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THE JAKOBSHAVNS EFFECT

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Abstract. The Jakobshavns Effect may have been a significant factor in hastening the collapse of palaeo ice sheets with the advent of climatic warming after 18,000 years ago and may precipitate partial collapse of the present-day Greenland and Antarctic Ice Sheets following CO_2-induced climatic warming in the decades ahead. The Jakobshavns Effect is observed today on Jakobshavns Glacier, which is located at 69°10'N on the west coast of Greenland. The Jakobshavns Effect is a group of positive feedback mechanisms which allow Jakobshavns Glacier to literally pull ice out of the Greenland Ice Sheet at a rate exceeding 7 km/a across a floating terminus 800 m thick and 6 km wide. The pulling power results from an imbalance of horizontal hydrostatic forces in ice and water columns at the grounding line of the floating terminus. Positive feedback mechanisms that sustain the rapid ice discharge rate are ubiquitous surface crevassing, high summer rates of surface melting, extending creep flow, progressive basal uncoupling, progressive lateral uncoupling, and rapid iceberg calving.

Introduction

The crest of the north-south ice divide of the Greenland Ice Sheet is bowed sharply eastward between 69°N and 72°N. In this latitude band, sheet-flow extends from the ice divide to the eastern ice margin, but on the western flank, sheet-flow becomes mostly stream-flow toward the western ice margin. There, twenty outlet glaciers discharge some 22 percent of Greenland ice into coastal fjords having a combined width of only 80 km [Bader, 1961; Carbonnell and Bauer, 1968]. Six of the twenty outlet glaciers discharge 21 percent of the ice and one, Jakobshavns Glacier, discharges up to 7.6 percent [Bindschadler, 1984]. It is the world's fastest-known glacier, with a midsummer velocity of 23 m/d at its terminus [Lingle et al., 1981]. In their computer model of ice dynamics, Radok et al. [1982] predicted a largely thawed bed on the west flank of the central ice divide and a largely frozen bed on the east flank. Sharp eastward bowing of the ice divide seems to be caused primarily by a loss of basal traction on the west flank caused by lubrication of the ice-rock interface. Secondary factors are a somewhat higher bed topography on the east that would tend to displace the ice divide eastward, and much heavier snow accumulation on the west that would tend to displace the ice divide westward [Weertman, 1973].

Loss of basal traction generates ice streams, which are fast currents of ice that develop toward the margins of ice sheets and discharge most of the ice. Stream flow begins almost 100 km east of the steep bedrock cliff that constitutes the headwall of Jakobshavns Isfjord, where Jakobshavns Glacier becomes afloat in water over 800 m deep [Carbonnell and Bauer, 1968]. Jakobshavns Glacier is therefore a floating ice shelf within Jakobshavns Isfjord and, to the extent that it has no bedrock pinning points, it has no basal traction at all. Instead, Jakobshavns Glacier acquires the enormous pulling power of a thick unpinned ice shelf, as analyzed by Weertman [1957]. Loss of basal traction allows Jakobshavns Glacier and the other west-coast outlet glaciers between 69°N and 72°N to literally pull ice out of the Greenland Ice Sheet. In turn, this pulling power seems to depend on high rates of summer melting over the heavily crevassed surfaces of the ice streams, with much of the meltwater passing through crevasses and lubricating the basal ice-rock interface. I have called this relationship between surface melting and pulling power in a heavily crevassed ice stream The Jakobshavns Effect [Hughes, 1983]. Now I wish to elaborate upon The Jakobshavns Effect and examine its influence on stability of the Greenland Ice Sheet.

Causes of The Jakobshavns Effect

The Jakobshavns Effect seems to be a consequence of several positive feedback processes.

Surface Roughness

Over all its length, the surface of Jakobshavns Glacier is a chaos of crevasses and seracs. This is the most distinguishing feature of a surging glacier [Paterson, 1981, p. 275]. It approximately triples the surface area of the glacier and allows the glacier to absorb much more solar energy by virtue of presenting a greater surface area to direct solar radiation and by permitting multiple reflections of indirect radiation between crevasse walls [Pfeffer, 1982].

Surface Melting

In July 1978, we measured surface melting rates that averaged 0.1 m/d on serac faces in the floating part of Jakobshavns Glacier [Lingle et al., 1981]. Melting rates on all faces, sunlit or in shadow, north or south facing, windward or leeward, vertical or horizontal, were substantial. All of this meltwater drained into crevasses to either refreeze or find its way to the bed. Latent heat released by refreezing enhances creep spreading rates because of thermal softening.

