CHAPTER 2 CLIMATOLOGY

2.1 Chapter Synopsis

This chapter presents a brief description of the historical climate of the Okanagan and Similkameen river basins (section 2.2), the changes being brought about by regional manifestations of global warming and the hydrologic mechanisms by which atmospheric temperature and precipitation influence runoff timing, volumes and peaks are briefly introduced in section 2.3. In section 2.4, technical aspects of ECCC's climate projections data set used in this work, named the CanLEADv1 data set, are described. How these data were adjusted for use in this project are detailed in section 2.5. In section 2.6, the projected climatic changes through the end of this century are analyzed to characterize changes in temperature, precipitation, length of freezing season and snowfall.

ECCC's CanLEADv1 projections indicate large rises in the minimum and maximum atmospheric temperature of a day, and this warming is expected throughout the year, for each of the 12 months. The minimum daily temperature generally occurs at nighttime, and the maximum occurs during daytime. The projected increase in the minimum daily temperature by the end of this century is greater than 5°C in any of the months and throughout the watersheds, and the maximum daily temperature is projected to rise by 3°C or 4°C. Rises in the minimum daily temperature (Tmin) carry important consequences as they diminish the capacity of the snowpack to lose during the night the solar heat gained during the day, thus raising snowpack temperatures and promoting snowmelt.

Rising projected temperatures shorten the annual freezing period. For example, at the Silverstar Mountain snow station, by the end of this century freezing is projected to start 5 weeks later and end 8 weeks earlier on average than at present. The projections show individual snow-free years starting to occur in the 2060s at Pinaus Lake (elev. 1,000m) or Princeton (elev. 700m); and in the late 2070s to the 2080s at high-elevation locations such as Silverstar Mountain (elev. 1,839m) and Blackwall Peak (elev. 1,940m).

Precipitation totals and daily intensity are projected to increase throughout the Okanagan and Similkameen river basins in October through May. These changes accentuate the existing contrast between wetter winters and drier summers at Silverstar Mountain, Brenda Mine and Blackwall Peak; and they introduce seasonality in the currently more uniform seasonal cycle such as at Mission Creek and Greyback Reservoir. Increases in the 75th percentile are larger than increases in the median, and increases in the 90th percentile are even larger. Increases seen in the maxima are often large, especially for the winter months. Storm duration is also projected to increase in December through February.

Snowfall is projected to decline due to rising temperatures, despite projected precipitation increases. However, high-elevation locations may experience an increase in average snowfall in December and January towards the mid-century, in some cases followed by a decline from mid-century to end-century.

2.1.1 Limitations on the Climatology Component of this Study

While there is a need to provide climate projections for a variety of planning purposes, the underlying projections of climate change are subject to large and unquantifiable uncertainty. The main sources of uncertainty are unknown future emissions of greenhouse gases, uncertain response of the global climate system to increases in greenhouse gas concentrations, and incomplete understanding of regional manifestations that will result from global changes (e.g., (Hawkins and Sutton, 2010). Additional potential sources of uncertainty include the downscaling (in space and time) of global climate model outputs, the overall accuracy of the hydrologic model, and the assumptions made of unchanged future land cover and soil conditions.

The temperature and precipitation projections developed in this work should therefore be considered to be plausible representations of the future, given the best current scientific information, and do not represent specific predictions. The actual future realizations of temperature and precipitation over the Okanagan and Similkameen river basins, and the actual future stream flows in these basins will differ from the projections considered here, and their difference compared to historical climate may be greater or smaller than the differences in the projections considered. Also, the actual future volumes, peaks, and timing of streamflow inputs to Okanagan Lake and other lakes and streams will differ in unknown ways from the projections developed in this work.

2.2 Historic and Recent Climate

The Okanagan watershed lies in a high plateau of BC's Southern Interior region, located in the rain shadow of the Coast Mountains and the Cascade mountain range. The watershed receives lower precipitation than most regions in BC, and experiences large evaporation losses during its hot summers. Estimated mean annual precipitation rates range spatially from 300-400 mm in the southern valley (e.g. about 320 mm at Osoyoos) to 800-1,000 mm at the highest plateaus (and surpassing 1,000 mm at the high-elevation Mission Creek headwaters, with a basin-wide average estimated around 600 mm (Alexander et al., 2013). The southern areas are driest, vegetated by sagebrush, perennial grasses, and cactus, while the somewhat wetter and cooler northern areas grow cedar and hemlock trees. The southern region between Oliver and the US border is classified as the Great Basin Biome.

With low average precipitation and high evaporation, the large and increasing Okanagan basin population has among the lowest water availability per capita in Canada. The annual hydrograph is dominated by the spring freshet, with April-June inflows representing roughly 90% of annual inflows to the Okanagan Lake and River system (Dobson, 2004). Inflows are low for all other seasons; hence all water uses depend on lake storage of spring snowmelt runoff.

The year-to-year variability of inflow volumes to Okanagan Lake, in particular, is of great importance to this project. Estimated annual inflows vary by more than an order of magnitude, from a minimum of 78 million m^3 in 1929 to 1.4 billion m^3 in 1997 (volumes which translate to 0.23 m to 4.12 m of lake storage) (Symonds, 2018).

2.3 Global Warming and Projected Regional Climate Change

The phenomenon of global warming manifests itself differently across global regions. The state of current knowledge of the global climate system is incorporated into computer simulation models of the global atmosphere, oceans, land and cryosphere, known as global climate models (GCMs), as well as models with smaller spatial domains covering a specific global region at greater spatial detail and better representation of topography, coastlines, and dynamic interactions between climate components, known as regional climate models (RCMs). Even though the volume of future anthropogenic greenhouse gas emissions and their atmospheric concentration are unknown, scenarios built on different plausible assumptions have been developed that lead to "representative concentration pathways" or RCPs. Global climate models are used for simulating the response from climate variables (such as temperature, precipitation, and wind at different world locations) to different RCPs. For example, RCP4.5 and RCP8.5 are two scenarios of future greenhouse gas concentrations estimated to lead to a global heat imbalance of 4.5 and 8.5 Watt/m^2, respectively, by year 2100.

The climate system is highly sensitive to small perturbations (a type of behavior termed "chaotic") and for this reason different model runs by the same GCM and the same RCP but with slightly different initial conditions lead to different future projections. By running the same model multiple times to create an "ensemble", any future trends in temperature, precipitation, etc., can be attributed to the RCP and represent the "climate change signal" associated with the RCP according to the specific GCM used.

The recent availability from ECCC of an ensemble of 50 runs of the Canadian GCM CanESM2 for RCP8.5, whose results were then refined (or "dynamically downscaled") by the Canadian RCM CanRCM4, represented an opportunity for this project. Given the role of human management in the Okanagan lake system, evaluation of future flood risk cannot rely on the fitting of an extreme value distribution to a relatively short period of hydrologic simulations. Not only the hydrology but also the management behavior must be simulated for evaluating flooding risk, and since a managed system may not follow a known distribution, the project benefits from simulating a long period of time, which is possible with the approach of using an ensemble of 50 climate projections, provided by ECCC's CanLEADv1 data set, described in the next section.

