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29 May 1996; accepted 28 August 1996

A Mini-Surge on the Ryder Glacier, Greenland, Observed by Satellite Radar Interferometry

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Satellite radar interferometry reveals that the speed of the Ryder Glacier increased roughly threefold and then returned to normal (100 to 500 meters/year) over a 7-week period near the end of the 1995 melt season. The accelerated flow represents a substantial, though short-lived, change in ice discharge. During the period of rapid motion, meltwater-filled supraglacial lakes may have drained, which could have increased basal water pressure and caused the mini-surge. There are too few velocity measurements on other large outlet glaciers to determine whether this type of event is a widespread phenomenon in Greenland, but because most other outlet glaciers are at lower latitudes, they should experience more extensive melting, making them more susceptible to meltwater-induced surges.

Discharge of ice through outlet glaciers represents a substantial part of the mass loss of the Greenland and Antarctic ice sheets and thus has a major impact on their mass balances. Few in situ observations have been made with which to assess the variability of outlet glacier flow (*1*). Satellite radar interferometry now provides an important means for measuring ice velocity (*2–4*). Using this technique, we documented a radical pulse in the speed of the Ryder Glacier, an outlet glacier at the northern edge of the Greenland Ice Sheet. This pulse or "mini-surge" (*5*) represents a significant, although short-term, increase in discharge from the ice sheet. There are only a few outlet glaciers from the large ice sheets on which substantial speed variations have been observed (*6*), and none have exhibited a similar short pulse of enhanced motion. Short pulses in speed have been documented on several valley glaciers, such as a large tidewater glacier in Alaska (*7*), and the Variegated Glacier during an extended surge (*8*).

The Ryder Glacier (Fig. 1) drains a basin of 28,300 km^2, about 1.7% of the inland ice area. The total accumulation for the basin is a water equivalent of 5.0 km^3/year (*9*), making the Ryder a moderately sized outlet glacier for Greenland. The Ryder has two branches, which converge at an elevation of 1000 m; it then flows out through the Sherard Osborn Fjord. At the head of the fjord, a prominent ice ridge is oblique to the fjord axis (Fig. 1). This feature is likely generated by ice flow over a subglacial bedrock ridge and shifts flow to the western side as ice enters the fjord. Ice backed up behind the ridge forms an ice plain (slope of ~0.002) covered by several large lakes (Fig. 1).

We created several interferograms of the Ryder from images taken by the synthetic aperture radars on board the ERS-1 and ERS-2 satellites. There are striking differences between the interferograms for September and October of 1995 (Fig. 2) over the fast-moving portion of the glacier below about 1100 m. The density of fringes (color cycles) in the October interferogram (Fig. 2B) is much greater than that in the September interferogram (Fig. 2A), indicating that flow was more rapid in October. The magnitude of the difference is far greater than the few fringes that may be attributable to differential propagation delays from atmospheric effects (*10*), and the patterns of enhanced fringes are clearly related to ice flow. Farther down-glacier, on the fastest moving parts, the pattern of fringes is lost completely in the October interferogram, whereas prominent fringes are still visible over this part of the September interferogram. The fringe loss is the result of gradients in velocity beyond the rate that can be measured with a 1-day separation of images. In the region where there is a rapid increase in the flow speed (white boxes in Fig. 2, A and B), the pattern of fringes is more complex (Fig. 2C) than it had been before the speedup.

The across-track component of velocity for the September observation (Fig. 3A) agrees well with another velocity map made from ERS-1 images acquired in March 1992 and appears to represent velocity in the normal flow mode of 100 to 500 m/year for most of the glacier. A map of the difference

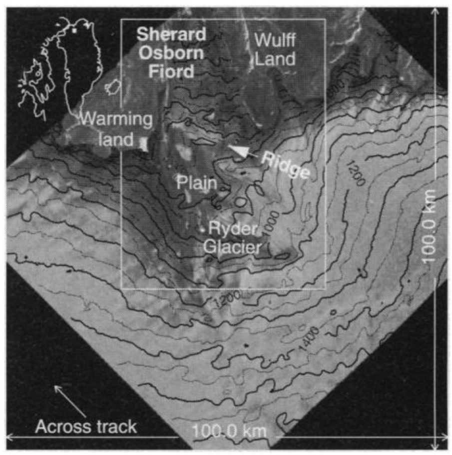

Fig. 1. ERS-1 amplitude image of Ryder Glacier acquired on 18 March 1992 at the location indicated by a solid-white box on the inset map. The pattern of low backscatter at the ice margin increasing to bright backscatter further inland is the result of the different scattering properties of the bare-ice, wet-snow, and percolation facies (*19*). The locations where lakes existed during the previous melt season appear as bright spots a few kilometers in diameter. Elevation contours at 50-m (thin) and 100-m (thick) intervals are plotted over ice-covered portions of the scene. We differenced pairs of interferograms to remove the displacement effect (*20*) to create this digital elevation model (DEM). The relative accuracy of the DEM is on the order of a few meters, although there may be long-wavelength errors of up to several tens of meters. White outlined box indicates area shown in Fig. 2.

