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On iceberg behaviour: observations, model results and satellite data

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Introduction

Iceberg calving events from the Antarctic ice shelves occur on a regular basis and amount to about 2000 Gt/a (Jacobs *et al.*, 1992). Large tabular icebergs originate in the Weddell and Ross seas from the Filchner-Ronne and Ross Ice Shelves. Smaller sized icebergs with length of the order of one kilometer or less might contribute an equal amount of freshwater to the Southern Ocean. Gladstone *et al.* (2001) suggest a freshwater input of 410 Gt/a for the Weddell Sea. Iceberg motion determines where the fresh water from the Anatrctic continent is supplied to the ocean. As part of the freshwater budget, like precipitation minus evaporation or differential freezing and melting of sea ice, the fate of icebergs might locally effect the stability of the water column with consequences for the formation of deep and bottom water and the biology of the surface mixed layer.

Some questions are:

- Where do smaller/medium sized icebergs drift?
- What is the influence of sea-ice on iceberg drift pattern?
- Where are the areas of major freshwater contributions?
- What is the quantity of freshwater input from melting? and
- What are the effects of iceberg melting on biological productivity?

This study addresses the questions by combining a) direct observations, i.e. icebergs tagged with GPS sensors, b) an iceberg drift modell, and c) SeaWiFS data.

Iceberg drift observations

Although the circumpolar tracking of icebergs has indicated the general drift directions (Swithinbank *et al.*, 1977) only limited information has been obtained in the Weddell Sea to date. Thus, 59 icebergs have been tagged with buoys in the Weddell Sea by AWI since 1999, mainly off Neumayer Station. For buoy deployment, details, and first results see Schodlok (2004) and Schodlok *et al.* (2005).

The GPS position was transmitted daily at noon and battery packs allowed a life-time of about two years. Icebergs with edges smaller than 2 km were preferred for buoy deployment, however, some icebergs tagged were much larger, among them A-43B with dimensions of 40 km by 7 km. A-43B was grounded southwest of South Georgia for about a year before it started to break up and move north again in early 2004. Part of the iceberg, containing the buoy, broke off about half a year earlier. The buoy survived this calving event and continued to transmit for 6 more months. Whereas the majority of icebergs transmitted for between one and two years, 27 % of the buoys transmitted for longer than 2 years with the longest record being around 4 years. Roughly the same number of buoys (26 %) transmitted for less than 6 months, which includes those released in the austral summer season 2003/04. Figure 1 shows the drift trajectories of all 59 iceberg buoys from the day of deployment until June 2004. Three areas of interest are highlighted (encircled areas):

- The Coastal Current indicating dependence of northward movement towards the inner Weddell Sea on iceberg size and season (A).

- The Weddell Scotia Confluence featuring a differing iceberg sea-ice behaviour with large icebergs moving north into the Scotia Sea before being trapped in ACC fronts and subsequent eastward drift, and sea-ice following the Weddell Gyre toward the east (B).
- The eastern part of the Weddell Gyre indicating possible recirculations towards the Antarctic continent (C).

Furthermore, three export scenarios are possible (including areas B and C): (1) complete export of tagged icebergs from the Weddell Sea (2) partial export to the north with some bergs remaining in the Weddell Gyre for more than one year and (3) all tagged icebergs stay in the Weddell Gyre.