The hydrologic model (Chapter 3) translates CanLEADv1's climatic projections of temperature and precipitation into projections of runoff through the end of this century. The hydrologic processes affected are represented schematically in Figure 2-1. Additionally, simulation of human management leads to projections of lake levels and flooding risk.

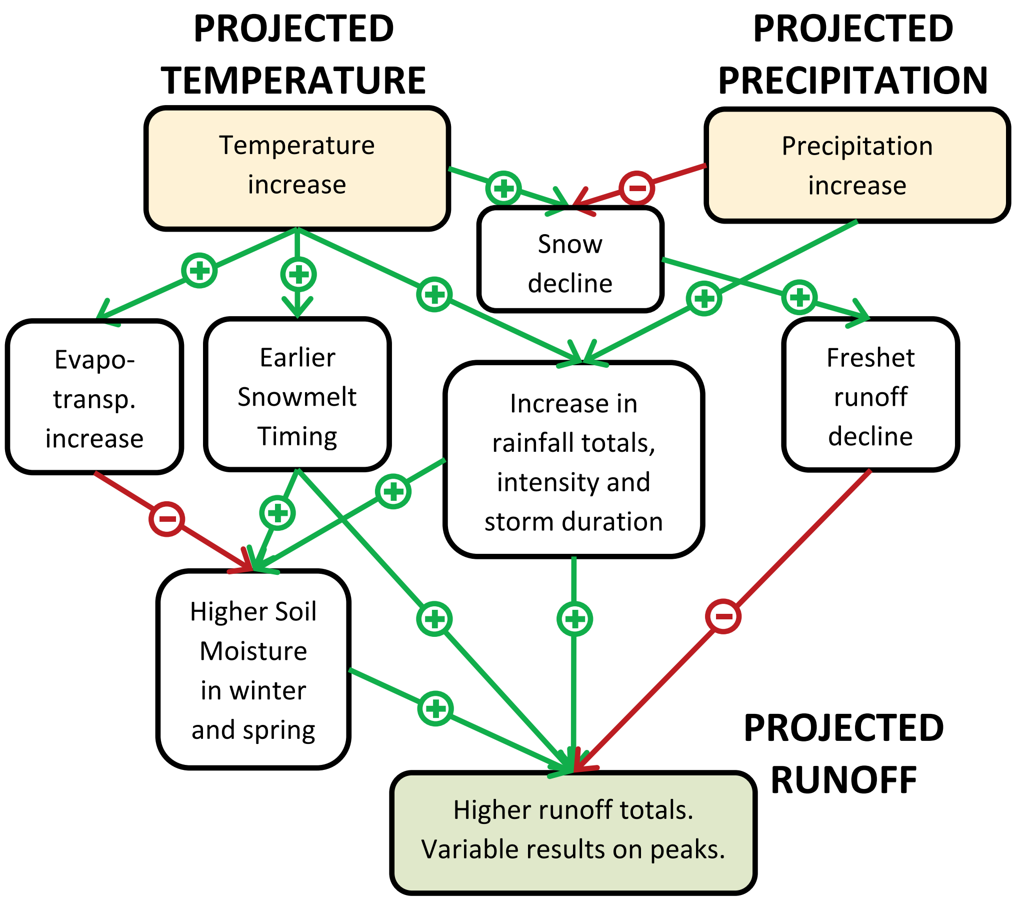

Figure 2-1 Hydrologic pathways by which projected climatic changes influence runoff in the Okanagan and Similkameen basins. Green arrows represent positive contributions towards the contents of a box, while red arrows represent opposing contributions. For example, the projected temperature increase contributes to the decline in snowfall and increase in rainfall. Opposing contributions from (a) higher rainfall totals and intensity and higher soil moisture versus (b) lower freshet runoff, result in complex impacts on runoff peaks that depend e.g. on subbasin size and elevation.

2.4 Description of Climate Ensemble

The Canadian Large Ensembles Adjusted Dataset version 1 (CanLEADv1), developed by ECCC, contains climate model simulation outputs of daily precipitation (pr), minimum daily temperature (Tmin or tasmin), maximum daily temperature (Tmax or tasmax), and other climatic variables, on a 0.5° grid covering North America. There are 50 climate model simulations forming an ensemble, from the Canadian Earth System Model Large Ensemble (CanESM2 LE)[1] for the future greenhouse gas

[1] https://open.canada.ca/data/en/dataset/aa7b6823-fd1e-49ff-a6fb-68076a4a477c, accessed 31 March 2020.

concentration pathway RCP8.5. The 50 GCM outputs were downscaled by the Canadian Regional Climate Model Large Ensemble (CanRCM4 LE). The data are adjusted statistically to remove model bias and ensure agreement with two observationally-constrained historical meteorological forcing data sets, S14FD and EWEMBI. In this project the version adjusted for S14FD was used.

2.4.1 Climate Ensemble's Global Climate Model (GCM) vs. Other GCMs

The global climate model used in the CanLEADv1 data set is CanESM2. In this section it is investigated whether CanESM2's projections for the Okanagan-Similkameen basins stand out as different from other GCM's projections. The Pacific Climate Impacts Consortium (PCIC) recommends for Western North America a list of GCM runs which are chosen to cover as wide a range as possible of differing projections[1]. This PCIC list was the basis for the selection of the five GCMs used in the Okanagan Irrigation Water Demand study (Neilsen et al., 2018). In this section those five GCM runs plus the 6th GCM run on the PCIC list are studied and compared with CanESM2 (r1). The GCM runs are listed in Table 2-1.

Statistically-downscaled projections of the seven GCM runs listed in Table 2-1 were downloaded from an archive supported by educational institutions and the U.S. government, for the grid cells shown in Figure 2-2. The CanESM2 (r1) projections in this section are not expected to agree quantitatively with those from the same model run that are part of CanLEADv1 used in this study. They agree only approximately but differ somewhat quantitatively because they were downscaled differently, and their spatial resolution is different. The CanESM2 (r1) projections used in this section, like all other GCM projections in this section, were downscaled using only statistical methods (specifically, the method known as BCCA) and have 1/8° spatial resolution (about 12 km); while CanLEADv1 uses dynamical downscaling with the regional climate model CanRCM4 followed by bias correction, and further statistical downscaling for this project to a 500 m resolution (described in section 2.5).

Because all GCM projections used in this section were downscaled by the same methodology, they are directly comparable for the purposes of determining whether CanESM2 (r1) stands out as significantly different in any of its projections. Differences between GCM runs are expected since the choice of GCM runs on PCIC's list is guided precisely by the goal of maximizing the spread of projections.

