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Key Points:
- Colored dissolved material is responsible for a significant part of the induced surface warming and sea ice loss in the Arctic Ocean
- The combined effect of optical constituents reduces the sea ice season by up to one month
- Considering the properties of optical constituents and their variability will enhance the plausibility of future modeling studies

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Amplified Arctic Surface Warming and Sea Ice Loss Due to Phytoplankton and Colored Dissolved Material

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Abstract Optically active water constituents attenuate solar radiation and hence affect the vertical distribution of energy in the upper ocean. To understand their implications, we operate an ocean biogeochemical model coupled to a general circulation model with sea ice. Incorporating the effect of phytoplankton and colored dissolved organic matter (CDOM) on light attenuation in the model increases the sea surface temperature in summer and decreases sea ice concentration in the Arctic Ocean. Locally, the sea ice season is reduced by up to one month. CDOM drives a significant part of these changes, suggesting that an increase of this material will amplify the observed Arctic surface warming through its direct thermal effect. Indirectly, changing advective processes in the Nordic Seas may further intensify this effect. Our results emphasize the phytoplankton and CDOM feedbacks on the Arctic ocean and sea ice system and underline the need to consider these effects in future modeling studies to enhance their plausibility.

Plain Language Summary The amount of microalgae and colored dissolved organic material in the ocean determines how much light is absorbed in the surface waters and how much can reach greater depths. The vertical distribution of energy affects the upper ocean temperature and general circulation. Here, we use a numerical ocean model with biogeochemistry and sea ice, in which the individual effects of microalgae and colored dissolved organic matter can be turned on and off separately. When both effects are turned on, the summertime surface temperatures in the Arctic are larger and consequently more sea ice melts, so that the sea ice season is shorter by up to one month. We find that, to a large extent, the colored dissolved material is responsible for these changes. An increase of this material due to climate change will amplify the observed Arctic surface warming. For better projections of climate change, new models should account for the effect of these light-absorbing water constituents.

1. Introduction

Light is attenuated in the ocean by its scattering and absorption by optical constituents such as water molecules, phytoplankton, as well as suspended and colored dissolved material. The attenuation affects the near-surface vertical temperature distribution (Zaneveld et al., 1981). In the Arctic, biologically induced surface warming, by enhancing sea ice melting, increases light availability for phytoplankton, which in turn may amplify the warming. The Arctic near-surface air temperature increased at least twice as much as the global average in the last decades (Wendisch et al., 2017). In this context, precipitation (Bintanja & Andry, 2017) and permafrost thawing (Grosse et al., 2016) are expected to increase and subsequently freshwater discharge and terrigenous dissolved organic matter (DOM). A fraction of the DOM is colored (CDOM) and can absorb ultraviolet and visible light efficiently. Depending on the region, Arctic CDOM may account for up to 85% of the total non-water absorption in the 443 nm wavelength band (Gonçalves-Araujo et al., 2018). Hence, higher CDOM concentration leads to enhanced absorption of solar energy in the Arctic surface waters and increased sea ice melt rates (Hill, 2008; Soppa et al., 2019).

In numerical ocean general circulation models, the penetration of solar radiation needs to be parameterized. The choice of parameterization may affect the circulation significantly, as well as the upper ocean water masses (Cahill et al., 2008) and their transformation rates (Groeskamp & Iudicone, 2018). Compared to parameterizations with constant light attenuation depths, numerical models with interactive biogeochemistry simulate higher sea surface temperatures (SST) that are related to stronger absorption by high chlorophyll-a concentrations (Lengaigne et al., 2009; Manizza et al., 2005; Oschlies, 2004; Patara et al., 2012; Wetzel et al., 2006). The light absorption due to CDOM has been parameterized in an Earth system model by prescribing interannually averaged and vertically constant absorption estimates based on satellite data (Kim et al., 2015). This method does not resolve important aspects of the seasonal cycle nor the feedback of increasing surface temperature and modified ocean dynamics on the distribution of CDOM, and hence the absorption. Here, we incorporate CDOM as a prognostic model variable in the underwater light attenuation scheme so that it interacts with the changes induced by its presence.

