

# AUTOMATIC COLLECTION OF TILT AND STRAIN DATA FROM TABULAR ICEBERGS

by

Monica Kristensen and Vernon A. Squire

(Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, England)

## ABSTRACT

Drift tracks of Antarctic tabular icebergs have been studied by means of satellite-tracked buoys since the early 1970s. More recently, a growing interest in the possibility of using Antarctic icebergs to supply fresh water to arid areas has made resources available for more sophisticated experiments, and in 1978 three prototype stations were designed to measure interactions between tabular icebergs and the ocean. These stations were deployed in late 1979, and in early 1981.

The purpose of this paper is, firstly, to communicate some of our experiences with an earlier type of automatic data collection platform, and, secondly, to show that the substantial amount of tilt and strain data available from this station is unsuitable for data analysis. We discuss aspects of the data collected by the first of the three automatic stations, paying particular attention to the quality of the recorded strain and tilt data. It is shown that an unfortunate choice of instrument sensitivity and range severely limits the usefulness of the collected data, and that limitations in the data sampling regime make data analysis by conventional statistical methods very difficult. Several changes are proposed for the design of future data collection platforms for tabular icebergs, and some suggestions are made about data sampling. As this paper only concerns iceberg research, we do not discuss investigations of sea-ice drift made in the same area.

## 1. INTRODUCTION

During the last ten years several oceanographic studies in the Southern Ocean have been made using radio beacons placed on Antarctic tabular icebergs. Early experiments were conducted by French scientists from 1972 to 1974, and the research was continued during 1975 to 1977 and in 1980. The main purpose of the French programme of research was to investigate the East Wind Drift (Tchernia 1974, 1977, 1980[pub. 1981], Tchernia and Jeannin 1980). Studies of the large Weddell Sea gyre in the Atlantic sector of the Southern Ocean have been made by Norwegian scientists using similar techniques from 1978 to 1979 and onwards (Vinje 1979, 1980).

In the late 1970s, research on tabular icebergs focused on their break-up along the Antarctic coast. This new initiative was largely due to the interests of several countries with a demand for fresh water, e.g. Saudi Arabia, who made resources available for feasibility studies and research into iceberg towing. Thus, rather than using the tabular icebergs as platforms to study oceanographic factors, the behaviour

of the icebergs themselves and their interactions with the ocean became topics of interest. In 1978 the Iceberg Transport International Co Ltd ordered three automatic data collection platforms from the Christian Michelsen Institute in Bergen, Norway. These prototype stations were designed to measure motion characteristics of tabular icebergs in a sea-way by recording meteorological, dynamic and geophysical parameters. The first of these stations (Identification Code 1080) was deployed by the Norwegian Antarctic Research Expedition (NARE) in 1978 to 1979. This station transmitted data for well over a year, while the second station (Identification Code 1081), deployed late in 1979 by Norwegian scientists on a German expedition to the Weddell Sea area, failed after a few months. Some modifications in the data sampling were made to the third station. It was placed on a tabular iceberg near the South Sandwich Islands in January 1981, but unfortunately failed soon after deployment. No meaningful tilt and strain data were therefore transmitted from this station. A fourth station (Identification Code 1588), with substantial changes in its design, was financed by Norsk Polarinstitutt, Oslo, and was deployed on a British-Norwegian expedition in January 1982. All the Norwegian-built stations transmit data through the TIROS N satellites and the ARGOS data collecting system. In order to distinguish these larger iceberg stations from positioning buoys and radio beacons, they have been described in the literature as automatic data collection platforms. Figure 1 shows the region of deployment and the drift track for station ID 1080. The data discussed in this paper are from this station.

