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Thaw Settlement Hazard of Permafrost Related to Climate Warming in Alaska

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ABSTRACT. Permafrost temperatures have increased in Alaska since the 1960s, and many impacts of climate warming are associated with permafrost thaw. Thaw of permafrost caused by increases in permafrost temperature may result in thaw settlement and significant damage to infrastructure. The goal of this research is to identify regions of Alaska at risk from thaw subsidence related to climate warming and to determine the relative risk of those regions. We developed a Permafrost Settlement Hazard Index (PSHI) by analyzing anticipated climate warming and the ecological characteristics that regulate thaw subsidence. This analysis provides statistical verification that the discontinuous permafrost region is at more risk of thaw settlement than other regions of Alaska. In addition, it estimates future thaw subsidence risk in Alaska in 2050 using future temperature increases projected by published climate models. Results indicate increased thaw subsidence risk in northern Alaska in 2050, with the greatest increase expected in parts of northwest Alaska. However, in the interior and southwest Alaska, projected disappearance of permafrost from the surface will reduce the risk of thaw subsidence.

Key words: Permafrost Settlement Hazard Index, permafrost, thaw subsidence, thaw settlement, thaw settlement risk in Alaska, climate warming

RÉSUMÉ. Depuis les années 1960, les températures du pergélisol de l’Alaska ont augmenté, et de nombreuses incidences du réchauffement climatique sont liées au dégel du pergélisol. Le dégel du pergélisol découlant de l’augmentation des températures du pergélisol donne lieu au tassement dû au dégel et à d’importants dommages à l’infrastructure. L’objectif de cette recherche consiste à cerner les régions de l’Alaska qui sont à risque d’affaissement attribuable au dégel résultant du réchauffement climatique, ainsi qu’à déterminer le risque relatif qui existe dans ces régions. Nous avons mis au point un indice du danger de tassement du pergélisol (PSHI) en nous appuyant sur l’analyse du réchauffement climatique prévu et sur les caractéristiques écologiques qui régularisent les affaissements résultant du dégel. Cette analyse a permis d’obtenir la vérification statistique selon laquelle les zones à pergélisol discontinu sont plus à risque de subir du tassement dû au dégel que les autres régions de l’Alaska. Par ailleurs, l’analyse permet d’estimer les risques futurs de tassement dû au dégel en Alaska en 2050 en s’appuyant sur les augmentations de température projetées par les modèles climatiques publiés. Les résultats indiquent que le risque d’affaissement attribuable au dégel sera accru dans le nord de l’Alaska en 2050, et que l’augmentation la plus grande devrait se produire dans le nord-ouest de l’Alaska. Cependant, dans l’intérieur et le sud-ouest de l’Alaska, la disparition projetée du pergélisol de la surface réduira le risque d’affaissement attribuable au dégel.

Mots clés : indice du danger de tassement du pergélisol, pergélisol, affaissement attribuable au dégel, tassement dû au dégel, risque de tassement dû au dégel en Alaska, réchauffement climatique

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INTRODUCTION

Average annual temperatures in Alaska have increased by 1.7˚C since 1949 (Alaska Climate Research Center, 2012), and climate models indicate continued rapid warming in northern latitudes (Nelson et al., 2001, 2002; Dey, 2003; U.S. Arctic Research Commission Permafrost Task Force, 2003; ACIA, 2004, 2005). Many consequences of climate warming in the high northern latitudes are associated with permafrost (Nelson et al., 2002). Permafrost is defined as subsurface earth materials that remain at or below 0˚C for two or more consecutive years (Brown and Péwé, 1973; Washburn, 1980; Schuur et al., 2008). Climate warming affects the temperature of the frozen ground, the depth of seasonal thawing (Romanovsky and Osterkamp, 2001; ACIA, 2004; Osterkamp, 2007), and the patterns of formation and stability of permafrost (Shur and Jorgenson, 2007). Permafrost temperatures in many Arctic regions have increased during the past few decades (Romanovsky and Osterkamp, 2001; ACIA, 2004), and mean annual ground surface temperatures along a north–south transect in Alaska have increased by 2.5˚C since the 1960s (Osterkamp

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and Romanovsky, 1999; Romanovsky and Osterkamp, 2000; Osterkamp, 2005). The effects of warming permafrost can disrupt human infrastructure such as roads, bridges, and buildings (Nelson et al., 2001; Romanovsky and Osterkamp, 2001; U.S. Arctic Research Commission Permafrost Task Force, 2003; ACIA, 2005). Permafrost thaw in coastal regions and along riverbanks can exacerbate existing risk to infrastructure from erosion.

Permafrost does not respond directly to air temperature change because of its thermal interaction with ecosystem characteristics such as topography, surface water, groundwater, soil properties, vegetation, and snow (Smith and Riseborough, 1996; Jorgenson et al., 2010). Rather, ecosystem characteristics regulate permafrost temperature and the depth of seasonal thaw (ACIA, 2005; Jorgenson et al., 2010). Therefore, disturbances of vegetation and soil by human activity or wildfire contribute to permafrost degradation (Shur and Jorgenson, 2007; Myers-Smith et al., 2008; Jorgenson et al., 2010). Heat from groundwater may advance permafrost degradation (Jorgenson et al., 2001), and removal of the insulative surface snow by wind also affects permafrost degradation (Zhang et al., 1997).