With this interactive parameterization, we examine how the light attenuation by phytoplankton and CDOM contributes non-linearly to surface warming and sea ice reduction in the Arctic Ocean. We quantify the changes attributed to the effect of CDOM, and we discuss the implications of light attenuation schemes in general circulation models.

2. Methods

We used a model configuration of the Massachusetts Institute of Technology general circulation model (MITgcm, MITgcm Group, 2002) based on a cubed-sphere grid (Menemenlis et al., 2008) with a mean horizontal grid spacing of 18 km and 50 vertical layers with thicknesses between 10 m near the surface to 450 m in the deep ocean. The model was forced by 3-hourly atmospheric conditions from the Japanese 55-year reanalysis (Kobayashi et al., 2015) over the period of 1992–2016. As initial conditions we used the model state described in Losch et al. (2010, their section 3).

The Darwin ocean biogeochemical model (Dutkiewicz et al., 2015) was coupled to the MITgcm and this system was used to simulate phytoplankton chlorophyll-a and CDOM (as important water optical constituents). We used three different parameterizations for light penetration with depth. The first used constant attenuation coefficients for longwave (IR) and shortwave (VIS) radiation following Paulson and Simpson (1977) (Equation 1a). This is the default parameterization in the MITgcm and was used for the control experiment (CTRL). The second one (GREEN) accounted for the self-shading effect of phytoplankton (Equations 1b and 1c), and the third (YELLOW) additionally took into account the light absorption by CDOM (Equations 1b and 1d). The corresponding vertical profiles of chlorophyll-a ([Chl]) and CDOM ([CDOM]) were computed by the Darwin model. A limitation, however, is the lack of a parameterization for the riverine CDOM. The equations can be written as:

$$I_{(\mathrm{z})} = I_{\mathrm{IR}} \cdot e^{-\mathrm{k}_{\mathrm{IR}}\,\mathrm{z}} + I_{\mathrm{VIS}} \cdot e^{-\mathrm{k}_{\mathrm{VIS}}\,\mathrm{z}} \tag{1a}$$

$$I_{\mathrm{pen}}(z) = 0.4 \cdot I \cdot e^{-\mathrm{k}_{\mathrm{pen}}(\mathrm{z})\,\mathrm{z}} \tag{1b}$$

$$k_{\mathrm{pen}}(z) = k_{\mathrm{w}} + k_{\mathrm{c}} \cdot [Chl](z)\ or \tag{1c}$$

$$k_{\mathrm{pen}}(z) = k_{\mathrm{w}} + k_{\mathrm{c}} \cdot [Chl](z) + k_{\mathrm{CDOM}} \cdot [CDOM](z) \tag{1d}$$

where the diffuse attenuation coefficients (k_{IR}, k_{VIS}) and the light partitioning correspond to Jerlov water type I (Jerlov, 1976). To be consistent with the control run, we accounted for the longwave radiation to be fully attenuated in the first vertical layer and the penetrative part (I_{pen}) to be 40% of the total flux (I) (Equation 1b). k_{w} (0.04 m^{-1}) is the spectrally averaged attenuation coefficient for pure seawater, while k_{c} (0.04 $(\mathrm{mmol\ chl/m^3})^{-1}$) and k_{CDOM} (10 $\mathrm{m^2}$/mmol P) are for chlorophyll-a and CDOM. The k_{CDOM} coefficient was calculated given specific CDOM absorption spectra as described in Dutkiewicz et al. (2015).

The Darwin model was initialized on 1 January 2000 by a state obtained from the model setup described in Losa et al. (2019). The period from 2000 to 2006 is assumed to be sufficiently long to get the upper ocean biogeochemistry in a quasi-steady state (Clayton et al., 2017). Our analysis focuses on 10-day averages of the last 10 years (2007–2016) of the simulations with special emphasis on 2012, where summer sea ice extent reached a minimum record (Parkinson & Comiso, 2013).

