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Measurements of Snowpack Temperature in a Colorado Subalpine Forest

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I. Introduction:

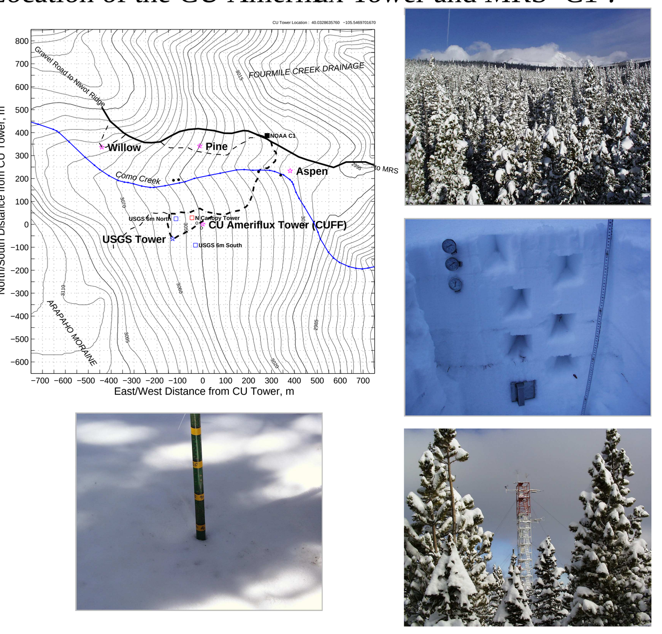


Figure 1: *Location of the CU Ameriflux Tower and MRS "C1".*

Large snowpack temperature gradients (on the order of 10°C m^{-1}) cause water vapor to migrate upward from the (warm) bottom of the snowpack and are a critical factor controlling the formation of depth hoar and the metamorphosis of the snow crystal structure (LaChapelle, 1992). The tranisition from a "cold" snowpack to an isothermal snowpack is a crucial event in the hydrologic cycle of the sub-alpine forest ecosystem as liquid water becomes available for trees which initiates large-scale photosynthetic uptake of CO_2 (Monson et al., 2005). In our study, four years of snowpack temperature data from the Niwot Ridge Ameriflux site were examined with respect to atmospheric conditions, radiation, and the turbulent surface fluxes of heat and water vapor. The average canopy height of the forest is around 11 m with a tree density on the order of 0.4 trees m^{-2}. Atmospheric measurements were provided by the University of Colorado (CU) Ameriflux 26-m tower and also from the LTER "C1" site (Figure 1). The snow temperature probes consisted of polycarbonate rods embedded with thermistors every 10cm (model TP101 probes, Measurement Research Corporation (MRC), Gig Harbor, WA, 98335). Soil temperature and soil moisture were also measured. In the winter of 2004, snow density profiles were determined weekly by manual snow pits. The primary objective of our study is to examine the cause of intense snowpack warm-up events described herein.

