AN ENGINEERING DESIGN STUDY OF ELECTRONIC SNOW WATER EQUIVALENT SENSOR PERFORMANCE

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ABSTRACT

The USA ERDC CRREL and the USDA NRCS developed an electronic SWE sensor based on the results of field and theoretical studies of SWE pressure sensor performance. The CRREL/NRCS sensor is about 3 m square and is modular consisting of nine perforated panels, a center panel and eight outer surrounding panels that allow water to percolate through the sensor. Water percolation minimizes thermal differences between the sensor and surrounding soil and the eight surrounding panels act to buffer the center panel, where SWE is measured, from stress concentrations that develop along the perimeter of the sensor. Two years of field-tests (winters of 2005—2006 and 2006—2007) at Hogg Pass, OR, demonstrate that the CRREL/NRCS sensor's center panel accurately measures SWE variations even when stress concentrations are observed on the sensor's outer panels. During the first winter, stress concentrations occurred on the outer panels during periods of rapid snow settlement following large snow accumulations and when the rate of snowmelt at the sensor/snow interface was significantly different from the snowmelt rate at the soil/snow interface of the surrounding ground. SWE measurement performance is optimal when the sensor has no freeboard.

INTRODUCTION

The USDA Natural Resources Conservation Service (NRCS) is supporting an effort to develop an electronic snow water equivalent (SWE) pressure sensor to replace the traditional antifreeze–fluid–filled snow pillow because of environmental concerns about antifreeze and to improve SWE measurement accuracy. As part of this effort, a series of experiments were conducted to identify the controlling physical mechanisms and develop a theory of SWE pressure sensor (SWE sensor) performance to help guide the new sensor design (Johnson and Schaefer, 2002; Johnson, 2004). These studies demonstrated that the primary source of SWE sensor error arises from snow bridging and stress concentrations along the perimeter of the sensor caused by differential settlement of the snow on the sensor compared to the snow on the ground. Snow bridging occurs when some, or all – in extreme cases, of the snow load over the SWE sensor is transferred to the surrounding snow. This occurs when snow resting on the SWE sensor is lost due to snowmelt or strong water vapor gradient flow into the snow above the sensor, creating a partial or total void over the sensor. Stress concentrations along a sensor's perimeter occur during periods of rapid snow settlement after a heavy snowfall or when the snowmelt rate at the SWE sensor-snow interface is different than the snowmelt rate at the ground-snow interface (Johnson and Schaefer, 2002).

Errors due to snow settlement occur when a SWE sensor's top surface is higher than the ground surface (freeboard) allowing the snow on the ground next to the sensor to settle with respect to the sensor over the freeboard distance, producing a shear stress across the perimeter edge of the sensor (Johnson, 2004). The magnitude of the shear stress concentration, and resulting SWE measurement error, depends on the rate of snow settlement, the freeboard height, and the snow viscosity. Differential snowmelt errors occur because of the difference in thermal properties between the SWE sensor, and its underlying soil, with the surrounding ground that cause a different rate of snowmelt at the SWE sensor–snow interface than at the adjacent soil–snow interface, when interface temperatures equal 0 ° C. The occurrence and duration of error events depend on the magnitude of snow shear viscosity and on the length of time that the soil–snow and SWE sensor–snow interfaces remain at the melting temperature (Johnson and Schaefer, 2002; Johnson and Marks, 2004).

The experimental and theoretical results describing SWE sensor performance indicate that to minimize environmental effects that cause SWE measurement errors the sensor design should have a high elastic modulus,

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little or no freeboard, allow water to percolate through the sensor, and have low thermal conductivity. The sensor should also measure SWE near its center to reduce the influence of any perimeter stress concentrations. For example, a modular sensor with a center panel and eight surrounding panels. Measurements taken on the center panel should provide the most accurate SWE. A small, or nonexistent, freeboard minimizes errors associated with snow settlement; water percolation through the sensor wets the underlying soil, reducing the thermal difference between the sensor installation (sensor plus underlying soil) and the surrounding soil. A high elastic modulus ensures that perimeter stress concentrations will be greater than the ambient SWE so that SWE errors are relaxed through snow creep, when snow viscosity is sufficiently low, rather than forming a snow bridge (Johnson, 2004).

An engineering version of the nine-panel sensor, which is designed for long-term practical use, as compared to research versions of the sensor that only needed to identify mechanisms and demonstrate feasibility, was constructed and tested during the winters of 2005–2006 and 2006–2007. The purpose of these tests were to determine if the engineering design met requirements that the sensor be robust, easy to install and maintain, reliable, and accurate.

