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Short Note

Climate Change in Polar Marine Ecosystems
(Perubahan Iklim di Ekosistem Marin Polar)

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ABSTRACT

Climate change will have a significant effect on polar marine ecosystems. While primary production is likely to fall in tropical and temperate seas, it is likely to rise in polar seas. This, however, will only support shorter food chains, which will lead to a decline in major vertebrate species. In polar seas climate change will lead to increased sea-water temperatures, decreased ice cover and a lower pH. Because ice cover is largely impervious to satellite observation, our understanding of polar sea ice and under ice phytoplankton biomass and productivity is still poor. It is generally thought that sea algal communities contribute up to 25% of total annual production in ice covered seas of both Polar Regions but that annual production in the Arctic Ocean is approximately 270 Tg y^{-1} while in the Antarctic Ocean it is between 980 and 3620 Tg y^{-1}. A simple model of ice reduction, due to global warming, in the Antarctic (the Arrigo and Thomas model) suggests a net increase of 21% in primary production will result in a 50% ice reduction and a further 7% with a 95% ice reduction. However, the location, concentration and position of this production are likely to be quite different to what it is now. A similar, simple model applied to the Arctic suggests that this region will also experience a significant net increase in marine primary production as more of the ocean becomes ice free in summer. A 50% reduction in summer sea ice in the Arctic Ocean would lead to at least an 80% increase in production. Once again, however, the nature, position and concentration of this production is likely to be very different from the current configuration. These changes are likely to induce major trophic realignments in both hemispheres.

Keywords: primary production, Antarctic, Arctic

ABSTRAK

Perubahan iklim akan meninggalkan kesan yang ketara kepada ekosistem marin kutub. Ketika pengeluaran primer di kawasan laut tropika dan bersuhu sederhana menurun, ianya akan semakin meningkat di laut kutub. Walaubagaimanapun situasi ini hanya menampung rantaian makanan yang lebih pendek seterusnya membawa kepada penurunan spesis vertebrata utama.Perubahan iklim di laut kutub akan menyebabkan peningkatan suhu air laut, mengurangkan litupan ais dan pH yang lebih rendah. Oleh disebabkan litupan ais adalah kalis daripada liputan satelit, pemahaman kita terhadap ais di laut kutub dan biojisim fitoplankton di bawah permukaan ais serta produktiviti di kawasan tersebut masih lemah. Secara umumnya dinyatakan bahawa komuniti alga laut menyumbang sehingga 25% jumlah pengeluaran tahunan di dalam kawasan diliputi ais di kedua-dua kutub namun, pengeluaran tahunan du kawasan Artik dianggarkan sebanyak 270 Tg y^{-1} manakala di Lautan Antartik adalah di antara 980 dan 3620 Tg y^{-1}. Satu model ringkas pengurangan ais disebabkan oleh pemanasan global, di kawasan Artantik (model Arrigo dan Thomas) mencadangkan bahawa peningkatan bersih 21% dalam pengeluaran primer akan menyebabkan 50% pengurangan ais dan peningkatan 7% dari jumlah tersebut akan mengakibatkan 95% pengurangan ais. Bagaimanapun, lokasi, kandungan dan posisi pengeluaran ini adalah berbeza denagan apa yang berlaku sekarang. Model ringkas yang hamper sama diaplikasikan di kawasan Artik telah mencadangkan bahawa kawasan ini turut mengalami peningkatan jumlah bersih yang signifikan dalam produktiviti primer marin di mana lebih ais mencair. Sejumlah 50% pengurangan

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ais pada musim panas di Lautan Artik boleh mengakibatkan sekurang-kurangnya 80% peningkatan pengeluaran di kawasan tersebut. Sekali lagi, keadaan semulajadi, kedudukan dan kandungan pengeluaran ini sangat berbeza dengan keadaan semasa. Perubahan ini mendorong kepada pengaturan semula trofik utama di kedua-dua hemisfera.

Kata kunci: Produktiviti primer, Antartik, Artik

INTRODUCTION

The climate is warming faster in major areas of the polar region than almost anywhere else on earth. In the Arctic summer, sea ice extent has been reduced to the lowest ever recorded and at a rate that has exceeded even the worst predictions of the IPCC. Similarly, in the Antarctic Peninsula region, mean annual temperatures have increased by more than 4°C over the last 50 years and sea ice has noticeably reduced. The ecosystems associated with these regions are being forced to adapt rapidly.
In most areas of the world's oceans and seas phytoplankton contributes more than 99% of total primary production. The exceptions are in shallow coastal areas where benthic microalgae and seaweeds make a major contribution and in polar seas where sea ice algae makes a major contribution.

