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Ecological impact of a large Antarctic iceberg

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[1] Satellite imagery has been used to document for the first time the potential for large icebergs to substantially alter the dynamics of a marine ecosystem. The B-15 iceberg ($\sim$10,000 km^2), which calved off the Ross Ice Shelf in the biologically productive southwestern Ross Sea, Antarctica, restricted the normal drift of pack ice, resulting in heavier spring/summer pack ice cover than previously recorded. Extensive ice cover reduced both the area suitable for phytoplankton growth and the length of the algal growing season. Consequently, primary productivity throughout the region was >40% below normal, which changed both the abundance and behavior of upper trophic level organisms. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 4207 Oceanography: General Arctic and Antarctic oceanography; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689)

1. Introduction

[2] Polar ice sheets and associated ice shelves are important indicators of climate change, responding to elevated temperatures with increased melt, accelerated motion, and/or increased iceberg calving [*Skvarca et al.*, 1999; *Scambos et al.*, 2000]. The calving of large tabular icebergs in the Antarctic has likely increased since the Last Glacial Maximum accompanying the formation of the Ross Ice Shelf [*Conway et al.*, 1999], with recent calving rates for large (>18.5 km) icebergs of 4.4 per year (iceberg tracking data obtained from the National Ice Center show that between 1978 and 2001, Antarctic ice sheets calved an average 4.4 icebergs larger than 18.5 km in length annually). Consequences of these calving events for marine ecosystems remain largely unexplored. Fortunately, the huge iceberg B-15 (at 295 km in length and up to 40 km in width is one of the largest icebergs ever observed), which calved off the Ross Ice Shelf in March 2000, is providing insights.

[3] The southwestern Ross Sea (Figure 1) is one of the most biologically productive regions of the Southern Ocean [*Smith and Gordon*, 1997; *Arrigo et al.*, 1998a]. Located on the Antarctic continental shelf, it owes its biological richness to the annual formation of the Ross Sea polynya, a region of diminished sea ice cover in the midst of heavy pack ice north of the Ross Ice Shelf. The Ross Sea polynya is formed by the strong, persistent katabatic winds that move sea ice offshore during winter, generally to the northwest [*Bromwich et al.*, 1992]. Come springtime, a large area of open water forms in this region as winds clear away the remaining sea ice. The resulting exposure of surface waters to sunlight is followed by a profuse growth of phytoplankton [*Arrigo et al.*, 1998b]. Concentrations of chlorophyll *a* (Chl *a*) in these blooms typically exceed 5 mg m^{-3} over an area of >100,000 km^2 (Figures 2a and 2b) [*Arrigo et al.*, 1998b; *Arrigo et al.*, 2000], compared to <0.05 mg m^{-3} in low productivity central ocean gyres. As a result of its high productivity, the Ross Sea supports large populations of upper-trophic level organisms, such as marine mammals and birds [*Ainley et al.*, 1984; *Kooyman and Burns*, 1999; *Kasamatsu et al.*, 1998]. Indeed, 25% and 30% of the world populations of the circumpolar Emperor (*Aptenodytes forsteri*) and Adélie penguins (*Pygoscelis adeliae*), respectively, nest at colonies in the Ross Sea [*Woehler*, 1993], which has a coastline <10% of the Antarctic continental margin.

2. Methods

[4] Sea ice distributions were computed from daily Special Sensor Microwave Imager (SSM/I) imagery obtained from the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center, University of Colorado, Boulder, CO. Images were processed to 6.25 km resolution using the algorithm of *Markus and Burns* [1995], and used to calculate open water areas. All satellite imagery were mapped to a common polar-stereographic projection using the Interactive Data Language (IDL, Research Systems, Inc.). Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data were obtained from the Goddard Earth Sciences Data and Information Services Center, DAAC. Chl *a* concentrations were derived from SeaWiFS Level 2 data (4 km resolution) and processed using the NASA SeaDAS image processing software and OC4v4 algorithm. Validation studies for the Ross Sea show that SeaWiFS surface Chl *a* retrievals are within ±15% of in situ observations [*Arrigo et al.*, unpublished]. Multi-day (<1 week) Chl *a* composites were constructed to reduce loss due to cloud cover. Primary productivity was calculated from SeaWiFS data using the algorithm of *Arrigo et al.* [1998a]. Iceberg positions were projected using MODerate resolution Imaging Spectrometer (MODIS) band 1 (620–670 nm, 0.25 km resolution) imagery except for images where the sun was below the horizon; then the thermal infrared band 24 (4.433–4.498 μm, 1 km resolution) imagery were used. MODIS data were obtained from the Goddard Earth Sciences Data and Information Services Center, DAAC.