## 2. DESIGN AND DEPLOYMENT

The automatic data collection platforms were built to measure the following parameters: barometric pressure, wind speed and direction, air and snow temperatures, iceberg heading, iceberg roll-and-pitch motions (tilting), and iceberg surface strain. The range and resolution of the corresponding sensors are given in Table I. The stations were positioned as close as possible to the centres of the surfaces of the icebergs. One of the axes of the tiltmeter and the strainmeter were aligned with the long axis of the iceberg. The other tilt axis was orthogonal to this direction. In the case of station ID 1080, the strainmeter was anchored with tubes 2 m long sunk into a trench approximately 2 m deep at the time of deployment. The battery container with the tiltmeter was placed in a drilled hole, so that the tiltmeter was level with the surface. The iceberg on which ID 1080



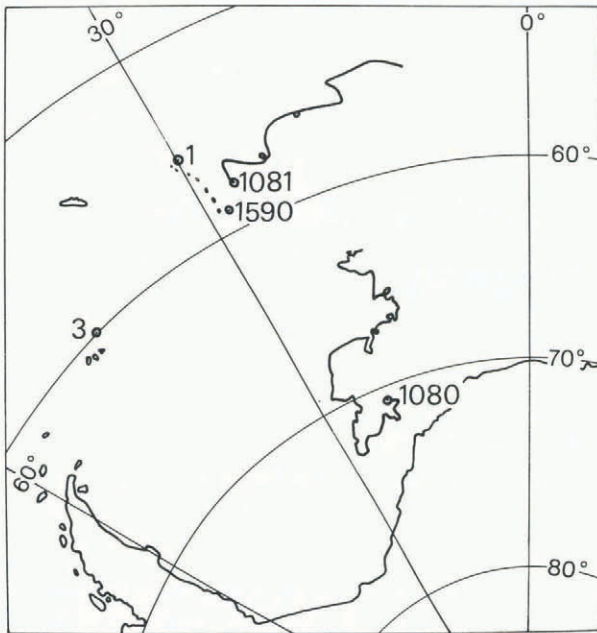


Fig.1. Position of deployment and subsequent drift of platform ID 1080, placed on a tabular iceberg in the Weddell Sea area (after Orheim and others 1982).

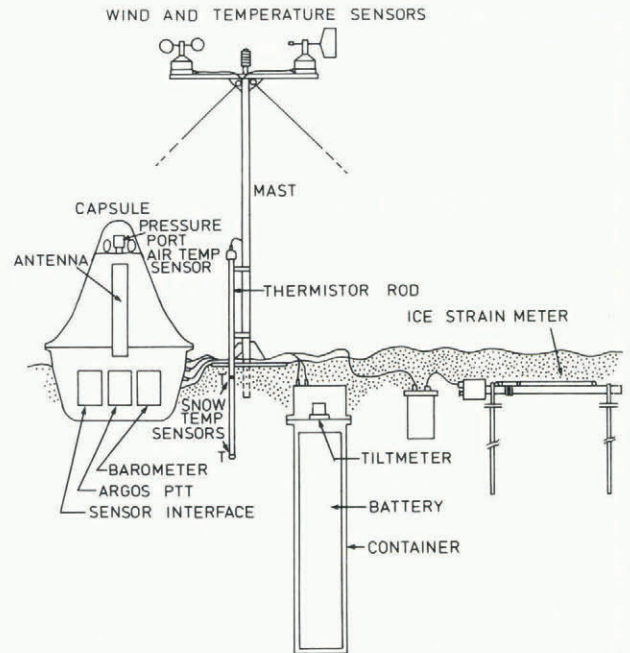


Fig.2. Different sensors employed in the automatic stations, and their relative positions after deployment (after Bø and others 1979).

was deployed was 1 030 x 900 m in area with a free-board of 34 m and an estimated thickness of 210 m (Vinje 1980). Figure 2 shows the layout of the stations after deployment on the icebergs (after Bø and others 1979). Details relating to oceanography have already been described in the literature (Vinje 1980), and in this paper we concentrate on specifications of the recording instruments associated with the dynamic behaviour of the tabular icebergs.

