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P2.5 - Estimating meteorological variables within glacier boundary layers, Southern Coast Mountains, British Columbia, Canada

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1 INTRODUCTION

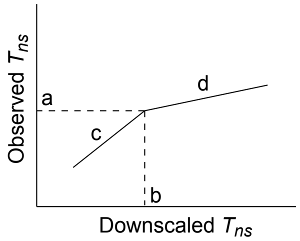
Distributed melt models are commonly used in glacier hydrology, yet a lack of knowledge of how processes in the glacier boundary layer influence air temperature, humidity, and wind speeds represent an important limitation with respect to the interpolation and extrapolation of input data used to drive distributed glacier melt models. Temperature data for glacier melt models are often obtained from local data sources such as a regional climate network (RCN) station or a study-specific automatic weather station (AWS). Given the scarcity of observing stations in high mountainous terrain, reanalysis data are now frequently used to estimate surface meteorological variables in regional modelling approaches. Yet both approaches are biased, in that "downscaled" temperatures do not account for glacier boundary layer effects.

A distinct feature of melting glaciers is a glacier boundary layer (GBL) which results from temperature differences between the snow or ice surface (assumed to be 0°C) and the overlying ambient atmosphere. Katabatic flows within the GBL are initiated when energy exchange processes (longwave emittance and/or sensible heat exchange) support continuous cooling along a slope. This cool air accelerates downwards in response to gravity, reinforcing sensible heat exchange with the surface and enhancing the temperature differential between ambient and observed temperatures.

A parameterization of GBL thermal properties is thus essential for modeling near-surface temperatures (T_{ns}), which may then be used to estimate sensible and latent heat fluxes, incoming longwave radiation, and positive degree day sums. Numerous observational studies have demonstrated that temperatures within the GBL are lower than those at the same elevation outside the GBL [Braithwaite, 1977, Greuell and Böhm, 1998, Strasser et al., 2004] or suggested that standard atmospheric lapse rates (6.0°C km^{-1}) are unsuitable for estimating T_{ns} [Munro, 2004, Klok et al., 2005].

A conceptual empirical model that can be used to evaluate the onset and the strength of glacier boundary layer cooling is shown in Figure 1. Above some critical ambient temperature (T_{crit}; point b), the temperature difference between the surface and the overlying air mass is sufficient to induce katabatic flow. Below T_{crit}, the slope of the best-fit line between observed and ambient temperatures (c) should be nearly 1, as the GBL (which is formed mainly through katabatic flow) is poorly developed. Above this threshold, the slope of the best-fit line (d) should reflect the strength of boundary layer cooling.

Figure 1 Piecewise regression model, with (a) y-intercept, (b) x-intercept, (c) slope below critical threshold, and (d) slope above threshold.



This paper has two goals: (1) to compare simple temperature downscaling techniques that might be applied to generate input data for regionally distributed glacier melt models, and (2) to develop an empirical parameterization of glacier boundary layer influences on air temperatures to remove bias associated with regionally downscaled temperature fields.

2 STUDY AREA AND METHODS

Six automatic weather stations (AWS) were in operation during the 2006 and 2007 ablation seasons at Place Glacier (4 km^2; Figure 2) and Weart Glacier (8 km^2; Figure 3), in the southern Coast Mountains of British Columbia. A floating station design kept the sensors at approximately the same height (1.75 m)

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throughout the summer melt season. Temperatures were sampled every 10 seconds with a Rotronic temperature and relative humidity sensor, and 10-minute averages were recorded using Campbell CR10X dataloggers.

Figure 2 Place Glacier AWS locations (stars), 2006 and 2007.

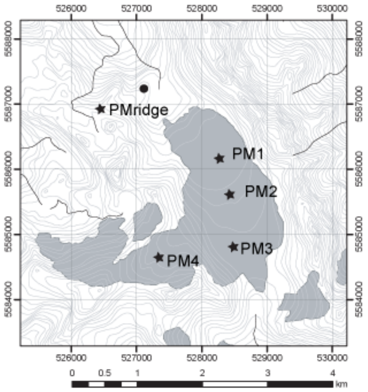
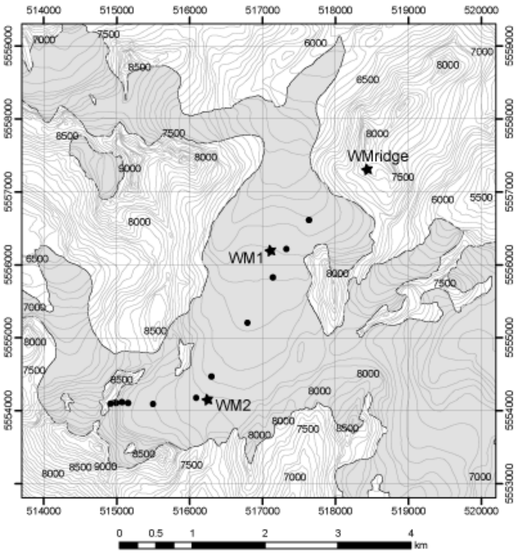