With respect to the daily minimum and maximum temperature (Tmin and Tmax), CanESM2 (r1) projects for the end of this century (year 2100) the highest warming rates among these seven GCMs, as seen in the distributions plotted in Figure 2-3 and Figure 2-4. However, the difference is not great and does not appear as an outlier run. Indeed, all seven projections appear mutually consistent. CanESM2 (r1) also projects higher precipitation increases in mean annual precipitation (by an overall 160 mm in the course of this century, i.e. 2001-2100) than any of the other GCMs studied in this section. Nevertheless, five of the other GCMs also studied project precipitation increases in this century, ranging from 43 mm for

[1] https://pacificclimate.org/data/statistically-downscaled-climate-scenarios, accessed 31 March 2020.

access1-0.1 (r1) to 104 mm for cnrm-cm5.1 (r1). Ccsm4.2 (r2), however, projects a small declining trend in precipitation, by about 40 mm in 2001-2100.

It is concluded that CanESM2 (r1) projects markedly warm and wet future conditions and it is inferred that the CanLEADv1 projections used in this study are likely warmer and wetter than would have been obtained from other GCMs. Nevertheless, the differences are not great.

Table 2-1 The seven GCM runs studied in this section.

Acronym (and run #)	GCM Name
ACCESS1-0.1 (r1)	Australian Community Climate and Earth System Simulator
CanESM2 (r1)	Canadian Earth system Model
CNRM-CM5.1 (r1)	Centre National de Recherches Météorologiques Climate Model
CSIRO Mk3.5-6-0.1 (r1)	CSIRO Mk3.5
INMCM4.1 (r1)	Institute of Numerical Mathematics Climate Model
CCSM4.2 (r2)	NCAR/UCAR Community Climate System Model
MIROC5.3 (r3)	University of Tokyo’s Model for Interdisciplinary Research on Climate

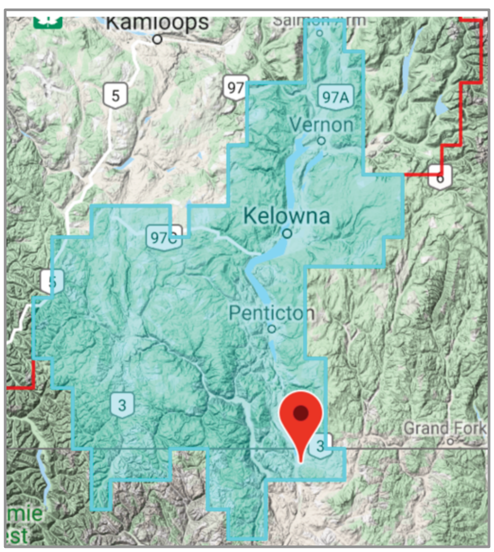

Figure 2-2 Grid cells for which downscaled projections are summarized in this section, corresponding to the watershed area defined by the indicated outlet location (latitude 50.5801°N, longitude 123.5941°E), encompassing the Okanagan and Similkameen river basins. Grid cells have a 1/8° spatial resolution, or about 12 km.

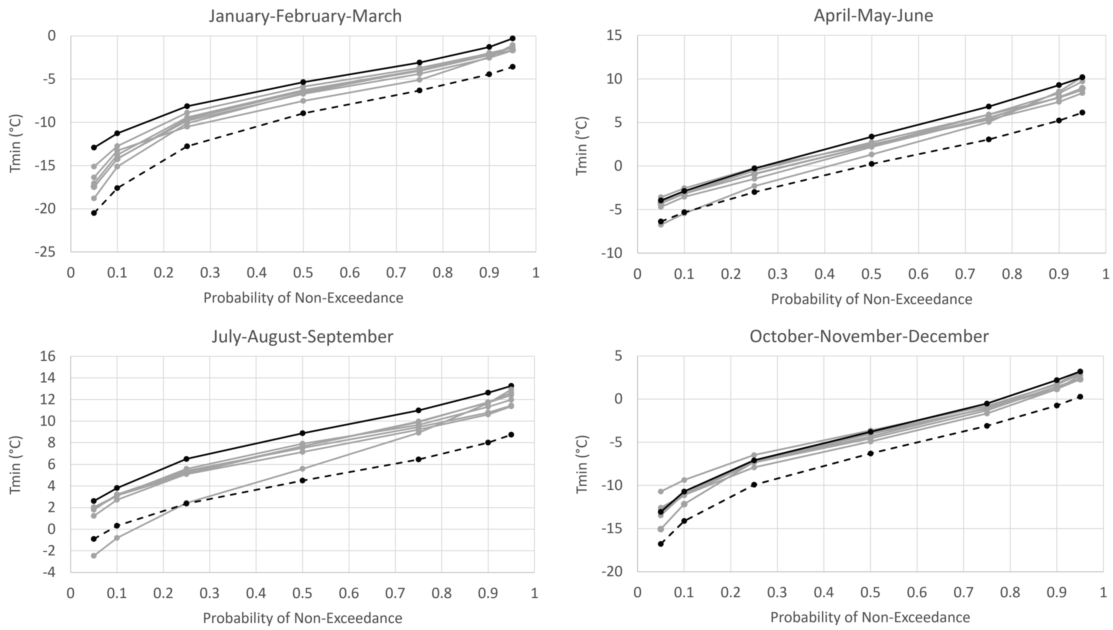

Figure 2-3 Comparison of CanESM2 (r1) projections for the end of this century (black line) for minimum temperature of the day, Tmin, against six other GCMs in Table 2-1 (grey lines). The historical period is represented by the dashed black line. These CanESM2 projections differ from those used in this study, as they belong to the same dataset as the other six GCM projections, which is necessary for direct comparison (see text).