2.1. Tilt measurements

A Singer-Kearfott tiltmeter was used to measure the roll and pitch of the iceberg. It consisted of an electrolytic vertical sensing element which detected angular displacement about two horizontal orthogonal axes to a resolution of  $3.5 \times 10^{-5}$  rad ( $0.12'$ ) within a range of  $\pm 4.4 \times 10^{-3}$  rad ( $15'$ ). The sensor was mounted on a levelling platform of the type normally used for theodolites, and did not have automatic re-zeroing facilities. Recent in situ measurements of roll on icebergs of different dimensions show that average tilt amplitudes are between  $10^{-5}$  and  $10^{-3}$  rad (Foldvik and others 1980, Kristensen and others 1981, 1982). This tiltmeter could therefore not resolve roll and pitch accurately

in all cases, and would undoubtedly suffer ranging problems should a slight change in the mean level occur. Unfortunately such a change could easily be produced by settling, since it is only necessary for the theodolite plate to tip by 1 mm for the instrument to drift out of range. Over-ranging could also be caused by changes in equilibrium due to ice calving off the edges of the berg. We shall return to these problems in section 4.

2.2. Strain measurements

A rod strainmeter was used to measure surface strain. It was similar to an earlier design by Goodman (unpublished), which was developed jointly by the Cavendish Laboratory and the Scott Polar Research Institute, University of Cambridge. The strainmeter comprised a 1 m invar rod fixed at the passive end to a mounting plate and at the active end to the core of a linear variable differential transformer (LVDT). Its resolution on maximum gain was 0.1 microstrain, and its effective range was  $\pm 6\ 000$  microstrain since the instrument will automatically re-zero should the measured signal drift over a preset limit. It has been shown that this type of strainmeter has a negligible heave response,

TABLE I. SENSOR PERFORMANCE ON AUTOMATIC DATA COLLECTION PLATFORM ID 1080 (from Bø and others 1979)

Sensor	Range	Resolution
Barometric pressure	920 to 1050 mb	0.127 mb
Wind speed	0 to 136 knots	0.53 knots
Wind direction	0 to 360 degrees	1.41 degrees
Iceberg heading	0 to 360 degrees	1.41 degrees
Temperatures	-30 to +20°C	0.20°C
Tilt (both axes)	-15 to +15 arc min	0.12 arc min
Strain	12 mm	0.1 m



i.e. the error in measured strain caused by the heaving motion can be ignored (Moore and Wadhams 1980). Strain in the range of 0.01 to 1.0 microstrain, has been measured on Antarctic tabular icebergs, although the latter value is rare (Kristensen and others 1982). The range of the instrument should therefore be sufficient, but the resolution is marginal and depends on the amplitude of the forcing ocean waves. Settling of the instrument will not interfere with the short-term cyclic surface strain records. The metal invar was chosen for the rod in the strainmeter because of its low coefficient of thermal expansion ( $0.9 \times 10^{-6}$  per  $^{\circ}\text{C}$  but subject to slight variation with temperature). This means that strain experienced by the instrument due to a change of  $0.1^{\circ}\text{C}$  in the invar rod is of the same order of magnitude as the resolution. We shall return to this point in section 5.

2.3. Data sampling

The measuring sequence on station ID 1080 was repeated every 3 h. Tilt and strain sensor signals were sampled 20 times at intervals of 6 s, thus giving a record lasting 114 s. Data were automatically transmitted and were relayed by one of the two TIROS N satellites as it passed overhead. The orbits of the satellites did not allow data transfer at regular intervals of 3 h so that sometimes data were repeated, while at other times there were gaps of up to 10 h. Figure 3 shows typical records of strain and tilt.

3. ANALYSIS OF VERY SHORT DATA RECORDS

The sampling pattern for tilt and strain data clearly poses serious problems for any statistical analysis. In this section, we shall compare a method

