Evolution of tabular iceberg A-38B, observation and simulation

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Introduction

Calving of Antarctic tabular icebergs is a decisive factor in the overall mass budget of the Antarctic ice sheet. With an ice loss of about 2000 Gt per year it is by far the largest negative term in the mass balance equation (surface ablation ~30 Gt yr^{-1}, basal melting ~550 Gt yr^{-1}. Jacobs et al., 1992). The processes triggering melting and decay of tabular icebergs are of great relevance within many domains. Being a source of cold freshwater during their drift and especially during their final decay, tabular icebergs have a significant impact on Southern Ocean water masses (Gladstone et al., 2001). Dust particles enclosed in the ice, released during melting processes, can have a fertilizing effect on algae in the upper water column. Thus, melting icebergs can also affect biology (Arrigo et al, 2002). Furthermore the decay processes of icebergs are of great interest to shipping, as fast disintegrating icebergs, releasing a huge amount of smaller icebergs in short time, can be a severe threat to shipping lines in the Southern Ocean.

In spite of its apparent relevance, little is known about tabular iceberg evolution and decay at the moment. To learn more about the role of ice dynamics in these processes, we simulate the inherent dynamics and evolution of gigantic tabular icebergs, by applying the numerical iceberg model COMBATIS (Computer-based Tabular Iceberg Simulator) based on the fundamental equations of ice shelf dynamics. In the following we will depict the evolution of a typical Antarctic tabular iceberg and present results of a simulation with the model COMBATIS (Jansen et al., submitted).

Iceberg A-38, observed evolution

In October 1998 the tabular iceberg A-38 calved off the Ronne Ice Shelf east of Berkner Island. This area of the Ronne Ice Shelf was characterised by several pronounced inlets, slowly grown in decades, obviously caused by stresses due to the Hemmen Ice Rise. The inlets were filled with a mélange of sea ice, snow and small icebergs (Hartl et al., 1994; MacAyeal et al., 1998).

The crack which lead to the calving of iceberg A-38 followed the connecting line between the tip of an inlet perpendicular to the ice shelf front and one front-parallel inlet at Hemmen Ice Rise, forming a tabular iceberg with an approximate size of 150 km by 50 km (Fig. 1). The calving probably occurred instantaneously, following a straight line except to a small bifurcation in the middle of the iceberg.

The iceberg was first detected on October 13th on radar data of an USA military weather satellite. The description of the further development of A-38 is also based on remote sensing data, which proved to be the ideal mean of observation, regarding the size and the position of the observed object. Shortly after the calving, the tabular iceberg split in two halves of about equal size: A-38A, the formally eastern part of the iceberg, still containing two major inlets of about 50 km length, and A-38B, the western part. The two parts then drifted along the Weddell Gyre in direction of the Antarctic Peninsula and then northwards. The drift velocity varied strongly with sea ice coverage and thickness, the icebergs moved much slower in winter. In February 2003 they reached the tip of the Antarctic Peninsula and proceeded

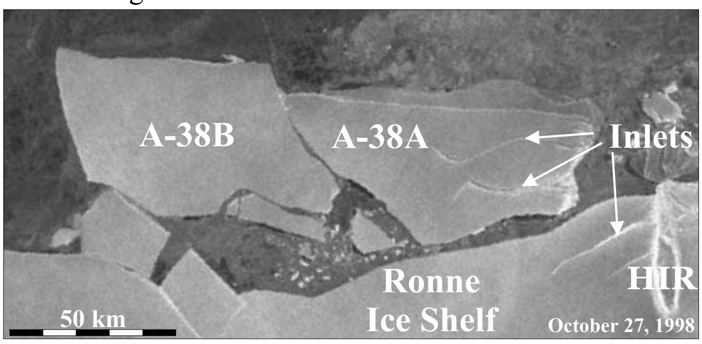


Figure 1: Icebergs A-38A and A-38B shortly after breaking apart. HIR: Hemmen Ice Rise. Image courtesy: RADARSAT.

