Glacier wastage on southern Adelaide Island, Antarctica, and its impact on snow runway operations

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ABSTRACT. The variations and dynamics of the southern edge of Fuchs Ice Piedmont, Adelaide Island (67°45′ 09′ S, 68°55′ 04′ W), Antarctic Peninsula, are presented. The snow-covered surface of the glacier has been used since the 1960s for landing aeroplanes in support of British, and more recently Chilean, operations at nearby Teniente Carvajal station (formerly known as Adelaide T). In recent years, snow conditions in the runway area have progressively deteriorated, due to increasingly early summer melting. Radio-echo sounding, global positioning system and remotely sensed data have been analyzed for mapping the crevasse and ice velocity fields, as well as the surface and subglacial topography of the area. The results show that the runway area is located on a local ice divide surrounded by crevasses which are appearing on the glacier surface progressively earlier in the summer, presumably due to higher snowmelt and perhaps higher ice velocities, in response to regional atmospheric warming. In the near future, landing operations will be further affected as more crevasses will appear in the runway area if present warming trends persist. This situation affects all coastal areas in the Antarctic Peninsula, hence the need to search for possible new locations of crevasse-free runways at higher elevations.

INTRODUCTION

Recently the Antarctic Peninsula has experienced a rapid regional warming trend which is much more pronounced than the observed trends in other Antarctic areas (Vaughan and Doake, 1996; Vaughan and others, 2003). This warming has affected the stability of ice shelves (Rott and others, 1998), resulting, in several cases, in their complete collapse, as well as in the acceleration of ice velocities and ice thinning of glaciers formerly feeding these ice shelves (Rott and others, 2002; De Angelis and Skvarca, 2003). In spite of recent increases in our understanding of the glaciological processes affecting the region (e.g. Morris and Mulvaney, 1995; Rignot and Thomas, 2002; Cook and others, 2005), more studies are needed to assess the spatial extent and magnitude of glacier wasting in the Antarctic Peninsula.

The atmospheric warming affecting the Peninsula has affected the viability and security of logistic and scientific operations. In this paper, we analyze recent dynamics and variations of Fuchs Ice Piedmont (67°45′ 09′ S, 68°55′ 04′ W; Fig. 1), a piedmont-style glacier located on the western side of Adelaide Island, directly calving into the Southern Ocean. The ice front of the glacier is grounded or very close to grounding.

Very few rock outcrops are observed along the margins of Fuchs Ice Piedmont. On the southern edge of Adelaide Island one of these ice-free areas is occupied by the Chilean Teniente Carvajal station (Fig. 1). This base was originally founded by the British Antarctic Survey (BAS) in 1961 as Adelaide T, being active until 1977 when all British operations were moved to Rothera R station (67°34′ S, 68°08′ W) after an evaluation carried out by BAS concluded that the runway area was hazardous for aeroplane landing (Conchie, 1975). The Chilean Air Force (FACH) took control of the base in 1984, when the British Government donated the station to Chile (Martin and Rae, 2001).

FACH usually initiates field activities in October, when DHC-6 Twin Otter ski-equipped aircraft land on the glacier surface, which at this time of the year is almost totally snow-covered, providing logistic support to annual operations. Later in the summer (January), the runway is progressively moved upstream on the glacier because crevasses and ice appear at the surface, precluding most operations near the base. At the end of the summer, the runway is inoperable due to deteriorating conditions, so the station personnel and equipment are evacuated by sea, with the logistic support of the Chilean Navy. In recent years, FACH pilots have experienced landing and take-off problems with crevasses at increasingly higher altitude (personal communication from FACH, 2002).

In January 1999, an accident involving Chilean personnel occurred at an altitude of ~325 m on the glacier (Fig. 7, shown later). A snowmobile fell into a crevasse due to the collapse of a snow bridge, as a result of which one person died and another was severely injured and had to be rescued from a 50 m deep crevasse. This accident showed the risks of operating in an area that had been considered safe.