ELECTRONIC SWE SENSOR DESIGN AND HOGG PASS INSTALLATION

Sensor Design

The CRREL/NRCS electronic SWE sensor is designed to be modular to ease installation and maintenance while still taking advantage of a larger sensor area to help reduce errors caused by sensor edge effects. The general design features of the Hogg Pass SWE sensor are that it consists of an instrumented center panel surrounded by eight panels that act to buffer the center panel from edge stress concentrations (Figures 1 and 2). Each panel is pre-constructed and consists of a top plate of aluminum perforated with holes to allow water flow through the sensor. Sensor top plates are supported along their edges and across their width by angle beams to provide strength and stiffness (Figure 1). The center panel is approximately 1.2 m (4 ft) square, side panels are rectangles with dimensions of about 1.2 by 0.9 m (4 x 3 ft), and the corner panels are about 0.9 m (3 ft) square. Each panel has a freeboard of about 50 mm (2 in). The dimensions of the angle beams supporting the top plates vary depending on the design SWE load and available sizes. The Hogg Pass CRREL/NRCS SWE sensor is designed to support SWE loads of up to about 1780 mm (70 in) of water with a resolution of about 0.25 mm (0.01in)

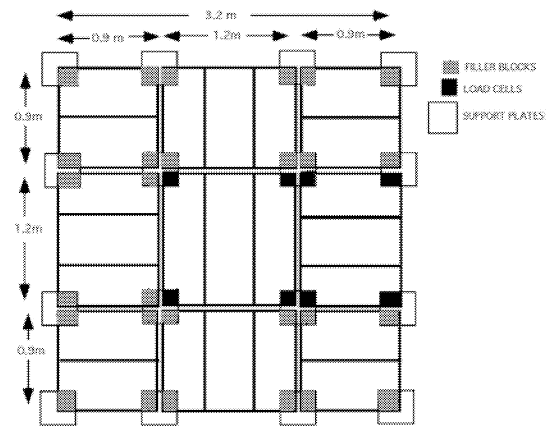

Figure 1. Top view of the CRREL/NRCS SWE sensor located at Hogg Pass, OR.

Each sensor panel is supported at its corners by either an aluminum pedestal or a hermetically sealed load cell, depending on the level of detail about the variation of SWE loading across a sensor panel that is needed. To determine the total load acting on each SWE sensor panel, load cells are needed under each corner. This distribution of load cells is needed if the SWE varies significantly across a sensor's panel. The number of load cells needed to support a panel can be reduced if SWE is uniformly distributed across a panel. For uniform SWE distribution on a panel, a corner load cell will detect 1/4 of the total SWE, with the snow located in the quadrant of the panel closest to the load cell contributing most of the load. Further account of variations in SWE across a panel can be taken by supporting a panel at opposite corners using loads cells, with the remaining corners supported by pedestals. This arrangement can detect when snow distribution across the panel is non-uniform and can provide additional data that can be averaged to provide more accurate SWE measurements. Ideally, one would use load cells at each corner for the SWE sensor's center panel, but considerations of cost dictate that the least number of load cells needed to determine SWE be used. Alternatives to using load cells at the panel corners were considered, but not used because of the increased complexity and concern that the mechanisms were too prone to freeze up if water accumulated in the sensor an froze.

As a means to determine when perimeter stress concentrations occur, load cells can be placed on one or more outer corners of the panels that surround the center plate (for example at locations B2 and B3 in Figure 3). Since SWE sensor errors are caused by the propagation of stress concentrations at the edge of a sensor into its center, SWE on the center panel and outer edge would generally equal until stress concentrations at the edge of the outer panel started building. By knowing that conditions are favorable for errors to occur, methods to detect and correct SWE measurement errors on the center panel can be implemented (Johnson and Marks, 2004).

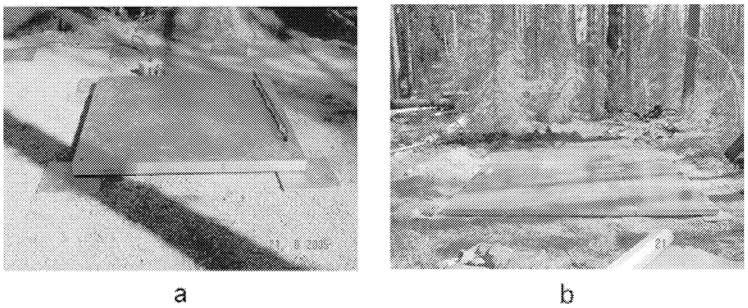

Figure 2. CRREL/NRCS SWE sensor installation at Hogg Pass, OR. The center panel is installed first and is supported by load cells or pedestals resting on aluminum base plates (a) then side and corner panels are placed (b).