Figure 3 Weart Glacier AWS locations (stars), 2007.

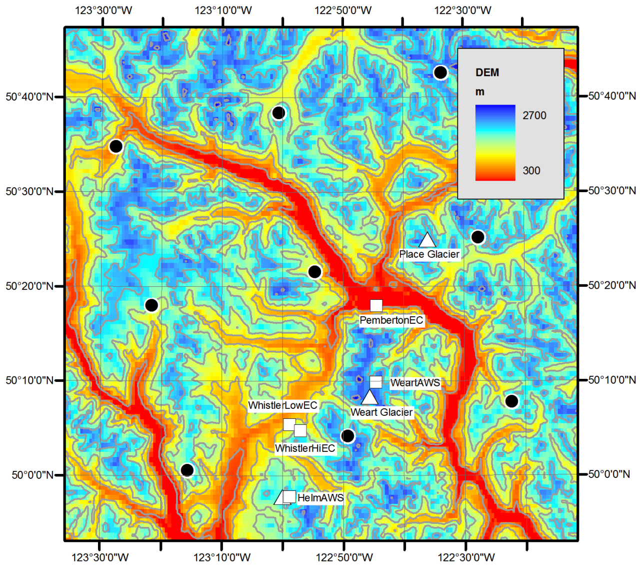


Near-surface temperatures were estimated for the glacier AWS sites using both North American Regional Reanalysis (NARR) data, and regional climate network (RCN) data at 3-hour timesteps. Surface station locations and NARR gridpoints are shown in Figure 4).

To estimate T_{ns} from gridded NARR data lapse rates were calculated at each grid-point using temperatures at each pressure level above the surface, up to the reference level of 700 mbar. If inversions were detected in the temperature profiles, observations above the inversion were removed from the lapse rate calculation. NARR lapse rates were then interpolated from the 33 km NARR grid to a 20 m DEM grid over the area of interest. Grid elevations at 20 m resolution were used to estimate T_{ns} from the interpolated lapse rates, using the 700 mbar temperatures as the reference level. Elevation differences between the glacier AWS and the corresponding grid cells were less than 20 m.

Near-surface temperatures were estimated from RCN data by calculating surface lapse rates at each time step from five regional climate stations, which range between 250 and 2400 m of elevation. Observed glacier AWS elevations were then used to estimate T_{ns}. This method does not specifically interpolate temperatures between stations, and assumes that lapse rates are constant throughout the region of interest at each time step.

Figure 4 Study area with locations of NARR gridpoints (circles), surface climate stations (stars), and glacier AWS sites (triangles).



Near-surface temperatures observed at the study sites were compared against values downscaled from the NARR and RCN datasets. To identify T_{crit} and strength of the GBL development, piecewise linear regressions were used to fit to downscaled T_{ns} to observed T_{ns}, following the form illustrated in Figure 1. Using the piecewise regression results, glacier AWS temperatures were then reconstructed from both NARR and RCN data.

3 RESULTS

At all sites, downscaling with both NARR and RCN data produced similar T_{ns} estimates (Figure 5), suggesting that surface data and atmospheric data are equivalent in their ability to model near-surface temperatures. A wider range of estimated temperatures is observed in the NARR series. Visual examination of Figure 5 suggests that temperature suppression within the glacier boundary layer is strongest at the lower elevations (PM1 and WM1), and is greatest at higher ambient temperatures, regardless of the method used for downscaling temperature.

Piecewise linear regressions confirm this conceptual model, and provide guidance for correcting the bias observed in temperatures downscaled using both NARR and RCN data (Tables 1 and 2). Slopes of the best fit line (d in the Figure 1) above T_{crit} are all less than 1, and the lowest slopes (giving the greatest deviation from ambient temperatures) are found at the lowest elevation glacier AWS sites (Figure 6 shows the results for PM2). Thresholds for evidence of glacier boundary layer cooling (points a and b in Figure 1) range from 3.0 to 7.7°C for both NARR and RCN temperatures. Piecewise model fits are reasonably strong, with coefficients of determination R^2 ranging from 0.53 to 0.94, with stronger fits observed when using RCN data.

