

THE INFLUENCE OF THERMAL, HYDROLOGIC, AND SNOW DEFORMATION MECHANISMS ON SNOW WATER EQUIVALENT PRESSURE SENSOR ACCURACY

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ABSTRACT

A five-year field study was conducted to determine the mechanisms that cause snow water equivalent (SWE) pressure sensor measurement errors. We monitored a 3-m snow pillow and installed three prototype electronic SWE sensors to examine how SWE errors occur. We measured heat flux in the sensors and the soil, snow temperature, soil moisture content, and soil thermal conductivity. The SWE of snow cores were used to assess the accuracy of the sensors. Results indicate that SWE measurement errors occur when the snow/SWE sensor and/or the snow/soil interfaces are at the melting temperature of snow. SWE over measurement errors occur when the sensor heat flux is less than the surrounding soil. SWE under measurement errors occur when the heat flux through the sensor is greater than through the soil. The most severe errors occur during the transition from winter to spring when the snow cover first reaches an isothermal condition producing a maximum difference in snowmelt rate between the snow/SWE sensor and snow/soil interfaces. SWE measurement errors are minimized when the sensor is designed to match the thermal properties of the surrounding soil, allow water to flow through the sensor, or to diffuse heat into the adjacent soil.

INTRODUCTION

Snowmelt runoff is a major resource in countries with mountainous terrain that can contribute to flooding and provides a significant portion of the water used for agriculture, hydroelectric power generation, recreation, and municipal and industrial water supplies. The long-term monitoring of the accumulation and recession of snow covers may provide information about climate and its change. The effective management of snowmelt runoff and the conduct of climate change studies requires accurate knowledge of the amount of water stored as snow (snow water equivalent, SWE), its spatial distribution, and the theories needed to forecast runoff (Blöschl, 1999; Engeset et al., 2000; Male and Gray, 1981). One of the most common methods of determining SWE and its spatial distribution is to use pressure sensors placed on the ground before winter snowfall begins. These sensors determine SWE by monitoring the change in pressure caused by the accumulation or ablation of the overlying snow cover. Over six hundred SWE pressure sensor (referred to as a SWE sensor for the rest of the paper) installations exist in the western U.S. and many additional sites are located around the world to monitor SWE, forecast stream flow, and provide information needed to develop snowmelt runoff models. The value of SWE sensors is their relative low cost and ability to provide continuous SWE time history measurements.

SWE sensor measurement accuracy is a critical factor in determining the cost and efficiency of water supply management, developing accurate snowmelt runoff models, and developing a better understanding of the climate. However, the factors that control SWE sensor accuracy are poorly understood and sensor design has of necessity been through trial and error experimentation. Experiments using snow pillows (a fluid-filled SWE sensor), demonstrate that they can accurately measure SWE where accuracy is defined as the percentage difference between SWE measured using a pressure sensor and SWE determined from manually measured snow core data. Snow pillows can also exhibit large errors (Beaumont, 1965; California, 1976; Engeset et al., 2000; Goodison et al., 1981; Morrison, 1976; Palmer, 1986; Smith and Boyne, 1981). SWE under or over measurement errors are generally attributed to snow bridging, which occurs when the snow over a snow pillow is partially or fully supported by the surrounding snow or, conversely, when the snow pillow supports some of the weight of the surrounding snow. This

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problem occurs most often in snow covers that undergo frequent thawing and freezing cycles and that contain ice layers (California, 1976). At a given location, the same snow pillow can accurately measure, over measure, or under measure SWE during different winters (Fig. 1). In addition, snow pillow SWE measurements can temporarily deviate from snow core measured SWE during the winter, which only adds to the confusion of interpreting snow pillow data. This condition commonly occurs during the transition from winter to spring just prior to the onset of isothermal snow conditions and extensive snowmelt runoff (California, 1976; Johnson, 1999). The inconsistent performance of snow pillows under conditions that are not well understood means that extensive, and expensive, verification efforts must be conducted by manually measuring SWE using snow cores and that interpreting the snow pillow SWE time history records is problematic.

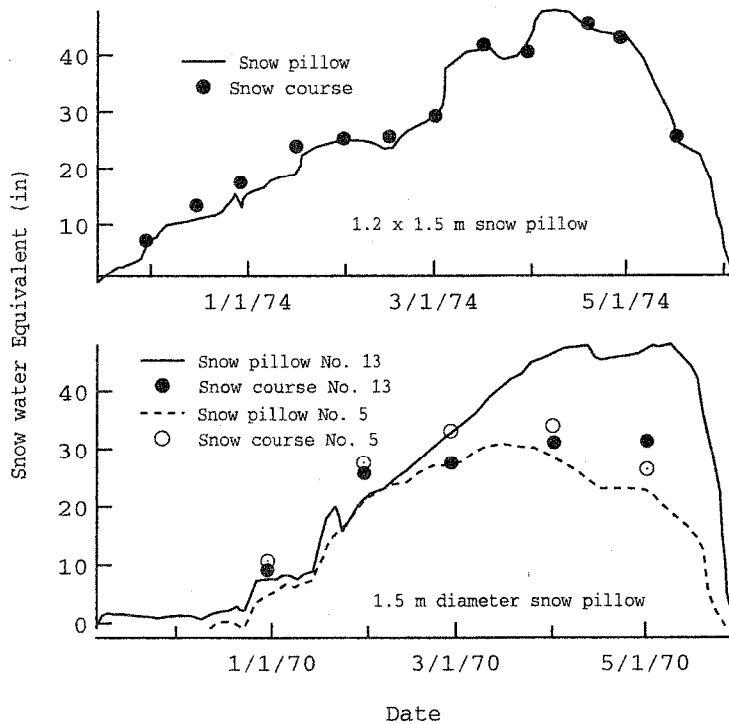


Fig. 1. SWE measurements using a 1.5 m snow pillow illustrating the year-to-year variation in accuracy that can occur and the variation in accuracy for two pillows at different locations during the same year (data from California, 1976).