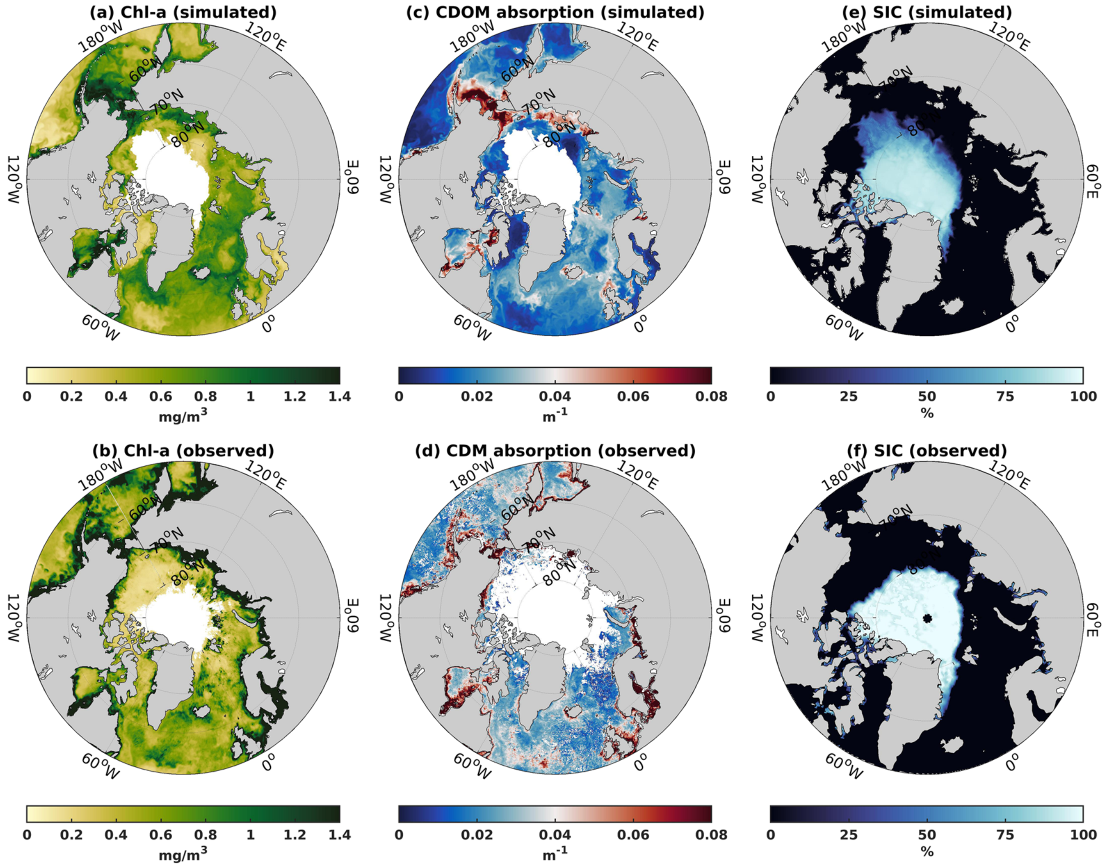

Figure 1. For September 2012: (a) simulated surface chlorophyll-a concentrations in YELLOW, (b) observed surface chlorophyll-a concentrations (Gohin et al., 2002) from the merged GlobColour product (ftp://ftp.hermes.acri.fr/GLOB/merged/), (c) simulated surface absorption by CDOM in YELLOW, (d) observed surface absorption of colored dissolved and detrital matter (CDM) at 443 nm (Werdell et al., 2013) from the NASA GSF Center (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Monthly/4km/). Although CDM accounts for the absorption from both detritus and dissolved material, it is the most suitable remote sensing product to compare against simulated CDOM. (e) Simulated SIC in YELLOW. (f) SIC from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3 (Peng et al., 2013).

3. Results and Discussion

The simulated surface chlorophyll-a concentrations and CDOM absorption are found to be in a similar range as the observed chlorophyll-a concentrations and the absorption by colored dissolved and detrital matter (CDM) (Figures 1a–1d), and except for some of the coastal regions, they follow the observed spatial patterns.

