Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Open Access Earth System Science Data Discussions

Daily temperature records from a mesonet in the foothills of the Canadian Rocky Mountains, 2005-2010

Wendy H. Wood[1], Shawn J. Marshall[1], Terri L. Whitehead[1] and Shannon E. Fargey[2]

[1]Department of Geography, University of Calgary, Calgary AB, T2N 1N4, Canada
[2]Department of Geography, University of Victoria, Victoria BC, Canada

Correspondence to: Wendy Wood (whwood@ucalgary.ca)

Abstract. Near-surface air temperatures were monitored from 2005 to 2010 in a mesoscale network of 230 sites in the foothills of the Rocky Mountains in southwestern Alberta, Canada. The monitoring network covers a range of elevations from 890 to 2880 m above sea level and an area of about 18,000 km^2, sampling a variety of topographic settings and surface environments with an average spatial density of one station per 78 km^2. This paper presents the multiyear temperature dataset from this study, with minimum, maximum, and mean daily temperature data available at https://doi.pangaea.de/10.1594/PANGAEA.880611. In this manuscript, we describe the quality control and processing methods used to clean and filter the data and assess its accuracy. Overall data coverage for the study period is 91%. We introduce a weather-system dependent gap-filling technique to estimate the missing 9% of data. As a sample application of the data, we present monthly and seasonal distributions of minimum, maximum, and mean daily temperature lapse rates for the region.

1. Introduction

Air temperature is a critical environmental variable across a wide range of disciplines and processes, affecting physical, ecological, and human systems. While temperature fields can be relatively homogeneous in simple topography and surface environments, the same generalizations cannot be made over complex terrain, such as mountain environments and where there are strong horizontal gradients in topography or surface cover. However, it is commonly necessary to estimate or model temperature in such environments, where direct data are unavailable. As examples, catchment-scale hydrological models require temperature estimates to calculate snow melt (e.g., Förster et al., 2014) and glacier mass balance (Hock, 2005), landscape models of vegetation phenology and agricultural yield need distributed temperature fields (e.g., Jochner et al., 2016; Schönhart et al., 2016), and temperature is one of the influences that regulates species range (e.g., Logan and Powell, 2001; Deutsch et al., 2008; Comte et al., 2014). Applications such as these foster tremendous interest in landscape-scale temperature patterns and their structure under different weather systems.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Temperature variability across the landscape also needs to be understood to support the growing demand to model climate change impacts on Earth systems (e.g., Thomas et al., 2006; Deutsch et al., 2008; Clarke et al., 2015; Zuliani et al., 2015; Yospin et al., 2015; Franklin et al., 2016). Weather and climate models generally operate at scales of 10s to 100s of kilometers, and mean grid-cell temperatures need to be distributed over the subgrid terrain for historical climate reanalyses, real-time weather forecasts, or future climate change scenarios. Typically, few ground control stations are available on this subgrid scale to inform the interpolation schemes or the accuracy of such downscaling efforts.

These considerations motivated the establishment of the Foothills Climate Array (FCA) in the foothills of the Rocky Mountain in southwestern Alberta, Canada. An area of roughly 18,000 km^2 (120 km × 150 km) was instrumented with a two-dimensional network of automatic weather stations recording temperature, relative humidity, and rainfall. The FCA was set up in a series of east-west transects, spaced roughly 10 km apart and running from the continental divide on the western end of the study region to the flat, prairie grasslands on the eastern edge (Figure 1). Station spacing along the east-west transects was about 5 km in the mountains and 10 km for the prairie sites. The grid was designed to be roughly the size of a global climate model (GCM) grid cell.

The main objective with the FCA was to understand and quantify spatial patterns of temperature structure as a function of elevation, topographic characteristics, surface type, and weather systems in this region. This includes conventional air temperature lapse rates (the change in minimum, maximum, and mean daily temperature with elevation) and their daily and geographic variability, but also other coherent patterns of temperature variance, to inform interpolation and downscaling models of temperature as a function of terrain and weather conditions. The FCA covers a large range of backcountry environments, with a high spatial density and five years of relatively complete data, spanning an elevation range of 890 to 2880 m. We are not aware of other mesonet arrays with this kind of spatial and temporal coverage in a mountain environment.

Here we present this unique multiyear temperature dataset, to support the public availability of this data and illustrate its relevance for environmental modelling and temperature downscaling. We describe the quality control and processing methods used to clean and filter the data, assess its accuracy, and present the distribution of daily temperature lapse rates in the region as a function of month and season. These lapse rate results can improve hydrological, ecological, or glaciological modelling applications in the region, where there is a need for distributed temperature estimates based on climate models or low-elevation reference stations.

2. Study Region, Design, and Instrumentation

The FCA study area extends from the continental divide of the Rocky Mountains in the west to the relatively flat prairie farmlands about 50 km east of the City of Calgary, Alberta, centred on approximately 51°N and 114.5°W (Figure 1). The Rocky Mountains, with peak altitudes up to 3500 m, form the boundary between British Columbia and Alberta, and are aligned northwest to southeast. The Bow River is a major river basin in the study area, cutting a southeast path through the mountains before turning east and exiting the mountains east of Canmore, Alberta. In the mountains, the floor of the Bow Valley has an

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

altitude between 1300 m and 1600 m, with peaks rising more than 1000 m on either side. There are also numerous alpine lakes and low-order creeks and tributaries of the Bow River that drain the steep mountain valleys.

The upper slopes of the mountains are above treeline and consist of rock and rubble, with sparse vegetation. Coniferous forest and alpine meadows occur below the treeline. The foothills are comprised of lower-elevation rolling hills, with coniferous and aspen forests interspersed with grassy meadows. The prairies are mostly shrub, grassland, and cultivated cropland, with farming the dominant land use. Sites are classified as mountain or prairie based on their elevation and terrain variability surrounding the site. Prairie sites are generally situated below 1250 m with little terrain variability. Ten sites are situated within the Calgary municipal boundary. Elevations drop to below 900 m at the eastern edge of the survey. Thus the area and site locations comprise a wide range of elevation, topography, and surface types, including grassland, cultivated farmland, urban, forest, shrub, meadow, and bare rock.

Each FCA installation consisted of data-logging rainfall, temperature, and relative humidity gauges mounted on a pole that was either pounded into the ground or supported with a cairn. Rainfall was recorded using HOBO RG2 tipping bucket rain gauges manufactured by Onset Computer Corporation. Temperature and relative humidity (RH) were recorded at 1-hour intervals, with instantaneous measurements taken at the top of the hour, using SP-2000 temperature-relative humidity data loggers manufactured by Veriteq Instruments Inc[1]. Daily mean temperatures are calculated as the arithmetic mean of hourly values. The data loggers were mounted inside radiation shields manufactured by Onset Scientific Ltd. to protect the loggers from direct sunlight and allow air circulation. The manufacturer-reported accuracy for the data loggers is ± 0.25°C between -25°C and +70°C, with a resolution of 0.02°C at +25°C. Where possible, temperature and RH were recorded at a height of 1.5 m above the ground. At sites in areas of significant snow accumulation (commonly at elevations above 2000 m), pole extensions were added to help keep the sensors above the winter snowpack and instrument heights were between 2 and 3 m.

Between 200 and 230 stations were in operation during the main recording period from July 2005 to June 2010. Site locations sampled the varying topography and land surfaces of the area, with an attempt to establish sites on a grid that would lead to a random sampling of the landscape. Logistical realities meant that the FCA realization was not a perfectly regular grid. The local farming and ranching communities were fabulously co-operative, but permission to establish FCA sites on private land in the eastern part of the domain was not always granted, leading to gaps and irregularities. There are also numerous irregularities and gaps in coverage for the mountain sites, as some locations on the grid were inaccessible. Nonetheless, sites effectively capture a range of elevations, slopes, aspects, and surface types (Table 1).

