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Critical Literature Review
(ANTA602)

Literature review: The effects of climate change on Ross Sea primary production and flow on effects to food webs.

Name: Lydia McLean

Student ID: 16826897

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Abstract:

The Ross Sea is the most productive area of ocean in Antarctica, yet it is vulnerable to the effects of climate change. An increase in Southern Annular Mode wind cycles has resulted in oceanographic changes including increased sea ice and enhancement of the Ross Sea polynya. The change in sea ice affects timing of phytoplankton blooms and proportions of species of primary producers in the ecosystem, with a possible favouring of the algal species *Phaeocystis antarctica.* This may lead to further changes in the ecosystem, including altered biogeochemical cycling, and an altered food web, due to the fact that *P. antarctica* is relatively inedible compared to other primary producers. The effects of the change in phytoplankton blooms in the Ross Sea community may lead to alteration of the food web, right through to top level predators.

Introduction

The Ross Sea is part of the Southern Ocean south of New Zealand. It is the southern-most stretch of ocean in the world, yet the most productive region in Antarctica. The Ross Sea lies off the coast of a large ice shelf, and is mostly covered by sea ice throughout winter. In spring, large areas of sea ice melt and enlarge the Ross Sea polynya, which is a stretch of open water continuous with the Pacific Ocean (Smith et al., 2012).

Most of the Ross Sea is shallower than 600m, and there are areas as shallow as 200m, meaning it can support a large range of species through providing a range of heterogeneous habitats at different depths, with currents bringing in nutrient rich water. Because of the high concentration of nutrients, primary production in the Ross Sea is among the highest in the Southern Ocean, and forms the base of a highly complex food-web (Arrigo, van Dijken, & Bushinsky, 2008; Smith, Ainley, & Cattaneo-Vietti, 2007).

Though it has been found to be the least affected area of ocean in the world, in terms of anthropogenic effects (Halpern et al., 2008), the Ross Sea is by no means immune to the influence that people have on it. Climate change, as a result of increased levels of CO_2 in the atmosphere is a challenge faced worldwide, and its effects in the Ross Sea must be understood in order to take action to reduce its detrimental effects. Climate change affects the Ross Sea on a range of levels, including physical oceanography, biogeochemical cycling, primary production, and the food web as a whole.

This literature review aims to examine how climate change is affecting the Ross Sea, and how it may be influenced in the future. The review will be divided into sections; the first will examine the physical changes to weather patterns and the resulting changes in ice and seawater composition. The second section will examine how these changes affect timing and ratios of primary producers, and will briefly examine some effects that changed primary production may have in higher trophic levels, and throughout the wider food webs.

Physical changes to ice in the Ross Sea due to climate change

The response of the Ross Sea to anthropogenic climate change is, at first glance, an anomaly. While the continent as a whole has been warming, the Ross Sea region has been showing signs of cooling since records began about 40 years ago (Stammerjohn, Massom, Rind, & Martinson, 2012).

There is considerable scientific consensus that the cooling is caused by an increase in the polarity of the Southern Annular Mode (SAM) (Arblaster &

Meehl, 2006; Lefebvre, 2004; Marshall, 2003; Thompson & Solomon, 2002). The SAM is the predominant climatic pattern in the lower latitudes of the Southern Hemisphere, and is formed by a north-south pressure gradient between the tropics and pole, with a more positive SAM enhancing the westerly winds encircling Antarctica (Marshall, 2003).

The cooling of the Ross Sea region has resulted in a positive trend in sea ice extent (Comiso, Kwok, Martin, & Gordon, 2011). There is increased export of ice from the ice shelf, while the timing of its advancement each season is around one month earlier, and retreat is one month later than four decades ago (Stammerjohn et al., 2012). Turner et al. (2009) used satellites to monitor the extent of sea ice each season, and similarly found that there has been a significant increase in Ross Sea ice cover over the past four decades of 0.97% per decade. This increase is consistent with findings from other studies (eg. Comiso & Nishio, 2008; Zwally, 2002). There is evidence that the thinning of stratospheric ozone has contributed to the strengthening of SAM winds (Turner et al., 2009), however this model does not rule out natural variability as the cause of the increase in sea ice extent.

