<arttitle> Icebergs boost phytoplankton growth in the Southern Ocean

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<abs> Icebergs which calve from the Antarctic ice shelves and drift in the Southern Ocean deliver fresh water, dust and minerogenic particles to the surface ocean along the iceberg's path. Each of these components may have an effect on growth conditions for phytoplankton, as might the mechanical effects of the iceberg keel disturbing the water. Although anecdotal evidence and small-scale surveys suggest that drifting icebergs increase local primary production, no large-scale studies have reported on this possibility in detail. A combination of satellite and automated iceberg tracking data presented here shows that the probability of increased surface phytoplankton biomass was two-fold higher in the wake of a tracked iceberg compared to background biomass fluctuations. Only during the month of February were the effects of icebergs on surface biomass likely to be negative. These results confirm icebergs as a factor affecting phytoplankton in the Southern Ocean and highlight the need for detailed process studies so that responses to future changes in the Antarctic ice sheets may be predicted.

<p-ni> Anecdotal evidence has, for many years, suggested a link between the presence or passage of icebergs and enhanced phytoplankton growth in the Southern Ocean[1,2]. There are several mechanisms by which icebergs could be thought to improve the growth environment, but also several potential negative impacts. Furthermore, a particular physical process associated with an iceberg may have varying impacts, depending on the oceanic[3] and ecological[4] conditions through which it is passing. Figure 1 illustrates one possible scenario, in which an iceberg with a deep keel, passing through deeply-mixed waters, mixes micronutrients from below the pycnocline into the surface and also, by shedding meltwater at the waterline, alters the density structure of the upper water column. Iceberg meltwater forms a stable lens of low-salinity water in which phytoplankton cells are bathed in sunlight, resulting in an increase in surface phytoplankton biomass. The same processes acting on different initial conditions, such as a well-stratified water column with high phytoplankton biomass in the upper layer, could produce the contrary effects of diluting the surface phytoplankton population through mixing and slowing growth by destroying the stable surface layer and thus forcing cells to adapt to lower light levels. The individual processes can be summarised in two groups:

<p> **1. Mechanical disturbance.** Surveys of iceberg size indicate that typical keel depths for medium-sized icebergs (dimensions of the order of 1 km) range between 140 and 600 m at the time of calving[5]. Near the coast, this may be sufficient for the berg to be grounded, potentially disturbing circulation patterns, sea-ice formation and consequently the entire ecosystem[6]. The case of grounded icebergs is not further discussed in this paper. Once an iceberg is adrift, the keel causes turbulent mixing, potentially enabling transfer of salinity, thermal energy, nutrients and phytoplankton cells across the pycnocline (the base of the mixed layer). The degree of turbulence is determined by the topography of the iceberg's keel and by the relative velocity of the iceberg and the surrounding water. Input of macro-nutrients (nitrate, phosphate,

silicate) would be likely to have a positive impact on phytoplankton growth late in the summer season, when the surface waters are stratified, with a shallow pycnocline (30 to 50 m) in which iron and silicate, in particular, are depleted[7]. Input of micro-nutrients (specifically iron) is likely to promote phytoplankton growth both in the late summer and at all times in the high-nutrient/low-chlorophyll (HNLC) regions[8,9]. An initially high concentration of phytoplankton cells near the ocean surface could also be mixed through the water column by the passing iceberg. For monitoring of surface chlorophyll using satellite-borne detectors, this would result in a decrease in the concentration detected. Whether cells are actually lost from the mixed layer would depend on the iceberg keel depth, which determines the degree of turbulent mixing relative to the mixed layer depth.

