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Snow accumulation, surface height change, and firn densification at Summit, Greenland: Insights from 2 years of in situ observation

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[1]   Weekly measurements of surface height change were made at an accumulation forest of 100 stakes at Summit, Greenland, over a 2-year period (17 August 2000 to 8 August 2002). On average, the surface height relative to the stakes increased 64 (±4.8) cm in the first year and 65 (±5.3) cm in the second, identical to the average (65 ± 4.5 cm yr^{-1}) previously reported for the period 1991–1995 in a similar forest 28 km to the southwest. The continuous 2-year data set indicates that the rate of surface rise was not constant, with the summers of 2001 and 2002 both showing markedly slower increases. On-site weather observations suggest that more new snow fell during the summer months than in any other season, consistent with results from previous snow pit and modeling studies yet apparently at odds with the slow rate of height increase. Density profiles from a series of 1-m-deep snow pits sampled monthly reveal that the thickness of the most recent year of accumulated snow (25 cm water equivalent) decreased rapidly between late May and early July, and the layers remained thin through early September. The thinning of the top year is clearly due to compaction in the snowpack. Combining the observed variations in annual layer thickness with a linear height increase based on assumed constant accumulation at 0.18 cm d^{-1} explains much of the variation in surface height found in the stake measurements. Estimated surface height changes can be forced to exactly match the stake measurements by combining changes in annual layer thickness with a variable accumulation rate over the intervals between pits. This exercise suggests that during the 2 years of this study a consistent seasonal pattern in accumulation was not apparent, rather the intervals indicated to have had enhanced accumulation in the first year (August–October and March–April) apparently had reduced accumulation in the second year.   INDEX TERMS: 1863 Hydrology: Snow and ice (1827); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 9315 Information Related to Geographic Region: Arctic region; KEYWORDS: firn densification, ice sheet, mass balance, satellite altimetry

1.   Introduction

[2]   Concern that mass balance of the polar ice sheets of Greenland and Antarctica may become negative in an anthropogenically warmed climate has stimulated much recent research. Because the overall balance for continental glaciers is the small difference between very large accumulation and ablation terms, it has proven difficult to establish current mass balance for Greenland and Antarctica with precision adequate to discern any recent changes. Satellite-based measurements of surface elevation may constrain the accumulation term much more tightly, but surface elevation reflects both variations in accumulation and compaction. Annual density variations in a firn core [*Gerland et al.*, 1999] and apparent large seasonal swings in surface eleva-

tion measured with satellite-based radar altimeters have led *Zwally and Li* [2002] and *Li and Zwally* [2002] to present a firn densification model which predicts that seasonal variations in temperature in central Greenland create variable densification rates large enough to result in an annual surface elevation oscillation of 18 cm if accumulation is assumed constant. This amplitude corresponded well to their multivariate fit of a sinusoidal function to the altimeter measurements at Summit; the altimeter data showed larger seasonal swings, with excursions exceeding 0.5 m in most years.

[3]   Earlier work on the impact of density variations in the firn column on altimeter measurements had investigated the interannual variations in surface elevation that would be produced by secular variations in accumulation rate, temperature change, or input density [*Arthern and Wingham*, 1998]. They found that response times ranged from one to many decades, with more rapid responses from accumula-

tion and density changes, and longer responses for temperature changes due to the time required for heat conduction. This densification model has also been used to explain the decadal variability of surface elevation changes measured by altimeters in Greenland [*McConnell et al.*, 2000a, 2001; *Davis et al.*, 2000]. The impact of changing accumulation and firn properties on elevation changes measured in Antarctica is discussed also by *Wingham et al.* [1998]; *Wingham* [2000] discussed the impact of changes occurring on short timescales.

[4] Direct measurements of accumulation are spatially sparse. In Greenland the NASA PARCA program has recently greatly increased the number of sites from which consistent, relatively long, records of annual accumulation have been recovered [e.g., *McConnell et al.*, 2000b]. While annually resolved records are adequate to assess accumulation for mass balance investigations, there is also interest in understanding seasonal variations in accumulation. Such data are needed to validate increasingly sophisticated model estimates of precipitation [*Bromwich et al.*, 1993, 2001] and also to properly invert glaciochemical records for assessing past changes in atmospheric composition [*Steig et al.*, 1994; *McConnell et al.*, 1997]. To date, seasonally resolved records of accumulation in central Greenland are very limited [*Shuman et al.*, 1995, 1998, 2001].

[5] The Summit, Greenland camp, established for collection of the GISP2 core, has recently been established as a year-round observatory. From August 2000 through August 2002 a multi-investigator team conducted a wide range of snow and atmospheric sampling programs targeting improved understanding of air/snow relationships and the impacts of postdepositional change on the preservation of glaciochemical records. These efforts also yielded unique data sets on surface height changes and compaction in the upper meter of the snowpack.