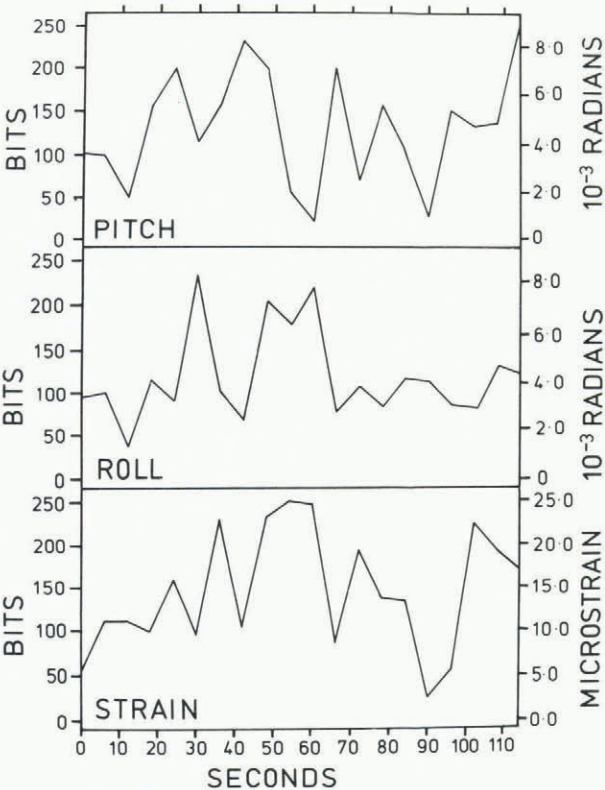


Fig.3. Examples of short records of pitch, roll and strain. The magnitudes of the pitch and roll motions in this illustration are particularly large compared with most of the recorded data.

of analyzing the short data records separately with an alternative approach which involves joining each short sample to the next to form a long time series.

3.1. Record response periods

A preliminary statistical analysis of the first data on tilt and strain received from automatic station ID 1080 was carried out by Kristensen and Orheim (1980). This analysis used mean periods of response to derive histograms from which the resonant periods of each iceberg could be inferred.

Assuming that each single record represents the mean response of the iceberg, it is possible to calculate a mean response period by counting the number of times the segments between data points cross the mean line in an upward direction. The total length of the record (114 s) is divided by this number to obtain the record response period (RRP). The RRP's of a large number of records then give a distribution of response periods which is indicative of the interaction between the iceberg and its environment. It is important to note that although the starting point of this method of analysis is the same as the method used by Tann (1976) to analyse short wave records, the data records are too short to develop the method further. Indeed the records consist of so few data points that it is meaningless to talk about distributions of data maxima. It is therefore not possible to calculate expected extreme values from the RRP's. The distributions of RRP's for tilt along two axes and for surface strain is shown in Figure 4. The usefulness of this method of analysis suffers because the cyclic variations are below the resolution of the instruments. This problem is particularly serious for the tilt results, where the consistent occurrence of response periods of 114 s in the distributions indicates that the amplitudes of cyclic motion are too small to be detected by the instruments.

3.2. Time series from joined-up records

Another approach to the analysis of the tilt and strain records is to join many records together and calculate distributions of response maxima. Several objections can be raised against this method. Firstly, it tacitly assumes that the environmental conditions remain the same from record to record (stationarity). Since the data are recorded at intervals of at least 3 h, it is very likely that the forcing from the ocean waves will not remain constant but will change between records. The data segments are too short for a stationarity test to be carried out. Secondly, a number of random jumps in both magnitude and phase will be introduced in the data due to changes in the mean value from record to record, and variations in the phase at the start of each new sample. Although steps in the mean level can be removed numerically with little difficulty, phase discontinuities are more problematic and cannot be dealt with effectively without creating or destroying data points. This is out of the question since only a few cycles of roll, pitch and strain data make up each transmitted record. A third objection to this method of analysis is in its final interpretation. Probability density functions (PDF) of roll, pitch and strain are shown in Figure 5. Since none of the histograms follows a Gaussian distribution, the PDF's of their maxima with respect to the mean line will not be Rayleigh-distributed. This implies that any application of extreme value statistics to predict behaviour at some later time will be considerably more complicated.

3.3. Aliasing

A final comment which is relevant to both of the above methods of data analysis is the problem of aliasing. It is not clear from the work of Bø and others (1979) whether the proposed 4 s Butterworth filter was implemented on both the tilt and strain sampling. However, since the Nyquist frequency of the sampling scheme is 0.083 Hz (12 s) and periods of roll and strain down to 6 s have been observed during in situ experiments, aliasing problems will occur in either case.