To analyze glaciological conditions and the deterioration of the runway area in recent decades, which could affect safety operations at the station in the future, a field campaign was carried out on Adelaide Island in November–December 2002. We collected radio-echo sounding (RES) data for mapping the subglacial topography of the area and the internal structure of the ice, and used dual-frequency global positioning system (GPS) receivers for surveying the surface topography of the glacier, as well as

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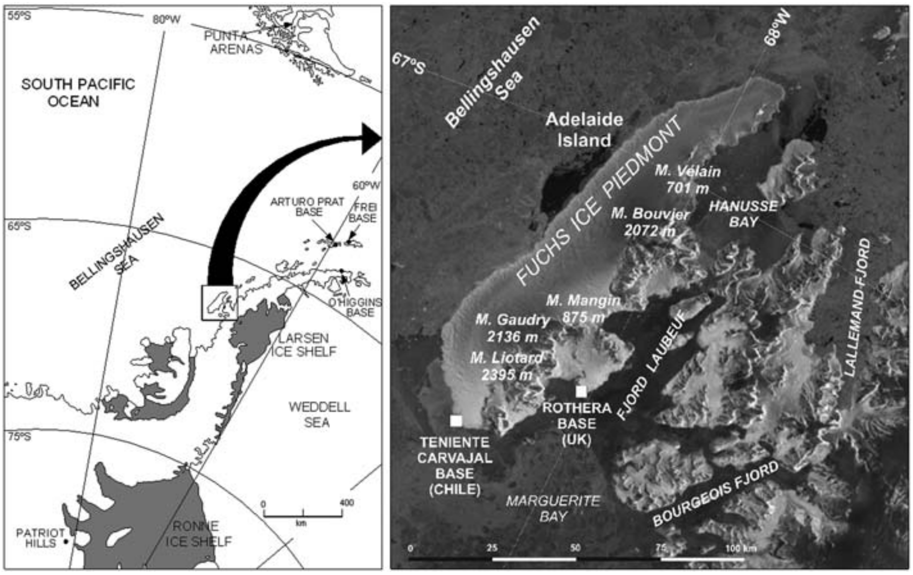

Fig. 1. Location map showing the study area on Adelaide Island, Antarctic Peninsula.

measuring ice velocities from a stake network, and snow variations and densities from stakes/snow pits. Maps, satellite images and aerial photographs of the area were analyzed, in order to determine the spatial variations of the glacier, the presence of crevasses, and snow conditions in different epochs. Historical reports, hand-held photographs and maps available at the BAS library, Cambridge, UK, were also collected and analyzed, in order to obtain a long-term series of glaciological variations of the area. In December 2002, an airborne survey of the area was carried out on board an Orion P-3 aeroplane of the Chilean Navy, allowing the surface topography of the glacier to be mapped with a laser altimeter.

DATA

Aerial photographs and satellite images

Nine vertical aerial photographs (23×23 cm) were provided by FACH. These photographs were obtained on 10 February 1989 during a campaign organized by the Institut für Angewandte Geodäsie of Frankfurt, Germany. They were used to map crevasses in the area near the station and for planning the field campaign.

Table 1. Satellite images

Satellite	Date	Resolution m
Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)	7 January 2003	15 (VIR[*])
Landsat Enhanced Thematic Mapper Plus (ETM+)	19 February 2001	28.5[†]
Landsat Thematic Mapper (TM)	18 February 1986	28.5
Landsat Multispectral Scanner (MSS)	14 December 1976	57 × 79

[*]Visible and near-infrared bands.
[†]Spatial resolution of all ETM+ bands with the exception of band 8 (panchromatic) which has a resolution of 14.25 m.

Several satellite images were obtained from the Earth Resources Observation Systems (EROS) Data Center (Sioux Falls, SD, USA) of the United States Geological Survey (Table 1). These images were geometrically rectified using the satellite orbital parameters in order to eliminate distortions and horizontal displacements of the images. The estimated horizontal error of the rectified scenes yielded approximately one pixel size of the respective satellite image.

The Landsat Enhanced Thematic Mapper Plus (ETM+) and Thematic Mapper (TM) satellite images were analyzed using the band ratio 4/5 (Paul and others, 2002), with the main aim of mapping the frontal position of the glacier, crevasses and ice-flow patterns. False-color composite images were also generated using bands 1, 4 and 5 of ETM+ and TM scenes, and bands 1–3 of a Landsat Multispectral Scanner (MSS) image.

