Kedging as a Means of Directing Iceberg Drift.

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Several of the largest tabular icebergs ever witnessed calved from the Ross and Ronne ice shelves of Antarctica during 2000[1]. Their initial dimensions were colossal, with areas ranging between 2,000 and 11,000 km^2, and lengths ranging between 100 and 300 km. The appearance of such mobile packages of pure, fresh water adrift in the ocean renews interest in the possible utilization of icebergs as a means to address the shortfall of fresh-water resources around the globe. Here we report results of a first year of iceberg-drift monitoring using automatic weather stations (AWS) and global positioning system (GPS) receivers affixed on B15A, a 4,000 km^2 iceberg that calved from the eastern Ross Ice Shelf in March, 2000. Our data show how rigid-body collisions between B15A and island coasts, ice shelves, other icebergs and the sea bed, control the iceberg's drift in spite of winds and currents that tend to drive it elsewhere. We term the new mechanism of iceberg-drift control 'kedging' after the nautical term used to describe how sailing ships of yore were manipulated through calms through judicious use of a kedge anchor.

The release of icebergs is a normal ablation process that reconfigures seaward fronts of the Ross and Ronne ice shelves and maintains mass balance of the Antarctic ice sheet. The historical record of iceberg calving is short compared to the frequency of such events[2], thus it is impossible to say whether the gigantic icebergs of Y2k signify permanent changes in the Antarctic ice sheet. Even so, scientific interest in the new icebergs is marshaled by the opportunity to examine how icebergs of this size manage to move about the Southern Ocean from their points of origin on Antarctica's continental shelves to their points of disintegration and melting within, presumably, the Antarctic convergence, well North of the continent[3,4].

To this end, we deployed in January, 2001, three AWS with GPS receivers on top of the largest of the icebergs, called B15A (Fig. 1A and 1C), that we could reach from the U. S. National Science Foundation's McMurdo Station. Position and rotational orientation measured by these stations was relayed to us every 30 minutes throughout the rest of 2001 through the POES/ARGOS satellite data retrieval system operated by National Oceanic and Atmospheric Administration (NOAA) of the U.S. This data allows us to map the iceberg's boundaries in detail on a sub-hourly basis—giving the iceberg's spatial orientation more frequently than data derived from satellite imagery available on a daily basis. We found this temporal resolution to reveal the essential characteristics of the iceberg's response to the currents and sea-surface tilts associated with ocean tides[5].

The greatest surprise revealed by our data was the extent to which B15A collided with its surroundings (*e.g.,* Ross Island, Franklin Island, Ross Ice Shelf ice front, the sea bed, and a grounded iceberg called C16, see Fig. 1A for locations). These collisions were so numerous and the forces of contact so great, that the net motion of the iceberg during 2001 was by collisions in spite of other oceanic and atmospheric forces that sent the iceberg's siblings (*e.g.,* the other half of the original B15 iceberg, called B15B) adrift on a trajectory creating more than 1000 km of separation with B15A. The derived iceberg motion over the period of 25 January to 31 December, 2001, is shown in Figs. 1A - 1C. Collisions between the iceberg and Ross Island, the ice front of the Ross Ice Shelf, and other features are indicated by the abrupt flattening in the drift trajectory, *i.e.,* as indicated by the arrows labeling collisions in Fig. 1C. To further illustrate the abrupt nature of the drift trajectory changes that seem to direct the drift of B15A, we show a section of a tilt meter record in Fig. 2. We used an Applied Geomechanics model 711-2(4X) biaxial bubble-type tilt meter with 1-μrad sensitivity, mounted on a 4-inch by 4-inch by 5 foot post in a snow pit on C16 located about 10 kilometers from the edge of the iceberg. Tilt data were recorded on a 5 second interval. The abrupt ringing events seen in the record signify flexural-gravity waves set up in the coupled iceberg, sub-iceberg water layer system in response to collisions with B15A.

The most significant movement of the iceberg during 2001 was a great counterclockwise rotation that occurred during the 6-month period from February to July. This rotation put the iceberg into the north-south orientation that antagonized penguins trying to migrate between feeding waters and rookeries[6]. Close inspection of the iceberg's rotation depended on the iceberg's contact with surrounding features acting as pivot points shown in Fig. (1A). These pivot points, and contact with C16 and shoals surrounding Franklin Island, produced a circumstance where the iceberg could thereafter 'disobey' normal drift patterns, i.e., as exhibited by small icebergs moving through the region simultaneously. In spite of the coastal currents and prevailing wind conditions of the region, which has driven smaller icebergs North, out of the Ross Sea, B15A has remained virtually in the same position for 14 months. Constant collision between the southern and western sides of the iceberg with Ross Island and C16 appear to be the main factor in keeping the iceberg on station.

