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The SCAR International Iceberg database.

By

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Summary

The Norwegian Polar Institute (Norsk Polarinstitutt, NPI) initiated an international programme for systematic collection of Antarctic iceberg data in 1981 with the endorsement of the Scientific Committee on Antarctic Research (SCAR). In the period from austral summers 1982/83 to 1997/98, iceberg observations were recorded by most research vessels cruising Antarctic waters, using the so-called "blue form" distributed and collected by NPI. The forms were read and digitized at NPI. From 1996, the iceberg data set was maintained in a Microsoft Access database, and distribution of the blue forms ceased after the 2000/01 season. Nevertheless, data continued to be collected until the 2009/2010 season, when the programme was terminated. Digitizing the forms from the most recent years, and thorough checking of all data, was completed in May 2020. This completed database is discussed here.

The NPI database contains records of positions of 323 520 icebergs from 26 634 individual observations. Of these, 262 007 icebergs have been classified by size into five different length categories: 10-50, 50-200, 200-500, 500-1000 and >1000 m. During the three decades of observations, most of the ocean around Antarctica has been observed, but there are large differences in data density, primarily because nearly all ship tracks follow repeated routes to the various research stations, and these are not evenly located around the continent.

The data sets of spatial distribution of icebergs in the region allow a number of assessments. These include regional variations and differences in total quantities, identification of drift patterns and exit zones from the continent, iceberg dissolution rates and calving rates. Some of these have relevance to climate discussions, including the mass balance of Antarctica.

The data show significant differences in the extent of icebergs observed over the years. These can primarily be ascribed to year-to-year differences in observation density and location, and do not identify variations in annual iceberg calving rates. There are large regional and seasonal variations both in the density and in the size distribution of icebergs.

The icebergs in general follow the counter-clockwise near-coastal current until reaching four main exit zones where they are transported northward into the clockwise (towards the east) circum-Antarctic circulation system. The iceberg concentrations vary from ~0.01 iceberg/km² in the coastal waters and exit zones, to ~0.001 iceberg/km² in the remainder of the Southern Ocean. A third of all icebergs are observed within 200 km of the coast, and most of the others

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in the four exit zones. A high iceberg frequency along the coast of East Antarctica indicates that calving rates here are larger than those determined from satellite observations alone.

The mean size generally decreases from November to April, and with distance from the continent. The average total number of icebergs in the ocean in the summer is approximately 130 000, of which 1000 icebergs are found north of the Southern Ocean boundary.

The database provides information on where icebergs are likely to be encountered, useful for ships wanting to avoid such regions and, perhaps in the future, of interest for anyone wishing to utilize icebergs to combat fresh-water shortage in locations like Cape Town.

The SCAR International Iceberg database presented here also includes ship-based iceberg observations collected by the Australian Antarctic Division (AAD) from the Australian National Antarctic Research Expeditions ships, operating in the 50-150° E longitude sector. The AAD work started independently of the NPI programme and for the seasons 1978/79 to 1983/84 used the same size classes. This set of 970 observations is included in the NPI database. From the 1984/85 season the AAD observations were made in seven classes: 25-100, 100-200, 200-400, 400-800, 800-1600, 1600-3200 and >3200 m. These data cover most seasons until 2010/11, and consist of 8061 observations of altogether 53 649 bergs, of which 38 756 were size classified. The AAD data are discussed most recently by Jacka and Giles (2007), who analysed data from 1978 to 2000. They are presented here as a separate entity. Fig. 1 shows the location of the altogether 34 695 individual observations in the NPI and AAD databases.

The strength of the present database is the large number of observations using identical recording protocols for standard iceberg sizes, providing systematic coverage over most parts of the waters around Antarctica. These data sets give a solid, long term record of Antarctic iceberg sizes, movement, and distributions before the era of polar orbiting satellites and on-board remote sensors, along with inferred calculations of dissolution rates, ocean currents, etc., upon which future remotely sensed iceberg data can be compared and tested. The data are particularly useful because they include systematic observations of all the smaller sizes of icebergs, not covered by current satellite-based iceberg databases.

Introduction

A program for systematic collection of Antarctic iceberg data was initiated in 1981 by Olav Orheim at the Norwegian Polar Institute. The initiative was motivated by a lack of data on the spatial and temporal distribution of icebergs in Antarctic waters. There had been various reports on iceberg sightings (e.g. Dmitrash 1965, 1973; Romanov 1975), but systematic iceberg recordings during a research cruise in the 1978/79 season on M/V *Polarsirkel*, travelling from Cape Town to the southern Weddell Sea and return, indicated that these reports from the coastal waters of East Antarctica were not representative (Orheim, 1980). The number of icebergs was small, and the sizes recorded were large, thus smaller icebergs and total numbers seemed seriously under-reported.

The program was endorsed by the Scientific Committee on Antarctic Research (SCAR) through its Working Group on Glaciology, and quickly gained support from nearly all SCAR nations. Already by the 1982/83 austral season, most ships going to Antarctica carried what became known as the “blue forms” on which the iceberg observations were recorded.

The instructions given (Appendix A) started by defining an iceberg as “a large mass of floating or stranded ice of greatly varying shape, more than five metres above sea level, which has broken away from a glacier or ice shelf”. They requested that iceberg observations should be made every six hours at the times of standard meteorological observations, and that recordings should start immediately after port departure, or after crossing 40°S, even though no icebergs might then be seen. In practice, many records started further south, with the first sighting of an iceberg.

The six-hour interval was chosen primarily because this provided a task load on the staff on the bridge that was acceptable for a voluntary assignment. This interval also gave reasonable statistical coverage, as it meant that a moving vessel would normally not make duplicate observations (see further below).

The instructions asked that all icebergs be recorded within five size classes according to observed horizontal dimension: 10-50, 50-200, 200-500, 500-1000 and > 1000 m. Additional information, such as freeboard, width, and breadth, was requested for the largest size class. The extent to which the latter was done varied from observer to observer.

The choice of five size classes was based on initial experiences from asking bridge personnel to carry out such recordings. It appeared that recording five classes was not too laborious. In order to make the classification easier, page 2 of each form gave a diagrammatic scheme showing which size class an iceberg would fall into, given an angular extent measured by sextant combined with distance measured by radar.

In reality, the horizontal dimension of a tabular iceberg recorded from afar will depend on the shape of the berg and its alignment in relation to the observer. For example, a ship observer seeing an approximately rectangular-shaped tabular iceberg in the far distance would simply record the width of the white shape and would not be able to distinguish the lengths of (usually) the two sides each at a slanted angle to the observer. This implies that the recorded horizontal dimension will be between the length and the width, depending upon the alignment. Thus, these records can be taken as the “average” horizontal dimension of such icebergs.

Although observers were requested to classify the icebergs by size, this was not always possible. Most often, this was due to low visibility so that the number of icebergs were counted by radar without size being determined. In some cases, only estimated numbers were given when a large number of icebergs were present in the smallest category. (Sometimes such numbers exceeded 100.)

Additionally, the observer noted ship position, date and time of observation, sea ice concentration and information on whether the observation was visual or by radar.

The number of ships contributing to the data set increased with time and reached a maximum in 1987/88, when data were recorded on more than 20 cruises. The number of ships sending reports thereafter gradually decreased until the 2000/2001 season, as personnel changes meant that NPI gave less support and follow-up. New forms were not sent out after 2000, nevertheless some countries continued submitting data, using blue forms they still had left, or making their own copies of the forms. All these later data reports are also included here.

The program was formally terminated in 2011/12. It was then decided that the data set should be published in a format making it available to other researchers. For that to happen the data were scrutinized once more to eliminate, as far as possible, human errors in the recordings, and data from recent forms were entered into the database.

The database contains 26 634 observations, comprising 323 520 icebergs, i.e. the average observation consisted of 12.1 icebergs.

Altogether 262 007 icebergs were classified by size, with the size distribution in the five classes as follows:

10-50	50-200	200-500	500-1000	>1000 m
103 243	86 434	46 886	18 992	6 452
39.4	33.0	17.9	7.2	2.5

Table 1. Total numbers and percentages of icebergs observed in each size class

This report describes the dataset and its uncertainties and presents various results that can be derived from the observed iceberg distribution in space and time.

Data quality control

Data were controlled in order to eliminate possible observer errors, duplicate observations or systematic errors. These controls were performed in the spreadsheet before importing the data into the database. It is believed that most typing errors have been eliminated through the various quality controls. The following were done:

Ship tracks
The ship tracks were inspected based on the recorded observation position, and checked for potential illogical parts caused by typing error or wrongly recorded position or time. For the same purpose, the ship speeds along the routes were looked at. Whenever an unrealistic value was encountered the observation was controlled and any typing error replaced or deleted if no logical resolution could be found.

Total number of icebergs
The total number of icebergs recorded at each instance was controlled against the sum of the icebergs given for individual size categories. Whenever these did not agree, it was assumed that the number in the individual size classes was correct and that the observer had made an error in addition. The total was changed accordingly. This was not done for the AAD data.

Observations with a high number of icebergs in the largest size categories were also controlled. The observations were changed if evidence existed that the figures had been placed in the wrong size category.

In only one instance was it obvious that numbers recorded were excessive. Further examination clarified that the observer in the early part of the cruise must have recorded sea ice floes rather than icebergs. These data were deleted. A more general observation is that observer accuracy and proficiency grew throughout a cruise, and from one season to the next in cases when the bridge was repeatedly manned by the same person(s).

Duplicate observations
If all observations are equally representative then duplicate observations will not cause errors in computations of average assemblages, i.e. number of icebergs per observation. Obvious duplications, typically arising when the ship was stationary or moved little for extended periods, have nevertheless been deleted to avoid potential errors caused by non-representative observations. This particularly concerns very large numbers of icebergs, which could influence total numbers, or the rare gigantic icebergs, which would affect total iceberg mass.

The maximum distance, R, at which an iceberg can be seen by radar or in adequate visibility depends upon observer elevation, h_1, and iceberg freeboard, h_2, according to
$R = 2.1\ (\sqrt{h_1} + \sqrt{h_2})$,
where R is expressed in nautical mile (1 852 m), and h_1 and h_2 in m. The unit nautical miles (nm) is used in the discussion in this section, as this is the only unit used on the bridge for speed (1 knot=1nm h^{-1}) and for distances measured e.g. by radar. It was therefore used for the blue forms.

Most ships travelling to Antarctica have bridge height at 10-20 m and radar 20-30 m, above sea level. Table 1 gives distances in nm at which icebergs of different freeboards can be seen by observer, or radar, at given elevation.

	Iceberg freeboard (m)			
Obs. elev. (m)	0	10	20	30
10	**7**	**13**	**16**	**18**
15	**8**	**15**	**17**	**19**
20	**9**	**16**	**19**	**21**
30	**11**	**18**	**21**	**23**

Table 2. Distances in nautical miles at which an iceberg can be observed.

Table 2 shows that commonly an observer cannot see icebergs much beyond 20 nm. In reality, swells, waves and sometimes sea ice will disturb the horizon, so that the observation radius is less. Wadhams (1988) showed that there was a rapid fall-off in registration of icebergs beyond 12 nm. View radius and/or height of bridge/radar, and visibility when reduced by e.g. fog, was in most cases reported on the blue forms. The average view radius of all observations is 11.88 nm (22 km) indicating that 12 nm is a good choice as a default value for view radius. This corresponds to observing icebergs within an area of 1553 km^2.

Typically, ships travelling to/from Antarctic stations travel at l0-15 knots (5-7.5 m s^{-1}). Taking observations every 6 h means that between observations, such ships will have travelled 3-5 times the maximum radius of the observation circles (Table 2) and will thus not produce duplications. Although the instructions asked that recording cease when the ship was not moving, this was not always adhered to.

Any observations outside realistic ranges were controlled. For example, iceberg freeboard does not normally exceed 40 m for tabular icebergs.

Icebergs in the largest size category account for the largest mass component of all the icebergs in Antarctica even though the frequency of such bergs is low. The records were examined to see whether exceptionally large icebergs had been observed with unusual repetition by different ships covering the same area. Such duplicate observations could especially occur in the Antarctic Peninsula region. Away from the continent, mean iceberg velocities over longer periods are typically 5-20 km d^{-1} (e.g. Vinje 1980, Tchernia and Jeannin 1984), and the very large icebergs were checked with regard to shape, position and drift, in order to ensure that these were not over-duplicated.

Systematic weaknesses in the data set

Underestimation of small icebergs.
The smallest icebergs may be systematically underestimated. By definition an iceberg must have freeboard >5 m, and "bergy bits" below 10 m in length were not recorded. However, bigger icebergs not much above 5 m may be missed unless the ship passes close by. Such icebergs are normally rounded and of ice only, i.e. their albedo is lower than the white tabular icebergs so that they will be difficult to see at distances of several nautical miles, especially in rough seas. This does not significantly affect iceberg mass considerations but needs to be taken into account in disintegration models.

Overestimation of iceberg density at low latitudes.
Many observers did not make recordings until the first iceberg was observed on the southwards voyage, even though they were requested to start registering after leaving port, or when crossing 40°S. They also often ceased recordings after a few instances of zero iceberg observations on the northbound voyage, even though 40°S had not been reached. In some cases, the excitement of seeing the first iceberg meant that this and some subsequent "low-latitude" icebergs were all recorded as they were passed by, i.e. more frequently than the six-hour interval. Some of these excessive observations have been deleted, but perhaps not all. Overall, the zero-berg observations are under-represented in the low-latitude portions of the records. The effect of this is discussed later.

The data presented in this database and the following tables and figures are the observed data only, with no correction for underestimation of small bergs or overestimation of frequencies at low latitudes.

Description of the collected data

The NPI database contains 233 ship reports from 68 individual ships, in some cases consisting of more than one cruise. The ships reporting for the different seasons are shown in Appendix B. The total number of observations is 26 634, and altogether 323 520 icebergs were observed, thus the average observation consisted of 12.1 icebergs. The average number of icebergs per observation has varied during the years, and the reasons for such variations are discussed below.

The iceberg database is available in CSV file format.

Field name	Data type	Field size	Range
ID	number	double	1, 2, 3, ….
Cruise-ID	text		See description below (1)
Vessel	text		Vessel name
Obs_Date_ISO	date/time		yyyy-mm-dd\Thh:nn\Z See description below (2)
Obs_Date_Excel	date/time		Excel time and date format as dd.mm.yyyy hh:nn See description below (3)
Obs_Lat	number	float	+/- 0-90
Obs_Lon	number	float	+/- 0-180
Ice_conc	number	byte	0-10
RV	text		R, V, RV, VR
Total	number	integer	
no10-50	number	integer	
no50-200	number	integer	
no200-500	number	integer	
no500-1000	number	integer	
gt1000	number	integer	
Freeboard	number	integer	
Length	number	long integer	
Width	number	long integer	
Dim_as_average	text	10	Y, N See description below (4)
View_radius	number	byte	See description below (5)
Comments	text	255	

Table 3. Format and ranges of the data in the database.

(1) "Cruise-ID" is in the format 9596xx where the first 4 digits give the season and xx is a running number. 959601 is for example cruise no 1 in the season 95/96.
Please note that this field must be treated as text, not number, due to Y2k-issues when using only the last two digits to represent a year. The cruise-ID "000102" (the 2000-2001 season) treated as a number will become "102", and thus less intuitive to work with.

(2) "Obs_Date_ISO" holds the observation time and date formatted in standard ISO date format.

(3) "Obs_Date_Excel" holds the observation time and date in a more human readable format.

