Assessment of a land cover driven TTOP model for mountain and lowland permafrost using field data, southern Yukon and northern British Columbia, Canada

Alexandre Bevington[1,2] & Antoni G. Lewkowicz[2]

[1]Ministry of Forests, Lands and Natural Resource Operations, Prince George, British Columbia, Canada
[2]Department of Geography, University of Ottawa, Ottawa, Ontario, Canada

ABSTRACT
Air, ground surface and top of permafrost temperatures (TTOP) were measured at 55 sites in three areas of Yukon and northern British Columbia in order to explore relationships between climate-permafrost transfer functions and environmental variables and to assess and validate the TTOP model. The strongest factors controlling climate-permafrost transfer functions are elevation and land cover, though slope, aspect, topographic position and surficial geology were also investigated. In 1000 iterations of the model using randomly-generated equally possible scenarios, 64% of the TTOP model predictions were within ±1°C of measured values, a result that is 6% better than applying a uniform 3°C total offset to the mean annual air temperature. A sensitivity analysis confirmed that the TTOP model is most sensitive to changes in the freezing n-factor, thermal conductivity ratio of the ground, and summer air temperatures.

RÉSUMÉ
Les températures de l'air, de la surface du sol et de la surface du pergélisol (TTOP) ont été mesurées pour 55 sites dans trois secteurs du Yukon et du nord de la Colombie-Britannique afin d'étudier les relations entre les fonctions de transfert climat-pergélisol et certaines variables environnementales avec pour but d'évaluer le modèle TTOP (Smith et Riseborough, 1996, 2002). Les variables environnementales les plus importantes pour les fonctions de transfert climat-pergélisol sont l'élévation et la couverture terrestre, bien que la pente, la direction de la pente, la position topographique et la géologie de surface aient également été étudiées. Lors de 1000 itérations du modèle, en utilisant des scénarios aléatoires tous également possibles, 64 % des prévisions du modèle TTOP étaient à l'intérieur de ±1°C des valeurs mesurées, un résultat qui est 6% mieux que d'ajouter 3°C à la température moyenne annuelle de l'air. Une analyse de sensibilité confirme que le modèle TTOP est plus sensible aux changements du facteur-n de gel, du coefficient de conductivité thermique des sols et de la température de l'air pendant l'été.

1 INTRODUCTION

Nearly all permafrost temperatures being monitored in North America have warmed during the past 20-30 years (Smith et al. 2010) and in the discontinuous permafrost zones, thaw has occurred (e.g. James et al., 2013). The impacts of warming or thawing permafrost include changes in the magnitude and frequency of geohazards such as rockfalls (e.g. Gruber et al., 2004), active layer detachments (e.g. Lewkowicz, 2007) and retrogressive thaw slumps (e.g. Lantuit and Pollard, 2008), infrastructure challenges caused by thaw settlement and deepening active layers (e.g. Nelson et al., 2002), and positive feedback to the global climate system due to greenhouse gases released from thawing organic materials (e.g. Schuur et al. 2015). Predicting where these changes may occur requires high-resolution spatial models of permafrost distribution (e.g. Bonnaventure et al. 2012).

Permafrost zones extend across 100% of the exposed land area of Yukon and 56% of British Columbia [BC], respectively (Figure 1). The areal percentage of permafrost in these zones varies spatially from >90% (continuous) to <10% (isolated patches) with the distribution primarily influenced by latitude and elevation (which affect mean annual air temperature) and snowfall (which affects heat loss from the ground in winter as well as the distribution of glaciers at high elevations). Using the upper and lower percentage of permafrost for each permafrost zone (e.g. continuous, isolated patches, etc.), estimates of the total terrestrial area that is underlain by permafrost in these regions are 54-86% of Yukon and 2-15% of BC. Considerable uncertainty exists in these estimates, however, and they are not very useful for local decision-making.

High-resolution permafrost distribution models developed using basal temperature of snow (BTS) measurements and models for the southern half of Yukon and northern BC are empirical-statistical in nature and estimate that overall 58% of the area is underlain by permafrost (Bonnaventure et al. 2012). These can be used to predict future permafrost distribution but only under equilibrium scenarios (e.g. Bonnaventure and Lewkowicz 2013).

The temperature at the top of permafrost (TTOP) model is a physically-based model that predicts the temperature at the bottom of the active layer under equilibrium conditions using air temperature and surface and subsurface site characteristics (Smith and Riseborough 1996, 2002). The TTOP model has been used to assess the impacts of climate change on permafrost (Smith and Riseborough 1996), to map permafrost at a continental scale (Henry and Smith 2001), and to assess the climate limits of permafrost (Smith and

Riseborough 2002). In addition, the TTOP model has been used to map permafrost distribution in Colorado (Janke et al. 2012), Norway (Gisnås et al 2013; Juliussen and Humlum, 2007), Alaska (Kerkering 2008), and the Mackenzie region (Stevens et al. 2010). Despite this widespread use, few studies have rigorously assessed the TTOP model using field data. The objective of this paper is to provide an assessment of the utility of the TTOP model using a large field dataset from southern Yukon and northern BC.

