Thermal Convection and the Origin of Ice Streams

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The density inversion at depth in the Antarctic Ice Sheet is the "elephant" in the living room all modelers pretend isn't there. But it is, and it is an enormous source of gravitational potential energy that, in every other dynamic system where density inversions exist, is ultimately converted into kinetic energy of motion and thermal energy linked to motion. The questions are, how is this conversion manifested, where does it take place, and how can it be detected?

The density inversion exists because Antarctic ice gets hotter near the bottom, and occurs when thermal expansion overcomes compression of ice by the weight of overlying ice. Without taking ice compressibility under pressure into account, the density inversion occurs about halfway down, as Tony Gow demonstrated in 1968 for the Byrd Station corehole, when the compressibility wasn't known. With that knowledge now available, the density inversion takes place in the last few hundred meters of ice above the bed. This greatly increases the volume of ice above the density inversion, but the reduced density difference keeps the reservoir of gravitational potential energy about the same.

When a fluid is heated from below, creating a vertical density inversion like the one in the Antarctic Ice Sheet, thermal convection produces "platform cells" with hot fluid rising in cell centers. If horizontal flow is added, the cells elongate in the flow direction and become convecting rolls with hot fluid rising between two rolls. Horizontal flow in the Antarctic Ice Sheet proceeds from interior ice divides and largely converges on ice streams toward the ice-sheet margin.

Ice is crystalline, so flow begins when internal stresses cause line defects called dislocations to migrate through the crystal structure. In polycrystalline ice, this begins with transient creep, which in turn begins with the infinite strain rate of elastic deformation. During transient creep, dislocations pile up at crystal grain boundaries where internal stresses are concentrated. This causes ice to recrystallize into a fabric of ice crystals having an orientation that maximizes the strain rate for the stress field causing dislocations to move. Therefore, the initially infinite strain rate falls to a minimum strain rate as dislocation pile up, and the strain rate increases during recrystallization to a steady-state strain rate that is stable for the imposed stress field.

The Antarctic Ice Sheet has two stress fields, one due to the height of ice above sea level that drives horizontal flow and one due to the density inversion that should drive vertical flow. Horizontal flow is obvious, vertical flow is not. Nonetheless, vertical flow driven by the density inversion should occur at least during transient creep in the timespan between the infinite strain rate and the minimum strain rate, and perhaps also onward to steady-state creep. In addition, vertical flow should occur in something like convection rolls aligned in the direction of horizontal flow, which is the downslope direction in which ice streams form, first as ice-stream tributaries. These tributaries then converge and merge to produce major ice streams.

Suppose a dynamic threshold is reached at which cold heavy ice above the density inversion begins to sink into the warm lighter ice below, and sinking occurs in directions of converging horizontal flow. Warm ice above the bed will continue to move downstream, but some of it may rise along the sides of the sinking slabs. The ice surface lowers as slabs sink, allowing cold ice from the sides to move into the surface depressions. This lateral motion will allow warm rising ice to overtop cold sinking ice in the depressions and partly replace it. Such a flow pattern would be a version of thermal convection.

Basal meltwater would move laterally into the sinking depressions, following the new pressure gradient. Sinking slabs of cold ice would move faster downslope, carried by the faster downslope motion of warm ice below that slides faster on a wetter bed. Warm ice rising along the sides of the sinking cold slabs would weaken their coupling to cold ice on either side, allowing the slabs to move faster. Since 90 percent of Antarctic ice is discharged by ice streams, 90 percent of the cold ice above the density inversion would be converted into kinetic energy of motion by this process.

Since the process begins with transient creep, which is intermittent and of finite duration, would it cause ice streams to turn on and off intermittently? As cold slabs sink, the vertical temperature gradient increases and may convert a melting bed into a freezing bed, suppressing basal sliding. This would slow downslope motion of sinking slabs, perhaps turning off the tributary ice streams until the original temperature gradient is restored.

Modelers need to investigate this process to determine if it allows their models to more closely reproduce the known behavior of the Antarctic Ice Sheet.