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Interactive comment on "Reply to "Basal buoyancy and fast-moving glaciers: in defense of analytic force balance" by C. J. van der Veen (2016)" *by* Terence J. Hughes

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Anonymous Referee #2 deserves a reply. He states, "Having read Hughes' criticisms, I still cannot find fault with Van der Veen's approach, his reasoning, or his conclusions." I also find no fault–when Van der Veen is discussing his analytic approach to the force balance based on integrating the Navier-Stokes equations. I find fault with his characterization of my geometric approach, which is probably my own fault for not making my approach clear enough for him. Anonymous Referee #2 may also be confused. So I'll try again.

My geometrical approach to the force balance for linear ice streams began in 1988 when I introduced my concept of the pulling power of ice streams quantified by my

floating fraction "phi" of the bed under an ice stream that was covered by water deep enough to drown bedrock projections into the ice (and, by extension, to supersaturate subglacial till so it also offered no resistance to glacier sliding). After extensive review, that work was published by the Journal of Glaciology in 1992: On the pulling power of ice streams, 38(128), 125-151.

My pulling power paper introduced my vertical force balance using floating fraction phi to determined the height up a borehole basal water pressure would drive basal water. That made it possible to map the floating fraction of ice at the bed by mapping the height of basal water in boreholes, a task undertaken by Barclay Kamb and Hermann Engelhardt several years later for West Antarctic ice streams, notably Kamb Ice Stream. Nothing more was needed to produce those maps. Integrating the Navier-Stokes equations cannot deliver that result.

At the same time, in 1988, I introduced my geometrical approach to the horizontal force balance in the direction of ice flow. This was a tougher nut to crack and several attempts to get it right were presented in papers of mine spanning the next 24 years when Nova published my book, Holistic Ice Sheet Modeling: A First-Order Approach, in 2012. That book presents two solutions, a robust approximate solution based only on the longitudinal force balance, and a more accurate solution based on both the force balance and the mass balance (both solutions good for flowlines and for flowbands of constant width).

My approximate solution is Van der Veen's Equation (12) in his 2016 paper. It is plotted in his Figure 1 (bottom) for Byrd Glacier. It has the considerable advantage of giving a good approximation to the floating fraction over the whole ice drainage basin of an ice stream consisting of tributaries that converge on the ice stream, without actually having to know the paths of tributaries. Specifying phi at any location specifies ice elevation above the bed at that location. This is a boon for reconstructing former ice sheets from glacial geology that doesn't show changing flow directions through time, see J.L. Fastook and T.J. Hughes, New perspectives on paleoglaciology, Quaternary

Science Reviews, 80, 169-194, 2013.

The more accurate solution overcomes the main defect of the approximate solution, namely, basal water pressure cannot push basal water higher than its height above the bed at sea level (or lake level) when the ice stream becomes totally afloat. Hence, floating fraction phi is tied to the ice thickness where an ice stream meets an ice shelf or becomes wholly afloat as an ice tongue. In the more accurate solution, basal water pressure pushes basal water up boreholes to the heights observed by Kamb and Engelhardt for West Antarctic ice streams, see B. Kamb, Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. In Alley, R.B., and Bindschadler, R.A. (Eds.), The West Antarctic Ice Sheet: Behavior and Environment, American Geophysical Union, Antarctic Research Series, Washington, D.C., pp. 157-200, 2001.

Fortunately, the robust solution for phi is sufficient for most ice streams draining past and present ice sheets. The more accurate solution is needed for West Antarctic ice streams because they are unusually long and low, owing the the advanced stage of gravitational collapse of the West Antarctic Ice Sheet.

Ice-stream thickness at an ice-shelf grounding line is linked to the ability of a laterally confined and locally pinned ice shelf to buttress ice streams that supply it with ice. The more buttressing, the thicker the ice, and therefore the higher the water column at the grounding line. This allows phi at any location drained by the ice stream to push water higher in boreholes. The product of these two values of phi, one at the grounding line and one in the ice drainage basin (combining the more robust and more accurate solutions) produces a basal buoyancy factor that allows ice streams to be assigned a position in their life cycle, from inception to growth to mature to declining to terminal. This has been done for all the major Antarctic ice streams at the present time, see T. Hughes, A simple holistic hypothesis for the self-destruction of ice sheets, Quaternary Science Reviews, 30(15-16), 1829-1845, 2011. This kind of insight and synthesis is not possible using only the Navier-Stokes equations in the force balance.

I hope, as a result of this exchange, I will have an opportunity to improve my reply to the 2016 paper by Van der Veen, especially by showing how both the vertical and longitudinal force balances are needed to quantify floating fraction phi so that measuring the height of water in boreholes allows the regions of ice-bed uncoupling to be mapped accurately under an ice stream and along tributaries supplying it. This is a major challenge that needs a solution in glaciology. A first step comes from the geometrical force balance.

It is always a mistake to embrace the "settled science" mantra. Integrating the Navier-Stokes equations is not the end of the story in understanding the force balance in glaciology, or in modeling ice sheets using the force, mass, and energy balances to obtain three dimensional numerical solutions for changing ice dynamics over time. That puts science in a box. Advances in science come from thinking outside the box.

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