Given the backcountry environment, the FCA design criteria necessitated portable, datalogging sensors that could be left in place for many years. We included sites that could be reached within a day's travel on foot or on bike (or commonly a combination of the two), and most of the mountain sites involved an off-trail approach (i.e. bush-whack) from the nearest trail or road. It required about 160 person-days per year (80 days for a team of two) to complete the annual rounds. The infrequent site visits and sometimes hostile conditions (e.g., high winds, tree-fall, avalanches, flooding, shootings, snow burial, wildlife

[1] Veriteq has subsequently been bought out by Vaisala, who continue to make an adapted version of this data logger.

interference) led to some challenges with data quality and missing data. The next section discusses data-processing and quality control procedures in detail.

The FCA installation began in spring 2004 and was completed in summer 2005. Data recording continued until fall 2010, when all of the stations were taken down except for one east-west transect. Prairie sites were more accessible and were visited twice annually for site maintenance and data downloads, during the spring and fall field seasons. Mountain sites were only visited once per year. Site maintenance included data collection, battery replacement, exchange of dataloggers as needed, instrument cleaning, and basic maintenance as required (e.g., reinstalled fallen or leaning instruments). The rain gauges, radiation shields, and sensors become dirty over time through exposure to dust, pollen, insects, and forest detritus (e.g., pine needles). Field notes and photographs were taken to document the physical location and condition of the sites during each visit.

Sites do not conform to World Meteorological Organization (WMO) standards, which specify that climate recording sites should be level, away from vegetation and buildings, and not in areas of variable topography (WMO, 2008). This prescription is not consistent with the purpose of the study, which is to examine topographic and surface environmental influences on weather. In fact, it was part of the project design to sample different slopes, aspects, and degrees of forest closure, to quantify deviances from flat, open control settings. This contributes to the complex patterns of spatial temperature variability that we recorded, but in a manner that is realistic with respect to landscape-scale temperature modelling. Examples of site locations are shown in Figure 2.

3. Sensor Accuracy and Quality Control

3.1 Instrument Calibration

Instruments were calibrated at the University of Calgary weather research station (WRS) before being set up in the field, and on an ongoing basis during the study. Calibration tests consisted of sensors set up at the WRS and recording instantaneous temperature at one, two, or five-minute intervals for one- to two-week periods. Data were aggregated to hourly intervals and compared with aggregated hourly temperature measurements at the WRS reference station, which uses a Campbell Scientific HMP35CF sensor mounted in a ventilated, Gill Model 41004-5 12 plate radiation shield.

Average hourly differences were calculated for all sensors for all hours in a day (24-hr), for hours between 00 and 06h (night), and between 10 and 16h (day). During the test period, if no absolute value of the hourly temperature difference between logger and WRS exceeded 3°C, a test was considered “good” and no further investigation of sensor performance was required. This was the result for 94% of calibration runs. Average differences by year are shown in Table 2. The average difference between the Veriteq loggers and WRS is –0.1°C.

Calibration tests after 2007 show more negative offsets relative to the earlier WRS values, possibly due to more tests being conducted during winter, where there may be less daytime heating effect in the unventilated sensors. Daytime heating can be an issue in unventilated radiation shields, with a potential warm bias under calm, sunny conditions (Nakamura and

Mahrt, 2005). Temperature sensors and shields have different associated errors, depending on the design of the shield, the type of sensor, and environmental conditions. The design of the shield should ensure that the air within the shield is at the same temperature as the surrounding air (WMO, 2008). Shields may rely on natural ventilation from prevailing winds or may be artificially ventilated using a fan.

Studies have investigated the magnitude of temperature differences for naturally- vs. artificially-ventilated sensors under different wind and solar radiation conditions. Daytime temperature differences are the greatest, due to solar heating, and it can be problematic at wind speeds less than 1 m s^{-1}. This heating effect may be from direct radiative heating of the sensor (Georges and Kaser, 2002) or indirect heating of the shield, which then heats the air inside the shelter. We performed an experiment at the University of Calgary WRS from October 2012 to September 2013 to quantify the effect of using naturally-ventilated sensors, as used in the FCA study, compared to a mechanically-ventilated sensor used at the WRS. The Veriteq loggers were set to record instantaneous temperature at five-minute intervals. These were aggregated to hourly values and compared with aggregated hourly average temperature measurements for the WRS reference sensor, which records at one-minute intervals.

For this set of loggers, the average difference between hourly average logger and WRS temperatures was 0.1°C for the test period. Differences averaged for the whole year for the combined wind speed and incoming shortwave radiation categories are shown in Table 3. The maximum difference of 0.7°C occurs at high solar radiation (greater than 600 W m^{-2}) and winds speeds less than 1 m s^{-1}. For high wind speeds and low solar radiation, the average difference is -0.2°C. Results in Table 3 are systematic and point to a relatively simple correction if hourly shortwave radiation and wind data are available. These are not available at the FCA sites, so this is a source of error that we must tolerate. However, the mean error in hourly temperature associated with the worst-case conditions is +0.7°C, and the daily average errors associated with unventilated sensors are much less (solar radiation is less than 600 W m^{-2} for most of the day, and throughout the winter). This source of error is likely insignificant for daily mean and minimum (overnight) temperatures, but it might affect maximum temperature measurements in sheltered locations. Sheltered sites may experience additional warming relative to exposed locations due to reduced ventilation, particularly in the summer months, but differences seldom exceed 1°C.

In the 6% of calibration tests with suspect logger performance, the logger was flagged for further examination and field records for these loggers were manually inspected. Calibration experiments exhibited a common form of sensor failure associated with periods of heavy rainfall and sustained high humidity. Under these circumstances, some sensors experienced errant, short-term behaviour, typically recording temperatures that were too high for a period of hours to days, then returning to normal. Careful examination confirms that values before and after the observed aberrations are reliable, so we retain these sensors, but quality control measures described below are designed in part to identify this behaviour. The sensors are adequately sheltered, such that rainfall itself (liquid water) is not likely the problem; rather, we suspect that water vapour diffuses into the data loggers and internal condensation can compromise the circuit board, until such time as humidity drops and the sensor dries out.

3.2 Quality Control

Assessment of data quality prior to data analysis is an essential step to ensure that only valid data are used. While sensors generally functioned well, periodically they malfunctioned or were damaged in the field, resulting in unreliable data. One challenge in identifying questionable data is to differentiate between extreme events and actual compromised data. Wade (1987) identified four general sources of measurement error, namely: instrument failure, drift, bias, and random error. Calibration tests identified that loggers do not show significant bias or drift, so these were not corrected for. Instrument failure is readily identifiable as missing data or unrealistic values. Random errors are more difficult to identify. We introduced a multi-step quality control/quality assurance (QC/QA) procedure for objective detection of errors.

Durre et al. (2010) detail comprehensive automated quality assurance procedures for daily meteorological measurements, as being applied operationally in the Global Historical Climatology Network (GHCN). Quality control procedures are designed to identify as many errors as possible with few false positives (that is, valid data flagged as unreliable data). Tests used in the procedure include: (i) physically reasonable bounds; (ii) internal consistency – the daily value should be within statistical bounds for that day in the year; (iii) external consistency – the value should lie within reasonable limits of surrounding stations; (iv) multiple duplicate or repetitive values; (v) unusually large changes in daily minimum and maximum values. We use similar tests in this study.

Quality control procedures for the FCA data include a sequence of automated (A) and manual (M) data checks applied to an entire file, hourly, daily, or monthly data, and run in the order shown below.

