Correspondence

Are ice-stream tributaries the surface expression of thermal convection rolls in the Antarctic ice sheet?

Figure 1 is a remarkable dynamic map of ice-stream tributaries draining the Antarctic ice sheet and converging on major ice streams. It was produced by glaciologists at the Jet Propulsion Laboratory of the California Institute of Technology and in the Earth System Science Department of the University of California at Irvine (Rignot and others, 2011). They used remote-sensing data provided by the European Space Agency (ESA), the Japanese Space Agency (JSA) and the Canadian Space Agency (CSA) using NASA technology. Dozens of scientists and technicians contributed to this project. Color-coded surface ice velocities increase from orange near interior ice divides to green in tributaries to blue in ice streams to red on ice shelves. The NASA News website gives viewers a 'flying carpet' tour of this dynamic map, zooming in on sectors of the ice sheet draining into the Ross, Amundsen and Weddell Seas (http://www.jpl.nasa.gov/news/news.cfm?release=2011-256&cid=release).

I have proposed that ice streams originate from thermal convection rolls having ice-stream tributaries as their surface expression (Hughes, 2009). Now I elaborate on this hypothesis by addressing specific questions linked to Figure 1. Then I propose two field experiments providing preliminary tests of whether convection rolls underlie the Antarctic ice-stream tributaries in Figure 1. Proposing these tests is the primary reason for this correspondence. Tributaries have lower surfaces than flanking ice due to creep thinning caused by downslope extension, so ice enters from the sides all along their length. Convective flow with ice rising in lateral shear zones and sinking in the tributary enhances advective flow across shear zones and surface lowering in the tributary. Measuring these enhancements constitutes the two tests.

What are thermal convection rolls in ice sheets? These rolls are long cylinders of ice moving in a downslope spiral due to advective flow in the downslope surface direction. Without advective flow, thermal convection as studied for Newtonian fluids is organized in polygonal platform cells, with warm rising flow along narrow cell boundaries and cool sinking flow in broad cell centers (Knopoff, 1964). When advective flow is superimposed on convective flow, the polygonal cells become rolls elongated in the direction of advective flow (Gallagher and Mercer, 1965; Davies-Jones, 1971). In the Antarctic ice sheet, advective flow is caused by the gravitational driving stress in the surface downslope direction (Nye, 1952). A cartoon showing how advective flow converts convecting polygonal platform cells under interior ice divides into convecting rolls elongated in the direction of advective flow that converges on ice streams was proposed by Hughes (1976, fig. 8).

What might be the size and spacing of thermal convection rolls in the Antarctic ice sheet? The ice-stream tributaries in Figure 1 average 4–6 km in width in ice 2–4 km thick and their spacing decreases from about 25–35 km near ice divides to being packed tightly together as they enter major ice streams. If each tributary is the surface expression of an underlying convection roll, these are the dimensions and spacing of rolls. When rolls do not contact each other, convective flow rises in lateral shear zones ~1 km wide for each tributary and sinks under the tributaries at widths of 4–6 km. This requires that rising flow should be two to three times faster than sinking flow. When rolls are packed together, rising convective flow diverges into adjacent rolls under tributaries. This should remove lateral shear due to advective ice flow because both tributaries will be moving at about the same velocity. However, the easy-glide ice fabric generated by horizontal advective side shear will remain because it also facilitates vertical convective side shear. With rising convective flow supplying sinking convective flow in adjacent rolls, the sinking velocity will be half of what it was when convection rolls were isolated from each other because the sinking width is doubled.

Why should thermal convection exist in the Antarctic ice sheet? Because the Antarctic sheet is heated from below, so a thermal buoyancy stress exists which attempts to mix cooler upper ice with warmer lower ice so the density inversion due to thermal expansion becomes so small the thermal buoyancy stress is unable to overcome stresses that resist this mixing.

How large is the thermal buoyancy stress driving convective mixing? According to the hypothesis presented here, ice-stream tributaries are the surface expression of thermal convection rolls, so the top of a roll will be the tributary surface. In this case, the thermal buoyancy stress driving thermal convection will be comparable with the driving stress for advective flow, ~45 kPa for warmer thinner West Antarctic ice and up to 100 kPa for colder thicker East Antarctic ice (Hughes, 2009, eqns (1) and (2)).