Polar marine environments are dominated by sea ice. It limits and controls light transmission, thus controlling pelagic primary production, and it provides a habitat and substrate for sea ice microbial communities and a refuge for zooplankton, krill, fish and higher organisms. Furthermore, the melting of sea ice in spring and early summer stabilizes the water column producing a shallow mixed layer, which promotes the extensive ice edge phytoplankton blooms that characterise many of these areas. Sea ice algal communities contribute between 25% and 30% of annual marine primary production in polar seas (Lizotte 2001). However for up to 9 months of the year they are the only source of primary production available and so play a disproportionately important role. Any organism that needs to survive the winter such as Antarctic krill will need to consume sea ice algae or something else that consumes it. In many polar seas the springtime ice edge blooms also contribute up to 50% of the total annual pelagic primary production making sea ice processes vital to the functioning of current polar ecosystems.

Global Climate Change and Marine Primary Production

Marine primary production is a function of light, chlorophyll abundance and cell physiology. However, while changes in cell physiology can cause changes in productivity by a factor of 3-4, light and biomass vary over several orders of magnitude and thus exert a much greater control. Phytoplankton biomass growth is dependent on both light and adequate nutrients and changes in the availability of either can lead to phytoplankton blooms or limitations. In most of the world's oceans, access to nutrients and light is principally determined by the depth of the surface mixed layer. A shallow mixed layer retains phytoplankton near the surface where there is adequate light for photosynthesis but also restricts access to nutrient-rich waters below. Conversely, a deep mixed layer gives access to a greater nutrient pool but can cause light limitation.

Behrenfeld et al. (2006) showed that in tropical and temperate seas there was a strong inverse relationship between higher sea surface temperatures (SST) and net primary production (NPP). This was thought to result from increased stratification that resulted in reduced nutrient supply and lower chlorophyll biomass with higher SST. While these authors were comparing recent changes in NPP caused by SST changes associated with an El Nino-La Nina transition, the implications of their work for assessing impacts of future climate change are clear.

Unlike tropical and temperate seas, polar seas are not permanently stratified. Low thermal input combined with deep wave and wind induced mixing ensures surface mixed layers are usually deep and stratification transitory. This deep mixing typically ensures that biomass remains low for much of the year. Melting sea ice in spring, which releases fresh water, allows the development of transitory shallow mixed layers, which retain cells close to the surface and promotes the development of strong ice edge blooms. In many polar seas macronutrients are in excess and so rarely limit primary production. However, some micronutrients such as iron are now known to cause chronic limitation to both phytoplankton and sea ice algae in large areas of the Southern Ocean (Pankowski & McMinn, 2009).

Sea ice plays a pivotal role in determining NPP (net primary production) in temporally ice covered polar seas. When the ice is present it prevents the transmission of light to the water column, reducing pelagic primary production to virtually nothing. The ice itself provides a habitat for large photosynthesising communities of sea ice algae that themselves contribute 25-30% of total annual primary production. When the sea ice melts in spring this biomass is released into the underlying water column and contributes to large ice edge blooms.

However, NPP is largely a function of light and sea ice reduces the amount of light reaching the water column to typically less than 1% of the surface irradiance for up to nine months of the year. Arrigo & Thomas (2004) have predicted that the Southern Ocean NPP will increase by as much as 29% as sea ice extent decreases (by 95%) with global warming. Their simple model made a number of important assumptions regarding nutrient availability, cell physiology and species distribution but the underlying direction of change is sound. Essentially, a reduction in ice cover allows greater quantities of light to reach the water column and this in turn leads to greater NPP. Here, a similar approach to that of Arrigo & Thomas (2004) is applied to the Arctic.

MATERIALS AND METHODS

Arctic NPP Model

This is also a simple model that makes no attempt to assess the impacts of climate change *per se* on Arctic NPP but rather approaches the subject with a ‘what if we were to remove sea ice’ question. Unsurprisingly, a number of major assumptions need to be made. Physical conditions, such as currents, nutrients, stratification, snow cover and water temperatures remain unchanged. Also, algal physiology and taxonomy remain the same.