Satellite chlorophyll-a estimates, however, are known to be highly overestimated close to the Siberian shelf (Heim et al., 2014), while CDM accounts also for the effect of all non-algal particles. The simulated sea ice concentration (SIC) was also compared against passive microwave observations (Figures 1e and 1f). The general spatial pattern of the model's sea ice distribution bears enough resemblance to satellite observations to be useful for our sensitivity study. The model reproduces the seasonal sea ice retreat along the Siberian and Alaskan coasts, but SIC is overestimated in the Beaufort Sea and underestimated in areas close to the Laptev Sea (Figure 1e).

Including the simulated chlorophyll-a and CDOM in the light attenuation scheme (YELLOW) leads to higher SST during summer, with maximum increases above 1°C in the Greenland Sea (Figure 2a). Limited surface cooling close to the sea ice edge is associated with a local increase of upwelling. By reducing the available heat at depth, the sub-surface layer cools in almost the entire Arctic (Figure 2b). At the same time, sea ice is reduced mainly in the Eastern Arctic (Figure 2c). With the dynamic attenuation due to chlorophyll-a and CDOM, the SIC distribution in the summer of 2012 is slightly improved (Figure 2c), compared to CTRL. Summertime surface warming induces more heat loss to the atmosphere (Figure 2d) primarily through latent and sensible heat flux. The local heat gain close to the sea ice edge, however, is directly linked to

