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Analysis of Daily Air Temperatures across a Topographically Complex Alpine Region of Southwestern Yukon, Canada

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ABSTRACT. This study provides an analysis of six years of daily air temperature data collected using 16 HOBO® UA-002-64 Pendant data loggers placed along a 280 km transect in southwestern Yukon and northern British Columbia. Correlation and time series analyses, including Seasonal Decomposition of Time Series by Loess (STL) methods, revealed very high correlations among all data series at daily to annual timescales. The two meteorological stations in the region are found to be generally representative of the greater area, and local temperature variability appears to be predominantly determined by synoptic-scale weather patterns. The annual temperature cycle in this region is complex and has annually repeating components at all study sites across the region. The analysis of daily data using the STL method can provide new insight into climate time series and enhance our ability to observe patterns and extremes in temperatures across varying spatial and temporal scales. Data loggers provide a cost-effective way of obtaining similar (and sometimes higher-quality) information compared to meteorological stations or gridded global datasets.

Key words: Yukon climate, HOBO data logger, meteorological station network, daily and hourly temperature dataset, time series analysis, seasonal-trend decomposition (STL)

RÉSUMÉ. Cette étude présente l’analyse de données sur la température de l’air prélevées au cours de six années à l’aide de 16 enregistreurs de données HOBO[MD] UA-002-64 Pendant le long d’un transect de 280 km situé dans le sud-ouest du Yukon et le nord de la Colombie-Britannique. L’analyse des corrélations et des séries temporelles, faisant notamment appel aux méthodes de décomposition saisonnière des séries temporelles de Loess (STL), ont révélé de très fortes corrélations entre toutes les séries de données aux échelles de temps allant de quotidiennes à annuelles. Les deux stations météorologiques de la région sont généralement représentatives de la grande région, et la variabilité des températures locales semble principalement déterminée par le régime climatique à l’échelle synoptique. Dans cette région, le cycle des températures annuelles est complexe. Il comprend des composantes récurrentes annuellement à tous les sites étudiés, à la grandeur de la région. L’analyse des données quotidiennes à l’aide de la méthode STL peut donner une nouvelle perspective des séries temporelles climatiques et rehausser notre capacité à observer les tendances et les extrêmes de températures pour des échelles spatiales et temporelles variées. Les enregistreurs de données constituent une manière économique d’obtenir des renseignements similaires (et parfois de meilleure qualité), comparativement aux données des stations météorologiques ou aux ensembles de données globales sous forme de valeurs aux points de grille.

Mots clés : climat du Yukon, enregistreur de données HOBO, réseau de stations météorologiques, ensemble de données de températures quotidiennes et horaires, analyse des séries temporelles, décomposition des tendances saisonnières (STL)

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INTRODUCTION

A significant obstacle hindering effective northern research is that only sparse networks of meteorological stations are available (Fleming et al., 2000; Price et al., 2000; Førland et al., 2002; Klein Tank et al., 2002; Førland and Hanssen-Bauer, 2003; Chronopoulos et al., 2008). Knowledge of spatial differences in temperature variability is often based on a small number of stations, typically located in settlements. Gridded air temperature datasets (e.g., New et al., 2002) can be useful in these situations; however, estimates need to be treated with caution when stations are hundreds of kilometers apart (Gyalistras, 2003; Hofstra et al., 2010). Further, these datasets cannot deal with anomalous meso-scale climates common to topographically complex regions, in part because their spatial resolution is determined by grid cell size (Fortin and Gajewski, 2012; Frei, 2014). In these regions, interpolation of temperatures between stations can also be difficult because of the complex relationship between temperature and elevation (Dodson and Marks, 1997; Chung and Yun, 2004; Wang et al., 2006; Chiu et al., 2009) and a lack of high-elevation stations in general

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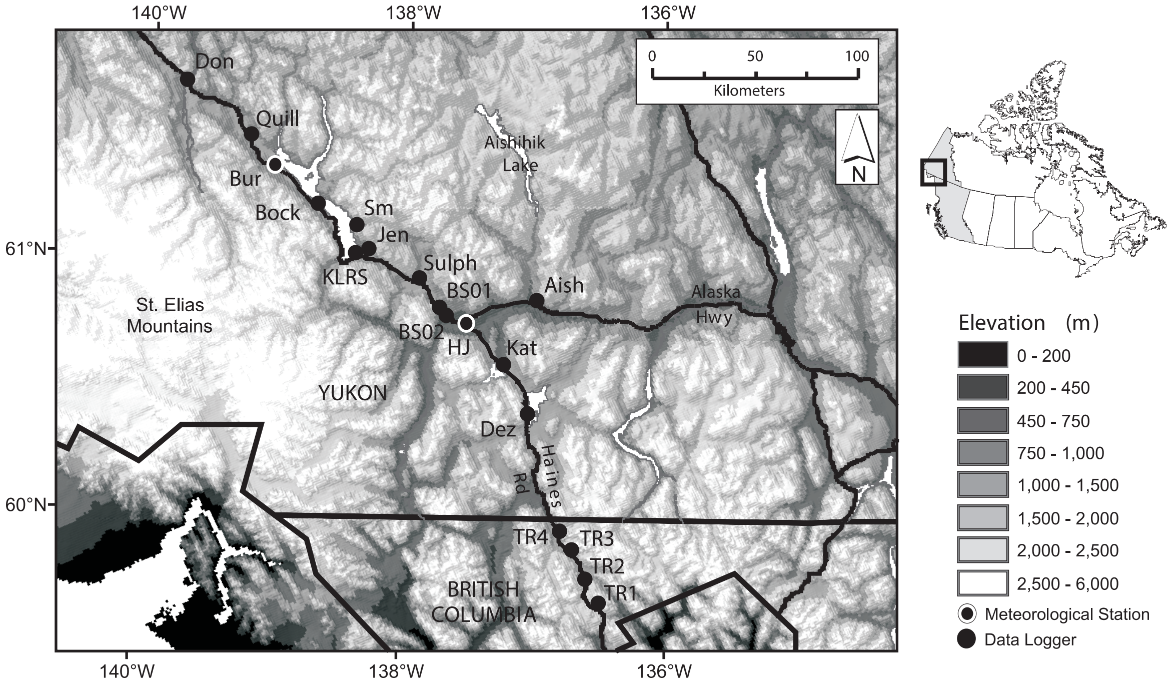

FIG. 1. Map of the study area showing the location of the 16 data logger sites and two meteorological stations (HJ and Bur). Station abbreviations are explained in Table 1.

(Agusti-Panareda and Thompson, 2002; Stahl et al., 2006; Pape et al., 2009). Although the question of station representativeness has been studied at a synoptic scale for longer timescales (e.g., Climate Normals: Vose and Menne, 2004), the extent to which data from existing meteorological stations can be spatially extrapolated across northern alpine environments at daily to monthly timescales is not clear.

This study was motivated by discussions with researchers attempting to explain the spatial patterning of plant communities in and around the Kluane region of northwestern Canada, as well as our own work developing calibration equations for quantitative paleoclimate reconstructions (e.g., Wilson and Gajewski, 2002, 2004; Bunbury and Gajewski, 2005). Although southwestern Yukon is an ideal location for studying mountainous environments, very few climate data are available. This fact has raised concerns over the validity of spatially interpolated climate data, particularly since this area is so geographically variable (e.g., tree line, mountains, valleys, etc.) and studies are often done at spatial scales smaller than the existing station network. Climate data are needed at field sites, and as a consequence, researchers have begun placing expensive meteorological monitoring stations in various areas.

To study the local climate characteristics of the Kluane region, 16 HOBO® UA-002-64 Pendant data loggers (Onset Computer Corp., Bourne, MA) were installed along the major highways crossing southwestern Yukon and northern British Columbia. The resulting temperature data were compared to the available climate records from nearby Environment Canada meteorological stations. The main objective of this study was to investigate the extent to which the few meteorological stations in the area are representative of the regional climate and to present a dataset that could be used to estimate temperature away from these stations. A second objective was to characterize the nature of the annual temperature cycle using daily climate data. The results are presented in three sections relating to 1) the relationship between loggers, meteorological stations, and gridded temperature data and the use of these to describe the spatial patterns of climate in the area; 2) the use of seasonal decomposition methods to analyze daily temperature data; and 3) case studies highlighting the efficiency of a spatial network of loggers for providing data on synoptic events.

METHODS

Study Area

The study area is centered on the Kluane Lake Research Station, which is the hub for extensive research activities concerning Arctic and alpine environments in southwestern Yukon (Fig. 1). Only two Environment Canada meteorological stations are currently recording data in the region, the Haines Junction and Burwash Airport stations, and the dataset from the latter is missing numerous data, especially in winter. Located 100 km apart and both on the grounds of local airports (Table 1), these stations serve as the only source of climate data for an area of at least 80 000 km^2. Annual precipitation in the area is approximately 280 mm, the majority of which falls during the ice-free months between May and September, and mean monthly air temperatures for January and July at Burwash Airport are −22.0˚C and 12.8˚C, respectively (EC, 2013).