Each major sea of the Arctic was modelled separately and only areas that had ice cover for some part of the year were considered. Monthly sea ice coverage data was taken from the National Snow and Ice Data Centre website. The year 2005 was chosen as the starting date as this predated the major summer sea ice contraction witnessed in subsequent years. Each area was divided into three zones; the Sea Ice Zone (SIZ), comprising areas permanently covered with sea ice and characterised by production within the sea ice only, the Marginal Ice Zone (MIZ), the area between annual maximum and minimum ice extent, and the Permanently open ocean zone (POOZ), an area that comes into existence only after ice disappears completely from these areas. Wherever possible, published sea ice and phytoplankton primary production data was used to estimate the annual (2005) NPP of each sea. However, outside of summer there is virtually no data available for most areas. Where no data exists, data from the closest area was used and values were extrapolated from biomass growth and decay rates. Outside of the Barents Sea area very little sea ice NPP data exists and as a result Barents Sea data has been applied to many other sea ice areas.

RESULTS & DISCUSSIONS

Model results are presented in Table 1. The model predicts that if 90% of the ice is reduced uniformly from across the Arctic, a NPP increase of 75.6% will result. There is strong evidence from many of the marginal seas, however, that phytoplankton blooms are already nutrient limited in summer. This would imply that a reduction in sea ice and a longer growing season would only have a marginal impact on NPP in these regions. When this is factored into the model, the net increase reduces to 32.6%, a figure not unlike the 29% predicted by Arrigo and Thomas (2004).

While sea ice extent will have the greatest effect on NPP, there are other climate change impacts that will also affect it. Rising sea surface temperatures and increasing ocean acidity are two such factors. In laboratory studies of Southern Ocean phytoplankton, most species have been shown to increase their photosynthetic and growth rates with temperature increases of up to 10°C above their ambient environmental temperature. It is therefore unlikely that rising SSTs will have an immediate negative impact on primary production and that an increase is more probable. However, as large areas of the Southern Ocean are already Fe-limited and this limitation is not predicted to change, significant increases in NPP are not likely in these areas. Areas that are not Fe-limited, such as those areas closer to the Antarctic coast mostly also have high macronutrient concentrations and so could benefit form warmer growth temperatures.

Ocean acidification is not likely to have a significant effect on Southern Ocean NPP although ideas on this subject are still developing. A reduction in seawater pH produces a greater concentration of dissolved carbon dioxide, a critical component in photosynthetic carbon fixation. However, many phytoplankton taxa have carbon concentrating mechanisms (CCMs) and are only rarely limited by CO_2 availability. An increase in CO_2 will therefore produce little change in their NPP. Phytoplankton taxa that do not have CCMs, however, are likely to benefit from elevated CO_2 levels. One such group is the calcareous scaled coccolithophoroids. This group has until recently been largely absent from the Southern Ocean but there is now recent evidence of a range extension to south of the Polar Front (Cubillos et al. 2007). It had been thought that because this group had calcite scales an increase in acidity would adversely impact their growth (Riebesell et al. 2000) but for moderate increases in acidity, this has been shown not to be the case (Inglaesias-Rodriguez et al. 2008).

A reduction in ice extent will not only affect the quantity of NPP but also the location and intensity of NPP. While the presence of sea ice reduces the quantity of light reaching the water column, it provides a substrate for colonisation by microalgae and invertebrates.

For nine months of the year when sea ice is present, it represents the only significant photosynthesising community in polar seas. Biomass can be high, reaching over 300 mg chl*a* m^{-2} in fast ice (Trenerry et al. 2003) and 30 mg chl*a* m^{-2} in pack ice (McMinn et al. 2007). During this time biomass in the underlying water column is virtually zero (<0.01 mg chl*a* m^{-2}). Any multi-celled organism that needs to survive winter will therefore either need to eat algae or something else that does. There is now mounting evidence that while adult krill can survive winter by living off stored energy reserves, juvenile krill rely on ice algae to survive. A reduction in ice extent will therefore have a direct impact on krill recruitment which will in turn impact the numbers of predators.

Melting sea ice in spring causes a brief period of shallow stratification that promotes the development of ice edge blooms. These often intense blooms are transient and move with the retreating ice edge back to the Antarctic (or Arctic) coastline. Biomass within these blooms can be very high. Because the biomass is so high, it allows similarly dense aggregations of grazers such as krill to exist. These in turn allow the existence of larger predators, such as whales, that require dense aggregations of prey species to enable them to feed efficiently. As climate change causes a reduction in ice extent and the intensity of resultant ice edge blooms, NPP may increase overall but its general lower concentration will reduce the efficiency of grazing and cause a decline in the abundance of large predators.