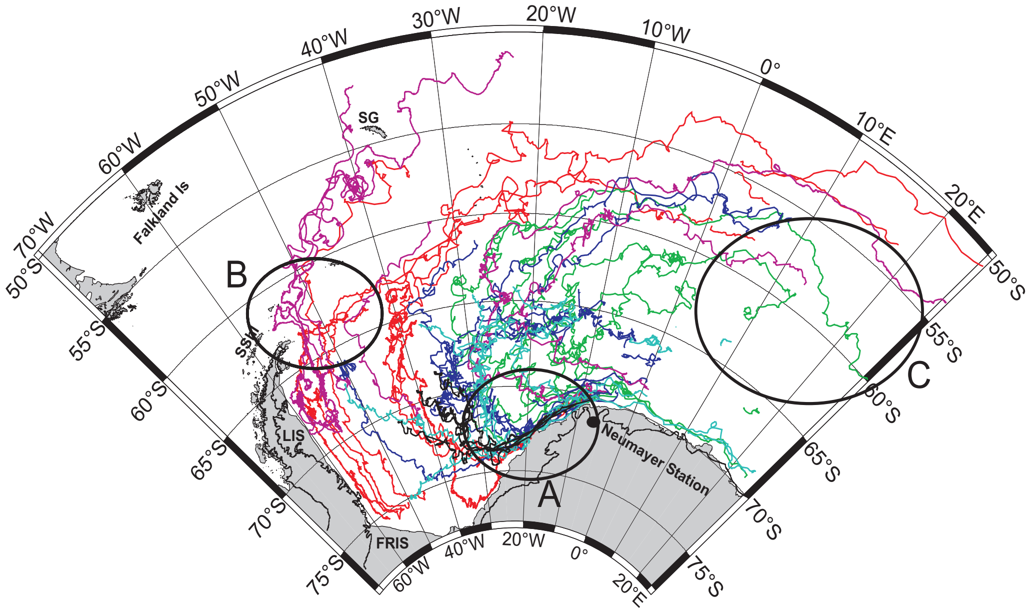

Figure 1: Drift trajectories of 59 iceberg buoys deployed in the Weddell Sea since 1999. The encircled areas depict areas of interest A) the interannual variability of the Coastal Current, B) the escape of icebergs into the Scotia Sea and C) the possible recirculation of icebergs within the Weddell Gyre

Two ensembles of drift buoys have been studied to investigate the behaviour of icebergs in sea-ice cover which is derived from satellite SSM/I data (Kaleschke *et al.*, 2001; Kern and Kaleschke, 2002). The first buoy array ensemble (deployed in the southern Weddell Sea in January 2002) contained three sea-ice and one iceberg buoy whilst the second ensemble (deployed in the eastern Weddell Sea off Neumayer in December 2000) contained only iceberg buoys. Preliminary results were presented at the FRISP 2003 workshop (Schodlok, 2004). Additional analyses using the change of area method (see Wadhams *et al.* (1989); Massom (1992)) allowed the calculation of differential kinematic parameters (DKP) which present a means to quantify the buoy array behaviour (Fig. 2).

Fig. 2(top) shows the time series of sea-ice concentrations at the individual buoys during their progression north. At the beginning of the track the 2002 buoys advanced more slowly towards the north compared to the ice edge due to the thermodynamic behaviour of the sea-ice growth and thus were soon enveloped in sea-ice concentrations above 90 %. From the beginning of April through mid-June the sea-ice concentration at the buoys is around 97 %. The DKPs are rather small for the period considered. Two anticyclonic movements at days 120 and ~150 are seen in shear deformation, and rotational movement and shear deformation, respectively. The small DKPs and high sea-ice concentrations suggest a mechanical link between sea-ice and iceberg. A correlation between sea-ice concentration at the buoy and the correlation coefficient, r^2, of the berg sea-ice buoy velocities revealed that a 95 % sea-ice cover is required to obtain a coherent sea-ice iceberg movement within 150 km of each other.

The 2000 iceberg buoys were released off Neumayer and drifted within the Coastal Current southeastwards before turning north. Soon afterwards, a coherent pattern was established in high sea-ice concentration which manifests itself in similar deviations from the mean northward course, e.g., a