TABLE 1. Location of measurement sites and meteorological stations. Except at Site 16, all loggers were placed approximately 2 m from the ground in white spruce trees, attached to branches near the trunk, and shaded from direct sunlight. The Site 16 logger was comparably located in a shrub willow. All measurement sites except Site 5 and Site 6 are along the Alaska Highway and Haines Road. Donjek Kettle is an unofficial name.

Site	Abbrev.	Site name	Latitude (˚N)	Longitude (˚W)	Altitude (masl)	Site description
1	Don	Donjek Kettle	61.6828	139.7660	733	Forest edge near shore
2	Quill	Quill Creek	61.4919	139.2822	784	Forest edge near creek
3	Bock	Bock's Creek	61.2228	138.7430	852	Forest edge near creek
4	Sm	Small Lake	61.1616	138.4291	804	Forest edge near shore
5	Jen	Jenny Lake	61.0478	138.3633	819	Near N shore
6	KLRS	Kluane Lake Research Station	61.0278	138.4125	768	~200 m from lake at Research Station
7	Sulph	Sulphur Lake	60.9381	137.9850	849	Near W shore
8	Aish	Aishihik Road	60.8559	137.0330	678	Forest edge
9	BS01	Bear Creek Summit	60.8640	137.7942	1000	Forest edge
10	BS02	Bear Creek Base	60.7997	137.6917	695	Forest edge
11	Kat	Kathleen Lake	60.6284	137.2881	763	Forest edge ~2 km from lake
12	Dez	Dezadeash Lake	60.5029	137.0709	724	Near W shore
13	TR4	TR4	59.9554	136.8081	891	Boreal forest
14	TR3	TR3	59.8901	136.7381	915	Boreal forest
15	TR2	TR2	59.7712	136.5976	909	Forest tundra
16	TR1	TR1	59.6673	136.5518	1039	In shrub willow in tundra
17	Bur	Burwash Airport Meteorological Station	61.3706	139.0400	806	Burwash Airport
18	HJ	Haines Junction Meteorological Station	60.7725	137.5802	595	~4 km from Haines Junction

Data Collection

Sixteen Hobo UA-002-64 Pendant data loggers instrumented with temperature sensors (resolution of 0.14˚C at 25˚C and accuracy of ± 0.53˚C from 0˚ to 50˚C) were installed along a 280 km NW-SE transect following and approximately equidistant from the Alaska Highway and Haines Road (Fig. 1, Table 1). Despite having a specified measurement range of −20˚C to +70˚C, the loggers recorded hourly air temperatures throughout the cold seasons properly, and did not suffer from battery failure due to temperature extremes. The data loggers were attached below dense branches of large white spruce trees (Fig. 2H) in spruce stands growing slightly away from the road. All were positioned close to the trunk to remain shaded and above the snowpack (Lundquist and Huggett, 2008; Holden et al., 2011; Kedzia, 2011) except the data logger at site TR1 (located in the tundra), which was installed in a shrub willow. The logger at site TR1 was one of four loggers placed in northern British Columbia along the Haines Road (Fig. 2A–D); these spanned the tree line from the boreal forest to the tundra, with one measurement site located in the tundra (TR1), one in the forest-tundra transition zone (TR2), and two in the open forest (TR3 and TR4). Two sites were chosen to study elevation effects, with one at the base and one at the top of a steep slope in the Bear Creek area along the Alaska Highway (BS01 and BS02). Although these two sites are only about 1 km apart, the difference in their elevations is 305 m. The remaining loggers were in or at the edge of a forest, and some were located near large (Dezadeash and Kluane) or small (Jenny and Sulphur) lakes.

Statistical Analyses

Hourly air temperatures were collected from 13 July 2006 to 13 June 2012, but the individual loggers were installed at different times, and battery exhaustion resulted in gaps in the temperature record at most sites (Appendix 1). Daily means were calculated and used in all analyses except detailed case studies, for which the original hourly data were used. Daily means were obtained using the aggregate function in R (R Development Core Team, 2013), which calculates a mean value for the days containing 24 hourly values and disregards days with missing values. Hourly temperature data for the Haines Junction and Burwash Airport meteorological stations were obtained from Environment Canada (www.climate.weatheroffice.gc.ca) and analyzed in the same manner as the logger data.

To compare these data to other data frequently used in environmental research (e.g., Whitmore et al., 2005; Rolland et al., 2009; Fortin and Gajewski, 2012), we obtained an additional estimate of mean July temperature for the years 1961–90 from the CRU CL 2.0 dataset (New et al., 2002; www.cru.uea.ac.uk/cru/data/hrg/). Monthly July temperatures were spatially interpolated at the location of the data logger sites in a geographic information system (GIS). These were plotted against the normalized mean July temperatures from the logger and meteorological station data; all data were normalized to rescale the range of values from the different sources.

To compare the annual cycle among the temperature records, the time series were decomposed into components that together sum to form the original data series using the seasonal-trend decomposition method (STL), which is based on locally weighted regression (LOESS; Cleveland et al., 1990). STL is a statistical procedure used to reveal nonlinear patterns in seasonal data (Lamon et al., 2004) that provides a simple and effective means of filtering time series into three additive components of variation: seasonal, trend, and remainder (Cleveland et al., 1990; Jiang et al., 2010). These components are produced by an iterative, locally weighted, nonparametric regression. The seasonal

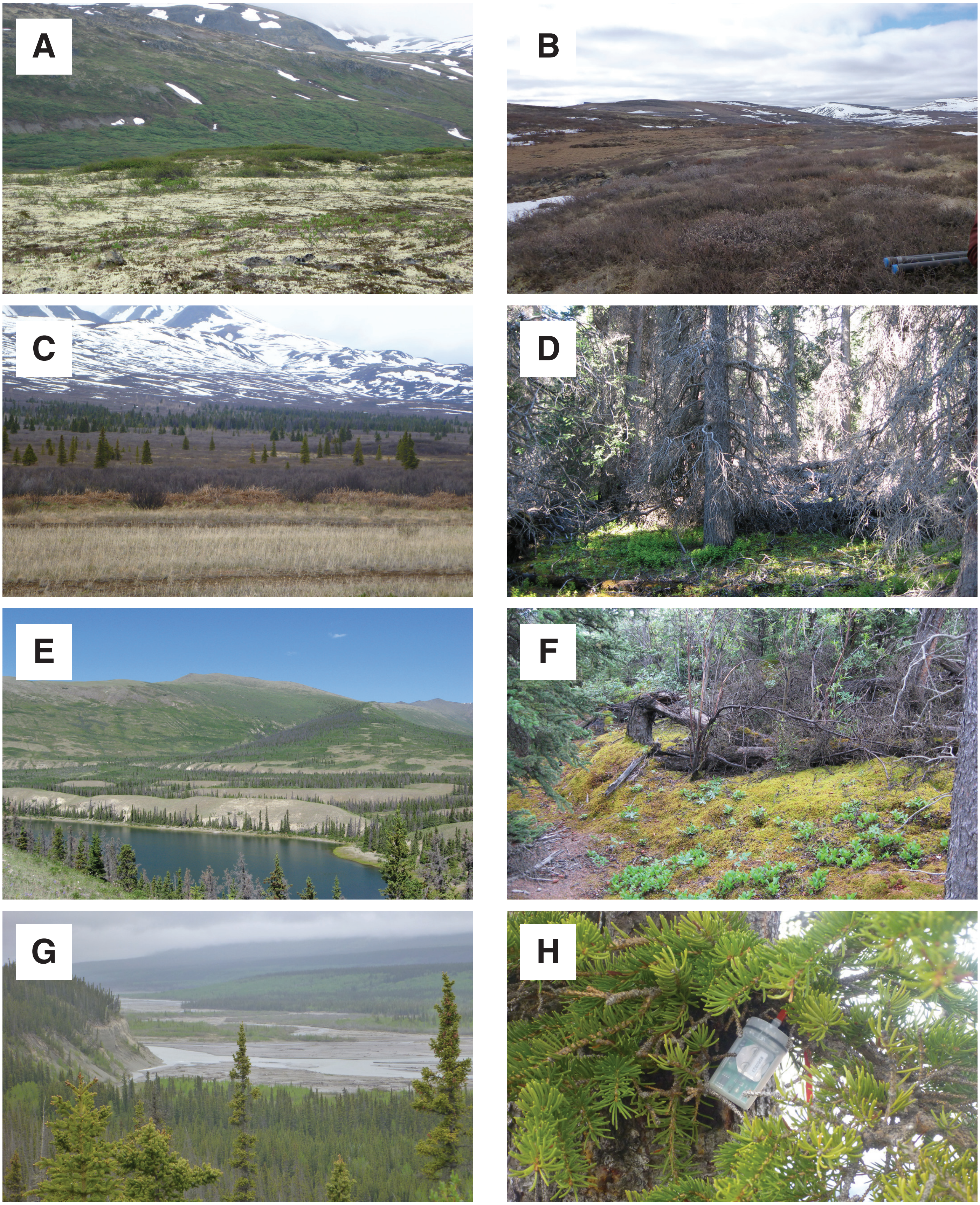

FIG. 2. Photographs showing the diverse landscapes across the area where the data loggers were placed. A and B: Tundra in northern British Columbia along Haines Road close to site TR1; C: Forest-tundra along Haines Road close to site TR2; D: Relatively moist forest near Donjek River and site Don; E: Forest and grassland east of Kluane Lake near site Sm; F: relatively dry forest with a moss and lichen ground cover near site Jen; G: Donjek River Valley; and H: an example of how the loggers were attached to the spruce trees.