[5] At three penguin colonies on Ross Island (Cape Royds, Bird, and Crozier), stomach samples were taken from 3–5 adult penguins each week for five weeks, 25 December to ca. 22 January. Adults were forced to regurgitate stomach contents using the water-off loading technique: filling them with warm water, then turning them upside down in a plastic bucket.

3. Results and Discussion

[6] Satellite imagery from a variety of platforms show that on March 2000, the iceberg B-15 (iceberg numbers are assigned by the National Ice Center, Suitland, MD, USA) calved from the eastern portion of the Ross Ice Shelf (Figure 1). Almost immediately after calving, B-15 began to fragment, and at the present time, there are at least nine separate sections, denoted B-15A through B-15I, drifting in and around the western Ross Sea. By far the largest of these are B-15A and B-15B. Tracking the movement of the icebergs using imagery from MODIS shows that B-15A ($\sim$6,400 km^2) drifted westward along the front of the Ross Ice

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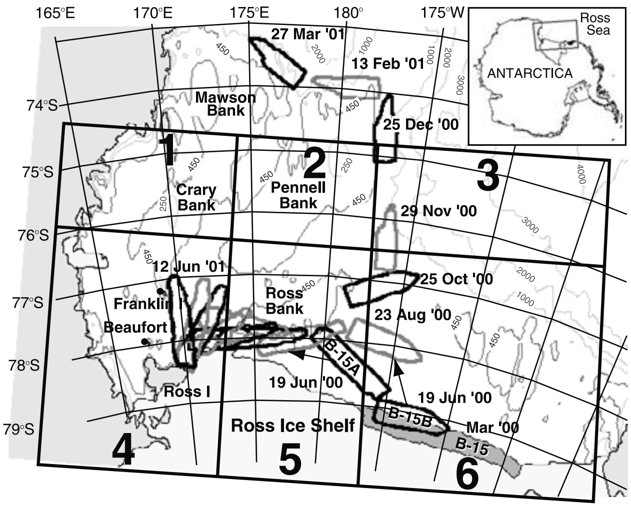

Figure 1. Map of the southwestern Ross Sea showing changes in the position of the B-15 iceberg and the location of the 6 regions referred to in the text. The sequential drift paths taken by B-15A and B-15B as determined from MODIS data are also shown. B-15A moved into its current position by edging past the Ross Bank but is now too large to move westward.

Shelf, likely guided by bathymetry and a narrow coastal current [*Keys et al.*, 1990] and is currently grounded near Ross Island at the face of the Ross Ice Shelf (Figure 1). B-15B first drifted to the north along the eastern edge of the Ross and Pennell banks and then moved west along the northern margin of the Pennell and Mawson Banks (Figure 1). It is now located near Cape Adare, over 1000 km from its original location. Like B-15A, however, other smaller icebergs (e.g. B-15C) remain grounded within the southwestern Ross Sea.

[7] In November 2000, nine months after the initial calving event, the pieces of B-15 were still in the southwestern Ross Sea, forming a barrier that greatly restricted the typical northwest drift pattern of pack ice (Figure 2c). As a result, sea ice concentrations measured using the SSM/I remained unusually heavy throughout November and early December 2000 (compare Figures 2a and 2b with 2c), the time when the southwestern Ross Sea normally shifts from being predominantly ice-covered to ice-free [*Arrigo et al.*, 2000]. As late as mid-December 2000, large amounts of sea ice remained piled up on the southeast side of the line of icebergs (Figure 2c), restricting the expansion of open water.

