Investigations of the Upper Snow Pack at Summit, Greenland

Report of the July 2004 Field Season

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Abstract

Three detailed snow-pit studies were completed around the Summit Camp in central Greenland during July 2004. At each site the temperature of the snow pack was measured with a digital thermometer and the thickness of different layers, the snow stratigraphy and the snow crystal size were documented. Snow samples were taken at 5 cm intervals with a tube of known volume and a steel box of known volume, the contents of which were later weighed on a scale in order to determine the density of the snow. Also oxygen isotopes samples were taken from one pit for analysis to get an estimate of the age of the snow. Three shallow cores (~6 m) were extracted and snow samples were taken in 10 cm intervals for isotope analysis and density measurements. The melt water samples were brought back to the laboratory at BPRC (OSU) for isotope analysis. This report is a summary of the findings and preliminary results of this field investigation.
1.0 Introduction

A field investigation was conducted in cooperation with University of Kansas from 12\textsuperscript{th} July to 26\textsuperscript{th} July 2004. The investigation occurred around the Summit Site (N 72.57885 W 38.459478, elevation 3200 m) located in central Greenland (Figure 1) as a part of the Polar Radar for Ice Sheet Measurement (PRISM) program. The radar engineering objectives of the project were to test and validate two different radar systems. One system measured ice thickness and mapped bedrock topography and deep internal layers. In addition this system will ascertain whether there is a thin water film between the bed and the ice. This is important because the presence of water can have a pronounced influence on ice flow by lubricating the bed. The second radar mapped the near-surface internal layers up to approximately 200 m depth to establish a record of (recent) accumulation rates, a key variable in mass balance calculations. A science goal focused on the relationship between passive microwave brightness temperature and the snow accumulation rate. Measurements of snow physical properties were acquired for latter use in developing empirical and theoretical relations between brightness temperature and accumulation rate. The approach will eventually be extended over different snow zones through the use of in situ and airborne observations of accumulation rate acquired across Greenland.

![Figure 1: Map of Greenland showing location of Summit Camp.](image-url)
Our experimental methodology involved careful observations of quantifiable properties such as snow density, and more subjective observations, such as stratigraphy and snow hardness. These observations are important for validating the accumulation rate radar. In particular they will be used to determine the physical cause of near surface radar reflections, which might represent either annual layers, temporally variable dust layers, ice layers or wind crusts. Density, oxygen isotope, grain size, and physical temperature measurements are also key to establishing the relationship between brightness temperature and accumulation rate in different snow facies. To obtain the needed data, one of us (Bhattacharya) studied three snow pits at locations near the radar tracks. Snow samples for isotope analysis were also acquired from one pit so that there is coincident isotope density and stratigraphy. In addition 3 shallow cores were collected to measure the density and oxygen isotope ratio variations of the upper firn. One of the cores was within the KU radar grid and the other two were 35.6 km apart from the camp site. The three cores were sited within three different SSMI pixels. The results of these investigations will be compared and correlated with acquired radar profiles. They will also be used to extract regional information on accumulation rate from Special Microwave Imager (SSMI) brightness temperature data.

1.1 Time Line

The team arrived at Kangerlussuaq on 11th July at 4.30 pm. We left for Summit Camp on the 12th and reached the camp site at about 10.30 AM. We spent the next day unpacking and understanding how to operate the hand auger, organizing equipment, assembling more field clothing and acclimatizing to the altitude.

On July 14th investigations started at snow pit-1. This pit was a practice pit and there were several mistakes. The pit was not big enough. The upper snow surface was not clearly identifiable. The snow-sampling wall was not straight. On the 15th we exposed another wall in this pit and the investigations proceeded from scratch. On the 16th we tested the hand auger to drill a practice core but the drill bit stuck at roughly 2 m deep. We dug out the drill bit and shifted the drilling site where a 4.5 m core was drilled out. On the 17th we drilled a 5.2 m core within the KU radar grid. We measured the stratigraphy and density in a 2 m pit located near the core site on the 18th. On the 19th we melted the snow samples and collected the melt water in bottles. The zip-lock bags were cleaned with de-ionized water and the bags were renumbered. The latitude and the longitude of the locations located outside of the KU radar grid were estimated for latter use in navigating to these sites. On 20th July we traveled 36.5 km from the base camp. At this site a 0.55 m pit was dug and then drilling was started and a 5.90 m long core was collected. On 21st July we went in the opposite direction for 36.5 km from camp. A 0.55 m deep pit was dug and then a 6 m long core was collected. On 22nd July we dug a 1.8 m pit, 1 km away from the previous pit on the Ku radar grid but could not complete the pit analysis due to bad weather. On 23rd July we went back to the same pit to do the pit analysis, but the weather was bad again so the stratigraphy analysis could not be done in detail but we successfully obtained the density samples with the help of the one of the science technical person (Katie Hess). On the 24th the weather was bad so the previous plan of investigating another pit was dropped. 25th July was the last full day at the camp.
and we completed packing the instruments and samples and everything was palletized. On the morning of 26th the team left the Summit camp for Kangerlussaq.

