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Key Points:

- Ross Sea will be modified in ice-free duration and summer ice concentrations
- Modeled summer mixed layers decreased by 26 and 46% in 50 and 100 years
- The food web will undergo severe disruptions in the coming century

Supporting Information:

- Supplementary Text
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Table S1

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The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century

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Abstract The Ross Sea is critically important in regulating Antarctic sea ice and is biologically productive, which makes changes in the region's physical environment of global concern. We examined the effects of projected changes in atmospheric temperatures and winds on aspects of the ocean circulation likely important to primary production using a high-resolution sea ice-ocean-ice shelf model of the Ross Sea. The modeled summer sea-ice concentrations decreased by 56% by 2050 and 78% by 2100. The duration of shallow mixed layers over the continental shelf increased by 8.5 and 19.2 days in 2050 and 2100, and the mean summer mixed layer depths decreased by 12 and 44%. These results suggest that the annual phytoplankton production in the future will increase and become more diatomaceous. Other components of the Ross Sea food web will likely be severely disrupted, creating significant but unpredictable impacts on the ocean's most pristine ecosystem.

1. Introduction

Observations and models of ocean-atmosphere interactions have clearly shown that changes in physical forcing, ocean circulation, and biogeochemistry in the Southern Ocean are occurring at a rapid pace [*Montes-Hugo et al.*, 2008; *Comiso et al.*, 2011]. Changes have been, and are predicted to be, large in polar systems and have been manifested as large increases in atmospheric temperatures [*Vaughan et al.*, 2003], changes in sea-ice concentrations and duration of ice cover [*Comiso and Nishio*, 2008; *Stammerjohn et al.*, 2012], and changed ecosystem dynamics and properties [*Montes-Hugo et al.*, 2008; *Smith et al.*, 2012]. One change that has been documented is that wind speeds over the Antarctic Circumpolar Current (ACC) have increased in the past 50 years and shifted southward [*Marshall*, 2003], which is thought to have increased the eddy activity in the ACC [*Meredith and Hogg*, 2006; *Hogg et al.*, 2008] and possibly changed the overturning transport [*Hallberg and Gnanadesikan*, 2006; *Meredith et al.*, 2012], as well as the transport of circumpolar deep water onto the Antarctic continental shelves [*Thoma et al.*, 2008; *Dinniman et al.*, 2012]. As a result, such changes in atmospheric forcing will likely have substantial oceanographic and ecological impacts throughout the Southern Ocean.

Changes in physical forcing on the continental shelves of Antarctica are not uniform. Sea-ice distributions and extent have dramatically decreased in the past 50 years in the Bellingshausen-Amundsen sector, which has been balanced by a net increase in the Ross Sea sector [*Comiso et al.*, 2011]. These observations show that the duration of ice-free days on the Ross Sea continental shelf (Figure 1) has decreased by over 2 months over the past three decades [*Stammerjohn et al.*, 2012], which may decrease the annual productivity and the role in the ecosystem of groups that rely on open water. Future projections of regional air temperature change however suggest that a substantial warming will occur in the next century in the Ross Sea sector [*Bracegirdle and Stephenson*, 2012], and while changes in the wind speeds over the continental shelf are somewhat uncertain, they are expected to increase just north of the Ross Sea over the ACC [*Bracegirdle et al.*, 2008], especially in the second half of the 21st century [*Bracegirdle et al.*, 2013]. These changes are expected to reverse the sea-ice trends in the future; however, the projected changes in heat content on the continental shelf and ecosystem dynamics that will occur as a result of such changes remain far from certain.

The Ross Sea continental shelf is not directly impacted by the ACC, but its effects on the shelf are driven by the Ross gyre, which arises from the ACC (Figure 1). The gyre includes a strong current that flows to the