Sensor Installation at Hogg Pass

A CRREL/NRCS SWE sensor was installed next to an existing NRCS snow pillow at Hogg Pass, OR, in the fall of 2005 (Figure 3). The site was prepared by laying down a thin layer of gravel to facilitate leveling the sensor. The support pedestals and load cells rest on aluminum base plates, placed on a gravel pad, and sized to support the expected SWE loading on the sensor (Figure 2). The locations of load cells under the sensor panels are shown in Figures 1 and 3 (labeled corners A1 — A4 and B1—B4 in Figure 3). This installation provided the ability to determine SWE by averaging data from all four load cells from the sensor's center panel and side panel as well as determining SWE for each of the load cell locations. This provides a way to determine the difference in the accuracy of measuring SWE using only one load cell versus four load cells. It also provides a way to examine stress concentrations that may build along the perimeter of the sensor during periods of rapid snow settlement or from differential snowmelt on the sensor and ground, when ground temperatures are at 0° C.

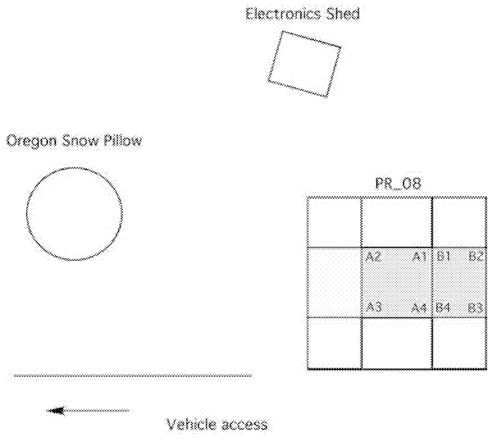

Figure 3. Hogg Pass test site and CRREL/NRCS electronic sensor panel layout.

During the initial installation, the SWE sensor was placed on the ground surface with a 50 mm (2 in) freeboard to keep installation simple. We were aware that the freeboard would produce a higher perimeter stress concentration than for a sensor installed with no freeboard, but felt that the sensor's side and corner buffer panels would protect the center panel from edge effects. Data from the 2005—2006 winter tests indicated that while the buffer panels did greatly reduce the influence of edge effects, rapid snow settlement after a major snowstorm produced significant edge stress concentration that propagated into the center panel. To reduce the freeboard, soil guards were installed and soil backfilled until the top of the sensor was flush with the soil surface (Figure 4).

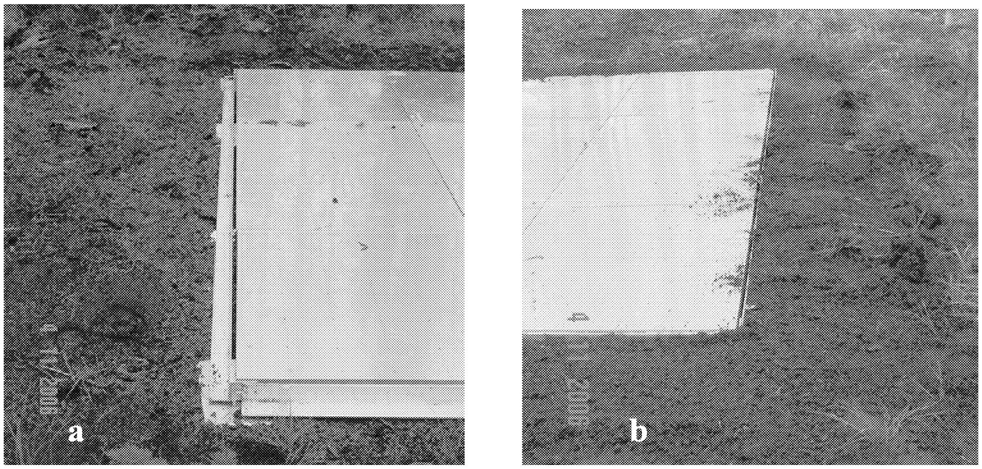

Figure 4. Soil guard around the perimeter of the SWE sensor (a) and soil backfilled against the soil guard (b).