Typical of continental mountain locations, Niwot Ridge experiences several cold-air "events" each winter when the night-time air temperature drops to -20°C. Depending primarily on the snowpack depth these cold air events may (or may not) affect the soil temperature beneath the snowpack (Figure 2). The winters of 2002-3 and 2003-4 both experienced relatively shallow snowpacks (in Nov/Dec) which exposed the soils at both C1 and in the forest to cold air temperatures and allowed the soil temperature at 5-cm depth to get as cold as -7°C. In contrast, the winter of 2004-5 experienced heavy snowfall in early December that provided insulation of the soils at both C1 and near the CU tower throughout the entire winter. We should note that the C1 soil sensors are in a location that is more exposed than the "forest" soil sensors near the CU tower. This difference in exposure results in snow-free conditions at C1 anywhere from a few weeks to a month earlier than complete ablation at the CU tower (Fig. 2c). However, the onset of snowmelt, indicated by a change in soil moisture, appears to occur with similar timing at both locations (Fig. 2d). (also note that the snowdepth sensor and soil temperature sensor at C1 are not co-located which explains why the diurnal cycle at C1 appears in the soil temperature prior to the date of complete snow ablation.) During the transition from winter to spring, the intensity of incoming radiation increases, days become longer, and air temperatures start to increase. These increased energy inputs lead to a snowpack with a temperature profile that is at or near freezing (the so-called "equitemperature" (ET) snowpack) and the phase transition of snow crystals into water begins. Any additional energy inputs after the snowpack has become ET are used to melt snow. From our snowpack observations, the transition from a cold, temperature-gradient (TG) snowpack to an ET snowpack can occur very abruptly (on a time scale of hours). If it is early in the season, the snowpack will (sometimes) revert back to a TG snowpack. Some of the transition periods to an ET snowpack are marked with vertical dashed lines in Fig. 3. Based on these data it appears that one common feature of most of the abrupt transitions to an ET snowpack is having air temperatures above freezing and unseasonably moist air (specific humidity on the order of 4 g kg^{-1}). Based on data from a single tower it is difficult to assess if the air humidity is increasing due to the melting of the snow or if the humid air is advected into the area as part of a larger-scale weather system. However, humid, warm air has the ability to condense on snow surfaces which releases latent heat energy into the snowpack and can initiate snow melt. This phenomena is known to be one of the most efficient processes for melting snow (Doesken and Judson, 1997). Our discussion will focus on one 10-day period in 2006 where a sudden warm-up of the snowpack occurred (this event is shown in Fig. 3d and Figs. 4 and 5)

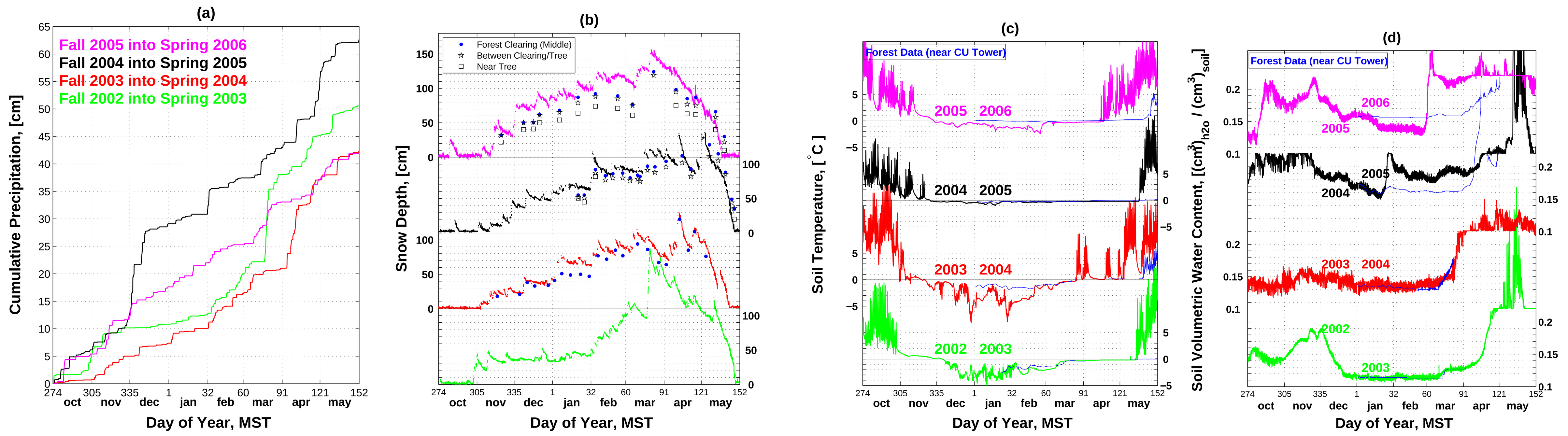


Figure 2: *The winter-long time series of (a) cumulative precipitation, (b) snow depth, (c) soil temperature T_{soil}, and (d) soil moisture q_{soil} from C1. For T_{soil} and q_{soil} the blue lines are from sensors near the CU tower (the CU tower q_{soil} data have been shifted to overlay the C1 data). Snow depths that are shown as symbols are from manual snow-pits or marked poles near CU tower.*