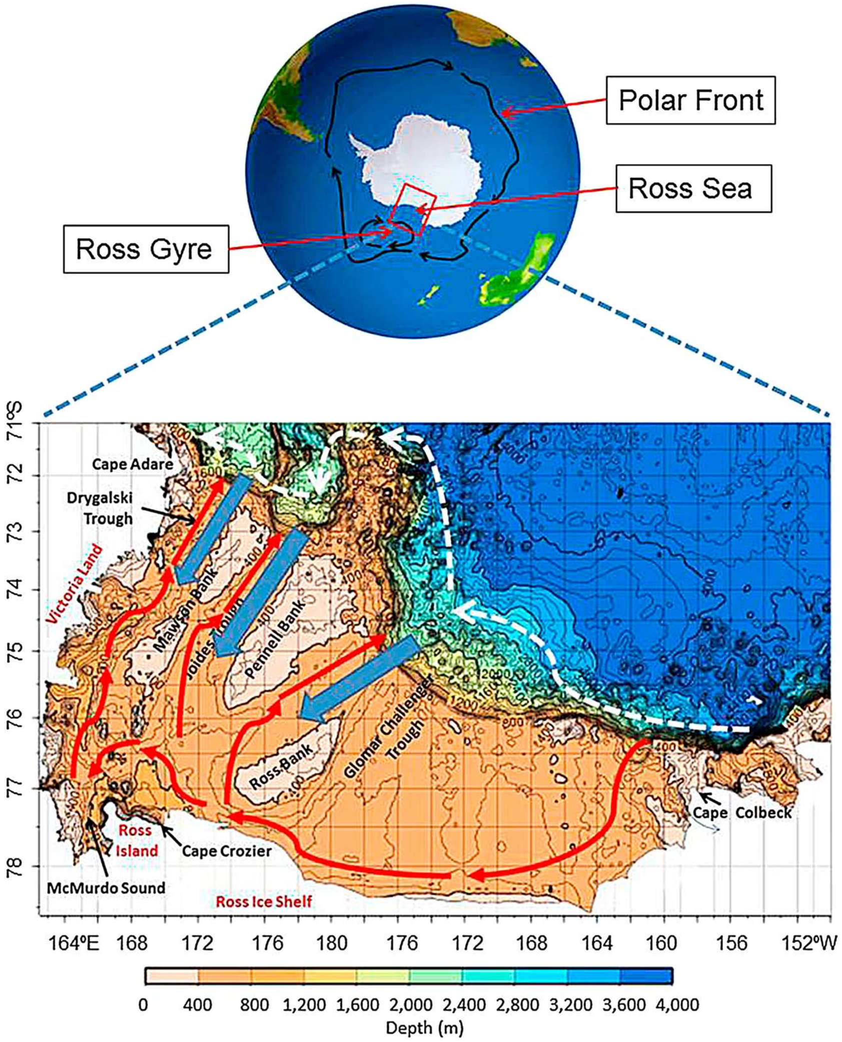

Figure 1. Map of the Southern Ocean and Ross Sea (enlarged area) with a schematic representation of the currents along the continental shelf break (white dashed line) and on the shelf (red lines), and the paths of intrusions of MCDW (solid blue lines) onto the shelf. The positions of the Ross gyre and polar front are indicated, as is the model domain (open red square).

west along the continental slope, which generates intrusions onto the shelf of Circumpolar Deep Water (CDW; Figure 1), both of which have been observed and modeled [*Jacobs*, 1991; *Dinniman et al.*, 2011; *Kohut et al.*, 2013]. As CDW moves onto the shelf, it is modified by mixing with shelf and surface waters and becomes Modified Circumpolar Deep Water (MCDW). Changes in the wind and/or cross-gyre salinity structure (due to changes in sea-ice formation or melt) would likely induce changes in the Ross gyre [*Wang and Meredith*, 2008], although there is an uncertainty about the future direction (stronger or weaker) of changes in the gyre strength [*Meijers et al.*, 2012; *Wang*, 2013]. Changes in the Ross gyre in turn would alter the frequency and strength of intrusions of MCDW and impact the Ross Sea continental shelf's heat balance, sea ice, biogeochemistry, and ecology (given that MCDW is a source of nutrients and warm water to the shelf).

In addition to the observed increased extent and duration of sea ice, changes in atmospheric conditions have occurred in the Ross Sea sector. The cold, southerly winds blowing northward from the Ross Ice Shelf over the Ross Sea have strengthened [*Turner et al.*, 2009], and stronger winds could result in increased vertical mixing in waters of the continental shelf, as well as the observed increased cooling at the surface and enhanced ice formation [*Comiso*, 2010]. The net oceanographic effects of altered MCDW intrusions (with its added heat) and the decreased atmospheric temperatures (and heat loss) are uncertain, and it is unclear how future changes in projected physical forcing might influence waters of the continental shelf.