(4) RV indicates whether observation is visual or by radar.

(5) Ice_conc gives the sea ice concentration in a range from 0 to 10, where 10 is complete sea ice cover.

(6) The field "Dim as average" defines whether the dimensions recorded for icebergs larger than 1000 m should be used as average in calculations. This is only relevant in cases when more than 1 iceberg is recorded in the > 1000 column. If "N" is given, a conservative estimate will be given for the latter icebergs.

(7) View radius is given in nautical miles. The view radius is taken from the information on radar range, visibility, or is derived from the altitude of the viewing platform.

Overview of the contents of the database and their potential use

Distribution of observations

Figure 1 shows the ship positions for all observations, i.e. also those where zero icebergs were recorded. The distribution of the observations reflects that most ships are servicing permanent Antarctic research stations and usually travel the shortest distance from ports such as Cape Town (South Africa), Ushuaia (Argentina), Punta Arenas (Chile), Invercargill (New Zealand) and Hobart (Tasmania, Australia) to the stations. The seas close to the continent are generally well covered by observations, with the south-western part of the Weddell Sea as the main exception. The lack of observations here is a result of the very heavy sea ice conditions in this area preventing ships from traversing. Other coastal areas of low observation density are mainly those with few or no stations.

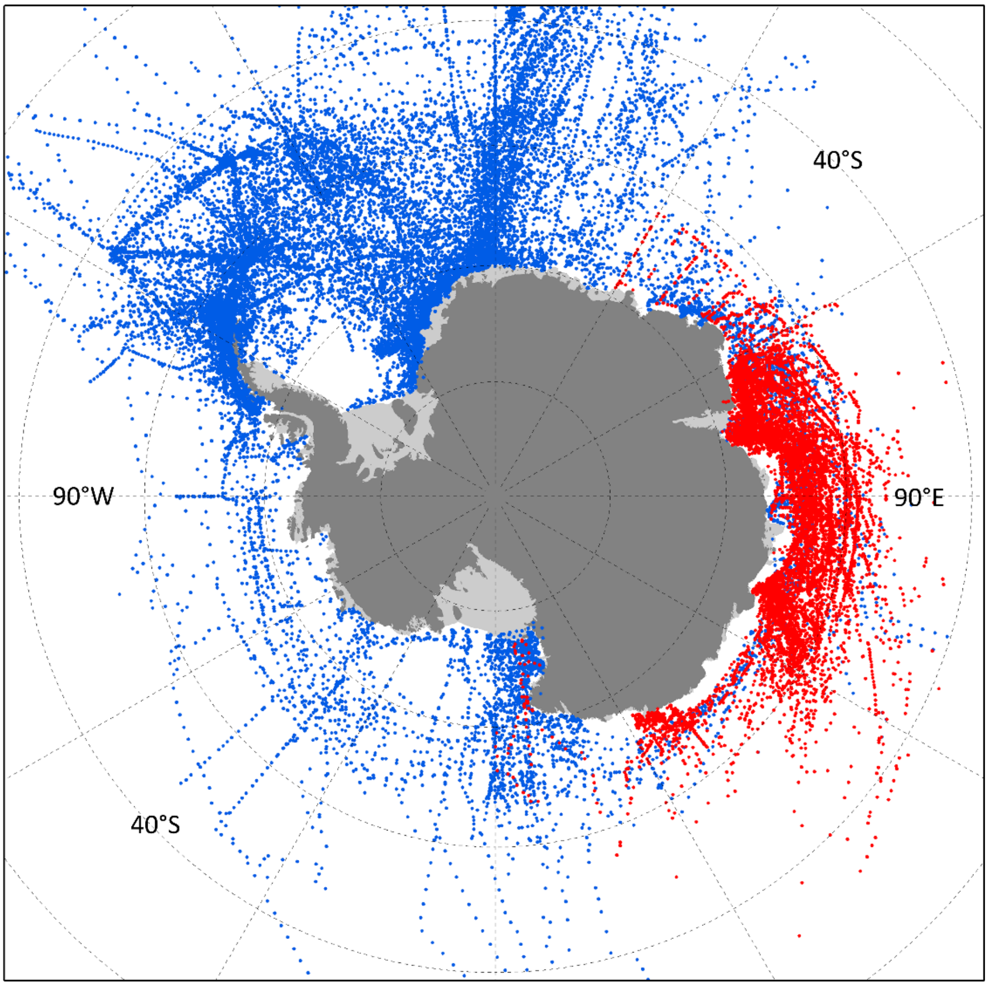


Fig. 1. The 34 695 individual observations in the SCAR database shown as blue dots for the NPI data collection scheme with 5 classes and red for the AAD data with 7 classes (described in subsequent sections). The red dots overprints and hides many blue dots, this is illustrated in more detail in Fig. 8. The distribution reflects the main travel patterns for the research and supply ships.

For some of the analyses, the data have been sorted into grid boxes of dimensions 1° latitude and 5° longitude. The areas of these boxes decrease with increasing latitude as shown in Appendix C.

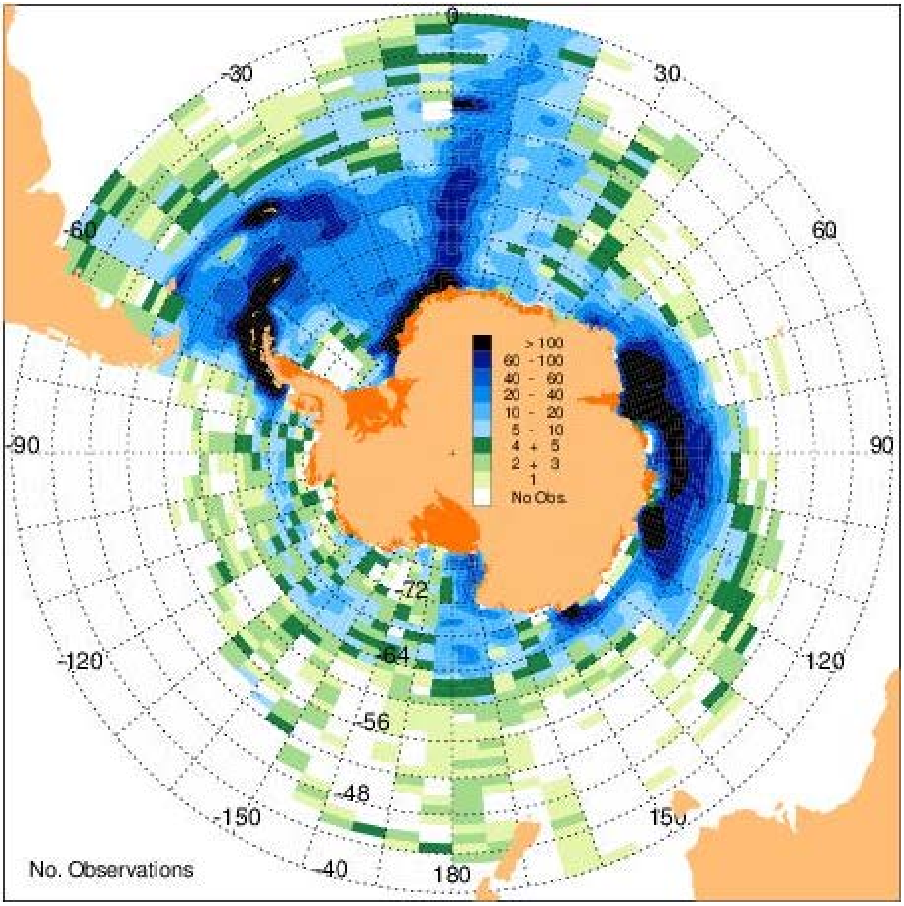


Fig.2. Frequency of observations in the oceans around Antarctica. The scale gives the number of observations in a 1°x5° grid box. Blue colours show high frequencies, and these are smoothed. The highest numbers of observations are in the vicinity of the stations; in many such locations the sum of observations over the multi-year period exceed 100. Green boxes contain few observations. Grid boxes without data are shown as white.

In Figs. 2-4, 6 and 8, the basic 1°x5° box distributions have been smoothed by the MIN_CURVE_SURF routine in IDL which interpolates and smooths sets of regularly gridded data. The remapping to polar coordinates for the plots is then taken care of within the IDL CONTOUR routine. However, because many grid boxes have zero or very low numbers of observations, the outer contours were considered to be rather misleading. These individual boxes were then precisely over plotted with a uniform colouring. White was used for boxes with no observations and shades of green, as shown by the scale bar, for the low value boxes.

Altogether the NPI database contains 1488 grid boxes of 1° latitude x 5° longitude with observations (including those of zero icebergs). With a total of 26 634 observations, this means that each box on the average contain 17.9 observations.

There are obviously very large variations in observation density around the continent, as shown by Figs. 1 and 2. The figures also illustrate the repetitiveness of some of the ship tracks. The most extreme example of this is near Bouvetøya (Bouvet Island) at 54°26'S, 03°24′E. The isolated Bouvetøya works like a magnet on the ships travelling between Africa and Antarctica, so that they take routes to get a glimpse of this fog-shrouded island, even if it means a small detour. This also results in zero or very few observations in adjoining grid boxes west of the island.

Caution with regards to results from locations with few observations:

Figure 2 shows regions where care should be applied when interpreting results of database analysis. As expected, grid boxes with few observations are primarily far from the continent, but this is also the case in a few coastal regions. Although results from all boxes with few observations should be treated with caution, there is a very large difference in the reliance that can be placed on averages from these different regions of low observation density. In the higher latitude regions, the observations will be taken well into the cruise, with no reason to expect any deviation from the observation protocol. Each recording can then *a priori* be expected to be representative for that location at that particular time. At the lowest latitudes, uncritical use of records of average concentrations may result in inflated iceberg concentrations. As described above, at low latitudes all icebergs were recorded, while zero observations were under-represented.

The effect of this is illustrated by examining Figure 2 together with Figure 3.

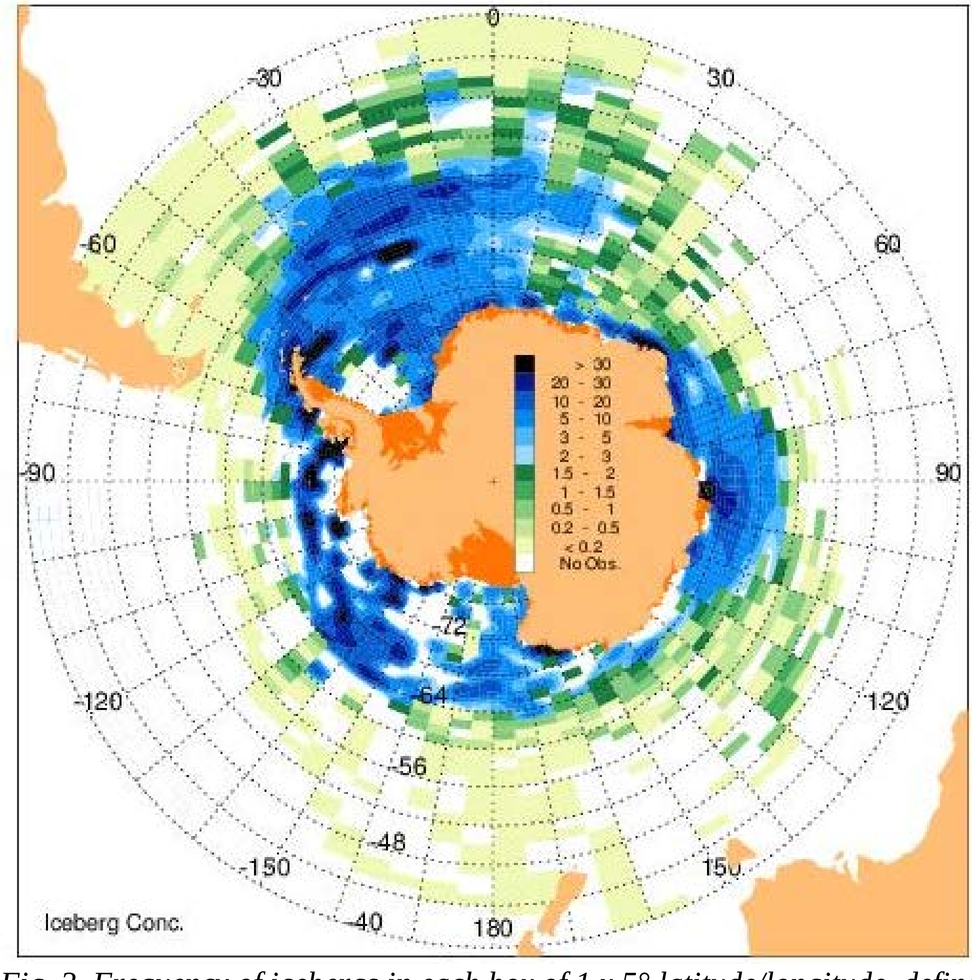


Fig. 3. Frequency of icebergs in each box of 1 x 5° latitude/longitude, defined as total sum of icebergs observed in the box, divided by number of observations. The blue colours are smoothed as in Fig. 1. The green colour scale gives the very lowest concentrations with.no smoothing applied for these categories.

The regional variations in number of icebergs per observation are shown in Figure 3. Not surprisingly the numbers are high near the continent and in regions where the icebergs become concentrated by ocean currents or by grounding in shallow waters. However, Fig. 3

shows also instances of apparently increased iceberg concentrations with decreased latitude at locations north of 50°S which are likely not to be representative.

For example, at 30-35°W and 100-105W°, these seemingly high concentrations are based on only one observation. Comparisons show several other instances where the numbers of observations are 1 or 2 only. The systematic lack of zero observations at lower latitudes implies that high concentrations at low latitudes are unrealistic.

Gaps in the records could be filled in order to calculate more precisely the average iceberg densities at the lowest latitudes. It would be relatively simple to introduce zero icebergs in the records at 6-hour intervals at appropriate locations, given that nearly all ships at low latitudes travel at a steady rate along great circle routes from/to the home port. As stated initially, no such artificial zero observation records have been introduced into this database.

