Overwinter Soil Moisture Changes

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ABSTRACT

FIELD measurements of the overwinter soil moisture changes, those occurring from freeze-up up to the time of snowmelt, in the Canadian Prairies show that moisture losses are common from the shallow depth adjacent to the soil surface whereas, depending on the soil moisture content at the time of freezing, the amount of moisture in a 0 to 1 m soil layer remains unchanged or increases. It is shown that on irrigated areas the amount of moisture migration to a freezing front in the depth, 0 to 1 m, greatly exceeds snowmelt infiltration; in dryland areas overwinter changes represent, on the average, 20 to 50% of the soil moisture increase between fall and the end of snowmelt. The need for identifying the primary mode of transfer, liquid or vapor, is emphasized. Information is provided on the interrelationships between overwinter changes, fall soil moisture and soil temperature.

INTRODUCTION

Moisture migration in response to a temperature gradient during freezing and thawing of unsaturated soils is a complex process involving the thermodynamics of the soil-ice-water regime. Much of the impetus for study of the phenomenon has originated because of its importance to the design and construction of engineering works, e.g., the "frost heave" of buildings, the development of "frost boils" under bituminous pavements and others. The results of numerous studies on frozen soils are reported in the literature. Most of these works focus on: (a) the thermophysical properties of frozen porous media (Williams, 1968; Anderson and Tice, 1972; Benoit, 1975; Burt and Williams, 1970; Jumikis, 1973); (b) the thermodynamics of the soil regime (Anderson et al., 1942; Hoekstra, 1966; Letey, 1968; Groenevelt and Kay, 1974; Aguirre-Puente et al., 1976; Steenhuis et al., 1977; Loch, 1978); (c) the effects of soil and water properties on moisture migration (Letey, 1968; Cary and Mayland, 1972; Anderson and Morgenstern, 1973; Jumikis, 1973; Jame, 1977; Kudryavtsev and Yershov, 1978; Kudryavtsev et al., 1978; Yarkin, 1978; Cary et al., 1979; Mageau and Morgenstern, 1980) and (d) the development and verification of models describing migration (Harlan, 1973a, 1973b; Guymon and Luthin, 1974; Aguirre-Puente et al., 1976; Jame and Norum, 1980; Sheppard et al., 1981). Despite these investigations several questions on the fundamental aspects of the process remain unanswered, in particular a clear consensus is lacking on the relative importance of the different modes of moisture transfer, e.g., as a liquid or vapor.

Not unlike most investigations in earth sciences, the number of laboratory studies on freezing, frozen or thawing soils conducted on small specimens in the laboratory vastly outnumber the field experiments. Because of the scarcity of field data and the difficulty in simulating field boundary conditions in laboratory experiments only general trends in agreement of the data from the two sources are evident. For example, Ferguson et al. (1964), Willis et al. (1964) and Sheppard et al. (1981) show larger amounts of moisture migration in a wet soil and where a water table was near the surface compared to the amounts transferred in dry unsaturated soils.

The material below summarizes the results of a study on the role and magnitudes of overwinter soil moisture changes, those occurring in the period from freeze-up in the fall to the time of snowmelt in the following spring, which was conducted in the Canadian Prairies. The primary objectives of the investigation were: (a) to establish a data base of in-situ measurements of changes, and other parameters which could be used to test, verify and develop models of the process; (b) to quantify the overwinter soil moisture changes and to study the factors affecting the phenomenon and (c) to study the effects of the change on the soil moisture content at the time of snowmelt (hence the snowmelt infiltration potential), the amount of water available for plant growth, fall irrigation practices and a potential cause of soil salinity problems. In discussing the results emphasis is given to trends in the data, for example, moisture gains or losses as affected by the availability of moisture for migration, snowcover, land use and soil texture; the practical significance and implications of the findings as they relate to agricultural water use and management problems and to the identification of the primary mode of transfer of the migrating water.

FIELD STUDIES

During the past five years a large number of soil-moisture and soil-temperature measuring sites have been established within the Brown and Dark Brown Soil Zones
in Saskatchewan. Most of the sites are located in glacial or lacustrine clay and clay-loam soils in fields used for the production of cereal grain by dryland farming. The land use of these areas during winter is either fallow or stubble which usually provides ranges in fall soil moisture and snowcover accumulation. In addition to the dryland locations, four sites, two in grass and two in stubble, were located in an irrigated area. The soil at this location is a fine sandy loam with a water table at approximately 2.75 m.