It may seem ludicrous to suggest that the confined motion of B15A over the last 14 months could suggest ways to direct the drift of icebergs as a means to harvest them for fresh water. The use of ocean-going tug boats to tow icebergs from the Antarctic to population centers in the Southern Hemisphere, for example, has been dismissed as impractical[7]. What our data suggest, however, is a means by which the iceberg's drift can be controlled through rigid-body contact with the iceberg's surroundings and seabed. If the effect of such contact seen in the gyrations of B15A (Fig. 1C) can be imitated using anchors and strong cables, then iceberg transport may be possible without ocean going tugs. In the days before internal combustion technology, *i.e.,* the 18th century, kedge anchors were frequently employed to move sailing ships in the absence of wind.

Kedging technology can, perhaps, be applied to icebergs. As illustrated in Fig. 1D, an iceberg is ferried across the Antarctic circumpolar current, to destinations in South Africa, South America or Australia, using a system of kedge anchors designed to both direct the iceberg's drift and to propel it. While invention of new, futuristic technology may often be what is looked to first as the means to address future fresh-water shortages, we suggest that old, 18th century technology should not be overlooked as a means of harnessing the service of icebergs as a fresh-water resource.

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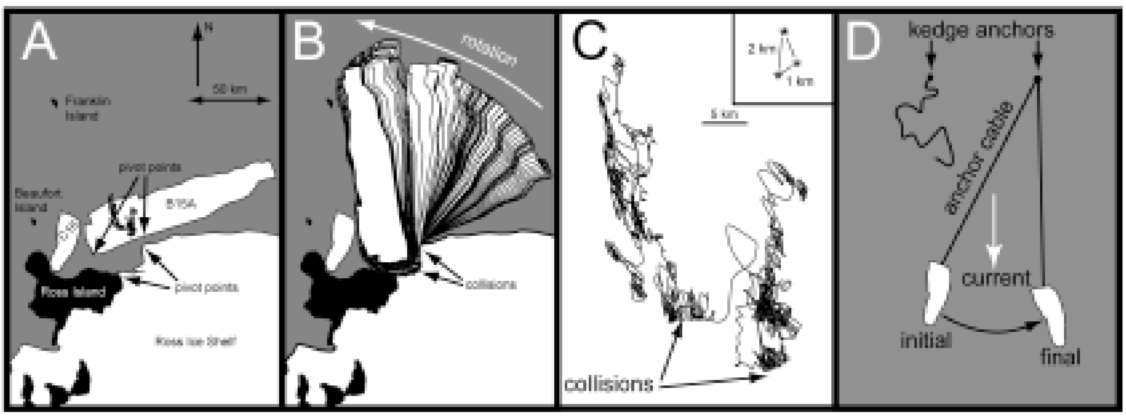


Fig. 1. (A) Configuration of icebergs B15A and C16 near Ross Island, Antarctica, on 25 January, 2001, the day on which autonomous iceberg-drift tracking instruments and weather stations were deployed on B15A. (B) Daily positions of B15A for the period of 25 January to 31 December, 2001. (C) Trajectory of one of three iceberg tracking stations deployed on the iceberg (station configuration shown in the inset). Collisions between B15A and the rocky coast of Ross Island, the front of the Ross Ice Shelf, or C16 created abruptly flattened segments in the otherwise smooth looping trajectory (repeated collisions are designated by arrows). (D) Idealized sketch of an iceberg kedging process. Ocean current pushes iceberg toward bottom of figure. Two kedge anchors are set and connected to iceberg with anchor cable. When cable attaching the iceberg to the left anchor is cut loose (represented by a zig-zag line signifying elastic rebound), the iceberg swings to align with the right anchor. Iceberg movement from initial

(left) to final (right) position is powered by natural forces. Maps in panels (A)-(C) are polar stereographic projections.