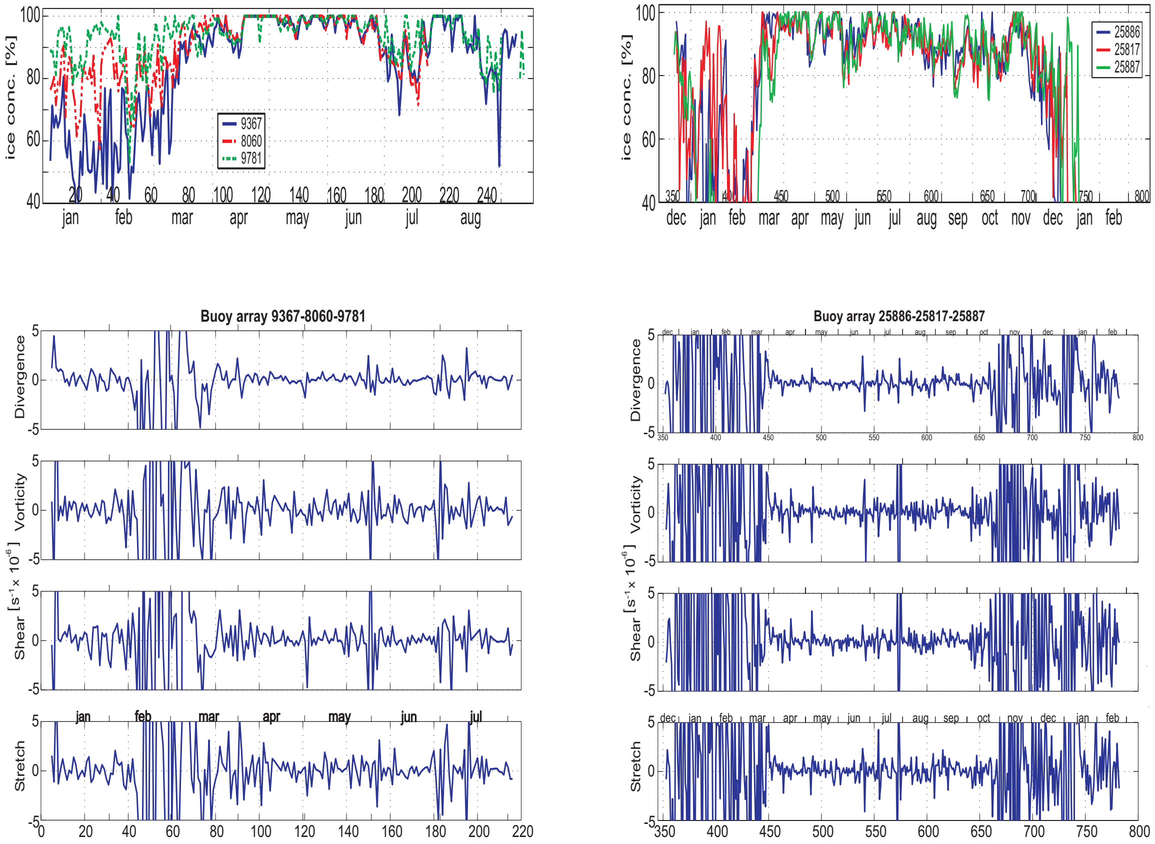

Figure 2: Sea-ice concentration at buoy arrays 2002 (top left) and 2000 (top right) and associated differential kinematic parameters divergence, vorticity, shear and stretch deformation.

$\sim$150 km (for 20 days) northeastward drift due to a shift in wind direction from southeast to southwest and northeast. At the beginning of the drift the sea-ice concentration was rather low increasing to around 95 % at which the coherent drift track starts. The DKPs show very low divergence, vorticity, shear, and stretch during the rather coherent movement of the buoys, except for a few excursions associated with cyclonic and anticyclonic diversions from the mean progression. As the wind acts on the sea-ice cover it is determining the drift of icebergs now linked to the sea-ice. The distance between the buoys ranged from 40 to 120 km. At the end of the coherent movement, which can be seen as irratic DKP values at around day 660, this distance had increased to 250 km. Correlating sea-ice concentration with the r^2 values of iceberg velocities revealed a threshold of 86 % necessary for a coherent iceberg sea-ice motion. This is a little less than the assumed sea-ice concentration threshold of 90 % in Lichey and Hellmer (2001).