Nelson et al. (2001) provide a geographic overview of the hazard potential associated with permafrost thaw in the Arctic and project that much of the existing infrastructure in potential high-hazard areas could be affected by thaw subsidence under the conditions of climate warming. They calculated a settlement index by multiplying the relative increase of active-layer thickness by the volumetric proportion of near-surface soil containing ground ice. However, Nelson et al. (2001) did not consider other ecosystem characteristics that influence permafrost thaw. Further, because their study surveyed the entire Northern Hemisphere, its results did not provide detailed information about the permafrost hazard in a specific area. A few years later, Smith and Burgess (2004) examined the sensitivity of permafrost to climate warming in Canada. The research presented here specifically examines thaw settlement hazard of permafrost in Alaska, concentrating on the factors that affect thaw settlement (such as ground ice, snow, and soil), creating a Permafrost Settlement Hazard Index (PSHI) for Alaska, and identifying areas at risk from thaw settlement. Results can be useful to local and state level planners in assessing climate risk in specific locations and in planning future infrastructure projects statewide.

The permafrost regions of Alaska occupy 85% of the state's area. Of that area, 33% is underlain by continuous permafrost, 39% by discontinuous permafrost, 12% by sporadic permafrost, and 1% by isolated permafrost (Brown et al., 2002). Some studies indicate that continuous permafrost and discontinuous permafrost respond differently to climate warming (Nelson et al., 2001; Romanovsky and Osterkamp, 2001; ACIA, 2005). It has been suggested that the reaction to temperature increases may be more crucial in discontinuous permafrost regions where the temperature is only a few degrees below the freezing point (Jorgenson et al., 2001; Nelson et al., 2002; ACIA, 2005). We use a method to test the hypothesis that the discontinuous permafrost region of Alaska is more at risk of thaw subsidence than the continuous permafrost region.

METHODS

Permafrost Settlement Hazard Index (PSHI)

The PSHI is based on the concept of the Sensitivity Index for Global Sea-Level Rise on Canadian Coasts developed by Shaw et al. (1998), which measures seven physical variables related to sea-level rise and identifies those regions in which the effects of sea-level rise are greatest (Shaw et al., 1998). Adapting the Sensitivity Index method to Alaska and the parameters of our research, we identified six ecosystem characteristics as variables that affect thaw subsidence in Alaska. We calculated the PSHI by combining the risk values of each variable through Geographic Information System (GIS) spatial analysis techniques, including overlay analysis.

Each variable was classified (e.g., ground ice was classified as high, moderate, variable, low, and unfrozen), and values within a chosen range of each variable were assigned a risk level from 1 to 5 (low to high). The assigned risk values were then combined with weights calculated using the Analytic Hierarchy Process (AHP: Saaty, 2008).

Variables

Numerous ecosystem characteristics contribute to permafrost formation and degradation and regulate permafrost temperature and thaw depth (Jorgenson et al., 2001, 2010; ACIA, 2005). Jorgenson et al. (2008) developed a permafrost map of Alaska showing surficial geology, mean annual air temperature, soil texture, permafrost extent, ground ice volume, and primary thermokarst landforms. They created it by setting aside the multicollinearity of each variable and focusing on the function of each element within nature. Because of limited data availability in Alaska, we considered the following six characteristics as variables: ground ice volume, air temperature, soil texture, snow depth, vegetation, and organic content of soil. These six ecosystem characteristics and their functions within nature are all related to each other, as were the elements that Jorgenson et al. (2008) considered for their permafrost map. However, we focus more, as they did, on the degree to which each of the six factors contributes separately to permafrost degradation. We used Jorgenson et al. (2008) maps for ground ice content, soil texture, snow depth, and organic layer. In addition, we used a vegetation map (Fleming, 1997) and temperature map (SNAP, 2010) to create the PSHI map in GIS.

The melting of ground ice affects the strength of frozen soils and results in loss of permafrost stability (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). The ground ice content in the area also has a strong influence on the climate-induced changes in permafrost (Nelson et al., 2002). Where permafrost contains massive ground ice or is ice-rich, extensive thaw settlement is possible (Romanovsky and Osterkamp, 2001; Smith and Burgess, 2004; Doré et al., 2006). The thawing of ice-rich soils causes subsidence, creating depressions in the ground surface (Romanovsky and Osterkamp, 2001; Jorgenson et al., 2010). Jorgenson et al. (2008) classify ground ice content as high, moderate, variable, low, or unfrozen. Because of the potential effect of temperature increase on ground ice content, we assigned a higher (larger) value to areas with a high volume of ground ice than to those with unfrozen ground.

Air temperature is another indicator of permafrost and is a reliable tool for estimating ground temperature (Smith and Burgess, 2004). Permafrost areas where ground temperatures are warmer than −2˚C have a high potential for thawing (Smith and Burgess, 2004). Williams (1995) states that permafrost starts to thaw from the surface, and that all permafrost will disappear when the mean annual temperature of ground surface rises above 0˚C. Smith and Riseborough (2002) explain that a value higher than −2.0˚C for mean annual air temperature (MAAT), which is the air temperature measured at standard height above seasonal snow cover, represents the threshold for the disappearance of permafrost in mineral soils.