Conversely to the Ross Sea, the Amundsen Bellingshausen Sea is experiencing the opposite effect, with a mean loss in sea ice (Comiso & Nishio, 2008; Stammerjohn et al., 2012). This is explained by a difference in sea level pressure across the Amundsen Bellingshausen Sea, where a lower pressure at sea level promotes influx of warmer northerly winds, while the higher pressure in the Ross Sea region causes an increase in cold southerly winds, thus promoting the growth of sea ice (Lefebvre, 2004).

Though the Ross Sea is capped by ice throughout winter, katabatic winds from the Antarctic continent drive the formation of a polynya, which is a large area of reduced sea ice cover (Bromwich & Carrasco, 1992). The Ross Sea polynya is an area in which sea ice is actively forming, and the freezing of seawater results in the rejection of salty and dense brine which then sinks and expands (Smith, Sedwick, Arrigo, Ainley, & Orsi, 2012), driving circulation, biogeochemical and biological processes. Katabatic winds have strengthened as a result of a stronger pressure gradient produced by the SAM, which has driven an increase in sea ice formation, and thus a larger polynya. Every austral spring/summer, the Ross Sea polynya enlarges, and becomes continuous with the South Pacific Ocean, which provides ideal conditions for a bloom of photosynthetic algae to take place (Smith et al., 2012).

The increase in the SAM has also been shown to increase the magnitude of Ekman divergence in surface waters, which moves surface water perpendicular to the wind direction, and causes upwelling of deeper water to take its place. 73% of variance in sea surface water temperature has been attributed to the effects of SAM, with a more positive SAM resulting in colder surface water (Arrigo et al., 2008).

The salinity of the Ross Sea has also been shown to be decreasing over the past five decades (Budillon, Castagno, Aliani, Spezie, & Padman, 2011), which alters circulation patterns and mixing rates, though an analysis of salinity trends are beyond the scope of this literature review.

It has been established that many physical changes are taking place to the oceanography of the Ross Sea as a result of climate change. The cooling of the region as a result of the increased pressure gradient of the SAM is increasing sea ice, enlarging the polynya, and altering the circulation patterns of seawater. It is important to gain an understanding of the effect these changes may have on the functioning of the ecosystem in order to inform and justify actions to protect the inhabitants of the Ross Sea.

Changes to timing and extent of primary production

A positive SAM phase has been correlated with a larger polynya, and increased biomass of phytoplankton (Arrigo et al., 2008). Primary production is higher in polynyas than in open ocean (Arrigo, Worthen, Schnell, & Lizotte, 1998). With few clouds, and areas of open, nutrient rich water, the Ross Sea polynya provides conditions necessary for a phytoplankton bloom to occur in spring (Arrigo, 2003b). As sea ice and the extent of the Ross Sea polynya continues to increase, this could mean that the biomass of phytoplankton may also increase each year (Smith et al., 2012).

The level of primary production has been measured using satellite images to gauge the amount of chlorophyll in the water, as well as using *in situ* observations. There is some inconsistency between the two methods of observation, with satellites producing a lower, but supposedly more accurate estimate of primary productivity in the Ross Sea to be 69 g C m^{-2} yr^{-1}. (Arrigo et al., 2008).

Arrigo and van Djiken (2004) found that phytoplankton blooms in the Ross Sea result in increased chlorophyll levels by mid-November. This bloom occurs much earlier than in surrounding areas, because the open water in the polynya exposes the underlying algae to a large amount of sunlight. A study by Montes-Hugo and Yuan (2012) found the timing of the spring phytoplankton bloom in the Ross Sea to be variable from year to year. Their evidence suggests the timing of phytoplankton blooms depends on shorter-term, local climate anomalies more than longer reaching (ie. > decadal) climate phenomena. However data for this study were collected during years when massive icebergs affected the amount of sea ice in the Ross Sea. It is likely that this event would have had an effect on the timing of phytoplankton blooms, thus producing results that are perhaps not representative of the average timing of the bloom.