1.2 Weather Conditions

The weather was good with clear skies and gentle to moderate breezes until the last few days of our work. From 22nd July to 24th July the weather was bad. The sun was not visible and there were strong winds (wind speed varying about 11-18 knots). On 24th July the sky was clear, but due to the strong wind it was not possible to work outside in the pit.

2.0 Pit and Core Sampling Strategy

This section summarizes the strategy used to site pits and cores and describes the methodology for sampling the near surface firn.

2.1 Methodology

Before leaving for the field camp, a detailed observation plan was prepared for the snow pit investigations and the core sample retrieval.

- Select location representative of larger area (look at undulations in the terrain).
- Record observer, location number, date, time.
- Record location (lat-long, elevation), distance from camp.
- Record weather condition (temp, cloudiness, precipitation, wind (direction/speed)) and miscellaneous conditions (e.g. slope).
- Dig snow pit.
- Sketch a picture of site and wall.
- Measure temperature at 10 cm intervals. Insert 3 dial thermometers and the digital thermometer at each position and then take the average.
- Record stratigraphy:
  - Measure thickness of layers
  - Determine grain size, shape and orientation of grains in each layer.
  - Measure snow hardness, strength
  - Note ice pipes, lenses, depth hoar, wind crust, annual layers
- Sample density every 10 cm.
- Retrieve a core from the bottom of the pit.
- Measure temperature of core and borehole (24 hr).
- Record stratigraphy along the core (the method is described above).
- Collect oxygen isotope samples (Need not take from each pit).
- Mark site.

The following are necessary for drilling the core
- 1 Hand drill and extensions.
- 1 Wooden platform with hole (if available).
• 1 Wooden lid for hole (for temperature measurements).
• Keep the drill bit at straight as possible.
• Note the stratigraphy and the temperature of the various segments of the core.
• While cutting the core with the saw, make sure to have the hand saw perpendicular to
  the cutting board.
• Measure the radius of the core.

2.2 Firn Core Sampling Sites

Core locations were selected such that each core fell within a separate cell of the
SSM/I passive microwave grid (Figure 2). Density and isotope data will be used to
construct annual estimates of accumulation rate. The accumulation rate will be regressed
against brightness temperature in order to establish an empirical relationship. Three
shallow cores were collected. One of the cores was within the KU radar grid. The other
two were approximately 36.5 km away from the camp site in two opposite directions
(Figure 2). The locations of shallow cores are listed in Table 1.

Table 1  Location and depth of core sites

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Depth</th>
<th>Distance from the camp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 1</td>
<td>N 72.59598</td>
<td>W 38.4760</td>
<td>3210 m</td>
<td>5.2 m</td>
<td>2 km</td>
</tr>
<tr>
<td>Distantcore 2</td>
<td>N 72.80885</td>
<td>W 37.65947</td>
<td>3172 m</td>
<td>5.93 m</td>
<td>36.5 km</td>
</tr>
<tr>
<td>Distantcore 3</td>
<td>N 72.34882</td>
<td>W 39.25946</td>
<td>3161 m</td>
<td>5.95 m</td>
<td>36.5 km</td>
</tr>
</tbody>
</table>

2.3 Snow Pit Investigations

Three different 2 m pits were investigated (Table 2). One pit location was in the
vicinity of the SUMMIT camp (Figure 3) and the other two were on the KU radar grid.
Location, altitude (GPS), date, time and weather conditions (temperature) were recorded
before digging a pit. The Snow Tractor with the accumulation radar mounted on it
traversed around pit-2 and pit-3.