Two functional groups, diatoms and haptophytes (specifically *Phaeocystis antarctica*), dominate in the Ross Sea. The two groups respond very differently to irradiance: *P. antarctica* dominates in austral spring in relatively deeply mixed environments (and hence in low-average irradiance conditions), whereas diatoms are found in more stratified (and high irradiance) habitats such as near-melting ice edges [*Kropuenske et al*., 2009; *Smith et al*., 2011]. Changes in vertical mixing would result in changes in the surface plankton composition and thus alter the region's biogeochemical cycles. Enhanced surface phytoplankton production has been observed to be associated with MCDW intrusions [*Peloquin and Smith*, 2007], although the exact nature of the stimulation remains unclear. We hypothesized that changes in the atmospheric forcing in the Ross Sea would generate substantial changes in sea-ice dynamics and the aspects of the oceanic conditions (MCDW formation, vertical mixing) that would drive substantial changes in the region's ecosystem.

2. Materials and Methods

Using an implementation of the Regional Ocean Modeling System [*Haidvogel et al*., 2008] for the Ross Sea and projected winds and air temperatures for 2050 and 2100, we assessed future changes in the oceanography of the region and their potential effects on the ecosystem. The Ross Sea is noticeably freshening [*Jacobs et al*., 2002], and it is thought that much of the freshening is not forced locally but rather is due to an increased advection of low-salinity water from the Amundsen Sea [*Jacobs and Giulivi*, 2010]. Therefore, we imposed a freshening (by 0.12) at the model boundaries to include the presently observed [*Jacobs and Giulivi*, 2010] rates of freshwater input change. The regional circulation model includes a dynamic sea-ice model and uses a 5 km horizontal grid spacing with 24 terrain following vertical layers. Daily winds and air temperatures for 9/1996–9/2000 (20th century) were taken from the Max-Planck-Institut European Centre/Hamburg 5 (ECHAM5) climate model [*Jungclaus et al*., 2006] 20th century experiment. However, comparison with the European Centre for Medium-Range Weather Forecasts-Interim (ERA-Int) Reanalysis temperatures showed that the daily ECHAM5 air temperatures were colder than expected, especially near the coast and Ross Ice Shelf front. Therefore, a monthly climatology of ERA-Int temperatures was used for the 20th century conditions. These baseline conditions reproduced the sea-ice climatology closely when winds on a finer spatial resolution are used (see supporting information).

The daily winds for 9/2046–9/2050 and 9/2096–9/2100 were taken from the Coupled Model Intercomparison Project phase 3 A1B emission scenario of the ECHAM5 model. The monthly climatologies of the difference between the ECHAM5 A1B and the 20th century air temperatures were constructed for both future time periods. The difference fields were added to the ERA-Int climatology to create climatologies for the two future times, and these were used to force the ocean model. The adjusted temperature mean relative to the 20th century mean was 1.66 ± 2.58°C warmer over the model domain for 2046–2050 (2050) and 2.50 ± 2.32°C warmer for 2096–2100 (2100).

The simulations done with the coupled sea-ice circulation-ice shelf model were as follows: baseline simulation that used the ERA-Int atmospheric temperature climatology (1996–2000) and ECHAM5 20th century daily winds and the 2050 and 2100 simulations that used the daily ECHAM5 A1B winds and adjusted ECHAM5 A1B/ ERA-Int temperatures (Table S1 in the supporting information). All simulations discussed here included freshening at the model boundaries. Circumpolar deep water is tracked using a dye tracer, which is placed off the continental shelf (defined by the 800 m isobath) at any depth with temperature greater than 0.0°C (an indicator of CDW) at the end of a 6 year model spin-up simulation [*Dinniman et al*., 2007, 2011] with an initial concentration of 100 arbitrary units. Once a simulation is initiated, the dye advects and diffuses over the entire model domain, providing the temporal evolution of the input and distribution of CDW on the Ross Sea continental shelf. The offshore dye source at the open boundaries provides a continuous source to the model domain; no surface or bottom fluxes of CDW occur. Additional model details are given in the supporting information.

3. Results and Discussion

Present ice concentrations over the continental shelf are near 100% in winter, but decrease substantially with the seasonal development of the Ross Sea polynya (an area of open water surrounded by ice;

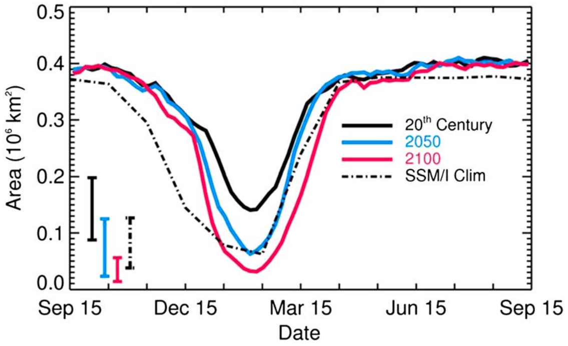

Figure 2. Simulated sea-ice area over the Ross Sea continental shelf calculated for present and projected future changes and the sea-ice climatology constructed from Special Sensor Microwave Imager (SSMI) observations for the time included in the 20th century simulations. The simulated sea-ice areas represent the average over the 4 years included in the simulations. The range of the summer minimum ice area for each simulation and SSMI (same 4 years as the 20th century simulation) is indicated (vertical bars).