2. Melting.

The presence of slightly reduced salinities surrounding icebergs has been reported for icebergs close to the Antarctic Peninsula[10]. Oceanic water layers are ordered according to density gradients, which are determined by both temperature and salinity. The net effect of melt water on the water column structure depends on the volume of water melting, the strength of wind-mixing and on the ambient temperature and salinity structure: Unless the ambient temperature is close to freezing, the melt water will have a negative temperature-component of buoyancy, while the salinity-component will be positive, since fresh water is less dense than saline water. A positive increase in density gradient caused by the input of freshwater must then withstand the physical mixing effect of the wind, or the new stratification will be destroyed. The melt water lens alleviates light limitation for cells trapped within it by suppressing vertical mixing[11,12]. In contrast, input of melt water at depth is likely to result in upwelling of water from below the thermocline, bringing nutrients into the surface mixed layer[13], The glaciers from which icebergs calve also accumulate dust, which falls with snow, over many thousands of years. Although Antarctica is too isolated at present to receive large inputs of Aeolian dust, this has not always been the case: The deposition rate of dissolvable iron within dust in East Antarctica was found to be a factor of two greater during interglacial than glacial periods[14]. Concentrations of dissolvable iron in modern snow deposited on sea-ice were reported by[15] to reach 23.7 nM, compared to ambient concentrations of below 4.5 nM below sea-ice and less than 1 nM in the open Southern Ocean[16,17]. As an iceberg melts and breaks up, the entire accumulated stock of iron is released into the surrounding water at a range of depths up to the keel depth. Finally, massive colonies of phytoplankton were observed growing on submerged faces of the icebergs[10]. These cells could alter the phytoplankton community composition of waters in which they are shed as melting proceeds, potentially out-competing the prevailing species.

While several theoretical studies have examined the fluid dynamics of iceberg melting and turbulence[13,18], none has yet sought to prove or disprove the hypothesis that drifting icebergs consistently have a marked impact on the food chain. The problems of modelling physical, chemical and biological processes in detail around an iceberg are many and various: the iceberg topography must be accurately simulated and melting, erosion and turbulence realistically implemented at high spatial resolution. Data to initiate such a model are scarce, and sufficient data to validate it are not known to exist. In the field, only one oceanographic survey has yet dedicated sufficient time and resources to address these problems: over a period of three weeks, two icebergs off the Antarctic Peninsula could be observed in great detail and were found to support considerable populations of phyto- and zooplankton[10]. Many more ship hours would be required to gather a statistically significant sampling of icebergs in all the conditions encountered in the Southern Ocean. An alternative means to modelling or *in situ* sampling is offered by satellite remote-sensing: If iceberg positions are accurately recorded, then records of surface chlorophyll concentration derived from satellite data can be consulted to determine whether the concentration before an iceberg transits a given location was higher or lower than the concentration afterwards[19]. This study pursues such an approach to test the null hypothesis that:

<fd>'An iceberg has no significant impact on the ambient chlorophyll dynamics'

To achieve this, a dataset of daily, automatically transmitted locations of tagged icebergs[20], was combined with the satellite-derived surface chlorophyll concentration record (henceforth 'chlorophyll'). Mean chlorophyll concentrations in a 6-day period prior to a tagged iceberg reaching each of its known locations were subtracted from those in a 6-day period after the iceberg transit, yielding the change in surface chlorophyll associated with the known passage of an iceberg, Δchl[iceberg]. Figure 2 demonstrates the methodological concept, together with some of it's drawbacks. It is evident from the true-colour composites in the second and third columns of Figure 2 that many more icebergs are present, at least within the first 5° of latitude adjacent to the Antarctic coast, than are, or realistically can be, tracked. These represent a potential influence on chlorophyll concentrations which can not be corrected for directly. Additional unknown factors include mixing, advection and the ambient phytoplankton growth dynamics. To address this, a dataset was generated in a similar fashion to the Δchl[iceberg] dataset but using chlorophyll values at each location when no tagged iceberg was present at the location, yielding a background dataset denoted Δchl[no iceberg]. The satellite-derived surface chlorophyll maps in the left-hand column of Figure 2 also illustrate the degree to which clouds and ice obscure the ocean surface, reducing the chances of finding valid chlorophyll data at a track-location both before and after iceberg transit.

<sec1ttl> Findings

Satellite-derived chlorophyll concentrations within 6 days both before and after transit of the iceberg across a given location were found in 215 instances, involving 24 of the 77 tracked icebergs. Details are given in supplementary materials Table S1. The background data set of locations along known iceberg paths at times when no iceberg was present comprised 685710 data points. As a Jarque-Bera test[21] showed that both the background and matchup datasets were not normally distributed ($\alpha = 0.01$, $p < 0.01$, $N = 685710$ and 215 for the background and matchup datasets, respectively), non-parametric tests were used for further comparison.