Table 2  Location and depth of shallow pit

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Depth</th>
<th>Distance from the camp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit 1</td>
<td>N 72.58079</td>
<td>W 38.4632</td>
<td>3206 m</td>
<td>2 m</td>
<td>241 m</td>
</tr>
<tr>
<td>Pit 2</td>
<td>N 72.59598</td>
<td>W 38.47600</td>
<td>3210 m</td>
<td>2 m</td>
<td>2 km</td>
</tr>
<tr>
<td>Pit 3</td>
<td>N 72.60268</td>
<td>W 38.49622</td>
<td>3198 m</td>
<td>1.95 m</td>
<td>2.92 km</td>
</tr>
</tbody>
</table>
The Summit camp and KU grid

SSM/I pixel (163,310)

Pit-1,2,3 and Core -1

SSM/I pixel (164,309)

Distant core 2

Distant core 3

Figure 2: Location of the pits and the core with respect to the SSM/I pixels. The size of each SSM/I pixel is 25km x 25km.
Figure 3: The KU radar grid and the location of the pits and core-1
3. Snow Pit Studies

This section summarizes physical property observations made at each pit site.

3.1 Stratigraphy

At each site the stratigraphy was observed and checked for the presence of ice layers, ice pipes, ice lenses and depth-hoar layers. Thicknesses of individual layers were measured and the grain size of the snow crystals determined using coated graph paper and a magnifying lens. Other characteristics such as snow strength and hardness were also recorded but the hardness measurement was qualitative. A photograph of the pit wall was taken after analysis of each pit (see Appendix 1). Between 60 and 65 cm below the surface a depth hoar layer was observed in all pits. Another comparatively thick hoar layer was observed roughly between 140 cm to 155 cm from the surface in all the three pits. Intermittent thin layers of hard ice, less than 1 mm thick, were observed in all the pits. The snow became harder at depth roughly 50 cm from the surface. The pit stratigraphies are shown from Figure 4, 5 and 6. The snow hardness measurements in pit-3 (Figure 6) could not be completed in the field due to bad weather for three consecutive days.
Figure 4: Stratigraphy of Pit-1
Figure 5: Stratigraphy of Pit-2
Figure 6: Stratigraphy of Pit-3. Unlike pit -1 and 2, no snow hardness data was recorded for this pit.
3.2 Grain Size Profiles

The grain size distribution from two pits are plotted in Figures 7 and 8 which show that the size of the grains tends to increase with depth. The grain size analysis of the third pit could not be done because of bad weather for two consecutive days. The orientation of the grains could not be estimated. The shapes of the grains were irregular to spherical.

![Grainsize profile in pit1](image1)

Figure 7: Grain size profile of pit 1

![Grainsize profile in pit2](image2)

Figure 8: Grain size profile of pit 2
3.3 Snow Pack Temperature

Both digital and dial stem thermometers were used to measure the temperature at 5 cm intervals. This was done on the wall shaded from the sun immediately after digging the pit so that the temperature profile would not be affected by isolation. The data shows that all temperature profiles are similar (Figures 9 to 11). The temperature profile of the third pit extends to only 1m depth as the weather deteriorated and the temperature profile of the whole pit could not be taken. The temperature measurement stopped at 50 cm from the surface in pit-2 because the near surface was heated by the sun over the course of the observations. Temperature measurements were made after the density data were collected and began at the base of pit-2.

**Figure 9:** Temperature profile of pit-1
**Figure 10:** Temperature profile of pit 2

**Figure 11:** Temperature profile of pit 3
3.4 Density Measurements

The density profile of the firn was determined at 5cm intervals. For this we used density tubes, the volume of which was measured with a graduated cylinder. Also a steel box, with known volume, was used for density measurement. The box was obtained from the science technical support group at the camp. The density samples were emptied in a ziplock bag (of known weight) and the total weight was determined using a temperature compensated spring scale. An electronic scale was also used which was available at the camp. The density profiles of the three pits are shown below in Figures 12, 13 and 14 respectively. The isotope profile of pit-3 is shown in Figure 15. The isotope measurements were made by Dr. Ping Nan Lin and Dr. Ellen Moseley-Thompson.

![Density profile of pit 1](image)

**Figure 12:** Density profile of pit-1
Figure 13: Density profile of pit-2

Figure 14: Density profile of pit-3
4.0 Shallow Core Studies

Three shallow cores of length 5.20 m, 5.93 m and 6 m respectively were drilled with a hand auger. The outer diameter of the drill bit was 11.5 cm and the diameter of the cores was measured to be 7 cm. A plywood board with a hole in the middle was used to put the drill bit through the hole into the snow.