2. Methods

2.1. Stake Measurements

[6] Stake measurements are a long-established component of mass balance studies. Depending on location on the glacier, the stakes are often referred to as accumulation, or ablation, stakes. In accumulation zones, like Summit, the snow surface rises up the stake over long intervals, and the observed surface height increase is often loosely referred to as accumulation. Decreases in surface height can be caused by wind scour, sublimation, and compaction of the snow between the surface and the depth at which the pole is anchored to the firn. Height changes on the stakes integrate increases due to accumulation, and decreases due to all three processes, over the interval between measurements. To extract accumulation from stake measurements it is also necessary to know, or assume, a density profile over the depth range between the surface and effective base of the pole. In this paper, stake-based measurements of change will be referred to as surface height change (SHC) to indicate that the change is relative to the base of the stake. These are not the same as changes in surface elevation above a datum like sea level, as are obtained by laser and radar altimetry from aircraft or space. However, SHC observed on stakes can be related to elevation changes if the background submergence of the stakes due to densifi-

cation below the stake base and to vertical flow of the ice is taken into account. In this paper, we assume that the rate of submergence of the stakes is constant in time in order to discuss the relationship between our field measurements and direct and theoretical treatments of the satellite altimeter record.

[7] In June of 1997 a 100 stake "forest" of bamboo poles was established on the south west edge of Summit camp (Figure 1). The center of the forest was approximately 400 m from the nearest permanent structure. Stakes were placed in 10 rows, with 8 m between rows and between stakes in each row. The poles were 3.7 m long and were planted approximately 1.2 m into the snow to ensure that they could withstand high winds. Tape was wrapped around each pole (before planting) approximately 50 cm from the top to provide a distinctive mark for repeated measurements. In July of 2000 and July of 2001 all of the poles were pulled out of the snow and replanted so that the marks were again approximately head high, to facilitate measurements through the 2 years of this investigation.

[8] The distance between the mark on each pole and the snow surface was measured to the nearest 0.5 cm with a 2-m-long aluminum rule at nominally weekly intervals. The snow surface adjacent to each pole was generally not flat enough (because of small drifts created by the pole) to warrant finer resolution. Measurements began 11 June 1997 and were continuous until 9 April 1998. All poles were also measured 2 times in the summer of 1998 and again in summer 1999. Weekly measurements resumed in the summer of 2000 and are the focus of this paper. In total, 93 sets of measurements were made between 17 August 2000 and 8 August 2002. Missing weeks reflect extended stormy periods during which it was deemed unsafe to be outside for the hour it took to measure all 100 stakes. Measurements were made on skis in order to minimize artificial drifting.

[9] A SHC line consisting of 122 stakes, nominally 100 m apart, was also established for this study. This line began 1 km past the site of the GISP2 deep ice core (approximately 1.2 km past the forest in the same direction from camp) and extended 12 km to the southwest. This line was measured at approximately monthly intervals, weather permitting.

2.2. Snow Sampling

[10] Daily sampling of the dominant surface layer was conducted for determination of the isotopic and ionic composition of the snow. These samples were collected from precisely determined areas, such that the inventory (mass cm^{-2}) of water and impurities in a given stratigraphic layer could be tracked over time. In addition, the samplers made extensive notes about the origin of each daily layer that identified new fallen snow and when a given dominant surface layer was buried (by new, but also windblown, snow).