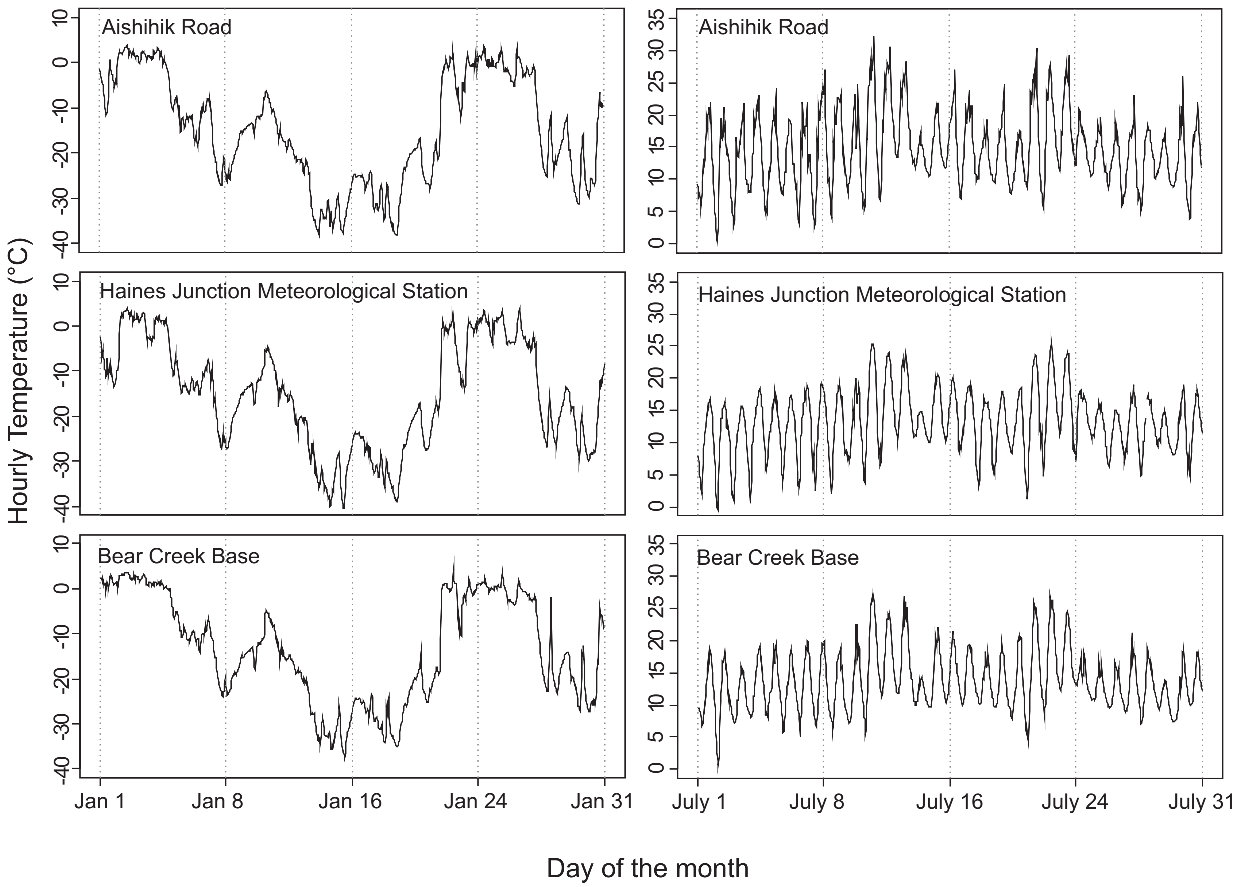

FIG. 3. Hourly air temperature data from January (left) and July (right) 2011, comparing the Haines Junction meteorological station to the two nearest loggers. The correlations between the January and July time series were all above 0.9.

component is found by averaging the series of all 1 January values, all 2 January values, and so on for the entire time series. This component is removed, and the remaining data are then smoothed to find the overall trend. The third component, the remainder, is the residuals from the sum of the seasonal and trend components. The first two necessary parameters to be selected are the number of backfitting and robustness iterations performed by two recursive procedures. An inner loop detrends, smoothes, and de-seasonalizes the seasonal and trend components, and an outer loop reduces the influence of outliers in the data. In this study, two inner iterations and zero outer iterations were chosen. The four remaining model parameters, chosen on the basis of characteristics of the temperature data and recommendations presented in Cleveland et al. (1990) and Jiang et al. (2010), were as follows: the number of observations per seasonal cycle and the smoothing of the low-pass filter for each subseries were both set to 365 days; the trend-smoothing parameter was 549 days; and the seasonal smoothing parameter was chosen as 365 days. For the purposes of STL only, intermittent daily gaps in the data (gaps no longer than four days of missing data) were filled with interpolated values from linear regression using the next available temperature value.

All analyses were performed in R, including the stats, tseries, zoo (Zeileis and Grothendieck, 2005) and STL packages (Cleveland et al., 1990). The stats and tseries packages enable the data to be analyzed as time series; the zoo package was used to calculate daily means; and the STL package was used to produce the STL decomposition plots. February 29th was eliminated from all series to maintain identical year lengths during analyses.

RESULTS

Spatial Pattern of Climate in the Region

In this region, mean daily temperatures can exceed 20˚C in summer and be as low as −46˚C in winter. All sites show a similar seasonal cycle; within-season variability is higher in the winter than in the summer, with rapid changes in temperature occurring over short time periods. In February 2008, for example, the Donjek Kettle record changed from −32.6˚C to −8.4˚C in five days. The time series plots of daily temperatures show similarity between mean daily temperature records from all data logger and meteorological station sites along a distance of 280 km (Appendix 1). Correlations between pairs of mean daily temperatures across all sites are all above 0.93 and significant at 95%.

A 31-day series of hourly winter and summer data from the Haines Junction meteorological station was compared to the two nearest logger records from Aishihik Road (Aish) and the Bear Creek region (BS02), located 28 and 16 km away, respectively (Figs. 1, 3). The remarkable coherence of the data from the two loggers with those of the meteorological station data, in spite of the distance separating them, suggests that the loggers are reliable and reasonably accurate recorders of the local climate. The means and standard deviations for these sites are not significantly different (January: Aish, −14.9 ± 12.01; HJ, −15.2 ± 11.84; BS02, −13.4 ± 11.77˚C; July: Aish, 14.8 ± 5.73; HJ, 13.2 ± 5.02; BS02, 13.8 ± 4.59˚C).

Scatterplots of daily temperatures from sites representing the entire transect clearly show high correlation, both across sites and between loggers and meteorological stations, while highlighting specific details (Fig. 4). The correlations decrease with distance, and scatter tends to be greater in winter, when the absolute temperature differences between sites are greater than in summer. The two sites close to Bear Creek, which differ by 305 m in elevation, highlight the occurrence of the Arctic inversion in winter: the higher-elevation site is warmer in winter, and the reverse is true in summer (Fig. 4A). A comparison of the northernmost site (Don) with one of the southernmost sites in British Columbia (TR3) shows that both have similar summer temperatures; however, the British Columbia site is warmer in the winter (Fig. 4B). Although the series are highly correlated, the temperature on any day can differ by more than 20˚C. The presence of large (Kluane) and small (Sulphur) lakes does not seem to have a great effect on local temperatures, as correlations with nearby stations remain high when the site of a logger is close to a lake (Fig. 4C, D).

Mean daily temperatures from the meteorological stations and nearby loggers show comparable correlations to those between pairs of loggers, in spite of instrumental differences (Fig. 4E–H). The logger on Aishihik Road is located 28 km from the Haines Junction meteorological station, but the two stations recorded similar temperatures in all seasons (Fig. 4E). The logger placed near the Donjek River and the Burwash Airport meteorological station are farther apart (55 km) and show a greater difference in seasonal temperature (Fig. 4F), although they are still highly correlated. The closest logger to the Haines Junction meteorological station, located at the base of Bear Creek, also shows high correlation to the station (Fig. 4G). Data from the Haines Junction and Burwash Airport stations (100 km apart), although highly comparable, show notable differences in absolute temperature, especially in winter (Fig. 4H).