[8] Changes in the seasonal dynamics of sea ice cover brought about by the presence of B-15 are exemplified in an SSM/I time series for Region 5 (Figure 1), an area of the Ross Sea that was moderately impacted by B-15 (Figure 3a). During the spring of typical years (e.g. 1998–1999 and 1999–2000), sea ice cover in Region 5 diminishes rapidly, and from the beginning of December to early March, these waters are more than 80% ice-free. In contrast, the presence of the B-15 iceberg during 2000–2001 dramatically reduced the rate of ice advection, resulting in a 2-month delay in the time to reach maximum open water area. In fact, all regions of the southwestern Ross Sea experienced fewer days with <50% ice cover in 2000–2001, compared to the normal sea ice pattern represented by the 1998–2000 time period (Table 1). In the three regions adjacent to the Ross Ice Shelf (Figure 1), the number of days with sea ice concentrations below 50% was reduced by 37–48% in 2000–2001, and Region 3 did not become ice-free all year.

[9] The heavy sea ice conditions of 2000–2001 caused by the presence of the B-15 iceberg had a dramatic effect on phytoplankton populations throughout the southwestern Ross Sea. In ordinary years, phytoplankton begin to bloom in mid-November (Figure 3b), just as the area of open water and the availability of light begins to increase (Figure 3a). Imagery from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) shows that typically, Chl *a* concentrations in the Ross Sea increase rapidly, as do calculated rates of primary production (Figure 3c), eventually peaking in late December. After blooming for approximately six weeks, phytoplankton growth rates begin to diminish. At this time, loss processes such as grazing and sinking exceed rates of growth, causing Chl *a* abundance and primary production to decline steadily.

[10] SeaWiFS imagery reveals, however, that the normal phytoplankton dynamics in the Ross Sea were markedly altered during 2000–2001, most probably a direct result of the effects of the B-15 iceberg. Diminished light availability due to the high concentrations of sea ice present throughout the southwestern Ross Sea in the austral spring and summer resulted in a dramatic delay in the initiation of the phytoplankton bloom in some regions and no bloom at all in others. In Region 5, the phytoplankton bloom was delayed by approximately two months due to abnormally extensive sea ice cover. As a result of the reduced length of the growing season, peak Chl *a* concentrations in this region reached only about 50% of normal values (Figure 3b). Unlike most years when the decline of the phytoplankton bloom is precipitated well in advance of ice freeze-up, the rapid drop in Chl *a* and primary production observed in many regions (e.g. Region 5) in 2000–2001 (Figures 3b and 3c) was due to a reduced ice-free growth season (Figure 3a).

[11] The extensive sea ice cover and delayed phytoplankton bloom in 2000–2001 resulted in a substantial drop in the annual phytoplankton production estimated for all regions of the Ross Sea, the severity of which varied spatially. The effect was most extreme in Region 3, where unusually high sea ice cover and an extremely short growing season (Table 1) reduced annual primary production by 95% (Table 1). Annual production in Regions 4 (dominated by

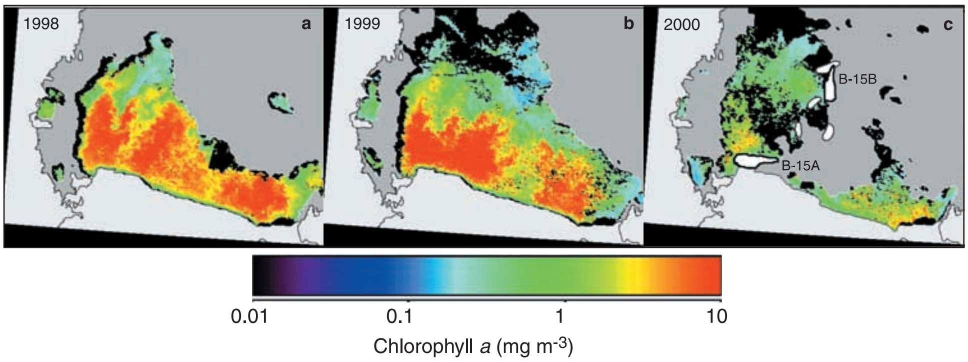

Figure 2. Mid-December distributions of sea ice (dark gray) from SSM/I and chlorophyll *a* concentrations from SeaWiFS for (a) 1998, (b) 1999, and (c) 2000. Black areas are open water regions obscured by clouds. Six large fragments of the B-15 iceberg determined from MODIS imagery are shown in white in (c).

