Using liquid-equivalent snow gauge measurements to determine snow depth - Preliminary Results

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Introduction

Snowfall and snowdepth measurements and forecasting affect various aspects of commerce, transportation, agricullture, and city utilities planning. Modeling snowdepth is a complex problem that can quickly evolve into a model involving a large number of different factors depending on measurements of air temperature, atmospheric pressure, water vapor mixing ratio, precipitation, wind speed, soil moisture, soil temperature, and surface albedo. *(Jordan 1991)* The number of factors considered may be increased to gain greater accuracy in measuring snowdepth indirectly, resulting in a miriad of measurement factors necessary for the snowdepth model. One goal of this report is to simplify the snowdepth model in order to estimate snowdepth based on liquid-equivalent snow gauge mesurements. Aside from modeling snowdepth indirectly, ultrasonic snow depth sensors (USDS), such as the Judd USDS and the Campbell USDS, have introduced the possibility of accurately measuring snowdepth directly. While the adaptation of USDS from their previous use in measuring creek and river heights is promising, the nature of the USDS instrument lends its measurements of snowdepth to both large and small amplitude variability. The USDS ability to measure snowdepth is inherently hindered by factors such as snow crystal type, the presence of blowing or drifting snow, extreme cold temperatures, uneven snow surfaces, snow density, intense snowfall, and wind.*(Brazenec 2005)* Another goal of this report is to compare estimates of snowdepth from factors measureable by a liquid equivalent snow gauge to the measurements of the Judd USDS and the Campbell USDS. The snowdepth estimate uses factors including changing snow density, wind speeds, and compaction from metamorphosis and overburden on snow depth. These factors are readily available from liquid-equivalent snow gauges.

Location and Scope

The liquid-equivalent snow gauge that is used to estimate snowdepth is installed at the Marshall Field Site in Marshall, Colorado at a latitude of 3956'45" North and a longitude of 10511'38" West. The elevation of the site is 5716' MSL. The Marshall Field Site is a flat, open field with a minimal amount of natural and manmade obstructions. The dates for which the snowdepth was estimated using the liquid-equivalent snow gauge and compared to the Judd USDS and Campbell USDS were for winter dates from 2003 through 2006. The snowfall events during the winter of these years ranged from liquid equivalent accumulation maximums of 1 inch to 1 foot of liquid equivalent snow for individual snowfall events. As such the scope of the estimate using the liquid-equivalent snow gauges should be applied to similar ranges in snowfall. The estimates referenced in this report are from a preliminary analysis.

Measuring Instruments

Liquid Equivalent Snow Gauge

The liquid-equivalent snow gauge used for estimating snowdepth is the Geonor Precipitation Gauge T-200. The Geonor instrument is a weighing precipitation gauge used to measure liquid precipitation accumulation and precipitation rates. A weighing bucket is suspended by three cylinders, each housing a vibrating wire. The vibrating wires are driven by a range of frequencies and vibrate at their resonance frequencies. The resonance frequency of each wire depends upon the tension in the wire, which is directly related to the amount of weight in the bucket. Information is processed and sent to a CR-10X data logger where one-minute average accumulations are stored. The Geonor uses a large DFIR wind shield in addition to a steel single alter wind shield treated with Vellox, a water repellant that prevents icing.

Figure 1: Picture of the Geonor T-200 liquid-equivalent snow gauge installed at the Marshall Field Test Site in Marshall, CO

Ultrasonic Depth Gauges

The Judd USDS and the Campbell USDS are the two ultrasonic depth gauges installed at the Marshall Field Test Site. The USDS works off of the principle that ultrasonic pulses can reflect off of dense objects. The USDS is mounted vertically above the ground at a height such that the instrument will not be submerged in snow. The USDS sends an ultrasonic pulse of 50kHz toward the ground and waits for the pulse to reflect off of the ground or snow below. The time it takes for the reflected pulse to return to the sensor can be used to determine the distance between the instrument and the snow or ground and thus snowdepth can be calculated. The USDS includes a temperature probe and radiation shield since the speed of the ultrasonic pulse depends on the density of the air through which it travels. *(Brazenec 2005)* The density of air is dependent on temperature, and to adjust the speed of sound in air, V_{sound}, given an ambient temperature, T_a in degrees Kelvin, the following equation is used:

$$V_{sound} = 331.4 * \left(\frac{T_a}{273.15}\right)^{\frac{1}{2}} \text{ (m/s)} \tag{1}$$

The Judd USDS uses the following equation to correct the measured snowdepth, D_{meas}, to get a corrected value for snowdepth, D_{snow}, at a temperature $T_{Celsius}$:

$$D_{snow} = D_{meas}\left((T_{Celsius} * 0.00183) + 1\right) \tag{2}$$

The Campbell USDS uses a similar correction using T_{Kelvin}:

$$D_{snow} = D_{meas}\left(\frac{T_{Kelvin}}{273.15}\right)^{\frac{1}{2}} \tag{3}$$

