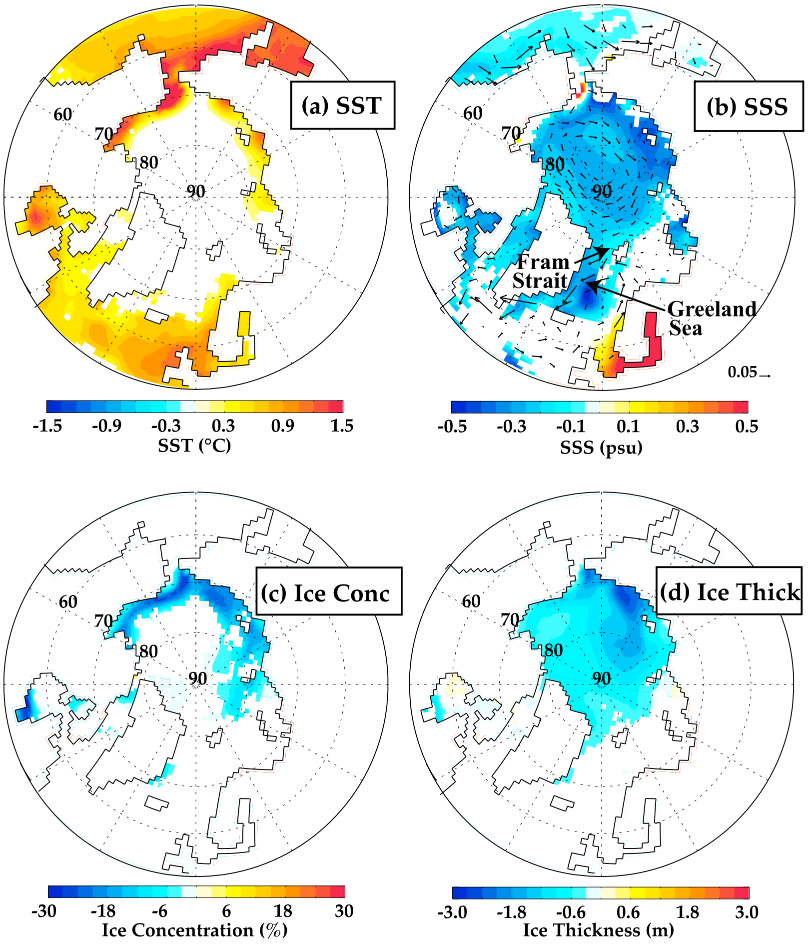


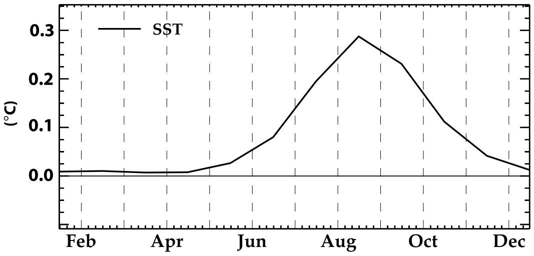
Figure 3. Differences between fullBIO and cstBIO simulations in September for (a) sea surface temperature, (b) sea surface salinity, (c) ice concentration and (d) ice thickness. Only differences statistically significant at 95% level are shown (using a Mann-Whitney test). Units are °C for temperature, psu for salinity, % for ice concentration and m for ice thickness.

Arctic region is related to the overall summer warming of the northern Atlantic and Pacific Oceans (Figure 3a). This warming increases evaporation over these regions in summer and therefore precipitation over Siberia and Canada and in the Arctic Ocean. This freshwater is exported through the Fram Strait and enters the Greenland Sea (Figure 3b), resulting in a reduction of the intensity of the Atlantic meridional overturning circulation (defined for cstBIO and fullBIO experiments as the maximum of the meridional stream function in the Atlantic) from 15 to 13 Sv. This effect was expected as the freshening of the North Atlantic is assumed to reduce the overturning strength through its effect on density [e.g., *Stouffer et al.*, 2006].

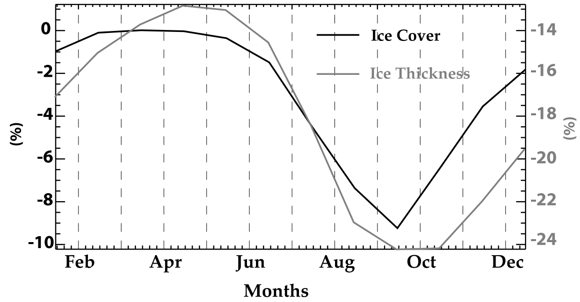
5. Summary and Concluding Remarks

[12] In this study, we have investigated the influence of marine phytoplankton on surface ocean and sea-ice in the Arctic Ocean using an Earth System model including a biogeochemical model that reproduces accurately the seasonal course of chlorophyll distribution in this region. Our results suggest that chlorophyll biomass strongly impacts the climate of the Arctic Ocean and improves the sea-ice distribution. This impact results from a direct biological heating through changes of water clarity amplified by an indirect contribution involving enhanced ice melting. Indeed, the phytoplankton blooms that occur concomitantly with the ice retreat along the coastal shelves of the Arctic Ocean act to trap the penetrating solar heat flux in the ocean surface layer, warming the SST along the coastal shelves of Alaska and Siberia. This warming triggers a reduction of sea-ice concentration in these regions that increases the solar energy penetrating into the ocean, providing a positive feedback that further amplifies the direct biological heating. The ocean response is maximum in late summer, resulting in a warming of ~0.5°C along the continental shelves of Alaska and Siberia and reduction of the overall Arctic Ocean sea-ice thickness (24%) and concentration (8%). Increased melting, precipitation and river runoff result in a freshening of the Arctic Ocean and the Greenland Sea, provoking a ~15% slowdown of the overturning circulation.

[13] These changes in the physical state are in turn likely to affect the biological processes (growth, grazing, remineralization). The influence of the bio-induced changes on the stability of the halocline layer, phytoplankton growth rates and nutrient uptake need therefore to be further investigated. In addition, accounting for these bio-physical feedbacks in greenhouse gases forcing experiments will also allow assessing their influence on the Arctic sea-ice decline in



(a) Arctic SST Difference



(b) Arctic Ice Cover and Thickness Difference

Figure 4. Seasonal differences in the Arctic Ocean (north of 66°N) between the fullBIO and cstBIO model experiments for (a) SST, (b) ice concentration and ice thickness. Units is °C for temperature and percentage of change is used for ice concentration and ice thickness.

our warming climate. It is however likely that the characteristics of this biological heating on sea-ice are sensitive to the Earth System model and parameterizations used. A realistic representation of sea-ice and chlorophyll structure is a necessary condition for properly representing its effect. From now, only few models capture well the seasonal cycle of Arctic sea ice extent [*Arzel et al.*, 2006]. More research using other oceanic, biological and atmospheric components need to be carried out to assess the robustness of these bio-physical feedbacks on the coupled system.

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