

## ***Interactive comment on “Refreezing on the Greenland ice sheet: a comparison of parameterizations” by C. H. Reijmer et al.***

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Review comments on “Refreezing on the Greenland ice sheet: a comparison of parameterizations” by C. H. Reijmer et al. (W.T. Pfeffer)

The good news is that the RACMO2 model and the 6 refreezing parameterizations the authors choose for comparison all do pretty much the same thing (“after some tuning”) – not too surprising given that all 7 approaches are working with essentially the same processes, just at different levels of sophistication. As written the presentation seems generally clear. A more detailed description of RACMO2 would have made the whole thing more understandable, but perhaps this paper isn’t the place for it. As it is, I can go out to various earlier publications (e.g. Greuell and Konzelman GCP (1994), Bougamont and Bamber, JGR (2005), Ettema et al, TCD (2010), etc.) and read what

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those authors do, but I'm left guessing a lot of the time as to whether the procedures described in those papers are telling me what's happening in RACMO2 or not. Perhaps the authors can be a bit more specific here as to what details of those papers are implemented in RACMO2?

The greater difficulty for me is whether any of these models/parameterizations are describing what's actually happening on the Greenland Ice Sheet. There really is no observational data available on downslope flow and runoff for confirmation – no one has yet figured out how to measure these. Observations exist on vertical infiltration and refreezing (although not many), but as for how much water is actually moving laterally on the ice sheet, and what the total runoff might be – we're still really in the dark. The fact that everyone's in agreement in the comparisons described here isn't a guarantee of validity – everyone might simply be modeling the same hypothetical situation that never actually occurs.

In particular I am concerned about the absence of any consideration of heterogeneous infiltration (i.e. piping) in the downward transport of water. All the parameterizations described here, as well as RACMO2, assume homogeneous infiltration of percolating meltwater into firn, whereas we know from many observations that heterogeneous infiltration, followed by a homogeneous wetting front, is more generally what occurs in the percolation facies. This turns out not to be an issue in seasonal snow, and thus not for Greenland below the ELA, but at higher elevations (and there's a lot of real estate between the ELA and the dry snow line, in West Greenland especially), this could be a major flaw.

All of the parameterizations described handle the capacity of the firn to capture infiltrating water by using some variation on the "thermally active layer," a surface firn unit of defined thickness in which a mass of water refreezes according to the firn's initial temperature and void space. In Pf1991 and JH2000, the thickness is the current year's accumulation  $C$ ; in HdW1999 and Wr2007 it's dice; in Oe1991, it's 2 m (via the total energy demand  $Q_{ice}$ , determined by the average temperature in the top 2 m of firn);

Re1991 doesn't calculate anything, but assumes a fixed retained fraction. RACMO2 doesn't limit the depth of infiltration to a specific value, but the refreezing capacity is nonetheless defined in terms of uniform infiltration: the cold content and pore space of the entire firn mass down to any given depth is involved. Any one of these formulation keeps the released latent heat and refrozen mass close to the surface where both aid (by eliminating cold content and reducing pore space) in preparing the surface firn for mobilizing water downslope.

In contrast to these models, heterogenous percolation can move water rapidly to depth in saturated pipes where the refreezing has no effect on near-surface firn properties; infiltrating melt passes through the near-surface, leaving the firn away from the immediate vicinity of the drainage pipes unchanged. The process of early melt removing cold content and reducing permeability doesn't happen in this case because the infiltration ends up refreezing so deep that the layers where runoff might occur will never feel it. Heterogeneous percolation is well-known to occur (e.g. Muller, 1976; Marsh and Woo, 1984; Benson, 1962; Pfeffer and Humphrey, 1996 and 1998) but terribly difficult to measure or even generally characterize, so it's not too surprising that no models include it as a process. In Pfeffer et al, 1991 I did consider this possibility by considering two bracketing extremes, the more restrictive of which required that the pore space of the entire firn column be filled in (i.e. piping got all the way to the firn/ice transition). Filling in the entire firn column is pretty far-fetched, to be sure, but it was a stab at finding out how much water piping could trap.

So that's a process that no one is looking at. Does it matter? It might matter a lot: piping can move water very quickly and through a small number of vertical drainage paths (pipes) down 4 to 10 m depth, and even deeper, low in the percolation facies in west Greenland, where there is a lot of surface melt that either is getting out (if piping matters) or isn't getting out (if piping does matter). The potentially deep reach of piping was suggested in observations by Benson back in the '60s, and by us (Pfeffer and Humphrey, 1998) more recently, as well as other authors. We also have a new pa-

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per in press (Humphrey et al, “Thermal tracking of melt water retention in Greenland’s accumulation area”, JGR, 2012) that documents deep (10+ m) refreezing through temperature measurements.

I don’t suggest that everyone now go back to the drawing board and add this process into all the models – for one thing, we still don’t know how it works! But for the purposes of this paper, it would good to mention the existence of piping, and even take a new stab at estimating its effect. For example, since this only matters far enough above the ELA that the firn is deep enough to remove the infiltration from the surface processes, what fraction of total melt occurs above the ELA? Using RACMO2’s surface energy balance algorithms, it seems like there’s enough data to answer this, and it should be fairly straightforward to calculate the fraction of melt above and below, say, 10 km inland from the ELA, for a few locations on the ice sheet. In places like the EGIG line in west Greenland, it probably matters a lot; in other regions maybe not. One could also play around with a crudely parameterized piping fraction: what happens if the first x% of infiltrating melt is lost to deep infiltration? How big does x have to be for this to matter? Ideas like these can at least be mentioned as areas for future improvement. That would make a good conclusion to this paper: it’s great that everyone’s model is in agreement, but do they agree on the important processes? Where do we go next?

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Interactive comment on The Cryosphere Discuss., 5, 2723, 2011.

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