Historical temperature records are sparse in Alaska. To determine air temperature, we used spatially explicit, downscaled CRU TS 3.1 historical temperature data provided by the Scenarios Network for Alaska & Arctic Planning (SNAP, 2010). The data were downscaled via the delta method, using Parameter-Elevation Regressions on Independent Slopes Model (PRISM) 1961 – 90 2 km resolution climate normals as baseline climate. It was necessary to determine a reasonable MAAT threshold at which permafrost becomes vulnerable to temperature change. However, Williams (1995) and Smith and Burgess (2004) base their estimates on ground surface temperature, whereas Smith and Riseborough (2002) base theirs on air temperature. In addition, each estimate is based on a different time standard, and only Smith and Riseborough (2002) clarify the time standard used (mean average). Therefore, it was challenging to set a single MAAT threshold. We initially selected a temperature threshold range of −4˚C to 0˚C based on a MAAT of −2˚C, the critical MAAT from Smith and Riseborough (2002), with a variation of −2˚C and +2˚C in order to account for the temperatures discussed by Williams (1995) and Smith and Burgess (2004). However, since a MAAT of 0˚C, which is the number obtained by adding +2˚C from the base number (−2˚C), is already a warm temperature, we concluded that it may not be the threshold temperature. Thus, a variation of −1˚C was given to 0˚C to come to a conclusive range of −4˚C to −1˚C. On a scale of risk values from 1 to 5, we assigned the highest value (5) to the threshold MAAT range (−4˚C to −1˚C). Assigned risk values decreased as MAAT increased above (or decreased below) the threshold range (see Fig. 1). The risk value declines symmetrically because at MAATs below the threshold range, permafrost is stably frozen, and at MAATs above the threshold range, permafrost is rare.

Soil texture affects soil moisture and thermal properties (Shur and Jorgenson, 2007; Jorgenson et al., 2010); for example, gravelly soils tend to be well drained, while fine soils tend to be poorly drained. Soil texture also strongly affects distribution of ground ice. Fine-grained materials (such as silts and clayey silts or peat) are generally ice-rich and therefore are more prone to thaw settlement (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). Since we also examined organic soil independently as one of the variables, focusing on its thermal conductivity, the risk value of soil texture was assigned according to the likelihood of ground ice. We assigned risk values from 1 to 5 corresponding to the delineation of the geological features and soil texture, as outlined in Jorgenson et al. (2008). Therefore, soil with silty composition or fine-grained material was given a higher risk value than soil of gravelly composition.

Snow has low thermal conductivity and is a strong, effective insulator that limits the heat transfer between atmosphere and ground (Romanovsky and Osterkamp, 2001; Smith and Burgess, 2004; Camill, 2005; Zhang, 2005). In addition, snow has high albedo and emissivity that cool the surface. However, snow has a high degree of absorptivity and takes in more energy, resulting in a warming of the snow-covered surface (Zhang, 2005). The overall impact of snow depth depends on the duration, accumulation, and melting processes of seasonal snow cover (Smith and Burgess, 2004; Zhang, 2005). Thus, it is a challenge to attempt to quantify the effect of snow on permafrost. Nevertheless, many studies point out that increased snow cover may result in a significant increase in permafrost temperature. Osterkamp et al. (2009) and Jorgenson et al. (2001) show that the increase of snow cover in Alaska has contributed to permafrost degradation.

We used a mean snow depth calculation from Jorgenson et al. (2008) that measured snow depth from October to April. Since their data incorporated ground properties, vegetation cover, and their effect on heat turnovers through the snow, there may be information overlap with other variables in our study, especially regarding geological features. However, we used these data because there was no alternative source material for snow depth in Alaska. The effect of snow on soil temperatures is nonlinear, but current knowledge of how snow depth affects ground temperature is incomplete (Jorgenson et al., 2001). Therefore, we broadly grouped snow depths in numerical ranges and provided relative risk values. Areas with thick snow cover were given a higher risk value than those with little snow cover because the increase in snow cover contributes to permafrost degradation (Jorgenson et al., 2001; Osterkamp et al., 2009).

Vegetation has an important effect on permafrost by insulating it and making it resilient to increased air temperatures (Jorgenson et al., 2010). Vegetation also regulates soil temperature by dampening the impact of air temperature changes on permafrost (Shur and Jorgenson, 2007). Jorgenson et al. (2001), through their study of the Tanana Flats in central Alaska, determined the relationships

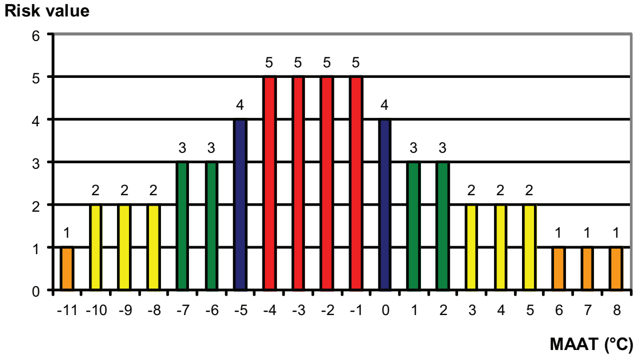

FIG. 1. Risk values assigned to a range of mean annual air temperatures (MAATs). Risk values range from 1 to 5 (lowest to highest risk) and are color-coded: 1: orange, 2: yellow, 3: green, 4: blue, 5: Red. Risk is highest in the threshold MAAT range (−4˚C to −1˚C) and decreases above and below that range.

between permafrost degradation and vegetation types. We assigned risk values to specific vegetation types on the basis of results from that study and Jorgenson et al. (2010). We assigned high-risk values to barren land or tundra and low risk values to tall forest areas.

The organic layer of the soil plays an important role in regulating permafrost temperature (ACIA, 2005; Jorgenson et al., 2010). This layer tends to be poorly drained and to have higher thermal conductivity in winter than in summer. This difference results in rapid heat loss in winter and slower heat penetration in summer, and it accounts for the thermal offset between the ground surface and the permafrost table (Romanovsky and Osterkamp, 1995). On the other hand, organic and fine-grained materials generally contain a high volume of ground ice, which causes permafrost to thaw and eventually destabilizes the construction foundations built above the permafrost (Smith and Burgess, 2004). Since we considered ground ice volume and soil texture as separate variables in this study, we focused only on the thermal conductivity and offset properties of organic soil. Organic soil is often termed "peat," "bog," "fen," "moor," and "muskeg" (Gore, 1983; Galloway et al., 1999). Low risk values were assigned to soil with organic material, and high-risk values were given to soil containing no organic material.