The upper snow layer was not removed for the first coring attempt (the core on the KU radar grid, figure2). Unfortunately, the upper 30 to 40cm of the snow disintegrated as soon as the drill bit was extracted and so the samples were lost. The snow below this depth came out as one piece and the sampling was started from this section. The total length of the core was 5.20 m. This means that the actual depth of the bottom of the core is 5.50 to 5.60 m from the surface. The core was cut by a hand saw in 5 cm pieces, and each 5 cm cylindrical piece was put into ziplock bags. Rubber gloves were used to hold the samples to avoid contamination.

The next core was drilled at a location 36.5 km away from the camp. At this site a 0.55 m deep pit was dug and then the drilling was stared. The first few centimeters (12 cm) of the core could not be collected as it fell apart when pulled out of the drill. But after this depth good core was obtained. This core was sampled in 10 cm pieces and not in 5 cm pieces as the number of samples bottles were limited. The actual depth to the bottom of the core was 6.67m from the surface.

The procedure for the third core was the same as the procedure for the second core. A 0.55 m pit was dug and drilling commenced in the pit. Still, the upper 18 cm were lost as
snow fell apart when the drill bit was taken out. Consistently good core was obtained for a length of 5.99 m. The core sampled to a depth of 6.72 m. The ziplock bags which were reused for the sample collection were washed prior to use in the green house with de-ionized water in order to avoid any contamination.

All the core samples were kept in the green house to melt and then the water was poured into plastic bottles. The bottles were filled with water so as to leave no air in the bottles. Finally the bottles were sealed with duct tape. All these samples were then packed in cardboard boxes and where brought back to the lab for isotope analysis.

The density data obtained from the two distant cores is shown in Figure 16 along with the data collected by Bolzan in 1987. There appears to be a systematic bias in the 2004 observations compared to the Bolzan data and the pit results (also shown in figure 16). We believe there might have been error in estimating the diameter of the core. In the field we estimated the diameter to be 7 cm. Jezek using the same drill bit measured a diameter of 7.6 cm during a previous investigation. We plot the densities computed using a core diameter of 7.6 cm in Figure 17. Figure 17 shows that the corrected densities are very similar to the Bolzan density data and the density from the pits. Isotope data are included on the accompanying CD.

**Figure 16:** The density profile obtained from the distant cores, from the pits and from the density data obtained by Bolzan
The plot of the density data from cores and pits after correction for the core diameter

Figure 17: The density profile obtained from the distant cores after correcting for the volume, from the pits and from the density data obtained by Bolzan
5.0 Discussion

In this section we discuss modifications to our planned procedure when faced with real field conditions. We discuss the implications of the modifications on the data set. We go on to make several data comparisons to validate the quality of our data set and to identify possible errors.

5.1 The Deviations from the Planned Method in the Field

The density samples and temperature measurements in the pit were collected at 5 cm intervals. The grains shape could not be clearly documented as they were mostly irregular or tending to round shape. The hardness of the different layers was measured qualitatively. Hard ice layers could be observed but ice pipes, ice lens were not present in the pits.

We planned to dig a pit and then drill a core, but digging a 3x2x2 cubic meter pit was impractical (the plywood drill platform itself was large so as to provide some extra space on the board where the sample could be marked, cut and stored in plastic bags). So for the two distant core sites, 0.55*3*2 cubic meter pits were dug first and then the drilling was done. For the first core at the KU grid, core was first drilled out then the pit was studied on the next day adjacent to the core site. The stratigraphy could not be observed clearly in the core hence it was not recorded.

5.2 Density Data Validation: Comparison with Other Density Estimates

To validate the density profile obtained from the three shallow pits, we compared our data with the density data collected by John Bolzan (1987, Figure 18), the data collected by Paul Mayewski and Sallie Whitlow from snow pits at Summit, Greenland (1987, Figure 19) and the data collected by the science technical support group at the summit camp (June, 2004). The location of all these sites are different (except the data from the science technical support group who collected data about 500 m away from pit 1), but they are in vicinity of the three pits which were investigated during this summer field. The absolute value of the densities computed from the three pits were found to be comparable to the absolute values obtained from the three other individual density data sets i.e. the Bolzan data, the Mayewski and Whitlow data and the Science techie data. Figure 20 shows the plot of the datasets. It can be seen from the plot that except for one data point in pit1 (mentioned above) the values are all reasonably consistent in the mean.
Figure 18: Density profiles from Bolzan data (1987) at the summit camp

Figure 19: The density data from Mayewski and Whitlow at Summit Camp
Figure 20: Plot of all the density data

A line was fit to each of these density profiles. Then this line was subtracted from the measured data and the residuals were obtained. The standard deviation of the residuals of all the profiles was calculated and it was found that the standard deviations were comparable. This suggests that the density values obtained from the three pits are reasonable and display a variation comparable to the other data. The standard deviations for all these data sets are given below in Table 3.