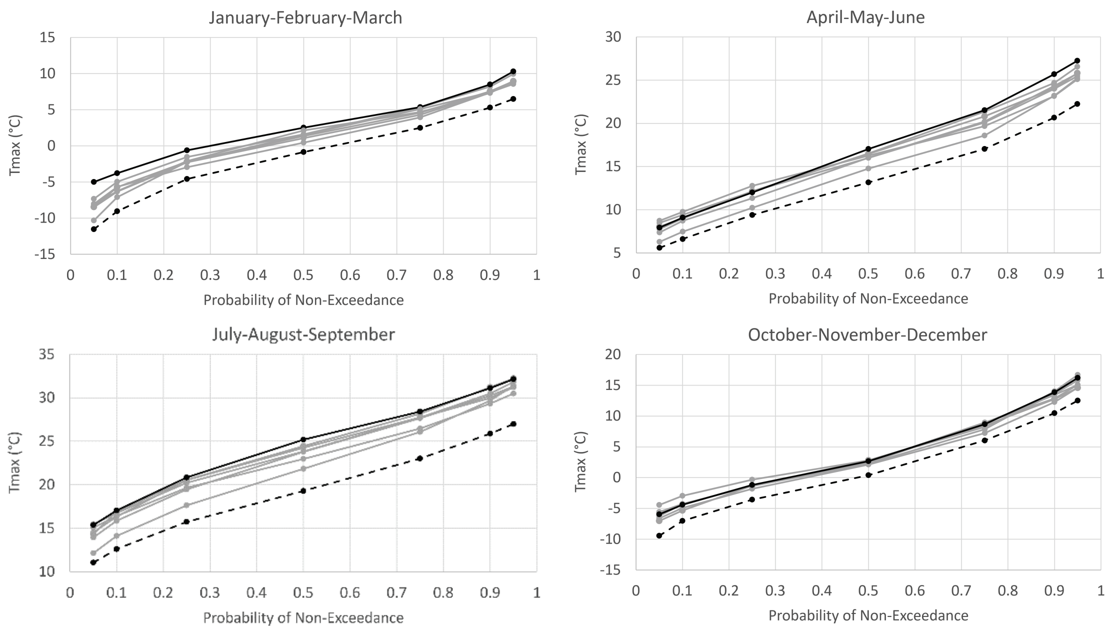

Figure 2-4 Comparison of CanESM2 (r1) projections for the end of this century (black line) for maximum temperature of the day, Tmax, against six other GCMs in Table 2-1 (grey lines). The historical period is represented by the dashed black line. These CanESM2 projections differ from those used in this study, as they belong to the same dataset as the other six GCM projections, which is necessary for direct comparison (see text).

2.5 Downscaling of the Climate Ensemble to the Okanagan and Similkameen Basins

The spatial resolution of the CanLEADv1 data set is 0.5° of latitude and longitude (or about 55 km x 37 km), and the temporal resolution is 3-hourly. A much finer climatic projections dataset was desired by OBWB for this project as well as future envisioned projects. The desired spatial resolution is 500 m and the desired temporal resolution is daily. The desired data set was developed using statistical downscaling methods.

2.5.1 Developing an Observations-Based Climate Dataset

Statistical downscaling methods rely on a target dataset of gridded values of each climatic variable derived from observations. Observations-based climatic datasets appropriate for use in Canada (namely, NRCanmet and ClimateBC) were not eligible because they do not extend into the United States. Instead, (Associated Environmental, 2019a, 2019b) used a combination of two data sets: (a) the spatially coarse-resolution (1/12°) but daily-scale PNWNAmet dataset[1] developed by PCIC (Werner et al., 2019), which spans 1945-2012, and (b) a spatially high-resolution (500 m) but monthly-scale dataset developed by

[1] https://www.pacificclimate.org/data/daily-gridded-meteorological-datasets, accessed 31 March 2020.

Associated Engineering using the ClimateNA[1] tool in conjunction with a 500 m DEM that covers the Okanagan and Similkameen watersheds. This methodology was proposed by Sobie and Murdock (2017). The result was a daily observations-based gridded climatological data set covering 1945-2012 at 500 m resolution. This data set inherited the BC Albers projection from the 500 m DEM. An example, corresponding to precipitation intensities for a particular day, is shown in Figure 2-5.

[1] https://sites.ualberta.ca/~ahamann/data/climatena.html, accessed 31 March 2020.

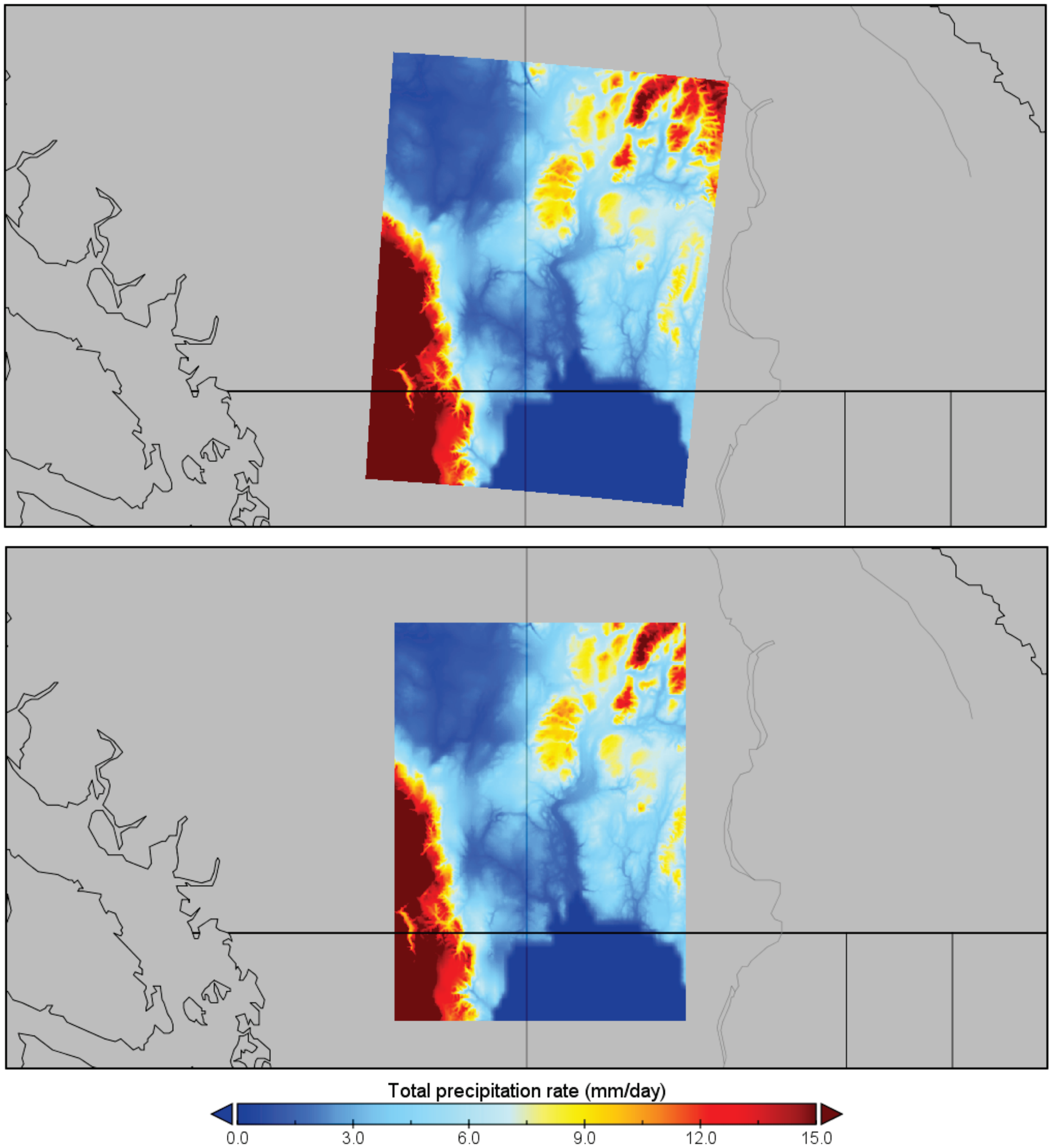

Figure 2-5 Precipitation rates on example day January 4, 1945 in the original grid provided by AE (top panel) and resampled to a regular lat-lon grid (bottom panel). The three climatic variables, pr, tasmin and tasmax were resampled in this way.