Weighted Index

The permafrost instability caused by climate warming depends on complex interactions among ecological components (Jorgenson et al., 2001, 2010). However, the relative contribution of each ecological factor to permafrost degradation is still not well understood. Therefore, in this study, we estimated weights for the PSHI through the analytic hierarchy process (AHP) of Saaty (2008). The AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities (Dey, 2003). For example, the researcher breaks down the problem into separate elements or variables, ranks these variables in order of relative importance, and uses pair-wise comparisons to derive a numerical importance value for each variable (Pineda-Henson et al., 2002).

First, we ranked the variables in order of importance for the comparative judgment. The amount of thaw subsidence expected depends on ice content (Nelson et al., 2001; Doré et al., 2006). We considered ground ice to be the most significant factor in thaw subsidence because ground ice is a precondition of thaw subsidence (Kääb and Haeberli, 2001). Extensive thaw settlement may be expected where permafrost contains massive ground ice or is ice-rich (Romanovsky and Osterkamp, 2001; Smith and Burgess, 2004; Doré et al., 2006). Next, as most permafrost studies mention temperature as the main factor in determining the occurrence, degradation, and characteristics of permafrost (Osterkamp and Romanovsky, 1999; Andersland and Ladanyi, 2004; Smith and Burgess, 2004), we ranked temperature as the second most important variable in thaw subsidence. Though the effect of snow cover has usually been cited as the principal cause of permafrost temperature increase (Osterkamp and Romanovsky, 1999; Smith and Riseborough, 2002; Osterkamp, 2005; Osterkamp et al., 2009), in this study, we accorded greater importance to soil texture because of its influence on ice volume (Andersland and Ladanyi, 2004; Smith and Burgess, 2004). In some surface temperature models (e.g., Camill, 2005), organic soil condition follows snow cover and vegetation in importance, and we adopted Camill's findings when ranking these variables. In our final ranking, we judged ice volume to be the most important variable, followed by temperature, soil texture, snow cover, vegetation, and organic soil.

We then calculated weights for each PSHI variable with the AHP process, following (Saaty, 2008). The AHP process pairs each variable with each of the others (6 variables make 15 pairs). It compares the two variables in each pair and judges which is most important. The two variables can be judged equally important (1), or one variable can be judged moderately (3), strongly (5), very strongly (7), or extremely (9) more important than the other. These judgments were translated into numerical values on a scale of 1 to 9 as shown in Table 1. Table 2 shows the combination of pairs of all six variables and our judgment of how variables rank in importance. On the basis of this ranking and the scale of relative importance for pairwise comparisons (Table 1), we assigned the intensity of importance for each pair from 3 to 9. We transferred these numbers (the relative importance of each pair) to a matrix, using a method unique to AHP. The matrix lists variables in the same order from left to right in the columns and from top to bottom in the rows. We displayed the relative importance of each pair and the reciprocal of that number (e.g., the importance value of each variable is listed in row 1 and its reciprocal in column 1, and this procedure continues for row 2 and column 2, etc.). In the matrix, we computed the sum of each column and then divided each number in the column by the computed sum to normalize the weights. Then, by averaging the values of each row of normalized weights, we obtained weights for each PSHI variable (Ground ice: 0.44,

TABLE 1. Adapted from Table 1 of Saaty (2008:257). Saaty's table illustrates the method in the context of comparing activities, while we are comparing variables. Saaty's scale has nine steps. We have retained his original numbers for importance values, but the four intermediate categories (numbered 2, 4, 6, and 8) are not shown here.

Intensity of importance	Definition	Explanation
1	Equal importance	Two variables contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one variable over another
5	Strong importance	Experience and judgment strongly favor one variable over another
7	Very strong or demonstrated importance	A variable is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one variable over another is of the highest possible order of affirmation

TABLE 2. The combination of pairs of all six variables and judgment of how variables rank in importance. Also shown are the three test cases (T1, T2, and T3) for each pair of variables.

Criteria/ Ecosystem characteristics			Relative importance of pair			
A	B	More important characteristic	Original	T1	T2	T3
Ground ice volume	Temperature	A	3	4	4	3
Ground ice volume	Soil texture	A	5	6	6	5
Ground ice volume	Snow depth	A	7	7	6	6
Ground ice volume	Vegetation	A	8	8	7	7
Ground ice volume	Organic soil	A	9	9	8	8
Temperature	Soil texture	A	4	5	5	4
Temperature	Snow depth	A	5	6	6	5
Temperature	Vegetation	A	7	7	6	6
Temperature	Organic soil	A	9	9	8	8
Soil texture	Snow depth	A	3	4	4	3
Soil texture	Vegetation	A	5	6	6	5
Soil texture	Organic soil	A	7	7	6	6
Snow depth	Vegetation	A	3	4	4	3
Snow depth	Organic soil	A	5	6	6	5
Vegetation	Organic soil	A	3	4	4	3

Temperature: 0.27, Soil texture: 0.14, Snow depth: 0.08, Vegetation: 0.04, Organic soil: 0.03). Therefore, the permafrost hazard value of each pixel of the PSHI map was calculated by weighting the assigned risk values.

Statistical Analysis

We hypothesized that the discontinuous permafrost region of Alaska is more at risk of thaw subsidence than the continuous permafrost region. To test this hypothesis, we used nonparametric statistics, which are appropriate for comparing two or more independent groups when there is no assurance that the observed data follow a normal distribution (Elliott and Woodward, 2010). The Wilcoxon rank-sum test (also called the Mann-Whitney Test) is used to determine whether there are significant differences (values) between two samples; here, we used it to compare two distributions of permafrost hazard settlement values: (1) in continuous permafrost regions and (2) in discontinuous permafrost regions.