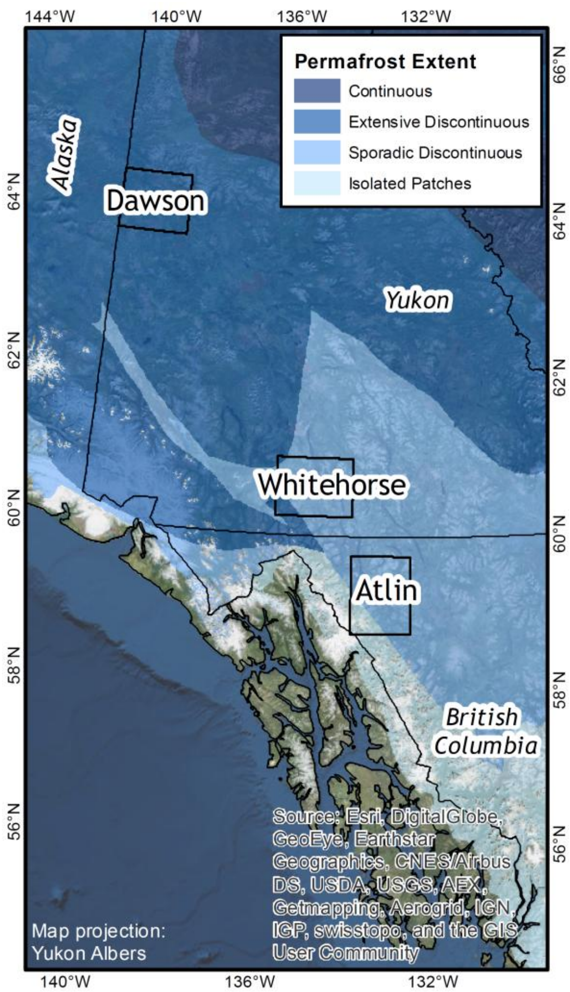

Figure 1. Permafrost zonation in Yukon and British Columbia, Canada (Modified from Brown et al. 1997). The three study areas are outlined by rectangles.

2 STUDY AREAS

Three study areas between 8.1 and 9.5 thousand square kilometers were selected for this study: Atlin in northern British Columbia, and Whitehorse and Dawson in Yukon (Figure 1). The areas are distributed along a southeast to northwest transect extending from roughly 59°N to 64°N and also along a continental gradient, with Atlin being the least continental and Dawson the most. The degree of continentality affects both climatic conditions and permafrost distribution in relation to the physiography in each area. Atlin exhibits permafrost only in the mountains, permafrost in Whitehorse is mostly present in alpine areas but has also been observed at sites below treeline, and in Dawson, permafrost is frequently present in valley bottoms. Mean monthly air temperature Environment Canada (EC) normals from 1981-2010 show that the valleys in the three regions experience similar air temperatures in July with Dawson as the warmest (15.7°C) followed by Whitehorse (14.3°C) and Atlin (13.4°C). January temperatures show a much larger variation with Dawson averaging -26.0°C, while Whitehorse averages -15.2°C and Atlin -12.8°C (Environment Canada, 2015).

Atlin is broadly characterized as having sporadic discontinuous permafrost and isolated patches of permafrost towards the Pacific Ocean in the southwest (Brown et al. 1997). Bonnaventure et al. (2012) predict a similar distribution with BTS modelling with the exception that permafrost can be extensive discontinuous or continuous above treeline (roughly 1300-1400 m a.s.l.). The Atlin area was glaciated at the time of the last glacial maximum (~21 ka) but only a small portion of the study area still has glaciers. There are twelve University of Ottawa climate stations in the Atlin study area. The only EC weather station is at Atlin (59°34' N, 133°42' W, 673.6 m a.s.l.).

The Whitehorse study area is mountainous with large U-shaped valleys and numerous large lakes. This region is broadly characterized as being within the sporadic discontinuous permafrost zone with areas of extensive discontinuous permafrost in the Coast Mountains (Brown et al. 1997). Bonnaventure et al. (2012) predict sporadic discontinuous permafrost throughout the landscape with extensive discontinuous and continuous permafrost occurring above treeline. The entire study area was glaciated at the time of the last glacial maximum (~21 ka) but none of the region remains glaciated at present. There are twenty-eight University of Ottawa climate stations in the Whitehorse study area. Data is also available from the Whitehorse Airport EC weather station (60°42' N, 135°04' W, 706 m a.s.l.).

The Dawson study area is mountainous, ranging in elevation from 251 to 1981 m a.s.l. This area falls within the extensive discontinuous permafrost zone (Brown et al. 1997). Bonnaventure et al. (2012) predict the presence of extensive discontinuous permafrost throughout the landscape including valley bottoms, with patches of sporadic discontinuous permafrost near treeline and continuous permafrost on high peaks above treeline. Only a small portion of the southwest sector and a larger part of the northeast sector of the region were glaciated during early- and mid-Pleistocene glaciations. There are fourteen University of Ottawa climate stations in the Dawson study area. The only EC weather station within the study area is the Dawson Airport station (64°02' N, 139°07' W, 370 m a.s.l.).