Trends in Δchl are shown in Figure 3. Median values of Δchl[iceberg] were positive and an order of magnitude higher than those of Δchl[no iceberg] for the dataset as a whole and also for the individual months of November, December and January. In February, the background dataset tended toward low but positive values of Δchl[no iceberg], whereas Δchl[iceberg] tended to be negative. That is, after the peak growth period (typically January), disturbance by an iceberg may act to shorten the growth season. In March, few iceberg matchup-points were found ($N = 8$), but for these points Δchl[iceberg] and Δchl[no iceberg] were roughly equal in magnitude but negative for Δchl[no iceberg], positive for Δchl[iceberg]. That is, once phytoplankton growth is generally in decline at the onset of austral autumn, an iceberg transit effectively extends the growth season. Differences between the Δchl[iceberg] and Δchl[no iceberg] datasets were significant for all data and for each month ($\alpha = 0.01$, N values given in Figure 3).

30 |Δchl| data points were extremely small, while a further 5 data points were too large to be realistic. To focus strictly on realistic and significant values, |Δchl| values

outside the range of 0.02 to 5 mgm^{-3} were excluded from further analysis. Using this restriction, the ratio of positive to negative changes in chlorophyll was 1.16 for the background case compared to 2.38 for known iceberg transit. That is, the presence of an iceberg raised the chances of observing an increase in chlorophyll by a factor of > 2 above natural chlorophyll dynamics.

The median values of chlorophyll prior to a known (absent) iceberg transit, chl_{bef}[iceberg] (chl_{bef}[no iceberg]), were 0.38 (0.31) mgm^{-3} in the case that chlorophyll subsequently increased, compared to 0.60 (0.52) mgm^{-3} when chlorophyll subsequently decreased. For chl_{bef}[no iceberg], the positive and negative cases were distinctive according to the Kruskal-Wallis test ($p \ll 0.01$, $N = 685709$), but the same was not true for chl_{bef}[iceberg]. This implies that whether an iceberg had a positive or negative impact on chlorophyll was not influenced by initial chlorophyll conditions. However, the similarity between chl_{bef}[iceberg] and chl_{bef}[no iceberg] suggests that a larger dataset for chl_{bef}[iceberg] might be required in order to detect, statistically, the effect of differing initial conditions (i.e. we have a Type II error at $N = 215$).

Figure 4 shows the locations of the Δchl results, with $0.02 < \Delta chl < 5$ shown as red plus signs and $-5 < \Delta chl < -0.02$ shown as blue down-arrows. No trends toward positive or negative values were found for the background case (Figure 4b). For known iceberg transit sites, positive-only incidents were grouped around the South Orkney and South Georgia islands and toward East Antarctica, while mostly negative values were found in the location of the Weddell Gyre.

This study is influenced by the seasonality of the SeaWiFS record: As a passive instrument detecting sunlight which is scattered out of the ocean, there are no measurements during cloudy periods, or when sea-ice cover is present, or during the dark winter months. The satellite signal also originates from varying depths, depending on the turbidity of the water: Although it has been shown that the algorithms used to derive chlorophyll are generally sound when compared with surface samples analysed by high performance liquid chromotography[17], the satellite may not detect deep chlorophyll maxima which are common in the Southern Ocean[9]. Confirmation of the results therefore requires a considerable *in situ* sampling effort. The study could also be expanded by applying automated iceberg tracking to visible, microwave and radar remote-sensing data, although this would require considerable computing resources as well as *in situ* data for algorithm validation.

For the period October through to February the impact of icebergs on surface chlorophyll has been shown here to be a net, statistically significant, increase above ambient concentrations. This is particularly significant for the common iceberg drift paths which have been identified so far as following the Antarctic coastal current westwards and transiting north via gyre circulations at numerous locations, into the eastward flowing Antarctic Circumpolar Current (ACC) to the north[20,22]. If borne out by in situ evidence, these results indicate that differences in phytoplankton activity between glacial and inter-glacial periods may have been influenced by iceberg distributions, and that any future change in calving patterns may affect phytoplankton growth, and thereby carbon sequestration, in the Southern Ocean.