2.5.2 Downscaling Process

The spatial resolution of the CanLEADv1 (55 km x 37 km) data set is much larger than the desired 500 m, with grid cell area differing by 4 orders of magnitude. For statistically downscaling of the CanLEADv1 data to the desired 500 m resolution based on the observations-based data set described in section 2.5.1, the code ClimDown developed by the PCIC in the R language was used. ClimDown includes two alternative algorithms, bccaq and qdm. With its emphasis on extreme value representation and achieving realistic spatial patterns, bccaq was our first candidate. However, unrealistic spatial patterns of precipitation were produced, possibly due to the great difference between the original and target spatial scales.

Algorithm qdm (quantile delta mapping) performed better, producing spatially coherent spatial patterns during days with significant precipitation. In some days that had only light precipitation, data artifacts were noted where a drizzle (low-intensity precipitation) marks the grid lines of the CanLEADv1 grid, but such effects are not consequential, and the qdm algorithm was used in this project for both precipitation and temperature (Tmin and Tmax) downscaling. Figure 2-6 shows one day as an example of the qdm algorithm performance.

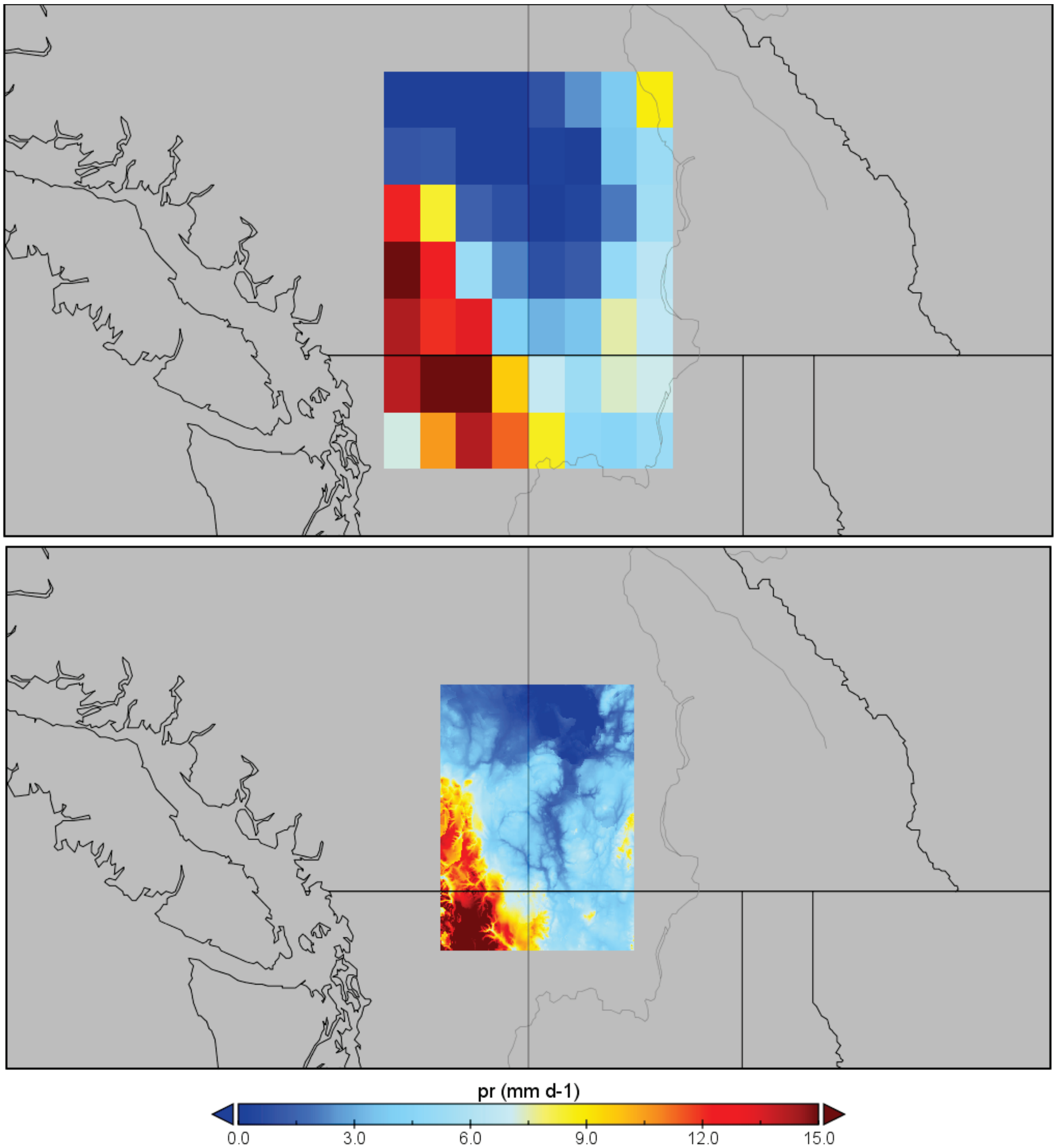

Figure 2-6 Precipitation rate in the original CanLEADv1 data set (top panel) and statistically downscaled by the qdm algorithm of the ClimDown code (bottom panel).

2.6 Assessing Projected Changes in Climate

This section describes the projected changes in climate for representative Okanagan and Similkameen locations (shown in Figure 2-7) ranging in their geographic and climatic conditions and including key snow stations and rain gauges. The projections shown correspond to the CanLEADv1 downscaled 50 realizations which are pooled together.