[11] At nominal monthly intervals snow pits were dug to at least 1.3 m. Between mid-August 2000 and the end of July 2002, 23 pits were excavated. Each of these pits was sampled to at least 99-cm depth, at 3-cm resolution, for isotopic and ionic analyses. Samples were collected with a 100 cm^3 density cutter and weighed to ±0.01 g, yielding density profiles at 3-cm resolution for each pit. Unfortu-
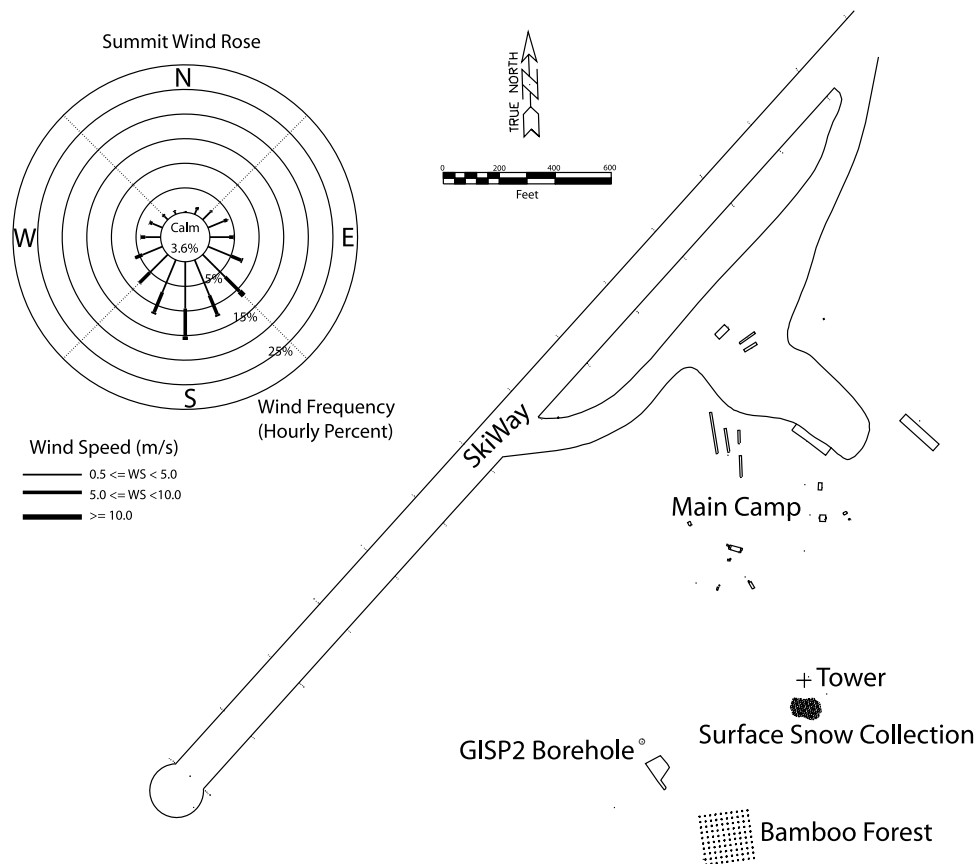
Figure 1. Site map of Summit station. Science locations discussed in this paper are all at the lower edge of Figure 1, except that the accumulation line begins just off the map and continues 12 km to the southwest. The station generator is located in the rectangular structure due north of the tower closest to the ski way apron and turnaround area (above and to the right of the "p" in "Camp"). Equipment traffic is largely restricted to the main camp area, except for ski way grooming immediately before flights into Summit.

nately, samples from the September 2000 pit were never weighed, so only 22 density profiles are available.

[12] All snow sampling discussed in this paper was conducted near the atmospheric sampling tower (Figure 1). This site was 300 m from the camp, along the path to the forest. Surface samples were collected in a restricted area about 20 m past the tower and the pits were sampled an additional 20 m south of this area. All pits were carefully refilled to avoid artificial drifting, and care was taken to make sure that each pit was at least 10 m removed from all previously sampled pits.

3. Results

3.1. Stake Measurements

[13] Comparison between the mean SHC measured on the 100 stakes in the forest and the 122 stakes along the line show no significant differences. The average SHC measured in the forest was 129 ± 9.0 cm over the 2 years (Figure 2), compared to 131 ± 13.9 cm for the line. The two annual totals in the forest were very similar, with a 64 ± 4.8 cm increase between 17 August 2000 and 17 August 2001 and a further increase of 65 ± 5.3 cm through 8 August 2002. The same is true for the measurements along the line, where the averages were 65 ± 8.7 cm between 13 August 2000 and 11 August 2001, and 66 ± 9.6 cm in the second year

(through 9 August 2002). Furthermore, these annual SHC are indistinguishable from the average of 65 ± 4.5 cm yr^{-1} determined for 5 years of measurement (1991 through 1995) at a similar forest 28 km southwest of the Summit camp
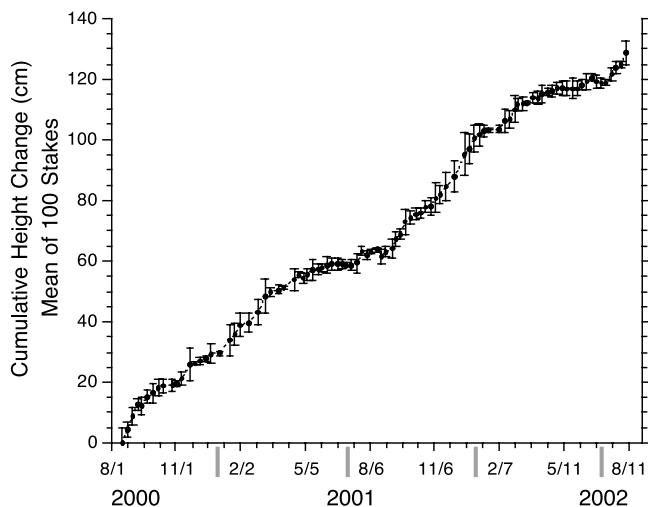
Figure 2. Cumulative change in the height of snow surface as measured on 100 stakes. Mean values are plotted with standard deviation at the date of each measurement.