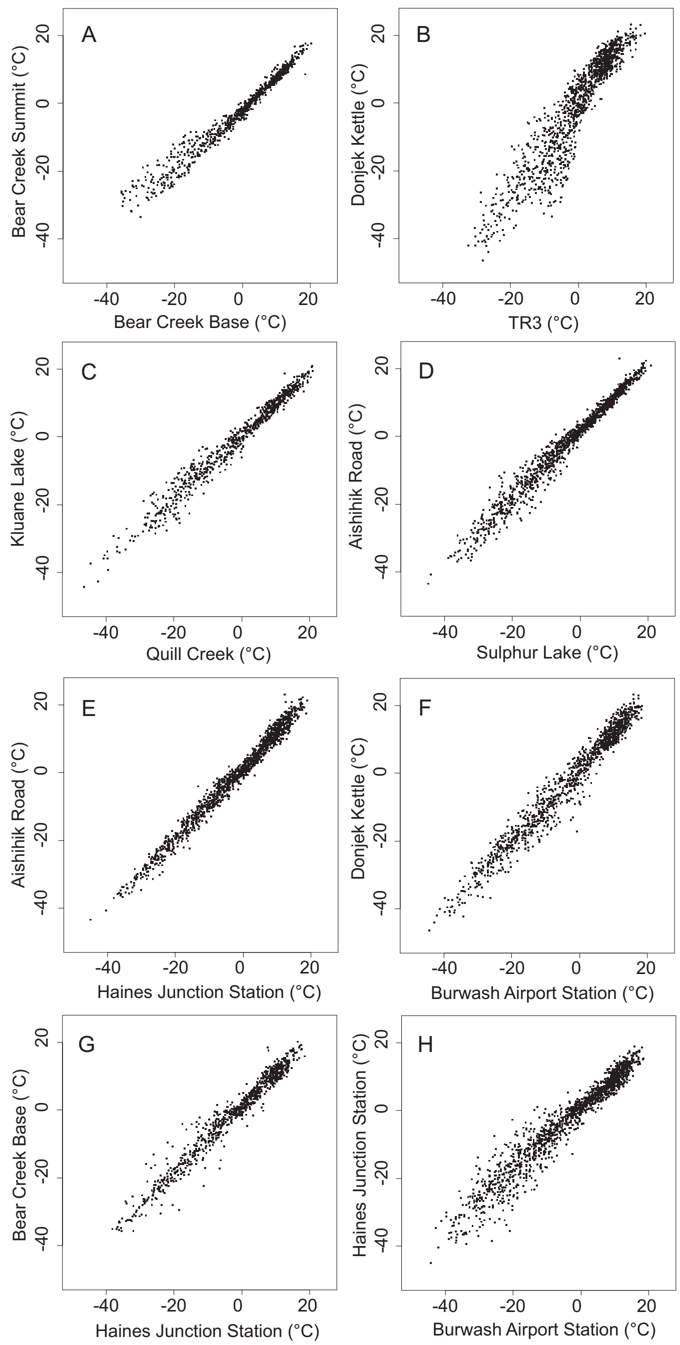

FIG. 4. Scatterplots of mean daily air temperature recorded by eight data loggers and two meteorological stations between 13 July 2006 and 13 June 2012. Only available data were used, resulting in different numbers of point pairs for the various plots. All correlations are above 0.94.

Loggers were placed at four sites in northern British Columbia, where the Haines Road traverses the tree line, thereby spanning tundra, forest-tundra, and boreal forest ecosystems. In spite of this clear biogeographic boundary, the data are all highly correlated, although the absolute temperatures are not the same (Fig. 5). The logger at site TR1 was located in a shrub willow since there were no spruce trees in the tundra; therefore, leaf shading was less. The resulting increase in variability was likely due to radiation loading (Fig. 5a). Nevertheless, the high correlation between all sites suggests that temperature variability does not change across the tree line. In addition, mean daily temperature at the four sites is not statistically different, although temperatures are slightly warmer at the northernmost lower elevation site (TR4) in summer and at the southernmost higher elevation site (TR1) in winter (Fig. 5b). As with the two sites near Bear Creek, these warmer temperatures resulted from the inversion characteristic of this environment in winter.

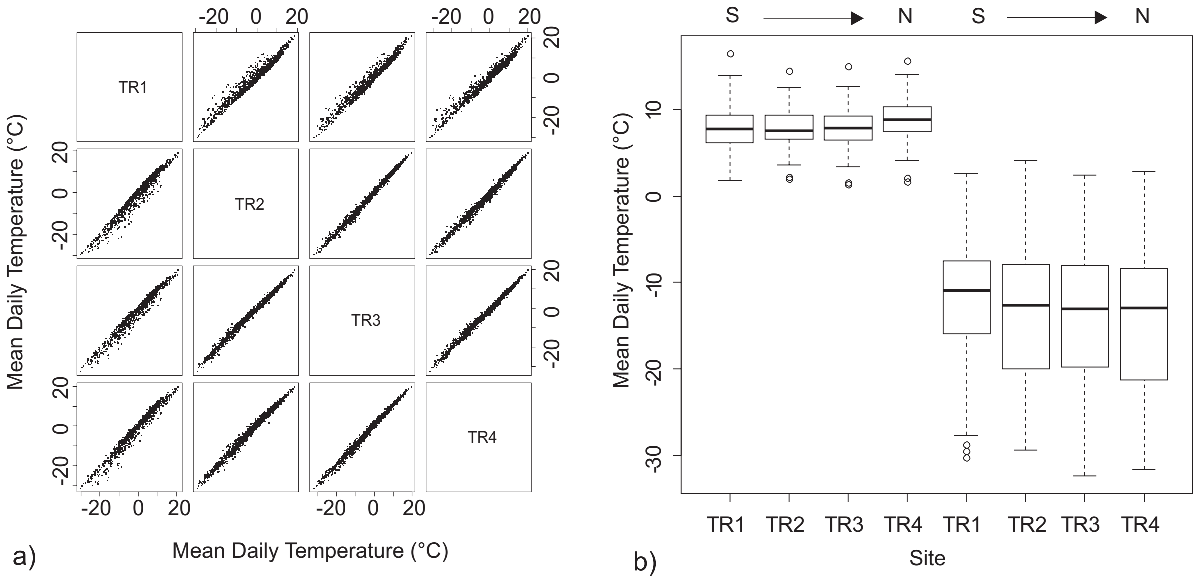

FIG. 5. a) Scatterplot matrix of mean daily air temperature recorded by four Hobo data loggers at sites traversing the tree line in northern British Columbia. b) A boxplot shows the mean daily air temperatures from Hobo loggers at the same four sites. The left-hand group represents data recorded between 1 June and 31 August 2008. The lower group represents data recorded between 1 December 2008 and 28 February 2009. TR1 is located in the tundra (1039 masl), TR2 is in the forest-tundra (909 masl), and TR3 and TR4 are in the boreal forest (915; 891 masl). The circles represent values that lie outside the interquartile range.

To determine the extent to which the logger and meteorological station data are representative of the temperature in the region, we compared these data to the CRU CL 2.0 mean July gridded global data series (New et al., 2002), a dataset typically used in environmental studies to interpolate temperature data at study sites (Fig. 6; Rolland et al., 2009; Fortin and Gajewski, 2012). The gridded dataset (10′ latitude/longitude spatial resolution) is the average of 29 years (1961–90), and four years of logger and meteorological station data are plotted in comparison. In spite of the difference in averaging period, the values from the logger and gridded datasets are similar across the entire transect. However, the values from the meteorological station data do not follow a similar pattern. Only the Haines Junction and Burwash Airport stations are included, since they are the only ones found in the study area, and the next closest station (Carmacks) is 160 km away. The mean July temperature at site TR1 in 2009 is abnormally high because the daily temperature rose above 20˚C for a few days during July. Site BS01 appears anomalously cold in comparison to other data logger sites and to the gridded dataset, possibly because this site is at a higher elevation.

Seasonal Decompositions of Time Series

The results of an STL decomposition from three of the longest data logger records and the Haines Junction meteorological station show similar time evolution in all cases and in all three components (Fig. 7). The annual cycle can be divided into two "seasons" based on day-to-day variability. "Winter," the period between approximately 1 November and 31 March, is characterized by high variability, as well as cold temperatures. "Summer" has much lower variability and lasts from 1 April to 31 October, although much of this period is relatively cool.