RESULTS AND DISCUSSION

2005—2006 Winter Results

The SWE measurement results for the CRREL/NRCS SWE sensor at Hogg Pass during the 2005—2006 winter are shown in Figure 5, for the center panel, and in Figure 6, for the side panel. In Figure 5, the SWE for the center panel determined by averaging the four load cell measurements located at each corner of the panel are compared with the NRCS snow pillow (Oregon snow pillow) (Figure 5a). The calibration of the CRREL/NRCS sensor was set to provide a best fit to the NRCS (we are currently devising an independent calibration methodology for the sensors). The CRREL/NRCS sensor center panel SWE measurements agree in general with the snow pillow except for a period in December (double arrow spanning Figures 5a and b) and the snowmelt period from late April onward (single arrow in Figure 5a).

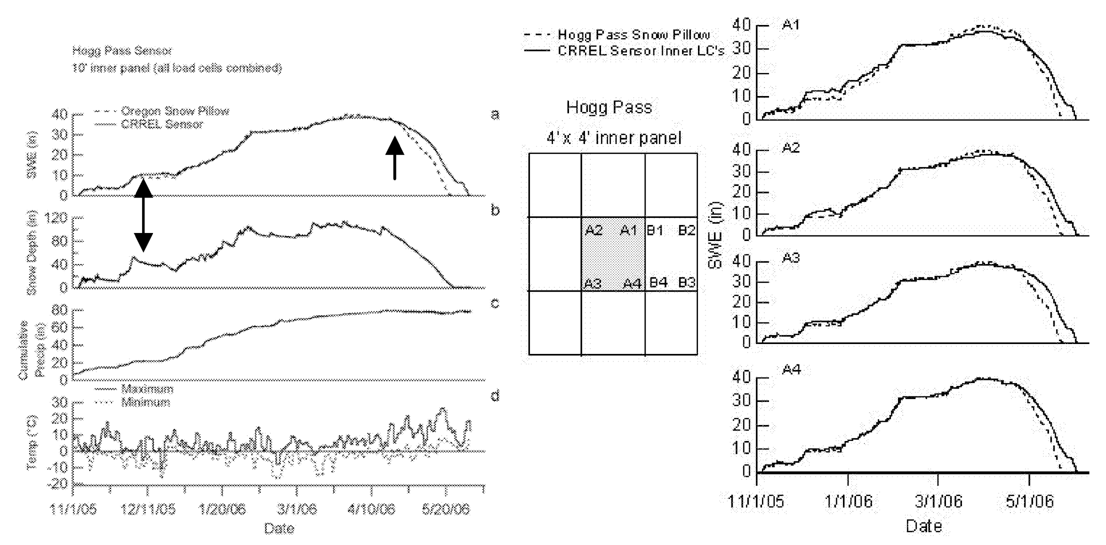

Figure 5. Comparison of CRREL/NRCS SWE sensor center panel measurements with the NRCS snow pillow (Oregon snow pillow) for the 2005—2006 winter. SWE for the snow pillow and SWE from the average of the CRREL/NRCS SWE sensor center panel load cells [A1—A4] (a), snow depth (b), cumulative precipitation (c), and temperature (d). SWE output for the individual load cells on the center panel: upper right corner (A1), upper left corner (A2), lower left corner (A3), and lower right corner (A4).

The differences between the snow pillow and the CRREL/NRCS sensor in December are associated with rapid snow settlement after a large early winter snowfall (Figures 5a and 5b). The differences between the snow pillow and CRREL/NRCS sensor in the spring are due to the early melt-out of snow on the snow pillow. This was confirmed by a site visit shortly after the end of the snow melt-out period that showed that all of the snow on the snow pillow had melted while snow still remained around the CRREL/NRCS sensor (Figure 7). The snow pillow had been installed on a mound to facilitate connecting fluid plumbing lines to monitoring equipment. The elevated location of the snow pillow compared to the surrounding terrain may have resulted a shallower snow cover over the snow pillow and/or more exposure to sunlight transmission through the snow in the spring than the surrounding terrain. Either of these conditions would produce early snow melt-out. Comparison of the SWE determined from the four individual load cells mounted on the corners of the center panel with their average value indicates that SWE was uniformly distributed over the sensor (Figure 5a compared to Figures 5 A1—A4). This means that SWE determined by using data from any of the individual load cell measurements were essentially the same.