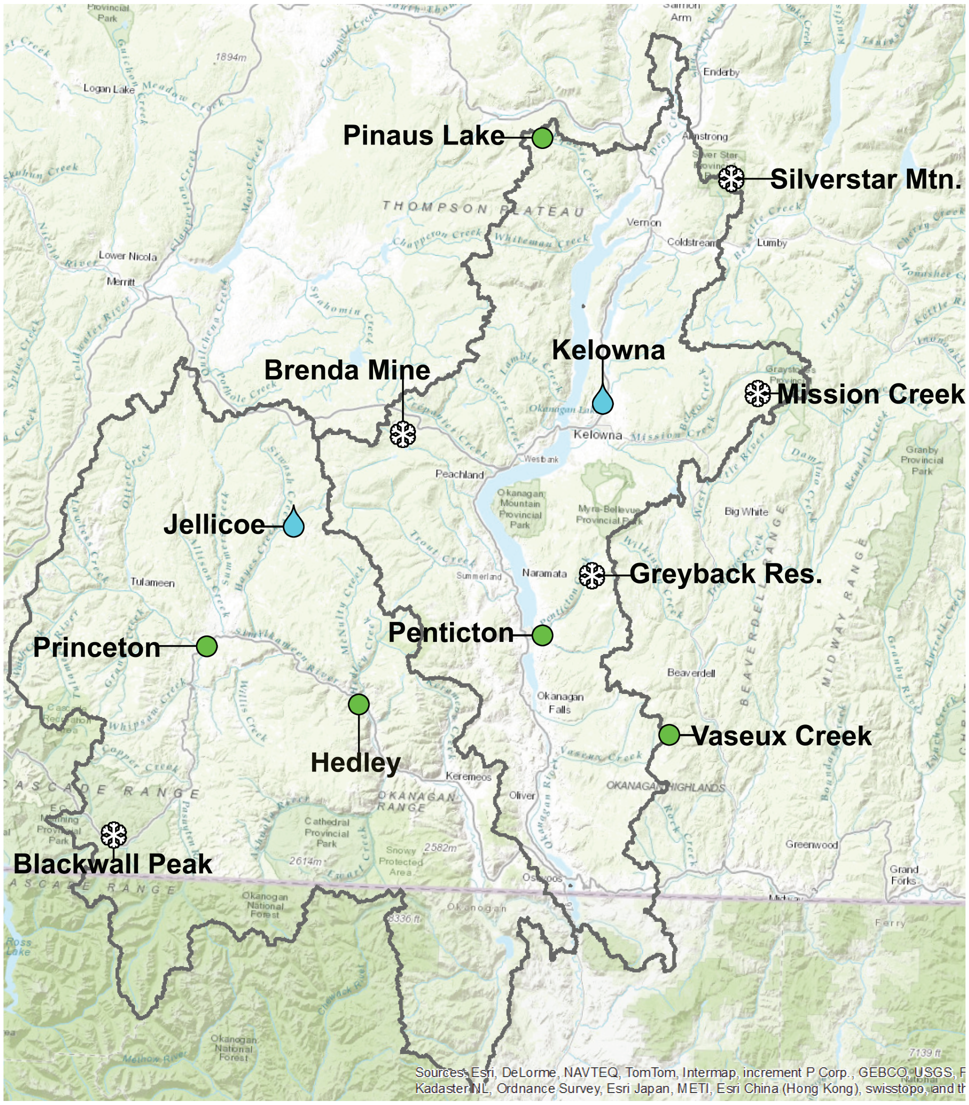

Figure 2-7 Representative locations studied in this section. Snow stations and rain gauges are indicated by a snowflake and blue drop symbol, respectively. Other locations are marked with a green dot.

2.6.1 Temperature and Freezing Season Duration

Temperature projections for representative locations are displayed in Figure 2-8 through Figure 2-10 for the daily minimum temperature (Tmin, normally occurring at night time) and in Figure 2-11 through Figure 2-13 for the daily maximum temperature (Tmax, occurring at day time). All boxplots in this chapter indicate the median (central horizontal line), the 25th and 75th percentiles (lower and upper box boundaries), and the 10th and 90th percentiles (whiskers). Color indicates the decade, from 2001-2010 through 2091-2100.

Large increases in Tmin and Tmax are projected for each of the 12 months, with Tmin rising by more than 5°C but less than 10°C in every month, and Tmax rising by 3°C or 4°C by the end of this century. Rises in Tmin carry important consequences as they diminish the capacity of the snowpack to lose during the night the solar heat gained during the day, thus raising snowpack temperatures, and promoting snowmelt.

Rising projected temperatures shorten the annual freezing period. This is shown in Figure 2-14 where the freezing period length is indicated by the red line, which represents the distance in days between the grey line (start of the freezing period) and the black line (end of the freezing period). Freezing period is defined by a mean daily temperature below 0°C. The curves represent annual averages for the downscaled 50 realizations of CanLEADv1. Given year-to-year variability, individual years in each realization differ from the average of the 50 realizations. This is shown for selected locations in Figure 2-15, where some freeze-free years are also seen, even at high-elevations such as Silverstar Mountain and Blackwall Peak, and especially at lower-elevations such as Penticton.