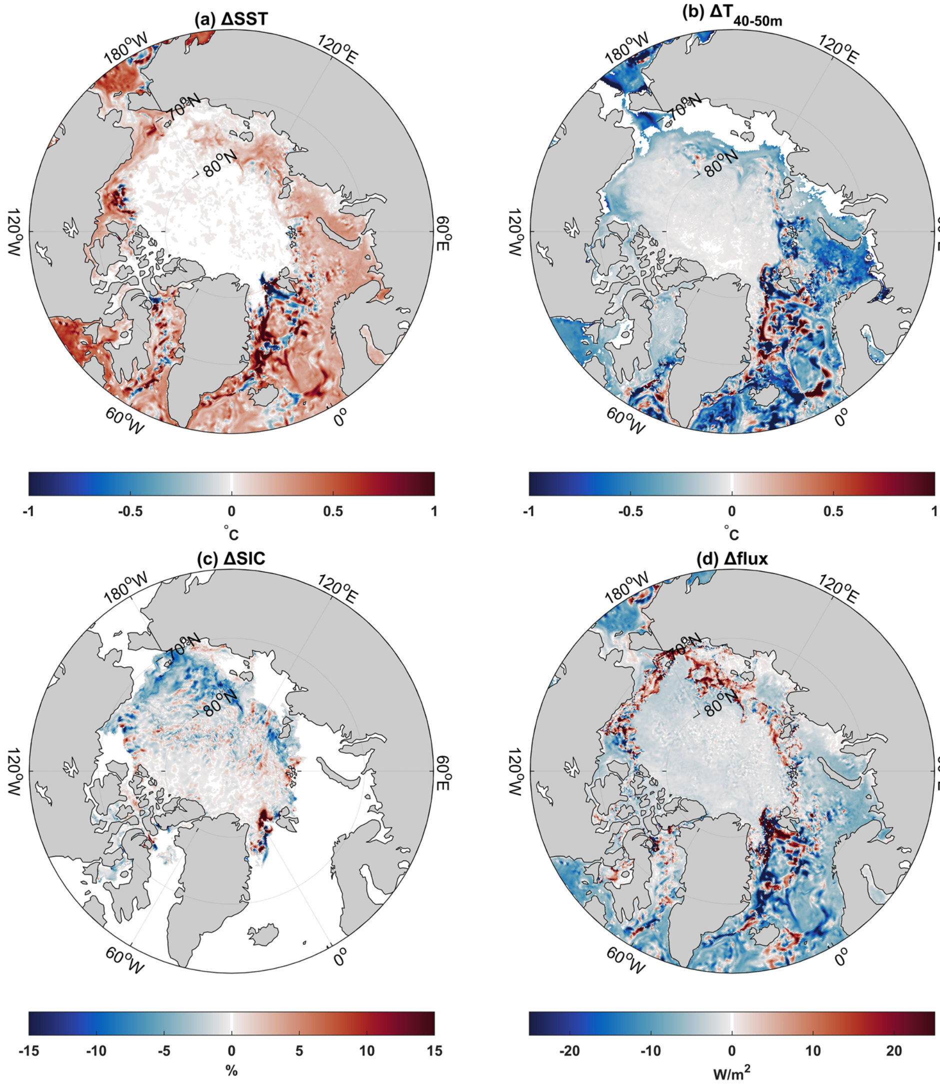

Figure 2. Mean differences between YELLOW and CTRL for (a) SST, (b) 40–50 m temperature, (c) SIC, and (d) surface heat flux (positive changes indicate heat gain for the ocean), for August 2012.

reduced SIC (Figure 2d). By accounting for the combined effect of chlorophyll-a and CDOM (YELLOW - CTRL), the ice-free season, in 2012, increases by one month in the Eastern part of the Arctic (Figure 3a). In contrast to the summertime surface warming, lower SSTs occur in winter (not shown here). These changes are accompanied by an amplified seasonal cycle of surface temperature (Figure 3b) implying changes in temperature extremes (Gnanadesikan et al., 2019) with potential ecological implications.

Over the last 10 years of the simulations, the mean SST of the warmest climatological month (July) in the Arctic Ocean increases by 0.3°C. From June to September, 48% of the observed changes in surface temperature (YELLOW-GREEN) are attributed to the effect of CDOM absorption. In contrast to Kim et al. (2018), we find a small increase in the annual mean SST due to CDOM, especially in the sub-polar North Atlantic (Figure 3c).

The induced local changes in temperature result from the direct thermal effect of altering the light attenuation profile and the indirect dynamical effect of changing the mixed layer depth (MLD) (Figure 4a). Two indirect mechanisms may cause a non-local effect: (1) differential surface heating along chlorophyll-a and CDOM concentration gradients induces horizontal density gradients, which modify the structure of velocity and hence the advective flux (Figure 4b) and (2) changes of SIC close to the sea ice edge also affect the density through insolation and salinity differences. In late spring and summer, the direct effect dominates

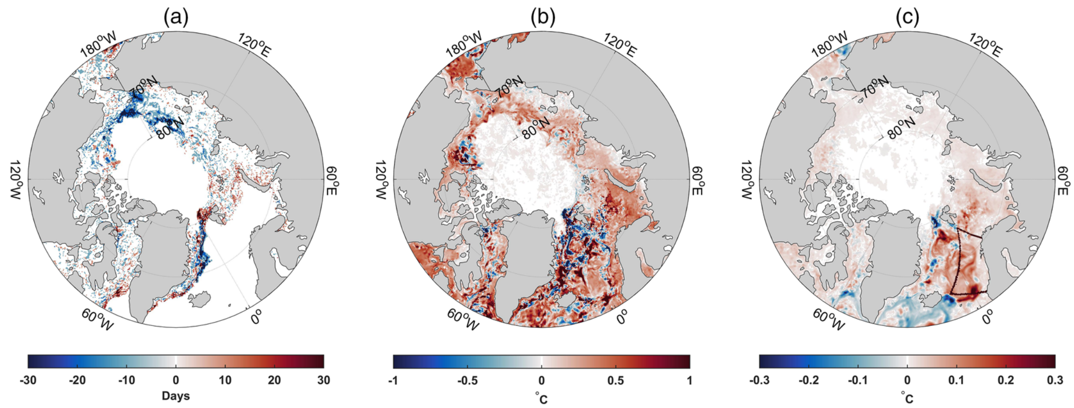

Figure 3. Difference between YELLOW and CTRL for 2012, in (a) days with more than 15% SIC and (b) in SST annual range. In order to assess the contribution of CDOM to the induced SST changes, the (c) annual mean SST differences between YELLOW and GREEN for the 2007–2016 time period are shown. The area enclosed by the black line is considered in Figure 4.

due to high solar input and the development of the thermocline, and also due to the abundance of optical constituents.