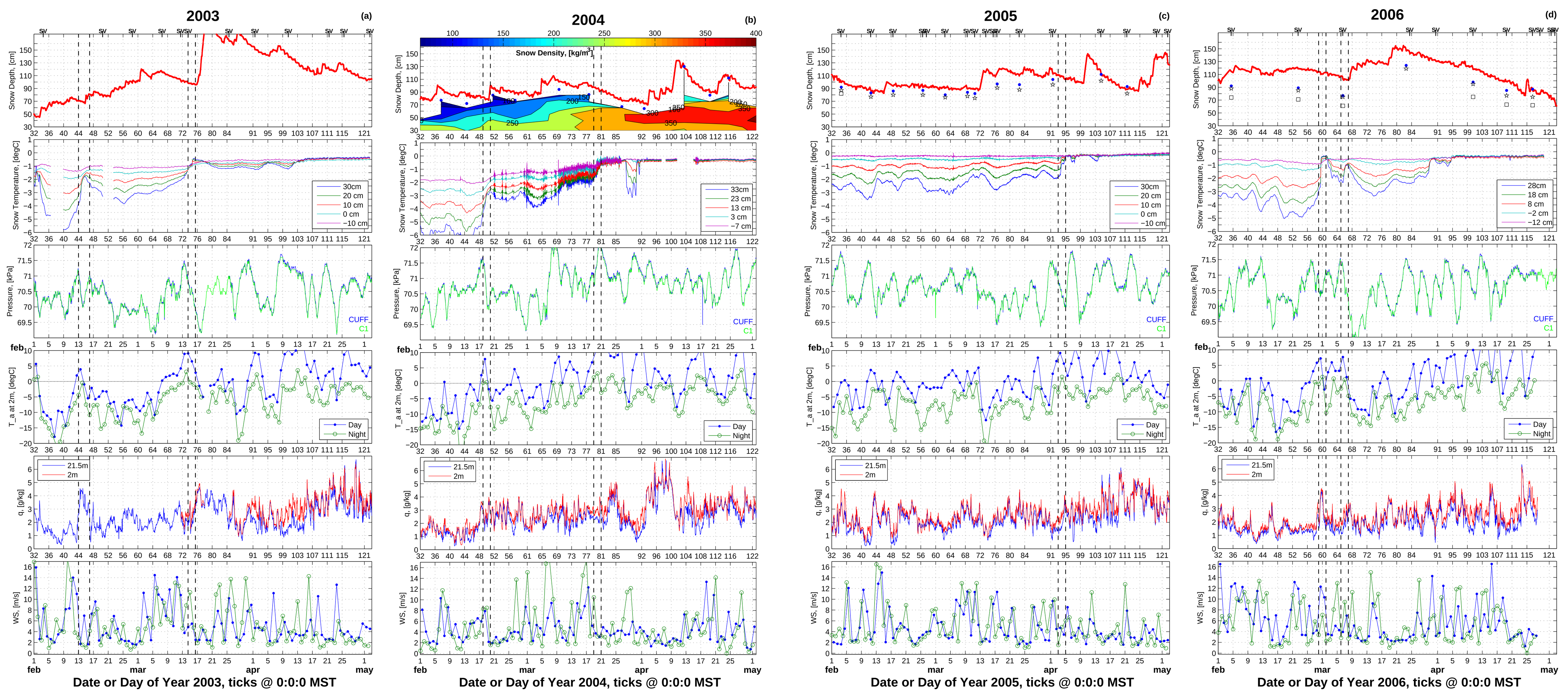


Figure 3: *Time series of (top panel) snow depth, snowpack temperature, atmospheric pressure, air temperature T_a, specific humidity q, and (bottom panel) wind speed WS from Feb 1 to early May for 2003-2006 (a-d). For T_a and WS the mean daytime (11:00-15:00 MST) and night-time (23:00-3:00 MST) values are shown. Dashed vertical lines indicate significant snowpack warming events.*

II. Snowpack Heat Budget:

The energy balance of snowpacks has been well studied (Cline, 1997; Hayashi et al., 2005). For a snowpack of depth h, the energy inputs that affect changes in snow temperature (T_s) can be written as,

$$\int_0^h \rho_s C_s \frac{\partial T_s}{\partial t} dz + Q_m = R_n + Q_{soil} + Q_e + Q_h + Q_p$$