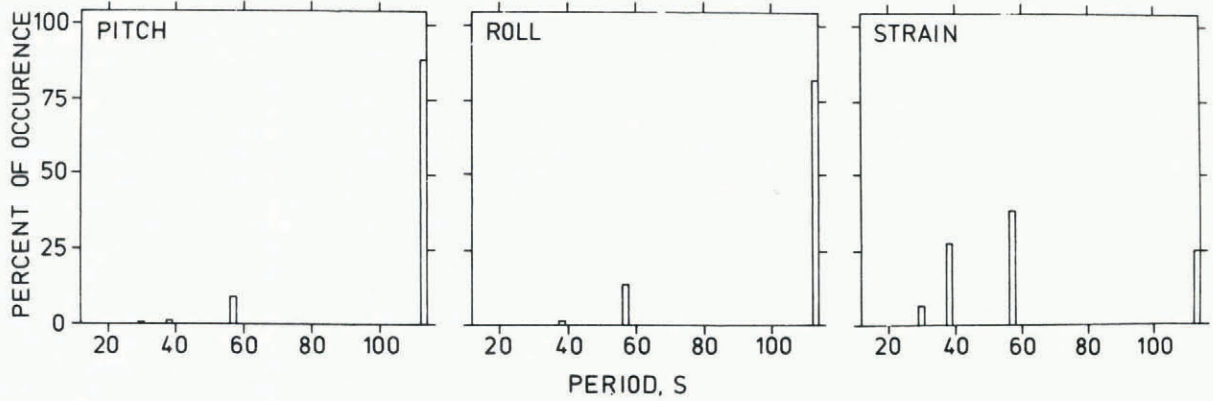


Fig.4. Histograms showing distributions of RRP's of pitch, roll and strain motions for the period 4 to 27 February 1979.

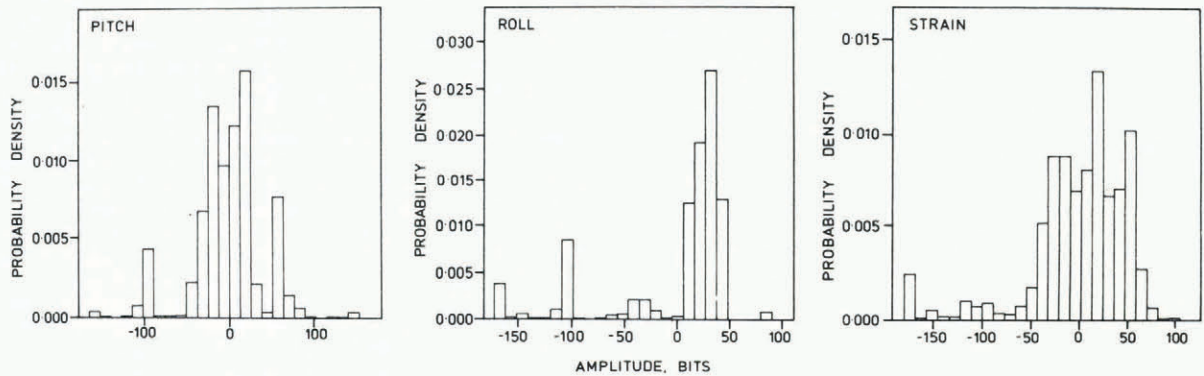


Fig.5. PDFs for pitch, roll and strain for comparison with Gaussian distribution.

4. LONG-TERM TRENDS IN THE MEASUREMENTS

We now return to the possibility of analysing trends in the data records. A feature of immediate interest concerns the use of mean values of tilt and strain records to reveal new information on the break-up of icebergs. In the following we show that due to some unfortunate choices in the design of the station, long-term trends in the data are unlikely to be directly connected to large-scale fracture problems. However, some events in the tilt data could be related to the calving of small pieces from the sides of the iceberg. In the data available from station ID 1080 (4 February 1979 to 10 March 1980) the mean values of tilt along both axes of symmetry of the iceberg show major changes on two occasions (Fig.6). Firstly, on 24 February 1979, both tilt trends jumped by approximately 0.002 rad. If this event was caused by changes in stability due to localized calving from the sides, a mass of  $2 \times 10^6$  kg would be necessary to produce a jump of this magnitude. With vertical dimension equal to the freeboard and assuming that the ice calved from a corner, this would imply that the ice falling from the berg had sides of approximately 25 m. Other events in the trends of the tilt data seem to indicate that much smaller pieces of ice frequently calve off the sides. The second major change occurred from 25 January 1980 onwards, when the mean value of tilting along both axes showed considerable variation. The cause of this variation is likely to be settling of the instrument rather than changes in equilibrium due to significant ablation of the iceberg at its sides, as substantial melting undoubtedly occurs at the upper surface of the iceberg (Fig.6(b)). In Figure 6(b) the temperature curves of the sensors T3 and T4, originally