In contrast, there is little light in winter, and the upper ocean is well mixed, so that indirect effects may be important. In this period, the mixed layer tends to entrain the sub-surface water. CDOM-induced wintertime near-surface cooling or warming (Fig. 4c) in the sub-polar North Atlantic is determined by the sign of the advection changes. A northward increase in the meridional component of advection (Fig. 4b) increases the upper ocean temperature in the Nordic Seas in most years (Fig. 4c, 2007, 2008, 2013, 2014), while the opposite effect leads to cooling (Fig. 4c, 2009, 2010, 2016). This finding underlines the potential of indirect changes in advective processes in intensifying the direct thermal effect of CDOM.

4. Implications and Conclusions

Our underwater light attenuation scheme based on interactive biogeochemistry (YELLOW) increases the simulated summertime SST compared to the CTRL run consistent with previous work (Lengaigne et al., 2009; Manizza et al., 2005). However, some of our results, such as the increased annual mean SST, do not agree with previous reports of reduced annual SST due to interactive biogeochemistry

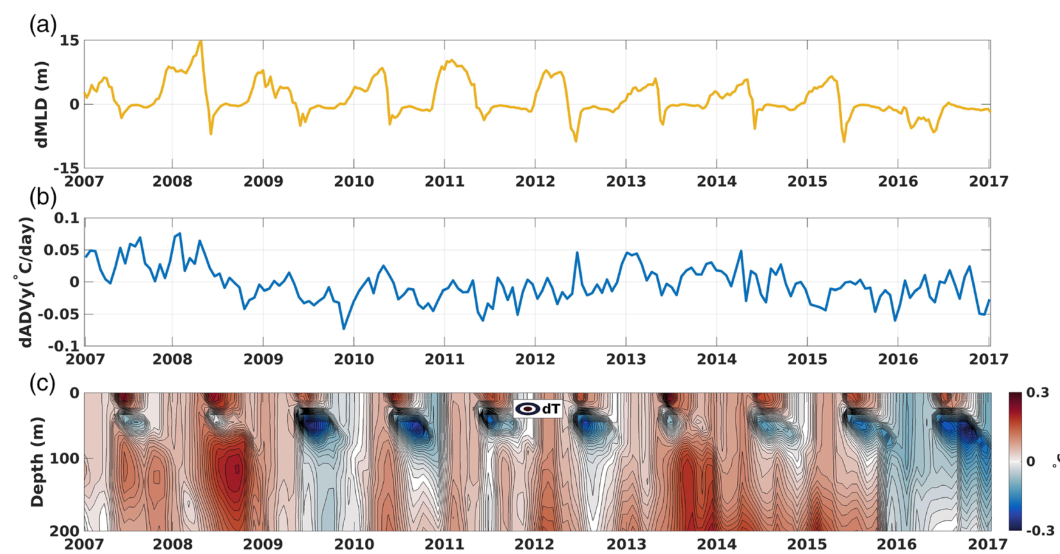

Figure 4. Mean differences in the highlighted area of Figure 3c between YELLOW and GREEN, in (a) mixed layer depth (dMLD), (b) 100–200 m meridional advection (dADVy), (c) upper 200 m temperature profile (dT). The MLD differences for this region are on the order of 5% (winter) to 15% (summer).

(Mignot et al., 2013) or increased winter-only SST in the Arctic (Wetzel et al., 2006). One reason for this difference may be the plethora of reference simulations that make the comparison between studies difficult. The assumptions used to parameterize light penetration in the different control runs vary from constant light attenuation depths of 11 m (Wetzel et al., 2006) to 25 m (Oschlies, 2004) to fixed chlorophyll-a concentrations (Lengaigne et al., 2009; Mignot et al., 2013) or a vertically varying chlorophyll-a climatology (Lim et al., 2018; Park et al., 2015). Whether positively or neutrally buoyant phytoplankton groups are included in the sensitivity run, also makes a difference in the vertical temperature distribution (Sonntag & Hense, 2011).