The nature of the USDS makes its measurements very sensitive to the object that is to reflect the ultrasonic pulse back to the sensor. The USDS works best when the object below the instrument is dense and flat or level below the instrument. Snow rarely meets such ideal conditions and while the instrument pulse utilizes a cone of 22 degrees over which measurements are taken, the USDS is often unable to obtain any reading due to non-ideal conditions. The factors that can affect the conditions for whcih the USDS is unable to make measurements or reports false measurements include snow crystal type, intense snowfall, wind speed, uneven snow surfaces, extreme temperatures, and the presence of blowing or drifting snow.*(Sicart 2002)* For this reason, the data obtained from the Judd and Campbell instruments must be quality controlled extensively to remove errors. *(Brazenec 2005)* Figure 2 shows the USDS measurement inconsistencies notable over a two day period during a snowfall event.

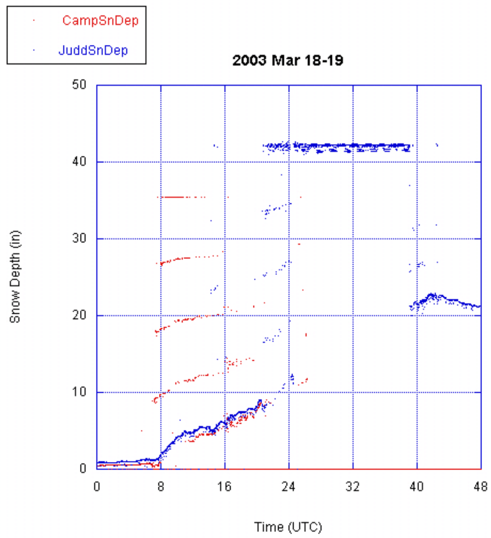

Figure 2: Measurements taken from the Campbell USDS and Judd USDS during a snowfall event.

Snowdepth Estimation Method

The model for estimating snowdepth will include the effects on snowdepth of precipitation rate, snow density, wind speed, ambient temperature, and compaction calculations from metamorphosis and overburden. All measurements necessary for the estimate are taken from the Geonor liquid-equivalent snow gauge and a 10 meter wind gauge. For this reason the estimate is readily applicable to the majority of existing weather stations with no modifications or extra instruments necessary.

Snow Density

The density of falling snow plays an important role in estimating the amount of snow that has fallen relative to liquid-equivalent precipitation rate measurements. Many factors can affect the density of snow and they include in cloud processes that determine the size and shape of snow crystals, sub cloud processes that change the snow crystal as it falls, and compaction due to metamorphism and overburden. The affects of compaction will be addressed seperately from determining the snow density as it falls. *(Roebber 2003, Meister 1985)*

The equations used for calculating snow density are adapted from a one dimensional mass and energy balance model used in the SNTHERM numerical model for snow. The SNTHERM model simulates most snow cover properties and processes including heat change, phase change, water flow, snow ablation and accumulation, densification, grain growth, surface absorption of solar radiation, and surface energy exchange. *(Jordan 1991) Jordan* [1991] gives a more detailed description of SNTHERM. However, the equations of interest for this report are for the change in density of snow. The SNTHERM equations are of particular use since they describe snow density as a function of ambient temperature and wind speed. These two variables are easily obtained from a stations having a liquid-equivalent snow gauge.

The relation that is used to determine the amount of snow that is falling, S_{amt}, as a function of the liquid-equivalent precipiation rate, P_{rate}, the ambient temperature, T_a(Kelvin), and the 10 meter wind speed, U_{10}(m/sec), is given by the following equations from the SNTHERM numerical model: *(Jordan 1991)*

$$S_{amt} = P_{rate} * \frac{\rho_{water}}{\rho_{snow}} \tag{4}$$

where ρ_{water} is the density of water (1000kg/m^3) and ρ_{snow}(kg/m^3) is the density of snow given by:

$$\rho_{snow} = 500\left\{1 - 0.951exp\left[-1.4\left(278.15 - T_a\right)^{-1.15} - 0.008U_{10}^{1.7}\right]\right\} \tag{5}$$

For $\quad 260.15\mathrm{K} < \mathrm{T_a} \leq 275.65\mathrm{K}$

$$\rho_{snow} = 500\left\{1 - 0.904exp\left[-0.008U_{10}^{1.7}\right]\right\} \tag{6}$$