3 TTOP MODEL

The top of permafrost delineates the boundary between the active layer and the perennially frozen ground beneath. Although the position of this boundary varies inter-annually (Shur et al. 2005), its temperature can be used to simplify the influence of climate on permafrost. The TTOP model developed by Smith and Riseborough (1996, 2002) is a physically-based equilibrium model that predicts TTOP based on air temperature, a surface offset that links air temperature to ground surface temperature, and a thermal offset that links ground surface temperature to TTOP (Romanovsky and Osterkamp 1995), it can be expressed as:

$$TTOP = [R_K \bullet N_T \bullet TDD_A - N_F \bullet FDD_A]/P \quad [1]$$

where R_K is the ratio of the frozen and thawed thermal conductivities of the active layer materials, N_T is the ratio of thawing degree days in the air (TDD_A) and at the ground surface (TDD_S), N_F is the ratio of freezing degree days in the air (FDD_A) and at the ground surface (FDD_S), and P is the period of one year. A major advantage of the TTOP model is that it bundles complex processes into simple offsets and indices. The concomitant disadvantage is that it may oversimplify complex site parameters and consequently does not, for example, account for the spatial or temporal variability of ground ice and unfrozen moisture. Notwithstanding these drawbacks, given the limited data available in most parts of the Canadian North, the TTOP model is probably the most complex model that can be used at a regional scale. It should be underlined that this is a steady-state model and its predictions apply only when permafrost is in thermal equilibrium with climate.

4 DATA

Hourly data collected from three EC weather stations (Environment Canada, 2014) and 55 University of Ottawa (UO) climate stations between 2008 and 2013 are used in this modelling study (not all stations were operational for the entire period). EC stations measure dry bulb temperatures to 0.1°C. The UO stations are equipped with Onset HOBO Pro data-loggers that record hourly or bi-hourly air, ground surface and ground temperatures with an accuracy of ±0.2°C.

A 30 x 30 m digital elevation model (DEM; Geobase, 2010) and the earth observation for sustainable development of forests (EOSD) land cover classification dataset (Geobase, 2010) were used to investigate the relationships between environmental variables and climate-permafrost transfer functions. Slope and aspect were calculated in ArcGIS 10.1 using the Spatial Analyst extension and a topographic position index (TPI) was calculated using the Land Facet Corridor Designer toolset in ArcGIS 10.1 (Jenness et al., 2013). TPI is an index of the relative position of a DEM pixel compared to the average elevation of a surrounding neighborhood. The size of the neighbourhood influences the size of the features captured, for example a large radius (e.g. 700m) will capture large features such as U-shaped valleys and mountain tops, whereas smaller neighbourhoods will capture gullies and peaks. Land cover classes from the EOSD dataset were reclassified into the following six classes (as was found appropriate by Kremer et al. (2011) with a further division for maritime tundra as was found by Lewkowicz et al. (2012): coniferous/mixed forest, deciduous forest, exposed rock, shrubs, tundra, and maritime tundra.

5 METHODS

5.1 Model Parameters

N_F and N_T principally reflect, respectively, the thermal influences of snow cover and shading by vegetation on seasonal ground surface temperatures, while R_K incorporates the influence of active layer seasonal thermal conductivities on TTOP.

The model parameters were calculated for every complete year at each of the 55 UO climate stations (2008-2013) while the three EC stations are excluded because ground surface and TTOP temperatures are not measured. Topographic attributes (elevation, slope, aspect and TPI) and land cover classes were investigated as possible controls on these parameters. In addition, the parameters were assessed for covariance based on the observed presence or absence of permafrost.

The "Total Offset" (TOFF) is the difference between the measured MAAT and TTOP values (i.e. TTOP-MAAT). This parameter accounts for all surface processes and interactions in a single value. The TOFF was calculated from measured values in order to compare the TTOP model results with a TOFF model. The TOFF model is calculated using the mean TOFF value, and can be expressed as:

$$TTOP = MAAT + TOFF \quad [2]$$

5.2 Model Assessment

The large field dataset permitted a quantitative modelling approach to assess and validate the TTOP model. The model was implemented in R (http://www.r-project.org/) with the Classification and Regression Training (caret) package (http://cran.r-project.org/web/packages/caret/) and compiled all individual station-years that have complete records for FDD_A, TDD_A, N_F, N_T, R_K and TTOP. The data were divided using a random sampling scheme into testing and training datasets. In order to understand the impact of the sample size on the success of the TTOP model, the sampling was done five times to create training datasets of 5%, 25%, 50%, 75% and 95% of the original data, and results were tested against the entire dataset. The entire dataset was used as a test dataset because when training is 95%, the test dataset is very small (only 5%) and the model substantially over performs. The model may also over perform by using the entire dataset as training, although the relative success of different sample sizes remains comparable. All land cover classes are sampled in the iterations.

The training datasets were used to determine the model parameters (N_F, N_T and R_K) for each land cover classification, which were used with the measured values of FDD_A and TDD_A to generate the modelled TTOP values. In order to model a variety of scenarios within the measured limits, seven values (the 1st, 5th, 25th, 50th, 75th, 95th, and 99th percentiles) of the three model parameters (N_F, N_T, R_K) were calculated from the measured values of the training dataset (total of 21). These 21 values were assigned to the testing dataset based on the land cover at the station location. The data (N_F, N_T, and R_K) are normally distributed within each land cover classification (Bevington, 2015) and the percentiles were calculated from the distribution curve. The model was then iterated 1000 times for each random sampling scheme using the measured values of FDD_A and TDD_A for each station year. Seven TTOP scenarios from warm to cold were calculated using randomly generated values within the measured limits.

The sensitivity of the TTOP model was assessed by iterating the model in the same way as previously described, except all measured values were used, except for one of N_F, N_T and R_K, to test each of their sensitivities. In addition, changes in FDD_A and TDD_A were explored by modifying FDD_A and TDD_A by ±100°C-days and ±500°C-days.