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between the September and October velocity maps (Fig. 3B) shows that speed increased from 20 m/year up to more than 150 m/year (*11*). Noisy fringes and areas of complete fringe loss prevented us from making quantitative comparisons of the October velocity on the fastest moving regions of the glacier (*12*). Visual comparison of the noisy fringes in the October interferogram with those in a 3-day interferogram from March 1992 indicates that over much of the active area, ice flow exceeded three times its normal rate during the mini-surge (*13*).

We also created an interferogram using images from 8 to 9 November 1995. These images were acquired from a satellite track that is nearly orthogonal to that of the other interferograms. Because different horizontal components of motion were measured by these interferograms, we cannot make direct comparisons of horizontal velocities. Sensitivity to vertical displacement of the ice as it flows over bumps, however, is independent of look direction. Comparison of the high-frequency bull's-eye patterns in the interferograms indicates that the November data are consistent with the September observation (*14*), indicating that by 8 November, flow on the Ryder had returned to close to its normal mode. Thus, the Ryder experienced a relatively short speedup (less than 7 weeks, and possibly as short as a few days), during which velocity increased by a factor of 3 or more.

It is likely that in both the normal and mini-surge modes much of the glacier motion is the result of sliding. The low surface slope over much of the glacier makes it unlikely that the high velocities arose from ice deformation alone. Fluctuations in sliding velocities are commonly related to changes in subglacial water pressure caused by variable input of surface water or rearrangements in the basal water system (*15*). The mini-surge of the Ryder may have been caused by drainage of supraglacial (surface) lakes, which could have elevated subglacial water pressure. In the September image

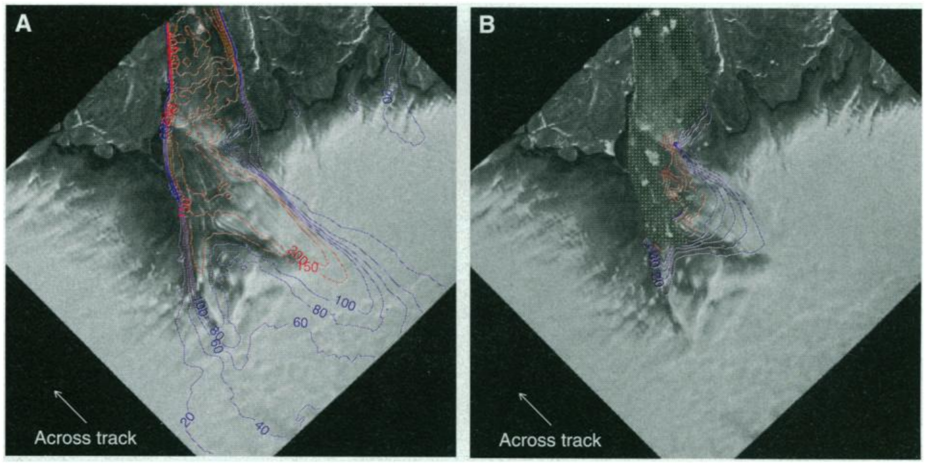

Fig. 3. (**A**) Contours of September across-track velocity plotted over the amplitude image acquired 21 September 1995 (same area as Fig. 1). Blue contours at 20-m/year are used for velocities up to 100 m/year, and red contours at 50-m/year intervals are used for velocities greater than 100 m/year. Surface slopes were used to reduce the effect of vertical displacement (*21*). (**B**) Difference between the October and September velocity estimates plotted over the 26 October 1995 image. Green stippled areas indicate where the October velocity could not be estimated.

