Preliminary Assessment of the Impact of Lakes on Passive Microwave Snow Retrieval Algorithms in the Arctic

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EXTENDED ABSTRACT

The retrieval of snow water equivalent (SWE) and snow depth (SD) information from passive microwave brightness temperatures is theoretically straightforward: as the depth and/or density of snow increases, so too does the amount of volume scatter of naturally emitted microwave energy. Shorter wavelength energy (i.e. 37 GHz) is more readily scattered than longer wavelength energy (i.e. 19 GHz), so the difference in scatter between these two frequencies (19 GHz–37 GHz) has been exploited to estimate SWE and SD. In reality, the relationship between snow depth, density, and microwave scatter is complicated by the physical structure of the snowpack (for example, ice lenses, the presence of liquid water, snow grain size variability) and the microwave emission and scattering characteristics of vegetation. The imaging footprint for spaceborne passive microwave data is large so these complicating factors are compounded by considerable within-grid cell variability in snowpack structure and any overlying vegetative cover.

Snow surveys conducted during late winter of 2003 and 2004 in the Coppermine River basin of the Northwest Territories indicate that SSM/I derived estimates of SWE significantly underestimate actual SWE when utilizing an algorithm developed for SWE retrievals in open prairie environments, which we will refer to as the Goodison algorithm hereafter (Derksen and Walker, 2004). Lakes (ice-free or snow-covered) pose a challenge due to their unique microwave emission characteristics compared to terrestrial surfaces. In the Arctic tundra water bodies comprise a significant portion of the surface yet fractional lake area is presently not accounted for in any passive microwave SWE or SD retrieval algorithms. In the northern Hudson Bay Lowland, Canada, mostly shallow lakes occupy as much as 41% of the landscape. Other circumpolar high latitude regions such as Alaska, northern Scandinavia and northern Russia share this substantial areal coverage by lakes. On the North Slope of Alaska, for example, there are thousands of lakes that typically cover 20% of the land in most places, and as much as 40% near the coast.

The need to examine the impact of lakes on SWE and SD estimates in lake-rich regions, and to reevaluate current retrieval algorithms, is further reinforced by published works on passive microwave remote sensing of freshwater ice (Hall *et al*., 1981; Chang *et al*., 1997) and recent field measurements of snow cover characteristics, including SWE and SD, on land and lakes in the tundra region (Sturm and Liston, 2003). In contrast to other land surfaces, the brightness temperature over lakes is higher at 37 GHz than 19 GHz during both the ice-free and ice-covered periods. As a result, the brightness temperature difference algorithms typically used to estimate SWE and SD over land result in negative values over lakes for much, if not all, of the winter

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period (Figures 1 and 2). Hence, it is expected that SWE (and SD) values derived from SSM/I and AMSR-E will often be underestimated in lake-rich regions due to the presence of sub-grid cell resolution lakes.