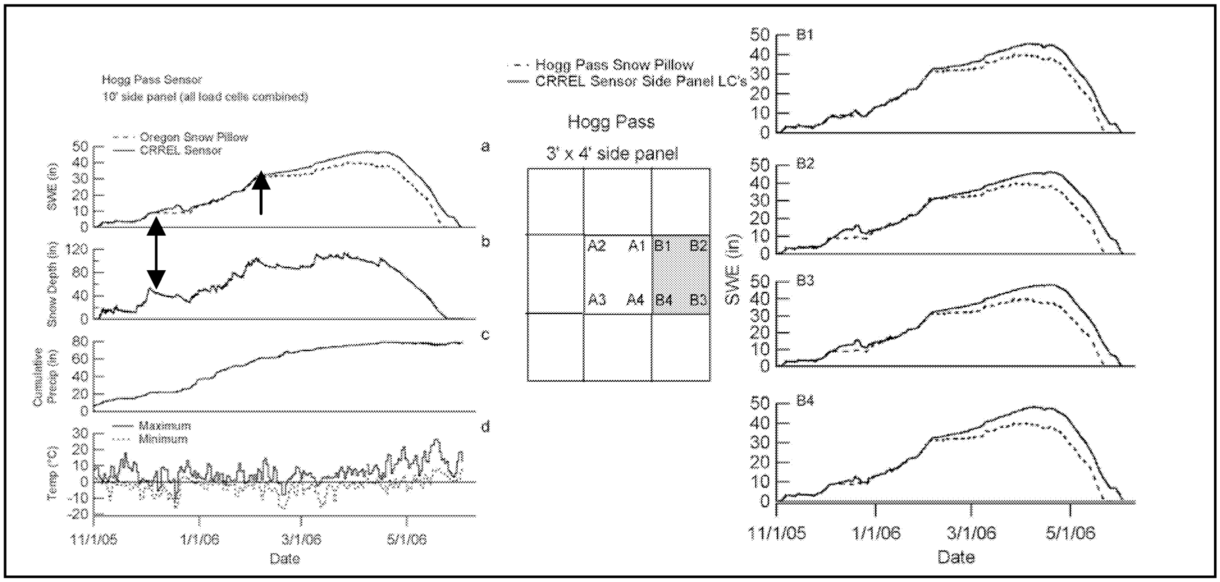

Figure 6. Comparison of CRREL/NRCS SWE sensor side panel measurements with the NRCS snow pillow (Oregon snow pillow) for the 2005—2006 winter. SWE for the snow pillow and SWE from the average of the CRREL/NRCS SWE sensor side panel load cells [B1—B4] (a), snow depth (b), cumulative precipitation (c), and temperature (d). SWE output for the individual load cells on the side panel: upper left corner (B1), upper right corner (B2), lower right corner (B3), and lower left corner (B4).

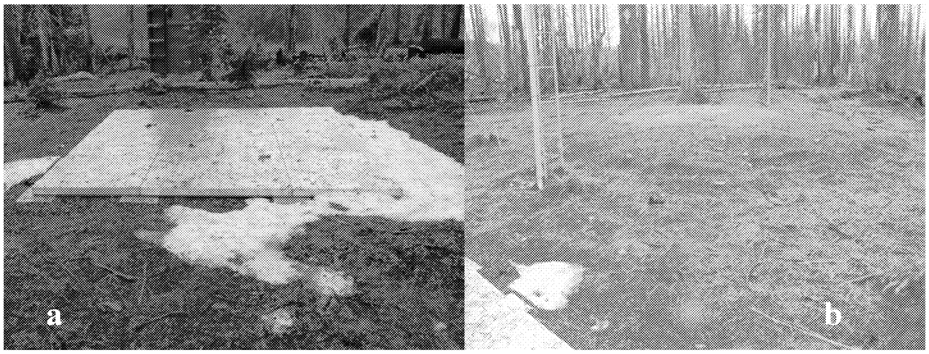

Figure 7. CRREL/NRCS SWE sensor (a) and NRCS snow pillow (b) installations at Hogg Pass after snow melt-out on the snow pillow. The edge of the CRREL/NRCS sensor can be seen in the lower left of (b).