Table 3  Standard deviation of the density data obtained by various workers

<table>
<thead>
<tr>
<th>Location</th>
<th>Standard Deviation (gm/c.c.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolzan_site_13</td>
<td>0.0293</td>
</tr>
<tr>
<td>Bolzan_site_15</td>
<td>0.0263</td>
</tr>
<tr>
<td>Bolzan_site_31</td>
<td>0.0292</td>
</tr>
<tr>
<td>Bolzan_site_summit</td>
<td>0.0326</td>
</tr>
<tr>
<td>Mayewski_Wiltow_pit3</td>
<td>0.039</td>
</tr>
<tr>
<td>Mayewski_Wiltow_pit5</td>
<td>0.038</td>
</tr>
<tr>
<td>Science_techie__summit_may</td>
<td>0.0412</td>
</tr>
<tr>
<td>Science_techie__summit_june</td>
<td>0.0415</td>
</tr>
<tr>
<td>Indra_pit_1</td>
<td>0.0307</td>
</tr>
<tr>
<td>Indra_pit_2</td>
<td>0.0376</td>
</tr>
<tr>
<td>Indra_pit_3</td>
<td>0.0446</td>
</tr>
</tbody>
</table>
The average standard deviation for all the density data is 0.0355 gm/c.c. Figure 20 shows that one data point in pit 1 (the density at a depth of 65 cm) is an outlier by more than 2 standard deviations. We concluded that this record is probably not correct. The error was caused most probably by the fact that the density tube used to collect the sample was jammed too far into soft snow, so a faulty mass was measured.

We make a rough estimate of errors on the density data based on the measuring equipment and a subjective estimate of human error. The least count of the weighing scale was 0.5 gm and the error in measuring the volume is of the order of 1 ml. Considering the human error in collecting the mass to be 5%, the error in the density is ± 0.01 gm/c.c.

6.0 Preliminary Results

We used our observations to calculate accumulation rate. We describe our calculation in this section and compare our estimate to other, independent observations.

6.1 Accumulation Rate from Snow Pit Data

Based upon the isotope profile and the density data from pit 3, the snow accumulation between 2003 winter and 2002 winter is approximately 26.98 cm of ice equivalent (24.28 cm water equivalent). From the winter of 2002 to 2001 the accumulation rate is approximately 27.18 cm of ice equivalent (24.46 cm water equivalent).

6.2 Comparison of Recent and Long-Term Accumulation Rates

From the website of University of Maine, Arctic Program, a time series of snow accumulation at the Greenland summit site is available (from the year 1840-1990), Figure 21. The pit derived accumulation rate found for the years 2002 and 2001 is comparable with the average value (24.6 cm) given in the University of Maine time series.
Figure 21: Annual accumulation of snow at Summit, Greenland (in water equivalents). Blue line represents 600 year average for accumulation at Summit (0.246 m/yr). The yellow and green dots show the accumulation rate calculated from density and isotope analysis for 2001 and 2002 respectively.

6.3 Comparison of In-Situ and Passive Microwave Deduced Accumulation Rates

Bolzan and Jezek (2000) developed an empirical approach for computing annual accumulation rates from passive microwave data. They used SMMR data for the analysis because the SMMR time period corresponded to the ages available in the firn cores. We have extended the analysis forward in time by using the Bolzan and Jezek regression coefficients and recalibrating the SSMI data to SMMR. An example of the result is shown in Figure 22. We compare our results to modeling estimates provided by Jason Box. We are presently trying to understand the differences. We also plot our Summit Site result, located about 77.35 km away from site 73.
6.4 Short-Term Variations in the Density Profile

The science technical support group at Summit camp measured the monthly properties of the upper firn from 1 m deep pits, from August 2003 to the June 2004. The measurements are in support of a science project led by Roger Bales. A new pit is dug at approximately the same location to observe changes in the firn properties. The plots of the pit density profiles from August 2003 to December 2003 and from February 2004 to June 2004 are shown below. The first profile is for the month of August and the successive months profiles are arranged from left to right.
The density profiles reveal that vertical variation patterns do not persist in the density profiles between several consecutive months. We expected to see a gradual change in the density profile with time. This was not the case. A low density layer is found at a depth of approximately 20 cm from the surface (Figure 22A). This layer could be roughly identified in following 3 months only before vanishing. This suggests that either the accumulation and densification of firm at summit is not a simple linear process or that there are very rapid spatial changes in the density profiles and these compromise time series analysis of even closely spaced pits.