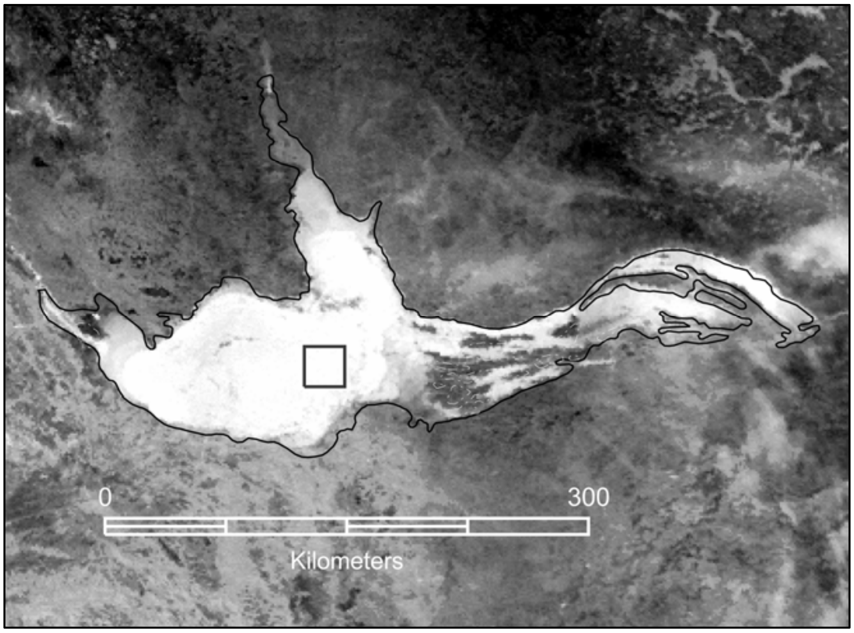
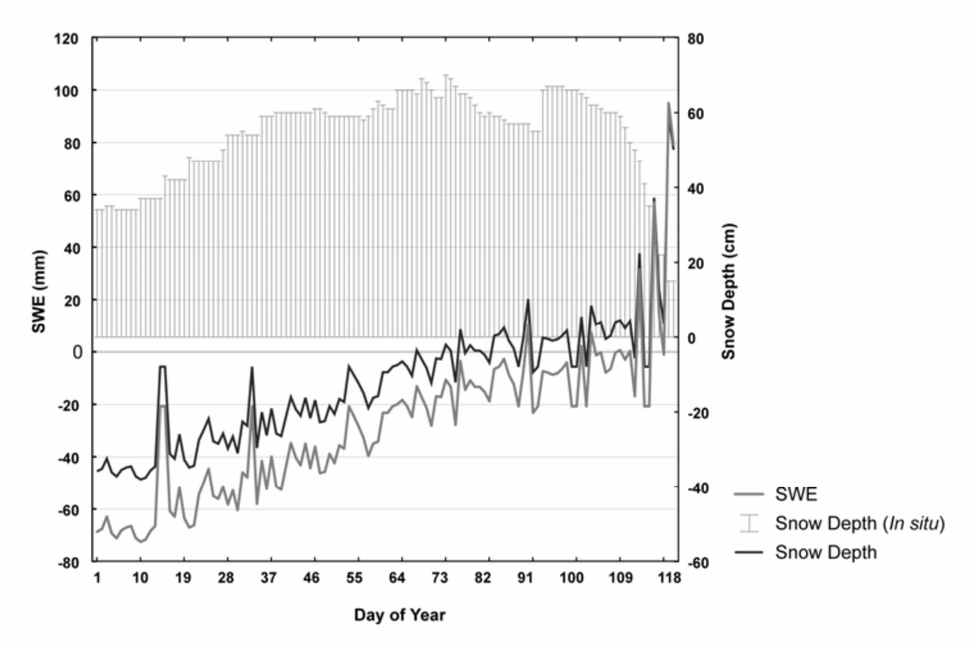


Figure 1. Location of SSM/I EASE-Grid pixel (box) on Great Slave Lake, Northwest Territories.