RESULTS

PSHI

The PSHI was developed to enable analysis of anticipated thaw subsidence caused by climate warming. Figure 2 maps the results of our PSHI findings. The colors on the map represent rounded numerical PSHI values from 1 (lowest) to 5 (highest). The higher the value is, the greater the risk of thaw subsidence of the permafrost. Dots on the map represent the locations of the Alaskan cities and villages. By overlaying the PSHI map with the locations of cities and villages, we could identify the hazard value for each locale. Also, overlaying the map of permafrost distribution (Brown et al., 2002) with the PSHI map (see Fig. 2) allowed us to plot permafrost distribution and PSHI values for certain areas.

We used this novel technique to test the hypothesis that the discontinuous permafrost region is at greater risk of thaw subsidence than the continuous permafrost region. This hypothesis was confirmed with statistical significance, $\alpha = 0.01$.

Sensitivity of PSHI

To verify our calculated PSHI results, we tested them with different sets of importance ratings for each pair of ecosystem variables. Table 2 indicates three different sets of importance ratings for the sensitivity test (T1, T2, and T3).

From the importance ranks assigned to each variable, we assigned a relative importance to each pair. To produce test cases for comparison, we then randomly changed the original relative importance value of some pairs by adding or subtracting 1. Table 2 shows the three test cases (T1, T2,

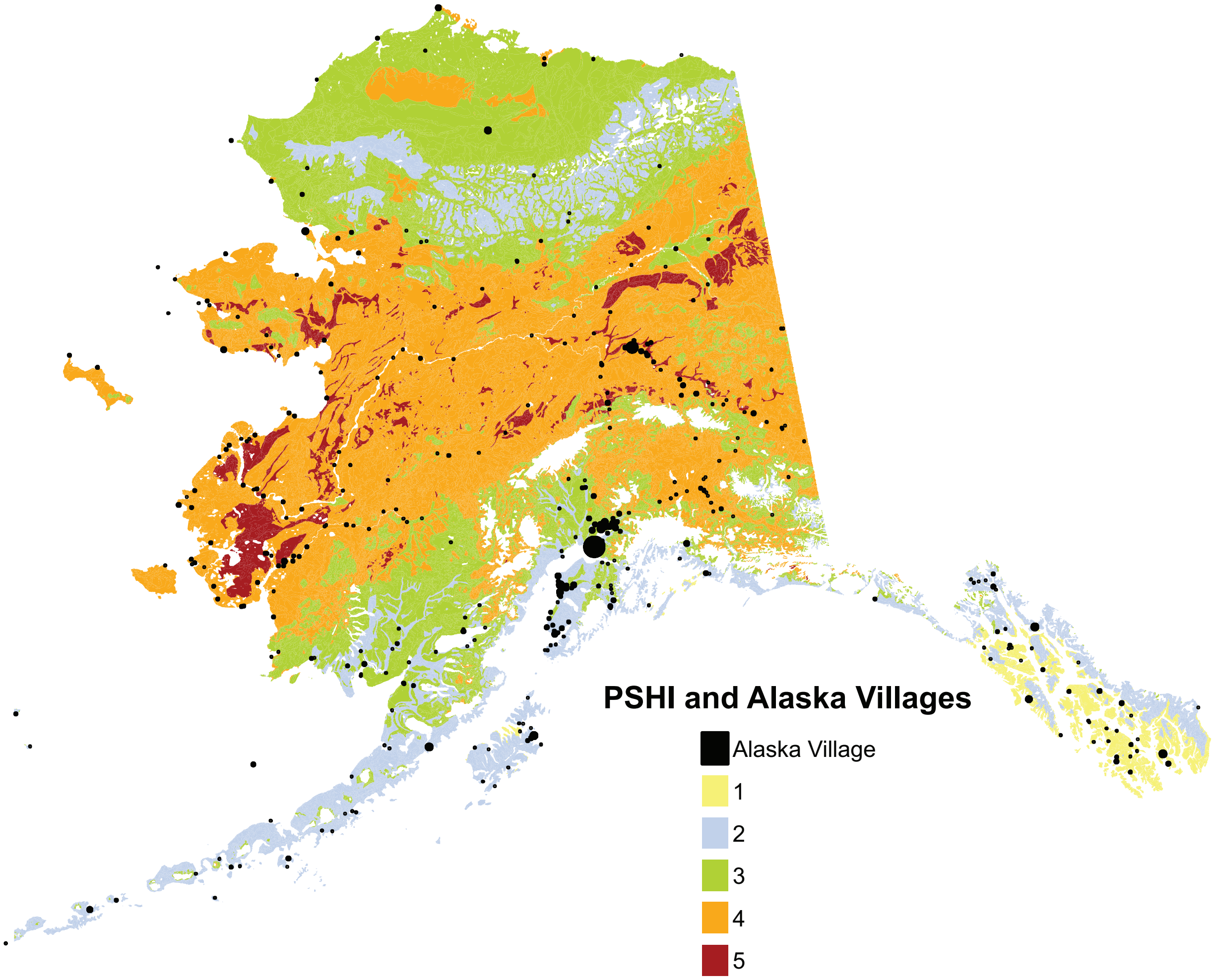

FIG. 2. Permafrost Settlement Hazard Index map.

and T3) for each pair of variables. The relative importance of each pair within each case depends on the others because it is based on importance rank of variables. For example, the value of ground ice–temperature should not exceed that of ground ice–soil texture because soil texture is less important than temperature. These three cases help to confirm our original spatial hypothesis that discontinuous permafrost is more likely to degrade than continuous permafrost.