Recently, environmental concerns about the anti-freeze filled snow pillow and the lack of understanding of the mechanisms that control snow pillow accuracy prompted the U. S. Department of Agriculture Natural Resources Conservation Service (NRCS) to support a study to develop a replacement electronic SWE sensor for the snow pillow. During this effort we conducted experiments to examine the mechanisms that control SWE sensor accuracy as a first step to developing an improved SWE sensor. In this paper, we discuss our observations, the physical mechanisms affecting SWE sensor accuracy, and key design features needed to improve SWE sensor performance characteristics.

EXPERIMENTAL IDENTIFICATION OF MECHANISMS AFFECTING SWE PRESSURE SENSOR

ACCURACY

Pressure sensors have a long history of use for measuring pressure in soil and ice, and the factors affecting their response are well known (Askegaard, 1963; Metge et al., 1975; Taylor, 1945; Templeton, 1978). The theory of pressure sensor action in soil, and practical experience, indicate that accurate pressure measurements can be made using sensors that are thin and wide (low aspect ratio) and that have an elastic modulus that is greater than the surrounding soil. Snow pillows and most other SWE sensors meet or exceed soil pressure sensor design requirements, yet still exhibit inconsistent accuracy. This implies that more complex mechanisms affect pressure

sensors buried in snow than are seen in soil or ice. To identify these mechanisms and determine their effect we conducted a series of field experiments beginning in 1997 and used observations from an extensive study of snow pillows conducted in the Sierra Nevada Mountains (California, 1976).

Experimental procedures

The experiments reported in this paper were conducted at the U. S. Department of Agriculture's Agriculture Research Station (ARS) Reynolds Mountain field test site near Boise, Idaho. For the first year, we constructed a SWE sensor using soil stress sensor design concepts without any special consideration for the presence of snow (SWE sensor A). The results of the first year's measurements indicated that the source of SWE measurement errors was due to thermal mechanisms at the snow/ground and snow/SWE sensor interfaces. These early observations motivated the direction of the study and we modified SWE sensor A, added instruments, and changed our installation methods as required to obtain the measurements needed to understand the important mechanisms affecting SWE sensor measurement accuracy. The SWE of snow cores, measured by ARS technicians with more than 20 years of experience, were used as a reference to assess the accuracy of the SWE sensor measurements throughout the study. The test facility layout for the 2001/2002 winter monitoring program is shown in Fig. 2 and the history of instrument installations is given in Table 1.

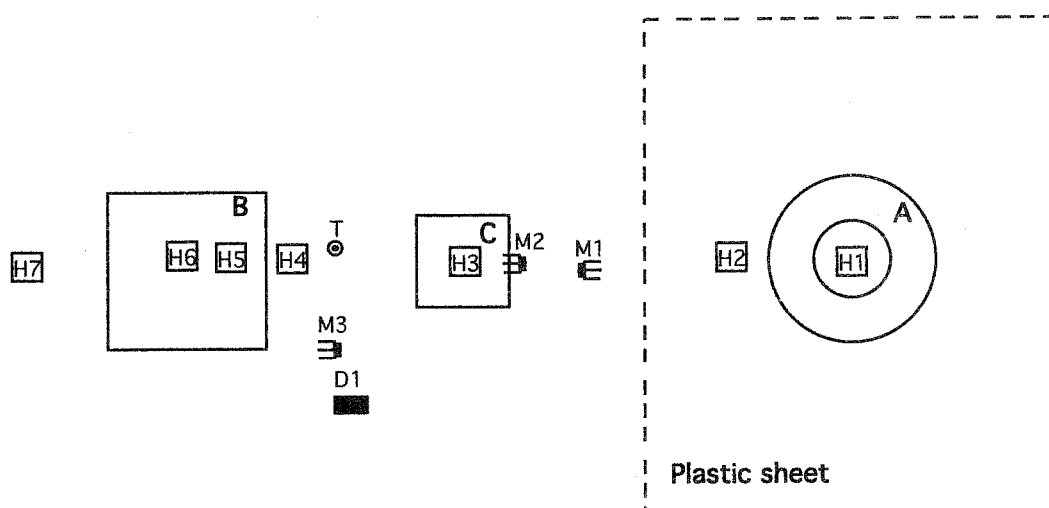


Fig. 2. The site plan for the SWE sensor monitoring program for the 2001/2002 winter. The instruments include the original SWE sensor A, the two new permeable SWE sensors B and C, heat flux meters H1-H7, soil moisture gauges M1 – M2, thermal conductivity/diffusivity gauge D1, Thermistor string T, and the plastic sheet cover for the SWE sensor A. Table 1 gives the installation history.

The SWE sensor A was constructed with a 0.23-m radius center plate and a 0.27-m wide annulus (Fig. 3a). The center plate is supported by three load cells and is used to measure SWE. The annulus is inert, it does not respond to snow load, and is incorporated into the design to reduce the influence of any stress concentrations produced at the edge of the sensor. Stress concentrations that arise at the edge of a pressure sensor decrease to negligible levels about a third of the distance toward its center (Chen, 1981). SWE sensor A was first installed at the ARS field test facility in 1997 and was modified in 1998 by attaching thermal conductivity straps from the center plate to the annulus and the bottom plate (Fig. 3b). The modifications to the sensor were done to make the thermal conductivity of the center plate and annulus more uniform. The installation mode of SWE sensor A was modified during each of the five winters to improve its thermal compatibility with the surrounding soil (Figs. 3a through 3e). Laboratory measurements indicate that the effective thermal conductivity ratio between the center plate and the annulus of SWE sensor A was about 0.65 prior to the installation of the conductivity straps and about 0.83 after installation of the straps. The effective thermal conductivity of the SWE sensor A was determined to be in the range of 0.2 to 0.35 W/m-K; the uncertainty of determining absolute thermal conductivity values being greater than for determining relative values.