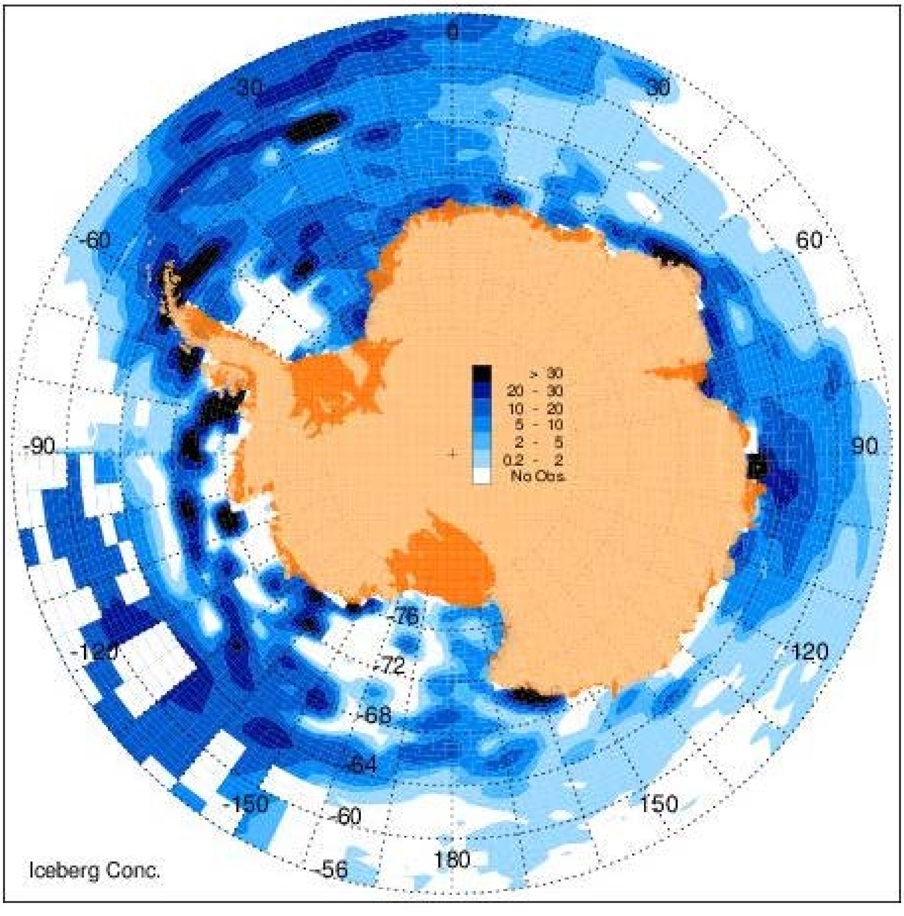


Fig. 4. Frequency of icebergs in the Southern Ocean south of 56°S defined as the number of icebergs seen in a box divided by the total number of observations within the box in the same manner as in Fig. 3. Note that the colour scale differs from Fig. 3. Smoothing has been applied to all the data.

Fig. 4 shows in more detail the variations in concentration in the Southern Ocean above 56°S latitude. As explained above, this shows too high concentrations for some northern segments of the Southern Ocean, e.g. the Pacific sector. However, for the Atlantic sector it seems that the major problems with low observations arise north of 52°, i.e. the presentation gives a fair representation of reality.

Sea-son	obs	Ice-bergs	iceb / obs.	10-50	50-200	200-500	500-1km	>1k	Classi fied	10-50	50-200	200-500	500-1000	>1000
09/10	176	628	3.6	209	316	13	1	1	540	38.7	58.5	2.4	0.2	0.2
07/08	198	1642	8.3	1243	217	72	15	5	1552	80.1	14.0	4.6	1.0	0.3
06/07	757	14538	19.2	6814	4354	1867	565	112	13712	49.7	31.8	13.6	4.1	0.8
05/06	405	8017	19.8	5323	1822	692	127	43	8007	66.5	22.8	8.6	1.6	0.5
04/05	454	4053	8.9	748	696	442	338	65	2289	32.7	30.4	19.3	14.8	2.8
03/04	893	5576	6.2	3047	1536	365	187	93	5228	58.3	29.4	7.0	3.6	1.8
02/03	828	10659	12.9	4769	3360	1223	293	55	9700	49.2	34.6	12.6	3.0	0.6
01/02	688	7676	11.2	677	1480	547	315	187	3206	21.1	46.2	17.1	9.8	5.8
00/01	956	15241	15.9	5627	3808	2363	938	268	13004	43.3	29.3	18.2	7.2	2.1
99/00	860	6437	7.5	1705	1304	625	291	68	3993	42.7	32.7	15.7	7.3	1.7
98/99	1143	9606	8.4	2756	2862	1549	739	402	8308	33.2	34.4	18.6	8.9	4.8
97/98	1631	19027	11.7	6788	5376	2651	1146	633	16594	40.9	32.4	16.0	6.9	3.8
96/97	370	4892	13.2	1402	892	421	322	128	3165	44.3	28.2	13.3	10.2	4.0
95/96	537	13817	25.7	6865	3934	1256	434	110	12599	54.5	31.2	10.0	3.4	0.9
94/95	916	10340	11.3	2320	2889	2173	1154	390	8926	26.0	32.4	24.3	12.9	4.4
93/94	654	10398	15.9	1765	1705	994	399	106	4969	35.5	34.3	20.0	8.0	2.1
92/93	846	9184	10.9	1903	2453	1629	444	132	6561	29.0	37.4	24.8	6.8	2.0
91/92	771	8110	10.5	2443	2642	1537	662	164	7448	32.8	35.5	20.6	8.9	2.2
90/91	992	8431	8.5	2392	2760	1612	686	294	7744	30.9	35.6	20.8	8.9	3.8
89/90	781	9961	12.8	3540	3455	1613	583	194	9385	37.7	36.8	17.2	6.2	2.1
88/89	1212	15225	12.6	2761	4107	2879	920	286	10953	25.2	37.5	26.3	8.4	2.6
87/88	1782	24332	13.7	7582	6612	3395	1434	351	19374	39.1	34.1	17.5	7.4	1.8
86/87	1391	24161	17.4	8642	7596	4062	1646	505	22451	38.5	33.8	18.1	7.3	2.2
85/86	1197	13533	11.3	4424	3657	2157	813	298	11349	39.0	32.2	19.0	7.2	2.6
84/85	1569	12313	7.8	3871	3393	1879	635	147	9925	39.0	34.2	18.9	6.4	1.5
83/84	2345	31740	13.5	8554	7603	5154	2627	893	24831	34.4	30.6	20.8	10.6	3.6
82/83	1001	13780	13.8	2824	3683	2802	1025	401	10735	26.3	34.3	26.1	9.5	3.7
81/82	548	4377	8.0	1232	1252	698	147	45	3374	36.5	37.1	20.7	4.4	1.3
80/81	129	494	3.8	12	23	21	4	39	99	12.1	23.2	21.2	4.0	39.4
79/80	93	359	3.9	22	6	1	4	19	52	42.3	11.5	1.9	7.7	36.5
78/79	352	3100	8.8	983	641	194	98	18	1934	50.8	33.1	10.0	5.1	0.9
76/77	159	1873	11.8	0	0	0	0	0	0					
Total	26634	323520	12.1	103243	86434	46886	18992	6452	262007	39.4	33.0	17.9	7.2	2.5

Table 4. Iceberg data collected during the programme. In Table 4, and Table 5 below, the first column shows the period covered, the second the number of observations and the third the total number of icebergs observed. Column 4 shows number of icebergs per observation, followed by five columns of icebergs observed in each size class. Column 10 shows number of icebergs classified by size (i.e. the sum of the previous five), and the final five columns are the percentages in each size category.

Table 4 gives an overview of the 5-class data collected during the programme. The time refers to the summer season, and all the years of recordings include observations from the summer months, defined here as the period December-March. Nearly all years also contain April data.

Time	No. obs	bergs	b/obs	-50	-200	-500	-1000	>1000	classif.	-50	-200	-500	-1000	>1000
Jan	6982	97912	14.0	35189	29030	14437	5482	2021	86159	40.8	33.7	16.8	6.4	2.3
Feb.	5925	80010	13.5	25131	19461	10816	5008	1808	62224	40.4	31.3	17.4	8.0	2.9
March	3955	54821	13.9	16132	13018	7385	2670	693	39848	40.5	32.7	18.4	6.7	1.7
April	1843	16228	8.8	3923	4163	2476	884	318	11764	33.3	35.4	21.0	7.5	2.7
May	400	3162	7.9	905	964	633	194	74	2770	32.7	34.8	22.9	7.0	2.7
June	156	818	5.2	239	444	63	3	2	751	31.8	59.1	8.4	0.4	0.3
July	182	427	2.3	245	156	17	1	1	420	58.3	37.1	4.0	0.2	0.2
August	92	103	1.1	38	61	3	0	0	102	37.3	59.9	2.8	0.0	0.0
Sept.	139	429	3.1	72	71	105	7	5	260	27.7	27.3	40.4	2.7	1.9
October	327	3311	10.1	1320	639	544	245	100	2848	46.3	22.4	19.1	8.6	3.5
Nov	1533	11571	7.5	3538	2804	1550	610	233	8735	40.5	32.1	17.7	7.0	2.7
Dec	5100	54728	10.7	16511	15623	8907	3888	1197	46126	35.8	33.9	19.3	8.4	2.6
Total	26634	323520	12.1	103243	86434	46936	18992	6452	262057	39.4	33.0	17.9	7.2	2.5
Summer	21962	287471	13.1	92963	77132	41545	17048	5719	234407	39.7	32.9	17.7	7.3	2.4
Winter	969	4939	5.1	1499	1696	821	205	82	4303	34.8	39.4	19.1	4.8	1.9

Table 5. Iceberg data sorted by months and by summer/winter season.

Table 5 shows how the size categories vary for the different months; the lower two lines compare summer and winter data. Winter is here taken as the months May to September. The iceberg frequency is much higher for the summer period, but it is in this connection important to bear in mind the significant differences in location of winter and summer observations; the winter data are mostly collected much further north in the Southern Ocean. In mid-winter (June-August) the frequencies of icebergs in the largest ice classes are particularly low, but the few data and the location aspects mean that this conclusion should be viewed with caution. For analyses of seasonal variations in iceberg densities and sizes it is necessary to compare individual grid boxes for different periods.

Does the NPI database represent fairly the iceberg distribution around Antarctica?

To answer this question, we examine three issues: a) the extent of the areal coverage, b) the data coverage over time and c) whether the numbers seem reasonable in relation to other knowledge on Antarctic iceberg production and distribution.

a) The extent of the areal coverage.

For this issue, we consider the distribution of the observations within the "Southern Ocean" (SO), which is the term used here to describe the cold seas around Antarctica. The SO is bounded to the north by the Antarctic Convergence (AC), a broad (> 100 km wide) zone where the cold waters from the south meet and mix with the warm Pacific, Atlantic and Indian oceans. The AC is at its narrowest at Drake Passage. North of the AC the surface waters are much warmer and icebergs will be a rare occurrence because of high melt rates.

The ocean area south of the Antarctic Convergence can be taken as 37 x 10^6 km^2, but the AC is not a precise boundary. It moves with the seasons, being furthest north in the winter, and for calculations a precise boundary is desirable. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) addresses the waters south of the AC. It has defined this boundary as follows: "a line starting at 50°S, 50°W; thence due east to 30°E longitude; thence due north to 45°S latitude; thence due east to 80°E longitude; thence due south to 55°S latitude; thence due east to 150°E longitude; thence due south to 60°S latitude; thence due east to 50°W longitude; thence due north to the starting point.” This boundary (Fig. 5) defines an ocean area of 35.72x10^6 km^2, i.e. ~10% of Earth’s oceans.

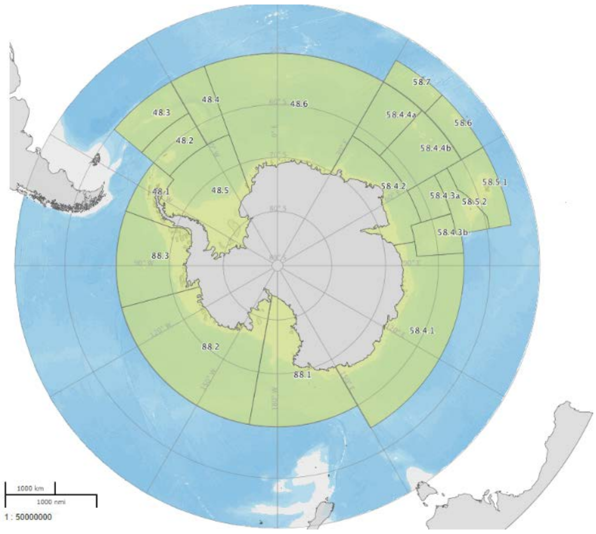


Fig. 5. The ocean south of the Antarctic Convergence, as defined by CCAMLR, is shown as beige colour. These waters are here termed the “Southern Ocean”.

In the following, the SO is taken as the ocean area defined above by CCAMLR. It contains approximately 1260 1°x5° grid boxes, either in the open sea or with at least 50% ocean when adjacent to the Antarctic continent.

Fig. 2 illustrates that there are large variations in observation frequency. Fortuitously, high density of observations tends to coincide with areas of high iceberg frequencies. There are ~200 of the 1°x5° grid boxes within 200 km of the continent, and only 17 of them have no data. Of these, ten are in southwest/central Weddell Sea, three in the Amundsen Sea and four scattered around East Antarctica. In other words, apart from the permanently sea-ice-covered part of the Weddell Sea, more than 96% of the coastal seas have data coverage. These are the seas with highest iceberg frequencies.

Similarly, for the whole southern half of the SO, of the ~ 630 1°x5° boxes only 31 lack data, namely 15 from the southwest/Weddell Sea, eight from eastern Ross Sea, four from the Amundsen Sea, and four scattered. In the northern half of the SO where icebergs are scarcer, the data coverage is weaker. 132 of the 630 boxes lack data, but with large geographic variations. In the Atlantic sector, there are only two boxes without data, and as shown in Fig. 3 this is also the sector that contains most of the icebergs that travel far north. Three quarters of the boxes without data are in the Indian Ocean sector from 35°-80°E and the remainder are in the Pacific, mostly in the sector 80°-130°W.

Altogether 24 220 of the 26 634 ship-borne observations were made within the Southern Ocean as defined above. In addition, there are also 376 1°x5° grid boxes with observations north of the SO. These include many observations of zero icebergs. The total number of observations here is 2414, of which more than 2000 are from the South Atlantic Ocean. On average, there are 21.6 observations in each 1x5° box with observations in the Southern Ocean, while the corresponding number north of the boundary is 6.4.

In conclusion, the geographic data coverage is very comprehensive for the regions where the majority of icebergs occur, which implies a good basis for statistical considerations.

b) Data coverage over time.

Table 3 shows that there are large variations between the years both in numbers of icebergs per observation, and in the distribution within the size classes. Such differences can arise from annual variations in iceberg production, or result from the variations in time and space in the ship tracks.

A first approach to evaluate this is to examine known variability in the ice discharge from the continent.

The surface mass balance of Antarctic ice masses is everywhere positive, except for very small areas in the northern part of the Antarctic Peninsula and nearby islands, and very small blue-ice localities. Most studies indicate that practically all mass is lost by iceberg calving (~ 45%) and by melting from the underside of the floating ice shelves (~ 55%) (Rignot et al. 2013, Depoorter et al. 2013). Ice fluxes from the ice sheet are generally determined from measured or estimated ice velocities and thicknesses around the perimeter of Antarctica. The total ice flux across the grounding line provides an estimate of the steady ice discharge to the ocean, whereas the ice flux across an outer circumference near the fronts provides a steady-state estimate of iceberg calving, although the year-to-year variability can be large (Liu et al. 2015). The difference between these two sets of numbers is then the ice shelf mass balance, from which basal melting can be estimated if the surface mass balance is known.

Various studies for different individual years or different multiyear periods and extending back to the start of these iceberg observations have given similar numbers for annual discharge, of around 2000 Gt (e.g. Kotlyakov et al. 1978, Budd and Smith, 1985, Orheim, 1985; Warrick and Oerlemans, 1990, Jacobs et al., 1992). Recent numbers agree within 5-10% depending on time period and data used, e.g. Rignot et al. (2013, 2019), Deporter et al. (2013) and Gardner et al. (2018). These differences are small compared with the recorded variations in time and space in the iceberg observations.

However, the ice discharges computed from considerations of velocities and ice thicknesses are not the same as the calving rate. Icebergs of a wide range of sizes break off from the whole perimeter of Antarctica. Possibly the frequent smaller calvings, with sizes up to ~ 1 km, are stochastic, independent events. However, we know this is not the case for giant icebergs. It is therefore particularly important to evaluate whether calving of the largest icebergs cause spikes in the data, which could invalidate assumptions behind combining the annual records.