Each soil moisture site contained two PVC tubes (52.5 mm ID) spaced 304 mm center to center and inserted vertically to a depth of 1.6 m. These served as access tubes for a two probe gamma density meter which was used to monitor changes in density of the soil profile. By assuming the mass of soil confined between the tubes at a given depth remains constant, i.e., no major structural changes in the soil occur, changes in density of a layer can be attributed to changes in the mass of water. The equivalent moisture change is calculated from the density readings assuming a density of water equal to 1000 kg/m³. Details on the use of the two probe system for measuring soil moisture and density is well documented in the literature (for example, see Troxler, undated; Smith et al., 1967; Ligon, 1969; Ryhiner and Pankow, 1969; Reginato and Jackson, 1971; Jame and Norum, 1980).

Density measurements were obtained at 20 mm increments of depth to 1 m and at 40 mm increments between 1 m and 1.6 m. Repeatability tests conducted with the equipment in the field showed a standard error of estimate of the moisture content for the soils encountered in the study of about ±2.5 mm in a 1-m profile. All systems were extensively tested and calibrated to operate reliably under cold weather conditions (to −20°C).

Profile measurements were made in the fall prior to freeze-up and continued throughout the winter, snowmelt and post-melt periods up to a date close to the time of seeding when the tubes had to be removed. Every effort was made to service each site at least once every three weeks.

At several locations soil temperature probes with automatic recorders were also installed to provide measurements at depths of 25, 50, 100, 200, 400, 800 and 1600 mm. Daily maximum and minimum air temperatures were also recorded. The temperature data were used to help identify: the layers of soil where overwinter moisture changes occurred; periods of midwinter melt and infiltration; the time of snowmelt in the spring and drainage during the thawing process; and to establish rates and depths of freezing and thawing.

RESULTS AND DISCUSSION

A general review of the field data suggested the overwinter soil moisture changes could be discussed most conveniently by dividing the soil profile into two zones in which changes occur, herein referred to as an “Upper” zone and a “Lower” zone. The “Upper” zone is that layer of soil extending from the surface to a depth of approximately 300 mm. In this zone moisture transfer (other than infiltration) occurs primarily as a vapor and the changes are greatly affected by those factors influencing the energy and vapor exchange processes within the soil and at the air/snow and snow/soil interfaces. Observations indicate that moisture losses from this zone are most common. The “Lower” zone, located immediately below the “Upper”, undergoes moisture changes by the upward migration or relocation of water in response to freezing or by drainage below the frost line. Moisture may move either as a vapor or a liquid and overwinter gains are common.

Soil Moisture Changes

Figs. 1 and 2 show typical plots of changes in temperature and moisture (includes water plus ice) regimes at selected dates throughout the period from freeze-up in the fall of 1982 through to the spring of 1983 measured in two different fields of stubble. The Saskatoon site (Fig. 1) was a heavy, lacustrine silty clay having a high fall moisture content (range 24 to 45% by volume; see Fig. 3a) in which the depth to the water table is greater than 4 m. The changes shown represent unusually high fluxes for the landuse, which are primarily the result of the high fall soil moisture status. The Outlook site (Fig. 2) was an irrigated, fine sandy loam having a fall soil moisture near field capacity (~25% by volume; see Fig. 3) and a water table at 2.55 m. It is important to point out that the moisture fluxes shown for Outlook typify those that have been found during the past four years.

The data in Figs. 1 and 2 exhibit both similarities and differences in the patterns of soil moisture change and these are considered for two periods: (a) Overwinter -period extending from the day the initial measurements were made in the fall to the last day of measurement prior to snowmelt; i.e., Saskatoon - Nov. 16/82 to Mar. 8/83; Outlook - Nov. 17/82 to Feb. 10/83, and (b) Melt and Post Melt - period following overwinter to the last day of measurement (which is within ~15 days of the seeding date), i.e., Saskatoon - Mar. 8/83 to May 31/83; Outlook - Feb. 10/83 to May 16/83.

![Soil Temperature (Deg. C.)](image)

![Soil Water Change (%-Vol.)](image)

![Soil Temperature (Deg. C.)](image)

![Soil Water Change (%-Vol.)](image)

Fig. 1—Soil temperature and soil moisture changes in a silty clay soil measured at Saskatoon, Sask. In the period from Nov. 16/82 to: (a) Dec. 2/82; (b) Dec. 17/82; (c) Jan. 13/83; (d) Feb. 8/83; (e) Mar. 8/83; (f) Mar. 29/83; (g) Apr. 18/83 and (b) May 31/83.
Fig. 3—Effects of gradients and Santeford (1978) has reported moisture gradient metamorphism as a result of the flow of soil heat and moisture to the snowcover. Benson and Trabant (1973) and Santeford (1976) have observed that as the rate of downward movement of the 0°C isotherm decreases (Figs. 2d and 2e) a zone of moisture loss develops in the unfrozen soil. This is attributed to the natural drainage of water, which could include water which was in transit to the frost front. The increase in the depth to the water table during freezing (Figs. 2a, 2d and 2e) and its reversal in the spring (Fig. 2h) suggests the saturated zone is the primary source of the migrating water.