further north, leaving the area of permanent sea ice coverage. The evolution of the large tabular icebergs has been documented by medium resolution (250 m) optical images from MODIS. In Figure 2 image sequences of A-38A and A-38B are shown for several stages of their evolution. During drift the iceberg shape only changed insignificantly, except to small scale calving at the margins. The filling of the inlets in iceberg A-38A had diminished during drift but was still recognizable on remote sensing data. Leaving the Weddell Sea and the sea ice behind, the icebergs accelerated their drift considerably and reached South Georgia Island by December 2003. They passed the island in the east and grounded in January 2004 north east of South Georgia. On March 15th, 2004 A-38A broke apart in three pieces (Fig. 2 e). The new icebergs were partly confined by the former inlets and started to drift northwards again, but disappeared from medium resolution image data within a few weeks. Iceberg A-38B , which grounded about 100 km off the shore of South Georgia, broke apart on April 17th, 2004 in two nearly equal sized halves (Fig. 2 f). The part located closer to the island was still grounded, while the other part was drifting again northwards and also decayed within several weeks. The grounded part broke into several parts during August and September 2004 and has now totally disappeared.

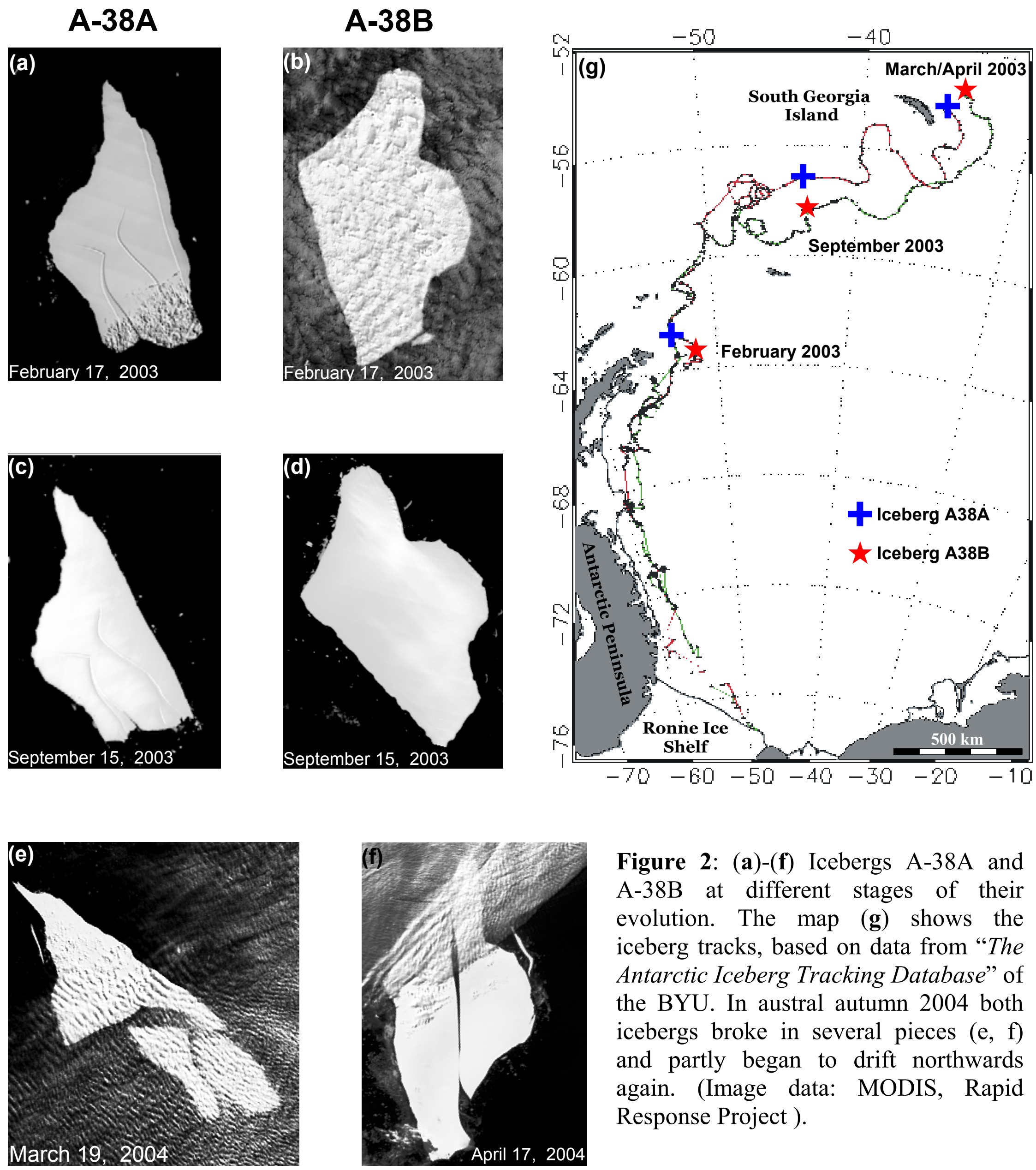
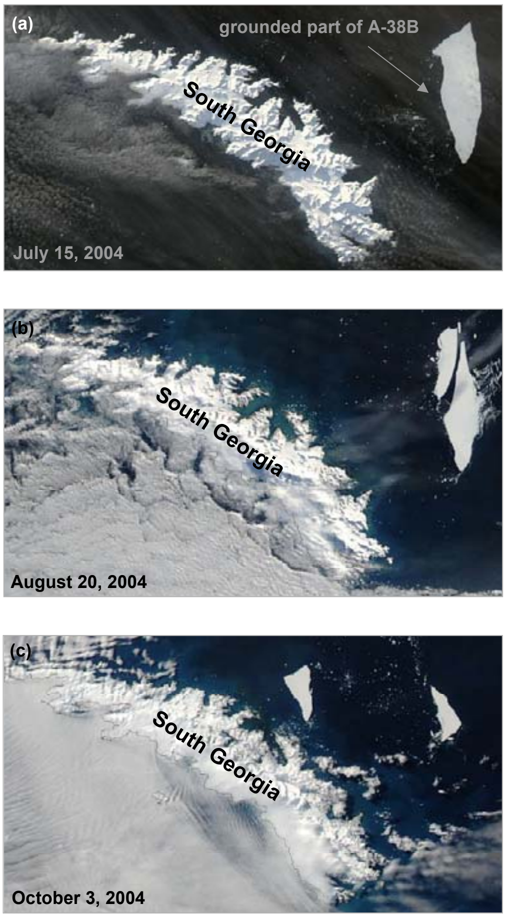