1. Field checks (M - entire file)
2. Time shifts (M - hourly)
3. Spikes (A - hourly)
4. Extreme values (A - hourly)
5. Snow burial (A/M - monthly)
6. Neighbourhood consistency (A/M - daily)
7. Review questionable loggers based on field notes and calibration tests (M – daily/hourly)
8. Final review (M – daily/hourly)

Field checks

During the download process, each logger's data was compared with one or more near neighbours. Downloads were characterized as "good", "some bad" or "bad" using this comparison. Where a download was characterized as bad, the entire file was excluded. Files characterized as "some bad" were included and queries were used to delete sections readily identified as erroneous based on a visual review.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Time shifts

The loggers adopt the start and end time from the computer doing the setup and download. The Spectrum v3.7c software uses the computer download time to assign a time to each measurement. Multiple machines were used for field downloads and at times the clocks were set to the wrong time zone, or alternated between daylight savings time (DST) and mountain standard time (MST). Times were commonly out by several minutes. In addition, on occasion some loggers malfunctioned and missed recording data for hours or days at a time, as seen in comparisons with neighbours. This was noted in the field notes.

The data loggers are able to store approximately 18 months of data recorded at one hour intervals. If the time between site visits was too long, or a logger was inadvertently set to record at a shorter time interval, the memory filled up and no more data were recorded. By comparing multiple neighbours, and reviewing field notes which included the actual download time and whether time was DST or MST, files with time shifts and missing data were identified. Once the data were loaded into the database, the necessary time shifts were applied. Where possible, periods of missing data were identified and measurement times adjusted to align data with neighbours.

Spikes

A directional step test used by Hall et al. (2008) identifies consecutive measurements exceeding a user-defined limit. Limits vary by location (climate region), measurement interval, and direction (rise or fall). Temperature changes of up to 9°C in five minutes have been observed in the Oklahoma mesonet. Due to such events, Graybeal et al. (2004) found step tests were capturing real frontal events, whereas actual data problems were predominantly one hour spikes rather than step changes in the data. In southern Alberta, chinook winds and cold fronts cause both large rises and falls in hourly temperature measures, but these conditions usually persist after the step change.

A review of FCA data identified by step tests indicates spikes, either up or down, lasting one or more hours can be real errors. A brief spike may not influence daily mean values enough to be identified as unusual relative to neighbours (cf. neighbourhood consistency check described later), but spikes lasting four or more hours will. Therefore, a spike test to identify spikes lasting from one to three hours was applied to FCA data. A spike was defined as a value exceeding subsequent or previous measures up to three hours apart by 5°C, either up or down.

Extreme values

Extreme values were identified using Environment Canada monthly extreme minimum and maximum values for Calgary and adding or subtracting a set amount to account for variations due to differences in elevation. Hourly values were flagged as extremes when the value exceeded the Calgary monthly maximum extreme by more than 5°C or was lower than the extreme minimum by more than 10°C.

Snow burial

Some of the high mountain sites were prone to burial by snow during late winter. Snow burial is apparent through a small diurnal range. For the snow burial test, we flag entire months where at least 25 days have a diurnal range of less than 3°C.

Days on either side of the flagged months are examined for snow burial signal and manually flagged. In general, snow burial was also identified during field checks, and blocks of data were deleted.

Neighbourhood consistency

Neighbourhood consistency checks are used to identify unusual values at a site relative to neighbouring stations. The method, threshold values, and number of stations used depend on station density, topography of the area, and the weather variable being checked. In all cases, estimated values calculated from neighbouring sites are compared to observed values and large deviations are flagged as potential errors.

Shafer et al. (2000) use a weighted average of neighbouring stations to calculate a value for the station being checked, with differences exceeding three standard deviations flagged as suspicious. In mountain regions, Lanzante (1996) suggests using vertical neighbours (closest station with a similar elevation) as an alternative to horizontal proximity.

As a means of identifying most appropriate neighbours, we specified two spatial neighbourhoods for the FCA data. A horizontal proximity neighbourhood was defined using all sites within a 25-km radius of a site (50 km for boundary sites), and a vertical neighbourhood was defined using sites in 200-m elevation bands, e.g., 1400 to 1600 m, 1600 to 1800 m. All sites above 2200 m are grouped together; therefore, this group includes the two high elevation sites above 2800 m, with the remainder of the sites being less than 2500 m. In all cases, groups consist of at least 10 sites.

The spatial proximity test accounts for local variability and the elevation band accounts for elevation consistency. The test examines daily minimum, maximum, and mean values for each site compared to the average and standard deviations calculated from all sites within elevation and horizontal proximity neighbourhoods. In calculating the neighbourhood average and standard deviation for each day, the site(s) with the lowest and highest values within the group are excluded, as are all site/days flagged as errors in previous quality control tests.

As an initial screening procedure, site/days are flagged as suspect if their daily minimum, maximum, or mean value differs from both horizontal-proximity and elevation-band neighbourhood means by more than five standard deviations. All suspect site/days are then manually reviewed and flagged as either natural variability or unreliable data. For sites identified as unreliable data, manual review generally indicated erratic sensor performance, and the threshold for questionable data was reduced to three standard deviations. All days for these sites are flagged as unreliable where any of the daily minimum, maximum, or mean exceeds the group mean values by three or more standard deviations.

Manual review of field notes

Field notes indicated any obvious issues with the site itself or unusual data. For instance, stations were sometimes found to have fallen or been knocked over. In this situation, station data were examined in relation to elevation and proximity neighbours as in the neighbour consistency check, to identify the time at which the station fell over. Sensors at ground level record too-high maxima and too-low minima during summer, and would typically become snow-buried during the winter. All data from the time of station compromise were removed.

Final review

Apart from entire files or obvious bad data blocks excluded from the compiled file, data are flagged as bad rather than being deleted. A different flag is assigned for each quality control test failure. The final review looks at groups of data with flags turned on or off to verify that tests have correctly identified errant data, and no suspect data remains. Any further bad data identified in this final review, most commonly seen in days on either side of failed test days or very few days remaining in a month, are flagged.

As the topography of the FCA and the climate of southwestern Alberta show high variability, quality control checks were applied leniently in order to retain interesting data; therefore, some questionable data may be retained as well. On average, 91% of data were good and 9% of data were flagged as unreliable and excluded from the analysis. Missing data are distributed randomly in the study area, with missing or suspect data affecting 70% of the sites.

4. Gap-Filling of Missing Data

While overall data coverage is excellent, given the remote nature of the FCA and the infrequent site visits, missing data do compromise the utility of the dataset, e.g. in determination of monthly or annual means. Stooksbury et al. (1999) show that three-day data gaps can result in errors of ±1°C in the calculation of monthly means, with larger errors during winter and in continental interior locations. Missing or erroneous data can also cause poor performance in interpolation or modelling of temperature surfaces. We therefore introduce gap-filling measures for the 9% of the data that is missing, to make for straightforward and reliable application of this dataset.

Approaches to gap-filling depend on the environment and the neighbourhood of stations that are available for modelling of missing data. Nkemdirim (1996) created monthly regression equations using closely-correlated stations to recreate daily minimum and maximum temperatures in southern Alberta. Eischeid and Pasteris (2000) used between one and four most closely correlated neighbouring stations to estimate daily minimum and maximum temperatures for the western United States, using a version of the general linear least squares regression estimation – least absolute deviations criteria. Both studies calculated correlations on a monthly basis. However, Courault and Monestiez (1999) note that station correlations vary with wind direction and topographic location, indicating that the most correlated station may vary during any month.

We tested gap-filling methods using the most closely-correlated stations, calculated by month and by weather type. The latter requires a classification system for regional weather systems, which we describe briefly below. Station temperatures are highly correlated, but the coefficients and most highly-correlated station vary by month and weather type. For each station, the most highly-correlated neighbour station with available data is used as the predictor variable. Because of missing data, different neighbours can be used to estimate the same station data for a given month or weather type. A regression/prediction

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

equation is generated for each station-neighbour pair. The next two sections briefly describe the weather classification system and the accuracy of the gap-filling methods. Readers are referred to Wood (2017) for further details.