As shown in Table 3, we calculated three different sets of weights for each test case (T1, T2, and T3) and created three different PSHI maps, one for each case, which permitted us to confirm our initial hypothesis. Nevertheless, the spatial patterns of the PSHI maps were similar; that is, the difference in weights may change exact risk values, but it does not change the spatial pattern of the original PSHI. Statistical analysis of the PSHI map for each of the three test cases revealed that the discontinuous permafrost region is significantly more at risk of thaw subsidence than the continuous permafrost region ($\alpha = 0.01$). This result indicates that a slight change of the original importance of each pair within the same importance rank of variables does not affect the direction of the PSHI.

TABLE 3. Weight calculations for each variable for the three test cases (T1, T2, and T3).

	Weight			
Variable	Original	T1	T2	T3
Ground ice	0.44	0.45	0.43	0.43
Temperature	0.27	0.26	0.26	0.27
Soil texture	0.14	0.14	0.14	0.14
Snow depth	0.08	0.08	0.09	0.09
Vegetation	0.04	0.05	0.05	0.05
Organic soil	0.03	0.02	0.03	0.03

We also tested the PSHI by exchanging the importance rankings of ground ice volume and temperature. Originally we considered ground ice volume to be the most significant factor in thaw subsidence. For this test, however, we ranked temperature first and ground ice volume second, obtaining a slightly different result (Fig. 3). Comparing to the original PSHI (Fig. 2), we note that some areas in northern Alaska originally classified as group 4 were changed to group 3, and some areas on Kodiak Island on the south coast of Alaska, exchanged places in groups 1 and 2. Nevertheless, changing the importance rank does not affect the

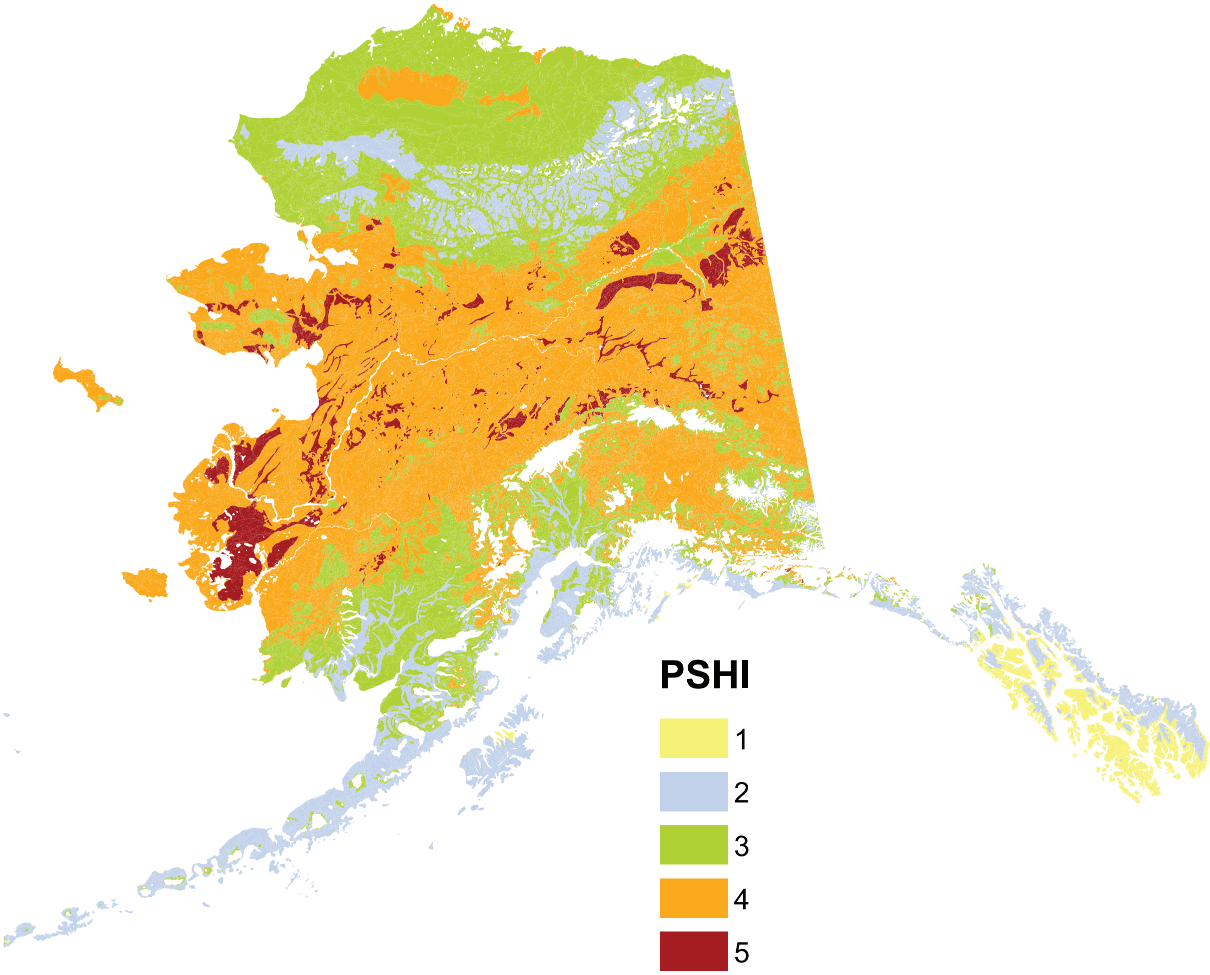

FIG. 3. Permafrost Settlement Hazard Index map with different ranking of ecosystem variables (temperature most important).

direction of PSHI; in particular, there was little change in mid-Alaska, which corresponds to the discontinuous permafrost area in Alaska, and the areas at high risk of thaw subsidence (Group 4 and Group 5) are still concentrated in mid-Alaska.