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Meltwater reaching the bed allows greater basal sliding rates in grounded ice because it lubricates the ice-bed interface and increases basal water pressure. An enormous volume of water is involved. A 0.1 m/d midsummer melting rate on a rough surface that triples the surface area of the 8 km long by 6 km wide portion of Jakobshavns Glacier floating in Jakobshavns Isfjord removes 0.3 m/d of vertical ice thickness. Averaging 0.3 m/d in midsummer with 0 m/d in midwinter gives 55 m/a of ice thinning over 48 km^2 of floating ice. This releases 2 x 10^{18} cal/a if all the meltwater refreezes internally; otherwise it delivers 20 km^3/a of water to the bed. Figures for the grounded part of Jakobshavns Glacier would be less, but probably the same order of magnitude.

Extending Flow

If all surface meltwater refreezes internally, the 55 m/a of vertical thinning over 48 km^2 of floating ice requires a velocity increase of 550 m/a at the 6 km wide and 800 m thick calving front of Jakobshavns Glacier, because of volume conservation (water freezing in a crevasse allows the crevasse to reopen). Ice velocity from the fjord headwall to the calving front increases from 15 m/d to 23 m/d [Lingle et al., 1981], giving 2920 m/a caused by a combination of internal refreezing and creep spreading in the floating ice. Averaging this velocity increase over the 8 km floating length gives a longitudinal strain rate of over 0.3/a in extending flow. The mean ice temperature would have to be -5°C in order to maintain this extending strain rate in a glacier of constant thickness floating between fjord sidewalls that were essentially frictionless and parallel [Weertman, 1957; Paterson, 1981, Table 3.3].

Basal Uncoupling

Since lateral shear zones alongside the fjord sidewalls are nearly parallel, a 0.3/a extending strain rate is also the thinning strain rate. Applying the buoyancy requirement of a floating glacier to the 90 m ice surface elevation at the headwall grounding line gives a grounding-line ice thickness of about 900 m. Uniform creep therefore thins the floating ice about 270 m/a, which raises basal ice some 240 m/a at the grounding line. Surface meltwater reaching the bed, instead of refreezing internally, is a real loss of ice mass. Melting 55 m/a vertically on the rough surface raises ice at the grounding line about 50 m/a if all surface meltwater reaches the bed. Raising basal ice at the grounding line 240 m/a by creep thinning and up to an additional 50 m/a by surface melting is a powerful means for basal uncoupling, which consists of bedrock lubrication in the grounded glacier, eliminating bedrock pinning points in the floating glacier, and causing the grounding line to retreat. Grounding-line retreat of Jakobshavns Glacier has apparently been halted at the steeply-rising headwall of Jakobshavns Isfjord.

Lateral Uncoupling

Stream-flow emerges from sheet-flow 100 km east of the calving front of Jakobshavns Glacier. This is evidence that lateral uncoupling alongside an ice stream can begin long before the ice stream becomes an outlet glacier confined between fjord walls. Lateral uncoupling is most complete inside Jakobshavns Isfjord, however, as demonstrated by the nearly constant transverse profile of ice velocity between the lateral shear zones [Bauer et al., 1967; Carbonnell and Bauer, 1968; Lingle et al., 1981]. A cushion of relatively stagnant ice lies between lateral shear zones and the rock sidewalls of the fjord in most places at the surface. This suggests that lateral uncoupling is facilitated by thermal and strain softening within the shear zones, at least near the glacier surface. Glacial sliding at the ice-rock interface may account for true lateral uncoupling at deeper levels if the fjord sidewalls, which curve inward with depth, intersect the shear zone before the glacier becomes afloat.

Rapid Calving

If the 23 m/d midsummer velocity of Jakobshavns Glacier is maintained in midwinter, the annual velocity is 8.4 km/a and the iceberg calving rate must also be 8.4 km/a if the calving front fluctuates about a stable position. Calving is intermittent and produces tabular icebergs that often roll over. In July 1985, we watched the calving front retreat nearly 2 km in only 45 minutes, after some weeks with no major calving. Calving mechanisms have been examined by Reeh [1968], Holdsworth [1977], Robin [1979], and Fastook and Schmidt [1982], among others. It would seem that some bottom crevasses are necessary to allow tabular icebergs to calve from Jakobshavns Glacier. Bottom crevasses can open from extending flow in the floating glacier [Weertman, 1980] and from tidal flexure along grounding lines [Lingle et al., 1981]. Bottom crevasses, being filled with water, can extend up to sea level and meet surface crevasses.

Summary and Discussion

All feedbacks seem to be positive in The Jakobshavns Effect. Surface crevasses are a consequence of extending flow, and crevassing is ubiquitous at surge velocities. Surface melting is enhanced greatly by extensive surface crevassing. Surface meltwater that refreezes internally helps to increase the creep rate to over 0.3/a by releasing huge amounts of latent heat. Surface meltwater that reaches basal ice increases the basal sliding rate of grounded ice by lubricating the ice-rock interface. Increasing both creep and sliding rates increases velocity, surface crevassing, and meltwater production in that order. Ice thinning by creep and by melting raises the floating ice from bedrock pinning points, thereby allowing a faster ice-stream velocity by reducing ice-shelf buttressing. An unpinned ice shelf allows a faster iceberg calving rate because it can thin more rapidly by creep. Enhanced creep thinning shortens the vertical ice thickness that must be fractured by crevasses and allows crevasses to penetrate farther. Rapid iceberg calving reduces the length of floating ice and therefore the potential number of ice-shelf pinning points. An unpinned ice shelf has a potentially huge pulling power on the ice stream, because its pulling force increases as the square of the floating ice thickness [Weertman, 1957] and the maximum pulling force is at the grounding line, because there the floating ice is thickest[Sanderson, 1979].