Overwinter Period

For the overwinter periods the data given in Figs. 1 and 2 show:
1. Both sites exhibited a moisture loss from the Upper zone (0-200 mm). The loss was also evinced by the coarse, rounded, large-grained texture of the snowcover at the soil surface - an indication of strong temperature-gradient metamorphism as a result of the flow of soil heat and moisture to the snowcover. Benson and Trabant (1973), Peck (1974) and Santeford (1976) have recognized the coupling between moisture migration in a soil and an overlying snowcover as a result of thermal gradients and Santeford (1978) has reported moisture flow from a moss to a snowcover in the black spruce/permafrost region of interior Alaska.
2. Large fluxes of water migrate to the frozen Lower zone in response to the freezing action. Within a 1-m depth, these increases amount to ~47.8 mm at Saskatoon and ~95.7 mm at Outlook. The profiles show that: (a) the accumulation of water/ice occurs immediately above the freezing front and (b) the elongation and extension of the zone-of-accumulation coincides with the downward movement of the 0°C isotherm into the soil.
3. There was no pronounced soil moisture gradient in the unfrozen soil. The absence of a hydraulic gradient below the freezing front would suggest that the transfer of moisture occurred as a vapor; or if capillary (liquid) flow, the transport mechanism is analogous to a coupled hand-to-hand exchange process. For Outlook, it can be observed that as the depth to the water table during freezing (Figs. 2a, 2d and 2e) and its reversal in the spring (Fig. 2h) suggests the saturated zone is the primary source of the larger amount of water frozen.

Melt and Post Melt Periods

The moisture increases in the soil layer (0-300 mm) during the melt period, shown in Figs. 1f, 1g and 2f, indicate snowmelt infiltration. These amounts at Saskatoon and Outlook were 23.3 mm and 4.5 mm respectively for corresponding snowcover water equivalents of 125.8 mm and 8.4 mm. Note, the soil temperature was below 0°C during infiltration and the depth of penetration of meltwater into the soil was less than 300 mm, being limited by refreezing.

During melt the moisture regime of the soil profile below the zone of infiltration remains relatively stationary and unchanged; following melt the frozen soil thaws progressively from the top and bottom. Some drainage can be observed at lower depths in the early part of the thaw sequence, however major changes to the soil moisture regime do not occur until the temperature throughout the profile is above 0°C (see Figs. 1h and 2, 2h). In 1983 this condition was not reached until the latter part of April through to mid May.

The above results demonstrate that significant fluxes of water may occur to the freezing front where conditions favor migration. Lacking fall rains, soils under stubble are usually relatively dry at freeze-up. A soil frozen in this condition can develop a moisture profile in the lower zone which exhibits alternating layers of gains and losses throughout its frozen depth. Measurements of soil moisture changes made at Saskatoon in 1982/83 illustrate this condition (Fig. 4). Fig. 4a shows a zone of low moisture between 300 to 800 mm at the time of freeze-up; the result of withdrawal by the crop during the growing season. Fig. 4b shows alternating zones of approximately equal gains and losses. Applying a
moisture balance to the frozen zone (170 to 1520 mm) the net change was calculated as 1.1 mm (which is within the error of measurement). These results substantiate the findings of other researchers indicating the net transfer of water by freezing in dry soils is negligible. Note, the Upper zone (0 to 170 mm) typically showed a loss of 26.1 mm in the period.

Average Statistics of Overwinter Changes

Table 1 gives some general statistics on the average overwinter moisture changes measured at fifty sites under dryland farming during the period 1980-1983 inclusive. These data demonstrate a wide range in values. The relative magnitude of changes in the soil layer 0-300 mm of −11.1 to 5% by volume are greater than those in the 1-m depth of the root zone, i.e., −3.4 to 4.3% by volume. Usually, gains are common in a 1-m profile. The differences in the overwinter changes between land use practices can be assumed to be due to differences in snowcover, soil moisture and temperature regimes. The ratio of snowmelt infiltration to the total change in moisture in a 1-m profile for the period from freeze-up to the end of melt (INF/TC) is of practical importance. The mean value of INF/TC for all sites was 0.79; for those sites where migration could be identified it was 0.50, that is 50% of the total overwinter change was due to migration. These data support the proposition that a soil moisture change calculated as the difference in fall and spring measurements may not accurately reflect snowmelt infiltration. They also emphasize the need to include the overwinter change in any model using only the fall soil moisture and snowfall or snowcover water equivalent for forecasting spring soil water reserves.