Figure 2). The modeled summer ice-free extent is smaller than observations (Figure 2), and this is likely due to the coarse resolution of the ECHAM5 winds (see supporting information). Substantial interannual variability exists and is driven by large-scale forcing as well as localized effects of large icebergs [*Comiso et al.*, 2011]. Under the scenario for 2050, sea-ice concentrations in winter are similar to modeled present conditions, but decrease to a far greater extent in summer (the mean minimum ice area is 44% of that at present). This reduction is mostly due to an increase in the strength and duration of in situ melting (Figure S2 in the supporting information). Furthermore, the timing of polynya formation is shifted, with the mean day of retreat below 15% ice concentration over the continental shelf occurring 5 days earlier, but the mean day of advance occurring at the same time, although some locations have a shorter ice-free period due to a slight shift in the location of the summer polynya (Figure S3a in the supporting information). For the 2100 scenario, sea-ice concentrations continued to decrease in summer and were only 22% of those found during the present summer minimum. The duration of the ice-free season becomes even longer (Figure S3b in the supporting information) with the mean day of retreat now occurring 11 days earlier and the advance occurring 16 days later (Table 1). The difference in the mean duration of the ice-free season between the 20th century (39 days) and the 2100 (67 days) cases is much greater than the interannual present variability (Table 1). Hence, predicted wind, temperature, and salinity changes will result in an earlier formation of the polynya and greatly reduced summer sea-ice conditions throughout the Ross Sea. Both will result in greater annual irradiance penetrating into the water column.

Present conditions provide for a substantial amount of MCDW to be advected onto the continental shelf along the troughs that occur on the shelf (Figure 3) and mixed into the upper water column. For the 2050 and 2100 simulations, the amount of MCDW that enters the upper 50 m of the water column (averaged over the entire continental shelf) decreased by 24 and 8%, respectively. The decrease was greater in 2050 than in 2100 because although the projected future warming and freshening reduces the vertical mixing

Table 1. Predicted Oceanographic and Biotic Modifications in the Ross Sea That Will Result From Future Climate Changes[b]

Year	Present	2050	2100
Oceanographic Changes			
Change in the mean annual atmospheric temperature from present (°C)		1.66 ± 2.58	2.50 ± 2.32
Mean summer mixed layer depth (m) + standard deviation	14.6 ± 10.6	12.8 ± 6.6	8.2 ± 5.2
Annual range (m)	13.6–17.8	8.7–13.9	7.9–8.8
Mean duration of yearly ice-free[a] period (days)	39.2 ± 47.1	44.2 ± 41.6	67.3 ± 42.4
Annual range (days)	27.7–46.4	39.6–59.8	62.6–78.7
Period of mixed layer less than 25 m (days)	95.1 ± 25.4	103.6 ± 22.1	114.3 ± 21.5
(East half of shelf)	89.6 ± 27.6	102.3 ± 23.6	113.5 ± 23.2
(West half of shelf)	99.5 ± 22.4	104.8 ± 20.8	114.9 ± 20.0
Annual range (days)	80.3–100.4	98.1–109.2	110.8–122.0
Total annual on-shelf CDW flux (Sv)	2.10 ± 0.52	1.61 ± 0.60	1.82 ± 0.43
Biotic Changes			
Total primary production (g C m^{-2} y^{-1}) (percentage of production attributed to diatoms)	104 ± 83 [40]	106 [42]	118 [48]
Phytoplankton composition	*Phaeocystis*/diatoms	*Phaeocystis*/diatoms	Diatoms/*Phaeocystis*

[a] Less than 15% ice cover.

[b] All model values are computed over the Ross Sea continental shelf for the last 2 years of each simulation (except the range of the annual average values which is given for all 4 years). The standard deviation for all oceanographic changes (except CDW flux) is over the spatial dimension of the model temporal (last 2 years) average.