Iceberg drift modell

The AWI iceberg drift model (Lichey and Hellmer, 2001) was improved through implementing the wave radiation force as a supplemental driving force as well as melt and decay processes, and prescribing a constant dust concentration in the ice. Along with ocean currents, wind and sea ice, wave action as a function of sea state is a driving force (see Smith (1993)). Iceberg decay was parameterised through various mechanisms; basal and lateral melt under the sea surface as well as decay through wave interaction. Influences of solar radiation are assumened to be less than 0.2 m d^{-1} (Smith, 1993) and are neglected. Wave erosion is a function of water temperature and sea state and is implemented as a reduction in iceberg length (see Gladstone *et al.* (2001)). The dust concentration is based on microparticles (Al, Fe, Mn, Ba etc.) in aerosol samples collected at Neumayer station with a sample error of 10 - 20 %. At the station, an annual mean of 0.10 ng mineral dust per kilogram air (Wagenbach, pers comm, 2003) is representative for the Antarctic near bottom atmosphere. Comparable observations are available from South Pole Station (Wagenbach, 1996). The dust concentration in the air is converted to a dust concentration in snow of 10 ng g^{-1} snow. As precipitation and accumulation rates are unknown, the dust concentration in snow is assumed to be between 4 ng g^{-1} and 20 ng g^{-1} (Suttie and Wolff, 1992; Planchon *et al.*, 2002). The model uses as a first approximation a depth independent concentration of 10 ng/g snow. The input into the water column is a function of the melt water injected into the upper water column.

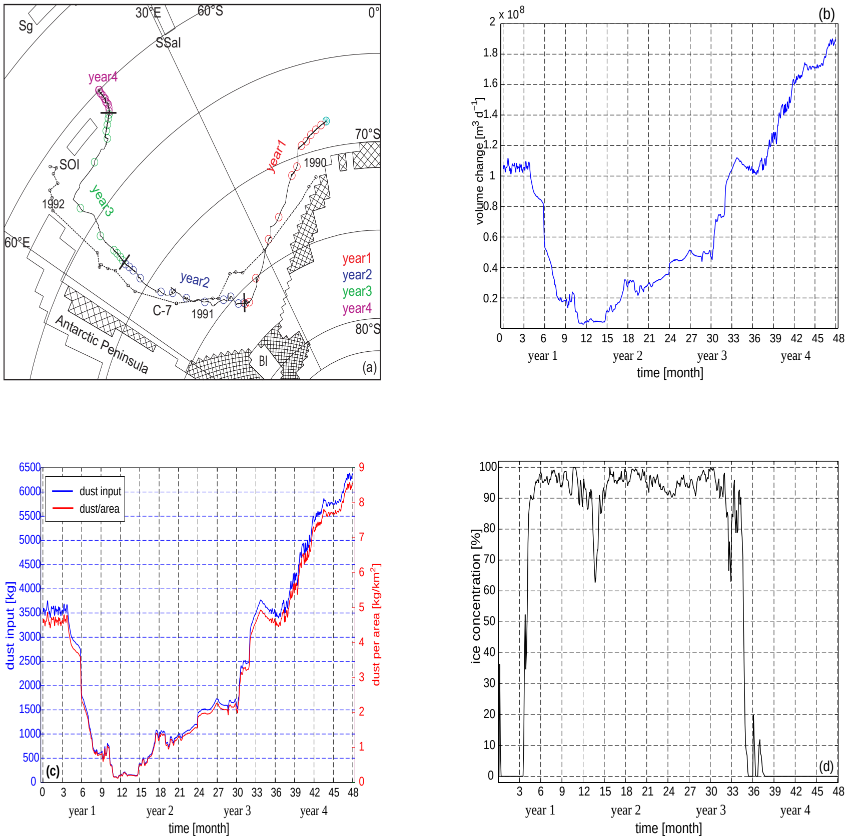

Figure 3: Modelled (4 years) and observed iceberg drift (C-7, from 1990 through 1992) (a). Related model drift features are: Volume loss due to iceberg decay, including basal and lateral melting and wave decay (b), mineral dust input into the upper ocean (c), and sea-ice concentration [%] along the drift trajectory of the iceberg (d).