**Figure 23:** The density profile from the string pits. Figure (A) to (E) shows the density profile from August 2003 to December 2003 and figure (F) to (L) shows the density profile from February 2004 to September 2004 (except July 2004). Data are courtesy of Roger Bales.
7.0. Summary

We successfully completed studies of three snow pits and three shallow cores. From the observed stratigraphy, two hoar layers were found to be consistent in all the three pits. The grain size tends to increase with depth and also the snow gradually become harder with depth. Intermittent thin ice layers were observed in all the three pits and occasionally they were also seen in some of the core pieces. These data will be used to validate the radar profile obtained by the KU radar. We used the data to calculate accumulation rates and found an average accumulation rate of 24.28 and 24.46 cm water equivalent for 2002 and 2001 respectively. This is comparable to the 24.6 cm/yr water equivalent based on a 600 year average.

8. References

3. [http://arcss.colorado.edu/data/arcss048.html](http://arcss.colorado.edu/data/arcss048.html)
5. [http://jan.ucc.nau.edu/~cvm/latlongdist.html](http://jan.ucc.nau.edu/~cvm/latlongdist.html)
Appendix 1:

Snow Pit -2
Ice Core
Appendix 2:

The Excel sheets with all the data are being provided in a CD. The names of the Excel sheets and the contents in each sheet are documented below.

1. Bolzan_and_Mayewski_Wiltow_pit_data:- This Excel sheet has one data sheet with all the pit data obtained by Paul Mayewski and Sallie Wiltow from Summit Greenland, 1987 and the data obtained by John Bolzan at sites 13, 15, 31 and Summit, Greenland. In addition three graphs are provided. One graph showing the density profile at site 13 obtained by Bolzan, the next one showing the density profile calculated by Bolzan from four sites and the last graph shows the plots of all the data from Bolzan and by Mayewski and Wiltow.

2. Science_techiedata_and_OSU:- This sheet has the data from the string pits collected by the science technical support group at summit camp. There are plots of these density data for every month. In addition a plot of all the density profiles obtained from different individual datasets i.e. by Bolzan, Mayewski and Wiltow and by Bhattacharya is also provided in this sheet.

3. Location_core_pit:- In this sheet the latitude and the longitude of pits and the cores are provided. Two graphs are provided. One shows the KU radar grid and the pits and core near the KU radar grid and the other graph depicts the location of the cores and pits with respect to the SSMI pixel.

4. OSU_pit_data:- In this sheet all the data of the pits and cores collected by Bhattacharya are provided. The plots of the density profiles, grain size, temperature profile, stratigraphy of all the pits is provided. The isotope data of pit-3 is included. Also the firn-core density data and the plots of the core density data (before and after correcting the error in the diameter) are provided.
Addendum:
The oxygen isotope profile of distant core-1 and distant core-2 are given below in figures (a) and (b).

**Figure (a):** Oxygen isotope data from distant core-1

**Figure (b):** Oxygen isotope data from distant core-2
The accumulation rates from the core were determined between successive summer peaks and winter peaks in oxygen isotope value. The accumulation for the year 2003 refers to the accumulation year from summer of 2003 to the summer of 2002 when we considered summer peaks. The annual accumulation rate (in cm of water equivalent per year) from distant core -1 is tabulated below in Table-A.

**Table -A**

<table>
<thead>
<tr>
<th>Year</th>
<th>Summer Accumulation</th>
<th>Winter Accumulation</th>
<th>Average Accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>18.12</td>
<td>25.17</td>
<td>21.64</td>
</tr>
<tr>
<td>2001</td>
<td>22.31</td>
<td>22.19</td>
<td>22.25</td>
</tr>
<tr>
<td>2000</td>
<td>18.66</td>
<td>18.23</td>
<td>18.45</td>
</tr>
<tr>
<td>1999</td>
<td>19.16</td>
<td>19.72</td>
<td>19.44</td>
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The annual accumulation rate (in cm of water equivalent per year) from distant core -2 is tabulated below in Table-B.

**Table –B**

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<th>Average Accumulation</th>
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