6 RESULTS

6.1 Model Parameters

The complexity of influences on ground temperature conditions at a given location is indicated by the variability and distribution of the total offset. The field measurements show TTOP averages 3.0°C warmer than MAAT in the three study regions and that total offsets for individual station-years vary from as little as 0.5°C to as much as 6.5°C (Figure 2).

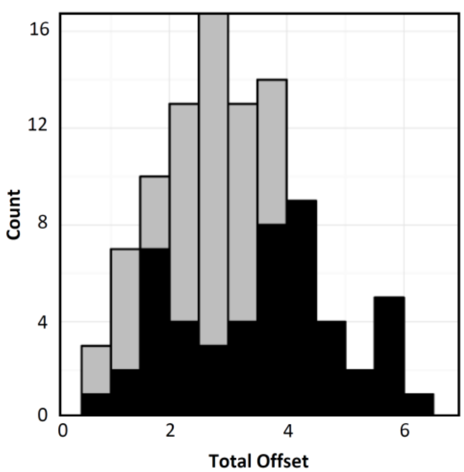

Figure 2. Histogram of the total offset (TTOP-MAAT). The black boxes are sites with seasonally frozen ground and the grey boxes are sites with permafrost.

Topographic attributes were examined as potential controls on the model parameters using linear regression analysis. Elevation, slope, aspect and TPI were calculated for each site using the 30 x 30 m DEM as previously described and measured model parameters are given for all complete station-years. The sample sizes in this section vary depending on the completeness of the data collected.

N_F is significantly (p-value < 0.05) and positively correlated with elevation (r = 0.36; n = 173) showing that N_F increases at mountain sites. N_T and elevation are also significantly (p-value < 0.05) positively correlated (r = 0.65; n = 123) as are R_K and elevation (r = 0.31; n = 124).

Relationships between slope, aspect and the parameters in the TTOP equation were not statistically significant (p-value > 0.05). It should be noted, however, that the steepest slopes monitored are less than 35° and the results might have been different, at least for N_F, if sites which shed snow by avalanche in the winter had been sampled. Polynomial models were attempted for elevation and slope, but there was no significant improvement in the strength of the relationships.

TPI700 (i.e. calculated with a search radius of 700 m) and N_F are significantly (p-value < 0.05) positively correlated (r = 0.2; n = 173) suggesting that higher N_F values tend to be found in more convex terrain. However, individual high N_F values are also present in both flat and concave topography. TPI700 and N_T have a similarly weak but statistically significant positive linear correlation (r = 0.19, n = 123), while the positive relationship with R_K is slightly stronger (r = 0.31; n = 124).

The relationships between N_F and TPI700 shows that N_F is higher in more convex terrain and lower in more concave terrain, presumably because snow is removed from the former and accumulates in the latter. Since only TPI700 (and not TPI200 or TPI50) is significant, broader landscape features apparently influence N_F more than local features. However, it is probable that TPI700 is also capturing land cover associations (i.e. tundra and bare rock) since convex sites tend to be higher elevation sites. Similarly, the relationships between TPI700 and N_T is probably due to the ground surface being less shaded at higher elevations due to changes in vegetation cover, but also a higher level of incoming solar radiation due to greater insolation. The relationship is also statistically significant with TPI search radii of 200 m and 50 m. Overall, R_K is higher in more convex terrain and lower in more concave terrain. This suggests that the thermal conductivity of active layer materials is more similar in summer and winter on convex terrain than in concavities. This could be explained by drier soil and more bedrock being present in convex terrain.

6.1.1 Land Cover

The mean N_F for all land classes is 0.41. The two forested classes, the shrub and the maritime tundra classes have median N_F values below the overall mean and both rock and tundra are above it (Figure 3A). The mean of the N_T value is 0.99. The two forested classes, the shrub and the tundra classes have median values below the overall mean and both rock and maritime tundra are above it (Figure 3B). Relatively low N_F values tend to be associated with relatively low N_T values (compare Figure 3A-B) but maritime tundra has the opposite relationship with relatively low N_F values and high N_T values. The mean R_K value is 0.95. Medians for individual land cover classes are all similar to 0.95, although the range of values in each class varies considerably (Figure 3C).

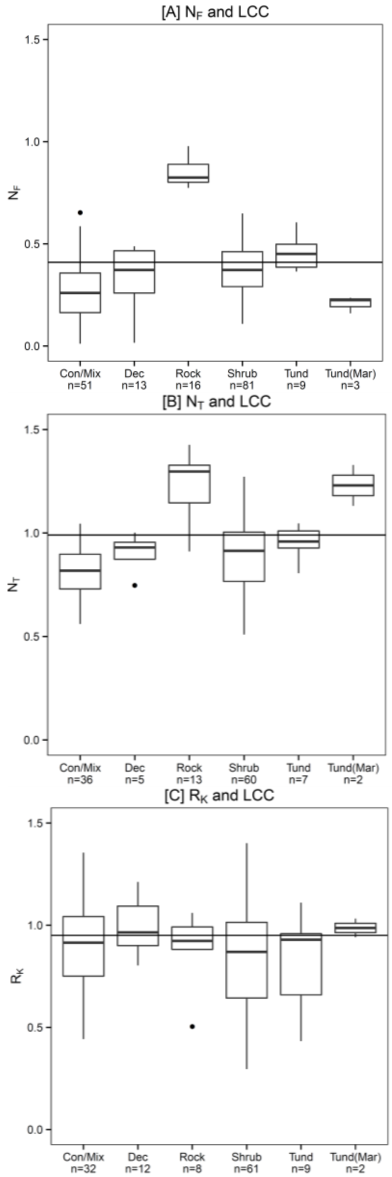

Figure 3. Boxplot distributions of (A) N_F (B) N_T and (C) R_K by land cover classification. The edges of the box represent the 25th and 75th percentiles, the whiskers represent the 5th and 95th percentiles and the black line represents the median. The mean of the medians of all of the classes is represented by a horizontal black line. Outliers are black points outside of these limits. The sample size (n) is given below each category.