Figure 2: (**a**)-(**f**) Icebergs A-38A and A-38B at different stages of their evolution. The map (**g**) shows the iceberg tracks, based on data from "*The Antarctic Iceberg Tracking Database*" of the BYU. In austral autumn 2004 both icebergs broke in several pieces (e, f) and partly began to drift northwards again. (Image data: MODIS, Rapid Response Project).

Especially the icebergs final decay was observed and documented carefully by remote sensing data to achieve a better understanding of iceberg fracture processes (Fig. 2 e and Fig. 3 a - d). However, the cloud cover in the area of South Georgia Island is extremely dense, therefore a gapless documentation of the decay process is not possible. Figure 3 d shows an ASTER image of a part of iceberg A-38B, partly grounded, which is absolutely cloud-free. No distinct features are visible on the iceberg surface. However, it becomes obvious that high resolution images provide information about small scale calving processes at the iceberg margins and a possibility to estimate ice loss due to calving. The characteristic size of the smaller icebergs may even give a hint on iceberg thickness. The further development of the remaining small icebergs originated during the decay of A-38B could not be documented by ASTER image sequences, as they started to drift again and the image acquisition has to be ordered several weeks in advance including the exact position of the icebergs.



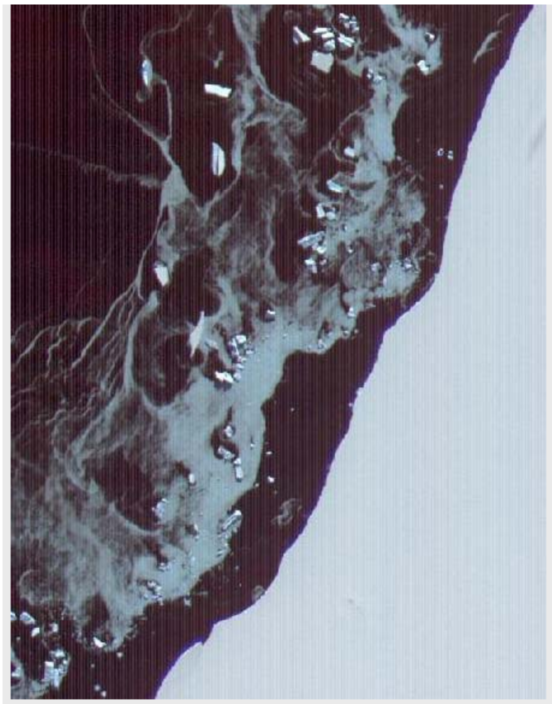


Figure 3: (**a**)-(**c**) MODIS image sequence showing the decay of A-38B northeast off South Georgia Island between July 15th and October 3rd, 2004.
(**d**) ASTER image section of the iceberg A-38B during its grounding phase northeast off South Georgia Island. This high resolution image resolves small scale calving events at the iceberg margin.