4.1 Weather System Classification

We classify daily weather type based on a discriminant function analysis (DFA), seeded with the surface characteristics of the primary weather patterns that occur in our study region (Table 4). Daily weather conditions are characterized from the long-term data available at the Meteorological Service of Canada station at Calgary International Airport (Environment Canada, 2015). The seasonal cycle in weather variables is removed in order to use a year-round classification. We calculate mean daily conditions using an 11-day moving window for the period 1970-2010. The DFA uses weather anomalies relative to these mean daily values (Wood, 2017).

The control groups for the DFA weather types are based on manually-classified daily weather systems and conditions from October, 2013 to September, 2014. The identified weather classes include: (i) cold, dry (i.e. continental polar) air masses (CD), (ii) chinook conditions (Ch), (iii) cool, wet (cyclonic) weather systems (CW), (iv) warm, high-pressure conditions (Ht), (v) cold-front transition days (Tr), and (vi) normal conditions (Nl), which are defined as days with all surface weather characteristics generally within one standard deviation of their long-term mean value. Selected characteristics of these weather types are listed in Table 4.

The accuracy for the final DFA model is 81% using jackknife cross-validation, where each day is left out in turn, prediction functions are calculated with the remaining data, and these functions are used to predict the omitted day. The CD and Nl types are consistently well-predicted, with accuracies between 80 and 90%, while the remaining types vary from 50 to 90%, with transition days proving most difficult to capture.

The spatial characteristics of weather systems were found to vary seasonally, so weather types were further divided into seasonal sub-groups. Three seasons were defined: winter (November to February), summer (May to August), and autumn/spring (September, October, March, April). As the normal weather type (Nl) comprises more than 50% of days, and correlations and topographic influences show an annual cycle, correlations were also calculated for Nl days grouped by month.

4.2 Accuracy of the Gap-Filling Models

Mean absolute errors by month and weather type are shown in Table 5 for minimum ($T_{\min}$), maximum ($T_{\max}$), and mean daily (T_d) temperatures. Values are further divided into mountain and prairie subsets of the data. Weather-type estimates are better than those based on monthly correlations, with T_d having the lowest errors, followed by $T_{\max}$ and $T_{\min}$. Errors for all temperature measures are larger in the cold months, November to February. Although there is still a lot of inherent variability within weather types, seasonal weather type correlations improve estimates by ~7% over monthly correlations. Error reductions based on weather type are most significant for cold-front transition, cool-wet, and chinook days.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Missing temperature data in the FCA are gap-filled using regression equations generated using the most closely correlated station for each site, where correlations are calculated by seasonal weather type. Mean absolute errors based on seasonal weather type range from 0.40°C (T_d in the prairies) to 0.84°C ($T_{\min}$ in the prairies). Of site/day errors for all methods, 90%, 95%, and 98% are less than 2°C for $T_{\min}$, $T_{\max}$ and T_d, respectively. The geographic distribution of errors is shown in Figure 3. Figure 4 plots mean site error estimates vs. elevation. Errors in $T_{\max}$ and T_d increase with elevation and are lowest for the prairie sites. Errors for $T_{\min}$ show no relationship with elevation.

5. Sample Application: Monthly Lapse Rates in the Foothills Region

The FCA dataset provides a rich multi-year dataset sampling spatial and temporal patterns of temperature variability in the Canadian Rockies foothills and prairies of southwestern Alberta. The detailed regional temperature structure will be analyzed elsewhere as a function of daily weather type. Here we report on the daily, monthly, and seasonal temperature lapse rates recorded by the array over the period July 2005-June 2010.

Mean daily lapse rates are calculated based on a regression of temperature vs. elevation over all available FCA mountain data for each day. We calculate this for $T_{\min}$, $T_{\max}$, and T_d. Mean values and standard deviations are summarized in Table 6, and Figure 5 plots the distribution of lapse rates for mean daily temperature for each month. Monthly values are based on the mean of individual days; over five years, this gives $N \sim 150$ for each month in Table 6. Inversion frequency is also reported for each period and temperature measure, calculated from the percent of days with positive lapse rates.

As Shea et al. (2004) report for the region, there is strong monthly and seasonal variability in the near-surface temperature lapse rates, with shallower lapse rates in the winter months. The FCA dataset provides an unprecedented level of detail in lapse rate estimates, with a large number of stations sampling higher elevations in the foothills. This provides much more reliable estimates of the seasonal lapse rate structure, as the long-term meteorological records used by Shea et al. (2004) are primarily restricted to the valley bottoms. Seasonal temperature structure and its relation with elevation across the region are highly variable, but several systematic results are evident in Table 6.

There are significant differences between minimum, mean, and maximum temperatures and the monthly inversion frequencies for each. Maximum temperature has the steepest lapse rates in all months and is the least prone to inversions with altitude. Monthly values range from –5.5 to –8.9°C km^{-1} and are steepest in the spring and autumn. On average, maximum temperature inversions occur only 1.5% of the time outside of the winter months (i.e., from March through November), and 9.3% of the time from December through February (DJF). Winter inversions are common in this region in association with cold, continental polar air masses (e.g., Cullen and Marshall, 2011), and these air mass inversions are sometimes strong enough to persist through the day, affecting the late afternoon (maximum) temperatures. Under these conditions, comparatively warm, westerly air commonly overrides the shallow, cold air mass that is in place, supporting the inversion structure.

We are not certain why spring and autumn lapse rates are steeper than those in the summer. High levels of solar radiation in the summer months may drive warming at higher elevations, where radiation is stronger and there is less topographic shading. Conversely in spring, snow cover at higher elevations will help to maintain cold temperatures through both its direct thermal influence (maintaining ground temperatures at or below 0°C) and through its high albedo, which reduces the net shortwave radiation available to warm these altitudes. This supports steep lapse rates during this season.

Mean and minimum temperatures show similar seasonal structure to maximum temperatures, with the steepest and shallowest values in spring and winter, respectively. Inversion frequency and lapse rate variability are much greater in the winter season, and are lowest in the summer. Monthly lapse rates for mean temperature vary from –3.0 to –6.5°C km^{-1}, with an annual mean of –4.8°C km^{-1}. This is shallower than the free-air lapse rates that are typically used for temperature downscaling in mountain weather applications such as ecological, hydrological, or glaciological modelling. Regional-scale inversions occur on 21% of days in the winter season, but are relatively rare in the spring, summer and fall (2% of days).

Minimum temperature lapse rates are even more shallow, varying from –0.1 to –3.8°C km^{-1}, with an annual mean of –2.0°C km^{-1}. This is a large departure from free-air lapse rates, and is driven by the overnight development of cold-air drainage and pooling at lower elevations, as well as the prevalence of cold, shallow air masses in the study region, particularly in the winter season. Minimum temperature inversions are observed on 38% of days in the winter months and 24% of days annually, and are common in all seasons. The shallow minimum temperature lapse rates are important to consider for applications such as snowpack thermal modelling for avalanche studies (e.g., for modelling of surface hoar development) and minimum-temperature controls on invasive species (e.g., sensitivity of mountain pine beetle to cold temperatures; Logan and Powell, 2001).

6. Summary

Data gathered within the Foothills Climate Array (FCA) offer a unique collection of high-density, multi-year observations in complicated mountain terrain. These data provide a detailed three-dimensional view of the near-surface temperature structure and its temporal variability as a function of season and weather type.

The Veriteq temperature instruments used in this study performed exceptionally well, with high accuracy and no drift over time. Multi-stage quality control procedures were successful in identifying and removing questionable data. In total, 9% of data collected at the ~230 sites between 2005 and 2010 are missing or unreliable. Missing and unreliable data are distributed randomly in the study area. While the dense station network provides some redundancy and the percentage of missing data is not high, gap-filling to create a complete dataset has benefits for applications requiring monthly means or for creating interpolated temperature surfaces. We have therefore gap-filled the data that is made available here, with a flag to denote that these data have been estimated.

