Title
"Crack!" in the polar night

Permalink
https://escholarship.org/uc/item/5j39c1jt

Journal
Eos, 82(43)

ISSN
0096-3941

Authors
Bindschadler, R
Rignot, E

Publication Date
2001-10-23

DOI
10.1029/01EO00294

License
CC BY 4.0

Peer reviewed
"Crack!" in the Polar Night

It happened during the long dark, polar night just over a year ago. It wasn't noticed until months later. Its climatic significance isn't clear yet, but it provides new insight into the process by which the Antarctic ice sheet periodically launches massive icebergs from around its perimeter and heightens concern that this area of Earth's largest frozen continent is changing.

"It" is the sudden formation of a large rift nearly three-fourths of the distance across the Pine Island Glacier (75°S, 102°W), a major outlet glacier of the West Antarctic ice sheet. The long rift was observed independently by researchers reviewing images collected in two separate mappings of Antarctica with two different sensors. The initial analysis of this dramatic event, including a prognosis of the rift's future growth and impending iceberg formation, incorporates recently collected data from no less than six sensors on five satellites operated by three space agencies. This study illustrates beautifully the new power of multisensor monitoring of the Earth from space.

Icebergs are routinely released by any large mass of moving ice that terminates in water. The thicker the ice mass and the deeper the water, the larger the icebergs. Iceberg B-15, released from the edge of the Ross Ice Shelf in the summer of 2000, set a new record for iceberg volume (over 3500 km$^3$) and covered an area as large as the state of Connecticut.

After formation, the iceberg drifted westward across the front of its parental ice shelf, occasionally colliding with the ice shelf. It broke into a few large pieces and is presently lodged against the western edge of the shelf. It is likely to remain in the southern Ross Sea for many years to come and is currently being monitored and studied.

Other icebergs have made headlines as well. On both sides of the Antarctic Peninsula, episodes of icebergs stampeding out of embayments have caused ice shelves, present since the Last Glacial Maximum approximately 20,000 years ago, to disappear in a climatic blink of the eye. Extensive surface melting is believed to be the culprit in removing in weeks, months, and years of ice that required thousands of years to form [Vaughan and Doake, 1996; Rott et al., 1996; Scambos et al., 2000].

The production of icebergs, especially large ones, appears to be on the rise in recent years, increasing concern that this phenomenon portends some recent climatic trend. Alternatively, the trend may represent natural variability. Our increased ability to observe calving from this remote continent using the expanding suite of satellite sensors may contribute to our heightened awareness. New studies on iceberg calving have begun, but results are not in yet.

Mapping Antarctica from Space

Routine imaging of Antarctica at the spatial resolution of a kilometer or so has been performed for decades, but it is the collection of imagery at finer spatial resolutions of a few tens of meters that has dramatically expanded our view of the dynamic nature of Antarctica and its active role in global climate. More detailed imagery can resolve the fractures, or crevasses, caused by the stresses imposed on the ice as gravity forces the ice to move. Crevasses are used to track the speed of the ice and their patterns reveal the nature of the imposed stress field.

The first complete high-resolution mapping of the Antarctic continent was accomplished in 1997 with the synthetic aperture radar (SAR) onboard the Canadian Space Agency's Radarsat satellite. This satellite completed a second Antarctic mapping mission last autumn with an emphasis on multiple collections around the perimeter of the continent for the purposes of SAR interferometry. This mission avoided the risks of turning the satellite to look south and produced imagery that will provide a complete set of ice velocities around the edge of Antarctica north of 79°S. A review of the SAR data as they were being collected revealed a large rift across the Pine Island Glacier; however, the rift went unreported (Joughin, pers. commun., 2001).

A few months later, when the Sun had returned to the southern extremes of the planet, the ETM+ sensor onboard Landsat-7, which was unable to collect data during the polar night, began its second austral summer of mapping Antarctica. Its primary goal this season was to collect imagery during the
ascending portion of its orbit. Normally, imagery is not collected during this portion of the orbit, but at high latitudes in summer the Earth's surface is sunlit. This condition afforded scientists the opportunity to collect entirely new views of the Antarctic surface with the Sun at different azimuth angles. A review of these data also revealed the same new rift seen earlier on Pine Island Glacier.

Landsat data from the previous March clearly showed no rift. Something big had happened. This time, however, the word went out to other researchers more familiar with this glacier.