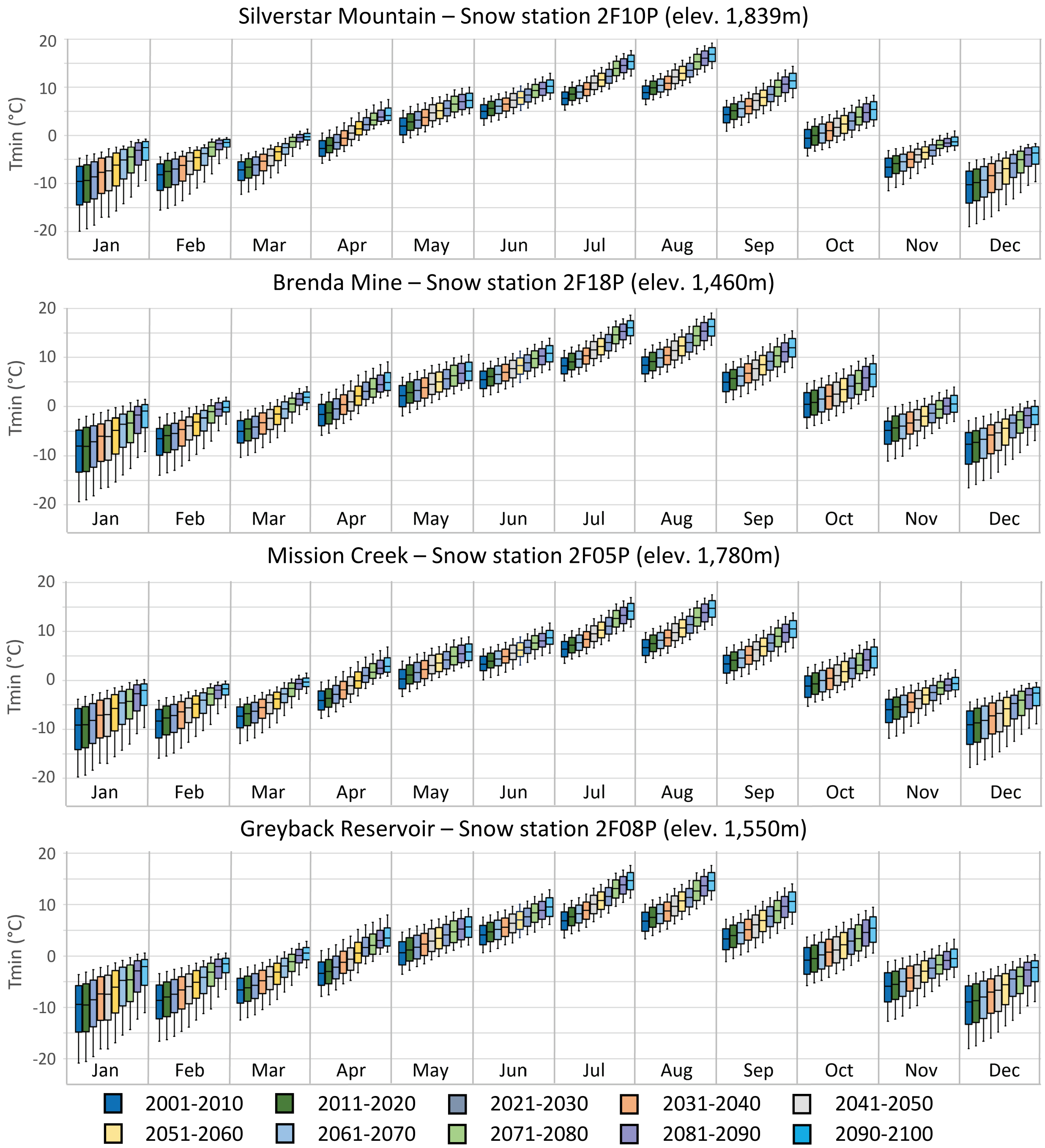

Figure 2-8 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four snow stations in the Okanagan basin.

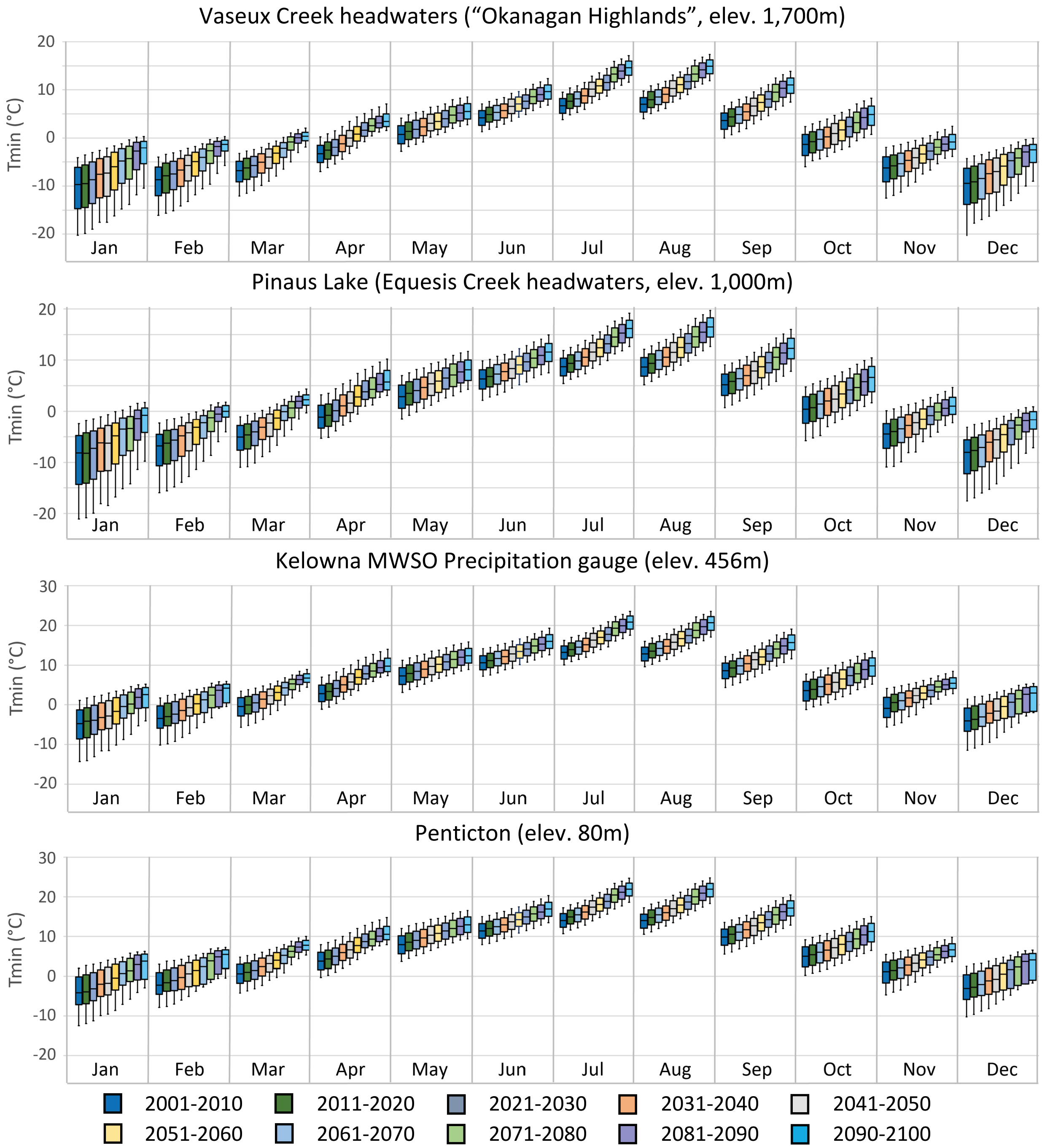

Figure 2-9 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four representative locations in the Okanagan basin, covering a range of elevations.

