THAW DEPTH MEASUREMENTS IN MARINE SALINE SANDY AND CLAYEY DEPOSITS OF YAMAL PENINSULA, RUSSIA: PROCEDURE AND INTERPRETATION OF RESULTS

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Abstract

Measurements of thaw depth in permafrost areas are possible using several techniques. Insertion of a metal rod is based on the change of mechanical properties at the transition from thawed to frozen ground. Temperature measurements and frost tubes use the phase transition temperature as evidence. Direct observations of a core take into consideration visual ice occurrence and other perceptible features. Measurements with the probe (metal rod) do not account for subsidence of the heaved active layer and underestimate thaw depth, excluding centimeters of winter ice from the reading. Frost tube measurements register subsidence by the lowering of the surface around the tube, and allow correction of thaw depth for the difference.

Maximum thaw depth in the study area during the period of observations was in 1995 when summer temperature was the highest. Vegetation is the main factor determining spatial fluctuations in thaw depth.

Introduction

Measurements of thaw depth are possible using several techniques. Insertion of a steel probe is based on the abrupt change of mechanical properties at the transition from thawed to frozen ground. Temperature measurements and frost tubes use 0°C as evidence of phase transition. Direct observations of core or sections take into consideration visual ice occurrence and other perceptible features. Comparable tests were performed by J.R. Mackay (Mackay, 1977) and showed that a large error can be made when probing fine-grained soils with a high content of unfrozen water. This error can be much larger when probing saline fine-grained soils which have greater unfrozen water contents at lower temperatures.

These methods were used while active layer monitoring within the framework of the CALM project at the research station "Vaskiny Dachi" in the central Yamal Peninsula. Saline clayey deposits are often found in the active layer together with non-saline sandy and silty sediments. Regular thaw depth measurements, chemical tests and temperature measurements have been performed here since 1990. Various environments and lithological types are under study.

Discussion

Thaw depth was monitored at a cross-section stretching over a hill with clayey marine saline deposits, covered by sandy-silt aeolian and slope sediments on the top and upper portions of the slope. The salinity of clay in the active layer may be as high as 1.6% (Leibman and Streletskaia, 1997). Some parts of the slope were subjected to landsliding which removed the sandy-silt deposits to expose saline clay. Measurements started in 1990 at 17 points and proceeded in 1991 with 53 points (site 1). In 1993 a grid 100x100 m with 121 points of measurement was added, and 400 more points were measured from 1995 onwards (site 2).

Table 1. Thaw depth in late August 1996 (cm), measurements by various methods

<table>
<thead>
<tr>
<th>Lithology</th>
<th>clay</th>
<th>clay</th>
<th>clay</th>
<th>silt</th>
<th>clay</th>
<th>sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point #</td>
<td>86</td>
<td>115</td>
<td>99</td>
<td>106</td>
<td>52</td>
<td>13</td>
</tr>
<tr>
<td>Probe depth</td>
<td>96</td>
<td>115</td>
<td>128</td>
<td>115</td>
<td>78</td>
<td>122</td>
</tr>
<tr>
<td>Tube depth</td>
<td>91</td>
<td>115</td>
<td>128</td>
<td>106</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of 0°C</td>
<td>103</td>
<td>103</td>
<td>110</td>
<td>82</td>
<td>113</td>
<td>101</td>
</tr>
<tr>
<td>Max. difference</td>
<td>5</td>
<td>12</td>
<td>25</td>
<td>9</td>
<td>-4</td>
<td>9</td>
</tr>
</tbody>
</table>
In fine-grained soils, mechanical strength changes gradually with decreasing unfrozen water content. When clayey soil is saline, the changes are much less apparent. At the same time, the freezing point is different from zero. Table 1 presents the maximum thaw depth measured by a metal probe in comparison with thermal measurements showing 0°C temperature position.
tion, and frost tube measurements of the fresh water freezing depth at the same time. It shows that in clayey soils, the probe is inserted to the depth 5 to 25 cm greater than that of the 0°C depth (compare, 23 cm in early summer in Mackay, 1977). In sand and silt, the probe insertion can be even less than 0°C depth due to mechanical resistance of the thawed layer. The probe can be inserted into the clay to a depth with ground temperatures of -0.5 to -1.0°C (-0.6 to -0.9°C in Mackay, 1977).