Table 1. Monthly Summary of Fresh Snow Events at Summit, Based on Daily Sampling of Surface Snow for Determination of Ionic Composition

	2000		2001		2002	
	Number of Events	Water Equivalence, cm	Number of Events	Water Equivalence, cm	Number of Events	Water Equivalence, cm
January			2	0.56	4	0.25
February			5	1.01	6	0.38
March			1	0.15	13	0.99
April			2	0.22	9	0.83
May			10	1.22	8	0.76
June			16	3.65	11	4.36
July			16	5.09	15	2.74
August[a]			8	0.85		
September	7	1.21	7	0.78		
October	3	0.38	4	0.40		
November	6	0.72	5	0.45		
December	2	0.29	8	0.79		

[a]Six events delivered 1.39 cm water equivalence (weq) of snow during the last half of August 2000; three events delivered 0.89 cm w. eq. during the first 10 days of August 2002.

[*Kuhns et al.*, 1997]. This indicates either that the enhanced accumulation caused by permanent structures at Summit does not extend as far as 400 m, or that any artificial hill has become a stable part of the region over the 12 years between camp construction and the beginning of this investigation. Perhaps more importantly, the agreement between the two sets of SHC measurements provides reassurance that the small drifts caused by each of the 100 poles in the forest did not combine to create enhanced accumulation uniquely in the forest. The conclusions of this paper would not be altered if the presence of the Summit camp is causing subtle enhancement of accumulation over a very wide area. However, combining measurements of compaction and height changes of the surface from sites approximately 100 m apart would be complicated if the forest itself was causing further enhanced accumulation.

[14] Interestingly, *Shuman et al.* [1998] suggest that annual accumulation in water equivalents (e.g., explicitly considering density variations in the near surface snowpack) at Summit decreased over the interval 1992–1995. Modeled precipitation averaged over the entire Greenland ice sheet has also trended downward over the 1985–1999 interval, though the central region (including Summit) was found to have a small upward trend in precipitation in this analysis [*Bromwich et al.*, 2001]. These apparent discrepancies highlight the fact that neither SHC nor variation in precipitation are direct indicators of accumulation, even in a dry snow zone with no melt.

[15] Another notable feature of the time series of SHC in the forest is the fact that the trend is clearly not strictly linear. The slope is definitely flatter from mid-April through August 2001 and again for April through July 2002 (Figure 2). On average, surface height increased 2.63 cm month^{-1} during the 9 complete months between April and August in the 2-year study, compared to the 24-month average of 5.21 cm month^{-1}. While it is tempting to attribute the decreased rate of height increase to reduced accumulation in summer, several lines of evidence suggest exactly the opposite. *Shuman et al.* [1995, 1998] used correlations between isotope records and satellite-based surface temperature estimates to provide subseasonal dating of several

snow pits at Summit and found that accumulation (mass based) was about 20% higher in summer and early fall than during winter. Similar seasonality was found in precipitation modeling [*Bromwich et al.*, 1993, 2001]. Further, the staff at Summit observed new snow falling on nearly half the June–August days of the 2000–2002 study (Table 1). In many of the events identified as fresh snow it was also noted that the surface snow was blowing and drifting at the same time; thus the collected sample was a mix of new and aged snow. These complications make it impossible to construct a quantitative budget of new snow input to Summit from our records. However, it is clear that neither summer could be considered a drought, rather more than half the identified new snow fell in the 3 summer months (Table 1).

3.2. Density Profiles

[16] The ensemble of 22 snow pits show reasonably smooth variations in density profiles through the changing seasons. The density of near surface snow was quite low (<0.2 g cm^{-3}) in late April through August 2001, in contrast to values >0.25 g cm^{-3} in winter pits (Figure 3). This contrast was preserved during burial, e.g., the low-density snow from summer 2000 was still an obvious low-density layer near 45 cm depth in spring 2001, then near 75 cm by the end of that summer, and near the bottom of pits sampled in winter 2001/2002. The burial of higher density snow that accumulated in early 2001 can likewise be tracked through subsequent pits (Figure 3).