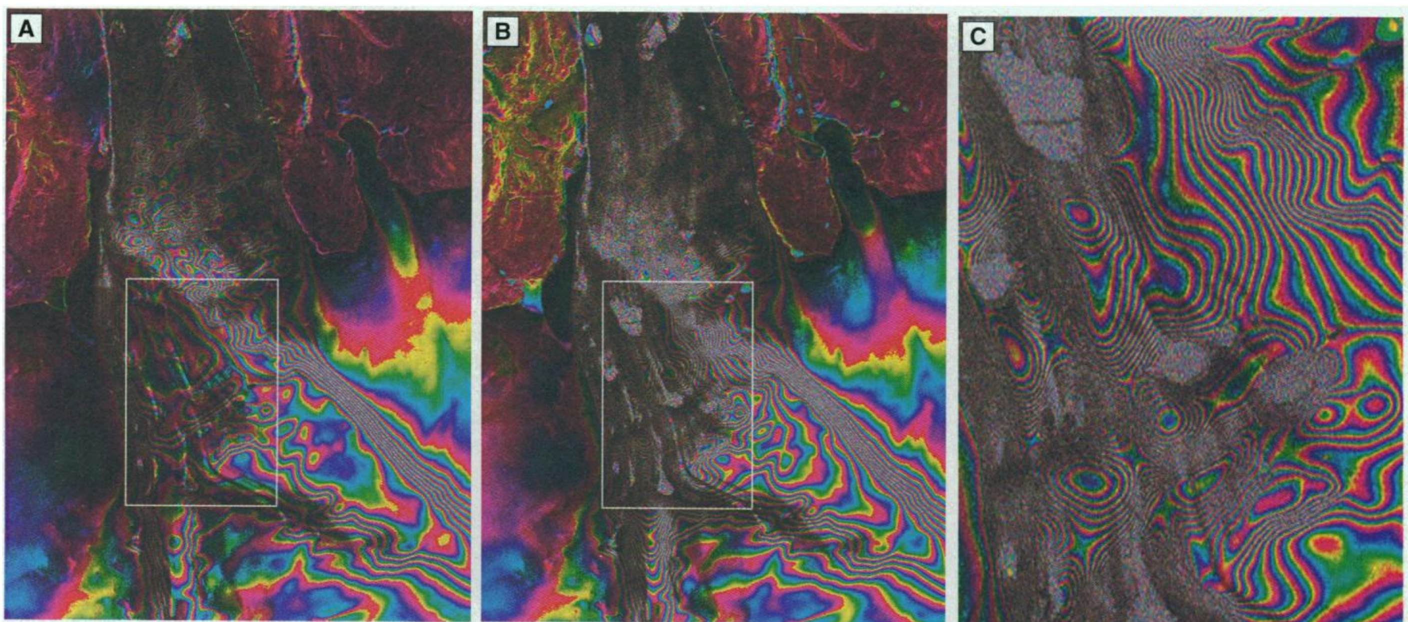

Fig. 2. Interferograms of the fast-moving area of Ryder Glacier (white box in Fig. 1) displayed as hue-saturation-value images with value (brightness) determined by amplitude, hue determined by phase, and constant saturation. Topographic effects were removed so that each fringe (yellow-red transition) represents 2.8 cm of displacement directed toward or away from the radar. (**A**) Interferogram for the interval from 21 to 22 September 1995. Vertical displacement from ice flow over bumps introduces closed-contour, bull's-eye patterns. Velocity gradients across shear margins yield linear, tightly spaced parallel fringes. (**B**) Interferogram spanning the period from 26 to 27 October 1995. Denser fringes indicate a dramatic change in velocity compared with the September observation. Noisy or indiscernible fringes are caused by temporal decorrelation (*16*) and phase aliasing. (**C**) Reprocessing of the data to higher resolution restores fringes in some areas, as shown by this higher resolution blowup of an area [white boxes in (A) and (B)] from the October interferogram. The lack of fringes on the lakes indicates complete decorrelation (*16*).

(Fig. 3A), several lakes show up as small, dark areas, whereas the same lakes appear as bright features in the October image (Fig. 3B). The change in signature indicates that the lakes may have drained over the period from September to October, causing the ice on the surface to collapse. The lake basins are regions of low correlation (*16*) in the October interferogram (Fig. 2C), indicating that they underwent substantial surface change during the 1-day period, such as would be caused by drainage-induced fracturing of the ice on the lake surface. This suggests that the probable drainage of the lakes was related in some way to the increase in velocity.