Figure 7 demonstrates near-surface temperature reconstructions at PM2, using a two-step process involving 1) the downscaling procedures described above and 2) a bias correction based on the piecewise linear regressions. However, autocorrelation in the residuals appears to be high. Diurnal temperature patterns are do not appear to be well-captured by the NARR data; part of the issue here is the use of 700 mbar temperatures as the reference level for estimating T_{ns}, since the diurnal temperature signal is weak at this level.

Figure 5 Observed versus downscaled near-surface temperatures from NARR data (blue) and RCN data (red).

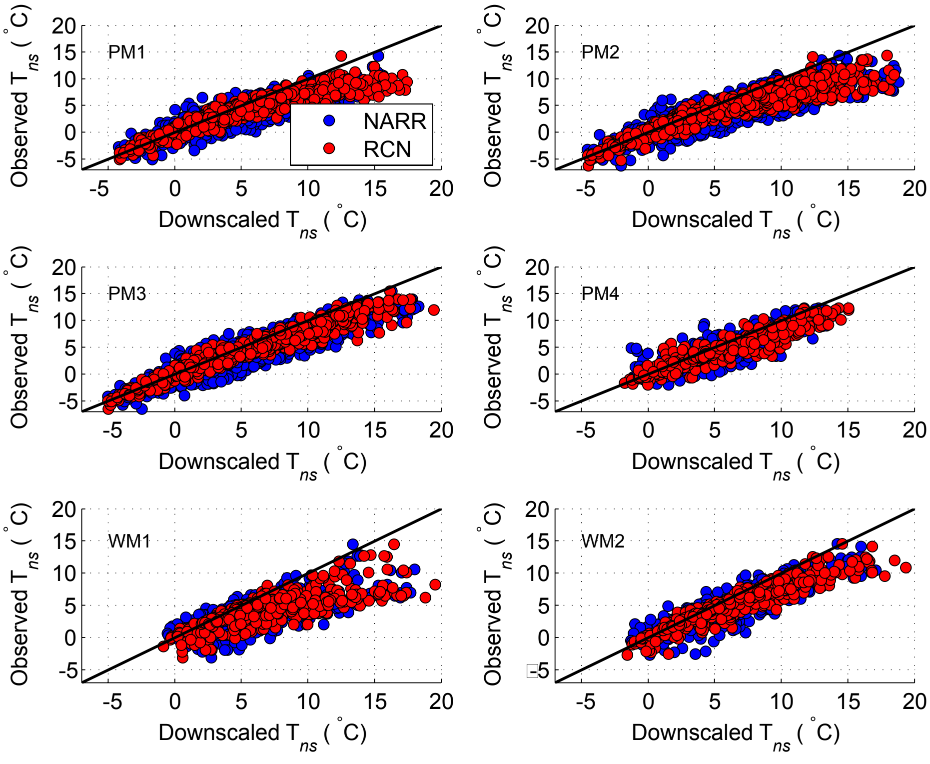


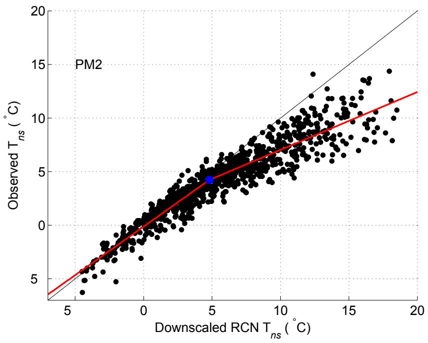
Table 1 Optimized coefficients for estimating temperatures within the glacier boundary layer, using NARR data and initial estimates of $a = 4, b = 4, c = 1, d = 0.6$.

Site	a	b	c	d	R^2
WM1	3.5	5.3	0.5	0.4	0.53
WM2	3.0	3.9	0.7	0.7	0.78
PM1	3.0	3.8	0.7	0.6	0.77
PM2	4.4	6.0	0.8	0.5	0.76
PM3	3.0	4.1	0.8	0.8	0.84
PM4	4.8	6.9	0.6	1.0	0.71

Table 2 Optimized coefficients for estimating temperatures within the glacier boundary layer, using surface temperature data and initial estimates of $a = 4, b = 4, c = 1, d = 0.6$.