Table 1. Regional Differences in Length of Growing Season[a] and Annual Primary Production in the Southwestern Ross Sea in 1998–1999, 1999–2000, and 2000–2001 by Region

Region	1998–1999		1999–2000		2000–2001		% Change[b]	
	Growing Season (Days)	Primary Production (Tg C)	Growing Season (Days)	Primary Production (Tg C)	Growing Season (Days)	Primary Production (Tg C)	Growing Season	Primary Production
1	83	4.9	91	4.9	80	3.0	−8	−40
2	105	5.1	121	5.5	112	3.7	−1	−31
3	59	2.5	81	4.5	0	0.2	−100	−95
4	77	6.0	76	6.9	48	4.4	−37	−32
5	118	9.5	107	10	59	5.5	−48	−44
6	88	13	93	19	54	10	−39	−35
All		41		51		27		−41

Regions are shown in Figure 1.

[a] Defined as the number of continuous days with <50% sea ice cover.

[b] % Change was calculated as the difference between 2000–2001 and the mean of 1998–1999 and 1999–2000.

diatoms), 5 and 6, where blooms of the alga *Phaeocystis antarctica* are generally the most intense [*Arrigo et al.*, 1998b; *Arrigo et al.*, 2000], was diminished by 32%, 44%, and 35%, respectively in 2000–2001. Taking into consideration the reduction in both open water area and Chl *a* concentrations in 2000–01 (Figure 3c), annual primary production in the southwestern Ross Sea was only 27 Tg C, approximately 41% below normal (Table 1). Primary productivity was also reduced substantially in regions where B-15 caused relatively small changes in sea ice cover (e.g. Region 2). This is because phytoplankton blooms in the Ross Sea generally begin just to the north of the Ross Ice Shelf, in waters that are first to become ice-free (e.g. Region 5), and later progress northward as the open water area increases. However, because phytoplankton blooms in areas like Region 5 were delayed so long in 2000–2001 due to heavy ice cover (Figures 3b and 3c), phytoplankton growth was insufficient to allow for the normal northward intensification of the bloom into Region 2.

[12] Modification of the temporal bloom dynamics and primary production caused by B-15 on such a large a scale is almost certain to impact the entire pelagic ecosystem of the Ross Sea. *P. antarctica* and diatoms differ greatly in their nutrient uptake characteristics [*Arrigo et al.*, 2000] and in the grazer populations each supports [*Goffart et al.*, 2000]. Shifting from one phytoplankton population structure to another will influence higher trophic levels as well as alter important biogeochemical processes such as carbon drawdown [*Arrigo et al.*, 1998b], particle export [*DiTullio et al.*, 2000], and sedimentation [*Dunbar et al.*, 1998]. In addition, many Antarctic organisms have evolved lifecycles predicated upon the availability of a predictable and ample food supply in the austral spring and summer. Zooplankton such as copepods and krill use lipids stored from the previous season to fuel the production of eggs that are released to coincide with the phytoplankton bloom in spring [*Hagen*, 1999]. A delayed bloom will either result in a lowered food supply at the usual time of egg hatching, or if the organisms delay reproduction, cause a reduction in lipid reserves available for egg production. Larger organisms such as Emperor and Adélie penguins time their reproduction so that their chicks fledge in the early summer [*Ainley*, in press], at the time of maximum food availability. These organisms will be particularly sensitive to any environmental perturbation that shifts temporally the availability of their food source.