Applications

The results above have several practical applications. Some of direct interest to agriculturalists and engineers are listed below.

1. Because the snowmelt infiltration potential of a frozen Prairie soil is inversely related to the soil moisture (ice) content of the soil layer 0-300 mm at the time of melt (Granger et al., 1984) overwinter soil moisture changes directly affect the amount of soil water recharge from a snowcover.

2. The large fluxes of moisture due to freezing in irrigated areas which contain a water table at shallow depth put in question the value of fall irrigation for increasing spring water reserves. The practice may enhance moisture migration, reduce snowmelt infiltration, contribute only small additions of water to the root zone over those that would occur by natural migration due to freezing, increase runoff, and retard thawing in the spring.

3. The amount of water that migrates in response to freezing and is retained within the crop root zone depends on the moisture content and drainage properties of the soil. It would appear that established crops, such as biennials or perennials, would always benefit to some extent from these additions, particularly in the early part of the growing season. In this regard, the case may be made for the use of winter wheat for better moisture conservation and utilization in the northern Prairies.

4. A special concern is whether the migrating water contains salts which are free to move to the soil surface in response to evaporation and contribute to soil salinity. This depends entirely on the mode of transport (vapor or liquid).

Effects of Fall Soil Moisture Content and Soil Temperature on Overwinter Changes in the Upper Zone

Fig. 5 is a scatter diagram of the overwinter change plotted with the average soil moisture content of the Upper Zone (0 to 300 mm) at the time of freeze up. The lack of correlation between the two variables is obvious. This may be attributed to differences in many factors, for

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**Table 1. Average Overwinter Moisture Changes in Uncracked Silty Clay and Clay Soils Under Dryland Farming, mm.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Depth increment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-300 mm</td>
</tr>
<tr>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Fallow</td>
<td>−27.2 → 11.8</td>
</tr>
<tr>
<td>Stubble</td>
<td>−33.3 → 15.1</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Fallow</td>
<td>−7.5</td>
</tr>
<tr>
<td>Stubble</td>
<td>1.3</td>
</tr>
<tr>
<td>INF/TC*</td>
<td>Average†</td>
</tr>
<tr>
<td>Migration‡</td>
<td>0.50</td>
</tr>
</tbody>
</table>

*Ratio of the amount of snowmelt infiltration (INF) to the total change in soil moisture in a 1-m profile in the period from freeze-up to the end of melt (TC).
†Average = mean value calculated using data from all sites.
‡Migration = mean value for those sites where moisture migration could be identified.

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Fig. 5—Scatter diagram of overwinter change plotted against the average fall moisture content for the soil layer, 0-300 mm.
example, soil properties, soil moisture distribution, soil temperature regime, snowcover and others. It is also believed the lack of association indicates the major moisture transfer mechanism within the soil layer and between the layer and the snowcover is by vapor flow. Likely, a frozen soil whose temperature is several degrees below zero, would not contain a large amount of liquid water (Jame, 1972) and the relative humidity of the soil air would be close to 100%. That is, both the liquid and vapor regimes are relatively independent of soil moisture content. Under these conditions water would move primarily as a vapor in response to a temperature gradient.

A study was also undertaken in an attempt to relate the overwinter moisture change in the Upper zone to the average soil temperature gradient during the period of freezing over which most of the change occurred. From a study of numerous profiles the length of the freezing period was established as 60 days following the start of freeze-up. In the analysis, use was made of the degree-day concept, based on the soil temperature at 200 mm, as an index of freezing. This index can be used with confidence for this purpose under conditions where the temperature and temperature gradient reflect the energy content and the dominant energy flux. Note, a high degree of association was found between the degree-day and the average temperature gradient between 100 and 200 mm (correlation coefficient = 0.86). The results of the investigation proved negative however as little association was found between the overwinter moisture change and the degree-day index. Three plausible reasons for the lack of correlation are: (a) overwinter moisture changes in the soil layer are relatively insensitive to soil temperature and its gradient; (b) the changes are strongly affected by the exchanges of heat and mass at the soil-air-snowcover boundary or (c) the degree-day index using soil temperature is not sufficiently sensitive to describe the changes or a good indicator of the energy exchange processes.