Evidence of stress concentrations acting at the edge of the CRREL/NRCS sensor and propagating in to the center of the sensor can be seen in the SWE measurements for the sensor's side panel (Figure 6). The side panel exhibits an over measurement of SWE in December (Double arrow spanning Figures 6a and b) and the individual load cells (Figures 6 B1—B4). This over measurement error propagated into the center panel (Figure 5a). A second over measurement error occurred on the side panel starting in February and continued until the start of snowmelt (Single arrow in Figure 6a). This error event did not propagate to the center panel and was likely caused by thermal differences between the sensor and surrounding soil that produced different rates of snowmelt at the sensor/snow interface and the soil/snow interface. These different snowmelt rates created a stress concentration at the edge of the panel that can be seen by comparing the SWE from the CRREL/NRCS center panel (Figure 5a) with the side panel SWE (Figure 6a).

The results of the 2005—2006 winter indicated that the 50 mm freeboard created stronger perimeter stress concentrations than was originally assumed. The freeboard was eliminated for the 2006—2007 winter as described in the sensor installation section (Figure 4).

2006—2007 Winter Results

The SWE measurement results over the 2006—2007 winter for the CRREL/NRCS SWE sensor center panel and side panel are shown in Figures 8 and 9, respectively. It was noted early during the winter that the calibration for the center panel with respect to the snow pillow had changed slightly from the previous year while the calibration for the side panel remained the same. The cause of this change may have been due to an unrepresentatively shallow snow cover over the snow pillow compared to the CRREL/NRCS sensor or the result of forest litter falling into the space separating the center panel from the side panel, creating additional resistance for the center panel. This will be further examined during a summer visit to Hogg Pass; covering the separation space between sensor panels will eliminate the potential problem of forest litter.

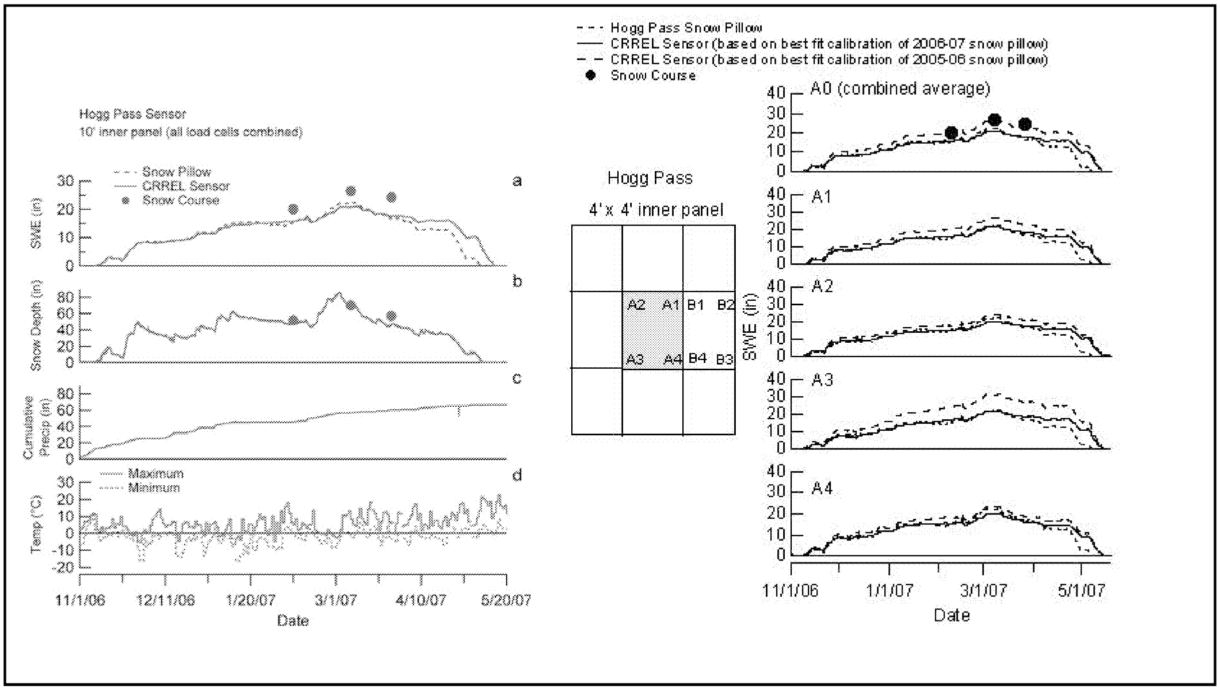

Figure 8. Comparison of CRREL/NRCS SWE sensor center panel measurements with the NRCS snow pillow for the 2006—2007 winter. SWE for the snow pillow and SWE from the average of the CRREL/NRCS SWE sensor center panel load cells [A1—A4] (a), snow depth (b), cumulative precipitation (c), and temperature (d). SWE output for the average of the load cells [A1—A4] (A0), and individual load cells on the center panel: upper right corner (A1), upper left corner (A2), lower left corner (A3), and lower right corner (A4).