THAW DEPTH MEASUREMENTS IN ICE-RICH ACTIVE LAYER DEPOSITS

Measurements in highly ice-saturated (after winter freezing) active layer with the probe do not account for subsidence of the heaved active layer. A frost tube registers subsidence by lowering of the surface around the tube, and corrects the depth of thaw for the difference. Measurements with a probe and in three frost tubes at the same site were undertaken at the research station "Vaskiny Dachi" (Figure 1). The active layer thawed to depths of 55-85 cm without subsidence. At greater depths, subsidence is as high as 10-14 cm. In tube A (Figure 1A), thaw depth is the lowest, so relative subsidence is the largest. Subsidence in part gives information on the ice content of the active layer developed during the previous winter(s).

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Thaw index, degree*months</th>
<th>Site 1 (profile)</th>
<th>Site 2-121</th>
<th>Site 2-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>6 September</td>
<td>26.3</td>
<td>92.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1991</td>
<td>4 September</td>
<td>23.9</td>
<td>80.4</td>
<td>90.6</td>
<td>-</td>
</tr>
<tr>
<td>1992</td>
<td>24 August</td>
<td>14.9</td>
<td>75.1</td>
<td>81.1</td>
<td>-</td>
</tr>
<tr>
<td>1993</td>
<td>15 August</td>
<td>27.9</td>
<td>82.1</td>
<td>88.5</td>
<td>83.9</td>
</tr>
<tr>
<td>1994</td>
<td>16 August</td>
<td>23.8</td>
<td>84.5</td>
<td>90.6</td>
<td>85.1</td>
</tr>
<tr>
<td>1995</td>
<td>3 September</td>
<td>27.9</td>
<td>86.9</td>
<td>97.9</td>
<td>94.0</td>
</tr>
<tr>
<td>1996</td>
<td>23 August</td>
<td>20.2</td>
<td>91.0</td>
<td>91.5</td>
<td>88.1</td>
</tr>
</tbody>
</table>

TIME SERIES IN THAW-DEPTH MEASUREMENTS

Three series of records were analyzed. Site 1 started in 1990 with 17 points. Site 2 started in 1993 and additional points were added in 1994. Mean values for each year and each site are presented in Table 2. Site 1 records were also analyzed separately for sandy and clayey active layer deposits (Table 3). Site 2 (grid-121) records were analyzed for different vegetation covers (Table 4). Site 1 points are mainly situated on slopes, while those of site 2 (grid-121 and grid-400) occupy the top of the hill and a gentle slope with a mainly sandy active layer. Both sandy top and clayey slope are sometimes bare or have sparse vegetation due to deflation on the tops and slip surfaces of landslides. As a result, site 1 has in general a lower thaw depth compared with site 2, which is evidence of the significant role of vegetation. Still, fluctuations well correlate with the period of thaw and even more with the air temperature during this period (Table 4).

Thaw depths in sandy and clayey active layer shows little difference (Table 3). In this case, the lithological influence is overridden by the effect of vegetation.

While total range of thaw depth at both sites is 60 to 130 cm, average values vary from year to year from 75 to 92 (site 1), and from 84(87) to 94(97) (site 2, both

Table 3. Dynamics of thaw depth (Vaskiny Dachi) and thaw index (Marre-Sale weather station) for 1991-1996

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Sept.</td>
<td>89.7</td>
<td>81.2</td>
<td>88.7</td>
<td>90.5</td>
<td>98.1</td>
<td>92.0</td>
</tr>
<tr>
<td>24 Aug.</td>
<td>80.7</td>
<td>87.8</td>
<td>91</td>
<td>97.2</td>
<td>92.7</td>
<td></td>
</tr>
<tr>
<td>15 Aug.</td>
<td>27.9</td>
<td>14.9</td>
<td>27.9</td>
<td>23.8</td>
<td>27.9</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Table 2. Thaw depth measurements at different sites in 1990-1996 with various number of points (n) taken to calculate mean values, research station "Vaskiny Dachi"
Table 4. Average thaw depth dynamics in 1993-1996 in relation to % vegetation cover (Vaskiny Dachi, site 2, grid-121), correlated with precipitation (Marre-Sale weather station)