Modeling iceberg evolution

The finite-difference iceberg model COMBATIS is based on the fundamental equations of ice shelf flow, which are the continuum-mechanical balance equations for mass and momentum, Glen's flow law and the heat transfer equation. We also apply the ice shelf approximation, thus, friction and vertical shear strain are neglected, and we assume hydrostatic equilibrium during the entire iceberg evolution. In contrast to horizontal flow velocities, temperature and density are allowed to vary with depth.
To test main modules of the iceberg model and to gain insight into basic ice dynamical characteristics of large tabular icebergs under prescribed environmental conditions, we performed a series of numerical experiments. We investigated the influence of strain thinning of tabular icebergs by applying the model to strongly idealized icebergs with constant density and temperature. We found that the amount of strain thinning is only comparable to the thinning due to basal melting in very cold regions. A typical tabular iceberg with a thickness of 250 m and a mean temperature of –15 °C would be subject to a strain thinning of about 1 m yr^{-1} (Jansen et al., submitted).

Model experiments on icebergs with realistic density and temperature profiles, interacting with ocean and atmosphere, revealed that iceberg geometry changes during drift are predominantly determined by basal melting processes, whereas is dominated by surface processes.
The tabular iceberg A-38B was selected for our first model application: Geometry and temperature profiles are well known and the iceberg has been subject to a long-distance drift under changing environmental conditions. Moreover, observations of A-38B are sufficient for a reliable description of its evolution and, in contrast to A-38A, it does not contain prominent geometry anomalies.
The changes of the environmental conditions are considered in the time dependent model forcing parameters basal mass balance (ocean model data), surface mass balance (positive degree model and measurements) and surface temperature (ECMWF data).
After five years of simulation the iceberg lost more than one half of its initial ice body volume. Due to moderate basal melting during its drift in the Weddell Sea the ice loss in the first four years amounts to about 23 %. The increasing melt rates in the Scotia Sea cause melting of 30 % of the initial ice body during one year. The overall decrease of mean iceberg thickness from 220 m to 106.3 m is caused

- to 95 % by basal melting (108.0 m)
- to 1 % by surface melting (1.2 m)
- to 4 % by strain thinning (4.5 m)

As iceberg thickness is the main driving force of ice flow, the mean flow velocity decreases from 20 m yr^{-1} to about 4 m yr^{-1} during the five year simulation period. The erosion of relatively warm ice causes steep temperature gradients at the top and the bottom of the iceberg, the temperatures in the inner part are little affected (cf. Jansen et al., submitted) .
At the moment we do not have the possibility to validate the model results, but the fast decay of A-38B in August 2004 indicates, that indeed the iceberg must have thinned considerably.

Our iceberg simulations clearly revealed that the thickness decrease during drift is mainly governed by basal melting. The only available melt rate estimates usually result from ocean modeling, but our preliminary evaluation of satellite altimetry suggests a promising possibility to quantify this fundamental model forcing parameter by means of observations.

Future work

In order to achieve more realistic simulations of tabular iceberg evolution, further model extensions and modifications are necessary. As a next step, the influence of local geometric anomalies, such as the mélange-filled inlets of iceberg A-38A, will be investigated. Small scale calving and decay processes at the iceberg margins will also be considered in an extended model version. Furthermore fracturing in various scales has to be included, which requires detailed studies of possible fracture mechanisms and an adequate parameterization of the relevant mechanical processes. However, existing studies of fracture mechanics in ice shelves already provide a basis for this part of the model adaptations (e.g., Rist et al., 2002).
In order to simulate gigantic iceberg evolution in dependence of course and duration of its drift, the advanced model will be applied to various tabular icebergs drifting along different paths. In addition, it is planned to integrate multiple icebergs into the model for simultaneous simulations.
Finally our aim would be an iceberg model coupled with an OGCM (Ocean General Circulation Model), applied for the Weddell Sea region. The objective is to simulate the ocean regime under the influence of the dynamic iceberg components. Beside the expected quantitative description of temporal variability of fresh water supply due to iceberg decay, the coupled model study will provide knowledge on the interaction between iceberg evolution and induced water mass modification.

Acknowledgements

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