[17] Density variations in the top 3 cm of the snowpack are much more pronounced than, and show little relationship to, variations in the average density of the entire profile (Figure 4). Except for the 2 July 2002 pit, density in the surface layer during summer (MJJA) never exceeded 0.24 g cm^{-3} (average 0.17 g cm^{-3}) compared to a winter (NDJF) average of 0.27 g cm^{-3}. In contrast, the minimum (in April 2002) and maximum (in October 2000) average densities in the top 99 cm only differ from the 22-pit grand average of 0.305 g cm^{-3} by 13% and 10%, respectively. It should be noted that pit average density was not consistently, nor significantly, higher during the late spring to summer periods when surface height measured in the forest

density profiles in 1 m pits (g/cm³)
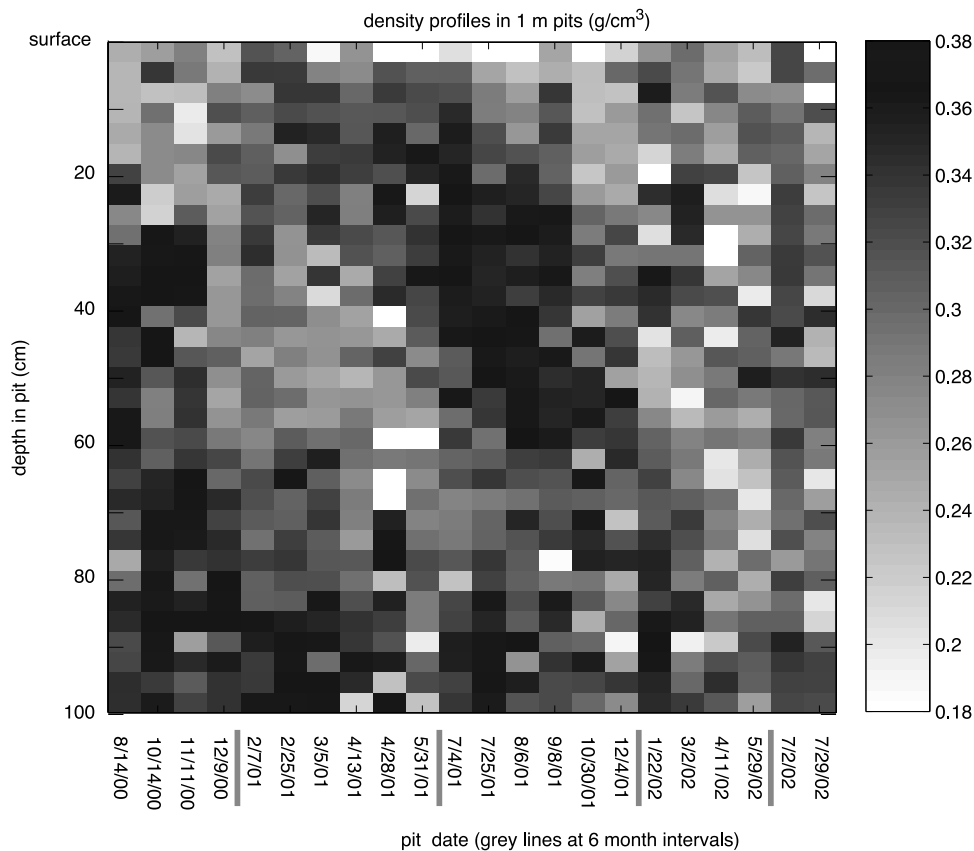
Figure 3. Density profiles from 22 snow pits, sampled approximately monthly over the 2-year investigation.

increased most slowly (Figure 2). In fact, the average density in the top 99 cm of all pits sampled in May–August, and also those sampled in November–February, was identical to the 22-pit average.

4. Discussion

[18] At face value, the various data sets appear to present a dilemma. The slow rate of SHC during the summer could be explained by reduced accumulation, enhanced compaction, or a combination of the two. Available information suggests accumulation is more likely to be enhanced than reduced during summer. Even if snow accumulated at a constant water equivalent (weq) rate throughout the year, the low density of surface snow in the summer should lead to a large increase of surface height in the forest. On the other hand, mean density in the top meter of the snowpack does not markedly increase during the summer, as would be expected if compaction was more rapid in this season.