Calving of icebergs (>100km in length) causes sea ice to retreat later in the season, which reduces irradiance and somewhat suppresses nutrient-rich currents, meaning phytoplankton blooms occur later in the presence of icebergs (Arrigo, 2002; 2003a). For example, in May 2002, the iceberg C-19 calved from the Ross Ice Shelf, and blocked the passage of sea ice out of the Ross Sea. This event resulted in a particularly high sea ice cover the following summer, as well as a reduction in the area of open water (Arrigo, 2003a). This ultimately caused primary production to be reduced by 40% on average, and as much as 95% for some areas, with ecological effects cascading through to upper trophic levels (Arrigo, 2002). A similar reduction in primary production occurred after the calving of iceberg B-15 in 2000 (Arrigo, 2002).

If similar conditions in sea ice were to be produced by sporadic calving of icebergs, or a more positive SAM, then a similar reduction in primary production may also occur. Modelling on the effects of increased SAM on timing of phytoplankton blooms could be the subject of future research.

Other factors influencing the timing of the phytoplankton bloom are oceanic influences such as mixing of deep water and stratification of water layers. Oceanic influences are not well studied, and future research is needed to elucidate the effects of climate change-driven ocean influences on the timing and geographical distribution of phytoplankton blooms.

Changes to species of primary producers

The main functional groups of primary producers in the Ross Sea are diatoms, cryptophytes, dinoflagellates and haptophytes. The haptophyte species *Phaeocystis antarctica* has a particularly important role in climate feedback and biogeochemical cycling, yet its connection to the food web is not well understood (Smith et al., 2007). *P. antarctica* grows rapidly in spring, reaching a maximum in December, before decreasing in January. The biomass in December is particularly large for three main reasons: It grows well under conditions of low light in spring,(Moisan & Mitchell, 1999), it forms large colonies which cannot be easily grazed, and sinking rates are low (Smith et al., 2012).

It has been suggested that *P. antarctica* adapted to grow in low light in order to gain a competitive advantage over other primary producers, in that it would be able to grow at a moderate rate under low irradiances; as opposed to fast growth under high irradiances, as is the case with many diatoms and other photosynthetic phytoplankton (Smith et al., 2007). If the change in climate of the Ross Sea region were to result in a significant increase in sea ice and thus a reduction in irradiation, then *P. antarctica* may gain an advantage over other phytoplankton species. This hypothesis, however, remains to be tested.

P. antarctica is known to produce high levels of methylsulfinate (MS), much of which eventually sinks to the sea floor (DiTullio & Smith, 1995). Analyses of sediment layers can thus give an idea of the amount of MS at different times throughout climate history, which may give an idea of the ratio of *P. antarctica* to other species of phytoplankton under different climatic conditions. There is a strong correlation between the area of open water and the amount of MS in the sediment (Rhodes et al., 2009). Having an understanding of the relationship of phytoplankton and historic climate changes may help to predict future rates of primary production under changed sea ice conditions.

Diatoms are another ubiquitous member of the phytoplankton community, and can form massive blooms near the edges of the ice shelf (Smith & Nelson, 1985) in shallower mixed waters. Surface water is mixed to about 50m in spring, while in summer mixing can be at depths less than 10m. *P. antarctica* is the dominant phytoplankton group in the lower light conditions caused by the deeper spring mixed layers, while diatoms dominate the shallower, lighter and more stratified layers in summer (Smith et al., 2007). *P. antarctica* is more common in highly-mixed water due to being more effective at photosynthesising in lower irradiances in mixed water (Arrigo et al., 1999).

Once *P. antarctica* has declined in late December, a bloom of diatoms takes place in these shallower mixed layers associated with melting of glaciers and sea ice. There are also localised blooms of other groups, such as dinoflagellates, silicoflagellates and cryptomonads (Arrigo et al., 1999). Diatom growth is constrained by availability of iron (Sedwick & DiTullo, 1997)**,** so growth cannot continue indefinitely.