Surface topography data

Two dual-frequency Javad Legacy GPS receivers were used during the field campaign to map the surface topography of the glacier. A base point was installed on a rock outcrop near the station, close to sea level (Fig. 2), where a metal pin was glued to a hole drilled into the rock. The second receiver was installed on board a snowmobile recording data in kinematic mode over the glacier. Stop-and-go measurements were also carried out on a stake network installed around the runway area on the glacier (Fig. 2), allowing positioning of each stake after a minimum measurement time of 10 min. The stake network was resurveyed after a minimum of 7 days using the same GPS receivers, allowing ice velocities and deformation to be determined. A differential correction procedure was applied to the stake network data, yielding a post-processed mean horizontal rms error of 1 cm and a mean vertical rms error of 1.5 cm.

Two single-frequency Trimble Geoexplorer III GPS receivers were also used to survey the surface topography of the glacier in a kinematic mode, during transit of snowmobiles between stakes. After applying a differential correction procedure, a mean horizontal rms error of 20 cm and a mean vertical rms error of 40 cm were obtained for these data.

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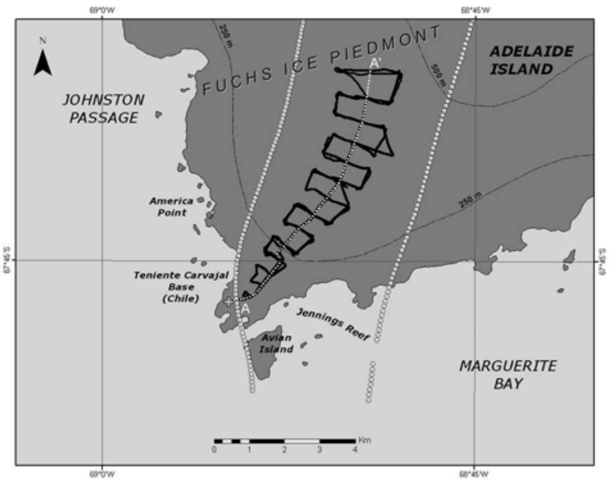

Fig. 2. Measured tracks in November and December 2002. GPS and RES data in black lines and ATM data in white circles. The location of the topographic profile A–A′ (white crosses) shown in Figure 4 is included. The contour lines were extracted from BAS (2001).

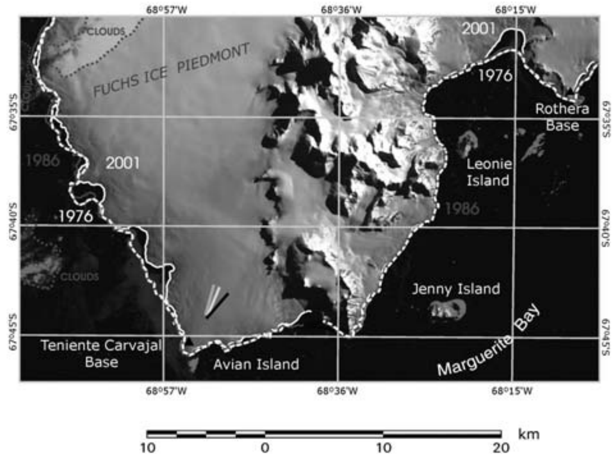

Fig. 3. Glacier frontal variations between 1976 (dotted white line), 1986 (dark grey) and 2001 (white line), based upon the interpretation of remotely sensed imagery (Table 1). The background image is a Landsat ETM+ acquired on 19 February 2001. The runway area is shown near Teniente Carvajal station as grey, white and black lines. The stations are shown as black triangles.

On 10 December 2002, an airborne survey was carried out by Centro de Estudios Científicos (CECS) and NASA, using an Orion P3 aeroplane of the Chilean Navy equipped with several sensors, including geodetic quality GPS receivers, an Airborne Topographic Mapper (ATM) laser altimeter and a RES system provided by the University of Kansas, USA. Two profiles of surface topography were measured on Adelaide Island (Fig. 2), with an along-track spacing of a dense array of $\sim$2 m footprint, within a 500 m wide swath. Elevations are expressed as World Geodetic System 1984 (WGS84), with a mean horizontal rms error of 25 cm and a mean vertical rms error of 40 cm being calculated for the ATM data (Thomas and others, 2004).