Can vertical temperature profiles down boreholes be used to compute density profiles in ice sheets? They can, provided a correction is made for the compressibility of ice at high pressures (Hughes 2009). In the Antarctic ice sheet, a temperature minimum and density maximum occurs about halfway down the borehole at Byrd Station, West Antarctica, where snow accumulation rates are high and no tributary exists (Gow, 1970; Hughes, 2009). However, in a tributary to Whillans Ice Stream, a major West Antarctic ice stream, the temperature increase begins virtually at the ice surface (Kamb, 2001). In East Antarctica, where snow accumulation rates are much lower, the temperature increase with depth also begins at the ice surface, especially when advective ice flow is slow (Robin, 1955). So the full ice thickness can reasonably be used to calculate the thermal buoyancy stress as a first approximation.

Does calculating the thermal buoyancy stress lead to calculating resisting stresses in the ice sheet in a conventional force balance? Yes. The thermal buoyancy stress is a gravitational driving stress. In thermal convection rolls, it is resisted by a horizontal tensile stress at the top of rising convective flow and at the bottom of sinking convective flow, a horizontal compressive stress at the top of sinking convection flow and at the bottom of rising convection flow, and shear stresses that are vertical between rising and sinking flow and horizontal above basal flow converging toward rising convective flow and below surface flow diverging from rising convective flow. These stresses will be in vertical planes transverse to convection rolls. Stresses linked to advective flow along convection rolls will also have to be included. In the absence of advective flow, the gravitational and resisting stresses are included in a