For $\quad \mathrm{T_a} \leq 260.15\mathrm{K}$

Using these equations to obtain S_{amt}, the first term of the snowdepth estimate D^1_{snow} can be calculated by:

$$D^1_{snow} = \sum_{t=0}^{t} S_{amt} \tag{7}$$

Preliminary analysis of these equations for snow events in 2003 showed promising correlation to the snowdepth measured by the Judd USDS and Campbell USDS without corrections to the snowdepth equation for compaction and melting. An example plot of the first term of the snowdepth estimate compared to the measurements of the Judd and Campbell sensors is shown in Figure 3:

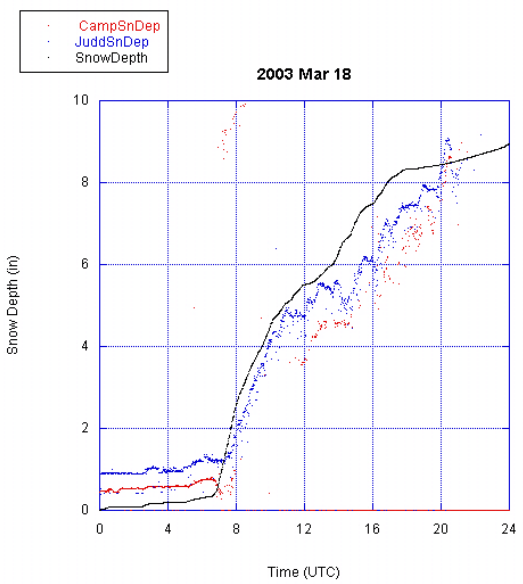

Figure 3: Plot of snowdepth using the first term of the snowdepth estimate versus the measurements of the Judd and Campbell sensors

As seen in the plot the first term followed the good readings of the ultrasonic sensors fairly well for this snow event. This was likely due to lack of compaction and melting during the snow event. The plot also shows the inconsistencies inherent in the Judd and Campbell sensor measurements. The outlying data points for the Judd and Campbell sensors may be due to reflections of the ultrasound pulses off of falling snow or wind, affecting the pulses to give a kind of resonance effect in the measured snowdepth.

The first term of the snowdepth estimate does not account for the processes that affect snow density once the snow is on the ground. Additional correction terms are necessary to model the change in snowdepth due to the effects of compaction and melting of the snow once it is on the ground.

Compaction

The compaction due to metamorphisis and overburden will be considered in developing the second term for the snowdepth estimate. Metamorphism is compaction due to the breakdown of snow crystals in snowpack. Overburden takes into account the weight of the upper layers of snow acting on the lower layers of snow in a snowpack. The equations that will be used to correct the snowdepth estimate for these compaction factors is taken from the SNTHERM.89 one dimensional snowpack model by R. Jordan in 1991. The compaction model presented by is dependent on ambient temperature, T_a (Kelvin), and the density of snow, ρ_{snow}, that was calculated in the equations for the first term of the snowdepth estimate. In addition, the model from Jordan uses the bulk density of water, γ_{water}, and the bulk density of ice, γ_{ice}. The equations for compaction due to metamophism and overburden are given below:

$$\left|\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right|_{metamorphism} = -2.778 * 10^{-6} * C_3 * C_4 * e^{-0.04(273.15-T_a)} \tag{8}$$

$$\begin{aligned} \text{If } \gamma_{\text{water}} = 0 \text{ and } \gamma_{\text{ice}} \leq 150\text{kg/m}^3 \qquad & C_3 = C_4 = 1 \\ \text{If } \gamma_{\text{ice}} > 150\text{kg/m}^3 \qquad & C_3 = exp[-0.046(\gamma_{ice} - 150)] \\ \text{If } \gamma_{\text{water}} > 0 \qquad & C_4 = 2 \end{aligned}$$

$$\left|\frac{1}{\Delta z}\frac{\partial \Delta z}{\partial t}\right|_{overburden} = -\frac{P_{snow}}{\eta_0} e^{-C_5(273.15-T_a)-C_6\rho_{snow}} \tag{9}$$

where

$$P_{snow} = \text{snow load pressure} = 248.976 * \text{liquid equivalent of snow in N/m}^2$$
$$\eta_0 = 3.6 * 10^6\ \text{N s/m}^2$$
$$C_5 = 0.08\ \text{K}^{-1}$$
$$C_6 = 0.021\ \text{m}^3/\text{kg}$$

The variables C_3 and C_4 take into account the different compaction rates depending on the wetness of the snowpack. The constant C_4 is set to 2, effectively doubling the compaction rate, if the temperature is above freezing (32°F). The snow density, ρ_{snow}, is used to estimate C_3 and C_4. The metamorphism equation is used to calculated the metamorphism snow depth and this value is used in the overburden equation only if uderlying snow is present. *(Jordan 1991)* These equations are used to develop the second term in the snowdepth estimate to correct for compaction due to metamophism and overburden.