Primary Transfer Mechanism: Liquid or Vapor

Since water vapor releases a much greater amount of energy than an equivalent mass of liquid water on freezing, one should be able to use this concept to distinguish the different moisture transfers in cases where a large difference in the amount of moisture transfer has occurred under similar freezing and snowcover conditions. Such a situation occurred at Outlook and Saskatoon in the winter of 1980/81. Fig. 6a shows the amount of soil water frozen plotted with the degree-days of frost (based on air temperature). Note: in both Figs. 6a and 6b no consideration is given to effects of differences in the texture and density of the soils at the two sites on the freezing action. The soil water frozen (in the soil layer above the frost front, i.e. 0°C) includes the moisture contained within the depth prior to freezing, water that migrated into the frozen zone due to the freezing action and infiltrated meltwater produced by thaw events during the winter. Table 2 lists these quantities. The direct summation of these components to obtain the amount of soil water frozen implies that the upward movement of water occurs as a vapor. That is, the amount of moisture migration was multiplied by the ratio of the internal energy of water vapor at the triple point (2708.7 kJ/kg) to that of liquid water (333.4 kJ/kg). This calculation gives the equivalent amount of liquid water which, on freezing, would release the same amount of energy as that produced by the vapor to solid phase change. The transformed data are plotted as Fig. 6b from which it can be seen the agreement in the relationship between frozen water and the energy index for the two sites is reasonably good; a significant improvement to that shown in Fig. 6a. These results suggest that upward moisture movement occurred principally as a vapor. Similar calculations performed on data from other sites gave results that were less clear insofar as identifying the predominant transfer mechanism. That is, both liquid and vapor transfers were likely to have occurred.

**TABLE 2. DEGREE-DAYS OF FROST AND THE COMPONENTS OF THE TOTAL AMOUNT OF SOIL WATER FROZEN ON DIFFERENT DATES AT SASKATOON AND OUTLOOK, SASKATCHEWAN, WINTER 1980/81.**

<table>
<thead>
<tr>
<th>Location and date, month/day</th>
<th>Degree-days of frost, °C-day</th>
<th>Fall moisture, mm</th>
<th>Migration, mm</th>
<th>Infiltation, mm</th>
<th>Total, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Saskatoon (fallow)</strong></td>
<td>12-21-81 -22.9</td>
<td>24.4</td>
<td>3.0</td>
<td>0</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>12-23-81 -22.9</td>
<td>24.4</td>
<td>0</td>
<td>0</td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>12-28-81 -22.9</td>
<td>24.2</td>
<td>0</td>
<td>0</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>12-30-81 -22.9</td>
<td>24.2</td>
<td>0</td>
<td>0</td>
<td>24.2</td>
</tr>
<tr>
<td><strong>Outlook (irrigated stubble)</strong></td>
<td>12-15-81 -32.3</td>
<td>81.2</td>
<td>36.8</td>
<td>6.8</td>
<td>124.8</td>
</tr>
<tr>
<td></td>
<td>12-16-81 -32.3</td>
<td>81.2</td>
<td>36.8</td>
<td>6.8</td>
<td>124.8</td>
</tr>
<tr>
<td></td>
<td>12-17-81 -32.3</td>
<td>81.2</td>
<td>36.8</td>
<td>6.8</td>
<td>124.8</td>
</tr>
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<td></td>
<td>12-21-81 -32.3</td>
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<td>12-23-81 -32.3</td>
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<td>81.2</td>
<td>36.8</td>
<td>6.8</td>
<td>124.8</td>
</tr>
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</table>

*Note: the change in fall moisture with time results from the increase in depth of soil that is frozen.*
SUMMARY

Field studies of the changes in the moisture regimes of some soils in the Canadian Prairies during winter show significant fluxes of moisture migration to the freezing front in both irrigated and dryland areas. The magnitudes of the fluxes are directly related to the moisture content and are greatest in the lighter-textured, irrigated soils having a water table at a relatively shallow depth. In soils which are dry in the fall the net change in the moisture status due to freezing is negligible.

Overwinter moisture losses from the soil layer 0 - 300 mm are most common whereas gains are most frequent in a 1-m depth. It was found that the overwinter changes in the surface (0 to 300 mm) were independent of the moisture content at freeze-up and the average soil temperature gradient in the zone during the 60-d period following freeze-up. It is shown that in dryland areas moisture changes in a 1-m depth due to migration represent, on the average, 50% of the total seasonal change (snowmelt infiltration plus overwinter change).

Further research is needed into the effects of the overwinter moisture changes on crop production, fall irrigation practices, and soil moisture models as well as their potential for causing salinity problems. The need for defining the primary mode of transport of migrating water, liquid or vapor, is emphasized.

References