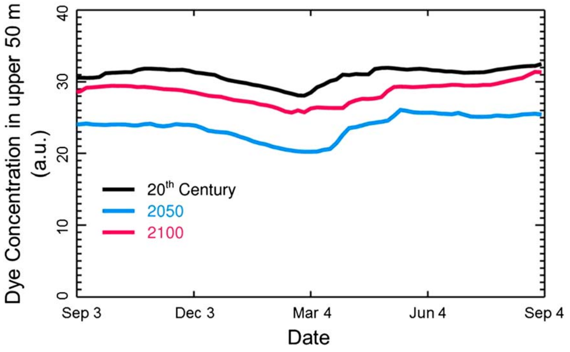

Figure 3. Simulated mean concentration of MCDW dye (in arbitrary units; analogous to the contribution of MCDW; see supporting information) in the upper 50 m over the entire Ross Sea continental shelf for present and projected future changes over the last year of each simulation.

of CDW into the upper waters, projected changes in the winds by 2100 (weaker southerlies near the coast and stronger winds near the shelf break and over deeper waters) drive an increase in the supply of CDW to the continental shelf, a result supported by a simulation (not shown) that used modified winds only (atmospheric temperature and boundary salinity were unchanged). Similar to the CDW, the total heat advected laterally onto the continental shelf (not shown) is greatest for the 20th century case (16.8 Tw), lowest for 2050 (10.9 Tw), and increased some by 2100 (12.6 Tw). The greatest changes in mixed layer depths were observed in the western Ross Sea (Figure S4 in the supporting information), which is the area of the greatest vertical mixing at present. Although much of the mixing of the MCDW into the surface waters occurs during winter, a period not conducive to phytoplankton growth, the decrease in mixing suggests that there might be a slight reduction in winter nutrient supply in the future.

Future changes in the water column vertical structure were assessed by examining the depth of the mixed layer across the continental shelf. The mean mixed layer depths (defined by a density change of 0.01 kg m^{-3} relative to the surface value) in autumn (when the mixed layer first deepens enough to significantly entrain nutrients from below) over the continental shelf at present, in 2050, and in 2100 were 91, 72, and 71 m, showing a reduction in the autumnal mixing. The mean summer mixed layers were 15, 13, and 8 m (significantly different from each other; $p < 0.05$), and the amount of time that the summer mixed layers were less than 25 m increased significantly (Figure 4) by 2050 (104 days) and 2100 (114 days) compared to the present (95 days; Table 1). The implications of the changed mixed layer depth are that less vertical replenishment of surface nutrients would occur, potentially altering initial nutrient concentrations at the start of the growing season, and that ocean stratification will persist for longer periods of time. Changes in the duration of the summer mixed layers are more marked east of 178°E in both the 2050 and 2100 scenarios (Table 1 and Figure 4). Substantial spatial variability (as is presently observed) in future changes in vertical stratification can be expected throughout the Ross Sea. Of the three potential impacts of altered forcing by climate change that could affect primary production, the two that are altered to the greatest extent are sea-ice distributions and mixed layer depths.

Such future changes would have extreme ramifications for biological distributions and processes in the Ross Sea. The large summer sea-ice reductions in the future would allow a greater period for phytoplankton growth, as irradiance is the primary control on photosynthesis over annual time scales [*Smith et al*., 2012]. Mixed layer depths will decrease in summer, and the ocean will also remain stratified for a longer period, resulting in a reduction of the relative contribution of *P. antarctica* to continental shelf productivity and an increase in the overall contribution of diatoms to annual production (now estimated to be 40%; Table 1) [*Smith et al*., 2014]. The total annual production will also increase by at least 14% (Table 1); these changes will be greatest in the more northern portions of the Ross Sea, which presently have a shorter ice-free period, as a result of the increased annual availability of irradiance in the water column. We recognize that micronutrient limitation might occur [*Smith et al*., 2012], but as irradiance is the primary control of productivity in the Ross Sea on an annual basis, an increase in production is expected with these future environmental changes. While predicting future changes in ecosystems is challenging, the Ross Sea, at present considered to be the world's least impacted (by humans) and most pristine marine ecosystem [*Halpern et al*., 2008], clearly will be extensively modified by future climate change.