Previous modeling efforts focused on the effect of phytoplankton on ocean physics. The CDOM effect was either not considered or constant values of its absorption were used in the model's light attenuation scheme (Gnanadesikan et al., 2019; Kim et al., 2016, 2018). In a step forward, Kim et al. (2018), by prescribing interannually averaged absorption estimates from a satellite data set, suggested that increased CDOM and suspended material may slow down the global warming effect on the ocean. Prescribed averages, however, necessarily neglect both the seasonality of CDOM and the feedback of modified SST and ocean circulation on CDOM distribution. Here, CDOM has a seasonal cycle and interacts non-linearly with the thermal and dynamical changes induced by its presence. Note that we do not include additional terrigenous sources of CDOM and suspended material. Depending on the region (Stedmon et al., 2011) and the time of the year (Juhls et al., 2020), we may underestimate CDOM absorption locally by up to an order of 10 times, compared to measured values (Heim et al., 2014; Juhls et al., 2019; Soppa et al., 2019). By accounting for the loading of major Arctic rivers, its effect is expected to be larger than shown here. Our results suggest that, due to permafrost thawing and increasing river runoff, a future increase of this material will amplify the observed Arctic surface warming through its direct thermal effect and indirect changes on the advective processes.

For an even better account of optical constituents in biogeochemical ocean models, the light attenuation coefficients should be wavelength dependent. CDOM absorbs light disproportionately in the ultraviolet and blue bands (Roesler & Perry, 1995), while phytoplankton absorption occurs mostly in the 400–500 and 650–700 nm, which is further spectrally varying due to its composition and physiological state (Bricaud et al., 1995). To be able to account for these effects in the future, multispectral parameterization schemes are required that consider their inherent spectral optical properties (absorption and scattering) correctly. Instead, current model setups use monochromatic (Oschlies, 2004; Patara et al., 2012), two-band (Kim et al., 2018; Manizza et al., 2005), or three-band approximations (Lengaigne et al., 2009) for the visible light. Besides light partitioning, multispectral data of solar radiation are necessary if their effects shall be incorporated into the optical modules (Dutkiewicz et al., 2015).

Climate models tend to underestimate sea ice decline in the Arctic (Stroeve et al., 2012), while model uncertainty remains very large (Senftleben et al., 2020). By including the dynamic attenuation due to chlorophyll-a and CDOM, the ice-covered season in 2012 reduces by as much as one month. Overall, the induced temperature and sea ice changes observed here, are of the same order of magnitude as changes due to different ocean model setups for the Arctic Ocean (Holloway et al., 2007; Johnson et al., 2007). With our forced simulations, however, the atmospheric response to the modulated SST and sea ice distribution cannot be assessed. Phytoplankton-induced changes in SST may affect the thermal energy flux to the atmosphere (Jolliff et al., 2012) as well as the wind stress patterns (Jolliff & Smith, 2014), amplify the Earth's greenhouse effect (Patara et al., 2012), and modify the atmospheric circulation (Patara et al., 2012; Wetzel et al., 2006). Furthermore, the induced thermal and dynamical changes feed back to the distribution of phytoplankton and CDOM. Modifications in marine phytoplankton will have an additional impact on polar climate, by altering biogenic gas emissions to the atmosphere (Kim et al., 2018).

The results and the implications discussed here suggest that the radiative effect of phytoplankton and CDOM is a significant source of predictive uncertainty in ocean models. Their variability and their optical properties need to be treated appropriately in Earth system modeling studies involving sea ice and temperature projections. Further research accounting for the interactions of the Earth system components need to be carried out to assess the optical feedback to a changing climate.

Data Availability Statement

Model output data related to this study are available on this site (Pefanis, Vasileios; Losa, Svetlana N; Losch, Martin; Janout, Markus A; Bracher, Astrid (2020): Global model output of chlorophyll-a concentration, coloured dissolved organic matter absorption, sea-ice concentration, sea surface and subsurface temperature, surface heat flux, ice-covered days, mixed layer depth, meridional advection of temperature. PANGAEA, https://doi.org/10.1594/PANGAEA.922976).

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