The winter season is characterized by an abrupt cooling around the beginning of November, followed by a brief warming during the month of December and a second abrupt cooling around mid-January that extends into a prolonged cold period (Fig. 7, data). This period is followed by a warmer, but highly variable period, before an abrupt increase into a new temperature regime. This pattern is robust enough that it is seen in all years and at all sites, although it is expressed somewhat differently in different years (Fig. 7, seasonal). Summer begins with a warm period during April and May, followed by a period of maximum temperatures lasting until late August and a slow decline into November, when an abrupt temperature decrease signals the arrival of winter (Fig. 7, data). The trend component suggests that temperatures in 2009 were cooler than average, 2010 was relatively warm, and the period from 2011 to 2012 was cooler than the previous year. The remainder plots show high-frequency variability interpreted to be large-scale synoptic events that occur all year, with significantly greater peak-to-peak variability in winter. The remainder plots also show the two very distinct seasons beginning and ending either on the same day or within a matter of days across years and across sites.

The four sites in northern British Columbia (TR1–4) were again chosen for a more detailed study using STL to investigate possible reasons for the location of this tree line (Fig. 8). Despite being on average 12 km apart and ranging from 1039 to 891 m in elevation, the seasonal and remainder components of all four time series remain remarkably similar through time; when plotted together, they are almost superimposed. The seasonal component shows only very small

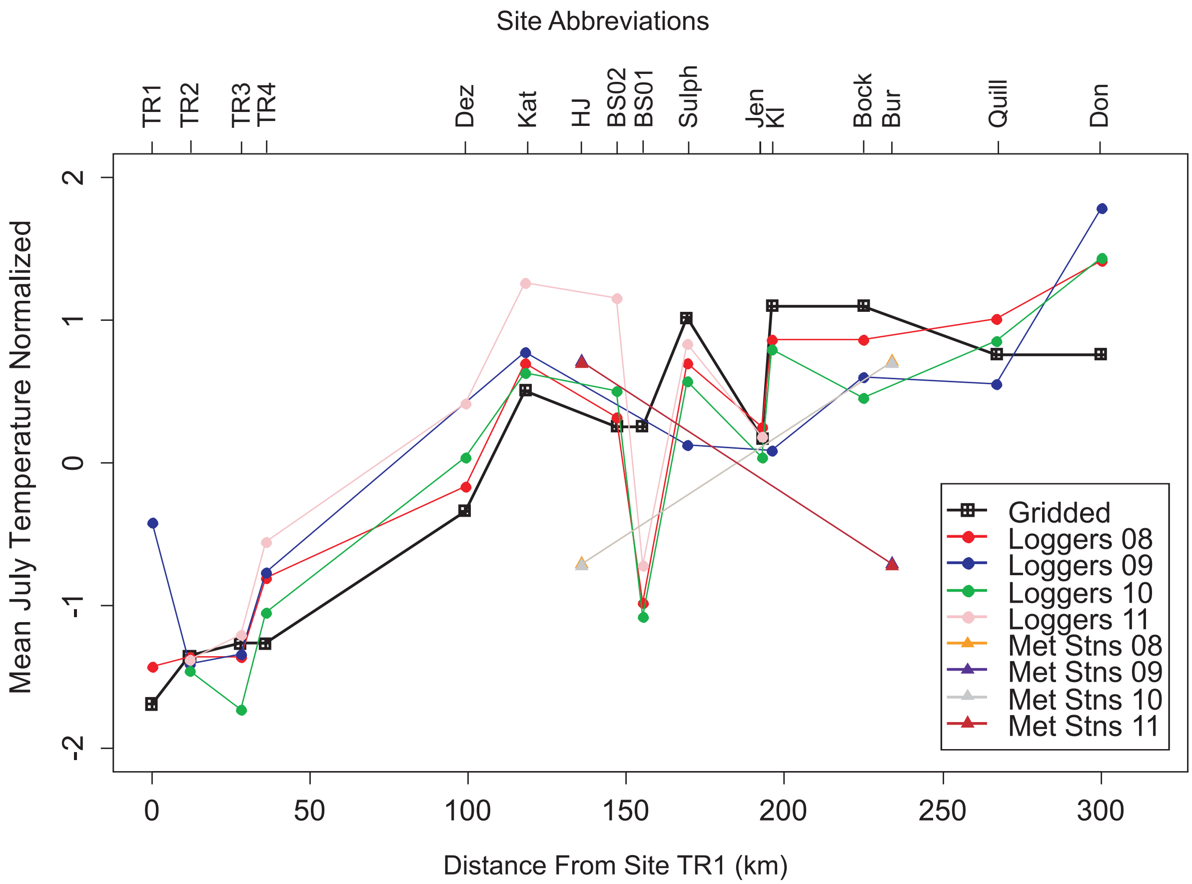

FIG. 6. Comparison of mean July temperatures from the meteorological station and data logger time series from 2008 to 2011 with values interpolated at the study sites from the CRU CL 2.0 gridded temperature dataset (New et al., 2002).

differences between sites, which are also clearly shown in Figure 5. The trend component shows that the southernmost site in the tundra (TR1) experiences the warmest temperatures overall; however, this result is likely due to radiation loading, since that logger was placed in a deciduous shrub. The remaining three trend series show the expected temperature sequence of higher temperatures at lower elevation sites.

The scatterplots of mean daily temperature (Fig. 4) show the fundamentally close association of the different data series. Nevertheless, the significance of the correlations is inflated by the high temporal autocorrelation inherent in the data series caused by the seasonal cycle and any long-term trend in the data. To account for this autocorrelation, we compared the residuals from the seasonal + trend fit from the STL for all sites and meteorological stations (Table 2). Relatively high correlations between the time series are still apparent, even at these higher frequencies. As shown in the scatterplots, correlations decrease with distance, although correlations between data loggers and stations remain above 0.7 for the majority of the pairs.

Case Studies

Hourly data were plotted for several shorter time periods to see if individual synoptic events can be traced across the area. The period from 1 to 31 May 2011 illustrates how the amplitude of the daily cycle is affected by passing fronts, and to a great extent, this effect occurs across the entire region at the same time (Fig. 9). The time evolution of the month remains similar across all of these stations. A second example from 1 to 31 December 2010 demonstrates the lack of a strong daily cycle in winter (Fig. 10). During this time period, temperatures increased from approximately −35˚C to 0˚C in the span of two days, the increase occurring slightly earlier at the southern sites. For the remainder of the month, only small fluctuations in temperature were visible during a cooling over several weeks, which was followed by more stable conditions and a second abrupt warming. This pattern is recorded at all sites along the transect, including the Haines Junction meteorological station. The increase in temperature between 3 and 4 December occurred approximately 12 hours earlier at the southern and westernmost sites, illustrating the movement of a warm air mass from the south and west (Fig. 11).

DISCUSSION

Climate of the Kluane Region

The sites chosen for this study spanned more than 400 m of elevation, three degrees of latitude, and different local