For this second PSHI test, calculated with temperature as the most important variable, the statistical analysis did not prove the hypothesis that discontinuous permafrost areas have greater risk of thaw subsidence than continuous permafrost areas. These two tests indicate that the PSHI is sensitive to the importance rank of variables, but not to the specific relative importance of each pair. The statistical analysis supports our decision to use the original importance ranking, in which ground ice ranks first in importance. However, temperature can accelerate thaw subsidence where ground ice exists.

Projected Future PSHI

Since permafrost temperatures are projected to continue rising (Markon et al., 2012), we created another PSHI based on future air temperatures projected by the Scenarios Network for Alaska and Arctic Planning (SNAP, 2010). This future PSHI was created with the same variables and the same method used for the current PSHI.

Larsen et al. (2008) assumed that each type of public infrastructure in Alaska has a different useful life period, and that hospitals, government buildings, and similar fixed assets have the longest "useful life" period of 40 years. We adopted this useful life estimate for our model and chose the year 2050, 40 years after 2010. Future temperature projections from SNAP were used. We compared surface temperature, precipitation, and sea level pressure from two sources: observation-based 40 Year Re-analysis data (ERA-40) from the European Centre for Medium-Range Weather Forecasts and global climate model (GCM) output variables. This comparison determined that the five GCMs that perform best across Alaska and the Arctic are ECHAM5, GFLD21, MIROC, HAD, and CCCMA (Walsh et al., 2008). The SNAP projection data were created by taking the mean values of output from these five GCM models. GCM output variables from AIB IPCC (Nakicenovic and Swart, 2000), the former mid-range emissions scenario, were downscaled via the delta method (Hay et al., 2000; Hayhoe, 2010)

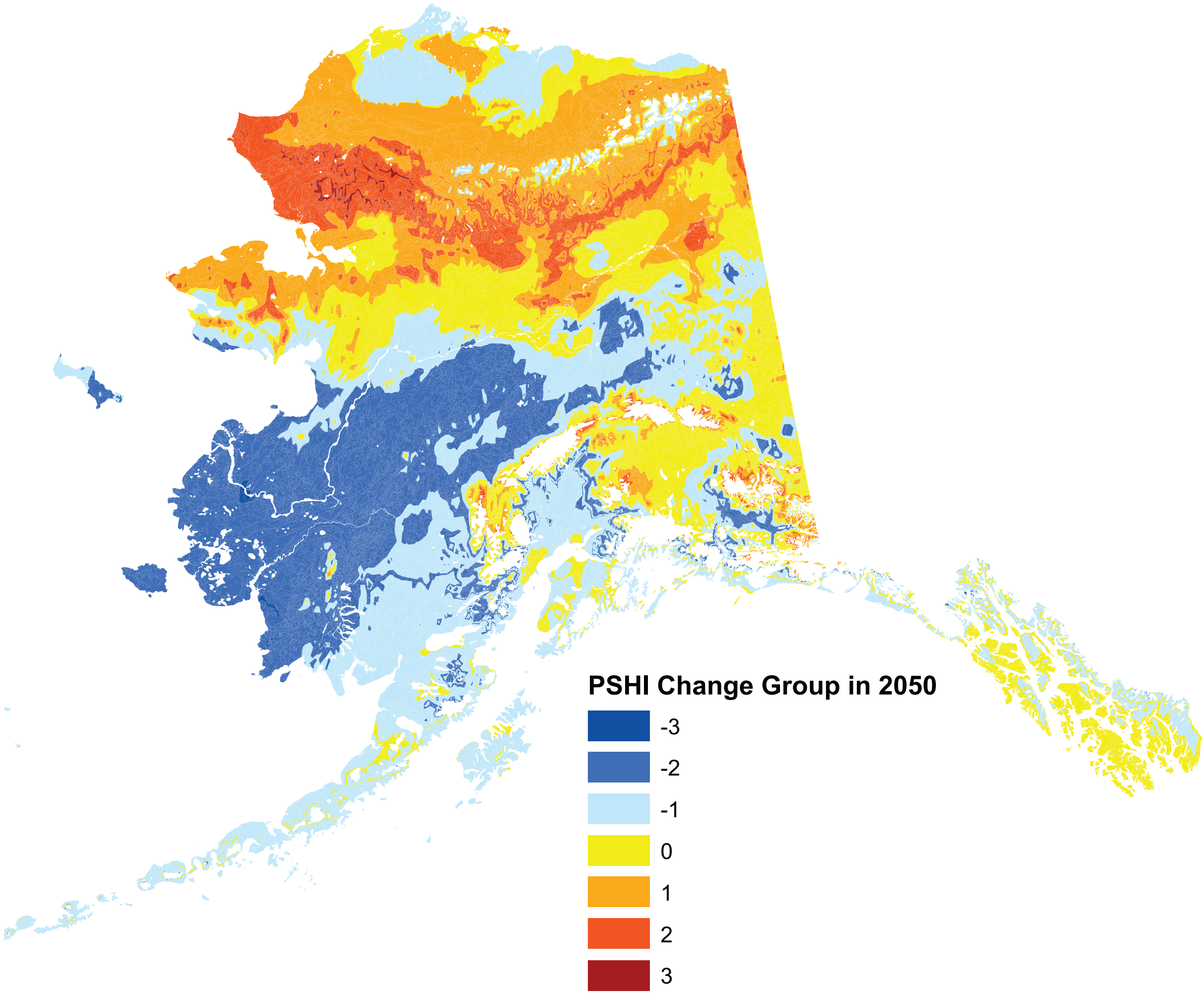

FIG. 4. Projected change in the risk of permafrost settlement from 2010 to 2050.

using the Parameter-Elevation Regressions on Independent Slopes Model (PRISM).