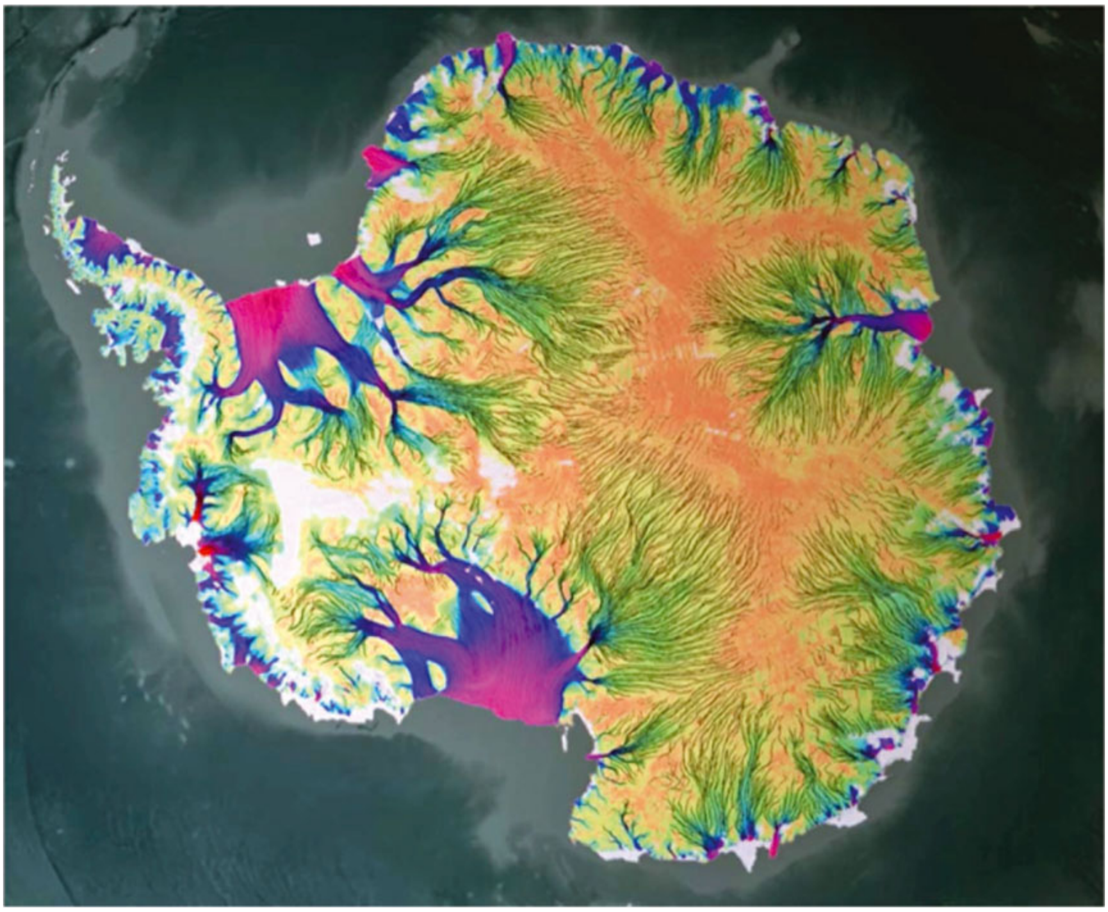

Fig. 1. A full map of Antarctic ice flow showing tributaries supplying major ice streams. This map was compiled by NASA-funded research at the Jet Propulsion Laboratory of the California Institute of Technology and the Earth System Science Department at the University of California at Irvine, using data from Earth-orbiting satellites provided by the Japanese, European and Canadian Space Agencies. Ice velocities increase from orange near interior ice divides to green in ice tributaries to blue in ice streams to red on ice shelves. A video showing motion of the tributaries is available on the NASA News website. Here we propose that ice tributaries are underlain by and driven by thermal-convection rolls aligned with surface ice flow. From Rignot and others (2011; see NASA News, http://www.jpl.nasa.gov/news/news.cfm?release=2011-256&cid=release).

force-and-mass balance that leads to a critical Rayleigh number for initiating thermal convection (Strutt, 1916). This balance is attained as a condition for neutral thermal buoyancy, as calculated by Hughes (1976) for the Antarctic ice sheet, following the Weertman (1967) calculation for convection rolls in the asthenosphere of Earth's upper mantle. In both cases, the resisting stresses cause the surface to be higher where convective flow rises and lower where convective flow sinks. This is compatible with ice-stream tributaries, which are lower than flanking ice.

What is the Rayleigh number? As defined by Strutt (1916), the Rayleigh number is the dimensionless ratio of the rate of heat transported upward by mass transport (thermal convection) to the rate of heat transported upward by the thermal vibrational energy of atoms fixed to their lattice sites (thermal conduction). When this ratio increases enough to overcome the resistance to upward mass transport, the Rayleigh number attains a critical value that allows neutral thermal buoyancy.

Is the Rayleigh number different for initiating convection in a Newtonian fluid compared with convection in a polycrystalline ice sheet? Yes. Thermal convection in an ice sheet begins as transient creep having an initially infinite strain rate that then lowers as steady-state creep sets in, but rises again as recrystallization to an ice fabric favoring convective flow develops (Hughes, 1976, 2009). Therefore, the Rayleigh number is initially infinite, so the initiation of thermal convection cannot be suppressed. In Newtonian fluids, there is no transient creep or recrystallization, so the Rayleigh number is calculated only for steady-state creep (Strutt, 1916). In the Antarctic ice sheet, transient creep becomes unimportant less than 1 year after it begins (Hughes, 2009). After that, steady-state creep dominates, with a slow rate before recrystallization and a fast rate after recrystallization (Hughes, 1976, 2009).

What causes recrystallization of ice in ice sheets? According to von Neumann's principle (Nye, 1960), a crystal fabric develops in polycrystalline materials such as glacier ice that minimizes the resistance to an applied stress field. Creep experiments on randomly oriented polycrystalline ice having a random fabric show that recrystallization begins at ~40% strain (Hughes, 2009). At this strain, dislocations causing creep deformation have piled up at grain boundaries enough to raise the strain energy at these sites to a level that provides the energy for nucleating new strain-free grains that then grow and consume the distorted crystal structure. The strain-free grains have low-angle grain boundaries, so dislocations move from grain to grain, thereby preventing dislocation pile-up (Weertman and Weertman, 1964). This satisfies von Neumann's principle.

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If tributaries are the surface expression of convection rolls, an easy-glide ice fabric exists in lateral shear zones, which facilitates equally horizontal advective flow and vertical convective flow.

What is the steady-state critical Rayleigh number for the Antarctic ice sheet? Following Weertman (1967), Hughes (1976) obtained 280 for visco-plastic exponent $n=1$ in the flow law of ice, and triple that, 840, for $n=3$. This assumes free top and bottom surfaces, which will be approximately the case if ice-stream tributaries overlie a wet bed and are the surface expression of convection rolls. In Newtonian fluids, the Rayleigh number ranges from 657 to 1708, depending on the upper and lower boundary conditions (Knopoff, 1964), but no allowance is made for raising and lowering the surface where convective flow rises and falls, respectively, due to the resisting stresses. Again, tributaries are lower than flanking ice, and this is compatible with stresses resisting convection rolls.

What strain rates would be produced in thermal convection rolls in the Antarctic ice sheet if tributaries are their surface expression? Since the gravitational driving stresses for advective and convective flow are comparable, so would be the resulting strain rates, allowing for a nonlinear strain-rate dependence on stress as quantified in the flow law of ice (Glen, 1955). The alternative is to argue the flow law applies to advective flow but not convective flow. Who wants to make that argument?