Daily temperature lapse rates in the southwestern Alberta foothills show a strong seasonal cycle, with shallower values and greater variability in the winter months. Lapse rates of maximum temperature are steeper and are similar to free-air lapse rate values (e.g. –7.5°C km^{-1}) that are commonly used in temperature downscaling or extrapolation in mountainous terrain, but lapse rates of mean and minimum temperature are much shallower, with mean annual values of –4.8°C km^{-1} and

–2.0°C km^{-1}, respectively. Minimum temperature inversions are frequent year-round, and are present on 38% of days in the winter months.

Because of the high degree of daily lapse rate variability, which is associated with different air masses and weather systems, a single value should not be adopted for the lapse rate in applications requiring temperature downscaling or extrapolation of low-elevation station data to higher elevations. Specific monthly values are recommended for temperature modelling, treating minimum, mean, and maximum temperatures differently. Within a month, the variability in lapse rates can be reasonably well approximated by normal or Poisson distributions, and for temperature modelling we recommend sampling of monthly distributions to better capture the variability and extremes in near-surface temperature. Sampling of a probability distribution also allows for a representation of temperature inversions with an appropriate frequency.

The lapse rate values and variability reported here are specific to our region, but the general behaviour of temperature lapse rates over the terrain, the observation of systematic daily and seasonal variability, and the recommended approach to temperature modelling are expected to be relevant to all mountain regions. In mid-latitude regions like our study area there is additional complexity due to air mass and frontal interactions, and their interaction with the terrain. These effects will be examined in more detail elsewhere, through consideration of daily weather types and their influence on regional temperature patterns and lapse rates.

Acknowledgements

The Foothills Climate Array was funded by the Canada Foundation for Innovation, the Natural Sciences and Engineering Research Council (NSERC) of Canada, and the Canada Research Chairs program. We thank Rick Smith at the University of Calgary weather research station for his invaluable help over the lifetime of the FCA study. Graduate and undergraduate students, summer research assistants, friends, and volunteers that contributed to the FCA study are too numerous to list, but prominent within this group are Kelly Racz, Kara Przeczek, and Bridget Linder. We could not have managed this study without their dedication and enthusiasm.

References

Clarke, G.K.C., Jarosch, A.H., Anslow, F.S., Radic, V. and Menounos, B.: Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8, 372-377, doi:10.1038/ngeo2407, 2015.

Comte, L., Murienne, J. and Grenouillet, G.: Species traits and phylogenetic conservatism of climate-induced range shifts in stream fishes. Nature Communications, 5, 5023, doi:10.1038/ncomms6053, 2014.

Courault, D. and Monestiez, P.: Spatial interpolation of air temperature according to atmospheric circulation patterns in southeast France. International Journal of Climatology, 19 (4), 365-378, doi:10.1002/(SICI)1097-0088(19990330)19:4<365::AID-JOC369>3.0.CO;2-E, 1999.

Cullen, R.M. and Marshall, S. J.: Mesoscale temperature patterns in the Rocky Mountains and foothills region of southern Alberta. Atmosphere-Ocean, 49 (3), 189-205, doi:10.1080/07055900.2011.592130, 2011.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak D.C. et al.: Impacts of climate warming on terrestrial ectotherms across latitude. Proceedings of the National Academy of Sciences of the U.S.A., 105, 6668–6672, doi: 10.1073/pnas.0709472105, 2008.

Durre, I., Menne, M.J., Gleason, B.E., Houston, T.G. and Vose, R.S.: Comprehensive automated quality assurance of daily surface observations. Journal of Applied Meteorology and Climatology, 49 (8), 1615-1633, doi: 10.1175/2010JAMC2375.1, 2010.

Eischeid, J. K. and Pasteris, P.A.: Creating a Serially Complete, National Daily Time Series of Temperature and Precipitation for the western United States. Journal of Applied Meteorology, 39 (9), 1580-1591, doi.org/10.1175/1520-0450(2000)039<1580:CASCND>2.0.CO;2, 2000.

Environment Canada, http://climate.weather.gc.ca/climate_data/daily_data_e.html?StationID=50430. Historical climate data for Calgary International Airport, last access 2 November 2015.

Förster, K., Meon, G., Marke, T. and Strasser, U.: Effect of meteorological forcing and snow model complexity on hydrological simulations in the Sieber catchment (Harz Mountains, Germany). Hydrol. Earth Syst. Sci., 18, 4703–4720, doi:10.5194/hess-18-4703-2014, 2014.

Franklin, J., Serra-Diaz, J.M., Syphard, A.D. and Regan, H.M.: Global change and terrestrial plant community dynamics. Proceedings of the National Academy of Sciences of the U.S.A., 113 (14), 3725-3734, doi: 10.1073/pnas.1519911113, 2016.

Georges, C. and Kaser, G.: Ventilated and unventilated air temperature measurements for glacier-climate studies on a tropical high mountain site. Journal of Geophysical Research, 107 (D24), 4775, doi:10.1029/2002JD002503, 2002.

Graybeal, D.Y., DeGaetano, A.T. and Eggleston, K.L.: Improved quality assurance for historical hourly temperature and humidity: Development and application to environmental analysis. Journal of Applied Meteorology, 43 (11), 1722-1735, doi:10.1175/JAM2162.1, 2004.

Hall Jr, P.K., Morgan, C.R., Gartside, A.D., Bain, N.E., Jabrzemski, R. and Fiebrich, C.A.: Use of climate data to further enhance quality assurance of Oklahoma Mesonet observations. 20th Conf. on Climate Variability and Change, 2008.

Hock, R.: Glacier melt: a review of processes and their modelling. Progress in Physical Geography, 29 (3) 362–391, 10.1191/0309133305pp453ra, 2005.

Jochner, S., Sparks, T.H., Laube, J. and Menzel, A.: Can we detect a nonlinear response to temperature in European plant phenology? Int. J. Biometeorol. 60 (10), 1551-1561. doi:10.1007/s00484-016-1146-7, 2016.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Lanzante, J.: Resistant, robust and non-parametric techniques for the analysis of climate data: Theory and examples, including applications to historical radiosonde station data. International Journal of Climatology, 16 (11), 1197-1226, doi:10.1002/(SICI)1097-0088(199611)16:11<1197::AID-JOC89>3.0.CO;2-L, 1996.

Logan, J.A. and Powell, J.A.: Ghost forests, global warming, and the mountain pine beetle (Coleoptera Scolyridae). American Entemologist, 47 (3), 160-172, doi:10.1093/ae/47.3.160, 2001.

Nakamura, R. and Mahrt, L.: Air temperature measurement errors in naturally ventilated radiation shields. Journal of Atmospheric and Oceanic Technology, 22, 1046-1058, doi:10.1175/JTECH1762.1, 2005.

Nkemdirim, L.: Canada's chinook belt. International Journal of Climatology. 16 (4): 441-462, 1996.

Schönhart, M., Schauppenlehner, T., Kuttner, M., Mirchner, M. and Schmid, E.: Climate change impacts on farm production, landscape appearance, and the environment: Policy scenario results from an integrated field-farm-landscape model in Austria. Agricultural Systems, 145, 39–50, doi:10.1016/j.agsy.2016.02.008, 2016.

Shafer, M., Fiebrich, C., Arndt, D., Fredrickson, S. and T. Hughes, T.: Quality assurance procedures in the Oklahoma Mesonetwork. Journal of Atmospheric and Oceanic Technology, 17 (4): 474-494, doi:10.1175/1520-0426(2000)017 <0474:QAPITO>2.0.CO;2, 2000.

Shea, J.M., Marshall, S.J. and Livingston, J.: Glacier distributions and climate in the Canadian Rockies. Arctic, Antarctic, and Alpine Research, 36 (2), 272-279, doi:10.1657/1523-0430(2004)036<0272:GDACIT>2.0.CO;2, 2004.