Site	a	b	c	d	R^2
WM1	3.4	4.3	0.9	0.4	0.65
WM2	6.3	7.7	0.8	0.6	0.90
PM1	5.2	6.1	0.9	0.4	0.89
PM2	4.2	4.8	0.9	0.5	0.89
PM3	3.3	3.5	1.0	0.7	0.94
PM4	3.1	3.8	0.8	0.8	0.88

Figure 6 Downscaled T_{ns} from RCN (x-axis) versus observed temperatures at PM2 (y-axis), 2007 ablation season. Piecewise fit results (see Table 2) demonstrate the substantial temperature bias observed at higher ambient temperatures.



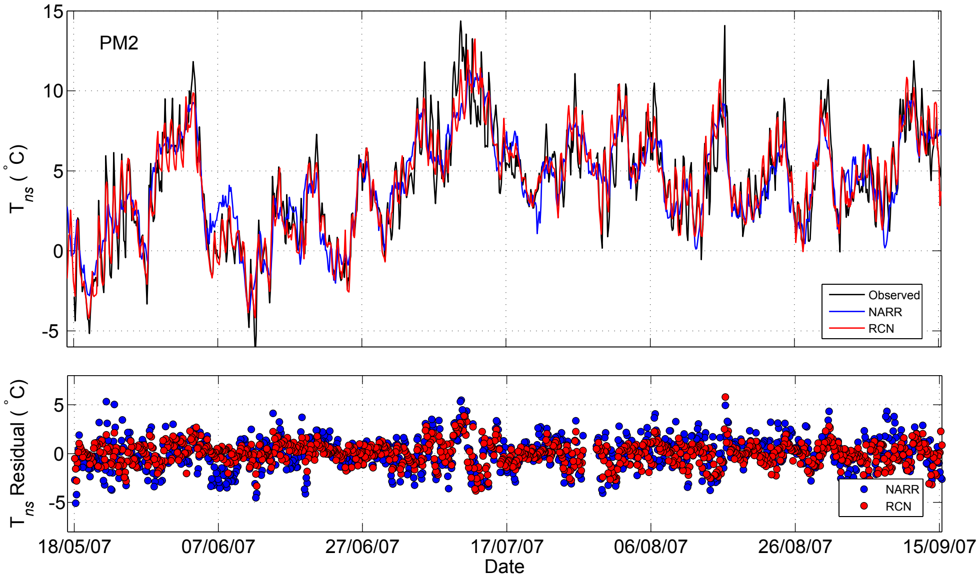
4 Discussion and Conclusions

It is encouraging to note the skill with which both surface-based and reanalysis data can be used to estimate near-surface temperatures, especially considering the heterogeneous terrain. In a regional modeling framework, reanalysis data will play a large role in driving glacier melt models due to the scarcity of surface climate stations, especially in high-elevation locations. Both NARR and RCN temperature reconstructions demonstrate a consistent bias from near-surface temperature observations at the glacier AWS; this bias appears to be greatest at the lower elevations of both glaciers. Using elevation as a predictor for the strength of GBL temperature suppression is an appealing option for correcting estimated temperature fields, and will be a direction for future research.

However, it is important to note that these empirical models have been developed only at two sites. Boundary layer development and katabatic flow, which will determine the observed near-surface temperatures, also depend on glacier geometry, direction and strength of geostrophic winds in relation to mountain and valley orientation, and on the exposure of the glacier in question. Glaciers which are not confined by high valley walls will be more exposed to geostrophic winds and thus less likely to have a well-developed katabatic boundary layer.

This study examined near-surface meteorological data collected at six automatic weather stations operating at two glacier sites in the Southern Coast Mountains of British Columbia. Empirical models for estimating near-surface temperatures were developed from both downscaled North American Regional Reanalysis (NARR) data and from a regional climate network (RCN). Consistent temperature biases between observed and reconstructed temperatures were identified through linear piecewise regression analyses, and empirically derived bias correction factors were used to correct the reconstructed temperature series for glacier boundary layer cooling. Results presented in this study highlight simple and effective parameterizations that can account for glacier boundary layer effects, which are important for developing snow and ice melt estimates in regional applications and at unmonitored sites.

Figure 7 Observed and reconstructed temperature series (top), and their residuals (bottom; observed minus expected) for the 2007 ablation season, PM2.



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