Analysis of characteristic snow parameters and associated factors in a cold region in northeast China

Qiang Fu, Li Peng, Tianxiao Li, Song Cui, Dong Liu, Peiru Yan and Hongguang Chen

ABSTRACT

Snow characteristics were measured in the comprehensive experimental field and the results of a detailed analysis of physical snow properties indicated that snowpack characteristics are affected by a variety of climate parameters. The average liquid water content of snow increased from 0.5% to 3.5%. The bottom snow layer exhibited larger parameter variations than those in the surface and middle layers. The average snow porosity was 72.3% for the entire snowpack, and the changing rate of porosity ranged from 4% to 19% during the accumulation period and from 7% to 25% during the snowmelt period. The porosity of the bottom layer displayed the fastest decline and the largest range. The air temperature, snow temperature and solar radiation showed significant positive correlations with the liquid water content of the snow, and the calculated correlation coefficients were all above 0.9. In addition, relative humidity and temperature were negatively correlated. All meteorological factors studied affected the melting capacity of snow to varying degrees. This study included the design and implementation of snow experiments on bare land under natural conditions as well as measurements of snow parameters in detailed snowpack layers and explained the characteristics of snow parameters combined with meteorological factors.

Key words | liquid water content of snow, snow depth, snow porosity, snow temperature

INTRODUCTION

Snow accounts for nearly 5% of the total precipitation on earth (Zhao et al. 2015). As surface water quality has continuously deteriorated, the proportion of snow in the anthropogenic water supply has increased, especially the proportion used for agricultural purposes. The high albedo, low thermal conductivity, large heat capacity and other characteristics of snow prohibit the effective insulation of lower layers from low temperature invasion from the upper layers and reduce heat exchange and heat loss from the atmosphere and soil (Domine et al. 2013). These characteristics prevent frost damage to crops and influence the soil freezing depth, freezing rate, frost heave and heat and mass transfer processes (Endrizzi et al. 2014; Yi et al. 2015).

The snow depth and liquid water content of snow are the fundamental physical parameters used to calculate the snow water equivalent (Rittger et al. 2016), simulate snowmelt runoff (Tiwari et al. 2016) and estimate the thermal conductivity of snow (Lin et al. 2015) and its reflection. The distribution of the liquid water content not only reflects the volume of snowmelt but also the energy transfer between snow layers. Snow porosity and other parameters, such as the liquid water content, snow density and snow depth, also contribute to the snow water balance and energy balance (Iwata et al. 2010; Stojković & Jaćimović 2016). Manzano et al. (2016) replaced stratified values with integrated data to analyze the relationships between deposition time and various snow parameters. Nosaka et al. (2016) used a non-hydrostatic
regional climate model to simulate snow depths in Japan and project their changes in the future. Wayand et al. (2015) tested hypotheses related to energy balance, soil processes and snow processes in a rain–snow transition zone in Washington State. Rasmus et al. (2016) analyzed the local and regional variations in snow conditions in a Finnish reindeer herding area. Snow porosity and other parameters, such as the liquid water content, snow density and snow depth, also contribute to the snow water balance and energy balance (Godio 2016). However, in China, especially in the cold northeast region, meteorological and hydrological observation sites are sparse; thus, data availability is limited, and few studies have addressed the changing rules of physical snowpack properties that affect agricultural production on the Songnen Plain.

This study analyzes snow experiments on bare land under natural conditions on the Songnen Plain in northeast China, summarizes the various rules governing characteristic snow parameters and associated factors, and explains the change characteristics of snow parameters combined with meteorological factors in agricultural production areas in cold regions.

MATERIALS AND METHODS

Study area

This study was conducted in a typical cold region with seasonal snow cover on the southeast Songnen Plain, northeast China (latitude: 45° 44’ 41” N; longitude: 126° 45’ 32” E; elevation: 139 m a.s.l.), as shown in Figure 1(a) and 1(b). The region is characterized by a temperate continental monsoon climate. The average monthly temperature (from 1985 to 2006) varies between −14.2°C in January and 3.6°C in July, and the mean annual precipitation is 529 mm/year, with most precipitation occurring between April and September. The average snow cover duration is 110 d based on historical data. Seasonally frozen soil is widely distributed in northeast China, especially on the Songnen Plain, and the maximum frozen depth can reach 180 cm. The black soil in the region, which is primarily composed of moderate and heavy clay loam, is a semi-leached soil containing rich nutrients that provide favorable conditions for crop growth. This region is one of the largest snow-covered areas in northeast China.