6.1.2 Covariance

N_F, N_T and R_K work together to change the magnitude of the surface and thermal offsets. They are usually examined independently (e.g., Henry and Smith 2001; Juliussen and Humlum 2007) and their inter-relationships are not well documented or understood. Figure 4 displays the covariance of the three parameters using the field dataset.

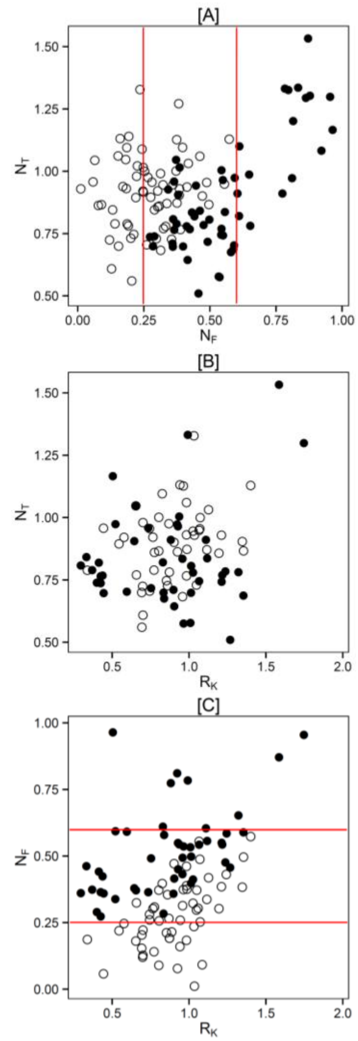

Figure 4. Scatterplots of the relationships among N_F, N_T and R_K. Filled and empty circles represent presence or absence of permafrost, respectively.

In the N_T and N_F scatterplot (Figure 4A), the right side contains only permafrost sites, the left side contains only seasonally frozen sites, and the middle section has a mixture. The graph shows that in the three study regions, permafrost is virtually guaranteed if N_F is >0.6 while if N_F is <0.25 permafrost is absent. In contrast, the presence or absence of permafrost can occur across the full range of N_T values. The mixed zone exists because of differences in R_K, FDD_A and TDD_A and in this part of the graph, permafrost is more common at lower N_T values. Positive correlations exist between N_F and N_T but are significant only for permafrost sites ($r = 0.66$, $n = 75$).

Figure 4B presents the relationship between R_K and N_T. There is a significant but weak positive correlation between the two variables ($r = 0.24$, $n = 173$) and no apparent differentiation between permafrost and non-permafrost sites.

Figure 4C compares N_F to R_K using the threshold values for permafrost and non-permafrost sites for N_F employed in Figure 4A to manually demarcate three zones on the scatterplot. As with N_T, above and below the threshold values, R_K is effectively irrelevant to the presence or absence of permafrost, but in the mixed zone, R_K is significant. It is evident that in this part of the scatterplot, permafrost sites are found primarily at lower R_K values (and hence at sites with larger thermal offsets) while non-permafrost sites are more common at higher R_K values. Statistically significant positive correlations exist between R_K and N_F when divided by frozen ground conditions: $r = 0.55$ for seasonally frozen sites ($n = 63$) and $r = 0.52$ for permafrost sites ($n = 61$). These relationships are most likely due to differences in soil moisture relating to topographic position, with higher R_K values and N_F values on well-drained convexities and concomitantly lower values in poorly drained concavities.

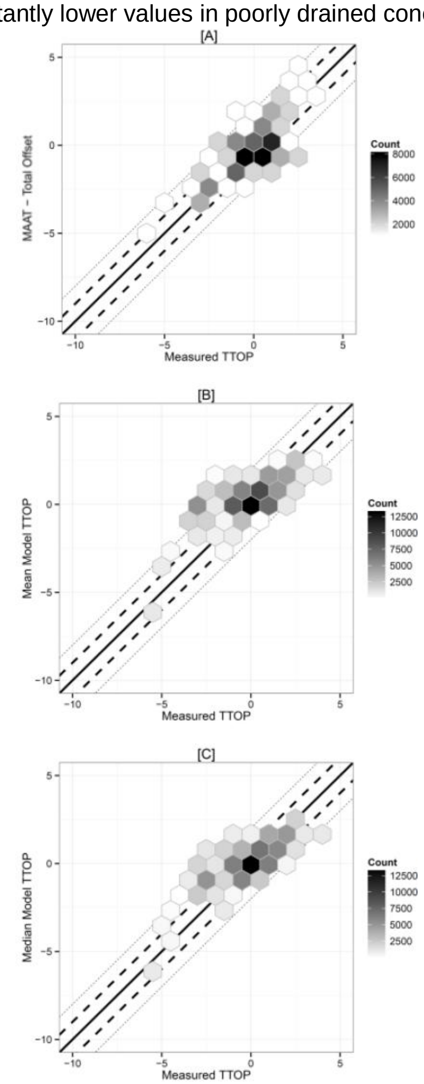

Figure 5. Hexbin plots of TTOP predictions compared to measurements using the 5^{th}, 50^{th} and 95^{th} percentiles of (A) the total offset model (average total offset of 3.0°C), (B) the mean TTOP model, and (C) the median TTOP model. The lines represent 1:1, ±1°C and ±2°C.