Stooksbury, D., Idso, C. and Hubbard, K.: The effects of data gaps on the calculated monthly mean maximum and minimum temperatures in the continental United States: A spatial and temporal study. Journal of Climate, 12 (5), 1524-1533, doi:10.1175/1520-0442(1999)012<1524:TEODGO>2.0.CO;2, 1999.

Thomas, C.D., Franco, A.M.A. and Hill, J.K.: Range retractions and extinction in the face of climate warming. Trends Ecol. Evol., 21, 415–416, doi:10.1016/j.tree.2006.05.012, 2006.

Wade, C.G.: A quality control program for surface mesometeorological data. Journal of Atmospheric and Oceanic Technology, 4 (3): 435-453, doi:10.1175/1520-0426(1987)004<0435:AQCPFS>2.0.CO;2,1987.

Wood, W.H.: Topographic and geographic influences on near-surface temperatures under different seasonal weather types in southwestern Alberta. Unpublished PhD Thesis, University of Calgary, 2017.

Wood, W.H., Marshall, S.J., Fargey, S.E. and Whitehead, T.L.: Daily temperature data from the Foothills Climate Array mesonet, Canadian Rocky Mountains, 2005-2010. *PANGAEA*, https://doi.org/10.1594/PANGAEA.880611, 2017.

World Meteorological Organization: Guide to meteorological instruments and methods of observations. 7th edition. World Meteorological organization, Geneva, Switzerland, 2008.

Yospin, G.I., Bridgham, S.D., Neilson, R.P., Bolte, J.P, Bachelet, D.M., Gould, P.J., Harrington, C.A., Kertis, J.A., Evers, C. and Johnson, B.R.: A new model to simulate climate-change impacts on forest succession for local land management. Ecol Appl., 25 (1), 226-242, doi:10.1890/13-0906.1, 2015.

Zuliani, A., Massolo, A., Lysyk, T., Johnson, G., Marshall, S., Berger, K. and Cork, S.C.: Modelling the northward expansion of Culicoides Sonorensis (Diptera Ceratopogonidea) under future climate scenarios. PLoS ONE, 10 (8), e0130294, doi:10.1371/journal/pone.0130294, 2015.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Tables and Figures

Elevation (m)			**Slope (°)**			**Aspect**			**Land surface**	
800-999	21		flat	66		EW	72		forest	66
1000-1199	56		1-5	71		N	33		grass-shrub	127
1200-1399	45		5-10	38		NE	44		rock-rubble	22
1400-1599	28		10-15	22		NW	9		urban	9
1600-1799	26		15-20	21		S	19		wetland	8
1800-1999	22		20-25	6		SE	31			
2000-2199	18		25-30	6		SW	24			
2200-2399	10		>30	2						
2400-2599	4									
>2800	2									

Table 1. The number of sites having different elevation, slope, aspect, and land surface types.

		Average temperature difference logger-WRS (°C)		
Year	**No. Tests**	**00h00-24h00**	**10h00-16h00**	**00h00-06h00**
2004	216	–0.02	0.13	–0.09
2005	67	–0.01	0.10	–0.08
2006	6	–0.13	–0.04	–0.20
2007	38	–0.05	0.16	–0.16
2008	48	–0.20	–0.25	–0.16
2009	73	–0.22	–0.26	–0.20
2010	140	–0.21	–0.23	–0.19
2011	83	–0.23	–0.36	–0.20

Table 2. Test result statistics by year showing the total number of tests performed, the average difference between the hourly logger and WRS temperatures for all hours 00h to 24h, hours between 10h and 16h, and 00h and 06h.

	incoming shortwave radiation (W m^{-2})		
wind speed (m/s)	**<300**	**300-600**	**>600**
<1	0.3	0.4	0.7
1-2	0.3	0.4	0.5
2-3	0.2	0.3	0.3
3-5	0.1	0.0	0.1
>5	-0.2	0.0	0.0

Table 3. The average hourly temperature difference (°C) between Veriteq loggers and the WRS temperature sensor at different wind speeds and incoming shortwave radiation values.

Weather type	500 hPa pattern	Surface temperature anomaly	Diurnal temperature range	Pressure anomaly	Wind direction	Relative humidity	Specific humidity
Cold dry (CD)	strong trough	strong negative	low/average	positive	N/NE		low
Chinook (Ch)	ridge	strong positive			W/SW strong	low	
Cold-front transition (Tr)	variable		high		variable		
Cool wet (CW)	large cyclone in southern Alberta	negative	low	negative	E/SE	high	high
Warm, high-pressure (Ht)	strong ridge	positive	high	positive	S/SW light		high

Table 4. Selected qualitative surface meteorological characteristics associated with different weather types in southern Alberta.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Open Access Earth System Science Data Discussions

Mean absolute error (°C) using correlated stations calculated by (a) month and (b) weather type.												
(a)		mountain		prairie			(b)		mountain		prairie	
Month	Tvar	mnth	wt	mnth	wt		Weather Type	Tvar	mnth	wt	mnth	wt
	Tmax	0.87	0.80	0.79	0.73			Tmax	0.88	0.86	0.62	0.61
Jan	Tmean	0.69	0.63	0.59	0.55		CD	Tmean	0.56	0.53	0.41	0.39
	Tmin	1.06	0.98	1.11	1.04			Tmin	0.86	0.79	0.85	0.79
	Tmax	0.83	0.80	0.76	0.72			Tmax	0.75	0.65	0.61	0.54
Feb	Tmean	0.63	0.60	0.53	0.50		Ch	Tmean	0.59	0.52	0.51	0.46
	Tmin	1.05	0.97	1.05	0.99			Tmin	1.01	0.94	1.06	0.99
	Tmax	0.76	0.71	0.65	0.61			Tmax	0.78	0.70	0.58	0.53
Mar	Tmean	0.50	0.47	0.46	0.43		CW	Tmean	0.43	0.36	0.36	0.30
	Tmin	0.93	0.85	0.93	0.85			Tmin	0.69	0.55	0.65	0.52
	Tmax	0.75	0.71	0.60	0.53			Tmax	0.72	0.70	0.55	0.52
Apr	Tmean	0.45	0.43	0.40	0.36		Ht	Tmean	0.55	0.53	0.43	0.41
	Tmin	0.79	0.75	0.85	0.80			Tmin	0.91	0.87	0.94	0.92
	Tmax	0.74	0.67	0.50	0.46			Tmax	0.76	0.71	0.58	0.55
May	Tmean	0.42	0.38	0.34	0.29		Nl	Tmean	0.52	0.49	0.42	0.40
	Tmin	0.72	0.64	0.80	0.73			Tmin	0.86	0.81	0.89	0.85
	Tmax	0.73	0.69	0.50	0.47			Tmax	0.86	0.74	0.71	0.63
Jun	Tmean	0.42	0.40	0.31	0.29		Tr	Tmean	0.53	0.47	0.42	0.36
	Tmin	0.72	0.67	0.72	0.67			Tmin	0.87	0.73	0.85	0.71
	Tmax	0.68	0.66	0.49	0.47							
Jul	Tmean	0.41	0.40	0.29	0.29							
	Tmin	0.75	0.71	0.70	0.68							
	Tmax	0.70	0.65	0.51	0.48							
Aug	Tmean	0.43	0.40	0.34	0.32							
	Tmin	0.75	0.68	0.76	0.71							
	Tmax	0.71	0.67	0.46	0.45							
Sep	Tmean	0.50	0.47	0.36	0.35							
	Tmin	0.77	0.74	0.81	0.78							
	Tmax	0.78	0.73	0.51	0.49							
Oct	Tmean	0.54	0.50	0.42	0.41							
	Tmin	0.83	0.78	0.86	0.83							
	Tmax	0.79	0.75	0.59	0.58							
Nov	Tmean	0.61	0.57	0.50	0.46							
	Tmin	0.99	0.93	1.01	0.94							
	Tmax	0.94	0.88	0.72	0.69							
Dec	Tmean	0.74	0.68	0.55	0.52							
	Tmin	1.07	1.00	1.08	1.03							

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Table 5. Mean absolute temperature errors (°C) calculated using the most highly-correlated station by month (mnth) and weather type (wt), shown for each (a) month and (b) weather type for prairie and mountain sites.