To demonstrate the possible impact of sub-grid cell resolution lakes on passive microwave SWE retrievals in the tundra region, we extracted 10 SSM/I pixels encompassing the 13 paired (land and lake) stations from the study of Sturm and Liston (2003) along a traverse route from Oumalik to Barrow via the village of Atqasuk on the North Slope of Alaska (Figure 3). In Figure 4, SWE values reported in Sturm and Liston (Table 1; 2003) are compared graphically to SWE estimates derived with the open prairie algorithm of Goodison (Goodison *et al.*, 1990) for two winters (1999–2000 and 2001–2002). This and other published algorithms all are applied to pixels with fractional lake coverage even though microwave emission from snow-covered lakes differs greatly from terrestrial emission (i.e. the basis of these algorithms). In each of the two graphics of Figure 4, the curves correspond to SWE estimates from the end of October (day 300) to late March 2000 (day 90—top panel) or to late April 2002 (day 120—bottom panel), at 30-day intervals. The thick black curves (SSM/I-derived) correspond to the same time period as the in situ measurements (black dots). As can be seen, the Goodison algorithm greatly underestimates SWE by anywhere from 30 to 120 mm in 2000 and 5 to 90 mm in 2002. The good match for sites 4, 5, and 7 in 2002 but not in 2000 suggests that the algorithm may be performing well at times, but not for the right reasons (i.e. random errors). The range of differences between in situ and satellite-derived SWE at each site (for the two years) indicates that the algorithm is not capturing two important factors that impact passive microwave responses of snow in this type of environment: fractional within-grid cell lake coverage and snow crystal-grain growth (i.e. depth hoar formation). Although percent fractional lake coverage within each SSM/I pixel remains to be calculated, it is likely that the large concentration of lakes largely explains SWE underestimation on this section of the North Slope (i.e. lake fractional coverage generally increases as one moves closer to the Beaufort Sea). The effect of depth hoar, on the other hand, tends to result in a general overestimation of SWE from passive microwave retrieval algorithms (Koenig and Forster, 2004—Kuparuk River Basin, Alaska). Time-evolving (dynamic) retrieval algorithms that consider the evolution of snow crystals have recently been developed to improve SWE and SD retrievals (e.g. Grippa *et al.*, 2004; Foster *et al.*, 2005) but, again, these do not consider within-pixel lake fractional coverage. Future research in this study area should thus consider the impact of both depth hoar formation and fractional within-grid cell lake coverage with a particular emphasis on the latter.

(a) Winter 1992



(b) Winter 2000

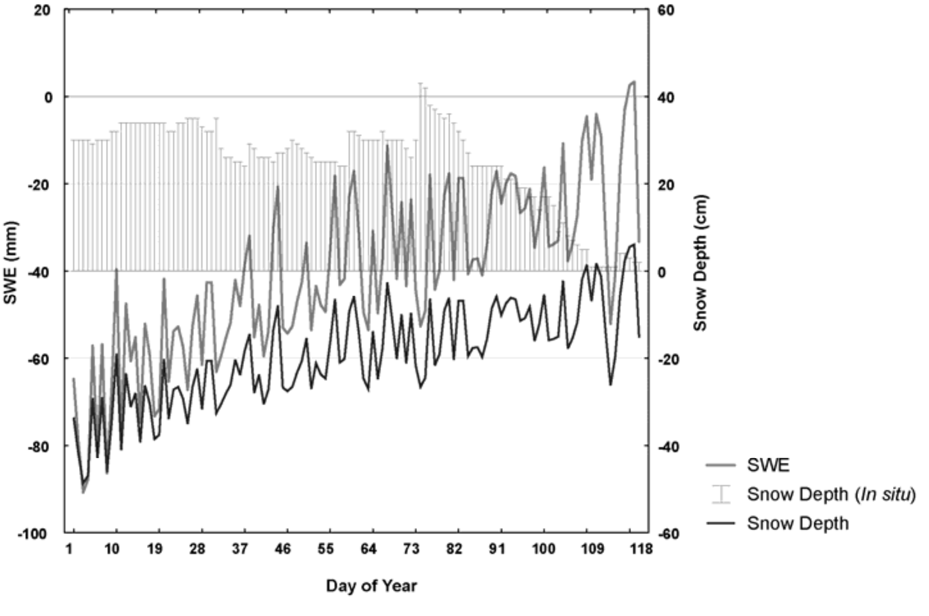


Figure 2. SWE and SD calculated for winters 1992 and 2000 for a single "pure" SSM/I pixel on Great Slave Lake, Northwest Territories (Figure 1). SWE was calculated using the Canadian Open Prairie algorithm of Goodison (SWE = –20.7 + –2.74 (TB37V – TB19V)) (in mm) and SD with the algorithm of Chang (SD = 1.59(TB19H – 6) – (TB37H – 1)) (in cm). Note that both algorithms give negative values for much of winter 1992 (a snowy winter) and all but one day in winter 2000 (dry winter).