**West Antarctica's Weak Underbelly**

Like large or numerous icebergs, Pine Island Glacier has made recent headlines. Years ago, Hughes [1981] suggested that this region may be the most susceptible to collapse in the continuing dialogue about the potential threat to global sea level posed by the West Antarctic ice sheet [Bentley, 1997; Bindschadler, 1997]. More recently, direct evidence of major changes taking place in this area has been accumulating. From 1992 to 1996, the glacier speed has increased 18% [Rignot et al., 2001]. At the same time, the grounding line, the point where ice leaving the continent begins to float, has retreated by 5 km [Rignot, 1998]. In concert with this behavior, the basin feeding Pine Island Glacier is thinning at 10 cm/yr [Wingham, 1998].

More recently direct evidence of major changes taking place in this area has been accumulating. From 1992 to 1996, the glacier speed has increased 18% [Rignot et al., 2001]. At the same time, the grounding line, the point where ice leaving the continent begins to float, has retreated by 5 km [Rignot, 1998]. In concert with this behavior, the basin feeding Pine Island Glacier is thinning at 10 cm/yr [Wingham, 1998], and Shepard et al. [2001] have found that the thinning intensifies near the glacier.

**First Observations (Data Mining)**

Once word of this new rift went out, a number of additional observations quickly came to light. The synthesis of these data focused on two research objectives: first, to determine when the rift first formed; and second, to determine if the rift was still growing and, if so, how fast and when a new iceberg might be released.

**Rift Initiation**

To achieve the first objective, MODIS (Moderate-resolution Imaging Spectroradiometer) data were examined. This sensor, onboard NASA's Earth Observing System's satellite Terra, collects data constantly at a spatial resolution as fine as 250 m and can view the Pine Island Glacier area daily. An image of Pine Island Glacier on September 17, 2000, confirmed that the large rift was present. Earlier data were sought, but persistent cloud cover, combined with the extended polar night, prevented MODIS data from further narrowing the time window of the initial rift event.

These cloud and sunlight limitations led us to examine what SAR data might be available. Fortunately, three images preceded the September 2000 Radarsat image of the rift and postdated the March Landsat-7 image prior to the rift event. All were collected by the European Space Agency's ERS-2 SAR and were clustered in the late spring of 2000. The latter pair of this image trio bracketed a dramatic crevassing event.

On April 10, 2000, there was no rift extending across the floating tongue of Pine Island Glacier. By May 15, 2000, a rift more than 20 km long was readily apparent in the SAR image. At this location, the glacier is 35 km wide. The rift clearly emanated from the largest of the shear crevasses on the north side of the glacier and progressively narrowed to its southern end. Details of the rift were difficult to discern because of image speckle, the grainy appearance of radar imagery caused by coherent noise within the data. The rift was at least 250 m wide at its northern end, but its precise southern termination was impossible to locate. Its orientation was roughly parallel to the ice front, approximately 15 km upstream from it and angled about 15° from the flow direction (Figure 1). The rift was remarkably straight over its entire length, which suggests that the fracture occurred as a single event.

To our knowledge, this is the first observation of such a large rift opening in such a short period of time. We do not know the specific circumstances that led to such a large energetic event.

**Rift Evolution**

Rift growth was addressed by using the most recent and highest-resolution imagery available. The Landsat-7 ETM+ instrument includes a panchromatic band with a 15-m pixel resolution. Often used for sharpening the resolution of the ETM+ multi-spectral bands, the panchromatic band is useful as a stand-alone band for our purpose. ASTER is another optical imager mounted on Terra. Although it is not always collecting data, it did image Pine Island Glacier on December 1, 2000. ASTER data also have a spatial resolution of 15 m, and both ETM+ and ASTER are nadir viewing, so they could be easily co-registered and directly compared. In Figure 1, the ASTER and ETM+ data are co-registered with the ERS-2 SAR image to show the movement of the rift and the extension of the glacier as it flows downstream.

The distance from the rift to the terminus increased in subsequent images due to the lateral spreading of floating ice. Because distortion in the SAR image may not be accurately corrected due to poor knowledge of surface elevations in this area, the most reliable calculation of this lateral spreading rate is obtained using the ASTER and Landsat images. Over 43 days between these images, an 18 km distance from the rift to the terminus in the ASTER image had stretched to 18.7 km in the Landsat data, resulting in a longitudinal strain rate of
0.086 atm. This is very close to the theoretical limit for a laterally confined ice shelf [Paterson, 1994].

More details about the rift can be seen in the ASTER and Landsat imagery. The edges of the rift are vertical cliffs between which the sunken surface is composed of smaller ice fragments. The shadow length cast by the east cliff of the rift wall is approximately 11 pixels. With the known Sun elevation and azimuth, 29° and 60°N, respectively, the shadow length can be converted to a cliff height of 87 m. This is roughly 10% of the ice thickness and strongly suggests the rift severs the ice glacier through its entire thickness.