To understand the thermal conditions at the base of the snow cover we installed instruments throughout the study period (Table 1). Two heat flux meters (International Thermal Instrument Co. GHT-1B-xxx) were installed in

Table 1 Instrumentation installation history (see Fig. 2 for installation site plan)

Installation/ modification date	Instrument type and modifications	Measurement parameter
October 1997	SWE sensor A installation	Snow water equivalent
October 1998	Added thermal conductivity straps to sensor A	
October 1998	Heat flux meters H1 and H2 installation	Heat flux
October 2000	Heat flux meters H3 – H7 installation	
October 2000	Install thermistors at 0, 0.045, and 0.09 m depth in the soil (Fig. 2, Marker T)	Thermal conductivity (with heat flux sensor)
October 2000	SWE sensors B & C installation	Snow water equivalent
October 2001	Remove inner support frame in sensors B & C and replace strain gauges with load cells	
October 2001	Soil moisture gauges M1-M3 installation	Soil moisture
October 2001	Soil thermal conductivity gauge D1	Soil thermal conductivity

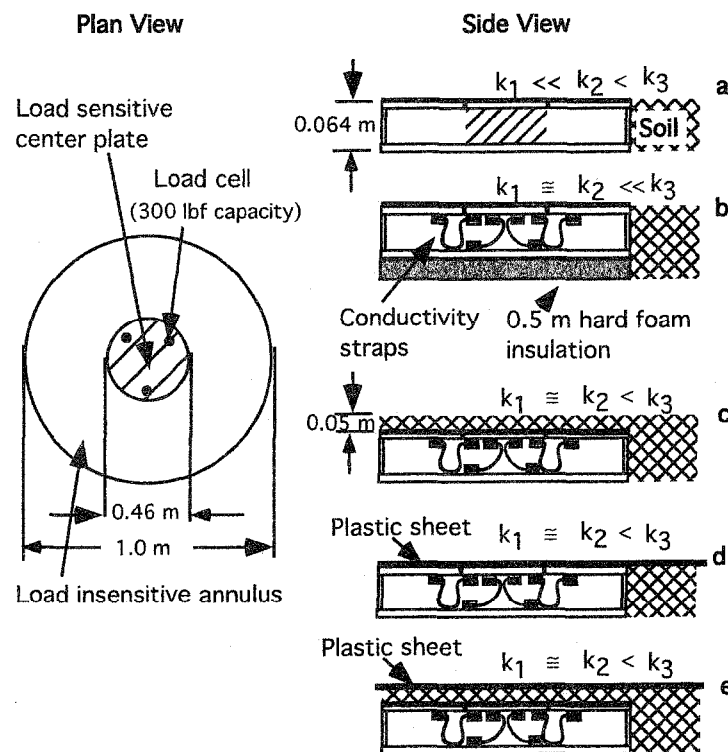
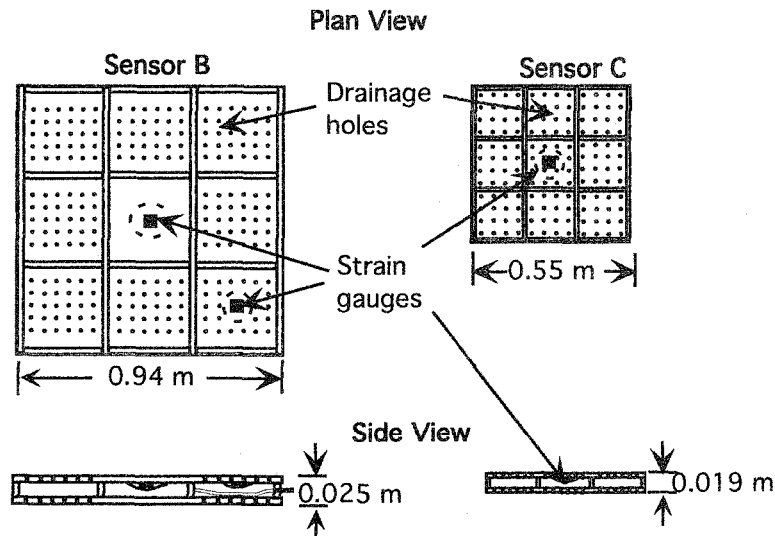


Fig. 3. SWE sensor A configurations and installation modes used to examine the mechanisms that affect SWE sensor accuracy. The side views illustrate the original sensor configuration (a) and the addition of thermal conductivity straps (b) to improve the sensor's thermal uniformity. Installation modes include placing the sensor flush with the soil surface (a), adding conductivity straps and placing a layer of hard insulation under the sensor (b), placing a 0.05-m layer of soil over the sensor and removing the underlying insulation (c), placing a 3-m square plastic sheet over the sensor and surrounding soil (d), and placing a 0.05-m layer of soil over the sensor and covering both the soil and sensor with a 3-m square plastic sheet (e).