Experiment details

Snow characteristics were observed in a comprehensive experimental field of the Water Conservancy and Architecture College, Northeast Agricultural University. Experiments were performed from November 8, 2015, to mid-March, 2016. Four 10 m × 10 m plots with no vegetation or residue cover were established (Figure 1(c)). We measured the snow parameters on three plots and used the overall average as the reported value. One plot with no snow cover was used as a control. The measured parameters were as follows: the snow depth was measured using a laser snow depth sensor in the Jinzhou Sunshine Technology Model PC-3 automatic weather station; at the same time, we measured the snow depth of every experiment point using a millimetre-scale ruler to guarantee accuracy. The snow temperature was measured using a probe-type thermometer, and the liquid water content of the snow was measured using a Toikka Engineering, Ltd snow analyzer (Snow Fork).

The snow depth was divided into three layers: the top layer, middle layer and bottom layer. Five measurement points were established in each layer. The automatic weather station collected data, including air temperature, air humidity, atmospheric pressure, wind direction, wind speed, snow depth, total solar radiation and other parameters at a step size of 60 minutes.

Methods

Relationships between meteorological factors and characteristic snow parameters

We calculated the correlations among the following parameters using the Pearson correlation coefficient: average daily temperature, total radiation and relative humidity. The snow observation data and meteorological observation data were then normalized and plotted.

Snow porosity calculation

According to Wen et al. (2012), snow porosity can be calculated generally using related physical snow parameters. Ideally, only snow density and ice density are needed to determine the porosity, but snow is a combination of ice,
vapor and liquid states of water under natural conditions. Water vapor can be ignored in the calculation, but the liquid water component is important, especially during the snowmelt period. The volume of liquid water increases with increasing air temperature and directly affects the snow porosity. Thus, the volume of liquid water is considered in the calculation as follows:

\[ V = V_i + V_w + V_a \]  
\[ m = m_i + m_w \]  

where \( V \) is the volume of snow, \( V_i \) is the volume of solid-state ice in the snow, \( V_w \) is the volume of liquid water in the snow, \( V_a \) is the void volume in the snow, \( m \) is the mass of the snow, \( m_i \) is the mass of solid-state ice in the snow, and \( m_w \) is the mass of volumetric water content liquid water in the snow.

Based on the definition of the liquid water content in the snow, the volumetric water content is

\[ W_{vol} = \frac{V_w}{V}. \]
the weight-based moisture content is

\[ W_{\text{WGT}} = \frac{m_w}{m}, \] (4)

and the relationship between the two contents is

\[ W_{\text{WGT}} = \frac{W_{\text{vol}}}{\rho}. \] (5)

Thus, the snow porosity equation is as follows:

\[ \phi = \frac{1 - \rho_i (1 - W_{\text{WGT}}) - W_{\text{vol}}}{\rho_i}. \] (6)

Equation (3) can be further derived to establish the following expression:

\[ \phi = \frac{1 - \rho - W_{\text{vol}} - W_{\text{vol}}}{\rho_i}. \] (7)

where the density of ice \( \rho_i = 0.9168 \text{ g/cm}^3 \).

**RESULTS AND DISCUSSION**

**Analysis of snow depth**

There were 124 days in the snow cover period. The first phase is identified as the accumulation period. Heavy snowfall was concentrated during this phase. Snow densification and grain coarsening due to snowmelt increased under the overlying snow pressure and its own gravity. The second phase was called the stable period. After the maximum snow depth was observed, the air temperature remained low and the soil generally froze. One-way melting was observed at the snow surface, external energy inputs were rare, the snow depth fluctuated, and the melting rate stabilized at 0.45 mm/d. The third stage was called the melting period. The air temperature gradually increased to zero, and thermal radiation from the sun at the upper snow interface increased continuously. Lower soil layers also began to gradually thaw, and the sensible heat flux and latent heat flux slowly increased. The deep frost layer at the bottom of the snow profile began to melt in both vertical directions, and meltwater infiltrated the soil continuously. The average rate of snowmelt reached 3.20 mm/d, eventually producing snowmelt-based flow.

**Analysis of characteristic snow parameters**

**Analysis of the liquid water content of snow**

**Analysis of the liquid water content of snow during the entire study period.** The liquid water content of snow varied from 0.200% to 3.627% in the three snow layers, as shown in Figure 2(a). The liquid water content of snow in the bottom layer fluctuated considerably, ranging from 0.500% to 3.627%, and generally reflected the maximum value during most time intervals. The top and middle layers exhibited similar trends, and most liquid water content values varied between 0% and 2.000%. Liquid water was adsorbed in the solid snow layer and regularly condensed into ice crystals due to the interfacial tension between snow crystals and capillaries. Vertical infiltration occurred regularly due to the gravity of the melting water, and some lateral seepage occurred due to various potholes and gradients. These processes resulted in different distributions of the liquid water contents of snow in different layers.