6.2 Model Assessment

89 complete station-years at 55 stations are used in 100 iterations. Five sets of 89 000 predictions were calculated using training datasets of 5% (n=9), 25% (n=25), 50% (n=47), 75% (n=68) and 95% (n=82). Seven TTOP predictions were made for each random sampling scheme using the 1^{st}, 5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th}, and 99^{th} percentiles of N_F, N_T, and R_K, and a mean scenario (total 3.56 million predictions).

As a first approximation of TTOP, we used a total offset approach. This ignores all environmental variability and simply applies an offset between MAAT and TTOP, with TTOP always being warmer than MAAT. MAAT plus the 50th percentile of the total offset (3.0°C) was compared with measured TTOP values: 58% of predictions are within ±1°C of the measured values and 89% are within ±2°C (Figure 5A).

Mean and median TTOP scenarios were modelled using average and median values of N_F, N_T and R_K. A comparison of the mean model results with the measured TTOP values gave 64% of predictions within ±1°C of the measured values and 85% are within ±2°C (Figure 5B). For the median model, 63% of the predictions are within ±1°C of the measured TTOP values and 92% are within ±2°C (Figure 5C).

As expected, smaller training datasets were less successful than larger training datasets and the lower and higher percentile scenarios (1^{st}, 5^{th}, 95^{th} and 99^{th}) were more successful at including measured values within their limits because their ranges are larger (Figure 6). There are 84% of predicted TTOP temperatures are within the limits of the 25^{th} and 75^{th} percentile predictions using a training sample size of 95% (n = 82) of the input data (Figure 6). This percentage falls relatively slowly until the training sample size drops below 50% (n = 47; Figure 6). With a 25% (n = 25) training sample size, only 66% of the predicted TTOP temperatures are within the limits of the 25^{th} and 75^{th} percentile predictions. The narrower limits of the 25^{th} to 75^{th} percentile predictions include fewer predicted TTOP values but the trend of the success curve is similar to that of the other limits.

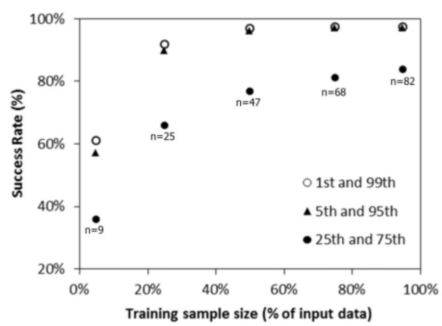

Figure 6. Percentage of measured TTOP values that are within the limits of cold and warm predictions using the 1^{st} and 99^{th} percentiles, the 5^{th} and 95^{th} percentiles and the 25^{th} and 75^{th} percentiles of the input variables N_F, N_T and R_K.

6.3 Model Sensitivity

The sensitivity of the TTOP model has yet to be explored in the literature using field data. In order to examine the sensitivity of the TTOP model a random iteration of the model was undertaken, following the same methodology as the previous section, except that only one variable at a time was iterated and all other values were those measured in the field.