In our model, the projected temperature for the year 2050 was treated as an independent variable, assuming that other factors would remain the same. The SNAP data deal with uncertainty by averaging across all five models. Nevertheless, SNAP data had many sources of inherent uncertainty, such as simplified real world interaction, incomplete input data, and unpredictable variables (SNAP, 2012).

Figure 4 shows the projected future changes in PSHI between 2010 and 2050 based on the SNAP projections described above. During this 40-year period, three types of changes are projected: PSHI increase (a positive value, red), no change (yellow), and PSHI decrease (negative value, blue). The darkest red color indicates a larger PSHI increase, whereas the darkest blue color represents a larger PSHI decrease.

DISCUSSION

A novel technique was used to confirm that the discontinuous permafrost region of Alaska is more at risk of thaw subsidence than the continuous permafrost region. This result was demonstrated when ground ice was ranked of first importance in estimating weights for the AHP, but not when temperature was ranked first. Nevertheless, both cases show that the areas at high risk of thaw subsidence are concentrated in mid-Alaska, which corresponds to the discontinuous permafrost area. Also they illustrate that mid-Alaska and northern Alaska are at risk of thaw subsidence regardless of which variable was ranked first when estimating weights.

As an estimate of future thaw subsidence, this research includes uncertainties. The greatest uncertainty lies in the climate model itself. In practice, the future PSHI in Alaska in 2050 was created using the SNAP temperature projections based on the A1B IPCC scenario (Nakicenovic and Swart, 2000), the midrange emission scenario. However, the actual emissions trajectory since 2000 has been close to the highest-emission scenario, A1FI (Raupach et al., 2007). Therefore, the calculated PSHI may also underestimate the impact of climate-induced thaw settlement on infrastructure. Using additional IPCC scenarios to estimate future thaw subsidence could help to reduce the uncertainty associated with the climate model.

Regarding the future risk of thaw settlement, our model shows considerable variation within Alaska. The model indicates that the greatest increase in permafrost hazard risk between now and 2050 will occur in northwest Alaska, with isolated patches of higher risk throughout the Brooks Range, the Seward Peninsula, and the interior. The greatest decrease in risk will occur in southwest Alaska, the St. Lawrence and Nunivak Islands, and throughout much of the interior and northern foothills of the Alaska Range. Markon et al. (2012) project future surface ground temperature (1 m depth) in these regions to be at or very near to thaw conditions. This projection corresponds to the highest current PSHI values in these regions (Fig. 2), suggesting a scenario in which surface thaw occurs during the next 40 years, but conditions stabilize after that period. The projected PSHI decrease throughout parts of the North Slope corresponds to a projected temperature increase in that region during the same period. The temperature, which was either around or below the threshold range (the temperature threshold range of −4.0˚C to −1.0˚C, see Fig. 1) in 2010, is projected to be above the threshold range in 2050, and this would result in a lower risk value for temperature.

The projected PSHI is the static thaw settlement hazard model based on 2010 conditions, not a dynamic projection of thaw settlement. In this model, because of limited data on these variables, we assumed that ecosystem conditions in 2010, such as snow cover, would remain the same. Although data availability and current information are crucial for analysis, Alaska's data-poor environment limited the scope of this research. For example, the inclusion of groundwater or drainage as variables in PSHI would have strengthened the PSHI result, but those data were not available. Furthermore, the vegetation map available was compiled in 1996, but the pattern and distribution of vegetation may have changed because of external environmental changes such as wildfires, for example, the extreme fires in Interior Alaska in 2004 and 2005, when 4.6 million ha were affected (Kasischke et al., 2012).

CONCLUSION

This research documents current thaw settlement risk and projects future risk of permafrost degradation caused by climate change in Alaska. Permafrost temperatures across the Arctic have increased during the past few decades, and the depth of the active layer is also increasing in many regions (Romanovsky and Osterkamp, 2001; ACIA, 2004). We created a Permafrost Settlement Hazard Index (PSHI) and investigated current thaw settlement hazard in Alaska after examining ecosystem factors that affect thaw subsidence and calculating the weights for relevant factors and variables. Calculated PSHI values confirm that Alaska's discontinuous permafrost region will be more at risk from thaw subsidence than its continuous permafrost region, with greatest current risk in the interior and southwest Alaska. As the climate changes, we can expect that the risk of infrastructure failure by thaw subsidence may increase in many areas of the Arctic. We therefore also forecast thaw settlement risk in Alaska for the year 2050, using projected future temperature increases from published climate models. Our 2050 model indicates that the PSHI values in northwestern Alaska, isolated patches of the Brooks Range, and interior Alaska will be higher as temperatures rise, and the risk of thaw subsidence in these areas will become more serious. Projections of decreased future risk in parts of interior and southwest Alaska, where current risk is highest, suggest a scenario of surface permafrost thaw followed by relative stabilization over the coming four decades.

By overlaying the PSHI map with the locations of cities and villages, we could identify and compare the risk values for various localities. This information will allow state and federal agencies to identify and target particularly vulnerable areas when making funding and assistance decisions for hazard planning and mitigation, as well as when planning future infrastructure construction. This site-specific information on current and future thaw subsidence risk will help planners anticipate potential infrastructure damage and mitigate its effects. This information will also help mitigate economic loss resulting from infrastructure damages by avoiding the areas anticipated to be at risk of thaw subsidence.

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