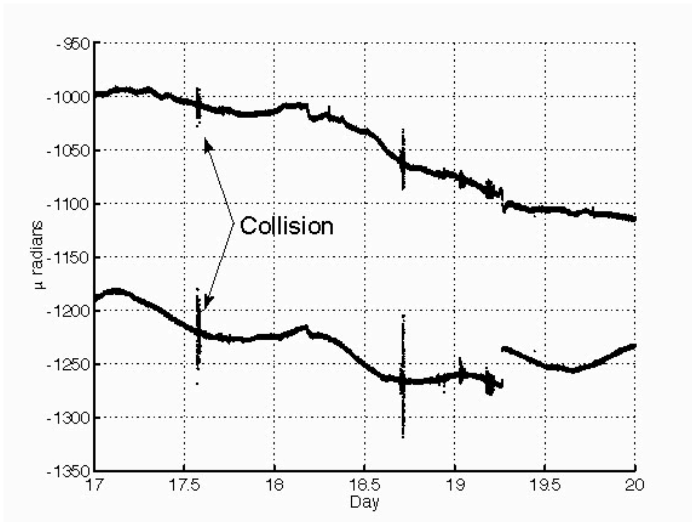
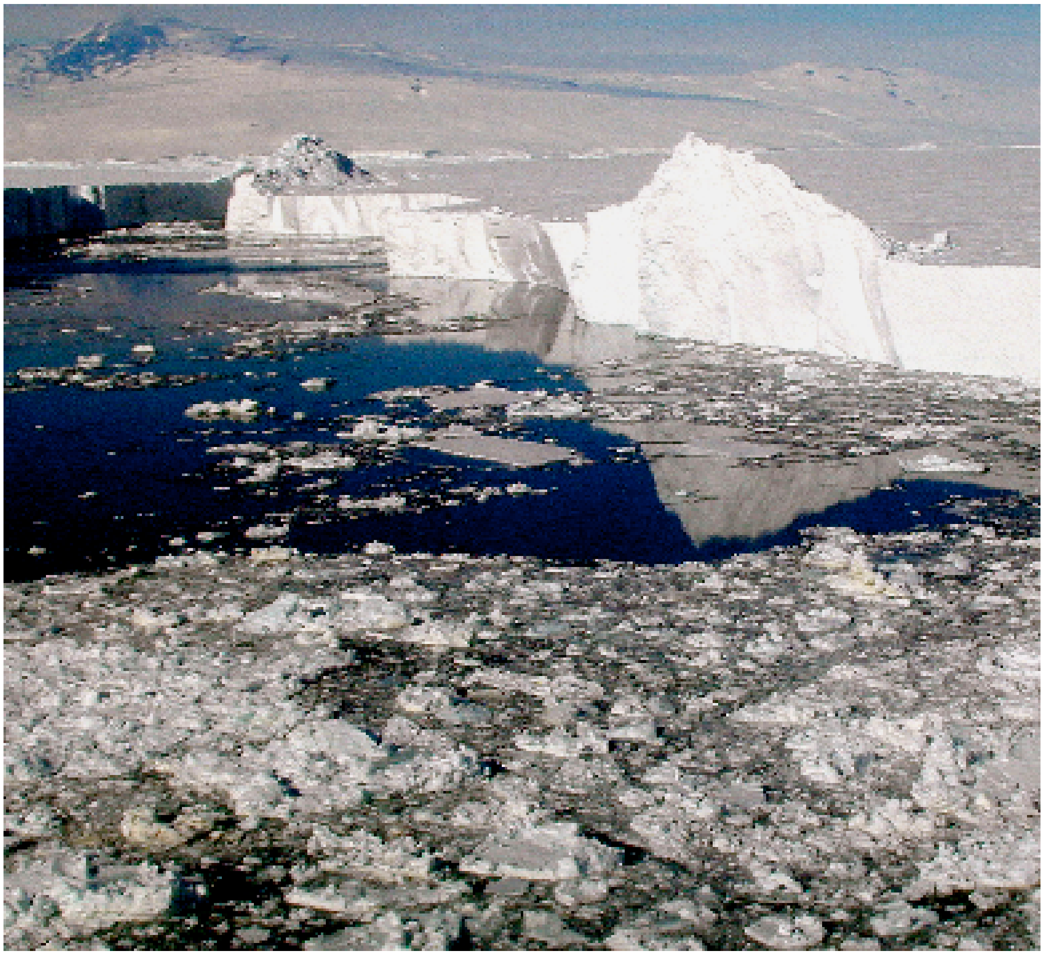


Fig. 2. Tilt meter record from C16 (see location in Fig. 1A) showing effect of collisions with B15A. Top line, East-West tilt; bottom line, North-South tilt. Days (horizontal axis) are of January, 2002. Collisions between C16 and B15A are signified by the abrupt scatter of tilt data points aligned vertically.



Cover Photo. Kedging mounds pushed up on the side of iceberg C16 as a result of collisions with iceberg B15a (seen in the extreme left). Mount Terror, Ross Island, Antarctica seen in background. Kedging mounds are approximately 50 meters high, and rise about 25 meters above the top of the normal ice cliff that characterizes the edge of a large tabular iceberg. (Photo: Peter West, National Science Foundation of the U.S.)