[13] B-15A has been grounded near Ross Island for more than one year and its northwestward drift (the direction of the prevailing currents) is now impeded by Franklin and Beaufort islands as well as the Ross and Crary banks (Figure 1) which are shallower (180–450 m) than the probable maximum draft of the iceberg (∼500 m). Consequently, unless B-15A disintegrates, it will almost certainly remain grounded for many years, as has B-9, which calved from the Ross Ice Shelf in October 1987 but over the past decade has moved little from its present location (67.4°S, 148.5°E). If B-15A remains grounded, it is likely to have a substantial impact on ocean circulation near Ross Island and McMurdo Sound, the site of numerous penguin colonies [*Woehler*, 1993; *Ainley et al.*, 1998] and seal breeding grounds [*Testa and Siniff*, 1987; *Kooyman and Burns*, 1999]. During the summer of 2000–2001, the diet of Adélie penguins nesting at Ross Island colonies was abnormally dominated by the euphausiid species, *Euphausia crystallorophias*, which usually is associated with sea ice overlying Antarctic neritic waters [*Ainley et al.*, 1998]. At the three Ross Island colonies in 2000–2001, *E. crystallorophias* contributed 72.1 ± 0.05% (n = 15) by mass of the Adélie Penguin diet, compared to 35.4 ± 7.8 to 60.1 ± 0.7% in the previous four summers ($F_{4,\ 70} = 19.87$, $P < 0.001$). This change in penguin diet might reflect an increase in *E crystallorophias* populations, since the latter has been shown to occur in response to greater than normal sea ice extent [*Ainley et al.*, 1998] such as that precipitated by B-15. B-15A now blocks entrance to Cape Crozier to both Emperor and Adélie penguins. Should the iceberg remain in place, local penguin populations must either modify their route to the current breeding grounds or choose alternative breeding sites.

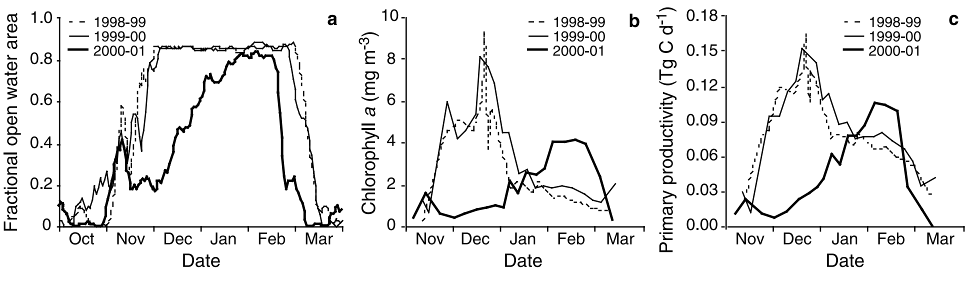

Figure 3. Austral spring and summer changes in (a) fractional open water area, (b) chlorophyll *a*, and (c) primary productivity for the years 1998–1999, 1999–2000, and 2000–2001.

[14] Studies suggest that the Ross Ice Shelf front has been relatively stable over the last century [*Bentley*, 1998] and throughout several major calving events observed in the last few decades. Large tabular icebergs calve along ice-front-parallel rifts that form ~30–40 kilometers behind the ice front. Given ice front speeds of ca. 1 km yr^{-1} [*Thomas et al.*, 1984], the northeast corner of the Ross Ice Shelf calves every 3 to 4 decades on average. However, because calving occurs cyclically elsewhere as well, icebergs may calve from other sections of the front within that interval. In fact, another large crack in the Ross Ice Shelf has formed 40 km south of the location where B-15 calved, and is a likely site of the next large iceberg to be released into the Ross Sea. On longer timescales, the grounding line of the West Antarctic Ice Sheet in the Ross sector has been retreating since the Last Glacial Maximum and will likely continue to do so as a result of Holocene climate change [*Conway et al.*, 1999]. This retreat is responsible for the present Ross Ice Shelf, and may dictate changes in the position of the ice front and in future calving behavior. Changing patterns of ice discharge in West Antarctica on the few-hundred-year time scale have been observed but the debate about the future of the ice sheet continues [*Bentley*, 1998; *Bindschadler*, 1998]. The stability of ice shelves in a warming climate is in question; warming has been a factor in the loss of small ice shelves along the Antarctic Peninsula where many ice shelves (e.g. the Larsen and Wilkins) are disintegrating rapidly [*Doake et al.*, 1998; *Scambos et al.*, 2000].

[15] Icebergs calve frequently around the Antarctic continent and despite their constant presence and evidence to suggest that the rate of calving may increase, almost nothing is known about the ecological impact of these events, particularly in highly productive coastal regions. This initial investigation of a large iceberg shows clearly that the impact can be substantial. It would now be instructive to determine whether this sequence of events happens elsewhere and how might the advent of ice shelves, and thus icebergs, have changed ocean biology and the historical records recorded in sea floor sediments. In addition, one wonders what the impact on coastal ecosystems might be if large calving events were to increase in frequency in the future.

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