1998 to determine the difference in heat flow through SWE sensor A compared to the surrounding soil. One heat flux meter (H1) was installed under the center of SWE sensor A and a second heat flux meter (H2) was installed at the same depth in the soil (0.064 m) as the first, but next to the SWE sensor A (Fig. 2). Three thermistors were installed at depths of 0, 0.045, and 0.09 m (Marker T, Fig. 2). Snow and soil temperatures were determined from the ARS thermistor probes. Soil moisture gauges (Vitel Hydra soil moisture probe type A), a soil thermal conductivity gauge (Hukseflux thermal properties sensor TP01), additional heat flux sensors, and two new permeable SWE sensors (sensor B and sensor C) were installed in October, 2000 (Fig. 2 and Fig. 4).

a. Sensor installation for 2000/2001 winter



b. Sensor installation for 2001/2002 winter

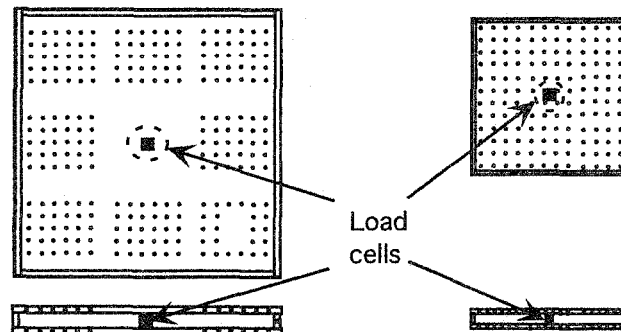


Fig. 4. Plan and side views of SWE sensor B and sensor C for the 2000/2001 winter (a), and for the 2001/2003 winter (b).

The two new SWE sensors were constructed in the same manner, but with different widths to examine the effect of sensor size and the effect of water percolation at the snow/soil interface. The sensors were constructed with perforated aluminum sheets separated by a framework of aluminum bar stock. Measurement of the bending strains of the center and corner panels of the top aluminum sheet of SWE sensor B and the center panel of SWE sensor C were used to determine SWE (Fig. 4a). The corner panel strain gauge on SWE sensor B was used to determine if stress concentration effects near the edge of the sensor could be detected. For the 2001/2002 test season the strain gauges and the internal support framework for SWE sensors B and C were removed and load cells were placed in the center of the load cell (Fig. 4b). These changes were implemented to reduce the thermal conductivity of the SWE sensors. The perforated aluminum top and bottom sheets allow water to drain through the SWE sensors wetting the underlying soil and keeping the moisture content, hence the thermal conductivity, of soil

under the sensors at a similar value as the soil around the SWE sensors. The thermal conductivity of SWE sensors B and C were not measured, but their theoretical values were 0.9 and 1.56 W/m-K, respectively, for 2000/2001 and 0.45 and 0.8 W/m-k, respectively for 2001/2002.

As more instruments were added to the ARS test site and the thermal compatibility of the SWE sensors with the soil was improved our ability to isolate the mechanisms that contribute to SWE sensor measurement errors increased. Consequently, the results from all five years of the study are needed to fully understand the important action mechanisms and to develop a physical model of SWE sensor behavior in snow.

RESULTS AND DISCUSSION

A comparison of SWE sensor A measurements with snow core data taken by hand next to the sensor are shown for five consecutive years in Fig. 5. The agreement between SWE sensor A and the snow core data improved

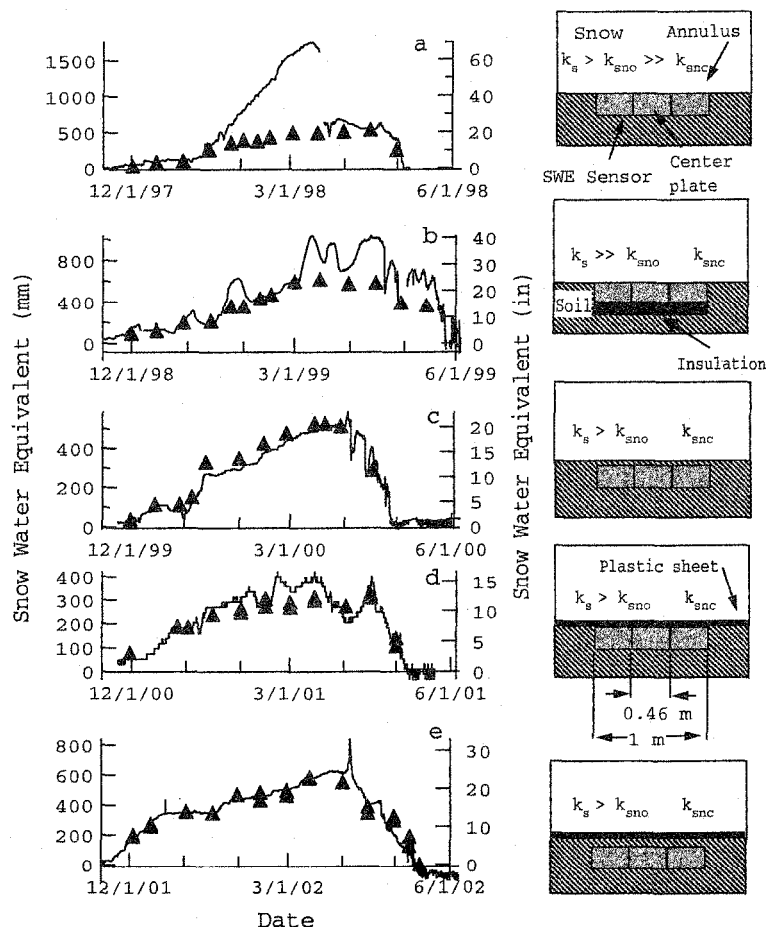


Fig. 5. Comparison of SWE sensor A measurements with SWE from hand measured snow core data next to the sensor for five consecutive winters. The SWE sensor installation for each winter is shown to the right of the data plots.