Time-Variation of Snow Temperature	Melt/Freeze Energy	Net Radiation	Soil Heat Flux	Latent Heat Flux	Sensible Heat Flux	Precip Energy

where the terms on the left are internal changes to the snowpack energy (ρ_s and C_s are the snow density and heat capacity, respectively) and the terms on the right side are primarily surface phenomena. A positive sign indicates energy added to the snowpack and a negative sign is energy extracted from the snowpack. All terms have units W m^{-2}. Next, we now consider some of these terms over our 10-day period of interest (Figs. 4 and 5). Radiative transfer in a forest is a complex process and we won't consider R_n except to note that most days in our 10-day period were cloud-free (and also precipitation-free). Fig. 4k shows that the heat fluxes are generally small with sensible heat (Q_h) warming the snowpack and evaporation (Q_e) cooling the snowpack. Note that the night prior to the formation of the ET snowpack there was an extremely strong downslope wind (the so-called Chinook or Foehn wind). Such a strong wind mixes warm (dry) air from aloft down toward the snow surface. As the windspeed drops at around noon on Feb. 28, the humidity of the atmosphere starts to increase, and the snowpack begins to transition from TG to ET. Fig. 5 shows that the snow "warmup" starts at the top of the snowpack and moves downward (presumably due to melted snow-water percolating through the snowpack). Also, the warming of the snowpack in the clearing starts about 1-2 hours earlier than the warmup of the snow near the trees. During the Chinook-wind period the net turbulent flux transferred energy into the snowpack and helped the transition from TG to ET. However, for the day following the transition to ET, there was a net cooling of the snowpack by the turbulent fluxes, and the snowpack reverted back to TG (Fig. 4l).

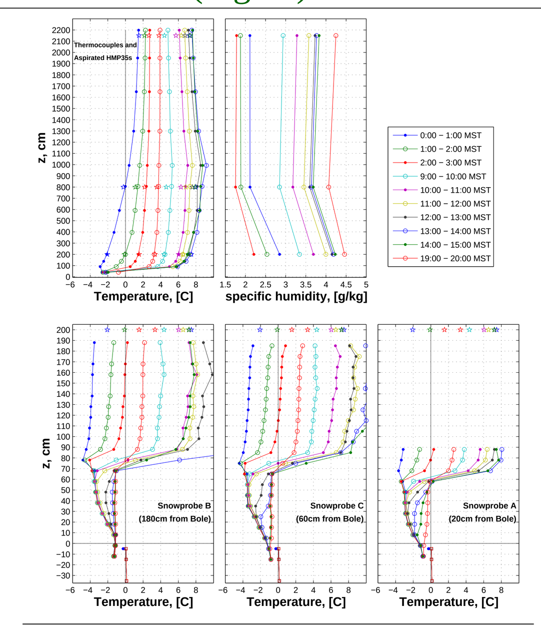


Figure 5: *Vertical profiles of air temperature T_a, specific humidity q, snow and soil temperature, during the snowpack warmup event on February 28, 2006.*