The drawdown of CO_2 from the atmosphere is much stronger by *P. antarctica* than other groups, such as diatoms. If climate warming were to lead to increased ocean stratification, then diatoms would become more dominant, and the capacity of the Ross Sea to take up CO_2 could be largely diminished (Arrigo et al., 1999). *P. antarctica* and diatoms also differ in the ratio of nutrients they take up, with *P. antarctica* taking up around twice as much nitrogen, and significantly more carbon than diatoms (Arrigo et al., 1999). If the ratio of *P. antarctica* to diatoms were to change, then the nutrients sinking to benthic communities would be altered, thus affecting biogeochemical cycling (Smith et al., 2012).

Cryophilic algae are another primary producer in the Ross Sea. The biomass of these ice algae can be three times that of the surrounding water, contributing around 20% of production to the Ross Sea. Cryophilic algae ‘seed’ the surrounding water with nutrients as the ice melts (Smith & Nelson, 1985), providing a food source for grazers such as crystal krill (*Euphausia crystallorophias*). The timing of ice algae production is earlier than phytoplankton associated with seawater, with growth occurring before the phytoplankton bloom in spring. They are released with melting ice in spring. If the trend of increasing sea ice each season continues, then this is likely to affect the release of cryophilic algae into the water column.

There is significant evidence that primary production in the Ross Sea is being affected by climate change. The timing of blooms each spring, as well as the proportions of species of primary producers in the ecosystem is influenced by small changes in ice and water conditions. If primary producers are changing, then species that rely on them for food will also be affected.

Flow-on effects to higher trophic levels

Effects of changed structure and timing of phytoplankton communities on higher trophic levels have been well studied, however these studies go beyond the scope of this literature review. Some brief examples of flow-on effects of a change in primary producers have been highlighted below, but these examples are by no means the extent of the impacts.

There are few studies on zooplankton in the Ross Sea, so their role in biogeochemical cycling and food webs is unclear. Zooplankton exist at relatively low densities, with a biomass estimated to be about 15% of that in the Scotia Sea (Deibel & Daly 2007). A phytoplankton-feeding pteropod *Limacina helicina* and its predator *Clione antarctica* were “virtually absent” from the food web under the heavy sea ice conditions following the calving of the iceberg B-15 in the summer of 2001-2002, which is likely due to the lack of food in the form of diatoms and solitary algae, as a result of lower levels of irradiance. There was a higher than usual proportion of colonial *P. antarctica* present in the water column that season, in place of more palatable diatoms. With no adequate food supply, pteropods had no energy source (Hunt et al., 2008)**.**

A keystone species in the continental shelf region of the Ross Sea, is crystal krill (*Euphausia crystallorophias*), which links primary producers to higher trophic levels (Sala, Azzali, & Russo, 2002). Crystal krill graze on ice algae and diatoms, and are themselves heavily predated by both meso- and apexpredators.

During the summer of 2000-2001, following the calving of iceberg B-15 and the subsequent increase in sea ice cover in the Ross Sea, ecological effects were felt throughout the trophic levels. Adelie penguins (*Pygoscelis adeliae*) were forced to switch from a diet consisting mostly of silverfish, to one of crystal krill (Arrigo, 2002), which are a species that favours conditions of heavy sea ice (Ainley et al., 1998). In fact, 65% of the variance in the size of Adelie penguin colonies was explained by levels of primary production, according to a study by Arrigo and Van Dijken (2003b).

This highlights the close relationship between higher trophic levels and primary producers in the Ross Sea. It is clear that higher trophic levels can be largely affected by changes in phytoplankton communities, and thus justifies taking urgent action to increase scientific understanding of ecological relationships in the Ross Sea.

Conclusions

Despite being heralded as the most pristine ocean on Earth, the Ross Sea is changing considerably under the influence of climate change. Physical changes in circulation, biogeochemical cycling, sea ice extent and polynya formation are having an effect on the ecosystem. Primary producers are affected by these changes, and the effects cascade throughout the ecosystem to the level of top predators.

Climate change is set to continue in the foreseeable future, and the associated physical, biogeochemical, oceanographic and biological changes are a challenge that must be addressed by science. Other human influences such as fishing may be compounding the negative effects of climate change on the Ross Sea ecosystem, and only with a sound knowledge of the functioning of the ecosystem can actions be undertaken to reduce the negative effects experienced in the Ross Sea.

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