each year as the sensor's configuration was modified and its installation mode changed to decrease thermal differences between the sensor and the surrounding soil. During the first winter (1997/1998), SWE measurement errors reached 270% (Fig. 5a). Excavation of the sensor in mid-March revealed that the center plate of SWE sensor A was covered with a disk of ice while the annulus was wet and clear of ice. This is evidence that the rate of snowmelt on the annulus was greater than over the center plate causing a snow load transfer onto the center plate from the surrounding snow. Subsequent measurements indicated that the annulus thermal conductivity was 150% greater than the center plate thermal conductivity. The comparison of SWE sensor A measurements with hand core

SWE data for the second year (1998/1999), after thermal conductivity straps had been added to the sensor and its installation configuration was changed, showed a marked decrease in SWE error magnitudes (Fig. 5b). The results of these tests indicate that both the snow/soil and/or snow/SWE sensor interfaces must be at the melting temperature and the heat flux through the SWE sensor must be different from the surrounding soil before SWE sensor measurement errors occur (Figs. 6 b, c, and d). The heat flux through SWE sensor A was about 8 to 10 times

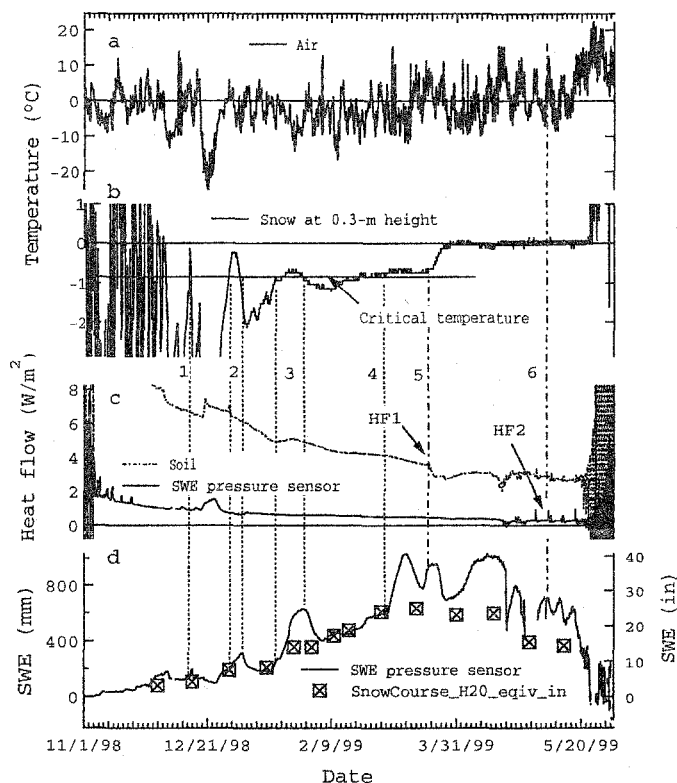


Fig. 6. Air temperature (a), snow temperature at 0.3-m height above the soil (b), heat flux under and adjacent to SWE sensor A (c), and SWE measurements from the pressure sensor and from snow core data during the 1998-1999 test winter (d).

less than the surrounding soil, which produces SWE over measurement errors (Fig. 6c). SWE errors appeared as excursions in the early and midwinter period, beginning when the snow temperature exceeded about -0.8°C at 0.3 m above the soil and decreasing when the snow temperature dropped below -0.8°C (Fig. 6 b and d, dashed tie lines 1, through 4). Our observations, indicate that the snow temperature at 0.3 m above the soil was about 0.8°C cooler than the snow/ground interface temperature until spring when the snow cover warmed to 0°C everywhere. The relaxation of SWE sensor errors after the snow temperature dropped below -0.8°C is most likely the result of snow creep that allowed the snow load to redistribute evenly over the sensor and surrounding soil. Once the snow cover warmed to 0°C throughout (isothermal conditions) a more complex pattern of SWE errors occurred that appeared to be related to heat flux variations (Fig. 6 b, c, and d HF1 and HF2 markers for tie lines 5 and 6).

The thermal compatibility of SWE sensor A with the soil was improved for the 1999/2000 test season by removing the insulation from under the sensor. We also covered the sensor with about 0.05 m of soil to help diffuse any difference in heat flux between the sensor and soil. These changes greatly improved the performance of the sensor, but errors still occurred during the spring (Fig. 5c). These errors begin when the snow cover reaches an isothermal temperature as indicated by the warming of the snow to 0°C at 0.3 and 0.6 m above the soil (Fig. 7a).

The strong correlation between the variation of SWE errors and heat flux can be seen in Fig. 7 b and c as the SWE errors for SWE sensor A move in synchronization with the soil heat flux. From these observations we hypothesized that the variation in heat flux was caused by a variation in the soil thermal conductivity as soil moisture from snowmelt water changed on diurnal and longer term time periods. We tested this hypothesis during the winter of 2000/2001 by covering SWE sensor A with a plastic sheet to keep snowmelt water from infiltrating

into the soil next to the sensor. We also added permeable SWE sensors B and C to the test site to examine the effect of allowing water to flow through the sensor to wet the underlying soil (Fig. 2, Table 1).