The calvings of the largest giant icebergs (exceeding 500 km^2) are episodic on timescales of 10-100 years (MacAyeal et al, 2008), and they mostly originate from the few largest ice shelves. The two largest known calvings, A22-A24 and B15, had surface areas of ~17000 and 11 000 km^2, and many exceed 5 000 km^2, as shown in Table 6.

Iceberg name	Surface area (km²)	Length (km)	Width (km)	Time of calving	Location and reference
Amery	10 000			Dec-63/Jan-64	Amery Ice Shelf[1]
Trolltunga	5 000	100	50	July 1967	Fimbulisen[2]
A20	7 284			January 1986	Larsen Ice Shelf
A22	5212			August 1986	Filchner-Ronne Ice Shelf
A23	5883			"	"
A24	6863			"	"
B09	5096	154	35	October 1987	Ross Ice Shelf
B10	5689			January 1992	Thwaites Glacier
A38	5603	144	48	October 1998	Filchner-Ronne Ice Shelf
B15	11 000	295	37	March 2000	Ross Ice Shelf
A43	5 000	167	32	May 2002	Filchner-Ronne Ice Shelf
C19	6 368	200	32	May 2002	Ross Ice Shelf
A68	5 800	200		Juy 2017	Larsen C Ice Shelf

Table 6. Known gigantic Antarctic icebergs that exceed 5000 km². The two earliest are described by Fricker et al, 2002[1] and Vinje, 1977; Swithinbank et al., 1977[2]. Subsequent icebergs are from National Ice Center (NIC) and Brigham Young University (BYU) satellite iceberg databases (Budge and Long, 2018). Icebergs A22, A23 and A24 formed when a ~210 x ~90 km section of eastern Filchner-Ronne ice shelf north of the Grand Chasm broke off. The section had already split into three icebergs when detected by satellite. Viewed as a single calving it is by far the largest.

Taking the thickness of the giant bergs in Table 6 to be 250-300 m means that these icebergs have masses ranging from 1000 to 2000 Gt, i.e. comparable with the reported annual discharge. Table 5 shows that such giant icebergs form only occasionally, yet in those years when these extreme events occur the Antarctic iceberg production must far exceed both the annual accumulation and the discharge across the grounding line.

Comparing Table 6 with the variations in iceberg extent given in Table 3 provides no evidence that the variations in the latter can be ascribed to the occasional calving of such giant icebergs. By chance, none of these giant icebergs were recorded in their initial stages by observations in this database, but ships in this programme subsequently encountered four of the giants identified as such in the records (A20, A22, A24, A38). Examination of the records show that these encounters did not cause a significant increase in the iceberg/observation ratio for the relevant season.

A further question is whether other giant calvings caused the year-to-year variations. Recording of all giant Antarctic icebergs with long axis >18.5 km was started by the US National Ice Center (NIC) in 1976 (Ballantyne and Long, 2002), initially from visual and infrared sensors. From 1979, icebergs of approx. >10 km length were registered in the Brigham Young University (BYU) satellite database (Budge and Long, 2018). Altogether 292 icebergs >18.5 km broke off from the continent between 1979 and 2020, i.e. on the average seven such giants are formed annually, but there are large year-to-year variations.

NIC designates the giant icebergs A-D for the sector "of birth", with numbers given consecutive in time. BYU additionally lists icebergs of size 10-18 km where the origin is not known. At present, January 2021, about 45 icebergs of size 500-5000 km² are listed with position in the NIC/BYU databases of giant icebergs.

Possibly part of the variations in annual iceberg frequencies in Table 4 are tied to the intermittent calvings of such 500-5000 km² icebergs. Altogether the present database contains 6452 icebergs of >1 km length, of which 93 of icebergs >10km, including icebergs A27, C7 and D11 that the onboard observers identified from NIC/BYU information. It is, however, not generally possible to identify the source for most of the icebergs >1 km. When observed, they may be of approximately their original calved-off dimensions, or be remnants from disintegration of yet larger icebergs. The dissolution of giant icebergs can take many years or decades. For example, a remnant of iceberg B15 is still tracked by NIC, 20 years after initial calving.

Even though some variations in iceberg density may be related to calving of giant icebergs, Appendix D shows instead how the year-to-year iceberg variations are mostly explained by differences in the regions traversed by the ships in different years. On this basis it is concluded that the annual variability is not primarily caused by variation in calving rates for giant icebergs, but rather by variations in the place and the season of the observations.

c) Are the observed iceberg numbers reasonable in relation to other knowledge on Antarctic iceberg production and distribution?

This issue can be evaluated by comparing with other databases of ship observations and of satellite observations.

Other ship records.
As indicated in the introduction, the collection of systematic iceberg information on the "Blue forms" was triggered by the observation that published ship records of Antarctic icebergs prior to 1980 seemed to be based on selective recordings. Four sets of iceberg data from coastal waters of East Antarctica published by Russian authors and which covered many seasons and ships totalled only 1663 icebergs. This was much less than those registered during either of two Norwegian Antarctic cruises (Orheim, 1980), and regional variations could not explain such large differences. Instead, the explanation for the differences between the Norwegian and Russian numbers seems to be that the latter recordings were episodic, focused on large or extraordinary icebergs.

There is now a much larger iceberg database available from Russian sources. Romanov et al. (2017) and Romanov and Romanova (2018) have presented compilations of records of approximately 70 000 iceberg observations from various Russian ship sources dating back to 1947. The core of the data derives from the research vessels of the Arctic and Antarctic Research Institute (AARI), but there are also substantial datasets from Russian whalers. Their data set also incorporates those parts of the present database that were collected by Russian vessels, and also part of the Australian data set.

In general, the Russian iceberg information, including the distribution patterns, agree closely with that shown by the present database. However, only the number of icebergs seen by radar was recorded in most cases. This, and perhaps other factors, may have introduced a bias with especially small icebergs not being recorded, as the database gives only 8 icebergs per observation for observation radius of 15 nm (Romanov et al., 2017). This is less than half the frequency of 12.1 icebergs/observation within 12 nm radius given in the present database

(0.036/0.08 icebergs/nm²). Beyond this, there are other differences in iceberg statistics between the Russian database and this database. A detailed comparison between the two databases should therefore be conducted, as appropriate. It would reveal whether there are systematic differences than can be ascribed to different observation instructions, or perhaps to differences in priority, i.e. the staff on a whaling vessel may not be prepared to spend much time recording icebergs in a busy whaling period.

The satellite records

As discussed above, the annual variations given in the present data base do not correlate with satellite records of giant icebergs with long axis >18.5 km. Far more relevant for comparison is the Altiberg database (Tournadre et al. 2015), which uses satellite altimetry for regular mapping of icebergs of area 0.1-10 000 km². It contains monthly estimates of iceberg area and volume for 100x100 km grid cells for the 1992-2014 period, and is thus a comprehensive satellite database that covers the two largest size classes of the ship records. However, the size determination for the smaller icebergs have considerable uncertainties.

The distribution patterns given in Altiberg show high accordance with the distribution given in the present database, e.g. compare Fig. 9 a,b in Tournadre et al. (2015) with Fig. 3 and 4 above. Where they overlap geographically, the satellite record therefore supports the results from the ship observations. However, the satellite record does not include ocean with sea ice cover. It therefore provides few data for the waters near the continent, where many of the icebergs are observed. For the same reason it has a very large seasonal variation in iceberg quantities, with very low numbers in winter when only the northern parts of the Southern Ocean are observed.

These databases are therefore complementary. The satellite data are fundamental for systematic detection of all the larger icebergs, which is critical for ice mass and discharge considerations and for studies of iceberg movement. However, the sum of the smaller icebergs is important for calculations of impact on the ocean water masses, and all sizes need to be included to understand the processes of iceberg dissolution. Thus, a combination of databases must be considered for many purposes.

High-resolution satellite data may answer other future needs, such as surveillance if icebergs enter low-latitude shipping lanes in warm water, or if plans materialize to tow icebergs from the Atlantic sector of the Southern Ocean to supply fresh water to e.g. Cape Town: https://www.bloomberg.com/news/features/2019-06-06/towing-an-iceberg-one-captain-s-plan-to-bring-drinking-water-to-4-million-people?srnd=businessweek-v2.

In summary, examination of the data and comparisons with other records of iceberg distribution support the conclusion that the database represents fairly the iceberg distribution around Antarctica. There is no evidence that episodic calvings of giant icebergs have caused spikes in the observed annual iceberg frequencies. The multiyear observations can thus be combined to arrive at the average iceberg concentrations for different parts of the Southern Ocean.

Based on such averages for icebergs of different sizes, a number of issues can be considered. The following sections provide analyses, or brief comments, on the following themes:

- **Iceberg distribution around Antarctica**
- **Total number of icebergs in the Southern Ocean**

- **Mass of icebergs in the Southern Ocean**
- **Different drift patterns of small and large icebergs**
- **Contribution of melting icebergs to ocean temperatures and salinities**
- **Iceberg dissolution rates and “life expectancy”**
- **Iceberg calving rates and the mass balance of Antarctica**

Iceberg distribution around Antarctica

Fig. 4 shows that the iceberg concentration varies considerably around the continent, caused both by regional differences in calving rates and by combinations of sea-bed topography, ocean currents and drift patterns. As expected, the iceberg concentrations are high close to the continent, indicating high incidences of iceberg production around most of Antarctica. However, high concentration may also be caused by iceberg drift and by grounding.

We consider first the coastal waters, which for most of the Antarctic circumference are dominated by counter-clockwise currents. Examining Fig. 4 clockwise around the continent starting at 0° E, it can be seen that the rate of calving seems high along most of East Antarctica, with low iceberg frequencies near the coast only from 15-35° E and 110-150° E. Here, as elsewhere, the iceberg distribution is also related to north-flowing currents that remove icebergs from the coastal currents in exit zones, described below.

The iceberg concentration in the southern part of the Ross Sea is very low, presumably as a result of low calving rate from the Ross Ice Shelf, which has produced mostly infrequent giant icebergs in the past. Much higher concentrations are seen in the Amundsen and Bellingshausen Seas and along the western side of the Antarctic Peninsula. The north-eastern part of the Antarctic Peninsula and the south-eastern part of the Weddell Sea also have high iceberg concentrations. Here the counter-clockwise coastal current around East Antarctica brings in additional icebergs.

We can compare this iceberg distribution with knowledge of iceberg production from other sources. First, regarding the largest or giant icebergs, the NIC/BYU satellite data base shows that over the past four decades, 113 of these originated from sector A (0-90° W), 100 from sector B (90°-180°W), 52 from C (90°-180°E), while only 27 broke off from the ice shelves in D (0°-90°E). These calving frequencies differ considerably from the observed iceberg concentrations, especially with regards to section D, but that does not imply a contradiction, given that the giant icebergs are so infrequent.

More relevant data are provided by Liu et al. (2015), who give a comprehensive analysis of iceberg calving rates around Antarctica for the 2005-2011 period based on Envisat Synthetic Aperture data and visual interpretations. They concluded that the highest calving rate was from ice shelves facing the Amundsen Sea, which agrees well with the ship-borne observations. However, their Fig. 1 gives a low iceberg calving for the ice shelves from 30° W clockwise to 110° E, which does not accord with the high iceberg frequencies observed along most of this coast. The most likely explanation for their low observed calving rates from this sector seems to be undetected smaller iceberg calvings, perhaps in combination with high numbers of grounded icebergs observed multiple time by ships. This issue is discussed further in the section on iceberg calving rates and the mass balance of Antarctica.

Moving away from the coastal waters, there are also high concentration regions far north of the continent, reflecting known iceberg drift patterns. Clockwise from 0° E we observe four main offshore exit regions of high iceberg frequencies. One is from ~85° to 120° E, where an exit zone extends north-westwards for more than 500 km, reflecting both high calving rates and offshore currents. The second is in the Amundsen Sea from ~115° to 140° W, extending westwards and north-westwards for more than 500 km also as a result of high calving rates and offshore currents. The third, and largest, zone extends more than 1000 km north-eastwards from the northern tip of the Antarctic Peninsula at around 60°- 65° S and 55° W. These icebergs must derive both from calvings on the eastern side of the Antarctic Peninsula and from icebergs that have drifted with the coastal current southwards into the Weddell Sea and then travelled northwards. After arriving at the northern tip of the Antarctic Peninsula these icebergs drift east-northeast with the clockwise Antarctic Circumpolar Current and persist in high concentrations to 55° S and 0° E.

The fourth exit zone extends from ~0°to ~40° W, and seems to reflect two sets of offshore currents. From ~0° to 15° W the zone extends north-westwards, and, in part, merges northwards into the zone above, and in part branches eastwards extending to ~30° E, 58° S. From ~15°to 40° W the zone extends westwards and north-westwards to give high concentrations of icebergs in the central Weddell Sea. As these icebergs continue to drift northwards and clockwise, they merge into the third high-frequency zone.

A common element of all the high-frequency zones is that the icebergs of high longevity end up in the Antarctic Circumpolar Current, where they may drift eastwards for many months before they disintegrate.

The variations in iceberg density around the continent can also be illustrated by looking at the data for different sectors, as shown by Table 7.

Sector	Obs	total	b/o	-50 m	-200	-500	-1000	>1000	class	- 50 m	-200	-500	-1000	>1000
0-44.999°W	9784	116036	11.9	39196	32442	16664	6877	2439	97618	40.2	33.2	17.1	7.0	2.5
45-89.999°W	7334	117168	16.0	45492	30111	15145	5580	1612	97940	46.4	30.7	15.5	5.7	1.6
90-134.999°W	471	8397	17.8	1503	2157	1294	469	164	5587	26.9	38.6	23.2	8.4	2.9
135-179.999°W	870	10017	11.5	2341	3134	1564	655	264	7958	29.4	39.4	19.7	8.2	3.3
180-135°E	1534	9227	6.0	2416	2275	1606	929	472	7698	31.4	29.6	20.9	12.1	6.1
134.999-90°E	1130	20184	17.9	2985	4692	3575	1892	743	13887	21.5	33.8	25.7	13.6	5.4
89.999-45°E	1762	24377	13.8	4178	5793	4422	1646	539	16578	25.2	34.9	26.7	9.9	3.3
44.999-0°E	3749	18114	4.8	5132	5830	2616	944	219	14741	34.8	39.5	17.7	6.4	1.5
Total	26634	323520	12.1	103243	86434	46886	18992	6452	262007	39.4	33.0	17.9	7.2	2.5

Table 7. Iceberg distribution in longitude sectors spanning 45° intervals. The data in each sector cover all latitudes of observations.

Table 7 presents a coarse overview of regional differences in the form of iceberg numbers for different 45° longitude sectors. By far the largest number of observations, and of icebergs, are from the sectors that include the Antarctic Peninsula. This region of many research stations shows a high density of small icebergs, which could be expected as there are here relatively many glaciers calving directly into the ocean without forming ice shelves.

However, the highest concentrations, however, are found in the adjoining sector to the west, with > 17 icebergs/observation. As discussed above this is related to very high iceberg concentrations north of the Amundsen Sea. Figs. 1 and 2 show that the number of observations in this area is low, so a few exceptional observations could perhaps explain the high densities. However, inspecting the individual observations from this part of the Southern Ocean shows many independent observations of large iceberg concentrations, indicating that the high concentration is a real multiyear feature. It is most likely caused by high iceberg calving rates in the Pine Island Bay area, and possibly also high iceberg production rates from other calving glaciers in this sector of West Antarctica. It thus reflects the dynamic nature of the glaciers in this region.