In the area near Jakobshavns Isbrae, several lakes periodically drain through large moulins (*17*). These moulins close off during the winter, when there is no meltwater input from the surface. After a lake forms in the summer, melting and water pressure reopen the moulin, allowing drainage. Some similar process, such as high basal water pressure opening or enlarging connections to the surface, may allow the lakes on the Ryder to drain near the end of the melt season. The increase in meltwater access to the bed might play a role in greater sliding velocity.

Alternatively, the increase in velocity could have opened crevasses, allowing the lakes to drain. In this case, lake drainage is an effect rather than a cause of the rapid flow, and the flow instability could be caused by changes in the basal water system alone. One possible scenario is that the presumed bedrock ridge causes ponding of subglacial water beneath the ice plain. This may take place if the upstream side of the bedrock ridge is 10 times steeper than the relatively low ice surface slope driving basal water downstream (*18*). Basal water pressure may increase to the point at which stable sliding is no longer possible and a mini-surge begins.

We do not know if mini-surges are common (perhaps seasonal) on the Ryder or other outlet glaciers. We also do not know if this is an indication of potential for a more profound flow instability, such as a surge, which could produce a substantial change in ice flux. Surging glaciers are known to shut down and restart (*8*). Perhaps what we observed on the Ryder was a surge that did not quite succeed.

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11. Velocity differences below 150 m/year are accurate to within about 10 m/year. Where we measured larger differences, the errors may be greater because of proximity to regions where the phase could not be unwrapped (that is, have the modulo-2π ambiguity removed).
12. Over large parts of the fast-moving areas, fringes remain visible but are too noisy to unwrap.
13. For equal flow rates, the pattern of fringes is three times denser for a 3-day versus a 1-day interferogram, because three times the displacement occurred. Where we could not estimate velocity, the noisy fringe patterns for the 1-day October interferogram were visually denser than for the 3-day interferogram (acquired March 1992 and representative of the normal flow mode), suggesting that the October 1995 speed is in excess of three times its normal rate over some of the faster moving area.
14. The effect of vertical displacement, which is proportional to horizontal speed, dominates the phase at length scales of less than a few kilometers (*3*). Thus, similar short-scale variation observed in the November and September interferograms indicates that the horizontal speeds are comparable.
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22. We thank B. Bindschadler and the reviewers for their comments on the manuscript, and C. Werner for providing the synthetic aperture radar processor. I.J. and R.K. performed this work at the Jet Propulsion Laboratory under contract with NASA. S.T. acknowledges support from the Henry and Grazyna Bauer fellowship. M.F. was supported under NASA Mission to Planet Earth grant NAGW4285. Radar data were supplied by the European Space Agency.

28 June 1996; accepted 21 August 1996

Observations of Near-Zero Ozone Concentrations Over the Convective Pacific: Effects on Air Chemistry

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A series of measurements over the equatorial Pacific in March 1993 showed that the volume mixing ratios of ozone were frequently well below 10 nanomoles per mole both in the marine boundary layer (MBL) and between 10 kilometers and the tropopause. These latter unexpected results emphasize the enormous variability of tropical tropospheric ozone and hydroxyl concentrations, which determine the oxidizing efficiency of the troposphere. They also imply a convective short circuit of marine gaseous emissions, such as dimethyl sulfide, between the MBL and the uppermost troposphere, leading, for instance, to sulfate particle formation.

Because of the reactions

$$O_3 + h\nu(\lambda < 320\,\text{nm}) \rightarrow O(^1D) + O_2 \quad (R1)$$

$$O(^1D) + H_2O \rightarrow 2OH \quad (R2)$$

where h is Planck's constant, ν is frequency, and λ is wavelength, ozone (O_3) is the precursor molecule for hydroxyl (OH) radicals (*1*), the atmosphere's main oxidizing agent. The small fraction of atmospheric O_3 that is located in the troposphere thus plays a large role in the chemical composition of the atmosphere. In the stratosphere, photolysis of molecular oxygen (O_2) forms O_3, of which a fraction is transported mostly to the extratropical troposphere (*2*).

In the troposphere, reactions R1 + R2, and, in addition, reactions

$$CO + OH \rightarrow H + CO_2 \quad (R3)$$

$$H + O_2 + M \rightarrow HO_2 + M \quad (R4)$$

$$HO_2 + O_3 \rightarrow OH + 2O_2 \quad (R5)$$

$$\text{net: } O_3 + CO \rightarrow CO_2 + O_2$$

are responsible for O_3 destruction (*3*). In the oceanic atmosphere, emissions of nitric oxide (NO) from the surface and lightning are small. With measured NO volume mix-