To study the growth of the rift, the ASTER and ETM+ images were co-registered using the surface features immediately adjacent to the south tip of the rift to eliminate displacements caused by the local flow field. These features are "snow mounds" that are believed to have formed by wind vortices created by wind pumping in voids. The voids are actually portions of crevasses where surface snow bridges have collapsed into the crevasse. These smaller crevasses are created by extensional flow well upstream on the glacier and they do not completely penetrate the glacier.

Figure 2 shows that the rift grew 650 m over the 43 days between the ASTER and ETM+ images at an average growth rate of 15 m/day. Comparison of the rift shapes (Figure 1) shows that the recent growth is altering the straight nature of the rift. Detailed examination of the ASTER and ETM+ images shows that the recent growth of the rift is accomplished by formation of a set of short en-echelon crevasses. These crevasses are opening in an orientation more in concert with the expected shear stresses caused by the resistance of glacier flow along the glacier's south margin. The larger crevasses seen at the south margin and extending upstream into the glacier confirm this stress pattern and illustrate the typical crevasse orientation at glacier margins.

It is possible to measure a slight rotation rate of approximately 1% per year of the ice seaward of the rift. This rotation is due to a lower resistance to flow on the rifted north margin of the glacier downstream of a grounded ice rise relative to the shear experienced on the southern margin, where the glacier passes by a more rigidly grounded boundary. This rotation is causing the rift's northern portion to widen as the rift's southern end grows. In the Landsat image, the rift's maximum width had grown to just over 400 m.

**Prognosis for the Future**

At the above recent rate of growth, the rift would reach the nearest point of the south margin in 450 days or April 8, 2002. When this occurs, a new iceberg would form. The recent curving of the rift tip suggests that the local stress field is influencing the crevasse process. Shear stress increases as the margin is approached. Thus, the growth rate may increase in the future, leading to an earlier iceberg calving event.

Past observations of Pine Island Glacier have been spotty; a direct result of its remote location, persistent shroud of clouds, and often impenetrable apron of thick sea ice. What observations do exist record a variable ice front position and episodic calving (Figure 3). Front positions of the glacier over the past 55 years range 15 km longitudinally and previous icebergs typically remove 5–10 km of the glacier length. At a flow speed of approximately 2500 m/a at the terminus, such calving is expected every 2–4 years.

One factor that makes the next calving event noteworthy is that it will remove more than twice the average amount of ice. Figure 3 shows that the glacier terminus has never been farther advanced nor the future terminus never so far upstream during the observational period. Even if glacier movement carries the new rift to the 1992 position before the iceberg is released, the southern extension of the rift will form an embayment across the terminus. This may be significant in the context of the increasing amount of change observed in this area. Within the ice shelf region immediately north of the glacier, isolated ice rises are gradually losing their grip on the subglacial rock, and the glacier itself has accelerated and thinned in the last decade [Rignot, 1998; Shepard et al., 2001]. What connection these observations have to the dramatically larger incipient iceberg reported here is unclear.

If the rift reaches the south margin before it reaches the 1992 terminus position, the retreat of the terminus could portend a continued retreat, possibly with a series of large icebergs. This behavior has occurred on calving tidewater glaciers and would be consistent with the recently observed acceleration and thinning of this glacier. It is a situation that is being monitored with night-penetrating SAR; with thermal sensors sensitive enough to see the thermal signature of the cold glacier against the background of the thinner, warmer sea ice heated by the underlying ocean; and optical sensors that may catch a moonlit glimpse of the glacier and its evolving rift.

**Acknowledgments**

This study was prompted by review of Landsat imagery collected by the U.S. Geological Survey and distributed by their Eros Data Center. Funding was provided by NASA. Bruce Raup identified the ASTER scene and Mike Abrams provided a processed version for our analysis. Ian Jouguin helped in processing the SAR data that were provided by the European Space Agency through the Alaska SAR Facility. The Goddard MODIS Data and Archive Center assisted in viewing the MODIS imagery.