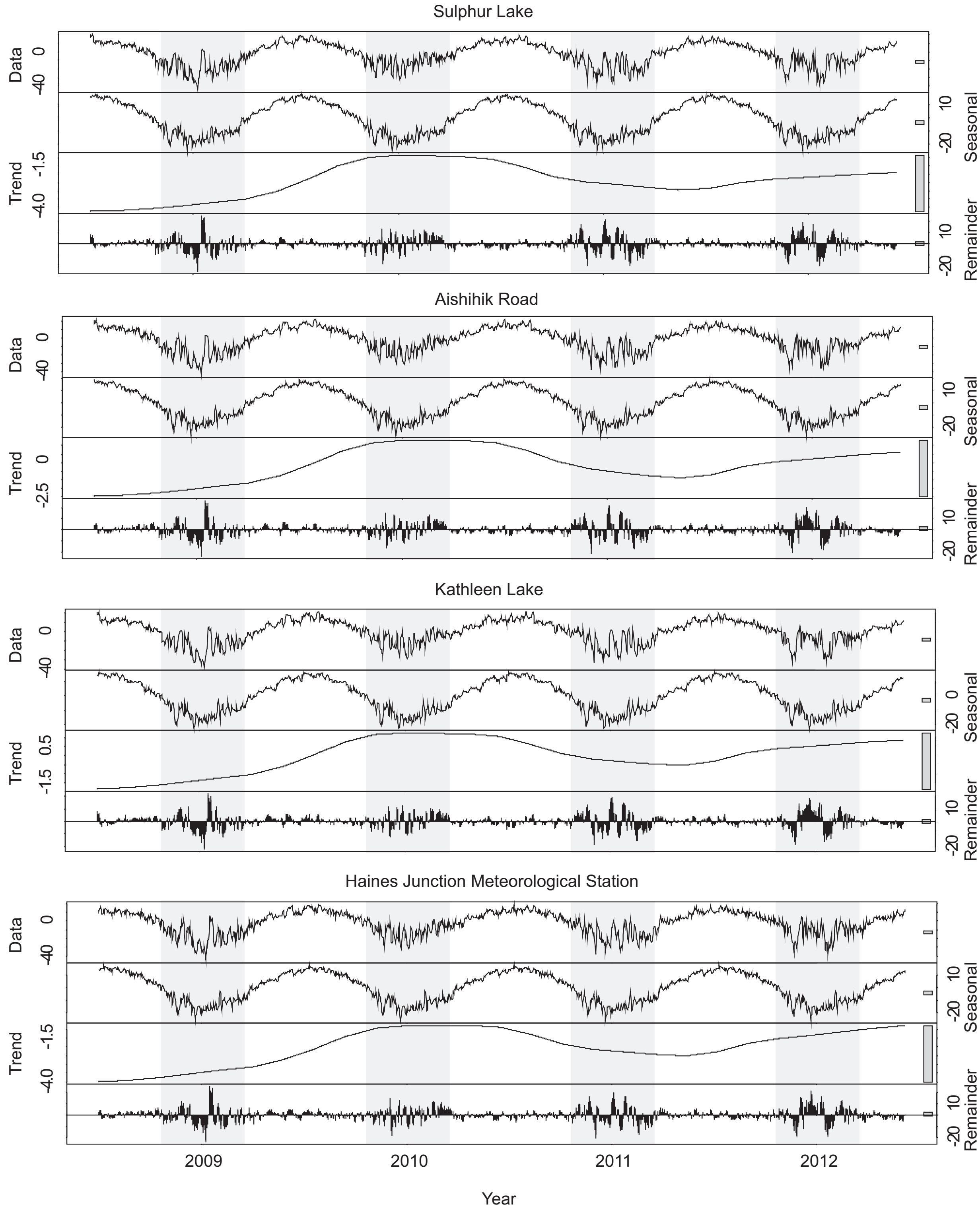

FIG. 7. STL decompositions of time series of mean daily air temperature for four sites with some of the longest records: Sulphur Lake, Aishihik Road, Kathleen Lake, and Haines Junction Meteorological Station. The grey scale bars on the right-hand side of each graph depict equal absolute values. The shaded areas represent the colder season, which occurs between 1 November and 31 March.

and regional environments (Figs. 1 and 2). Nevertheless, temperature data are highly correlated among all sites along the 280 km transect, indicating that temperature variability in both time and space is remarkably similar across the study area. These results suggest the strong control of the synoptic climate over local temperatures, even in such a topographically diverse region. Air masses traveling over this region are large in scale and hundreds of kilometers in length. The dominant airflow over the region leads to high resemblance of the temperature time series from the Donjek

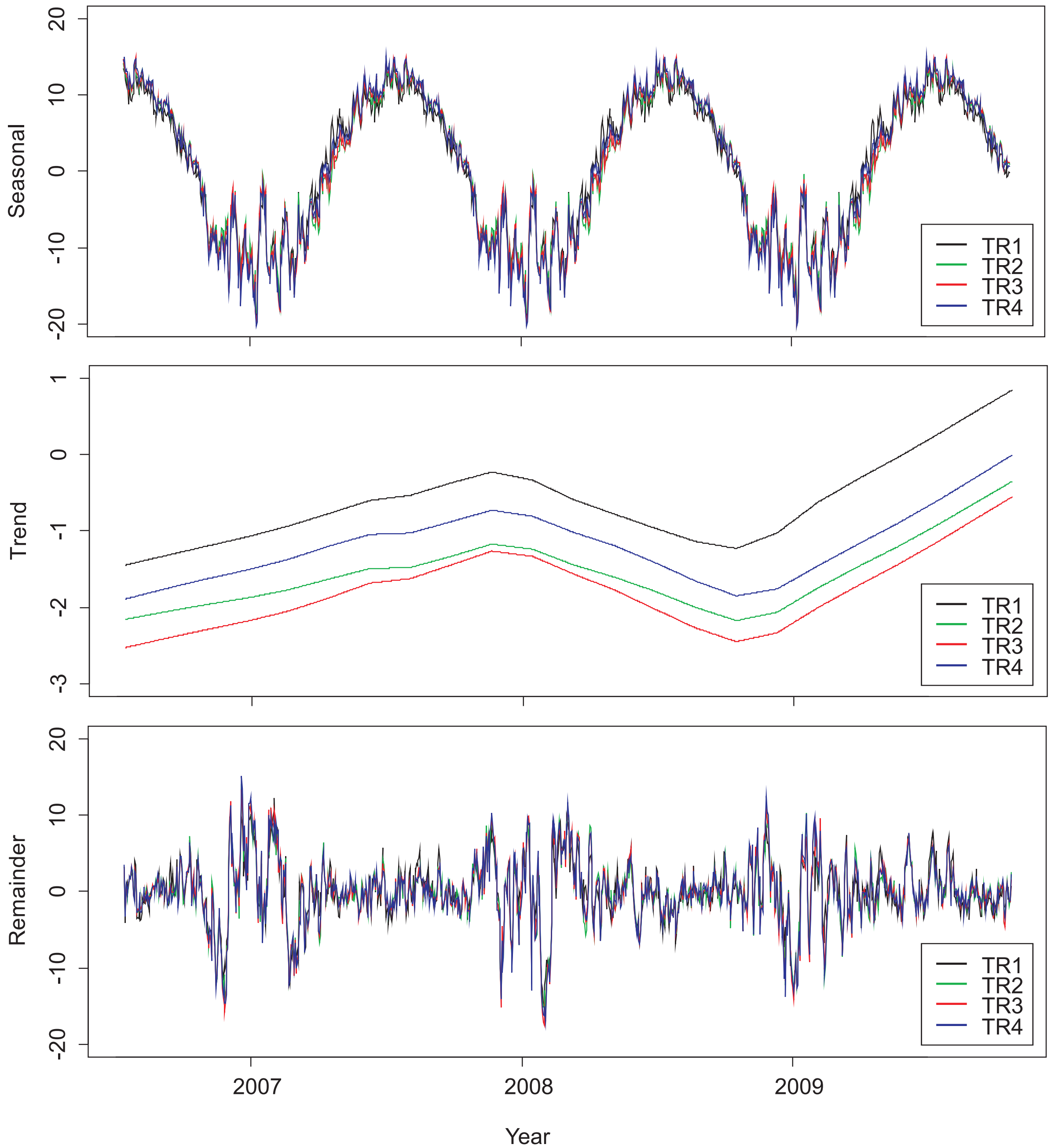

FIG. 8. STL decompositions of time series of mean daily air temperature for the four sites that cross the tree line (TR1–TR4). The four individual site values for each component are superimposed on one another.

River in the north to the high-elevation sites in the south. This synoptic effect tends to have a stronger influence on local temperatures than the local energy balance, in spite of the wide variety of slopes, vegetation types, and other potential influences on temperature. Regional phenomena such as large lakes or topoclimatic effects also seem to have little influence on local climates. Although the mean value of the temperature at a particular study site may differ from that of a nearby meteorological station because of latitude or a difference in elevation, the time evolution of the temperature should closely match that of the meteorological station. Given significant differences in the vegetation of the region (e.g., presence of black spruce and alder in the northern part of the study area and not in the south, the transition across the tree line, dry conditions near Aishihik Road not observed near Kluane Lake), we had anticipated more significant climate dissimilarities; nonetheless, apart from differences in the mean temperatures, the seasonal cycle and variability are the same across the entire area. The fact that the loggers were placed in a region where daily winter temperatures regularly exceed their specified measurement range does not appear to have influenced the results, although the accuracy of the recorded temperatures may have decreased at the coldest temperatures.

Four of the loggers were placed across the tree line in northern British Columbia, an area for which no weather

TABLE 2. Correlations between the remainders from the seasonal + trend fit from the STL of daily temperatures of study sites (lower diagonal); all are significant at 95%. Correlations are based on different subsets of data since the matrix is based on complete pairs of observations, and different series had gaps in the data that did not always overlap. Numbers of cases used to compute correlations are on the upper diagonal (shaded). Meteorological stations are separated by a bold line. Small Lake is omitted because its mean daily temperature record is very short.