The only feature tending to stabilize Jakobshavns Glacier is Jakobshavns Isfjord, whose bedrock sidewalls and headwall prevent The Jakobshavns Effect from spreading laterally and inland. Without these bedrock constraints, it is difficult to imagine what could prevent The Jakobshavns Effect, as observed in Jakobshavns Glacier and other outlet glaciers between 69°N and 72°N, from collapsing most of the Greenland Ice Sheet. Indeed, the calving front of Jakobshavns Glacier has retreated 27 km up Jakobshavns Isfjord from 1850 to 1964 [Carbonnell and Bauer, 1968], perhaps as a consequence of climatic warming following the Little Ice Age. The grounding line of Jakobshavns Glacier probably retreated a similar amount, because the sidewalls of Jakobshavns Isfjord are polished and scraped clean of lichens from a height that increases from near sea level to some 200 m above sea level over the 27 km of calving-front retreat. This former ice elevation would require floating ice to have been almost 2000 m thick at the present-day calving front, where floating ice is now only 800 m thick. So the former ice was probably grounded, unless the fjord is at least 1800 m deep.

Today, the Greenland Ice Sheet ends mostly on land in the south, at fjord headwalls in the center, and as a continuous tidewater ice wall along much of the northern coastline. This implies that The Jakobshavns Effect may have migrated northward with climatic warming since the last glacial maximum 18,000 years ago. Implications concerning a role for The Jakobshavns Effect in collapsing former ice sheets after that time and parts of the Antarctic Ice Sheet in the face of future CO_2-induced climatic warming are obvious.

References

Bader, H., The Greenland Ice Sheet, U.S. Army Cold Regions Research and Engineering Laboratory Monograph 1-B2, 18 pp., Hanover, New Hampshire, 1961.

Bauer, A., Fontanel, A., and Grau, G., The application of optical filtering in coherent light to the study of aerial photographs of Greenland glaciers, Journal of Glaciology, 6, 781-793, 1967.

Bindschadler, R.A., Jakobshavns Glacier Drainage Basin: A Balance Assessment, Journal of Geophysical Research, 89, 2066-2072, 1984.

Carbonnell, M., and Bauer, A., Exploitation des couvertures photographiques aériennes répétées du front des glaciers vêlant dans Disko Bugt en Umanak Fjord, Juin-Juillet 1964: Expedition Glaciologique Internationale au Groenland (EGIG), 1957-1960, Meddelelser om Grønland, 2, 1-78, 1968.

Fastook, J.L., and Schmidt, W.F., Finite-element analysis of calving from ice fronts, Annals of Glaciology, 3, 103-106, 1982.

Holdsworth, G., Tidal interaction with ice shelves, Annales de Geophysique, 33, 133-146, 1977.

Hughes, T., The stability of the West Antarctic Ice Sheet: What has happened and what will happen, CO2, 021, IV.51-IV.73, 1983.

Lingle, C.S., Hughes, T.J., and Kollmeyer, R.C., Tidal flexure of Jakobshavns Glacier, West Greenland, Journal of Geophysical Research, 86, 3960-3968, 1981.

Paterson, W.S.B., The Physics of Glaciers, 2nd Edition, 380 pp., Pergamon, Oxford, 1981.

Pfeffer, T., The effect of crevasses on the radiative absorptance of a glacier surface (abstract), Annals of Glaciology, 3, 353, 1982.

Radok, U., Barry, R.G., Jenssen, D., Keen, R.A., Kiladis, G.N., and McInnes, B., Climatic and Physical Characteristics of the Greenland Ice Sheet, Parts I and II, 193 pp., Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, 1982.

Reeh, N., On the calving of ice from floating glaciers and ice shelves. Journal of Glaciology, 7, 215-232, 1968.

Robin, G. de Q., Formation, flow, and disintegration of ice shelves. Journal of Glaciology, 24, 259-271, 1979.

Sanderson, T.J.O., Equilibrium profile of ice shelves, Journal of Glaciology, 22, 435-460, 1979.

Weertman, J., Deformation of floating ice shelves, Journal of Glaciology, 3, 38-42, 1957.

Weertman, J., Position of ice divides and ice centers on ice sheets, Journal of Glaciology, 12, 353-360, 1973.

Weertman, J., Bottom crevasses, Journal of Glaciology, 25, 185-188, 1980.

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