	Tmax			Tmean			Tmin		
Period	lapse rate	stdev	inv (%)	lapse rate	Stdev	inv (%)	lapse rate	stdev	inv (%)
January	–6.6	4.0	7.7	–3.7	4.1	19.4	–0.9	4.5	34.8
February	–6.2	4.7	9.2	–3.0	4.0	19.1	–0.1	4.2	41.1
March	–8.4	3.2	1.9	–6.0	2.6	3.2	–3.3	2.8	11.0
April	–8.2	3.4	2.7	–6.2	2.2	1.3	–3.8	2.4	7.3
May	–8.9	2.5	0.0	–6.5	1.4	0.0	–3.0	2.1	9.0
June	–8.3	2.1	0.0	–6.1	1.5	0.0	–2.7	2.2	14.0
July	–7.3	2.4	0.0	–4.9	1.6	1.0	–1.7	2.3	25.2
August	–6.8	2.6	1.9	–4.2	1.7	0.6	–1.1	2.6	34.8
September	–7.9	2.3	0.0	–4.2	1.8	1.3	–0.9	2.6	35.3
October	–8.2	3.0	1.9	–5.1	2.0	2.6	–2.3	2.5	18.1
November	–7.7	3.4	4.7	–5.1	3.1	8.0	–2.6	3.0	20.0
December	–5.5	4.2	11.0	–3.1	4.3	25.2	–0.9	4.1	38.1
DJF	–6.1	4.3	9.3	–3.3	4.1	21.3	–0.6	4.3	37.9
MAM	–8.5	3.1	1.5	–6.2	2.1	1.5	–3.4	2.4	9.1
JJA	–7.4	2.4	0.7	–5.0	1.8	0.4	–1.8	2.5	24.8
SON	–7.9	2.9	2.2	–4.8	2.4	4.0	–2.0	2.8	24.2
Annual	–7.5	3.4	3.4	–4.8	2.9	6.7	–2.0	3.2	24.0

Table 6. Mean and standard deviation of temperature lapse rates (°C km^{-1}) and inversion frequency (%) for daily minimum, maximum and mean temperature, by month and season.

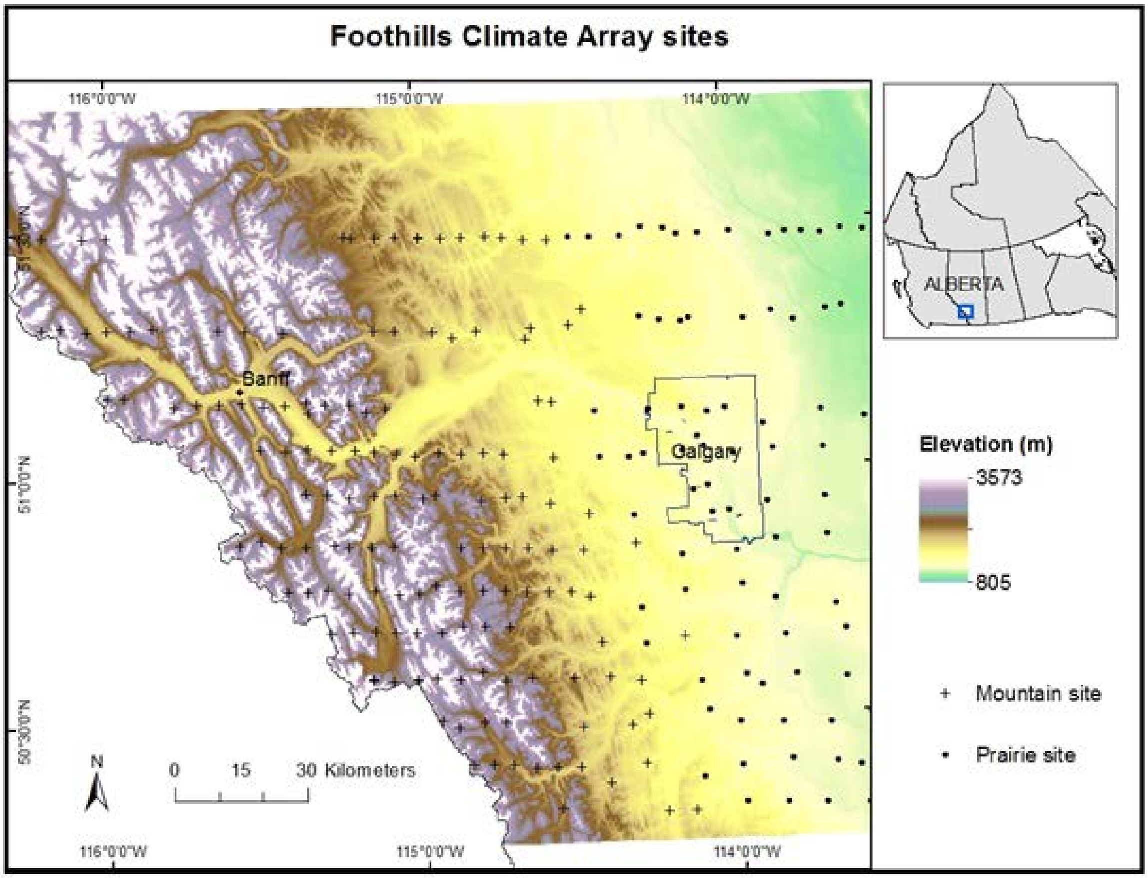

Figure 1. Foothills Climate Array study area. Crosses indicate mountain sites and dots are prairie sites. The City of Calgary municipal boundary is shown as a black outline. Sites within the boundary are classified as urban sites.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-107
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 21 September 2017

Figure 2. Site location examples: prairie, forest, urban, and mountain.