The adjoining sector covering the Ross Sea has, on the other hand, a low density of icebergs indicating that the Ross Ice Shelf is a source of infrequent iceberg calvings.

The 135°-180° E sector has the lowest iceberg concentration, and the coastal iceberg frequencies indicate lower ice discharge and lower iceberg production in parts of this region. The Totten Glacier which forms the Totten Ice Shelf at 116° E drains much of the East Antarctic ice sheet to the west of 135° E, while the glaciers and ice shelves flowing east to the Ross Sea subtract from ice available to flow north in this sector. Unfortunately, this part of the Antarctic coastline has few stations, and sea ice conditions are often difficult. Thus, few ships travel here, and the iceberg statistics are not as robust as elsewhere.

Looking at details for the whole Southern Ocean, it appears that icebergs <1000 m are distributed evenly and that their concentration decreases gradually away from the coast and in the current-driven corridors and zones. However, the largest sized icebergs show a more scattered distribution.

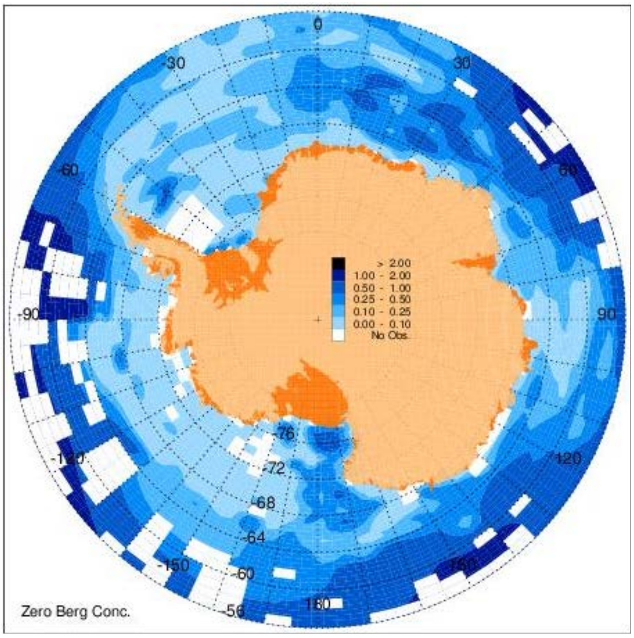


Fig. 6. Frequency of zero iceberg observations, calculated as the number of zero iceberg observations divided by the number of observations in the box. Grid boxes without observations are shown in white.

As shown by Fig. 6, the frequency of observations of no icebergs around the ship obviously generally increases with distance from the iceberg source. However, there are also other patterns: The frequency is for example, high at the Antarctic Divergence (upwelling zone at the southern front of the Antarctic Circumpolar Current). A ship travelling northwards will encounter more icebergs when moving north of this into the ACC. Also noticeable is the Ross Sea, where there are large numbers of zero iceberg observations in the near-coastal waters.

Total number of icebergs in the Southern Ocean.

Using all observations, we can calculate the average concentrations and total numbers of icebergs for all parts of the SO. As shown earlier there are large seasonal variations which then become masked. The dissolution of icebergs within the sea ice zone and in winter is slow, and sometimes near-zero. Once in the open water, however, the majority of icebergs <1000 m disintegrate and disappear within a few months. A ship travelling south in the early part of the summer will thus encounter more icebergs in the open sea then on a repeat voyage later in the season. However, for most regions of the SO the data coverage is not adequate to make robust calculations for different months. Given that most observations are from the summer, the following numbers can be seen as averages for that season.

In the following sections, the total number of icebergs, T, is calculated using the mean iceberg concentration in the individual grid boxes, defined as the total number of icebergs observed in the box divided by the number of observations. For a given region under consideration, the total, T, will then be the sum of icebergs for the latitude intervals φ_i- φ_j in the zone as follows:

$$T = \sum_{\varphi_i - \varphi_j} \left(F\varphi \times \frac{n\varphi}{n_o} \times \frac{A\varphi_i}{1553} \right)$$

where $F\varphi$ is the observed average iceberg frequency for the n_o grid boxes with observations at given latitude band, $n\varphi$ is the number of grid boxes at that latitude, $A\varphi$ is the area of the grid boxes for this latitude interval, and 1553 is the area in km² of one observation of 12 nm radius. The areas for each latitude interval are given in appendix C. Except for the northernmost waters, the few boxes that do not contain data have thus been assumed to have the same iceberg frequencies as the average frequency for the latitude interval in the zone under consideration. Using this approach means that each grid box is treated with equal weight, independent of the number of observations that were gathered in this box. A different approach would be to give each observation the same weight, i.e. grid boxes with most observations would have most influence. Because there are large differences in observation density, the results from the first approach are considered most likely to reflect reality. However, the second method would not result in large differences in derived numbers.

Table 8 gives further details of the calculations, including the special treatment of the northernmost boxes.

Naturally, high frequencies of icebergs are found in the coastal waters, within ~200 km of the continent. Here the average iceberg density is 0.0098 icebergs/km², but with large variations. Some regions have four times higher iceberg frequencies, but there are also regions of zero or very few icebergs. The total area of the zone within ~200 km is ~4.13x10^6 km², and the total number of icebergs near the coast is about 41 000.

Moving away from the coast, the iceberg densities continue to show large regional variations as described above, with exit zones of high concentrations where offshore currents bring the icebergs northwards. The calculations follow the order of exit zones described in the previous section. The boundary of each zone is judged to be where there is a large reduction in iceberg frequency between neighbouring grid boxes.

The first exit zone, from ~85° to 120° E, extends north-westwards to about 60°S. It covers an area of ~0.8 x10^6 km², has an iceberg density of 0.0072/km, and contains 6 000 icebergs.

The second zone, extending westwards and north-westwards from ~115° to 140° W, has an area of ~1.7x 10^6 km² with 0.0091 icebergs/km², for a total of 15 000 icebergs.

The ~500 km wide third zone extending east-north-eastwards from the Antarctic Peninsula to the Greenwich meridian shows particularly high iceberg frequencies. It covers an area of ~3.2x10^6 km² with an average iceberg density of 0.01 /km², for a total of 33 000 icebergs. This offshore zone is the only one with higher iceberg frequencies than that of the coastal zone.

The fourth zone, which includes much of the Weddell Sea, covers ~1.7 x10^6 km², has an iceberg density of 0.0069/km, and contains 12 000 icebergs.

Outside these zones the iceberg densities are an order of magnitude lower, apart from a few pockets of higher frequencies mostly next to the high-density zones described above. The iceberg total for the whole remainder of the Southern Ocean is 16 000. Possibly the number of icebergs at low latitudes is exaggerated because of under-reporting of zero icebergs, as discussed initially. However, the total numbers are small compared to the iceberg numbers in the denser areas.

In summary, the total number of icebergs in the SO in the summer is ~130 000 icebergs, and ~132 000 altogether in the southern hemisphere oceans (Table 8). This is lower than the number given by Orheim (1985) based on a much smaller set of iceberg observations, but very close to the result of Romanov et al. (2017). They give the instantaneous total number of icebergs in the SO as 132 269 (sic). The fact that the numbers are so close is surprising in view of their reported much lower average iceberg density, discussed earlier.

Zone	box with obs.	total boxes	total observ.	iceberg/ observ.	conc/ km²	mean latitude	area 10^6km²	Total
Coastal	183	200	2760	15.08	0.0098	70.2	4.19	41200
exit 1	28	28	312	11.14	0.0073	62.1	0.81	5900
exit 2	73	73	1033	14.15	0.0093	68.5	1.65	15400
exit 3	105	105	1646	15.68	0.0100	60	3.25	33500
exit 4	71	71	746	10.51	0.0069	66.9	1.72	11400
SO, S of 60°S	380	425	842	2. 22	0.0015	63.9	11.56	16000
SO, N of 60°S	104+222	326	306	0.94	0.0006	54	11.85	7300
Sum S. Ocean		**1228**					**35.03**	**130700**
N of AC		62	50		0.0005	48	2.56	1400
Total icebergs								**132100**

Table 8. Number of icebergs in the individual zones. The first column gives the number of 1x5° grid boxes with observations and the second the total number of boxes in the zone. The sum of frequencies divided by the sum of boxes with observations gives the average icebergs/observation/box in the zone, which multiplied by total number of boxes in the zone gives sum of icebergs. The exception is the case of the Southern Ocean north of 60°S. Here only 104 of the 326 grid boxes have observations. As discussed before many ships traversed at these latitudes without recording zero icebergs. The grid boxes without observations have therefore been defined as having observed zero icebergs.

The database also contains icebergs north of the SO boundary, as indicated by Table 8. These icebergs are primarily in two areas, the largest stretches north-eastwards from exit zone 3 to 45° S, 5° W-15° E. The second, much smaller, extends from exit zone 1 north-eastwards to 49° S, 130° E.

Mass of icebergs in the Southern Ocean.

The mass of icebergs can be calculated from Table 8 combined with the size distribution data. Coarse calculations give a total mass in the coastal waters of ~2500 Gt, and ~1000 Gt for the remainder of the Southern Ocean, where icebergs >1000 m represent more than 50% of the total. However, the giant icebergs recorded in the NIC/BYU satellite databases are underrepresented in the present database. Realistic calculations of total mass of icebergs in the Southern Ocean therefore need to also include giant icebergs from the satellite databases.

Different drift patterns of small and large icebergs

Icebergs drift under the influence of several forces. The ocean current integrated over the draught of the iceberg is the most important, but icebergs are also affected by the Coriolis effect, by sea-ice forces when sea ice is present (Lichey and Hellmer, 2001) and by a tilt force from different centre of buoyancy/centre of gravity (Engelhardt and Engelhardt, 2017).

In general, the iceberg distribution shows a good correspondence with the ocean circulation. As shown above, the icebergs generally follow the counter-clockwise westerly-directed coastal current to four main exit zones where they are transported north away from the continent until they join the easterly-directed Antarctic Circumpolar Current. However, within this broad picture the different sized icebergs show differences in drift patterns, with the larger icebergs veering more to the left of the current. This can be illustrated by looking at the proportion of largest size icebergs that either drift along the coast or enter exit zone 4, which extend west from 0°W. Here the counter-clockwise current that follows the coastline veers sharply to the left (south) at Cape Norvegia (10°W). In the coastal zone from 0-40° E the largest icebergs make up 2.7% of the total, while in the coastal zone from 0-40°W the proportion is 5.0%, and in exit zone 4 the proportion is only 1.0%. The corresponding numbers for the smallest size icebergs are 22.4%, 21.8% and 33.8%. In other words, a much larger proportion of the largest icebergs than of the smaller icebergs veer to the left and follow the coastline southwards into the Weddell Sea. In general the larger icebergs tend to “hug” the continent drifting in the counter-clockwise current. Similarly, the larger icebergs show a tendency to take a more northerly course than the smallest after exiting from the northern end of the Antarctic Peninsula.

One obvious cause for these track differences is the Coriolis effect which becomes relatively more important as the size increases, as it is proportional to the mass, while the water forces act on the surface areas. Another possible effect may result from the larger base area giving higher basal shear forces. Effects of vertical changes in current direction, including Ekman spiral, may also be a factor, although this should not apply to different sizes of tabular bergs as these all have similar draughts.

Comparing the tracks of giant icebergs from 1999-2010 in e.g. Budge and Long (2018) with the iceberg distribution in this database shown in Fig. 4 demonstrates that the giant icebergs take a markedly more northerly route than small icebergs, and it would be misleading to use the observed tracks and distribution of the giant icebergs as a tool for predicting where the smaller icebergs of this database can be expected to be found. The drift of giant icebergs has been simulated by Rackow et al. (2017). Their computed tracks of giant icebergs seem to be further north than indicated by satellite observations and would deviate even more for the smaller icebergs discussed here.

Contribution of melting icebergs to ocean temperatures and salinities.

While the mass of floating icebergs in the Southern Ocean is dominated by the largest icebergs, the situation is inverse for considerations of effect of icebergs on ocean salinities and temperatures, as the area in contact with water increases with decreasing size for a fixed mass of icebergs. A long-term average annual iceberg production of 2000 Gt (i.e. $2200x10^9$ m^3) icebergs evenly distributed over the $36x10^6$ km^2 area of the Southern Ocean would represent a rate of injection of 0.06 m/m^2, which is an order of magnitude less than the contribution from precipitation minus evaporation (Turner et al, 1999). However, as shown in the previous section, the icebergs are concentrated along the coast and in the four exit zones, and so the corresponding injection of fresh water from icebergs may have local significance, particularly from icebergs in exit zone 3. Such effects can be quantified using the iceberg densities in the present database. The fresh water injection from the largest size icebergs can be done from satellite databases, as shown by Silva et al. (2006) and Tournadre et al. (2012).

Iceberg dissolution rates and "life expectancy".

At any location along the coast, the observed icebergs can be both recently calved icebergs that have not undergone significant changes in size and older icebergs that have fractured and/or been reduced in size by attrition from the sides and melting. Fracturing will increase the number of icebergs, and significantly change the size class distribution, while attrition/melting will not change the numbers and only very slowly change the size distribution.

In cold waters, the most significant process of attrition is not melting, but the erosion by wave action at the water line. For ice shelves and tabular icebergs this leads to small-scale calvings from the undercut approximately vertical side(s), and the whole process produces ice fronts with protruding underwater "noses" (Klepsvik and Fossum, 1980). In mature cases the width of such protruding underwater platforms may exceed 50 m, at depths of 50-100 m (Orheim, 1987).

From the iceberg size distributions some tentative conclusions can be drawn with regards to dissolution processes. As a first approximation it can be assumed that all icebergs >200 m in length are tabular, originating from ice shelves. For them not to be prone to overturning, these must have horizontal dimension > ice thickness, which typically is around 250 m. Indeed, in the case of ice shelves with wide protruding underwater platforms the width of the broken off iceberg must be considerably above 250 m to avoid the immediate overturing after calving that can take place for smaller icebergs. The size distribution of the total numbers (Table 1) shows that icebergs >200 m account for 28% of the population, and that the numbers approximately double for each step down in size class, implying that fracture is the dominant process for ice classes 3-5. On the other hand, attrition is the dominant process for the dissolution of icebergs of less than 200 m horizontal dimension, with the number of icebergs in the smallest size class only 20% higher than in the next.

The dissolution processes can be quantified with knowledge of initial dimensions of iceberg populations, or by investigating changes in size for a selected population. Jacka and Giles (2007) showed for Australian data that the change in size distribution of icebergs moving in a confined "corridor" allowed calculation of dissolution rates. These were found to be approx. 0.03-0.05 m d^{-1}, a lower rate than that derived by Hamley and Budd (1986) using the same approach. Lack of data of drift speeds causes uncertainty in these results; the computations by Jacka and Giles (2007) apply an iceberg drift of 5 km/day.

The numbers in the present database reveal a significant decrease in iceberg frequencies and sizes through the summer period. These size changes can also be used to calculate dissolution rates and to arrive at estimates of residence times and of calving rates. Exit zone 3, from the Antarctic Peninsula, contains the most complete set of observations on icebergs leaving the Antarctic coast in a confined corridor. A Jacka/Giles-type analysis for this zone should thus give robust results for dissolution rates. Such detailed analyses remain to be done, but the next section provides some initial considerations.

Iceberg calving rates and the mass balance of Antarctica.