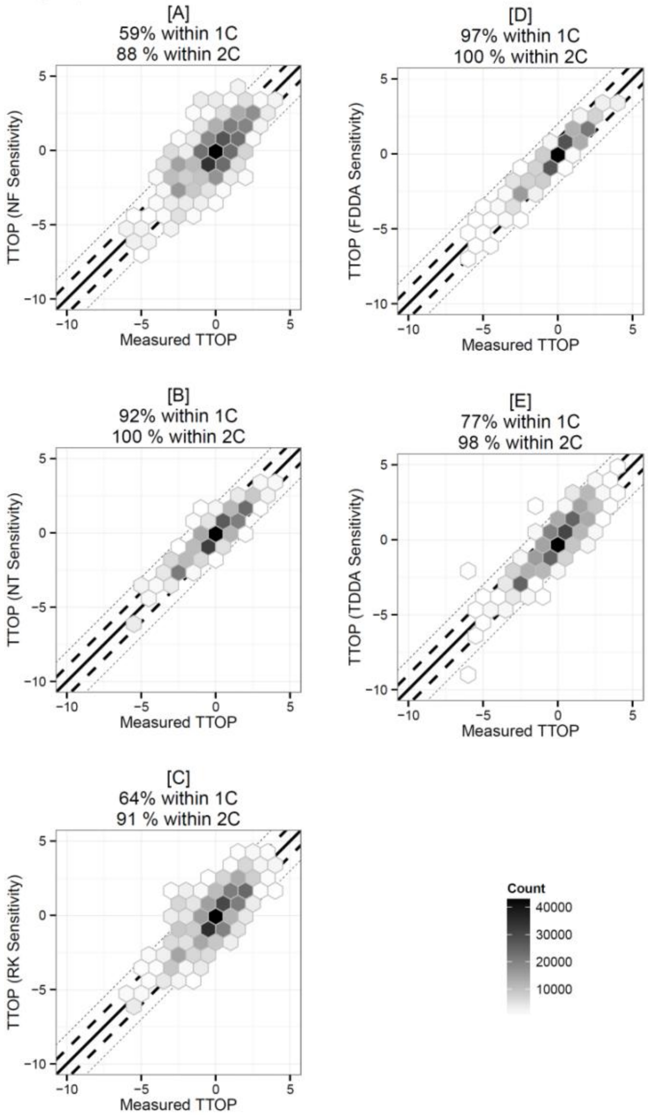

Figure 7. Hexbin plots of TTOP predictions compared to measurements to assess the model sensitivity to changes in (A) N_F, (B) N_T, (C) R_K, (D) FDD_A and (E) TDD_A. The lines represent 1:1, ±1°C and ±2°C.

Considerable scatter results when iteration of N_F was undertaken through all scenarios: 59% of TTOP predictions were within ±1°C of measured values and 88% of were within ±2°C (Figure 7A). Much less scatter developed when iterating through all scenarios of N_T: 92% of TTOP predictions were within ±1°C of measured values and 100% of were within ±2°C (Figure 7B). Iterations of R_K produced intermediate results: 64% of TTOP predictions were within ±1°C of measured values and 91% of were within ±2°C (Figure 7C).

The TTOP predictions using TDD_A ±100 and ±500°C-days (i.e. 4 scenarios) were compared with TTOP measurements: 97% of TTOP predictions were within ±1°C of measured values and 100% of were within ±2°C (Figure 7D). The TTOP predictions using FDD_A ±100 and ±500°C-days (i.e. 4 scenarios) were also compared with TTOP measurements: 77% of TTOP predictions were within ±1°C of measured values and 98% of were within ±2°C (Figure 7E).

The results show that the TTOP model is more sensitive to N_F than N_T (i.e. more scatter in the results) and this can be attributed to two factors. First, FDD_A values are greater than TDD_A values in the three study areas so that a change in N_F has a bigger impact on TTOP than the same change in N_T. Secondly, the impact of the range of N_F as a multiplier (from 0 to 1) is much greater than the impact of the range of N_T (from 0.5 to 1.5). The results also show that the TTOP model is more sensitive to TDD_A than FDD_A because variability in FDD_A is dampened by the snow cover (N_F<1) while TDD_A is usually dampened less or even amplified by N_T (N_T >1). The model is also moderately sensitive to R_K because R_K values above and below 1 serve to amplify TDD_A.

7 DISCUSSION AND CONCLUSIONS

A land cover driven TTOP-model was tested using data from 55 field climate stations. The mean of the measured TOFF values is +3.0°C, and values vary from +0.5°C to +6.5°C (Figure 2). Seasonally frozen sites have a greater range of TOFF values than permafrost sites in the region as the limit of TOFF observed for permafrost was +4°C. The TOFF values were used to model permafrost temperatures at field locations in order to investigate if the TTOP-model could improve on these results.

Elevation was found to have a significant influence on N_F, N_T and R_K, but topographic controls on model parameters are likely to be improved with a higher resolution DEM. Land cover was found to be the most suitable classification for the differentiation of non-topographic parameters and is used to associate model parameters to field sites. This dataset includes an additional field area and more years of data compared to that discussed in Lewkowicz et al. (2012), but the n-factors are broadly similar. However, tundra and rock classes were grouped together in that study whereas here they are analysed separately. The covariance of N_F, N_T and R_K demonstrate that R_K and especially N_F exert a significant influence on ground temperatures.

The TTOP-model had reasonable success at predicting TTOP values, but it offered only a 6% improvement on the extremely simple TOFF model. The TOFF model can therefore serve as a good first approximation of TTOP values and might be improved further by establishing TOFF values for each land cover class and each study area.

Training sample size proved to be important. Using only 5% of the input data (n = 9) achieved low success rates (<61%) whereas increasing to 50% of the input data (n = 47) increased success by 40% or more. Increasing beyond 50% of the input data yielded relatively limited improvement (Figure 6). Some published studies employing the TTOP model use measured input values (e.g., Gisnås et al. 2013; Janke et al. 2012; Juliussen and Humlum 2007) while others use only textbook values (e.g., Henry and Smith 2001; Stevens et al. 2010). This study demonstrates that about 50 station-years is the critical number of stations required for acceptable success rates.

A sensitivity analysis, one of the first of its kind using field data, confirms that the limits of discontinuous permafrost are strongly related to N_F as well as R_K. Our sensitivity analysis also shows that changes in summer air temperatures have a greater impact on permafrost temperatures than the same magnitude of change in winter air temperatures. Because of the differences in sensitivity, the overall impact on TTOP of changes in FDD_A may be less than smaller changes in TDD_A.

The land cover driven TTOP-model approximates ground thermal conditions, but a thorough understanding of the shortcomings and uncertainties of the model is imperative for interpretation of the results. Improvements may be made with higher resolution elevation and surficial geology datasets.

ACKNOWLEDGEMENTS

Financial assistance was provided by the W. Garfield Weston Foundation Award for Northern Research, the Northern Scientific Training Program, the National Geographic Young Explorer Grant and the Yukon Research Centre Northern Endowment Fund to AB, and by NSERC, and the University of Ottawa to AGL.