[19] An alternative quasi-"Eulerian" approach to search for seasonal variations in compaction rate in the top "year" of the snowpack is to plot the measured depth at which weq depth equals 25 cm (Figure 5). *Alley et al.* [1993] found the modern accumulation rate to average 24 cm weq, so 25 cm is approximately a year of snow accumulation. (Using any annual accumulation rate from 20 to 26 cm weq yields comparable results.) In this analysis the summer of 2001 stands out with 4 pits in a row (4 July through 8 September) having the smallest annual layer thicknesses (<77.8 cm). These are preceded by a general (though not monotonic)

increase in layer thickness from near 80 cm at the end of summer 2000 to about 85 cm in April and May of 2001 (Figure 5). Annual layer thickness returns to the narrow range of 84.3–85.7 cm in pits sampled between late October 2001 and early March 2002. Pits sampled in April and May 2002 suggest major accumulation of low-density snow, yielding very thick annual layers, followed by rapid
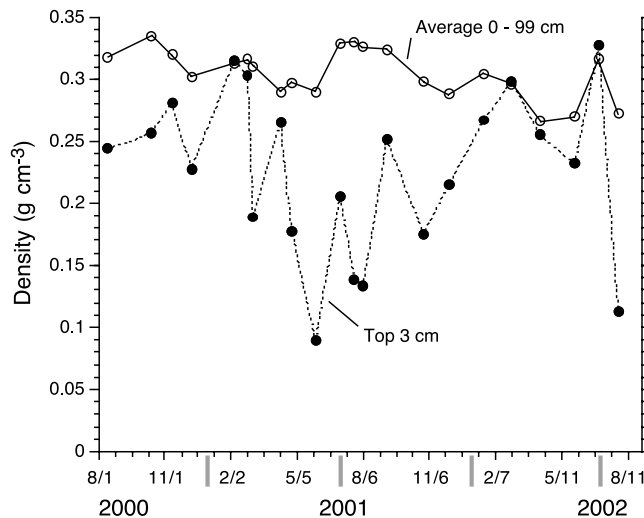
Figure 4. Average density in the top 99 cm (open circles) and density in the top 3 cm (solid circles) in a series of 22 snow pits.
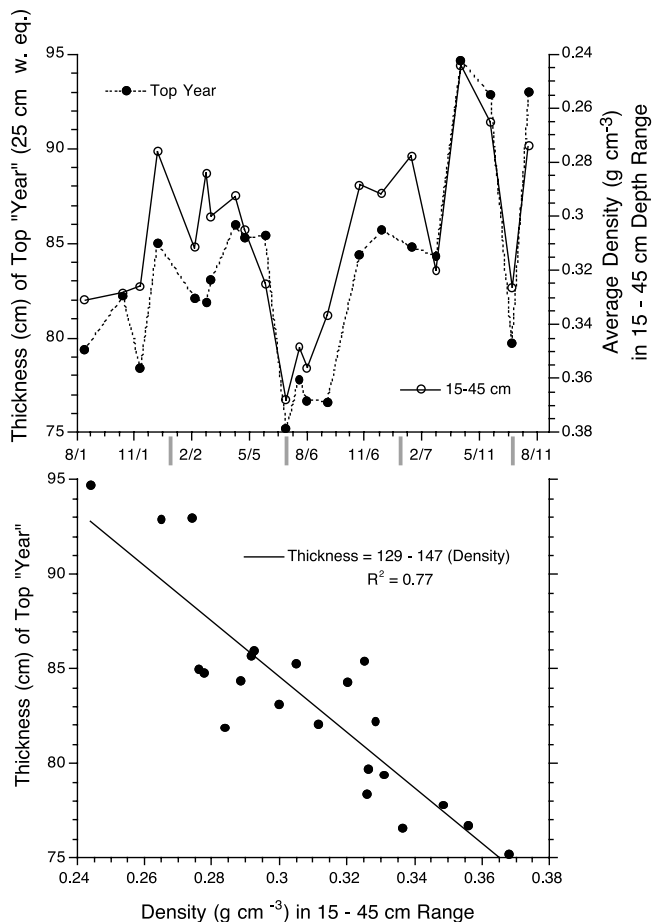
Figure 5. (top) Time series of annual layer thickness (depth from surface to 25-cm water equivalent) (solid circles) compared to average density in the 15- to 45-cm depth range (open circles). Note that the density scale (right axis) is inverted. (bottom) Least squares linear regression of annual layer thickness against average density in the 15- to 45-cm layer.

compaction leading to a 13-cm thinner layer in early July. However, the final pit of the study has the second deepest 25-cm weq depth out of all 22 pits (93 cm) (Figure 5). The large variability of annual layer thickness in the last four pits (also in the first four but to a lesser degree) provides a reminder that it is not possible to sample the exact same snow more than once. Inherent small-scale spatial variability will impact time series extracted from any single record [e.g., *Kuhns et al.*, 1997; *McConnell et al.*, 1997], as well as attempts like ours to create a single time series from several spatially distinct samples.