**Authors**

Robert Bindschadler and Eric Rignot

For additional information, contact Robert Bindschadler, Code 971, NASA Goddard Space Flight Center, Greenbelt, Md., USA; E-mail: bob@igloo.gsfc.nasa.gov

**Fig. 3. Observations of terminus positions of Pine Island Glacier are shown from various sources [Vaughan et al., 2001]. Position of new rift is indicated by solid magenta line. Original color image appears at the back of this volume.**
EU-sponsored Effort Improves Monitoring of Circulation Variability in the Mediterranean

PAGES 497, 504

The Mediterranean Sea, bordered by many North African countries and opening eastward to the Black Sea, is a strategic area for Europe. Its coast is one of the most heavily populated regions of the world. A large part of a coastal nation’s gross national product is produced through fishing, transportation, recreation, and other industries that depend on a healthy marine coastal environment. The risk of an incident likely to release harmful substances and cause massive pollution is considered high, as the Mediterranean is a major route for merchant vessels and the transport of oil and gas. Due to this risk, Mediterranean coastal countries need to organize and prepare for accidental marine pollution. Such permanent efforts have to be made at national, regional, and European levels. The management of this culturally diverse area presents a challenge.

The physical dynamics of the Mediterranean system influence the ecological health of a vast region of southern Europe and North Africa. The hydrological cycle, which strongly depends on the physical characteristics of the sea, influences the climate of the region. Changes in this cycle have been predicted, and they could have dramatic consequences, such as desertification of parts of southern Europe and threats to the Mediterranean’s living resources. Accordingly, the European Union Research and Technological Development Program began a supporting pilot project, the Mediterranean Forecasting System (MFS), in 1998 to explore, model, and quantify the environmental variability and predictability of the Mediterranean marine ecosystem (Pinardi and Rennings, 1998).

One of the tools for achieving these goals is a monitoring system that uses Expendable Bathythermograph (XBT) to collect thermal data in the upper layer of water, from surface to 460–760 m depth. Ships of opportunity—commercial ships hosting technical personnel over regular routes—are used to collect the data. The program has focused on new strategies for data decimation, extracting a small number of data at selected depths to represent the overall shape of the temperature profile, data transmission, as well as data management strategies for the dissemination of real-time data. Partial care was taken to ensure data quality control.

The 10-year MFS science and technology implementation program is divided into three phases:

- **Second phase (2001–2003):** Regional and medium-range forecasts, including a fully coupled ocean-atmosphere model and pilot forecast experiments of ecosystem models.
- **Third phase (2004–2008):** The entire observational and modeling systems will be released to national and international marine operational agencies.

The monitoring system was designed to follow the movement of Atlantic water from Gibraltar to the easternmost parts of the Mediterranean basin, to sample the main gyres, and to detect the variability of the dense-water formation areas. Monitoring began in September 1999 along six tracks crossing the Mediterranean from north to south and one track from east to west (Figure 1). During a training period lasting until November 1999, the surveys were carried out once a month. From December 1999, the monitoring was conducted every 15 days to capture the quasi-synoptic scale. The spatial sampling scale was 10–12 nautical miles.

**Fig. 1.** (a) The circulation pattern of the Mediterranean Sea is shown, as inferred from historical data. (b) The circulation picture emerged from the recent observations of Millot [1999] and Malanotte Rizzoli et al. [1997]. The numbers indicate: 1) Alboran gyre, 2) current instabilities in the Algerian basin, 3) Ligure-Provencal-Catalan current, 4) Bonifica gyre, 5) Tyrrhenian current, 6) Atlantic-Ionian stream, 7) Mid-Ionian Jet, 8) Pelops anticyclone, 9) Cretan anticyclone, 10) Mid-Mediterranean Jet, 11) Rhodes gyre, 12) Mersa-Matruh anticyclone, and 13) Shikmona anticyclone.
Fig. 1. In this image of Pine Island Glacier, insets at lower left show location of glacier and the Landsat-7 panchromatic band image of the glacier on January 13, 2001. Center image shows motion of rift (from upper right to lower left) by superimposing three images (magenta: ERS-2 SAR image, May 15, 2000; green: ASTER image, December 1, 2000; blue: Landsat-7 image, January 13, 2001). Inset is 5 km x 5 km detail of rift motion. Distortions in the SAR image resulted from errors in poorly known elevations used to project data to a horizontal datum. This causes apparent lateral shift of the terminus.

Fig. 2. Growth of rift is shown by superimposing ASTER image (blue) and Landsat image (red and green making yellow). Images are registered based on local field of snow mounds to eliminate glacier motion over the 43-day interval between images. New rift growth shows as blue because it is dark in Landsat but bright in ASTER. Image is 7 km x 7 km.
Fig. 3. Observations of terminus positions of Pine Island Glacier are shown from various sources [Vaughan et al., 2001]. Position of new rift is indicated by solid magenta line.