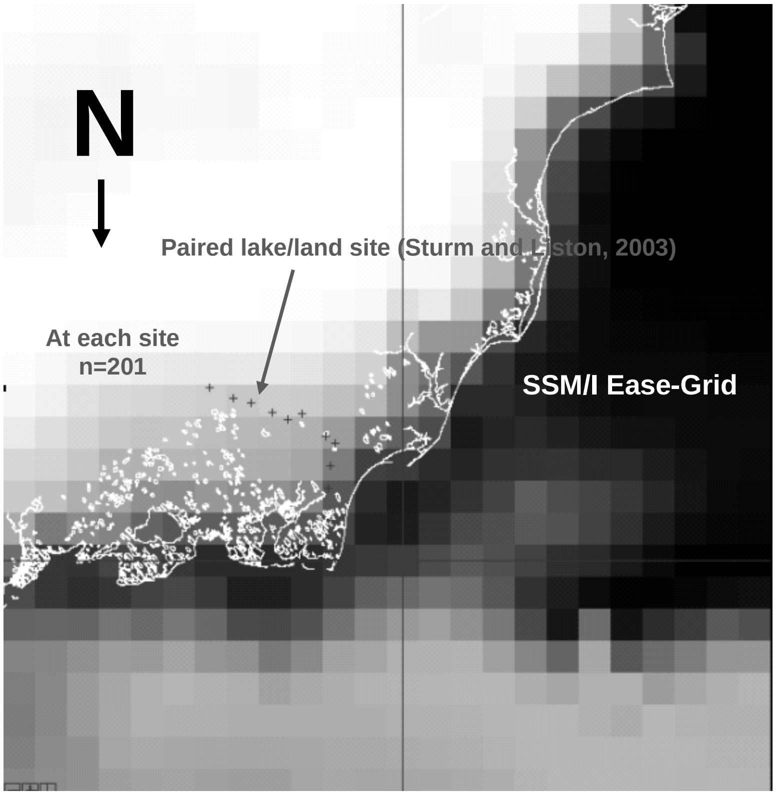
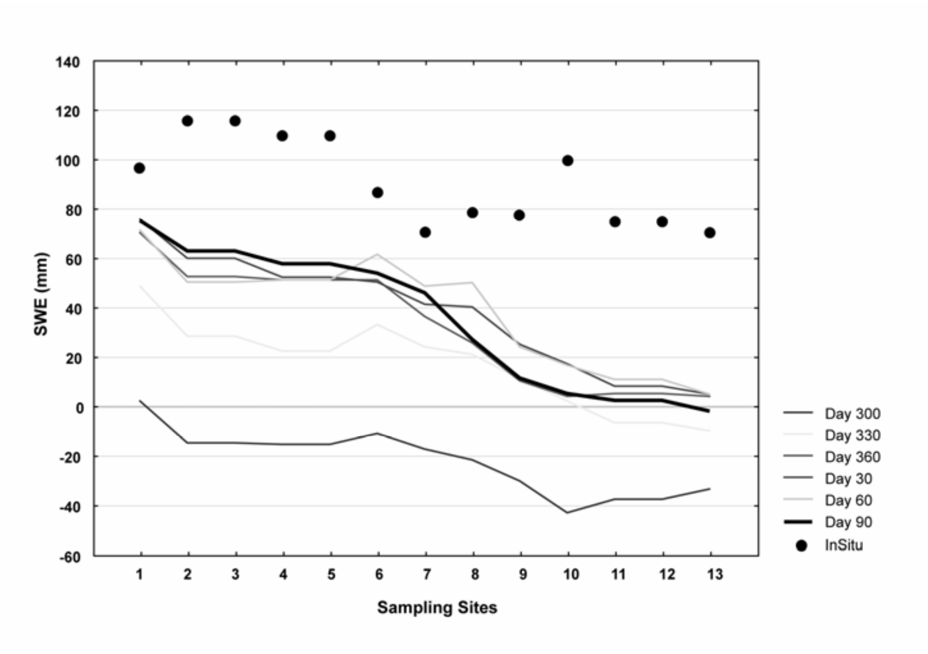


Figure 3. SSM/I EASE-Grid image of a section of the North Slope of Alaska with location of paired lake/land sites of the study of Sturm and Liston (2003).