[20] Variations in annual layer thickness (Figure 5) are obviously perfectly anticorrelated to changes in average density of the annual layer, but are also strongly related to average density calculated for most arbitrary depth intervals in the series of pits. We found that density in the 15- to 45-cm depth range had the strongest relationship with annual layer thickness of any 30 cm thick depth range (Figure 5), but do not want to imply that all or most compaction is occurring in this range. However, this example allows an important point to be clarified. The 10-cm increase in

annual layer thickness between early July and the end of October 2001 corresponds to a 22% decrease in average density between 15 and 45 cm (Figure 5). Clearly, the decreasing density cannot be due to inflation or mass loss over such a wide depth range. Rather, high-density snow has advected out of the bottom of the depth range as low-density snow moved in from the top. On the other hand, increasing density between 15 and 45 cm (e.g., in May and June 2001) (Figure 5) must largely reflect compaction, since snow above 15 cm was almost always less dense than what was already in the layer (Figure 3). The series of pits therefore supports the suggestion that compaction in the upper meter of the snowpack is enhanced in late spring and summer [*Zwally and Li*, 2002]. The observed densification-driven decrease in annual layer thickness is on the order of 70% of the 18 cm modeled as a general case by *Zwally and Li* [2002], but is within the range of changes they estimate by driving their model with 7 years of meteorological data [*Zwally and Li*, 2002, Figure 7]. The lowering modeled by Zwally and Li may be more directly compared to a value of $12-13$ cm because of the slowdown in SHC increase for the summer 2001; this value is estimated from Figure 1 by fitting a line to SHC values in the preceding and following winters and estimating the maximum summer deviation from this line. In either case, there is a good agreement in the phase of the surface lowering signal and the modeling of Zwally and Li. Part of the difference in amplitude of the signal may be due to the lack of a thin low-density surface layer, as was present in summer pits, in their model; it is likely, in addition, that interannual variations, as seen in both our records and their model runs, may be responsible.

[21] The timing and duration of the major decrease in annual layer thickness (increase in average density of top 25 cm weq) in summer 2001 (Figure 5) corresponds closely to the period of slow rate of SHC in the stake forest (Figure 2). To show this directly, we have assumed that accumulation was constant at a rate of 0.18 cm d^{-1} (measured height, not density corrected, equal to 65 cm/365 days) and calculated height change since 14 August 2000 for the date that each subsequent pit was sampled. This linear increase in surface height was then added to the estimated annual layer thickness (depth to 25 cm weq) in each pit and plotted, together with the 100-stake average cumulative SHC over the 2-year period (Figure 6). The two curves are quite similar from August 2000 through March 2002 but diverge significantly over the spring and summer 2002 period covered by the last four pits. Agreement between the two estimates of SHC over the first 20 months of the study suggests that compaction can account for most of the decrease in rate of SHC during the summer, and that assuming constant accumulation throughout the year is a very reasonable approximation. As noted earlier, we suspect the exceptionally thick (low density) annual layers in the pits sampled in April, May, and late July 2002 (Figures 5 and 6) reflect inherent spatial variability. If so, the agreement between the two curves in Figure 6 through the first 20 months is even more striking.

[22] If spatial variability over the approximately 10-m length scale between successive pits can account for most of the 13-cm increase in annual layer thickness from 2 July to 29 July 2002 (Figure 5), all other differences between the two curves in Figure 6 are well within noise. However, it
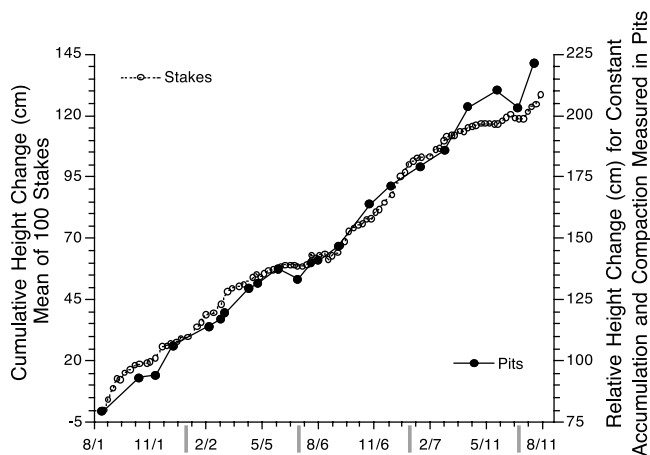
Figure 6. Comparison between the height change measured on stakes (from Figure 2) and height change estimated by adding assumed constant accumulation to observed changes in annual layer thickness (from Figure 5).