Surface contour lines were generated by interpolation of GPS data using an inverse distance-weighted method available in the ArcView 3.2 software package. The contour lines were manually edited in order to avoid artefacts derived from the interpolation method. Considering each data error as well as the error added by the interpolation method, the final vertical rms error of the contours yielded 1 m.

Subglacial topography data

A high-frequency RES system with a central frequency of 2.5 MHz was used for measuring ice thickness (Rivera and Casassa, 2002). The RES system was mounted on sledges pulled by snowmobiles using mountaineering ropes. An Ohio State University transmitter was connected to 20 m long half-dipole antennae which were resistively loaded. A Tektronics model THS 720A oscilloscope was used as a receiver and connected to a rugged notebook computer on which each measurement was recorded. The system allowed measurements whilst the snowmobiles were transiting around the stake network, recording data every 5 s at the same repetition time of the GPS receivers used to geolocate the snowmobile. The resulting data were analyzed in A-scope and raster format (Rivera and Casassa, 2002), allowing continuous mapping of the subglacial topography, with a vertical accuracy estimated as 5% of the total ice thickness, based upon comparison of data obtained at crossing points.

The RES data were also used to detect ice crevasses at depth based upon a method (Retzlaff and Bentley, 1993) where the diffraction hyperbolas appearing in the records are interpreted as reflectors presumably related to crevasses and ice faults (Clarke and Bentley, 1994).

RESULTS

Frontal variations

The frontal position of Fuchs Ice Piedmont since 1976 was mapped using available satellite imagery of southern Adelaide Island. Between 1976 and 1986 many sectors, especially at the western margin of the glacier, showed advance (Fig. 3), with a total net gain of 6 km^2, but between 1986 and 2001 most of the glacier showed retreat and area shrinkage, with a total area loss of 34 km^2. Over the complete period 1976–2001, the glacier retreated at a mean area change rate of 1.1 km^2 a^{-1}. Most of the changes took place at the western side of Fuchs Ice Piedmont. The southern edge of the glacier, where Carvajal station is located, was much more stable.

Surface and subglacial topography

The surface topography of the southern edge of the island can be seen in Figures 4 and 5. The runway area is located on a local ice divide of the glacier separating ice that flows towards the southwest and south. The area has a gentle slope with an altitude range from sea level to 325 m. The slope steepens only at the contact between the ice and the rock outcrop near Teniente Carvajal station. This steep area is frequently used by personnel in transit from the station to the runway, and is generally ice-covered due to snowmelt and wind erosion.

Unfortunately, the ATM laser altimeter data did not overlap with the ground GPS measurements obtained in the field. Nevertheless these airborne data were useful for extending the surface topography to the margins of the ice divide, where several hundred points were obtained along two semi-parallel tracks (Fig. 2) ranging from sea level to 350 m a.s.l.

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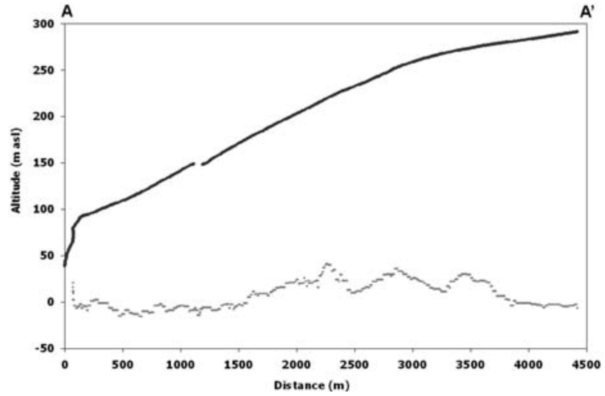

Fig. 4. Topographic profile along GPS track (A–A′) showing surface and subglacial topography of Fuchs Ice Piedmont. See Figure 2 for location of the profile.