	Don	Quill	Bock	Jen	KLRS	Sulph	Aish	BS1	BS2	Kat	Dez	TR4	TR3	TR2	TR1	Bur	HJ
Donjek Kettle (Don)		834	834	281	832	832	829	285	286	833	288	1327	1300	1304	1215	1552	1533
Quill Creek (Quill)	0.80		834	281	832	832	829	285	286	833	288	609	582	586	497	834	834
Bock's Lake (Bock)	0.74	0.94		281	832	832	829	285	286	833	288	609	582	586	497	834	834
Jenny Lake (Jen)	0.44	0.35	0.38		281	883	882	883	888	884	883	883	883	878	176	890	890
Kluane Lake (KLRS)	0.72	0.90	0.95	0.37		831	828	285	286	832	288	607	580	584	495	832	832
Sulphur Lake (Sulp)	0.68	0.62	0.66	0.69	0.70		1431	888	889	1435	891	1210	1183	1188	496	1435	1435
Aishhihik Road (Aish)	0.66	0.59	0.62	0.62	0.65	0.95		887	888	1431	890	1209	1182	1187	496	1431	1431
Bear Creek Summit (BS01)	0.60	0.40	0.44	0.90	0.41	0.69	0.67		888	888	888	887	887	883	181	888	888
Bear Creek Base (BS02)	0.52	0.35	0.38	0.89	0.38	0.73	0.74	0.95		889	889	888	888	884	182	894	894
Kathleen Lake (Kat)	0.64	0.56	0.63	0.61	0.64	0.93	0.96	0.69	0.75		891	1211	1184	1188	496	1436	1436
Dezadeash Lake (Dez)	0.60	0.45	0.48	0.87	0.48	0.71	0.72	0.96	0.97	0.75		890	890	886	184	891	891
TR4	0.73	0.55	0.59	0.62	0.57	0.79	0.80	0.72	0.73	0.83	0.77		1903	1907	1215	1930	1911
TR3	0.71	0.53	0.58	0.70	0.57	0.76	0.76	0.77	0.77	0.80	0.81	0.96		1898	1196	1903	1884
TR2	0.72	0.54	0.58	0.65	0.57	0.78	0.79	0.73	0.73	0.81	0.77	0.98	0.97		1205	1907	1888
TR1	0.73	0.42	0.45	0.45	0.42	0.52	0.54	0.74	0.64	0.60	0.76	0.87	0.85	0.86		1215	1196
Burwash Airport MS (Bur)	0.83	0.55	0.56	0.60	0.55	0.78	0.76	0.63	0.64	0.76	0.65	0.77	0.77	0.78	0.69		2142
Haines Junction MS (HJ)	0.76	0.53	0.56	0.60	0.60	0.90	0.93	0.65	0.71	0.89	0.69	0.85	0.82	0.85	0.72	0.81	

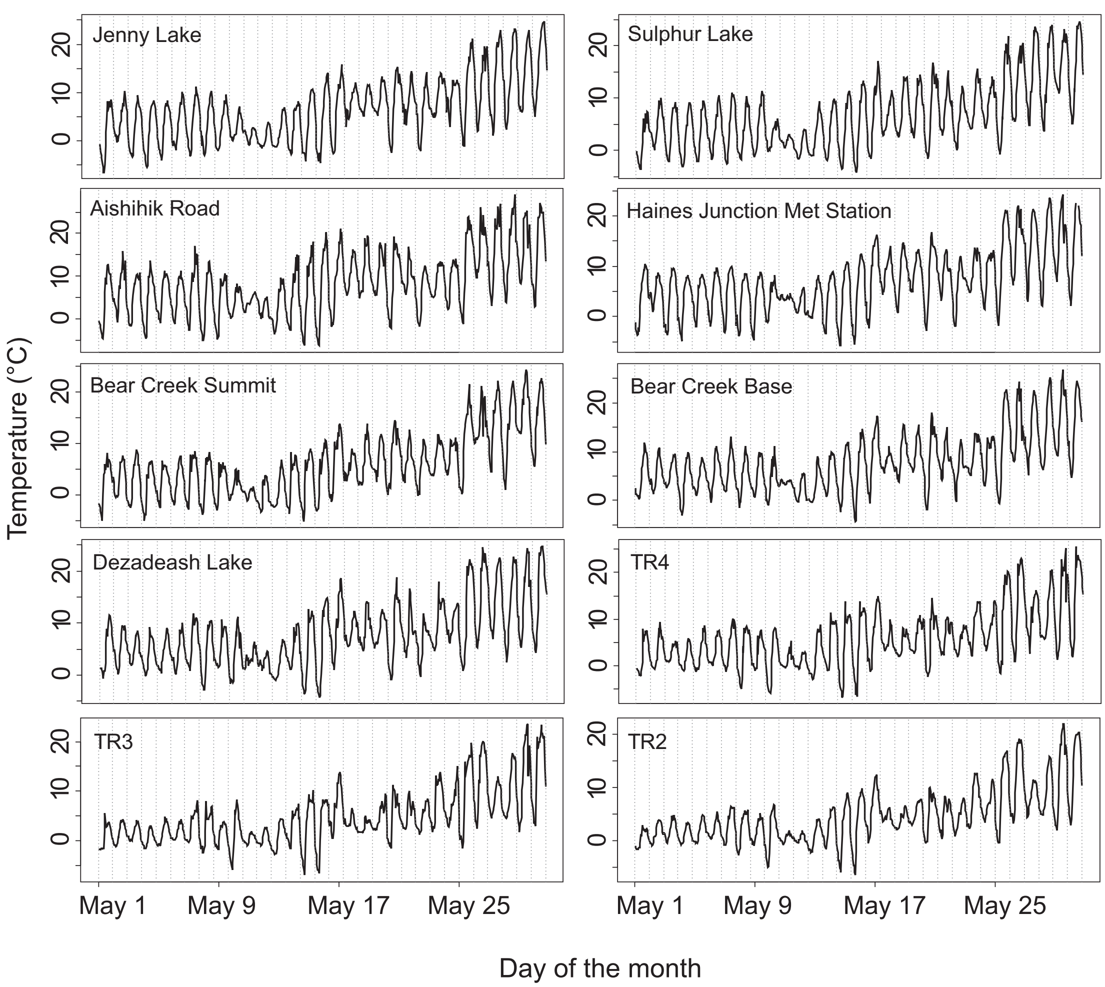

FIG. 9. Hourly air temperature data from 1 to 31 May 2011 for sites with available data during this period. Dotted lines represent 24-hour intervals.

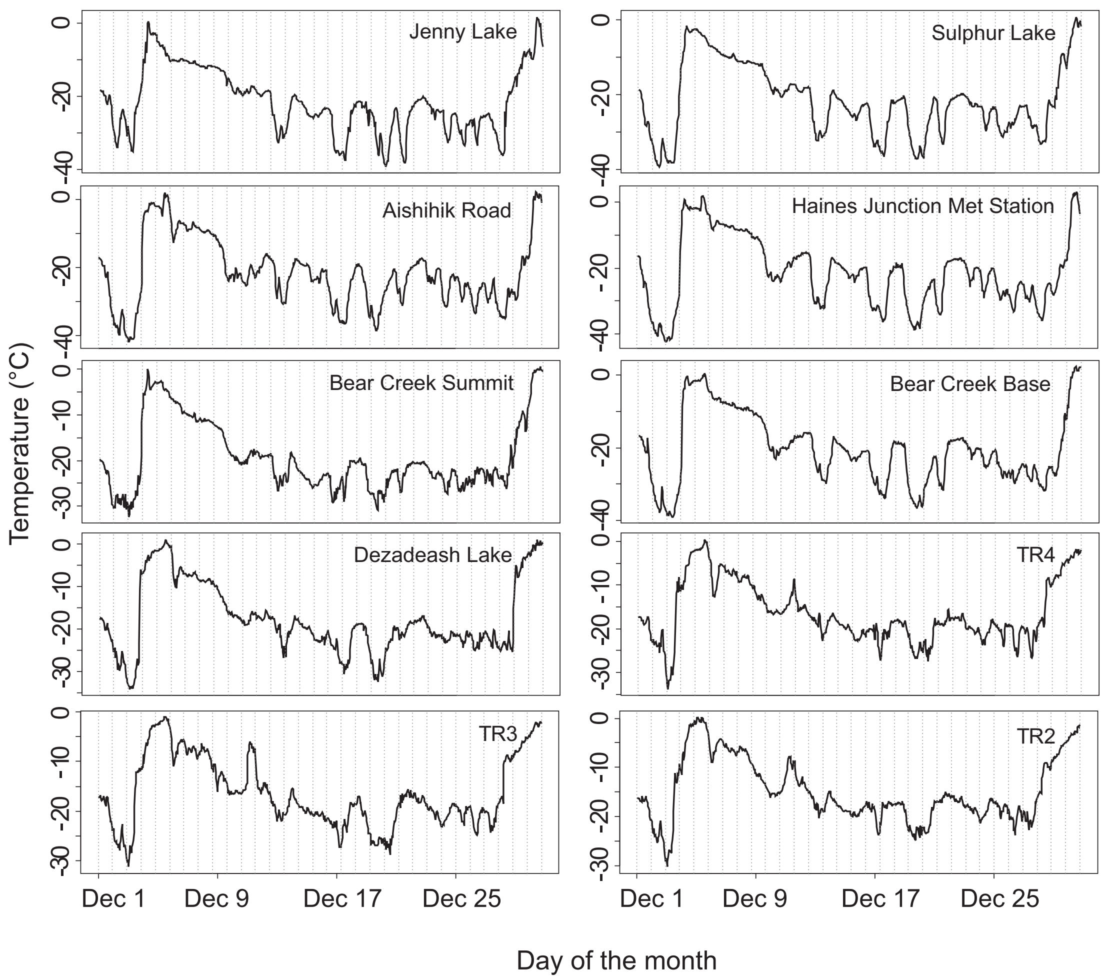

FIG. 10. Hourly air temperature data from 1 to 31 December 2010 for sites with available data during this period. Dotted lines represent 24-hour intervals.

data are available, to attempt to explain the location of this feature. The lack of a clear difference in the variability of the temperature across the tree line is a surprising outcome (Figs. 5 and 8): it suggests that the location of the tree line cannot be explained simply by temperature variability (Körner, 1998; Smith et al, 2003; Malanson et al., 2007). The tundra was the warmest of the sites, perhaps reflecting the winter inversion, although this difference may be inflated by radiation loading on the sensor. Drought effects or wind patterns may play a more dominant role in determining the position of this boundary between forest and tundra ecosystems (Danby and Hik, 2007; Holtmeier and Broll, 2007; Porter and Pisaric, 2011).

