# Relating Longitudinal Tension, Basal Shear, and Side Shear To Ice-Bed Coupling Beneath Ice Streams

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Ice-bed coupling can be quantified as the ratio of basal water pressure P(w) to ice overburden pressure P(i). Maximum coupling occurs when P(w)/P(i) = 0 and maximum uncoupling occurs when P(w)/P(i) = 1. In previous work, the longitudinal deviator tensile stress in an ice stream and its longitudinal force gradient have been related to P(w)/P(i) quantitatively using a geometrical force balance. That work is now extended to relate both the basal shear stress and the side shear stress to P(w)/P(i) such that resistance to stream flow is transferred from the bed to the sides of an ice stream as P(w)/P(i) increases from zero to unity. This allows transitions from sheet flow to stream flow to shelf flow to be expressed in terms of basal shear, side shear, longitudinal tension, and the longitudinal force gradient using two physical parameters. First, ratio P(w)/P(i) is a direct measure of ice-bed coupling. Second, since P(w) is directly related to the height h(w) of water above the bed that would be supported by the basal water pressure, h(w) is a direct measure of the hydraulic head that drives basal water from sources to sinks beneath an ice stream. The greater the variation in absolute values of h(w) and the steeper its longitudinal gradient, the more forcefully basal water will be transported from sources to sinks. Sources can include surface meltwater that reaches the bed through crevasses, and sinks can include discharge of basal water across an ice-shelf grounding line. The cause of P(w)/P(i) and of h(w) at any point along an ice stream, and their gradients from point to point, is the downstream resistance to stream flow that can be represented by a compressive back-stress at every point. This resistance can be reduced rapidly where surface meltwater reaches the bed and when all or part of a buttressing ice shelf disintegrates, as has happened for Jakobshavn Isbrae in Greenland and perhaps for some West Antarctic ice streams. The geometrical force balance therefore allows the significant stresses in an ice stream to be linked to ice-bed coupling and subglacial hydrology, and to processes at the surface and beyond the grounding line. Perturbations in these processes cause ice velocities and thinning or thickening rates to change rapidly along the whole length of an ice stream upstream from where the perturbations occurred.