<table>
<thead>
<tr>
<th>Vegetation type (%cover)</th>
<th>Moss, cm</th>
<th>1993</th>
<th>1994</th>
<th>1995</th>
<th>1996</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare surface (0%)</td>
<td></td>
<td>104</td>
<td>102</td>
<td>112</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>101</td>
<td>110</td>
<td>110</td>
<td>105</td>
</tr>
<tr>
<td>Sparse shrubs (&lt;15%)</td>
<td>0.5-2</td>
<td>87</td>
<td>85</td>
<td>96</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>2.5-4</td>
<td>81</td>
<td>83</td>
<td>93</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>5-8</td>
<td>73</td>
<td>80</td>
<td>83</td>
<td>78</td>
</tr>
<tr>
<td>Dense willows, up to 20cm high (up to 60%)</td>
<td>0.5-2</td>
<td>79</td>
<td>80</td>
<td>90</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>2.5-4</td>
<td>79</td>
<td>83</td>
<td>92</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>5-8</td>
<td>83</td>
<td>83</td>
<td>93</td>
<td>88</td>
</tr>
<tr>
<td>Dense willows, up to 90cm high (up to 80%)</td>
<td>0.5-2</td>
<td>77</td>
<td>79</td>
<td>90</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>2.5-4</td>
<td>77</td>
<td>79</td>
<td>90</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>5-8</td>
<td>82</td>
<td>84</td>
<td>91</td>
<td>89</td>
</tr>
<tr>
<td>Annual/summer precipitation, mm</td>
<td>459/95</td>
<td>353/118</td>
<td>425/115</td>
<td>279/93</td>
<td></td>
</tr>
</tbody>
</table>

grids), giving an amplitude of 17 cm in 6-7 years, or 10 cm in 3-4 years. The highest average thaw depth was measured in 1995. This year was not only warm but also had high summer precipitation. In 1993, when it was similarly warm and wet, the last readings were taken on August 15, while in 1995 they were obtained on September 3. Average thaw deepening during the period August 19 to September 3 in 1995 was 6.8 cm which would not cover the difference in averages of 1993 and 1995 (10.1 cm, Table 2).

Table 4 shows the spatial variations of thaw depth in relation to vegetation. The bare surface (with shrub cover less than 15\% and no vegetation mat) shows the closest correlation with air temperature. In dense shrubs (up to 60\% cover by willows), the average thaw depth is almost 20 cm less than beneath the bare surface (Table 4). Moss thickness ranges from 0 to 8 cm. This causes active layer thickness variability of 17 to 28 cm in sparse shrubs, but only up to 5 cm in dense shrubs (Table 4). Most likely this difference is due to the reduction of incoming radiation reaching the ground surface because of snow and shading by the shrubs. At the same time, the bare surface shows the highest thaw depth compared with areas covered with moss. This is probably due to more intensive water infiltration, which is not impeded by the moss. Areas with sparse shrubs (not more than 15\% cover by willows) show lower thaw depths than those with dense willows (up to 10 cm difference in thaw depth, Table 4). Probably in this case, snow has less of an insulating effect and at the same time intercepts water infiltration. This is also indicated by high thaw depths in the cool summer of 1994 beneath willows with thick moss, since this year had the highest annual precipitation (though low summer precipitation). The difference is due to snow. So the various climate parameters and other forcing factors determining the spatial and temporal distribution of thaw depths are: summer air temperature, and both summer and winter precipitation regulated by the density of willows and the thickness of the vegetation mat.

Conclusions

1. Measurements of thaw depth by probe in sandy deposits may cause an error of 2 to 4 cm due to the resistance of the soil. In saline clayey deposits, errors may be as high as 5 to 25 cm due to low strength at temperatures above -1°C.

2. In ice-rich deposits, probe measurements of thaw depth may give an error of 10 to 14 cm due to subsidence. Frost tube measurements used together with probe measurements may assist in determining the subsidence and give additional information on the ice content in the active layer.

3. In 1990-1996 average thaw depth varied through a smaller range (16\%) than summer air temperature (47\%). Vegetation is responsible for overriding the lithological variability and air temperature fluctuations.

4. The active layer response to climate fluctuations is more affected by vegetation type than lithology. The most significant climatic factors are summer temperature and both summer and winter precipitation, regulated by vegetation cover.
Acknowledgments

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