We conclude that in order to fully understand the impact of sub-grid scale resolution lakes on the passive microwave signal, a multi-scale approach must be adopted. This approach involves measurements at three scales: field, airborne, and pixel (satellite) scales. Such an approach is needed to separate the lake effect from the depth hoar effect; these are the two factors that most often complicate SWE and SD retrievals in the tundra region. This approach is also needed in order to examine the impact of floating ice and grounded lake ice on brightness temperatures. In the Arctic tundra, many of the lakes are shallow and thus freeze partially or totally to their bed in winter (Jeffries *et al.*, 1994). The timing of bottom freezing depends on the size/depth of the lakes and the amount of snow that accumulates on the ice surface (Duguay and Lafleur, 2003; Duguay *et al.*, 2003). At the imaging footprint of AMSR-E and SSM/I, a single grid cell from a late March acquisition over an area of the North Slope of Alaska, for example, can contain a combination of tundra (land), lakes with floating ice and grounded ice, and snow or no snow on the ice surface. The impact of grounded ice on passive microwave brightness temperatures is presently unknown (Boudreau and Rouse, 1994; Derksen and Walker, 2004).

(a) 1999–2000



(b) 2001–2002

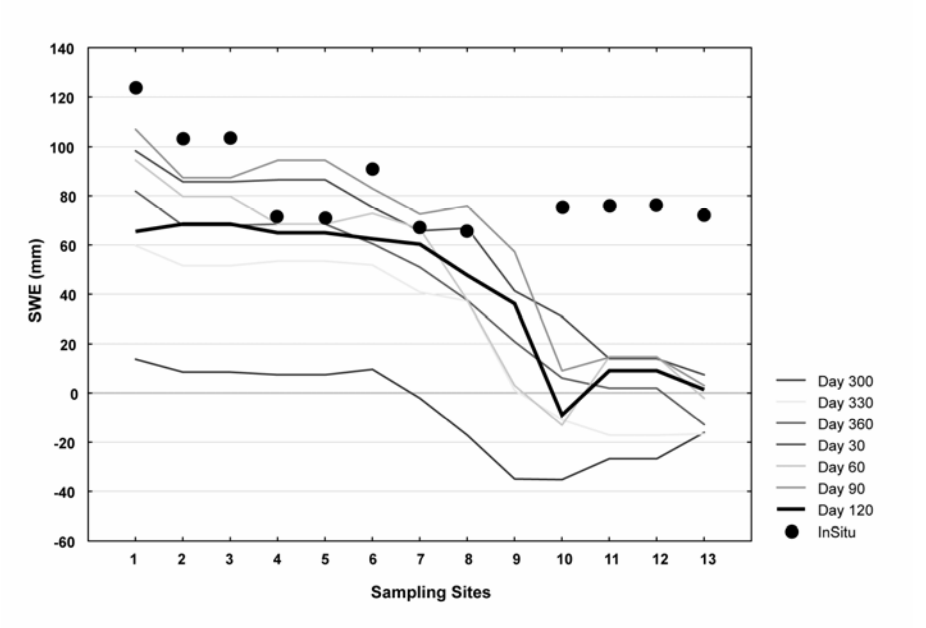


Figure 4. Comparison between in situ SWE measurements of Sturm and Liston (2003) and SSM/I-derived SWE (solid curves) for winters 1999–2000 (day 300 to 90) and 2001–2002 (day 300 to 120). Note that the sites are numbered from the most inland site (1 - near Oumalik) to the most coastal site (13 - Barrow) along the traverse route from Oumalik to Barrow. Sites 11–13 (closer to the Beaufort Sea) may be affected by "ocean overspill" in the SSM/I pixels (i.e. important fraction of sea ice within the pixels) and should therefore be interpreted with caution.

Keywords: snow water equivalent, snow depth, passive microwave, lakes, Arctic

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