On a more speculative note, these paths represent large swaths into which phytoplankton are transported via the island sanctuary of an iceberg[10], far from their coastal origins. Strong latitudinal gradients across the Southern Ocean, associated with the ACC, limit the south-north advection of phytoplankton cells. Transport of cells upon icebergs therefore represents an extremely efficient and unique means of bringing cold-adapted, Antarctic coastal phytoplankton northwards (and simultaneously modifying local conditions to encourage growth), perpetually replenishing species diversity, and this may explain why the dominant phytoplankton species in the ACC frontal systems vary dramatically from year to year.

According to these results, the logistical and financial cost associated with detailed *in situ* studies of iceberg colonisation and progress from the coastal current into open waters are certainly justified.

<meth1ttl> Methods.

<meth1hd> Surface chlorophyll concentrations were generated from Level 2 SeaWiFS data (oceancolor.gsfc.nasa.gov), mapped to 1km resolution and combined into daily composites using the SeaDAS software (http://seadas.gsfc.nasa.gov). The iceberg tracking dataset comprised 77 records from covering periods from months up to three years, with iceberg location recorded once per day at 12 UTC. Chlorophyll concentrations at every tracked iceberg location were extracted from the ten-year chlorophyll record, regardless of whether the date on which an iceberg occupied a given location matched the date of the chlorophyll record. Chlorophyll values below 1 x 10^{-3} mg m^{-3} were excluded from further analysis as being well below the satellite detection limit. It is evident from the true-colour composites in the second and third columns of Figure 2 that many more icebergs are present, at least within the first 5° of latitude adjacent to the Antarctic coast, than are, or realistically can be, tracked. In order to distinguish between the impacts of tracked and untracked icebergs, the along-track chlorophyll values were divided into cases in which valid data were available within both 6 days before and after an iceberg was known to pass a given location,

and those cases where valid data were available but no tagged iceberg was present. These two datasets were then used to produce records of Δchl, defined as the chlorophyll concentration in the 6 days prior to an iceberg event, chl_{bef}[event], minus the chlorophyll concentration in the 6 days following iceberg event, chl_{aft}[event], where the event could be either the known passage of an iceberg denoted by [iceberg] or no known passage of an iceberg, denoted [no iceberg] at that location.

<meth1> The Δchl datasets were tested for normality using the Jarque-Bera test[21]. Since neither of the datasets, nor any subsets thereof, were normally distributed, the non-parametric Kruskal-Wallis test was used to ascertain whether Δchl[iceberg] was significantly different to Δchl[no iceberg] for all time periods and for each month of the growth season (October to March) ($\alpha = 0.01$, N given in Figure 3). Kruskal-Wallis testing was also used to determine whether the impact of iceberg passage on surface chlorophyll was affected by initial chlorophyll concentration.

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<supp> **Supplementary Information** accompanies the paper on **www.nature.com/nature**.

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Level 2 SeaWiFS data were provided by the NASA SeaWiFS Project. Georeferenced quicklook MODIS images were provided by the NASA MODIS Science Team Level 1 and Atmosphere Archive and Distribution System. JNS performed the analyses and wrote the text. MPS performed quality control on the iceberg tracks, contributed to retrieval of satellite data as well as to the text. This paper is dedicated to pilot Stefan Winter who assisted with deploying the iceberg tracking devices and sadly passed away in Antarctica in March, 2008.

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List of Figures.