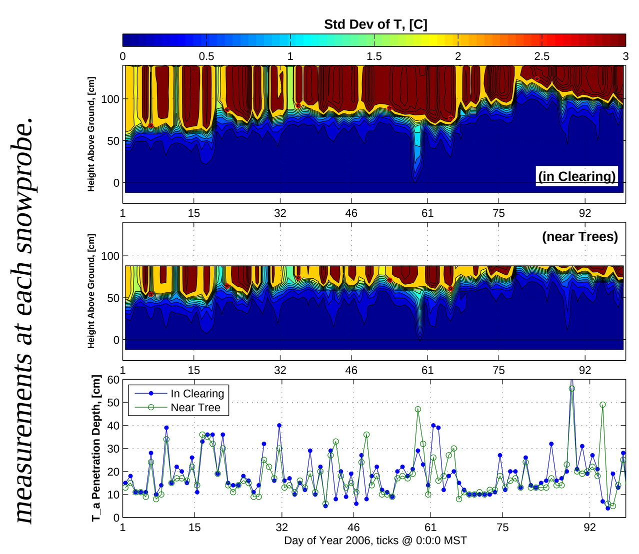
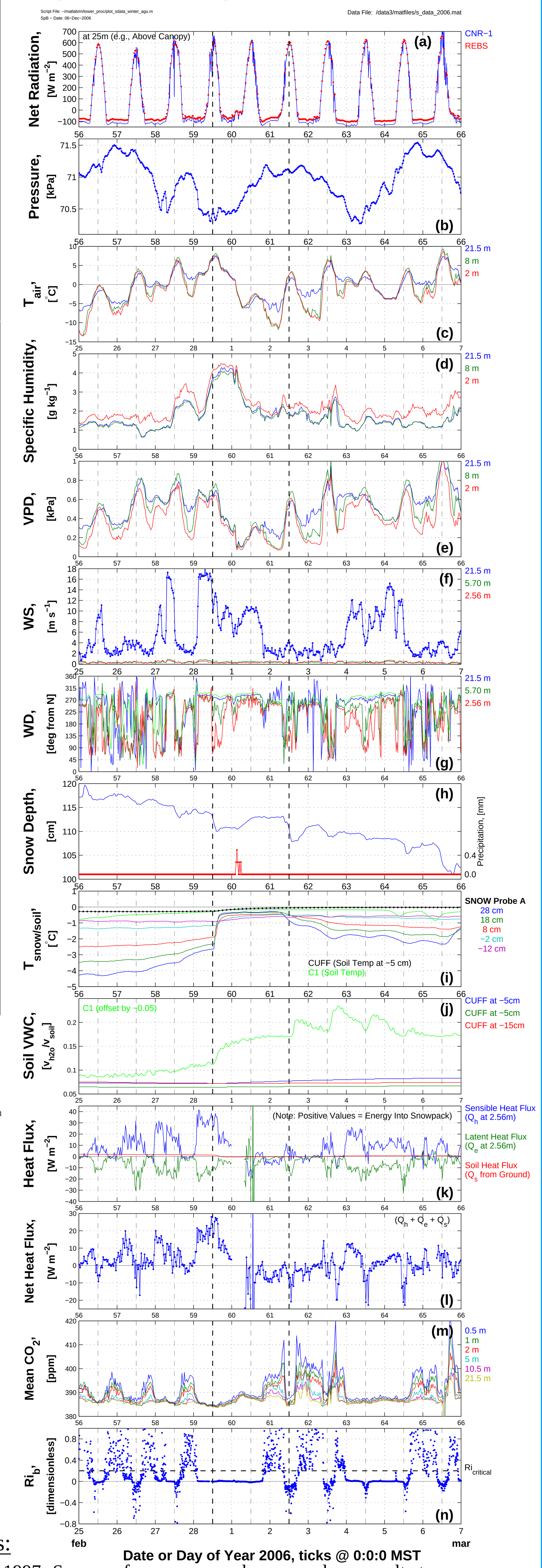


Figure 6: *Estimated depth of temperature penetration into the snowpack based on the 24-hour standard deviation of the snow temperature. Red circles are visual snowdepth measurements at each snowprobe.*

III. Conclusions:

- **Four years of snowpack temperature data from a Colorado sub-alpine forest were examined.**
- **Snow cover persists up at a month longer at our forest location compared to a more exposed location 500 m away; however, the initiation of snowmelt has similar timing at both locations.**
- **Abrupt transition from a TG to ET snowpack (and vice versa) occur about 2-3 times in late winter and early spring prior to a complete transition to an ET snowpack.**
- **Transitions from a TG to ET snowpack are often accompanied by warm (T > 0) and humid (q > 4 g kg^{-1}) air. (Should examine larger-scale weather patterns for better understanding.)**
- **Detailed examination of one TG-ET transition revealed that the Chinook winds were important in keeping the night-time 2-m air temperature above 0°C and helped to initiate the melt.**
- **Snowmelt near trees lagged that in a small forest clearing.**

Figure 4: *Ten-day time series as the snowpack goes isothermal at the end of February, 2006. The vertical dashed line represents the time period when the snowpack was isothermal.*



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