**Daily variations in the liquid water content of snow during each period.** Daily data from December 10, 2015, January 10, 2016, and February 10, 2016, were selected to represent the accumulation period, stable period and snow melting period, respectively. The liquid water content of snow data was collected every two hours from 8:00 to 20:00 on each day. A comparison of the daily variations in the liquid water content for different layers of snow cover is shown in Figure 2(b).
decreased rapidly in every layer because meltwater was quickly transported to the soil or snow surface; thus, the liquid water content generally ranged from 0% to 2% during this period. On January 10, 2016, the snow–soil interface was frozen, and a one-direction melting process was observed. Thus, the water content was high in the bottom layer, especially from 14:00 to 15:00, i.e., after the top and middle layers peaked, and the maximum content reached 2.503%, as shown in Figure 2(b2). The refreezing effect caused meltwater to condense into a solid state between different layers, and this process clearly varied between the stable period and accumulation period. On February 10, 2016, the air temperature slowly increased during the melting period and the soil gradually thawed. Additionally, meltwater flowed to the bottom layer until runoff was produced. Thus, the bottom layer approached saturation due to rapid thawing and melting. The water content in the bottom layer was approximately 3.219% at this time, as shown in Figure 2(b3), while the water content in the top and middle layers was generally below 1.500%.

Micro-response of the snow temperature and liquid water content. The micro-responses of the snow temperature and liquid water content in each layer provide an important index used to assess the freeze–thaw conditions. The average daily snow temperature ranged from 0°C to −20°C, and the lowest snow temperature was observed in the surface layer at −23.6°C. The snow temperature of the top layer fluctuated from 0°C to −25°C because of its direct heat exchange with the atmosphere. In addition to increasing the snow depth, the low temperatures caused a heat preservation effect, and the low geothermal flux resulted in one-way heat conduction. Therefore, the snow temperature of the bottom layer remained stable at −5°C, while the temperature of the middle layer was approximately −5°C to −10°C. When the air temperature rapidly increased to 0°C, the temperature of the top layer reached −5°C. Additionally, the liquid water content was high, and the snow layer entered a melting state. When the temperature of the top layer was lower than −5°C, the snow layer entered a frozen state. The correlation coefficient between the liquid water content and snow temperature was $R = 0.692 \ (\alpha = 0.01)$. 

**Figure 2** | Liquid water content of snow layers during the experiments; (a) shows the liquid water content curve for each snow cover layer, while (b) shows typical curves for daily changes during three periods for each snow cover layer. (a) Variations in the liquid water content of each snow cover layer during different accumulation–thaw periods. (b) Daily variations in the liquid water content of each snow cover layer during different snow periods: (b1) accumulation period; (b2) stable period; (b3) melting period.
In the snowmelt period, the surface temperature remained low and transferred little energy to the snow layer. Most of the energy from snow temperature changes was expended in melting the frozen snow layer. The energy that remained in the snowpack following the water content transfer was indicative of changes in the snow temperature.

**Analysis of the variation in the porosity of snow cover**

Snow porosity statistics were calculated for each layer and are shown in Table 1.

The porosities of the snow layers generally exhibited decreasing trends, and the porosity fluctuated considerably in the melting period. The average porosity of the snow cover was 72.3%, ranging from 80% at the beginning of the accumulation period to 70% at the end of the accumulation period. Although the porosity generally ranged from 60% to 70% during the melting period, the minimum value was 49%. The movement of meltwater between layers increased the porosity, which varied by $-2.8\%/d$ throughout the entire study period. The average snow porosity of the bottom layer was 62% overall and 55% in the melting period.

The decrease in porosity was caused by two primary factors: (1) the rapid increase in the air temperature caused freeze–thaw cycles and continuous snowpack compression; and (2) snowmelt-based water also filled pores, thereby reducing the snow porosity. This observation suggested that porosity is one of the key indicators of the water-holding capacity of snow cover.