In summer, there is a strong daily cycle that is comparably expressed across the entire region (Fig. 9). The daily cycle is not observed in winter because of the low insolation, yet higher day-to-day variability is observed, with abrupt changes in temperature of up to 10˚C – 15˚C per day, as is high variability on the scale of days to weeks (Fig. 10). Individual synoptic events can be traced across the entire region through the analysis of abrupt changes in local temperature that occur consecutively along the transect within a period of approximately 12 hours. Figure 11 shows a warm front that moved simultaneously northward up the Haines Road and northeastward up the Alaska Highway as it followed the topographic structure of the Kluane region. Therefore, one primary air mass is influencing temperatures across all these sites, even though it is not being registered as a lag in the daily data because the air mass moves at hourly time scales.

Use of Data Loggers

The temperature sensors housed within the data loggers need to be shielded from solar and terrestrial radiation to provide accurate air temperature measurements; however, they are still suitable for most meteorological applications (Whiteman et al., 2000). In this study, the sensors were housed in clear plastic cases sealed from moisture by a rubber O-ring, but they were not equipped with any shields to protect against direct solar radiation. Instead, they were installed under the crowns of large spruce trees (Holden et al., 2011; Kedzia, 2011), an effective strategy when distributing several small loggers across a large area (Lundquist and Huggett, 2008). Although the trees may be having a slight microclimatic effect on the temperatures recorded by the loggers, such as increased maximum daily temperatures due to absorption of solar radiation by the dark

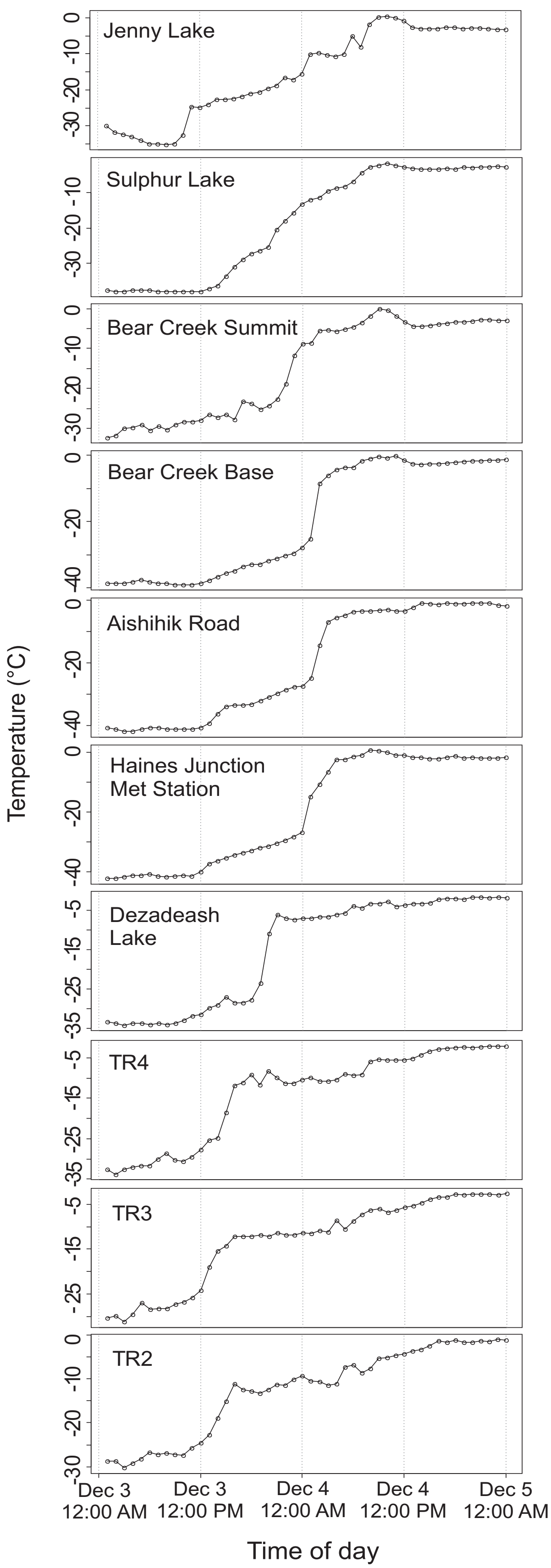

FIG. 11. Hourly air temperature data from 3 to 4 December 2010 for sites with available data during this period. Dotted lines represent 12-hour intervals.

needles, the daily series show coherent variability between sites. Although the sparse meteorological station network is generally representative of the area, the loggers can provide useful information about the gradient in temperature in northern regions.

The data used in this study were derived from instruments unlike those used in standard meteorological stations; however, the extremely close correspondence of data from stations and data from loggers suggests that the logger data can be used to characterize the local and regional climate (Fig. 3). Although the time series contained long data gaps due to battery exhaustion, there were sufficient data from these 16 data loggers to provide an accurate representation of the climate of the Kluane region, given the high correlations between all sites and the exceptionally similar time evolution. These data can be used to produce better estimates of climate at field sites.

STL Decompositions and Seasonal Variability

To our knowledge, this is the first time that daily temperature data have been used to study the high intra-annual variability of temperatures in the Kluane region. A dominant feature of the seasonal cycle of mean daily temperatures is higher variability in winter, and the abrupt transition between winter and summer seasons can be used to separate the year into these two periods (Fig. 7). There is also a distinct warming at the beginning and end of the winter season and considerable variability within a single season (Figs. 7 and 8). This pattern in temperature change is consistent across years, and it occurs within a matter of days across the different sites. Changes in the day-to-day features were identified using STL, a method that has proven to be highly useful and efficient for analyzing high-resolution temperature data covering a time period of more than one annual cycle. These data are non-stationary, and the STL clearly highlights the variability. The remainders are useful when studying microclimate effects in detail across sites and between years. In this study, nearly the same pattern is replicated in all of the time series originating from both the loggers and the meteorological stations, suggesting that microclimate effects are less apparent along this transect.

Surprisingly, the comparison of the logger data with a global gridded temperature dataset (New et al., 2002) showed a high correspondence with the logger data but a lower correspondence with the station data (Fig. 6). This result is unexpected, since meteorological station data are used to generate the gridded datasets, although the grid was based on a different averaging period than that of this study. The gridded data seem to have estimated the same temperature gradient as the loggers, as both are recording a synoptic pattern across the region, and the local effects are secondary.

Overall, the logger and station data seem to be capable of estimating the climate across the Kluane region. They can be used to interpolate data at study sites or to verify model-based interpolations. If properly maintained (e.g., loggers visited and batteries changed every year), logger data are reliable estimators of the local and regional climate. Loggers can potentially provide a complete time series with no missing data (which is not always the case for station data) and thus are a reliable, low-maintenance means of characterizing the regional climate. They can also sample and store data at higher temporal resolution than the hourly data recorded in this study.

CONCLUSIONS

The annual temperature cycle in the Kluane region is complex and can clearly be divided into two sub-annual components on the basis of temperature variability. The seasonal trend decomposition is an effective way to compare sites and resolve the scales of variability in the data. In this study, all scales were remarkably coherent along the transect of sites. We do not claim that there are no microclimatic differences in a subarctic mountain region; indeed, the aspect of a site, altitude, location in relation to wind flow, rainfall, and differences in incoming solar radiation will alter the local energy budget. However, the similarity of the time evolution of all of the temperature time series across the entire region is remarkable. Therefore, when studying the spatial variability of temperature in southwestern Yukon, the meteorological stations of Haines Junction and Burwash Airport can generally be considered representative of the entire region. The current station network captures the synoptic-scale patterns influencing much of the region, but data loggers can capture the site-to-site variability on a daily or hourly time scale. The incorporation of data-logger data permits a more precise spatial interpolation of these data. Although the data series used in this study are short, given the high correlation between these logger data and the standard meteorological stations, reasonably longer series can be computed for a particular site using simple regressions between short series and the longer series that are available.

Data loggers provide a cost-effective way of obtaining data similar (and sometimes higher in quality) to those from meteorological stations or gridded global datasets, and they do not require advanced technology or satellite communication. If field sites are visited regularly (e.g., annually), they are a practical and comparable method of obtaining high-resolution, site-specific data during field studies.

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APPENDIX 1

Time series of mean daily air temperature recorded by sixteen Hobo UA-002-64 Pendant data loggers between 13 July 2006 and 13 June 2012.