The plastic sheet over SWE sensor A eliminated springtime SWE errors; winter SWE errors reoccur because the soil layer used to diffuse heat flux differences between the soil and sensor was removed (Fig. 5d). The combined effects of placing a soil layer covered by plastic over SWE sensor A removed both the winter and spring time SWE errors, with the exception of a spike error that occurred just as the snow cover reached its isothermal temperature of 0 °C (Fig. 5e, 8a and 8b). A reasonable explanation for the spike error is that the progression of the 0 °C isothermal front through the snow cover is not uniform everywhere. Above SWE sensor A snow temperatures

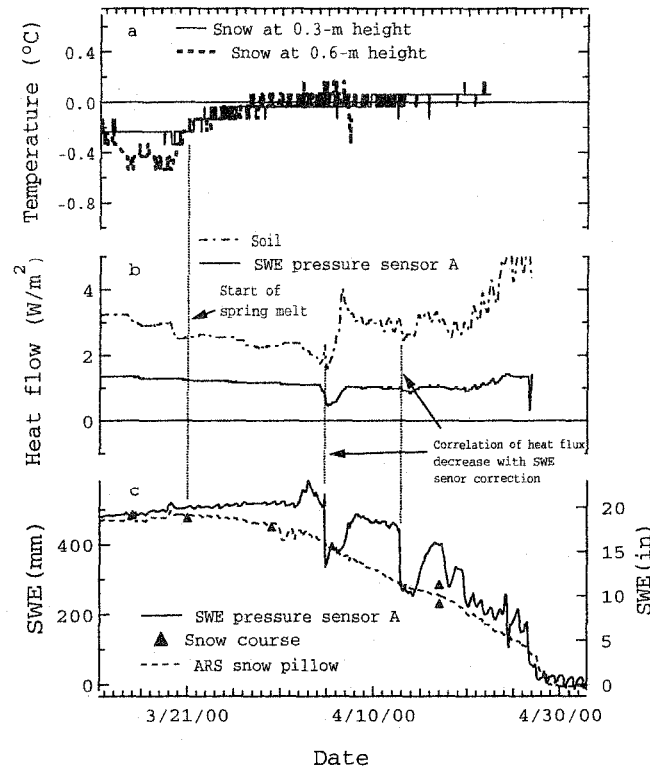


Fig. 7. Snow temperature at 0.3 and 0.6-m height (a), heat flux under and adjacent to sensor (b), and SWE for the ARS snow pillow, SWE sensor A, and snow core data during the spring of 2000 (c).

will likely be colder than for the surrounding snow at any given time during the winter because the heat flux into the snow from the soil is greater than from the sensor into the snow (Fig. 8c). In this situation, the 0 °C temperature front will reach the snow/soil interface before it reaches the snow/SWE sensor A interface producing a sudden increase in heat flux, moisture and thermal conductivity in the soil (Fig. 8b, c, and d). As a consequence, the snowmelt rate at the snow/soil interface will rise dramatically in comparison to the snowmelt rate at the snow/SWE sensor A interface as heat that had been conducted into the snow cover to warm it now melts the snow instead. The increased snowmelt at the snow/soil interface will result in a corresponding increase in the SWE error until the isothermal front also reaches the snow/SWE sensor A interface after which snow creep can act to equalize the SWE load between the sensor and surrounding soil (Fig. 8a). We did not have temperature sensors available to compare the snow temperature above SWE sensor A with the surrounding snow or to monitor the progression of the isothermal front. However, the hypothesis is supported by measurements of snow pillow temperatures that are less than the snow/ground interface temperatures during a winter season (California, 1976), and observations of lower temperatures above snow pillows compared to the surrounding snow (D. Marks, personal communication).

The response characteristics of the permeable SWE sensors B and C demonstrate the importance of matching the sensor's thermal conductivity with the surrounding soil and maintaining a uniform moisture content in the soil under and adjacent to a SWE sensor. During the 2000/20001 winter permeable SWE sensor B accurately measured SWE until the beginning of February and then under measured SWE until spring, an indication that the sensor had a higher thermal conductivity than the soil (Fig. 9a). The higher heat flux through the sensor, compared

to the soil, results in a higher snowmelt rate at the snow/sensor interface than at the snow/soil interface and causes a snow load transfer from the sensor to the surrounding snow (snow bridging). These results are consistent with the theoretical thermal conductivity for the sensor of 0.9 W/m-K and the measured conductivity for the soil of about 0.5 W/m-K. The results of permeable sensor C are not shown for the 2000/2001 winter since it exhibited a flat line response shortly after the first snowfall. The flat line response is assumed to be caused by a high snowmelt rate on its surface as a result of its relatively high thermal conductivity of 1.56 W/m-K compared to the soil thermal conductivity.

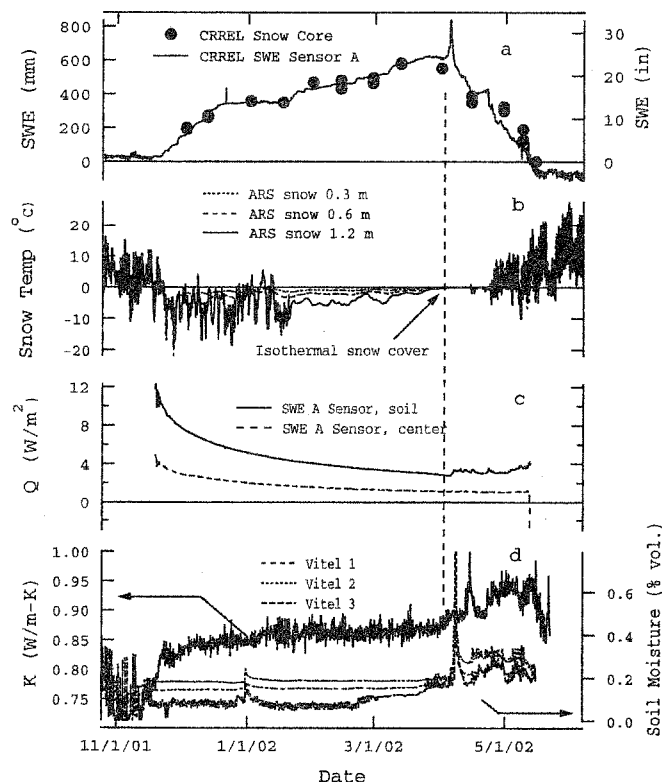


Fig. 8. Thermal conditions and SWE measurements for SWE sensor A. SWE measurements from SWE sensor A and hand core data (a), snow temperature at 0.3, 0.6, and 1.2-m height above the soil (b), heat flux through the snow/soil and snow/SWE sensor A interfaces, and soil thermal conductivity and moisture content (d).