may still be illustrative to examine the differences between the two estimates of SHC. Figure 7 shows the constant accumulation rate between each pair of pits that would shift the estimated height change based on the pit density profiles to exactly agree with the cumulative change measured in the forest. We also plot a weighted (1:2:1) three-point moving average to smooth these revised estimates of accumulation rate over approximately seasonal timescales. On the "monthly" timescale between individual pits, estimated accumulation rate varies widely (-0.3 to 0.5 cm d^{-1}) (Figure 7), with monthly oscillations between high and low rates presumably reflecting the impact spatial variability has on point estimates at an individual pit versus averages over 80×80 m^2 in the forest. The smoothed data suppress these oscillations, but fail to support any consistent seasonal variation in accumulation rate. In the first year, inferred accumulation rates in the late summer and fall (August–October) and in spring (March and April) are about twice as high as those in winter (November–January) (Figure 7). This roughly corresponds with the seasonal phasing of accumulation and precipitation found by *Shuman et al.* [1995, 1998] and *Bromwich et al.* [1993, 2001], but the magnitudes of apparent seasonal differences in Figure 7 are much larger. However, in the second year seasonal variations are mirror images of the first, with our analysis suggesting that accumulation was reduced in the periods August–October and February–May, with enhanced rates required in winter (December–January). *Shuman et al.* [1998] noted that the magnitude of apparent seasonal variations in accumulation decreased in a series of pits sampled at Summit between 1992 and 1995 from a maximum 20% difference between summer peaks and winter minima. Our analysis suggests that any seasonality in accumulation in 2 recent years is too small to discern over spatial variability.

5. Conclusions

[23] Year-round occupation of the Summit camp in central Greenland has provided unique insight into accumula-

tion and compaction of snow at high temporal resolution over the period August 2000 to August 2002. Increase in surface height measured on stakes was nearly identical in the 2 years of this study (64 and 65 cm yr^{-1} in the first and second years, respectively). These values are the same as the average measured between 1991 and 1995, based on site visits only during the summer. The continuous time series of height change from weekly measurements shows that the rate of surface rise was reduced in the summers of 2001 and 2002. Density profiles in 22 shallow snow pits indicate that the thickness of the top 25 cm weq of snow (approximately 1 year of accumulation) varied between 75 and 95 cm. In general, the uppermost annual layer was thinnest (had highest mean density) during the summer, despite the fact that surface snow tended to have lower density in summer. The density profiles in the series of pits demonstrate that rapid compaction in late spring and early summer creates the thin annual layers in summer.

[24] Combining the seasonal variation in annual layer thickness with assumed constant accumulation of snow at 0.18 cm d^{-1} provides an estimate of changing surface height that captures much of the variability seen in the stake measurements. Differences between the two estimates of surface height change can be forced to vanish by assuming variable accumulation rate over time, but they do not support the assertion that Summit experiences significant or consistent seasonality in accumulation. We found no convincing evidence for repeated seasonal variations in accumulation of snow at Summit between August 2000 and August 2002. Accelerated compaction in the top meter of the snowpack in late spring and summer is consistent with a recent study modeling densification. The thinning estimated from one summer's measured densifica-
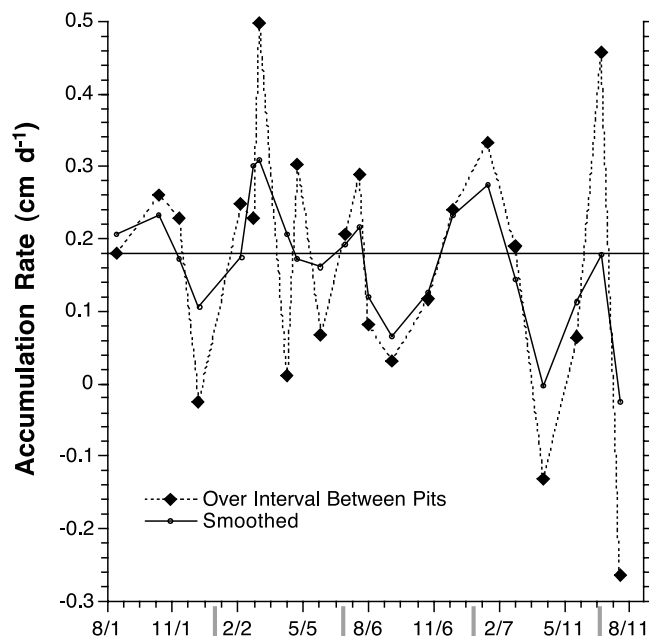
Figure 7. Constant accumulation rate between the dates of pit excavation that would force the pit-based estimates of height change to exactly equal height change measured on stakes (diamonds). A three-point weighted (1:2:1) average was also calculated to smooth pit to pit oscillations (circles).

tion in this study was on the low end of the range estimated by *Zwally and Li*'s [2002] model for the same site in earlier years. This may simply be due to interannual variability, which was present in both our measurements and in the model when driven with meteorological observations from different years.

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