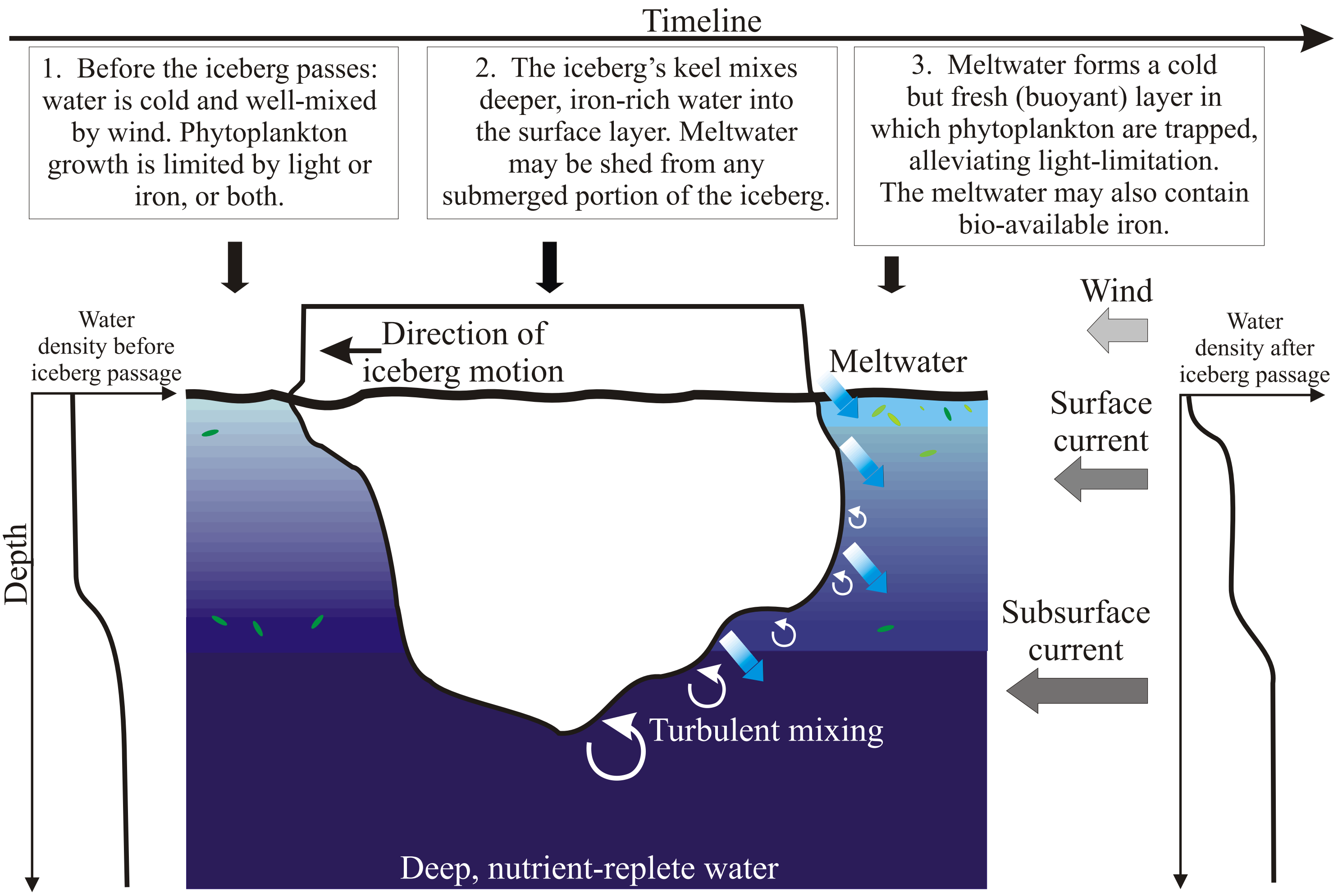
<LEGEND>Figure 1: One possible iceberg-ocean-biosphere interaction scenario.

<LEGEND>Figure 2: Demonstration of the methodology. First column: surface chlorophyll concentrations derived from SeaWiFS imagery from 3rd to 8th January, 2003, over a section of the Antarctic mainland and Weddell Sea; pixel of interest is ringed in black, white denotes pixels excluded because of contamination or obscuration by clouds or ice. Iceberg ‘14958_5’, with dimensions of ~ 380 x 380 m, occupied the pixel of interest on 6th January, 2003. Second column: 250 m resolution images derived from a single channel of MODIS. The Antarctic continental ice sheets and drifting icebergs appear white, while cloud cover appears puffy and grey. The pixel of interest is ringed in red. Third column: As second column but zoomed in to show the pixel of interest (red circle) as well as iceberg ‘14958_5’ (yellow squares indicate the iceberg location at 12 UTC each day). Since the time at which the satellite