Results and Discussion

The snowdepth estimate was tested on a variety of snow event days for the winter in the years of 2003 through 2006. The snowdepth calculation was compared to the mesurements of the Judd and Campbell snow depth sensors as a basis for the accepted snowdepth for each snow event. The estimate preformed suprisingly well in preliminary plots for its simplicity to a variety of snow events. The main problem inherent in the estimate was overestimation of the snowdepth during warmer snow events. The plot in figure 4 shows the first term of the snowdepth calculation versus the Judd and Campbell sensors. The first term of the estimate does not account for any decreases in snow depth due to compaction or other factors. Figure 5 shows the snowdepth estimate including all terms of the estimate and takes into account the compaction of the snow throughout the day. For this event the snow depth estimate correlated well to the Campbell USDS while it deviated from the Judd USDS. The difference in snowdepth measuered by the Campbell and Judd sensors for this event is typical for a snowfall event at the Marshall Field Test Site.

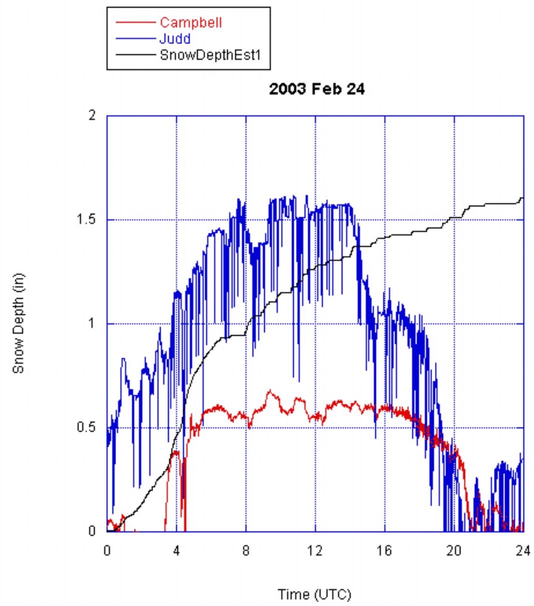

Figure 4: First term of snowdepth estimate versus the measurements from the Campbell USDS and Judd USDS

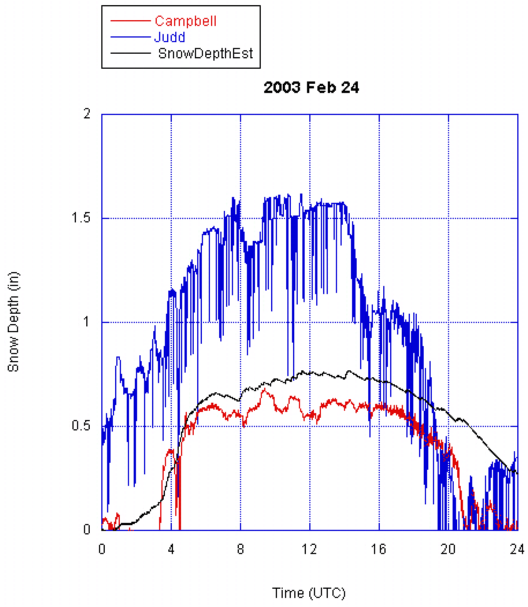

Figure 5: All terms of the snowdepth estimate versus the measurements of the Campbell USDS and Judd USDS

As seen in the previous plots, the Judd and Campbell snowdepth measurements are somewhat noisy. This event is a representative example of the typical behavior of the USDS measurements from both the Judd and Campbell instruments. While noisy, these instruments still provide useful information about snowdepth and are capable of reporting accurate values enough that the snowdepth estimate performance can be analyzed.

Conclusion

The snowdepth estimate presented takes into account measurements of liquid equivalent, temperature, wind speed, precipitation type, and precipitation amounts to estimate the density of falling snow as well as the effects of compaction in order to estimate snowdepth. The equation used for the calculating the density of snow is adapted from the SNTHERM numerical model. *(Jordan 1991)* This density calculation performs well in the preliminary analysis of relating snow density to snowdepth neglecting compaction and melting factors. The snowdepth estimate performance as compared to the measurements of the Campbell USDS and Judd USDS was good for an estimate in preliminary analysis. In order to gain more precision in estimating the snow density from liqud-equivalent gauges, additional terms may be added to the estimate to take into account further factors affecting snowdepth. The primary advantage of using the snowdepth estimate is that it is a reliable estimate that does not have the noise and inconsistencies that are associated with the use of ultrasonic snowdepth devices such as the Campbell and Judd instruments. In order to use the measurements from these USDS, extensive quality control must be done and in many instances good data is not available for minutes to hours at a time. The snowdepth estimate also has the advantage of being easily applied into liquid-equivalent snow gauge data acquisition systems to provide real time estimates of snowdepth without the need for any additional equipment. Should the success of preliminary analysis be reproduced for more cases, the snowdepth estimate will provide a useful tool for many weather stations.

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