Are there any field tests that would detect thermal convection associated with ice-stream tributaries? I propose two tests. The first test is to measure surface ice velocities moving across lateral shear zones into tributaries. If the velocity increases across the shear zone, it must be augmented by rising convection flow in the shear zone that is diverted into the tributary at the surface. The second test is to measure surface lowering in the tributaries. This would approximate the surface velocity of sinking convective flow if it exceeded the surface accumulation rate, assuming steady-state flow. Kenneth Jezek suggested this test. These velocity measurements can be obtained by combining interferometric synthetic aperture radar (InSAR) and GPS technology. Horizontal and vertical velocities can then be measured with an accuracy of centimeters and millimeters per year respectively. However, vertical surface velocities depend on creep thinning, surface accumulation and firn compaction rates. Creep thinning rates must be isolated, and then contributions from both advective and convective flow must be determined.

Assuming these surface velocities can be measured, what is the hypothetical strain rate in convective rolls? Referring to Figure 1, subtract the orange velocity from the green velocity across a tributary lateral shear zone, and divide by a shear-zone width of $\sim$1 km. Half of that is the first-order lateral shear strain rate for advective ice flow in tributaries. Take this velocity difference as 200 m a^{-1} and assume 50 m a^{-1} is due to rising convective flow. Dividing by 1 km gives transverse horizontal and vertical strain rates of 0.100 a^{-1} and 0.025 a^{-1} for advective and convective flow respectively. For ice 3 km thick and a tributary 5 km wide between lateral shear zones, ice rises 3 km in 60 years in the shear zones and sinks 3 km in 150 years in the tributary. Surface ice moving from rising to sinking flow averages 25 m a^{-1} over 2.5 km. The convective circuit of 11 km is completed in 410 years. During this time, the tributary has moved 82 km downslope. Hence, convective flow spirals downstream.

Are current ice-sheet models capable of including convective flow in ice-sheet dynamics? No. Models need to include solutions of the full momentum/equilibrium equations in a balance of forces, mass and energy in three dimensions through time. The solution will have to reproduce the networks of ice-stream tributaries in Figure 1, and show how they change in space and time as both internal and external boundary conditions change.

What field experiments are required to test such a model? If the two field tests at the surface, noted above, are supportive of an underlying thermal convection roll, a grid of deep drillholes along and between lateral shear zones of a tributary will be needed to measure borehole tilt, strain rates and temperatures over time in order to map the configuration of the convection roll causing the surface measurements.

Are there any counterparts to ice-sheet convection rolls in Earth's mantle that could guide these experiments? The prevailing paradigm for thermal convection in Earth's mantle is rising convective flow along oceanic ridges and sinking convective flow along oceanic trenches, both restricted to the asthenosphere. The distance between ridges and trenches is highly variable, and the side boundaries between ridges and trenches are transform faults that isolate tectonic plates in the simplest geometric configuration. The first attempt at modeling this situation using a thermal convection roll was by Weertman (1967) and his analysis was applied directly to the Antarctic ice sheet (Hughes, 1976). These studies are the best guide.

To summarize, a specific type of thermal convection is proposed in which ice-stream tributaries are the surface expression of underlying convection rolls. In this special case, two field experiments are proposed that require highly accurate measurements of horizontal surface velocities across lateral shear zones and vertical surface velocities between these shear zones. If both experiments point to thermal convection rolls under tributaries, these rolls will have to be mapped by exacting measurements of the strain-rate tensor down a surface grid of boreholes that measure strain rates, ice fabrics and temperatures at depth along and between lateral shear zones over time. These measurements are required to define the boundary conditions and specify physical properties of ice to constrain ice-sheet models that attempt to generate these tributaries and map the underlying convection rolls. This is why the two proposed surface experiments must be conducted first.

The two proposed experiments have important implications. A reservoir of cold heavy ice overlies warmer lighter ice throughout the Antarctic ice sheet. This gives rise to a vertical buoyancy stress that is not included in conventional ice-sheet models, even though this stress is comparable with the gravitational stress driving advective flow, provided that ice-stream tributaries are the surface expression of underlying thermal convection rolls aligned with downslope advective ice flow. Ignoring the thermal buoyancy stress amounts to claiming the flow law of ice applies to only some gravitational driving stresses. Abandoning this claim makes ice sheets much more dynamic systems in which ice streams and their tributaries are capable of turning on and off as the Rayleigh number for thermal convection moves above and below a critical value. This gives ice sheets the ability to regulate their ice discharge, and therefore their ability to rapidly self-destruct. This can trigger rapid changes in Earth's climate and sea level.

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