images were collected is between 30 minutes and 3 hours earlier than the time at which iceberg location was recorded, the iceberg is not always in the centre of the yellow square. The mean of valid chlorophyll values at the pixel of interest during the 6 days prior to 6th January, 2003 provides the chl_{bef}[iceberg] value, while the means of chlorophyll at the pixel of interest over 6 day intervals at any other time in the satellite record provide values of chl_{bef}[no iceberg]. Similarly, the mean chlorophyll value from 7th to 12th January, 2003 gives chl_{aft}[iceberg].

<LEGEND>Figure 3: Distribution of Δchl[iceberg] (right-hand column) and Δchl[no iceberg] (left-hand column) values for the full dataset and for individual months. Note the bias in Δchl[iceberg] toward positive values in all cases shown except February.

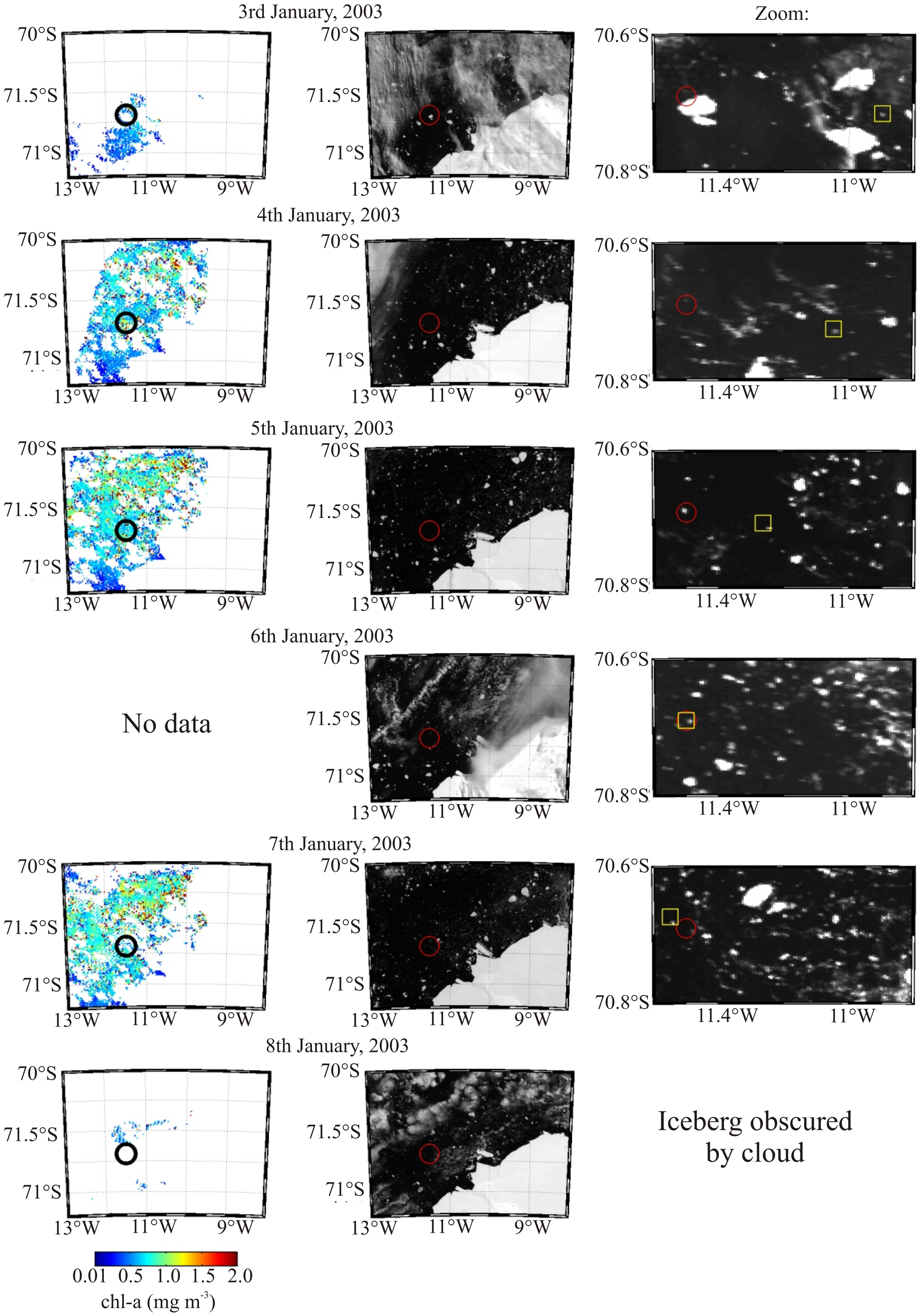
<LEGEND>Figure 4: a) Locations at which $0.02 < \Delta chl[iceberg] < 5.0$ mgm^{-3} (red plus-signs) and at which $-5.0 < \Delta chl[iceberg] < -0.02$ mgm^{-3} (blue down-arrows). b) As a) except for Δchl[no iceberg].