The iceberg distribution in coastal waters reflects the combination of local calving and advection of icebergs from adjoining seas. At the time of calving, the dimensions of icebergs from an ice shelf will differ systematically from icebergs calved from a tidewater or grounded glacier. The latter produces relatively small icebergs seldom exceeding 200 m in any dimension, and most such icebergs are much smaller. This is because these calvings occur along crevasses that form, more or less, parallel to the ice front, caused by stresses from the imbalance of the subaerial free face, and added to this, stresses induced by tidal motion as well as by ocean swell (Reeh, 1968). The distances of crevasses from the front will not normally exceed the thickness, which is normally <200 m.

Most Antarctic icebergs with dimensions >200 m, i.e. size class 3 or larger in this database, will thus have originated from ice shelves. Bindschadler et al. (2011) has identified the perimeter of Antarctica to be 53 610 km, and 2/3 of this is in the form of ice shelves. These produce the large icebergs that can be individually detected from satellites, and from 1979 onwards all giant icebergs > 10 km are recorded, as described above. Liu et al. (2015) have additionally for the 2005-2011 period recorded ~100/y iceberg calving events >1 km^2 from ice shelves exceeding 10 km^2.

There are relatively little data available on smaller calvings from the continent. The ship records from the coastal waters reduce this information gap and indicate that smaller ice shelf calvings may have gone undetected to an extent that they affect mass balance conclusion. To investigate this further we can examine the iceberg distribution in the coastal waters of East Antarctica, from 0° to 170° E longitude, a coastline almost completely made up of ice shelves and shorter sections of pinning ice rises. This part of the Antarctic circumference has the most regular geometry, being almost circular. The ocean current runs counter-clockwise along the coast, which means that observed icebergs have either advected from the east, or have calved locally. It is then possible to use the combination of iceberg frequencies and size class variations to derive information on calving activities along the coast.

Table 9 shows the distributions of icebergs <200 m and >1 km in the NPI database, together with icebergs of similar sizes recorded in the 7-class AAD database, which uses <200 m and >800 m as class intervals. These data add substantially to NPI data for the longitude interval 60°-120° E (see Fig. 8) and are therefore included. The AAD data are further described in the following section.

Long. °E	Class 1&2	Total	%	Class 5	%	Obs.	Density
165-170	132	560	23.6	33	5.9	46	12.2
160-165	469	1267	37.0	23	1.8	37	34.2
155-160	85	364	23.4	30	8.2	13	28.0
150-155	0	0		0		0	
145-150	33	266	12.4	64	24.1	73	3.6
140-145	520	978	53.2	246	25.2	273	3.6
135-140	1201	1417	84.8	15	1.1	137	10.3
130-135	96	189	50.8	8	4.2	46	4.1
125-130	62	153	40.5	5	3.3	41	3.7
120-125	17	65	26.2	2	3.1	35	1.9
115-120	129	225	57.3	1	0.4	41	5.5
110-115	914	1853	49.3	112	6.0	252	7.4
105-110	1817	3979	45.7	303	7.6	274	14.5
100-105	831	1137	73.1	68	6.0	61	18.6
95-100	476	1107	43.0	26	2.3	52	21.3
90-95	1963	5347	36.7	212	4.0	120	44.6
85-90	347	792	43.8	13	1.6	45	17.6
80-85	280	844	33.2	41	4.9	71	11.9
75-80	3006	6498	46.3	269	4.1	570	11.4
70-75	1342	3573	37.6	80	2.2	236	15.1
65-70	1176	3822	30.8	85	2.2	254	15.0
60-65	2237	4634	48.3	51	1.1	241	19.2
55-60	379	572	66.3	6	1.0	48	11.9
50-55	277	1091	25.4	46	4.2	64	17.0
45-50	1592	4606	34.6	220	4.8	132	34.9
40-45	353	787	44.9	45	5.7	54	14.6
35-40	154	498	30.9	21	4.2	36	13.8
30-35	24	83	28.9	19	22.9	16	5.2
25-30	19	207	9.2	19	9.2	25	8.3
20-25	74	180	41.1	2	1.1	17	10.6
15-20	21	54	38.9	1	1.9	22	2.5
10-15	723	1765	41.0	42	2.4	60	29.4
5-10	316	464	68.1	5	1.1	53	8.8
0-5	1255	1899	66.1	35	1.8	119	16.0
Sum	22320	51276	43.5	2148	4.2	3564	14.4

Table 9. The iceberg distribution at 5° longitude intervals for the ~200 km wide coastal zone of East Antarctica. The second column gives the number of observed icebergs <200 m horizontal dimension, i.e. size classes 1 and 2. The third column gives total number observed icebergs, the fourth the % of the smallest icebergs, the fifth and sixth the number and

percentages of the largest icebergs (class 5 for the 5-class NPI, classes 5-7 for the 7-class AAD), the seventh the number of observations, and the last the icebergs/observation for each segment.

In Table 9, the two smallest ice classes make up 44%, the largest 4.2% and the number of icebergs per observation are 14.4. For comparison, in the whole NPI database the corresponding percentages are 72.4% and 2.5%, and it has 12.1 icebergs per observation. This coastal region thus contains a much smaller proportion of small icebergs and higher proportion of the largest, while the frequency is only a little bit larger.

With the caveat that the years covered by the data are not always identical, and using caution for areas with relatively few observations, it is nevertheless clear that Table 9 demonstrates real differences across the longitude bands. These must mostly be related to local calvings. If advection of icebergs from the east were the main source of the differences, then a systematic reduction in size and possibly increase in numbers could be expected moving west following the coastal current, as the icebergs have the potential to drift across several latitude bands. Such systematic changes in size and frequency are not shown in the table. Instead, the table shows many abrupt changes that go in the opposite direction, compare e.g. numbers from 145° to 130°, and changes that can only be ascribed to high calving rates, see e.g. from 115° to 105° and 60° to 45° E. Inspections show also that the changes in dimension or frequency cannot be ascribed to advection into or from adjoining waters to the north. The only major iceberg drift in this respect are the icebergs leaving in exit zone 1, from ~85° - 120° E, described above.

The observations from Jacka and Giles (2007) can be used to get a perspective on the numbers in Table 9. They indicate a drift speed of 5 km/d and dissolution rate of 0.03 m/d in these cold waters. The travel distance at 5° latitude along 68° S is 217 km. It will thus take six weeks to cross one latitude band, and during this period the iceberg will have lost ~15 m from each side (and base). This loss will significantly affect the numbers of the smallest icebergs, but not the larger ice classes.

Table 9 indicates high calving rates at 155-170°, 140-150°, 90-115°, 45-55°, 25-35° and 10-15° E. It is of interest to compare these results with Liu et al. (2015), who have provided the most comprehensive analysis of iceberg calving rates around Antarctica. For the 2005-2011 period, they recorded 579 distinct iceberg calving events larger than 1 km² from the ice shelves exceeding 10 km² in area, and summarized an annual calving rate of 755 Gigatons (Gt/y) for all of Antarctica. Their Fig. 1 shows that of this, only 55 Gt/y came from the perimeter from 0° to 100° E, while 230 Gt/y came from the coast from 110° to 155° E. This is clearly not in accord with the data presented in Table 9 for the 0° to 100° E sector. This differs from the data presented in Table 9 for the 0° to 100° E sector. The likely explanations for their low observed calving rates from this sector representing a major part of East Antarctica are either less calving than normal during the 2005-2011 period or undetected iceberg calvings. With a resolution of 1 km, any smaller icebergs breaking off from an ice front with an approximately fixed front position may not be detected. The ship observations also indicate that their calving rates are too low for the glaciers calving into the eastern Weddell Sea.

Table 9 combined with the results of Jacka and Giles (2007) indicate that the icebergs in the coastal zone have a typical "life-time" of two-three years. It should be possible to make more precise estimates of this by comparing selected parts of the coastal zone where there are numerous data for the whole of the summer. Robust calculations should also be possible for the average life expectancy of icebergs that have left the coastal zone, especially for exit zone 3 where there are large amounts of observations for different months.

Assuming that the icebergs are present in the coastal zone last for 2.5 years, and an additional 1 year in the open waters north of this zone, the estimates of iceberg mass given previously of 2500 Gt in the coastal zone and 1000 Gt in the rest of the Sothern Ocean would indicate an average total annual calving rate of 2000 Gt. This is higher than satellite-based estimates of steady-state calving rates, ranging from around 1000 Gt/y (Liu et al. 2015) to around 1300 Gt/y (Depoorter et al. 2013, Rignot et al. 2013). Obviously, these calculations need to be refined by deriving more precise dissolution rates and residence times, and the satellite-based calculations should be refined by accounting for area changes of ice shelves at multi-decadal time scales.

The Australian contribution to the SCAR database

Also presented in this SCAR database are ship-based iceberg observations collected by the Australian Antarctic Division (AAD) from the Australian National Antarctic Research Expeditions (ANARE) ships. These generally operated in 50-150° E latitude sector. The Australian Antarctic programme had routinely collected data on iceberg location and size from 1948 from ships they operated, but a more rigorous data collection routine was initiated in 1977. For the period 13 December 1978 to 8 March 1984 the Australian observers used the same size classes as the NPI programme. The data for this period comprise 970 observations of altogether 13 502 icebergs, of which 5 978 were size classified. These data are included in the NPI database.

From the 1984/85 season AAD collected iceberg size data in seven size classes: 25-100, 100-200, 200-400, 400-800, 800-1600, 1600-3200 and >3200 m, and this programme was carried out in most seasons until 2010/11. Some early results from the Australian observations were published by Morgan and Budd (1978), Budd et al. (1980) and Hamley and Budd (1986). More recently Jacka and Giles (2007) analysed the AAD data from 1978 up to 12 March 2000.

The AAD database for the 1984-2011 period comprise 8061 observations of altogether 53 649 icebergs, i.e. 6.7 icebergs/observation. Altogether 38 756 icebergs were size classified as shown in Table 10.

Dimension	25-100	100-200	200-400	400-800 m	0.8-1.6	1.6-3.2	>3.2 km
Number	14790	11017	7387	3995	1177	290	100
%	38.2	28.4	19.1	10.3	3.0	0.7	0.3

Table 10. Summary of AAD iceberg observations 1984/85-2010/11.

The distribution of the AAD observations is shown in more detail in Figs. 7 and 8.

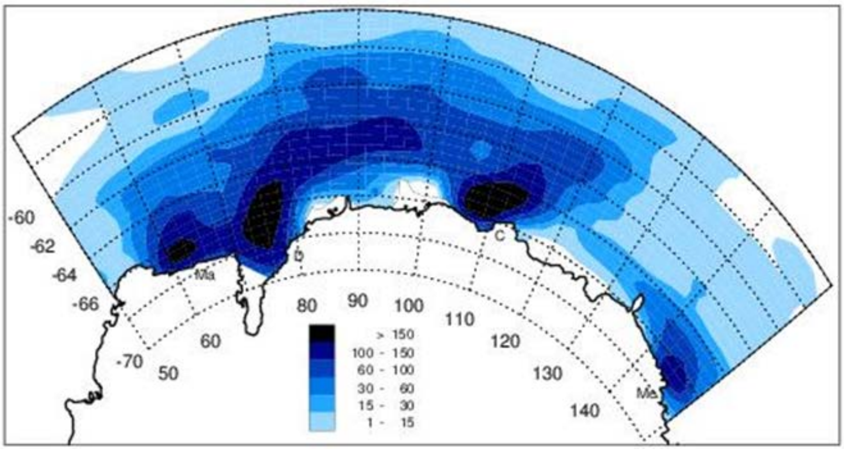


Fig. 7. Distribution of all the AAD observations from 1978/79 to 2010/11, smoothed by the same MIN_CURVE_SURF routine as in previous Figs. However, as this map covers few regions of low density of observations, no boxes have been over-plotted with uniform colour.

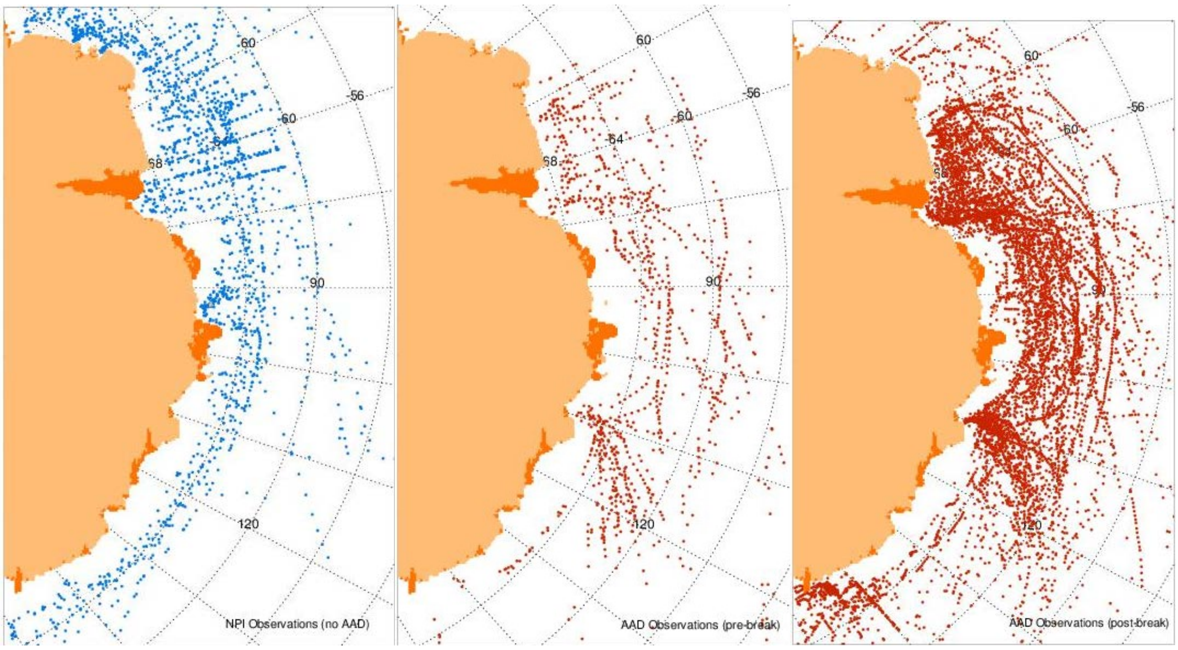


Fig. 8. The distribution of 5- and 7 class observations in the same area. The left Fig. shows the NPI 5-class observations but without 5-class AAD data. These pre-1984/85 5-class AAD data are shown in centre. The right Fig. shows post 1984-85 7-class AAD observations.

Figs. 7 and 8 compare the distribution of the AAD data with the total observations in the NPI database for this sector. It is apparent from the Figs. that the 7-class AAD observations provide the major data for this region. However, the non-AAD data are significant in giving geographic coverage outside the main travel routes to the Australians stations Mawson (67° 36′ S, 62° 52′ E), Davis (68° 34′ S, 77° 58′ E) and Casey (66° 16′ S, 110° 31′ E).

A joint program between NPI, AAD and the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) was established to carry out full analyses of all these iceberg observations. It was agreed that for utility, it would be practical to have both databases available from one source as the joint SCAR database, even though much of the Australian iceberg data has been available for many years through the AAD Data Centre. In the present dataset all the AAD data available as a separate database. These data can be retrieved in the same manner as from the NPI database, described in Table 3 and accompanying text.