**Correlation analysis between meteorological factors and the characteristics of snow**

The air temperature reflects the energy associated with solar radiation and longwave radiation from the atmosphere on rainy days. The radiation and temperature decreased from November 11, 2015, to January 23, 2016, resulting in gradual energy accumulation. The radiation and temperature increased from January 23, 2016, to February 29, 2016, and the rate of energy accumulation increased. Heat absorption from the atmosphere increased the snow temperature of the top layer as energy infiltrated the snow surface. Additionally, the meltwater stored in ice crystals gradually accumulated, leading to some of the changes illustrated in Figure 3. Significance analyses of the air temperature and liquid water content, snow temperature and liquid water content and solar radiation and liquid water content

![Figure 3](https://iwaponline.com/ws/article-pdf/19/2/511/592488/ws019020511.pdf)

**Table 1** | Snow porosity values in each layer

<table>
<thead>
<tr>
<th>Snow porosity (%)</th>
<th>Max</th>
<th>Min</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper layer</td>
<td>90.57</td>
<td>59.50</td>
<td>73.59</td>
<td>31.07</td>
</tr>
<tr>
<td>Middle layer</td>
<td>80.78</td>
<td>50.22</td>
<td>64.05</td>
<td>30.56</td>
</tr>
<tr>
<td>Lower layer</td>
<td>76.50</td>
<td>40.47</td>
<td>55.97</td>
<td>36.03</td>
</tr>
</tbody>
</table>

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resulted in correlation coefficient values of $R_1 = 0.621$, $R_2 = 0.709$ and $R_3 = 0.745$, respectively. These results suggest that the air temperature affects the temperature and liquid water content of snow layers.

As one of the main energy inputs associated with the snowmelt process, solar radiation directly affects the liquid water content. Because it is directly influenced by radiative energy, the top snow layer displayed the best correlation with solar radiation at $R = 0.926$. The correlation decreased gradually as the snow depth increased, with values of $R = 0.738$ in the middle layer and $R = 0.524$ in the bottom layer (Table 2). This trend is due to the transfer of heat energy to the air–snow surface through solar radiation, and this energy then propagates between neighboring layers and gradually decreases with distance. Thus, meltwater from the upper layer infiltrates and changes the liquid water content in the lower layer.

The relative humidity is mainly affected by wind, solar radiation and other factors that influence the sublimation process at the snow surface. After November 11, 2015, the increase in the relative humidity suggested that the percentage of the actual water vapor pressure in the saturation pressure increased. The saturation pressure decreased as the air temperature decreased. The correlation coefficient between relative humidity and air temperature was significantly negative at $-0.846$. When the relative humidity decreased, it inhibited snow surface evaporation, liquefaction and desublimation and it may have caused condensation, which increased the weight of each of the snow layers.

**CONCLUSION**

The trends and characteristics in a cold and snowy region in northeast China were observed by studying a combination of meteorological conditions and snow depth, snow density, liquid water content of snow, snow porosity and other parameters at the microscopic level. The conclusions of this study are as follows:

1. Throughout the snow characteristic experiments, the snow water content values exhibited the following order by layer: bottom > middle > surface, while the snow porosity exhibited the following order by layer: surface > middle > bottom.

2. The surface layer was directly affected by processes at the air–snow interface. Energy was then gradually propagated to the middle and bottom layers, and both the upper-layer processes and geothermal processes in the soil affected the bottom layer. Energy in the snowpack is mainly sustained during the surface energy change and water content transfer and becomes indicative of changes in the snow temperature. Thus, energy fluctuations were highest in the bottom layer, and the liquid water content of snow exhibited the most variation.

3. Through a correlation analysis of snow parameters and three important meteorological parameters, air temperature, solar radiation and humidity, we found that air temperature, snow temperature and moisture content were significantly correlated at a level of $P = 0.01$. The air temperature transmitted energy to the snow surface and was the key contributor to the melting progress. The correlation between the liquid water content and solar radiation was highest at the surface layer and then decreased as the snow depth increased. The relative humidity and air temperature exhibited a significant negative correlation with a correlation coefficient of $-0.846$. Low humidity levels led to increased sublimation.

**ACKNOWLEDGEMENTS**

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**Table 2** The correlation between liquid water content and solar radiation for each layer

<table>
<thead>
<tr>
<th>Snow depth (cm)</th>
<th>Snow layer</th>
<th>$a$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Top</td>
<td>0.01</td>
<td>0.926</td>
</tr>
<tr>
<td>10</td>
<td>Middle</td>
<td>0.01</td>
<td>0.738</td>
</tr>
<tr>
<td>15</td>
<td>Bottom</td>
<td>0.01</td>
<td>0.524</td>
</tr>
</tbody>
</table>


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