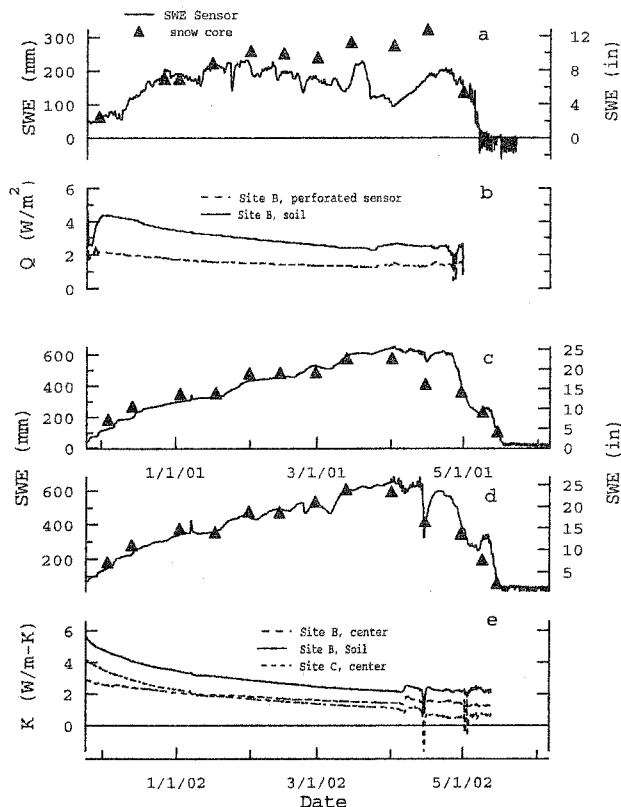


Fig. 9. SWE measurements for SWE sensor B during the 2000/2001 winter (a), heat flux for sensor B and the adjacent soil (b), SWE measurements for sensor B (c) and sensor C (d) during the 2000/2001 winter, and heat flux through sensors B and C, and the soil next to sensor B (e).

The measurement accuracy of permeable SWE sensors B and C were improved during the 2001/2002 winter after the active measurement surface area was increased and the thermal conductivity of each sensor was reduced by removing their internal support structure (Fig. 4b). SWE sensor B accurately measured SWE until the snow cover became isothermal (Fig. 8b) and SWE sensor C accurately measured SWE throughout the test season, with the exception of a brief period of SWE over measurement when the snow cover became isothermal (Figs. 9c, and 9d). These results further demonstrate the importance of matching the thermal conductivity of the SWE sensor with the soil. The thermal conductivity of SWE sensor B (0.45 W/m-K) was less than the soil and SWE sensor C's thermal conductivity (0.8 W/m-K) was about the same as the soil's, which ranged from 0.86 to over 0.9 W/m-K during the winter.

The permeable SWE sensors allowed water to flow through them, unlike the solid SWE sensor A or snow pillows, wetting the soil under the sensors, which keeps the soil moisture and thermal conductivity under the sensors about the same as the surrounding soil. This appears to reduce the difference in heat flux through the sensor compared to the surrounding soil even when the sensor's thermal conductivity is significantly different from that of

the surrounding soil. This can be seen by comparing the difference between the heat flux through permeable sensors B and C, and soil (Fig. 9b and e) to the heat flux difference between SWE sensor A and soil (Figs. 6c and 8c). Allowing water to flow through the sensor also appears to reduce the fluctuation of SWE errors that can occur during spring when the amount of snowmelt water can vary with diurnal and longer term variations in air temperature (Figs. 7c and 9a, 9c, and 9d).

SWE measurements from the ARS 3-m diameter snow pillow, located approximately 30 m from our test site, were monitored for the five test seasons (Fig. 10). The snow pillow SWE measurements were in close agreement with hand-measured snow core SWE for most of the time. The relatively high SWE measurement