BRIOS1.0 ocean and ice velocities (Beckmann *et al.*, 1999) as well as wind fields from NCEP reanalysis are used as forcing data (details of model forcing can be found in (Lichey and Hellmer, 2001)). The 4 year icedrift (Fig. 3) compares reasonably well with the observed trajectory of iceberg C7 which was tracked by NIC from 1990 to 1992. However, probably due to deficiencies in the forcing data the observed iceberg is faster compared to the modelled iceberg and thus reaches the tip of the Antarctic Peninsula earlier. At the beginning of the track in the eastern Weddell Sea there is little sea-ice cover, growing to more than 90 % for most of the drift with the perennial sea-ice of the western Weddell Sea until the iceberg is south of the South Orkney Islands (Fig. 3d). The sea-ice cover and freshwater flux are highly correlated as erosion due to wave decay is the most important mechanism (Løset, 1993). In the south-western Weddell Sea, with low temperatures and high sea-ice concentrations, melting is at its lowest increasing towards the north with increasing temperatures and decreasing sea-ice concentrations. The dust input into the upper water column which is a function of freshwater flux shows the same behaviour; high dust input in the eastern and northern Weddell Sea and little in the area of the perennial sea-ice cover. In the vicinity of the South Orkney Islands, the dust input amounts to 8.5 kg m^{-2} and taking the larger concentration of 20 ng g^{-1} to 17 kg m^{-2}. If one assumes that all of the dust in the meltwater is iron, then the 17 kg m^{-2} are of similar order to the amount used for fertilisation of the mixed layer during Eisenex (Volker Strass, pers. Comm, 2004) which induced a phytoplankton bloom.

However, are there enough micro-nutrients, including iron, in this dust to induce a similar biomass increase? Another unknown is the quantity of iron in the dust.

Biomass in SeaWiFS satellite data

In order to asses if and how icebergs contribute to biomass changes, we studied several years of SeaWiFS data which are available from August 1997, providing a reliable estimate of chlorophyll-a concentration. The Atlantic Sector of the Southern Ocean shows relatively high biomass in the western Weddell Sea and Scotia Sea but low biomass concentrations in the eastern Weddell Sea. However, there is no data for pixels containing clouds or ice, and as it is an optical sensor, there is no data in austral winter. Although we get an estimate of biomass along known iceberg tracks, there are many untracked icebergs and other environmental factors whose influence on the biomass we can not assess simply using SeaWiFS data. Thus, it may not be possible to distinguish the influence of icebergs from other factors.

Chlorophyll concentrations before and after the passage of an iceberg were taken from mapped level 2 chlorophyll data provided by NASA at 2 km resolution. A 6 day window before and after the iceberg passes the known position was applied and the changes in biomass computed. 4.5 years of SeaWiFS data, from 1999 to mid 2003, have been analysed so far. Incidences where the imagery was cloud and/or ice free both before and after the iceberg passes were rather rare, hence, data are sparse. Only 96 points from 17 icebergs are available with 44 instances of increased chl_a concentration after the bergs passage and 52 events of decreased chl_a concentration (Fig. 4 right).

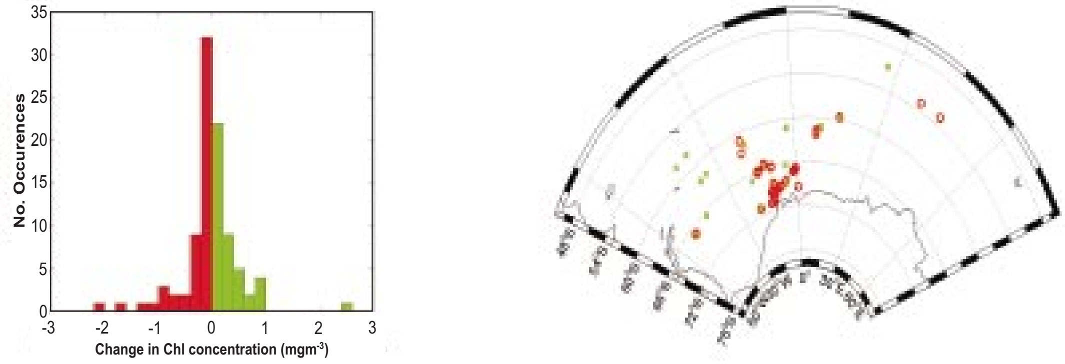

Figure 4: Change in chlorophyll concentration (mg m^{-3}) after iceberg passage. Positive values indicate more, negative values less chlorophyll concentration after iceberg passage (left). Spatial distribution of negative (circle) and positive (cross) events (right).