In this connection, the following exceptions to the specification of the NPI database columns given in Table 3 should be noted. Firstly, the ice concentration and RV columns in the AAD database file do not contain any information, these are deliberately introduced dummy spacer columns so that both data files follow the same column order layout. Secondly, the NPI columns for Freeboard, Length, Width, Dim-as-average, View-radius and comments do not exist in the AAD database. The data for these parameters, and the two dummy columns, were often recorded by Australian observers but were never formally typed up within the growing Australian database though many of these records still exist in some form. However, the pre-size-change Australian data that was sent to Norway on the standard blue forms were typed up there in the normal way and thus exists within the NPI database in the appropriate locations. Also, the AAD database includes all the Australian observations, in order to preserve the totality of AAD observations. This means that the AAD data collected before 1984/85 are found both in the NPI and in the AAD database.

Combining the 5-class NPI and 7-class AAD data sets?

Based on the satellite records, Tournadre et al. (2015) estimated that the size distribution of large and giant icebergs follows a power law with slope -1.52±0.32, close to -3/2 law for brittle deformation. Their data overlaps only with the largest size classes in these two databases. Work is underway to ascertain whether there are benefits in constructing a combined data base with consistent size classes for the NPI and post 1984/84 AAD data sets. For some types of analyses the two data sets can be immediately combined, as done in the previous section.

Acknowledgements.

The NPI database derives from 233 ship cruises involving 68 vessels from 20 different SCAR nations and have been collected by more than a thousand individual observers. With this database and publication, we extend our deep gratitude to the national Antarctic programmes for accommodating this programme on their ships, to the observers for their unfailing efforts, and to ship's officers for sharing knowledge and advice with those observers. We are also very grateful to the various directors and program leaders of NPI, AAD and ACE CRC who have supported the compilation of these databases.

Over the years, from when the programme started until today, several persons have also contributed to the registration of data and to considerations of how they should be analysed. In this connection we give special thanks to Øyvind Finnekåsa, Bjørn O. Johannessen, Stein Tronstad and Jan-Gunnar Winther, all working at the time at the Norwegian Polar Institute, and Bill Budd, Vin Morgan and Trevor Hamley, at the time at AAD.

References:

Ballantyne J. and D.G. Long, 2002. A multidecadal study of the number of Antarctic icebergs using Scatterometer Data. In *Proceedings of International Geoscience and Remote sensing Symposium (IGARSS), 24-28 June 2002*. Toronto, Canada.

R. Bindschadler, H. Choi and 16 others, 2011. Getting around Antarctica: new high-resolution mappings of the grounded and freely-floating boundaries of the Antarctic ice sheet created for the International Polar Year. The Cryosphere, **5**, 569–588.

Bouhier N., J. Tournadre, F. Rémy and R. Gourves-Cousjin, 2018. Melting and fragmentation laws from the evolution of two large Southern Ocean icebergs estimated from satellite data. The Cryosphere, **12**, 2267-2285.

Budd W.F. and I.N. Smith. 1985. The state of balance of the Antarctic ice sheet – an updated assessment 1984. In Polar Research Board, *ed. Glaciers, Ice Sheets and Sea Level: Effect of a* CO_2*-induced Climatic Change. Report of a workshop held in Seattle, Washington, September 13-15, 1984.* Washington, DC, National Academy Press, 172-177.

Budd, W.F., T.H. Jacka and V.I. Morgan. 1980. Antarctic iceberg melt rates derived from size distributions and movement rates. Ann. Glaciol., **1**, 103-112.

Budge J.S. and D.G. Long, 2018. A Comprehensive Database for Antarctic Iceberg Tracking Using Scatterometer Data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing **11** (2), 434-442.

Deporter M.A., J.L. Bamber, J.A. Griggs, J.T.M. Lenaerts, S.R.M. Ligtenberg, M.R. van den Broeke and G. Moholdt, 2013. Calving fluxes and basal melt rates of Antarctic ice shelves. Nature, **502**, 89-92.

Dmitrash Z.A, 1965. Rezul'taty nablyudeniy nad aysbergami [Results of observations on icebergs]. Trudy Sovetskoy Antarkticheskoy Ekspeditsii, **44**, 89-103.

Dmitrash Z.A, 1971. O nekotorykh osobennostyakh raspredeleniya aysbergov v Vostochnoy Antarktika. [Some characteristics of iceberg distribution in the eastern Antarctic]. Sovetskaya Antarkticheskaya Ekspeditsiya . Informatsionyy Byulleten', No. 82, 37-41.

Engelhardt H. and M. Engelhardt, 2017. An equatorward force acting on large floating ice masses: Polfluchtkraft, Ann. Glaciol., **58** (74), 144-151.

Fricker, H.A., Young, Allison, Coleman, 2002. Iceberg calving from the Amery Ice Shelf, East Antarctica. Ann. Glaciol., **34**, 241-246

Gardner A.S., G. Moholdt, T. Scambos, M. Fahnstock, S. Ligtenberg, M. van den Broeke and J. Nilsson, 2018. Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. The Cryosphere **12**, 521-547.

Hamley, T.C. and W.F. Budd, 1986: Antarctic iceberg distribution and dissolution. J. Glaciol., **32** (111), 242-251.

Jacka, T.H. and A. B. Giles, 2007. Antarctic iceberg distribution and dissolution from ship-based observations. J. Glaciol., **53**(182), 341-356.

Jacobs, S.S., A.L. Gordon and J.A.L., Jr., 1979. Circulation and melting beneath the Ross Ice Shelf. Science, **203**, 441-443.

Jacobs, S.S, Hellmer, H.H., Doake, C.S.M., Jenkins, A. and Frolich, R.M., 1992. Melting of ice shelves and the mass balance of Antarctica. J. Glaciol., **38** (130), 375-387.

Klepsvik, J.O. and B.A. Fossum, 1980. Studies of icebergs, ice fronts and ice walls using side-scanning sonar. Ann. Glaciol., **1**, 31-36.

Kotlyakov, V.M., K.S. Losev and I.A. Loseva, 1978. The ice budget of Antarctica. Polar Geogr. Geol., **2**(4), 251-262.

Lichey, C. and H. H. Hellmer, 2001. Modeling giant-iceberg drift under the influence of sea ice in the Weddell Sea, Antarctica. J. Glac., **47** (158), 452-460

Liu Y, J.C. Moore, X. Cheng, RM. Gladstone, J.N. Bassis, H. Liu, J. Wen and F. Hui, 2015. Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves. Proceedings of the National Academy of Sciences of the United States of America. **112** (11), 3263-3268. DOI: 10.1073/pnas.1415137112.

MacAyeal D.R., M.H. Okal, J.E. Thom, K.M. Brunt, Y. Kim and A.K. Bliss, 2008. Tabular iceberg collisions within the coastal regime. J. Glaciol., **54**(185), 371-386.

Morgan, V.I. and W.F. Budd. 1978. The distribution, movement and melt rates of Antarctic icebergs. In: Husseiny, A.A. (ed.) Iceberg Utilization. Proceedings of the first international conference, Ames, Iowa, 1977. New York, Pergamon Press: 220-228.

Orheim, O., 1980. Physical characteristics and life expectancy of tabular Antarctic icebergs. Ann. Glaciol., **1**, 11-18.

Orheim, O. 1985. Iceberg discharge and the mass balance of Antarctica. In Polar Research Board, *ed. Glaciers, Ice Sheets and Sea Level: Effect of a CO_2-induced Climatic Change. Report of a workshop held in Seattle, Washington, September 13-15, 1984.* Washington, DC, National Academy Press, 210-215.

Orheim, O., 1986. Flow and thickness of Riiser-Larsenisen, Antarctica. Norsk Polarinstitutt Skrifter, 167, 5-20.

Orheim, O., 1987. Evolution of under-water sides of ice shelves and icebergs. Ann. Glaciol., **9**, 176-182.

Rackow, T., C. Wesche, R. Timmermann, H.H. Hellmer, S. Juricke and T. Jung, 2016. A simulation of small to giant Antarctic iceberg evolution: Differential impact on climatology estimates. J. Geophys. Res. Oceans, 122, 3170-3190. (10.1002/2016JC012513.)

Reeh, N., 1968. On The Calving of Ice From Floating Glaciers and Ice Shelves. J. Glaciol., **7(**50), 215-232

Rignot, E., S. Jacobs, J. Mouginot and B. Scheuchl, 2013. Ice Shelf melting around Antarctica. Science, **341**, 266-270.

Rignot, E., J. Mouginot, B. Scheuchl, M. v d Broeke, M. J. v Wessem and M. Morlighem, 2019. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. PNAS, 116 (4), 1095-1103. DOI: 10.1073/pnas.1812883116.

Romanov, A.A., 1975. O razmerakh aysbergov v Vostochnoy Antarktike. (The size of icebergs in Eastern Antarctica. Sovetskaya Antarkticheskaya Expeditsiya. Informatsionnyy Byulleten', No. 87.

Romanov, Y.A., N.A. Romanova and P. Romanov, 2017. Geographical distribution and volume of Antarctic icebergs derived from ship observation data. Ann. Glaciol., **58**, 28-40.

Romanov, Y.A. and N.A. Romanova. 2018. Icebergs in the Southern Ocean and factors Defining Their Distribution. Russian Meteorology and Hydrology, **43** (3), 178-187.

Scambos, T., R. Ross, R. Bauer, Y. Yermolin, P. Skvarca, D. Long, J. Bohlander and T. Haran, 2008. Calving and ice-shelf break-up processes investigated by proxy: Antarctic tabular iceberg evolution during northward drift. J. Glaciol., **54**(187), 579-591.

Silva, T.A.M., G.R.Biggs and R.W. Nicholls, 2006. Contribution of giant icebergs to the Southern Ocean freshwater flux. J. Geophys. Res., **111**(C3), C03004. (10.1029/2004JC002843.)

Swithinbank, C., P. McClain and P. Little, 1977. Drift tracks of Antarctic icebergs. Polar Rec., **18**(116), 495-501.

Tchernia, P. and P.F. Jeannin, 1984. Circulation in Antarctic waters as revealed by iceberg tracks, 1972-1983. Polar Rec., **22**(138), 263-269.

Vinje, T., 1977. Drift av Trolltunga i Weddellhavet. Norsk Polarinstitutt Årbok, 1975, 251.

Tournadre, J., F. Girard-Ardhuin and B. Legrésy, 2012. Antarctic icebergs distributions, 2002–2010. J. Geophys. Res., **117** (C5),

Tournadre, J., N. Bouhier, F. Girard-Ardhuin, and F. Remy, 2015. Antarctic icebergs distributions 1992–2014. J. Geophys. Res. Oceans, **120**, doi:10.1002/2015JC011178.

Turner, J., W.M. Connolley, S. Leonard, G., J. Marshall and D.G. Vaughan, 1999. Spatial and temporal variability of net snow accumulation over the Antarctic from ECMWF re-analysis project data. Int. J. Climatol., **19**, 697-724.

Vinje T., 1980. Satellite-tracked iceberg drifts in the Antarctic. Ann. Glaciol., **1**, 83-87.

Wadhams, P., 1988. Winter observations on iceberg frequencies and sizes in the South Atlantic Ocean. J. Geophys. Res., **93** (C4), 3583-3590.

Warrick, R. and J. Oerlemans, 1990. Sea level rise. In Houghton, J. G. Jenkins and J. Ephraums, *eds. Climate change: the IPCC Scientific Assessment.* Cambridge University Press, 257-281.

Appendix A. The Blue Form.

The front page of the form.

ICEBERG OBSERVING PROGRAMME

Name of Ship:

Season and Country:

Elevation of Observing Platform:

The 1981 meeting of the SCAR Working Group on Glaciology endorsed an effort by the Norwegian Polar Institute to organize the collection of iceberg data through international collaboration. This form should be used on all ships traversing the oceans around Antarctica.

An iceberg is defined as: a large mass of floating or stranded ice of greatly varying shape, more than five metres above sea level, which has broken away from a glacier or ice shelf.

Please record the icebergs every six hours at the times of standard meteorological observations. More frequent observations may be made if convenient. Observations can be stopped when the ship is at the same location for longer periods.
Please start recordings on the first day after port departure, or after crossing 40 degrees S, even though no icebergs may be observed. Such zero observations are also of high value.
Record all icebergs irrespective of size, but make more detailed observations of the larger ones.
A rough estimate of numbers is adequate when many icebergs of the smallest group are present.
Note if possible also exceptional icebergs, or concentrations, observed between the regular recordings.
Page two of cover contains a guide to facilitate size determination.
Under “Comments”, include for example additional data on the larger icebergs, such as shape, and degree of tilt, or note the proportion of overturned icebergs. Please note if icebergs contain rock sediment. Please include information on visibility when limited.

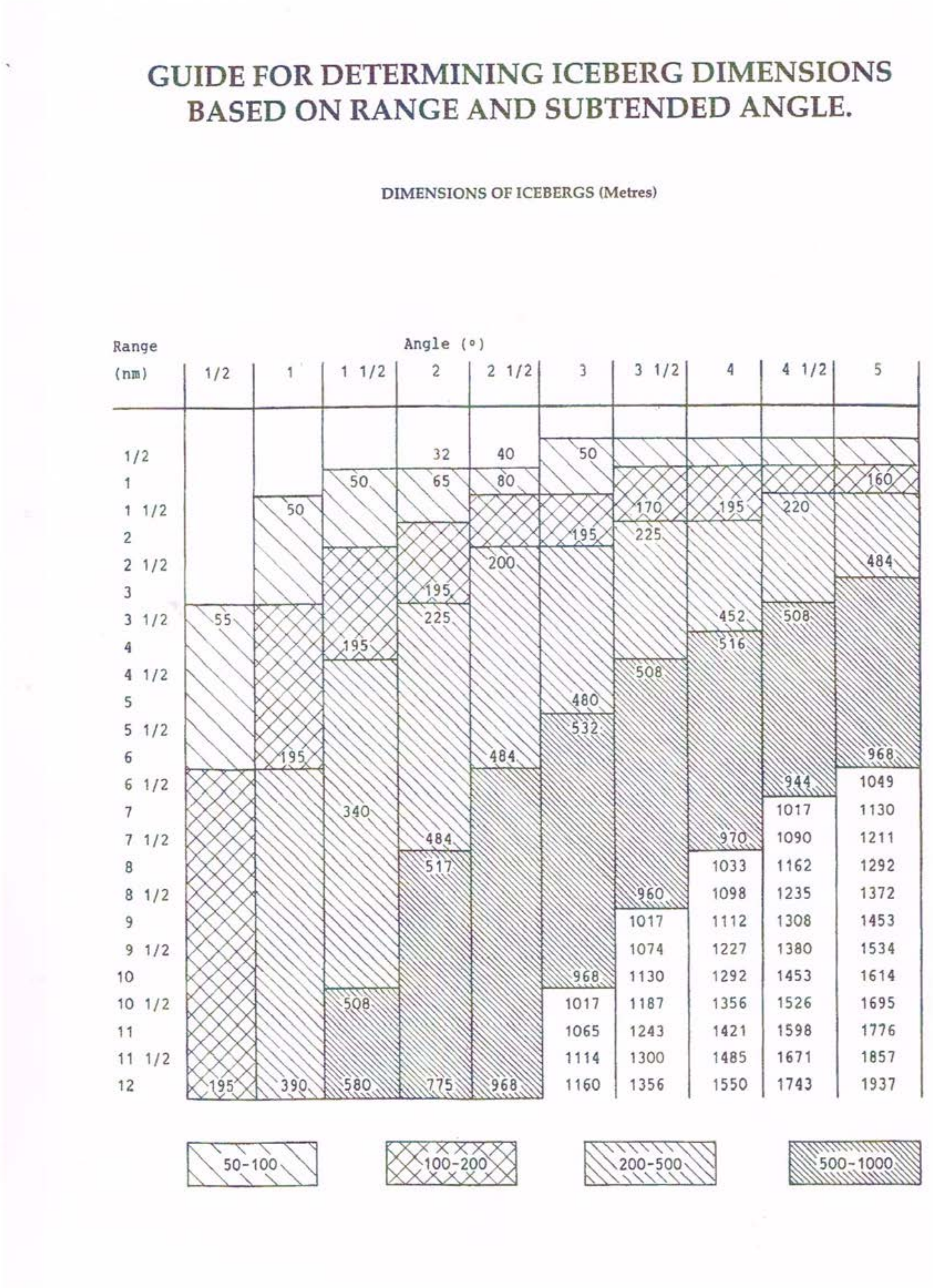
Two examples of how the form can be completed are found at the bottom of the last page.