Table 1. Net primary production (NPP) of Arctic seas. 2005 NPP values are in Tg yr^{-1}. Values after sea ice reduction (columns 3-5) represent % change in NPP. Lowest row (TOTAL – nutr.) gives NPP estimates for current nutrient-limiting conditions extending into the future. The following sources have been used primary production data: Okhotsk Sea (Sorokin & Sorokin 2002), Berring Sea (Sorokin 1999), Arctic Ocean (Harrison & Cota 1991, Cota et al. 1996), Barents Sea (Kogeler & Rey 1999, Reigstad et al. 2002, Olli et al. 2002, Engelsen et al. 2002, Luchetta et al. 2000, McMinn & Hegseth 2007), Greenland Sea (Rey et al. 2000), Baffin Bay (Jensen et al 1999).

	2005 (Tg C y^{-1})	10% reduction	50% reduction	90% reduction
Okhotsk Sea	49	3.1	15.6	27.9
Barents Sea	50.7	6.9	34.5	62.1
Bering Sea	43.9	2.3	11.5	20.8
Hudson Bay	103.7	1.5	7.5	13.5
Baffin Bay	41.3	4.5	22.4	40.4
Greenland Sea	11.8	13.9	69.5	125.0
Canada	7.8	6.8	33.9	61.1
Arctic Basin	264.6	12.5	62.5	112.6
TOTAL	572.6	8.4	42.1	75.6
TOTAL-nutr.		4.0	20.9	32.6

Trophic Impacts of NPP changes

Total primary production in polar seas is likely to either remain approximately the same or increase slightly as a result of climate change. However, these changes will impact higher trophic levels in significant ways.

Unlike most of the Southern Ocean, large areas of seas in the Arctic are relatively shallow, i.e. less than 200 m deep. There, sea ice algae provide an annual pulse of primary production to the benthos to at least 500 m depth. This highly nutritious food source provides food for a diverse invertebrate fauna and also for vertebrates such as the walrus. This production is released from the ice in a short pulse as the ice melts and falls largely un-grazed to the bottom. By contrast, phytoplankton production occurs throughout the ice-free summer months and is grazed constantly by zooplankton, supporting a pelagic food web. A decline in sea ice would lead to less carbon flux to the benthos and consequently a smaller and less productive benthic invertebrate fauna. It would, however, lead to greater pelagic production (McMinn 2005) (Fig. 1).

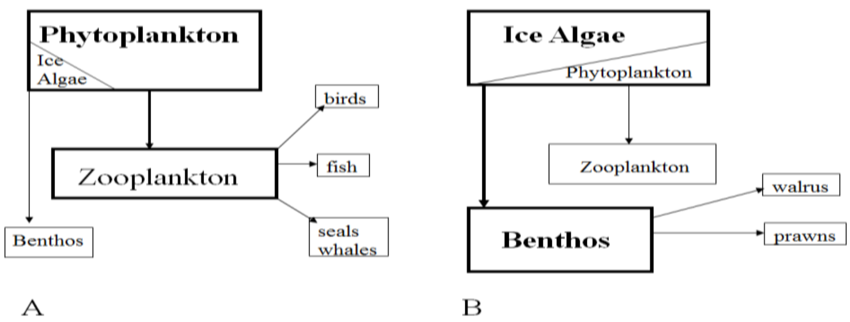

Figure 1: Affects of sea ice loss on Arctic ecosystems. A; high ice extent, equivalent to recent ice distribution patters. B; low ice extent.

In the Antarctic, krill has a particularly important place in the pelagic food web. Not only is it the primary food of most vertebrate species but it is also thought to consume much of the phytoplankton production. While adult krill can survive the winter months when there is almost no phytoplankton in the water column, juvenile krill cannot survive starvation and must graze continuously. They are thus dependant for their survival on the only source of food available, the sea ice algae. Climate change is likely to reduce the seasonal extent of sea ice and this will impact on the quantity of sea ice algae present. This decline will effect juvenile krill survival and consequently the abundance of all species that rely on krill for a food source. In areas around Antarctica where there is less sea ice, salps are the dominant zooplankton grazers. These are thought to have little nutritional value and few species are known to graze on them. A climate change induced reduction in sea ice is therefore likely to lead to pelagic ecosystems dominated by salps rather than krill and a large decline in dependant vertebrate species (Nicol et al. 2000) (Fig. 1).

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