Looking at random data points in the 4-year SeaWiFS data set a gaussian distribution centred at zero would be expected. In this analysis, a shift of ∼0.1 mg m^{-3} towards lower values was found (Fig. 4(left)), although the mean increase in biomass was 0.4 mg m^{-3}, whilst the mean decrease 0.3 mg m^{-3}. Thus, if there is a positive effect after the iceberg's passage it is slightly larger, but there are more negative events. The spatial distribution of positive (cross) and negative (circles) events of icebergs on biomass (Fig. 4, right) indicates that the negative events dominate in the Coastal Current region of the eastern Weddell Sea.

Conclusion

With an iceberg calving rate of ∼400 Gt a^{-1}in the Weddell Sea (Gladstone *et al.*, 2001) the tagged icebergs are equivalent to less than 3% of this flux (except in 2002 with 88% due to buoy deployment on A43b). However, one has to consider that only a minor portion of icebergs entering the Weddell Sea from the east has been tagged with buoys and that a significant number of bergs calving from Weddell Sea ice fronts move out of the region, i.e. iceberg volume in the Weddell Sea is a balance of the calving rate, plus import from the east, minus export to the north. If we assume that export to the north in the western Weddell Sea is compensated by the import from the east, then the 400 Gt amounts to a freshwater flux of ∼14 mSv. This corresponds to about 40% of the NCEP reanalysis P-E input into the Weddell Sea and is comparable to ice shelf basal melting (Hellmer, 2004). If, as in export scenario 3, the mean residence time for icebergs in the Weddell Sea is at least 1.5 years, this value increases to ≥ 21

mSv. In years of enhanced iceberg export across the northern boundary of the Weddell Sea (scenarios 1 and 2), the residence time is lower and the freshwater flux decreases. In addition, our study suggests that this freshwater is released not only in the Coastal Current as suggested by Gladstone *et al.* (2001) but across a large area of the inner Weddell Sea. However, model data and observations need to be combined to evaluate the interannual variability of the freshwater input.

Coherent sea-ice/iceberg motion was found to occur at sea-ice concentrations above 86 % which is slightly lower than the suggested value of 90 % for the iceberg drift model. Whether the difference between the 2002 (95 %) and 2000 (86 %) values is due to regional differences, i.e. the former is closer to the Antarctic Peninsula and thus at closer proximity to more compact, land-fast ice with higher viscosity, or due to uncertainties in SSM/I data has to be investigated. The length scale for coherent movement was estimated to be about 250 km which is less than determined for the Arctic. The lower mean sea-ice thickness in the Southern Ocean and thus weaker mechanical links might be the reason for this lower value.

Analysis of the available SeaWiFS biomass data record indicated that the passage of an iceberg through the water may have a slight negative effect (most frequently in the Coastal Current), or occasionally a significant positive effect (off the Antarctic Peninsula). This may be interpreted as a swift motion with correspondingly lower meltwater and, thus, dust input in the Coastal Current, where the iceberg's passage deepens the mixed layer beyond the compensation depth of the phytoplankton, so that the cells receive too little light. For a slower iceberg drift, and higher meltwater input, the dominant effect may be the formation of a stable lens of meltwater, i.e., decreasing the mixed layer depth to allow phytoplankton greater access to sunlight, or providing a significant input of the limiting trace metal iron. Other effects certainly play a role over these small length scales: the passage of the iceberg through a relatively high biomass region may at first deepen the mixed layer, leading to loss of biomass, but may also serve to bring nutrients into the surface waters by upwelling of nutrient-rich deep water, which can then be utilised once the mixed layer has restabilised. Further study via high spatial resolution physical models, coupled ecological models, and, most demanding, in situ data collected around icebergs, is required to improve our understanding of the influence of icebergs on the phytoplankton community.

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