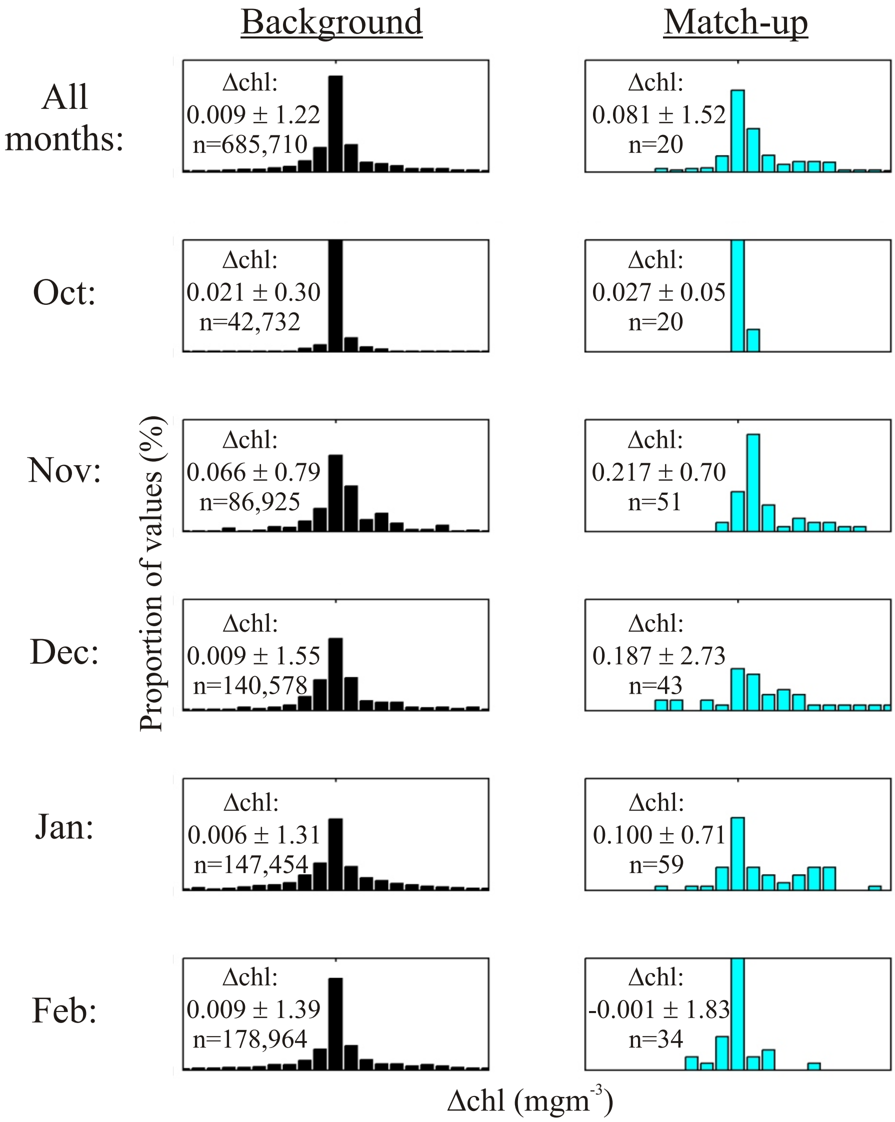


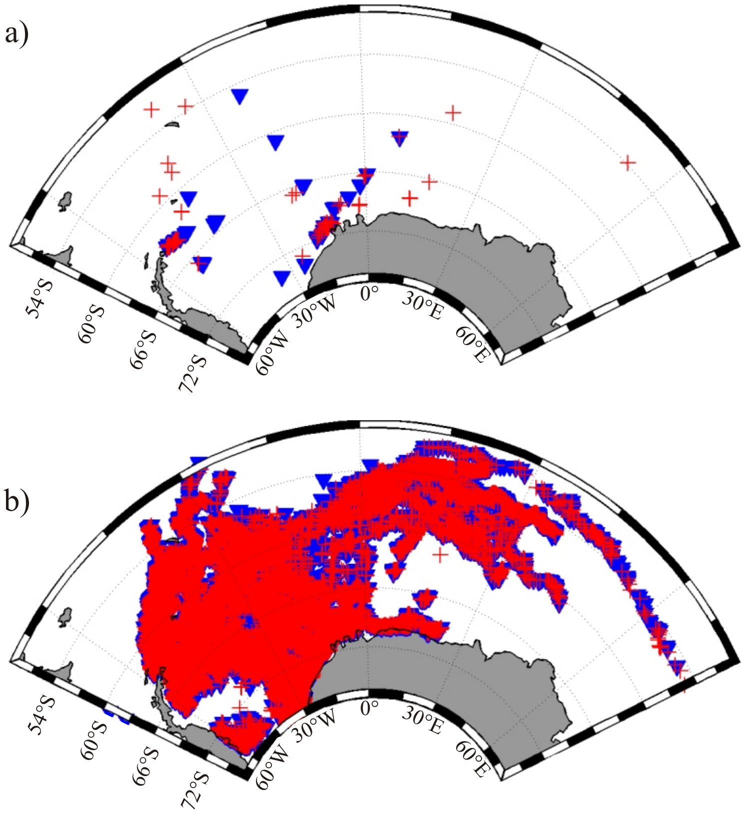
1. Before the iceberg passes: water is cold and well-mixed by wind. Phytoplankton growth is limited by light or iron, or both.

2. The iceberg's keel mixes deeper, iron-rich water into the surface layer. Meltwater may be shed from any submerged portion of the iceberg.

3. Meltwater forms a cold but fresh (buoyant) layer in which phytoplankton are trapped, alleviating light-limitation. The meltwater may also contain bio-available iron.


3rd January, 2003
Zoom:
4th January, 2003
5th January, 2003
6th January, 2003
No data
7th January, 2003
8th January, 2003
Iceberg obscured by cloud
70°S
71.5°S
71°S
13°W
11°W
9°W
70.6°S
70.8°S
11.4°W
11°W
0.01
0.5
1.0
1.5
2.0
chl-a (mg m^{-3})


Background
Match-up
All months:
Δchl:
0.009 ± 1.22
n=685,710
Δchl:
0.081 ± 1.52
n=20
Oct:
Δchl:
0.021 ± 0.30
n=42,732
Δchl:
0.027 ± 0.05
n=20
Nov:
Δchl:
0.066 ± 0.79
n=86,925
Δchl:
0.217 ± 0.70
n=51
Dec:
Δchl:
0.009 ± 1.55
n=140,578
Δchl:
0.187 ± 2.73
n=43
Jan:
Δchl:
0.006 ± 1.31
n=147,454
Δchl:
0.100 ± 0.71
n=59
Feb:
Δchl:
0.009 ± 1.39
n=178,964
Δchl:
-0.001 ± 1.83
n=34
Proportion of values (%)
Δchl (mgm^{-3})


a)
54°S
60°S
66°S
72°S
60°W
30°W
0°
30°E
60°E
b)
54°S
60°S
66°S
72°S
60°W
30°W
0°
30°E
60°E