Two calibrations were used for the CRREL/NRCS sensor center panel during the 2006—2007 winter. The first calibration was determined by the best fit between snow pillow and the CRREL/NRCS sensor (solid line in Figures 8a and 8 A0—A4) SWE. A second calibration was done using hand snow core SWE measurements (dashed line passing through the black circular markers in Figure 8A0). The second calibration using the hand snow core measurements is very close to the calibration developed for the 2005—2006 winter. This might imply that the SWE over the snow pillow was even less representative of the surrounding snow cover during the 2006—2007 winter than it was during the 2005—2006 winter. The CRREL/NRCS sensor calibration using hand core

SWE data is assumed to be most accurate since these measurements were taken next the CRREL/NRCS sensor and avoided the shallower snow cover near the snow pillow. The CRREL/NRCS sensor calibrations developed for the 2005—2006 winter are shown for the individual load cells in Figures 8 A1—A4, for reference.

The most important results from the 2006—2007 winter measurements are that the CRREL/NRCS sensor quite accurately followed the trends of the SWE history throughout the winter and the center panel exhibited no SWE over measurement errors, even during periods of stress concentration buildup along the sensor's perimeter. Two brief periods of stress concentration events on the side panel can be identified by a sharp increase in SWE (one event in December and one in February, single arrows in Figure 9a,) associated with a prolonged period of air temperatures greater than 0° C (Figure 9d) and then a relaxation as temperatures cooled. In neither case did the edge stress concentrations that developed on the side panel propagate into the center panel (Figures 8a and 9a).

Around the same time that stress concentrations developed on the CRREL/NRCS sensor side panel the SWE on the snow pillow decreased during the two warm periods, rising back to the same value as the SWE measured by the CRREL/NRCS sensor once temperatures cooled (Figure 9a). These are instances of snow pillow SWE under measurement errors associated with air temperatures greater than 0° C and are most likely caused because the ground is at the melting temperature of snow. The differential snow melt at the snow pillow-snow interface compared to the snow melt at the surrounding soil-snow interface probably increased enough to cause a SWE load transfer from the pillow to the surrounding snow. As air temperatures cool the magnitude of differential snow melt decreases and snow creep causes the stress concentrations along the perimeter of the snow sensors to relax allowing the snow pillow SWE to recover its original magnitude. The fact that the snow pillow under measured SWE indicates that the snowmelt rate at the pillow-snow interface was higher than at the soil-snow interface. Conversely, the over measurement of SWE by the CRREL/NRCS sensor side panel indicates more rapid snowmelt at the soil-snow interface than at the sensor-snow interface. This is reasonable since the fluid in the snow pillow strongly affects its conductivity and the CRREL/NRCS sensor has a low thermal conductivity compared to the surrounding soil.

No stress concentrations appear to occur along the perimeter of the CRREL/NRCS sensor during the spring snowmelt on either the center panel or side panel. The early snow melt-out for the NRCS snow pillow occurs during the spring melt, as it did during the 2005—2006 winter.