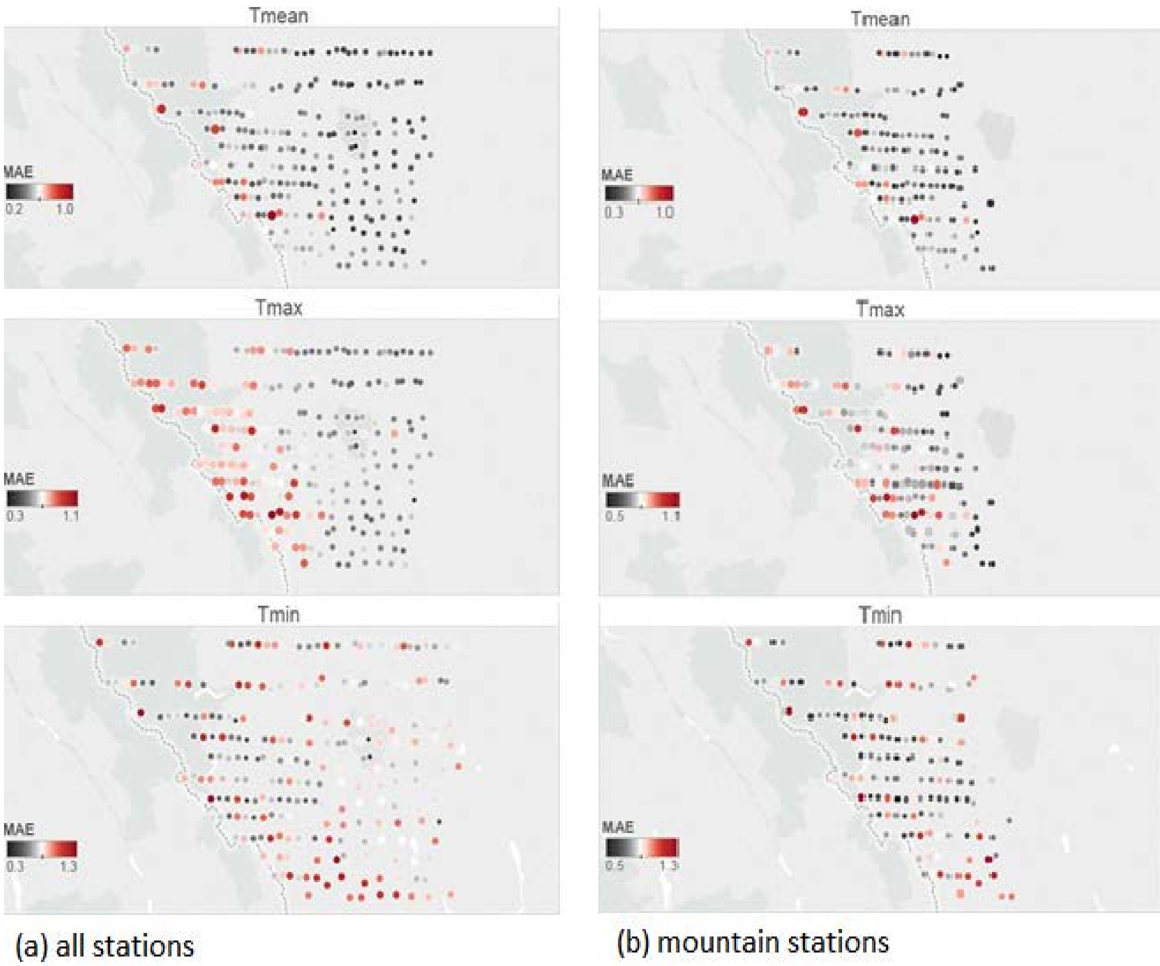

Figure 3. Mean absolute error (°C) distribution maps for mean, maximum, and minimum temperatures, for all stations (a) and mountain sites (b).

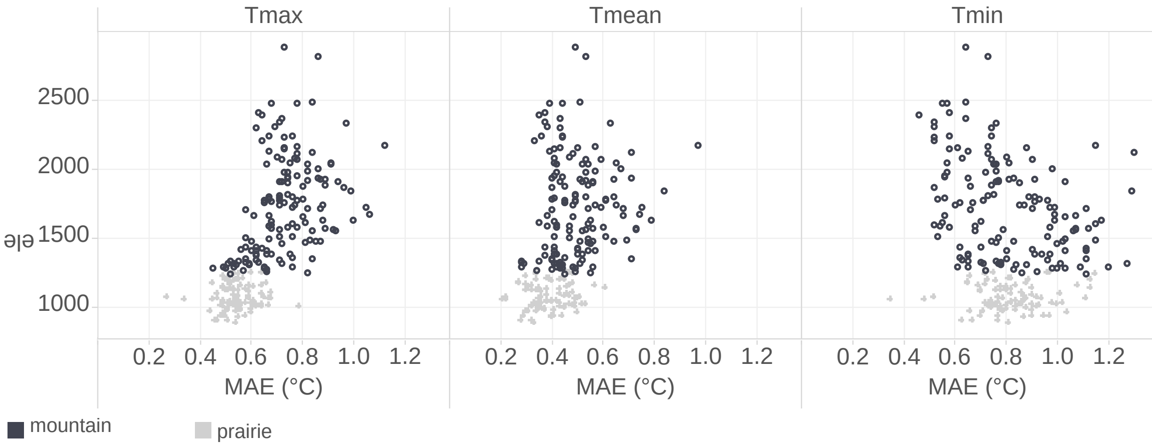

Figure 4. Mean absolute error (MAE) for each site as a function of elevation.

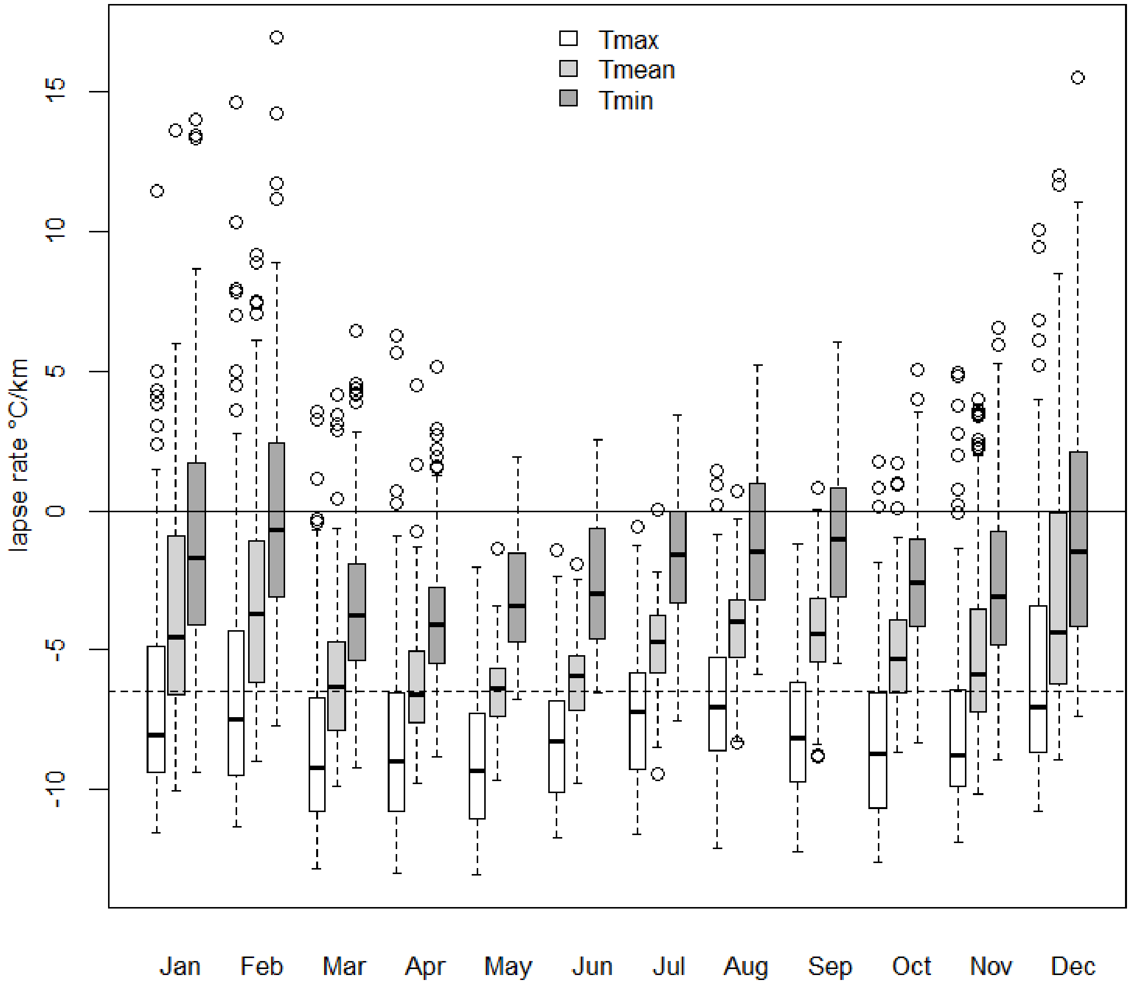

Figure 5. Boxplots showing the distribution of daily lapse rates by month and temperature measure. The box edges indicate the 25 and 75 percentiles and the thick black line is the median lapse rate. The dashed line shows the average environmental lapse rate of -6.5 °C km^{-1}.