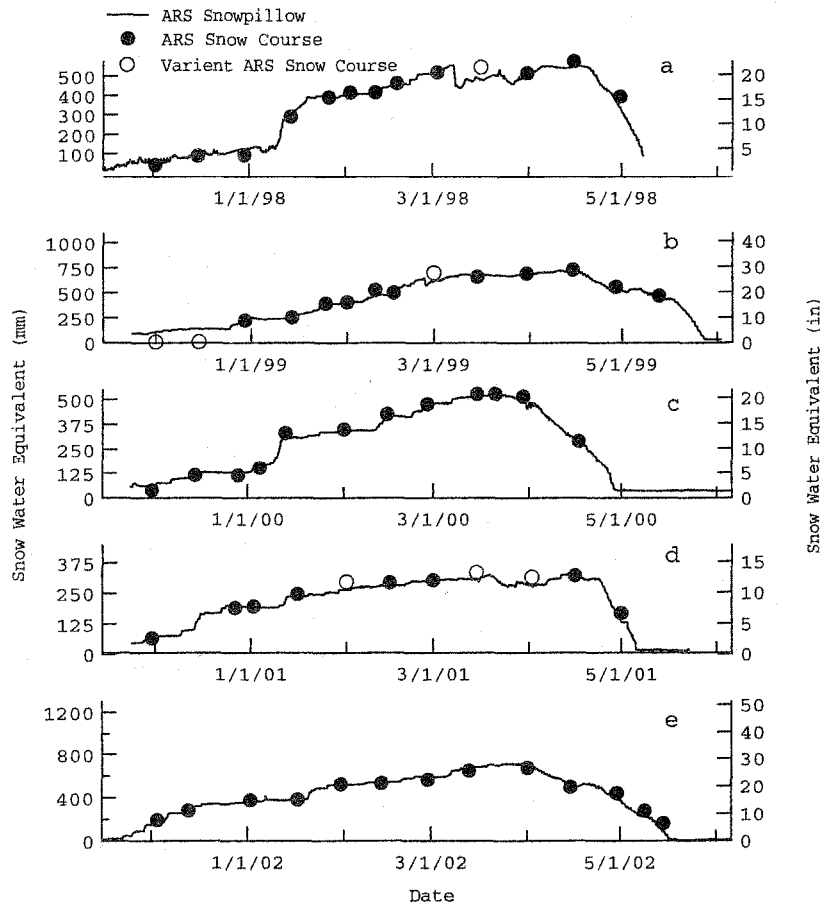


Fig. 10. Comparison of the ARS 3-m snow pillow SWE measurements with SWE from hand measured snow core data next to the sensor for five consecutive winters.

accuracy of the ARS snow pillow compared to smaller diameter snow pillows is an indication that increasing the diameter of an SWE sensor will reduce SWE errors (Figs. 1 and 10). This observation is in fact the basis of the trial and error design method used to develop the snow pillow (California, 1976). Occasionally, the ARS snow pillow SWE differed from hand-core SWE measurements (hollow markers, Fig. 10). Generally, these errors were due to SWE under measurement, an indication that the snow pillow thermal conductivity is greater than that of the surrounding soil. During the early 1999 winter the snow pillow over measured SWE, which can occur when the heat capacity of the snow pillow is greater than the soil's heat capacity. This will produce a different rate of cooling and temperature for the snow pillow compared to the soil (California, 1976) that can result in snowfall accumulating on the snow pillow while melting on the ground when the snow pillow is initially cooler than the ground. The opposite condition can occur when the snow pillow temperature is initially higher than the ground temperature.

The results of our experiments indicate that a strong correlation exists between the accuracy of a SWE pressure sensor, the thermal conditions at the base of the snow cover, and the mechanical properties of the snow.

With this information, it is possible to understand the physical mechanisms that control SWE sensor accuracy and develop sensor designs and installation modes to minimize measurement errors.

CONCLUSIONS

Physical mechanisms affecting SWE pressure sensor accuracy

The results of our experiments, and previous studies, provide much of the information needed to understand the mechanisms that affect SWE sensor accuracy. Our study indicates that SWE sensor measurement errors do not occur when the snow/soil and snow/SWE sensor interfaces remain below the melting temperature of snow. However, when the temperature of one or both of the snow/soil or snow/SWE sensor interfaces equals the melting temperature SWE sensor measurement errors may occur. The source of these errors is the difference in snowmelt rate at the snow/soil interface compared to the snow/SWE sensor interface that occurs when the thermal properties of the SWE sensor are different from those of the surrounding soil. The magnitude of SWE sensor over- or under-measurement errors depend on the difference in the heat flux through the sensor as compared to the surrounding soil, the aspect ratio and diameter (or width) of the SWE sensor, and the rate of snow creep. Consequently, SWE sensor measurement errors are more prevalent in snow covers that have snow/ground interface temperatures equal to 0 °C and that undergo multiple thawing and freezing cycles, producing ice layers that reduce the snow creep rate. The most severe conditions arise during the transition from winter to spring when the snow cover becomes isothermal and heat that had previously been conducted into the snow cover becomes trapped at the snow/soil and snow/SWE sensor interfaces producing additional snowmelt. A sudden, temporary, increase in SWE measurement error occurs when the 0 °C isothermal front arrives at the snow/soil or snow/SWE sensor interface at different times. The snowmelt rate at the snow/soil or snow/SWE sensor interface that is in contact with isothermal snow will suddenly increase producing a higher snowmelt and SWE sensor measurement error until the isothermal front reaches both interfaces. Once the snow cover becomes isothermal everywhere, diurnal or longer-term variations in snowmelt rates produce soil moisture and thermal conductivity variations between an impermeable SWE sensor and the surrounding soil that can produce fluctuating SWE measurement errors.

SWE sensors also modify the thermal conditions and amount of stored heat in the soil underlying a SWE sensor compared to the surrounding soil. Differences in the albedo, sensor permeability, and thermal properties (heat capacity, diffusivity, and thermal conductivity) between a SWE sensor and surrounding soil result in different amounts of absorbed sensible and solar heating, and water from rainfall or snowmelt (impermeable sensors). During the winter, the different amount of stored heat and moisture in the soil under the SWE sensor compared to the adjacent soil is one of the sources of the difference in heat flux between a SWE sensor.

SWE sensor design and installation modes to minimize errors

To minimize SWE measurement errors, the design and installation of a SWE sensor must minimize differences in heat flux through the sensor and the surrounding soil or enhance the creep deformation of snow to equalize the snow load between the sensor and soil. The snow pillow design and installation does not attempt to match the thermal properties of the soil. Instead, snow pillows use a large diameter to enhance the effects of snow creep to reduce SWE errors. This method works when differences in snowmelt rates are relatively small compared to the snow creep rate. Matching the thermal properties of a SWE sensor with the surrounding soil can be done by minimizing the sensor's heat capacity, allowing water to flow through the sensor, and making its thermal conductivity similar to that of the soil. Placing a layer of soil over the sensor to diffuse heat will also help reduce differences in heat flux between the sensor and surrounding soil. We have made significant progress in developing design criteria for relatively small dimension SWE pressure sensor. However, to overcome the severe winter to spring transition period we must further improve the thermal compatibility of SWE pressure sensors with their surrounding environment.

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