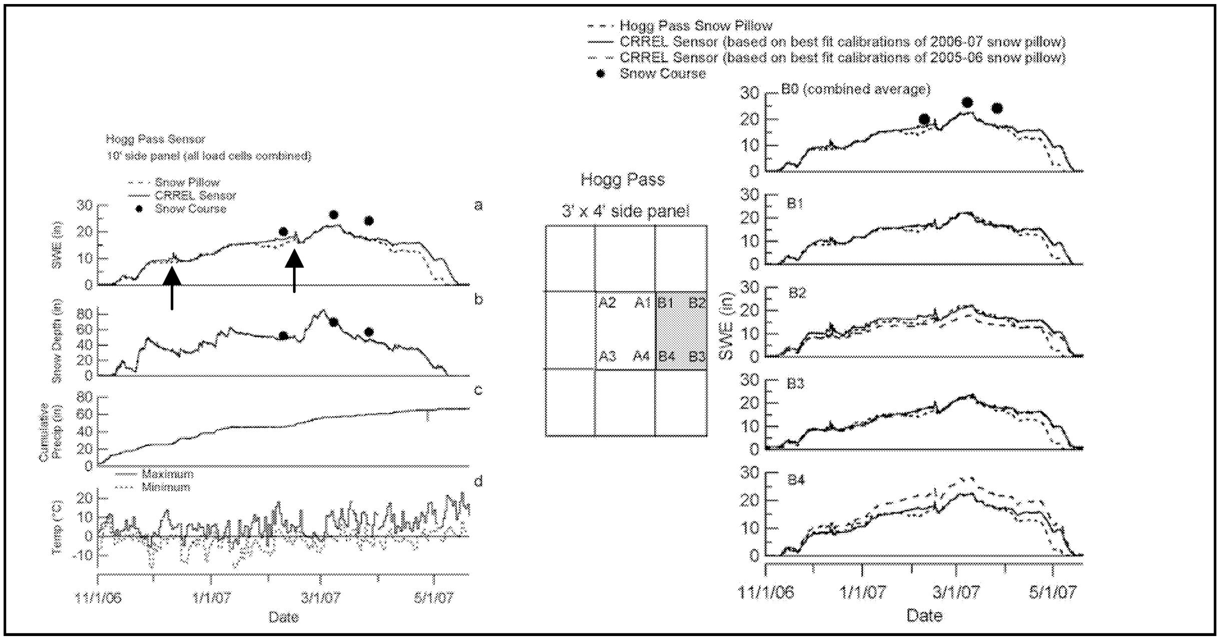

Figure 9. Comparison of CRREL/NRCS SWE sensor side panel measurements with the NRCS snow pillow for the 2006—2007 winter. SWE for the snow pillow and SWE from the average of the CRREL/NRCS SWE sensor side panel load cells [B1—B4] (a), snow depth (b), cumulative precipitation (c), and temperature (d). SWE output for the average of the load cells [B1—B4] (B0), and individual load cells on the side panel: upper left corner (B1), upper right corner (B2), lower right corner (B3), and lower left corner (B4).

CONCLUSIONS

A two-year program to monitor the performance of a CRREL/NRCS electronic SWE sensor indicates that the sensor's design feature of a center panel to measure SWE surrounded by eight buffer panels significantly reduces the influence of perimeter stress concentrations on SWE measurement accuracy. SWE distribution across the center plate was uniform, indicating that SWE determined using data from a single load cell installed under one corner of the panel, with inert pedestals under the remaining corners, agrees closely with the SWE determined by averaging data from four load cells supporting the panel.

The presence of freeboard for the sensor results in increased perimeter stress concentrations that can propagate into the center panel; eliminating SWE sensor freeboard significantly reduces the magnitude and frequency of occurrence of stress concentrations along the sensor's perimeter. Johnson's (2004) theoretical predictions that perimeter stress concentrations occur from the rapid settlement of new snow after a large snowfall and from a differential snowmelt on the sensor compared to the surrounding soil are confirmed. The prediction that stress concentrations are highest at the sensor's perimeter and that ambient or near ambient SWE exist over the center portion of the sensor are also confirmed.

Both the sensor design and its installation significantly affect SWE measurement accuracy. For the CRREL/NRCS electronic sensor, the optimal design and installation is a modular sensor that consists of a center panel, to measure SWE, surrounded by inert panels to buffer perimeter stress concentrations. Installation of the sensor with no freeboard provides the greatest reduction in perimeter stress concentrations and the most accurate SWE measurements on both the sensor center panel and side panel. The significant reduction in perimeter stresses for the CRREL/NRCS sensor that occurred when its freeboard was eliminated indicates that the sensor may be reduced in size from the present 3 m square dimension and still provide accurate SWE measurements. Further work is needed to develop a calibration method for the sensor that does not require nearby snow pillow SWE measurements or SWE hand core measurements.

The use of a single load cell at one of the corners of the center panel measures the SWE on the panel quartile closest to the load cell. This is adequate when SWE is uniformly distributed over the sensor. The addition of a load cell under the corner of the outer edge of a side panel provides the capability to detect the formation of perimeter stress concentrations. Perimeter stress concentrations are identified when the SWE increases on the side panel with respect to the SWE measured on the center panel. The addition of a third load cell under the corner of the center panel, but opposite to the first load cell, provides a means of detecting non-uniform SWE distribution over the center panel with increased accuracy when SWE is not uniform across the panel.

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