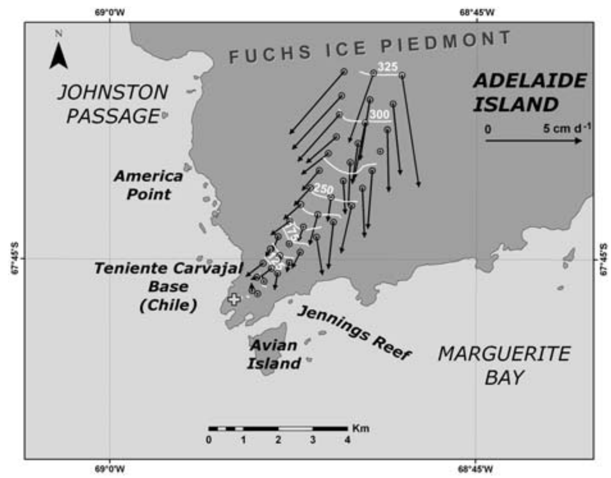

Fig. 5. Ice velocities (black arrows) and surface topography in m a.s.l. (white contour lines) around the local ice divide at the southern edge of Adelaide Island.

More than 30 RES profiles were measured with the profiling system pulled by snowmobiles. Most of the RES data clearly showed subglacial returns characterized by smooth bedrock with low-amplitude undulations (Figs 4 and 6). The subglacial relief (Fig. 4) showed a few sectors with elevations below sea level, especially under the runway area. In general, most of the subglacial topography of the southern tip of the island is located a few tens of meters above sea level.

Ice velocities

The stake network was surveyed twice with a spanning time of 7–28 days. The resulting velocities confirmed the presence of the local ice divide, with maximum velocities of $9 \pm 0.5\,\text{cm d}^{-1}$ at both margins of the divide at the northern edge of the measured area (Fig. 5). The velocities are reduced toward the south, showing longitudinal compressive flow along the ice divide toward the runway area where ice velocities are smaller than the errors. However, the velocities increase laterally from the ice divide toward the west and southeast respectively. This result indicates extensive flow on both sides of the divide.

Crevasse detection

Crevasses were detected primarily from aerial photographs and satellite images (Fig. 7). The imagery shows no crevasses along the local ice divide, but crevasses on both sides of the local divide, where the ice velocities show extensive flow. A more detailed mapping of crevasses was performed in the field using snow probes and direct observations, especially in the runway area, prior to aeroplane landing operations.

In order to extend the crevasse detection to areas where a more significant snow cover existed during the campaign, the RES records were analyzed, resulting in a more complete map of crevasses (Fig. 7). Some of the diffraction hyperbolas detected in the RES record (Fig. 6) were confirmed in the field as crevasses at the end of the field campaign, when most of the snow cover disappeared and several crevasses were visible approximately in the same location.

DISCUSSION

In the 1930s, Fleming (1940) reported that the island ice caps west of Graham Land would probably disappear completely in a few years if the then existing climatic conditions continued. However, in the 1960s Bryan (1965) reported positive mass balances at Fuchs Ice Piedmont, with an equilibrium-line altitude (ELA) at 190 m a.s.l. during summer 1962/63 in the runway area near the station. During the 2002 field campaign, crevasses and evidence of ablation were observed at altitudes as high as 325 m a.s.l. (Fig. 7). The annual amount of ablation on the glacier is related to normal interannual variations of the ELA, but given that the region has experienced a trend of atmospheric warming during recent decades (Vaughan and others, 2003), it is reasonable to assume that the area has been affected by higher ablation at progressively higher altitude. A similar process has been observed at nearby Rothera station (Smith and others, 1998) and Marguerite Bay (Fig. 1), where a migration of the ELA from sea level in the 1960s to 200 m a.s.l. in 1991 was reported by Fox and Cooper (1998).

Atmospheric warming affecting the Antarctic Peninsula has also been related to an increase in snow accumulation (Raymond and others, 1996) and more frequent precipitation events (Turner and others, 1997). In the Antarctic Peninsula there is also recent evidence of more frequent liquid, as opposed to solid, precipitation (Carrasco, 2001). However, if the current trend persists, the higher accumulation will be compensated by higher ablation, and meltwater leaving the glacier will induce negative mass balances (Morris and Mulvaney, 2003). In this context, landing operations will be affected by ablation and shortage of snow at the glacier surface at low altitude.

Our estimates of frontal changes at the southern tip of Adelaide Island since 1976 are in agreement with a more extensive study by Cook and others (2005), who show that the great majority of glaciers located between 66° and 68° S in the Antarctic Peninsula have retreated during the same period of time. These extensive and synchronous retreats affecting floating and tidewater glaciers illustrate a regional climatic forcing.