buried at 0.3 and 0.7 m under the surface, are plotted alongside the corresponding tilt records. Both sensors show clear diurnal variations. Comparing these with the larger amplitudes of the sensor T2, originally buried at the snow surface, we thus infer that sensor T3 is now close to the new surface of the iceberg. It is reasonable to assume that approximately 0.5 m or more of the battery capsule and tiltmeter now protrude from the surface, and that the upper surface layers of firn and ice surrounding the capsule are soaked with meltwater so that considerable settling is occurring. It is probably impractical to bury the tiltmeter at a greater depth, and the only real solution to temperature-induced settling is to employ a tiltmeter with a re-zero facility.

Large variations in the mean values of strain from each short record are observed throughout the year, and re-zero events are common. However, the strainmeters used in the automatic stations were designed to measure short-term cyclic strains and not the long-term strains associated with gradual plastic flow and creep. There are two serious drawbacks in attempting to interpret the gradual change in mean drift as an indication that ice deformation is occurring. The first is the temperature dependence of the instrument itself which is considerable even for small changes in temperature. The second is the expansion and contraction of the ice with temperature. This latter effect is so large that a change in temperature of only  $0.02^\circ\text{C}$  can give rise to a thermally induced strain of  $10^{-6}$ . Although the thermal conductivity of ice is small, temperature variation of this order is likely, especially when the ice begins to melt in the austral summer and the strainmeter effectively becomes nearer to the upper surface.



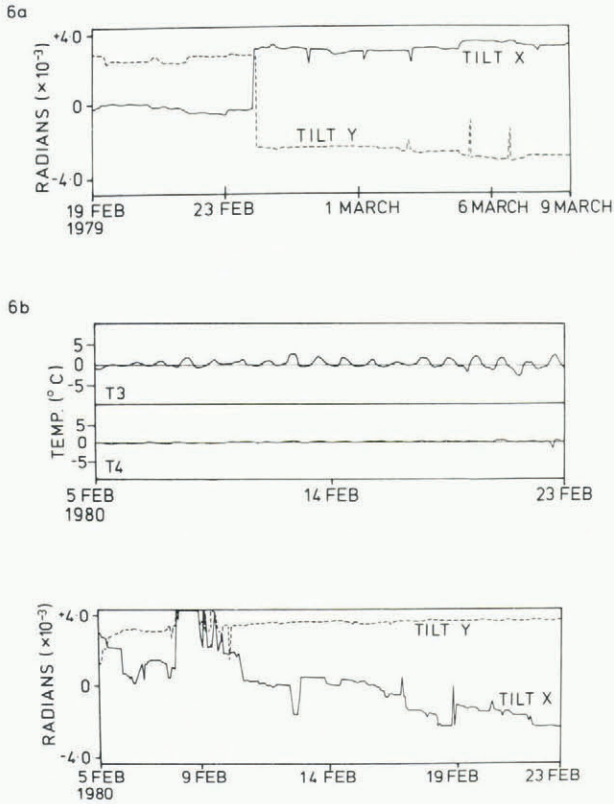


Fig.6. Examples showing large tilt variations seen on two occasions during the life of station ID 1080. (a): an event occurs in both trends on 25 February 1979. (b): the tilt variations and the temperature records from sensors T3 and T4 from 5 to 23 February 1980. (Figure redrawn from data obtained from Norsk Polarinstitutt, Oslo.)