4. Conclusions and Speculations

Although the Ross Sea is presently experiencing marked increases in ice concentrations, future changes in atmospheric temperatures and wind speeds will likely create a noticeably different environment on the

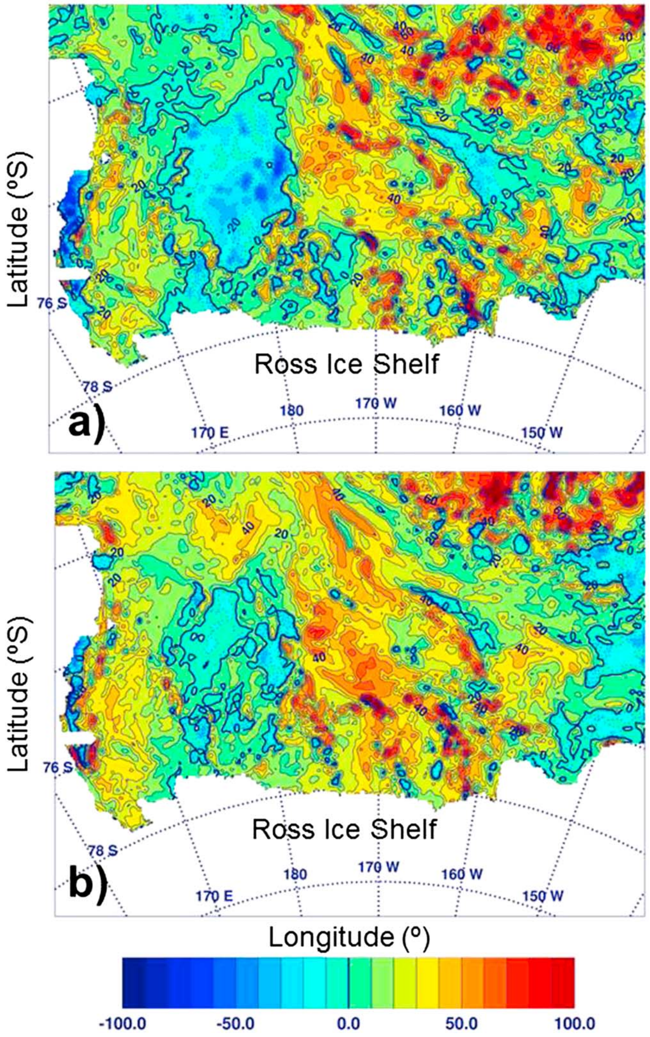

Figure 4. Change in the duration (days) of summer mixed layers shallower than 25 m between the 2050 and the 20th century simulations and between the 2100 and 20th century simulations.

continental shelf. Our simulations suggest that these changes will result in the Ross Sea polynya greatly expanding during summer (by 56 and 78% in 50 and 100 years from present). Modeled mean summer mixed layer depths will decrease by 12 and 44%, and the duration of shallow mixed layers will increase by 8.5 and 19.2 days in 50 and 100 years, respectively. The input of circumpolar deep water from off the continental shelf and mixed into the upper 50 m will decrease to a lesser extent (24 and 8%). Together these changes suggest that annual primary productivity will increase by ~14%. Furthermore, the contribution of diatoms to annual production will increase.

Diatoms are considered to be the preferred food of most marine herbivores such as copepods and krill [*Haberman et al*., 2003], and it is likely that secondary production may scale with diatom growth. However, substantial components of the ecosystem will be negatively impacted by decreased sea-ice concentrations, especially in summer (Table 1). For example, crystal krill (*Euphausia crystallorophias*), the major krill species in the Ross Sea, is thought to be associated with ice, and hence its distribution and role in phytoplankton grazing would decrease. Such a conclusion is in parallel with the known food web in the Ross Sea [*Pinkerton et al*., 2010]. Conversely, copepod grazing might increase in response to an increase in diatoms. Similarly, the impact of Antarctic silverfish (*Pleuragramma antarcticum*) might be substantial as well, as they use ice as a refugium like crystal krill. Antarctic silverfish feed primarily on copepods and hence potentially would have more food available. Changes in mesozooplankton would have significant impacts on higher trophic levels, as crystal krill are energetically important forms of prey for many top predators, such as minke whales (*Balaenoptera bonaerensis*), Adélie penguins (*Pygoscelis adeliae*), Emperor penguins (*Aptenodytes forsteri*), and crabeater seals (*Lobodon carcinophagus*). Adélie penguins also forage on Antarctic silverfish, but do so at greater distances from their nests in summer and therefore potentially could experience increased leopard seal predation. Baleen whales, Emperor penguins, and crabeater seals all would be expected to be negatively impacted due to a reduction in their major food source. The reduced ice might also allow for more humpback whales to enter the Ross Sea during summer, thereby further increasing predation on krill. Regardless of the exact nature of alterations, substantial portions of the food web that depend on ice in their life cycles will be negatively impacted, leading to severe ecological disruptions.

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