The RES data confirm the presence of crevasses at shallow depths in the runway area close to Teniente Carvajal station (~100–150 m a.s.l.; Fig. 7). These crevasses are covered by fresh snow during most of the year, but during mid-summer

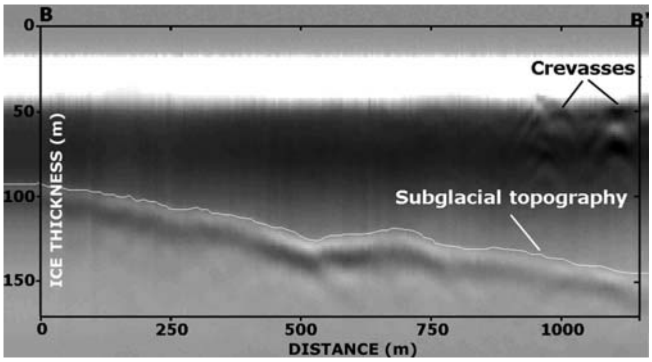

Fig. 6. RES profile (B–B′) measured on the runway area showing subglacial topography and internal structure of the ice. A couple of diffraction hyperbolas were detected in the data, which have been interpreted as crevasses. The location of the profile is shown in Figure 7.

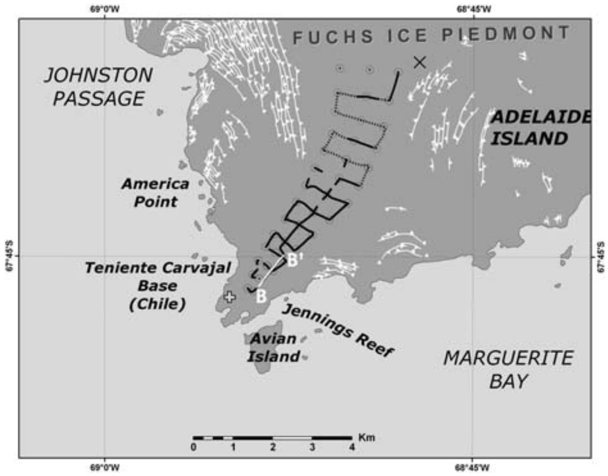

Fig. 7. Crevasse map obtained from interpretation of the Landsat ETM+ satellite image of 2001 (white lines), and based upon analysis of the RES record (black lines). Dotted black lines indicate areas where crevasses are presumed from the radar records. The circles indicate the stake network. B–B′ indicates the RES profile illustrated in Figure 6. '×' is where the fatal accident of January 1999 took place.

they normally appear on the glacier surface, precluding aeroplane operations. These crevasses are explained by extensional stresses at both sides of the local ice divide, as indicated by the velocity data in Figure 5, and probably continue to expand toward the end of the summer due to enhanced glacier flow.

The problem of moving runways upstream for aeroplane operations, due to crevasses, is not described in documents from the time when the British used the station. Before 1975, landing took place on two skiways near the station, where few crevasses were detected (BAS, 1975). The Chileans still use this area, but only in early summer. After December, FACH moves the runway upstream to a crevasse-free snow-covered surface.

If the present atmospheric warming trend persists in the near future, ice-flow acceleration will probably take place at low altitudes on the glacier, where the melting point is frequently reached during the summer (personal communication from FACH, 2002). Warming would also enhance glacial water production, resulting in increased opening of crevasses by hydrostatic pressure. In that context, the presence of ice and crevasses on the surface of the glacier at lower elevations would increasingly jeopardize landing and take-off operations on coastal glaciers in the Antarctic Peninsula.

CONCLUSIONS

The information available and data collected confirm the deterioration of the skiway area near Teniente Carvajal station. Snow conditions will progressively worsen for landing operations in the near future if the present climatic warming continues. Frontal variations experienced by the glaciers at the southern edge of Adelaide Island are in agreement with a generalized glacier recession trend in the Antarctic Peninsula, indicating a regional climatic forcing. In spite of a possible increase in snow accumulation due to atmospheric warming, a negative mass balance is expected for the area, due to the presence of liquid precipitation, higher ablation and summer runoff leaving the glacier. This process will probably enhance ice flow and meltwater production, resulting in increasingly difficult and dangerous conditions for operating ski-equipped aeroplanes on glacier runways near the Antarctic Peninsula coast.

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