## 6. CONCLUSIONS

Due to the inaccessibility of Antarctic tabular icebergs and the cost of research in these remote parts of the world, automatic data collection platforms are important tools of investigation. However, several design features of the prototype stations have severely limited the usefulness of the collected data. In this article we have discussed these shortcomings and have suggested possible improvements. These suggestions are summarized as follows:

- (i) The tiltmeter should include a re-zeroing facility. Its resolution could then be made better, and problems of the tiltmeter drifting out of range could be avoided.
- (ii) Tilt and strain data should be sampled more frequently and for longer periods. We suggest a sample interval of 2 s over a period of 12 min. Obviously such long records of data will be expensive to transmit in terms of satellite time, and the recording of other parameters would have to be limited. The new station ID 1588 has substantial changes in its design along these lines (personal communication from O Orheim 1982).
- (iii) It is essential that the tilt and strain data are filtered before sampling. Filtering digital data afterwards will not remove aliasing errors.
- (iv) A new high resolution strainmeter (Moore and Wadhams 1980) could replace the rod strainmeter used in station ID 1080. This instrument has now been deployed as part of an automatic station with an amended sampling scheme and low pass filter. First indications are that the deployment was successful.

The data from automatic stations are crucial to understanding the behaviour of Antarctic tabular ice-

bergs over a long period of time. Indeed, in many areas they are the only means by which the iceberg can be studied during the Antarctic winter. A second generation of automatic data collection platforms would therefore be invaluable to a complete understanding of the behaviour of an iceberg at sea.

## ACKNOWLEDGEMENTS

We acknowledge the helpful criticisms of Dr Olav Orheim, Torgny Vinje and Stuart Moore in preparing this paper, and the skills of Rob Massom in drawing the figures. One of us (MK) is a research student supported by the British Council.

## REFERENCES

- Bø R, Markussen J, Strømme J 1979 *Iceberg data collection stations. Technical Report*. Bergen, Chr. Michelsen Institute (Report CMI No. 78121-1)
- Foldvik A, Gammelsrød T, Gjessing Y 1980 Measurements of oscillations and flexure of icebergs. *Annals of Glaciology* 1: 29-30
- Goodman D J Unpublished. Creep and fracture of ice and surface strain measurements on glaciers and sea ice. (PhD thesis, University of Cambridge, 1977)
- Kristensen M, Orheim O 1980 Preliminary results from an instrumented iceberg in the Antarctic. *Annals of Glaciology* 1: 96
- Kristensen M, Orheim O, Wadhams P 1981 Field experiments on Antarctic tabular icebergs. *Polar Record* 20(128): 445-448
- Kristensen M, Squire V A, Moore S C 1982 Tabular icebergs in ocean waves. *Nature* 297(5868): 669-671
- Moore S C, Wadhams P 1980 Recent developments in strainmeter design. *C-CORE Publication* 80-21 [Also published in *Scott Polar Research Institute. Sea Ice Group. Technical Report* 81-2]
- Orheim O, Wadhams P, Kristensen M 1982 Iceberg response to sea state. *Iceberg Research* (Cambridge) 1: 10-15
- Tann H M 1976 The estimation of wave parameters for the design of offshore structure. *Institute of Oceanographic Sciences* (Taunton, Somerset). *Technical Report* 23
- Tchernia P 1974 Etude de la dérive antarctique est-ouest au moyen d'icebergs suivis par la satellite Eole. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* (Paris) Sér B 278(14): 667-670
- Tchernia P 1977 Etude de la dérive antarctique est-ouest au moyen d'icebergs suivis par la satellite Eole. In Dunbar Maxwell J (ed) *Polar oceans. Proceedings of the polar oceans conference, Montreal 1974*. Calgary, Arctic Institute of North America: 107-120
- Tchernia P 1980 [pub.1981] Observations of the Antarctic East Wind Drift current by using tabular icebergs tracked by satellite. *Antarctic Journal of the United States* 15(5): 83
- Tchernia P, Jeannin P F 1980 Observations on the Antarctic East Wind Drift using tabular icebergs tracked by satellite NIMBUS F (1975-1977). *Deep Sea Research* 27A(6): 467-474
- Vinje T E 1979 On the drift ice conditions in the Atlantic sector of the Antarctic. In *POAC 79: the fifth International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, Norway, 1979. Proceedings Vol 3*: 75-82
- Vinje T E 1980 Some satellite-tracked iceberg drifts in the Antarctic. *Annals of Glaciology* 1: 83-87