Please return the form, with additional comments, to your national organizer, or to the address below:

Norwegian Polar Institute
Polar Environmental Centre
9296 Tromsø
Norway

P. 2 of the Blue Form

This was a guide to help the observer to quickly place the observed iceberg in the correct size class, based on horizontal dimension measured by sextant angle, and distance by radar.



Appendix B. List of all 68 contributing ships, altogether 233 ship records.

Season	No	Names of ship providing the iceberg data
2009/10	1	Ernest Shackleton
2007/08	1	Ernest Shackleton
2006/07	1	Polarstern
2005/06	2	Polarstern, Ernest Shackleton
2004/05	2	Polarstern, Agulhas
2003/04	4	Polarstern, Agulhas, Ernest Shackleton, Italica
2002/03	5	Polarstern, Agulhas, Ernest Shackleton, OGS Explora, Ary Rongel
2001/02	5	Polarstern, Agulhas, Ernest Shackleton, Italica, Ary Rongel
2000/01	7	Polarstern, Agulhas, Almirante Irizar, Italica, Ary Rongel, Hesperides, unnamed
1999/00	8	Polarstern, JCR, Shackleton, Shirase, Italica, Rongel, Gurruchaga, Deseado
1998/99	7	Polarstern, JCR, Almirante Irizar, Italica, Rongel, N B Palmer
1997/98	11	Polarstern, JCR, Irizar, Italica, Rongel, Palmer, Deseado, Bransfield, Endurance, Inach, Polo
1996/97	5	Polarstern, JCR, Italica, Bransfield, OGS Explora
1995/96	7	JCR, Irizar, Italica, Bransfield, Castillo, Puerto Deseado, Umitaka Maru
1994/95	6	JCR, Almirante Irizar, Italica, Bransfield, OGS Explora, Mikhail Somov
1993/94	7	Polarstern, Agulhas, Irizar, Italica, Hesperides, Africana, Barao de Teffe
1992/93	7	Polarstern, Agulhas, Irizar, Bransfield, Barao de Teffe, Gurruchaga, Polarbjørn
1991/92	7	Agulhas, Irizar, Bransfield, Barao de Teffe, JCR, Italica, Gondwana
1990/91	11	Polarstern, Irizar, Bransfield, de Teffe, Italica, Gondwana, Explora, Las Palmas, Aviso Irigoyen, Gurruchaga, Cariboo
1989/90	10	Irizar, Bransfield, Agulhas, Gurruchaga, Cariboo, Thuleland, Andenes, VIII Brazil Ant. Exp., Columbialand, Biscoe
1988/89	12	Irizar, Bransfield, Agulhas, Somov, de Teffe, Shirase, Arctica, Viese, Zubov, Barken, Biscoe, Alvaro Alberto
1987/88	15	Polarstern, Irizar, Bransfield, Agulhas, Somov, de Teffe, Shirase, Viese, Zubov, Paraiso, Finnpolaris, Camara, Bernard, Kaiyo, Polar Queen
1986/87	10	Polarstern, Irizar, Bransfield, Agulhas, Somov, de T, Viese, Paraiso, Glacier, Aurora
1985/86	10	Polarstern, Irizar, Bransfield, Agulhas, Zubov, Paraiso, Glacier, Endurance, Polar Star, Biscoe
1984/85	14	Irizar, Bransfield, Agulhas, Paraiso, Endurance, Disc, Myshevskij, Andenes, Rulegi, Sibex 2, Halley, Jantar, Kaiyo, unnamed
1983/84	17	Polarstern, Irizar, Bransfield, Agulhas, Endurance, Myshevskij, Shirase, Nella Dan, Somov, Viese, Paraiso, de T, P Sea, Nanok S, Kaiyo, H Maru, unnamed
1982/83	14	Bransfield, Agulhas, Nella Dan, Somov, Viese, Zubov, Nanok S, Franklin, P Pardo, Alcazar, Polar Circle, Polarbjørn, Hero, Biscoe
1981/82	9	Bransfield, Agulhas, Paraiso, Irizar, Fuji, Polar Queen, Polar Circle, Nella Dan, Nanok S
1980/81	4	John Biscoe, Nanok S, Nella Dan, Thala Dan
1979/80	3	Bransfield, Nella Dan, Thala Dan
1978/79	7	Bransfield, Agulhas, Polarsirkel, Yelco, Nella Dan, Thala Dan, unnamed
1976/77	1	Polarsirkel

Key to abbreviated names:
Deseado=Puerto Deseado, JCR= James Clark Ross, Polo=Marco Polo, Rongel=Ary Rongel, Franklin= Lady Franklin, Viese=Professor Viese, Somov=Mikhail Somov, Zubov= Professor Zubov, Castillo=Aviso Subof Castillo, Irizar=Almirante Irizar, Paraiso=Bahia Paraiso, Camara= Almirante Camara, Bernard= Prof W. Bernard, Kaiyo=Kaiyo Maru, Disc=Discovery, Myshevskij=Kapt. Myshevskij, Rulegi=Kaiyo Rulegi, Halley=Depot Halley, de T= Barao de Teffe, P Sea=Polar Sea, H Maru=Hakuho Maru, P Pardo=Piloto Pardo, Alcazar=Capitan Alcazar, Biscoe=John Biscoe.
In three cases forms were sent in without information on the name of the ship.

Appendix C. Area of grid box measuring 1° latitude x 5° longitude

Range °lat.	Area km²
40-41	46949
41-42	46242
42-43	45521
43-44	44786
44-45	44038
45-46	43276
46-47	42501
47-48	41712
48-49	40912
49-50	40098
50-51	39273
51-52	38435
52-53	37586
53-54	36726
54-55	35854
55-56	34971
56-57	34078
57-58	33174
58-59	32260
59-60	31336
60-61	30403
61-62	29461
62-63	28509
63-64	27549
64-65	26581
65-66	25604
66-67	24619
67-68	23628
68-69	22628
69-70	21622
70-71	20610
71-72	19591
72-73	18566
73-74	17535
74-75	16500
75-76	15459
76-77	14413
77-78	13363
78-79	12309

Areas are calculated as 5/360 of circular annulus ring area computed from differences of ‘cap’ area of sphere at each latitude. Earth radius taken as 6367 km (half the polar plus equatorial radius).

Appendix D. Reality-check of the year-to-year variations.

To have confidence in the data it seems prudent to scrutinize the database to see whether the large year-to-year differences can be ascribed to variations in ship tracks. Table 4 demonstrates two main types of differences. The average number of icebergs per observation have for most years been in the range 10-15, but with a variation from 7.5 to 21.3. There are also large differences in size distribution between the years, even in those cases when large numbers of icebergs have been observed.

However, some of these records are from a few cruises only, and with small numbers of icebergs observed. For a reality-check it is most critical to look at the records with many observations. Table 11 shows the results from all the seasons in which more than 10 000 icebergs have been observed.

	No.	No.	Bergs/	by	Bergs	% of each size class				
Season	obs.	bergs	obs.	size	10-50	50-200	200-500	500-1000	>1000	
2006/07	757	14538	19.2	13712	49.7	31.8	13.6	4.1	0.8	year, April-March
2002/03	828	10659	12.9	9700	49.2	34.6	12.6	3.0	0.6	summer+June, July
2000/01	956	15241	15.9	13004	43.3	29.3	18.2	7.2	2.1	summer, incl. May
1997/98	1631	19027	11.7	16594	40.9	32.4	16.0	6.9	3.8	summer+May-July
1995/96	537	13817	25.7	12599	54.5	31.2	10.0	3.4	0.9	summer
1994/95	916	10340	11.3	8926	26.0	32.4	24.3	12.9	4.4	summer, incl. May
1993/94	654	10398	15.9	4969	35.5	34.3	20.0	8.0	2.1	summer
1988/89	1212	15225	12.6	10953	25.2	37.5	26.3	8.4	2.6	summer, incl. Oc. May
1987/88	1782	24332	13.7	19374	39.1	34.1	17.5	7.4	1.8	summer
1986/87	1391	24161	17.4	22451	38.5	33.8	18.1	7.3	2.2	summer
1985/86	1197	13533	11.3	11349	39.0	32.2	19.0	7.2	2.6	summer
1984/85	1569	12313	7.8	9925	39.0	34.2	18.9	6.4	1.5	summer, some Oct.
1983/84	2345	31740	13.5	24831	34.4	30.6	20.8	10.6	3.6	summer
1982/83	1001	13780	13.8	10735	26.3	34.3	26.1	9.5	3.7	summer, some Oct.

Table 11. The years with more than 10 000 observed icebergs.

Among these, the records from 1984/85 and 1995/96 are the most extreme in relation to numbers of icebergs per observation, while 1994/95 and 2002/03 are the outliers with regards to proportion of the largest icebergs. Deeper examinations illustrate that these differences can primarily be ascribed to differences in the cruises, primarily in location:

Comparing 1984/85 and 1995/96.

The 1569 observations made during the 1984/85 season were from fourteen ships of which only five operated in the Antarctic Peninsula, a very different proportion from 1995/96, when the records were from seven vessels of which five operated in the Peninsula area of high iceberg concentrations. These differences in cruise locations are a major reason why the iceberg concentrations are so different.

Comparing 1994/95 and 2002/03.

The high proportion of icebergs >1000 m, 4.4%, can be ascribed to observations from a single cruise of *Almirante Irizar* in 1994/95. Its records showed especially high numbers of large bergs at the northern end of the Antarctic Peninsula, where it made repeated visits months apart. This is an area famously known as “iceberg alley”, because at times many spectacularly large icebergs are seen here coming out of the Weddell Sea. This particular cruise spent much time here, and perhaps observed unusually many large icebergs resulting from calving events further south. Possibly the observer exaggerated sizes, however the records show that (s)he also frequently recorded zero and small bergs. It seems reasonable to explain the deviations as a result of the time spent in the area.

The 2002/03 records, on the other hand, contain relatively few observations from the Antarctic Peninsula, where only one of the five ships were working. The bulk of the observations are from cruises travelling fairly directly between Cape Town and stations on the coast of Dronning Maud Land, spending little time in the areas of known high concentrations of large icebergs.

Looking at other years confirms that the differences in iceberg statistics can mainly be accounted for by differences in location of the cruises.

On the overarching level, the time of observation seems less important. This can be illustrated by sorting the statistics by month of registrations, as shown in Table 5.

Looking at the variations with seasons, the immediate impression is that the differences in size distribution are small, and that the differences in iceberg density are the opposite from what could be expected. The number of icebergs per observation is e.g. lowest in winter, June-September, when the ocean is coldest and melting of icebergs is lowest, and thus the highest numbers of icebergs could be expected if the iceberg production was steady throughout the year. As discussed previously, inspection of the records shows that the main reason for the low densities is again one of location. It is simply that the extensive sea ice in winter forces the cruise tracks much further north than for the summer observations. There are very few overlaps in location for different seasons in the southernmost parts of the Southern Ocean.

The differences in location are also the main cause for the apparent paradox that the “winter” observations (May-September) show no significant difference in frequencies of sizes from the summer observations (December to March). In reality, the grid boxes with many observations for different parts of the year clearly show a decrease in iceberg frequencies and sizes through the summer period, in the same manner as shown by Jacka and Giles (2007).

Appendix E. Estimate of annual iceberg calving events from Antarctica.

It has been shown in previous sections that the waters around Antarctica contain ~132 000 icebergs of which ~41000 are in the coastal zone and have ~2.5 years residence time, with one year for the outer ocean. The icebergs recorded here reflect the original calved icebergs, modified by attrition and breakage and by export into more northern waters, and from these numbers an annual calving rate of ~105 000 icebergs (90 000 + 41 000/2.5) can then be derived. The following is a rough calculation to check how these numbers accord with what can be expected from the considerations of glacier physics.

The calving glaciers along the Antarctic Peninsula are mostly grounded and produce icebergs mostly <200 m, thus differing from the rest of Antarctica. This area is a prolific source of these small icebergs, having thousands of glaciers that terminate in the sea and a complex topography. Very few of these glaciers have been studied, and there are little direct data on velocities, thicknesses or calving rates. Some have low velocities and calve perhaps at intervals of months. Others may calve every day, as indicated by warnings of glacier-caused "tsunamis" to small boats and shore parties in tourist site descriptions issued by the International Association of Antarctic Tour Operators (IAATO).

For the present discussion the average ice-front velocity of the Antarctic Peninsula glaciers is taken as 100 m a^{-1}, and the calved icebergs taken to be 100 m in all three dimensions. Taking the length of glacier fronts in the Peninsula to be 5000 km means that 50 000 icebergs annually calve from this region.

Along the remaining perimeter of the Antarctic continent the glaciers are seldom confined by exposed rock, but are made up of pinning ice rises and ice shelves. The ice rises, where the ice is grounded, have typically a width on the order of 10 km. The grounded ice is affected by sea-induced stresses, so that the calvings from the ice fronts do not normally produce large tabular icebergs. For this discussion, the icebergs from grounded ice fronts are considered to average 250 m in three dimensions, flowing seawards with an average velocity of 50 m a^{-1}. Taking 10 000 km to be the length of the grounded ice fronts, these then produce 8 000 icebergs annually.

The icebergs that calve from ice shelves show much larger variation in size and frequency. To a considerable degree, the frequency of calvings is related to the presence of crevasses, which in turn in part depends on the width of the ice shelf and the length of time it takes to travel from the inner grounding line to the ice shelf front. The longer this is, the longer time will the ice shelf have to "heal" the crevasses formed by upstream inland flow disturbances or by tidal and other effects at the grounding line, as demonstrated by the low calving frequencies of the Filchner/Ronne and Ross ice shelves. From any ice shelf, tabular icebergs break off in sizes with a minimum length of a side the same as the thickness, i.e. 250-300 m, but many are much larger. Some ice shelves, e.g. Stancomb-Wills Ice Tongue, produce relatively small tabular bergs. One reason for this can be internal weaknesses originating from the grounding line, which have not been "healed" in the subsequent multiyear flow towards the coast (Orheim, 1986).

For the present estimate, the average upper-surface size of icebergs calving from ice shelves is taken as 500 m x 1000 m with the long side parallel to the ice front, and having an annual velocity of 250 m a^{-1}. Floating ice shelves extending 38 000 km will then annually produce 19 000 icebergs.

The total annual number of Antarctic iceberg calvings will then be approximately 80 000, which is in reasonable accordance with the statistics in this iceberg database. Without any major changes in ice discharge, these calvings should be independent. With around 10^5 calvings annually, the statistics of large independent events indicate there is no *a priori* reason to expect any annual variation in such iceberg calvings from the Antarctic continent.