We are grateful to Max Duguay, Tyler de Jong, and Anna Schmidt for field assistance in 2012 and 2013 and the Taku River Tlingit First Nation in Atlin for their in-kind support. Many other graduate students and colleagues, especially Dr. Philip Bonnaventure, collected data and serviced the climate stations in the preceding years and we thank them all. Dr. Mike Sawada and Dr. Denis Lacelle provided helpful reviews of the thesis from which this paper is derived.

REFERENCES

Bevington, A. 2015. Towards a TTTOP-model of permafrost distribution for three areas of southern Yukon and northern British Columbia. *Master's Thesis*, Department of Geography, University of Ottawa.

Bonnaventure, P.P. and Lewkowicz, A.G. 2013. Impacts of mean annual air temperature change on a regional permafrost probability model for the southern Yukon and northern British Columbia, Canada. *The Cryosphere*, 7, 935-946.

Bonnaventure, P.P., Lewkowicz, A.G., Kremer, M. and Sawada, M.C. 2012. A permafrost probability model for the southern Yukon and northern British Columbia, Canada. *Permafrost and Periglacial Processes*, 23(1), 52–68.

Brown, J., Ferrians, O.J.J., Heginbottom, J.A. and Melnikov, E.S. 1997. International Permafrost Association Circum-Arctic Map of Permafrost and Ground Ice Conditions. *U.S. Geological Survey*.

Environment Canada. 2015. Canadian Climate Data. Retrieved from: http://climate.weatheroffice.gc.ca/

Geobase. 2010. Data. Retrieved October 1, 2013, from http://www.geobase.ca

Gisnås, K., Etzelmüller, B., Farbrot, H., Schuler, T.V. and Westermann, S. (2013). CryoGRID 1.0: Permafrost Distribution in Norway estimated by a Spatial Numerical Model. *Permafrost and Periglacial Processes*, 24(1), 2–19.

Gruber, S., Hoelzle, M. and Haeberli, W. 2004. Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophysical Research Letters*, 31(13), L13504.

Henry, K. and Smith, M.W. 2001. A model-based map of ground temperatures for the permafrost regions of Canada. *Permafrost and Periglacial Processes*, 12, 389–398.

James, M., Lewkowicz, A.G., Smith, S.L. and Miceli, C.M. (2013). Multi-decadal degradation and persistence of permafrost in the Alaska Highway corridor, northwest Canada. *Environmental Research Letters*, 8(4), 045013.

Janke, J.R., Williams, M.W. and Evans, A. 2012. A comparison of permafrost prediction models along a section of Trail Ridge Road, Rocky Mountain National Park, Colorado, USA. *Geomorphology*, 138(1), 111–120.

Jenness, J., Brost, B., and Beier, P. 2013. Land facet corridor designer. Corridor Design.

Juliussen, H., and Humlum, O. 2007. Towards a TTOP ground temperature model for mountainous terrain in central-eastern Norway. *Permafrost and Periglacial Processes*, 184(2), 161–184.

Kerkering, J. 2008. Mapping past and future permafrost extent on the North Slope Borough, Alaska. *Master's Thesis*, Duke University.

Kremer, M., Lewkowicz, A.G., Bonnaventure, P.P. and Sawada, M.C. 2011. Utility of classification and regression tree analyses and vegetation in mountain permafrost models, Yukon, Canada. *Permafrost and Periglacial Processes*, 22(2), 163-178.

Lantuit, H. and Pollard, W.H. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology,* 95(1), 84-102.

Lewkowicz, A.G. 2007. Dynamics of active-layer detachment failures, Fosheim Peninsula, Ellesmere Island, Nunavut, Canada. *Permafrost and Periglacial Processes*, 18(1), 89-103.

Lewkowicz, A.G., Bonnaventure, P.P., Smith, S.L. and Kuntz, Z. (2012). Spatial and thermal characteristics of mountain permafrost, northwest Canada. *Geografiska Annaler: Series A, Physical Geography*, 94(2), 195–213.

Nelson, F.E., Anisimov, O.A. and Shiklomanov, N.I. 2002. Climate change and hazard zonation in the circum-Arctic permafrost regions. *Natural Hazards*, 26, 203–225.

Romanovsky, V.E. and Osterkamp, T.E. 1995. Interannual variations of the thermal regime of the active layer and near • surface permafrost in northern Alaska. *Permafrost and Periglacial Processes*, 6, 313–335.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., … and Vonk, J. E. 2015. Climate change and the permafrost carbon feedback. *Nature*, 520(7546), 171-179.

Shur, Y., Hinkel, K.M. and Nelson, F.E. 2005. The transient layer: implications for geocryology and climate-change science. *Permafrost and Periglacial Processes*, 16(1), 5-17.

Smith, M.W. and Riseborough, D.W. 1996. Permafrost monitoring and detection of climate change. *Permafrost and Periglacial Processes*, 7, 301–309.

Smith, M.W. and Riseborough, D.W. 2002. Climate and the limits of permafrost: a zonal analysis. *Permafrost and Periglacial Processes*, 13(1), 1–15.

Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.,… Throop, J. 2010. Thermal state of permafrost in North America: a contribution to the international polar year. *Permafrost and Periglacial Processes*, 21(2), 117–135.

Stevens, C.W., Moorman, B.J. and Solomon, S.M. 2010. Modeling ground thermal conditions and the limit of permafrost within the nearshore zone of the Mackenzie Delta, Canada. *Journal of Geophysical Research*, 115(F4), F04027.