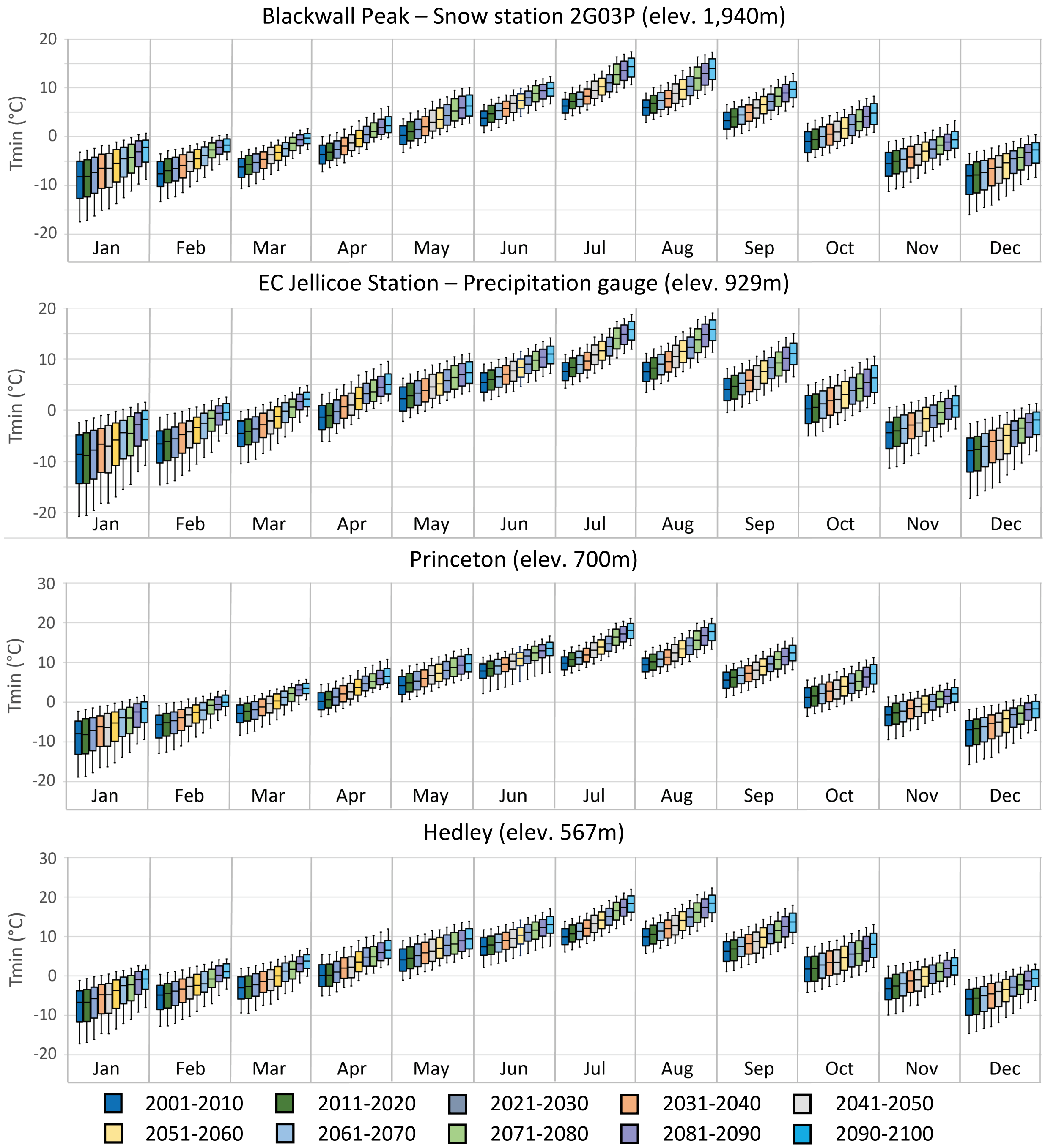

Figure 2-10 Statistical distribution of projected daily minimum temperature, Tmin, in each decade for four representative locations in the Similkameen basin, covering a range of elevations.

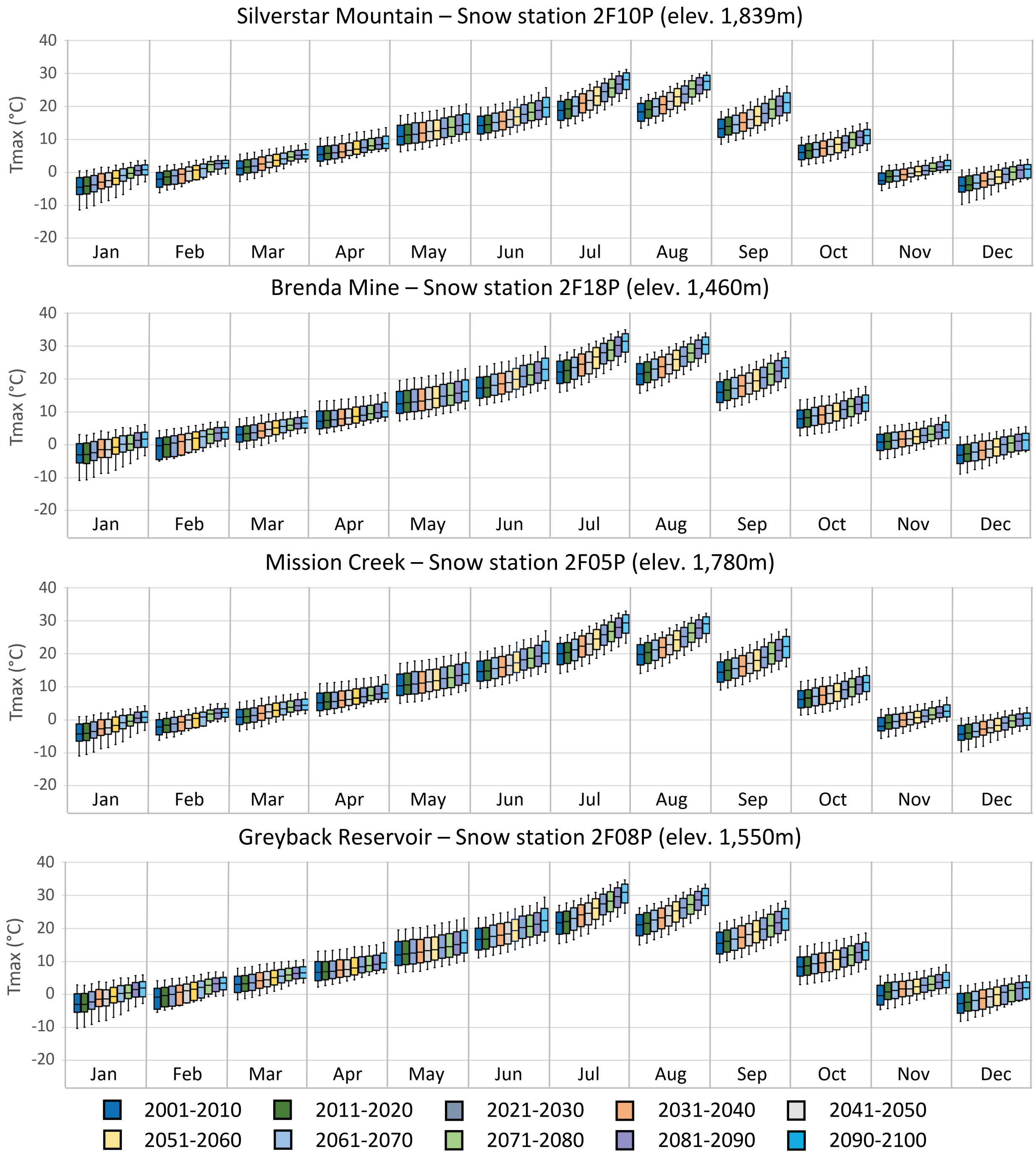

Figure 2-11 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four snow stations in the Okanagan basin.

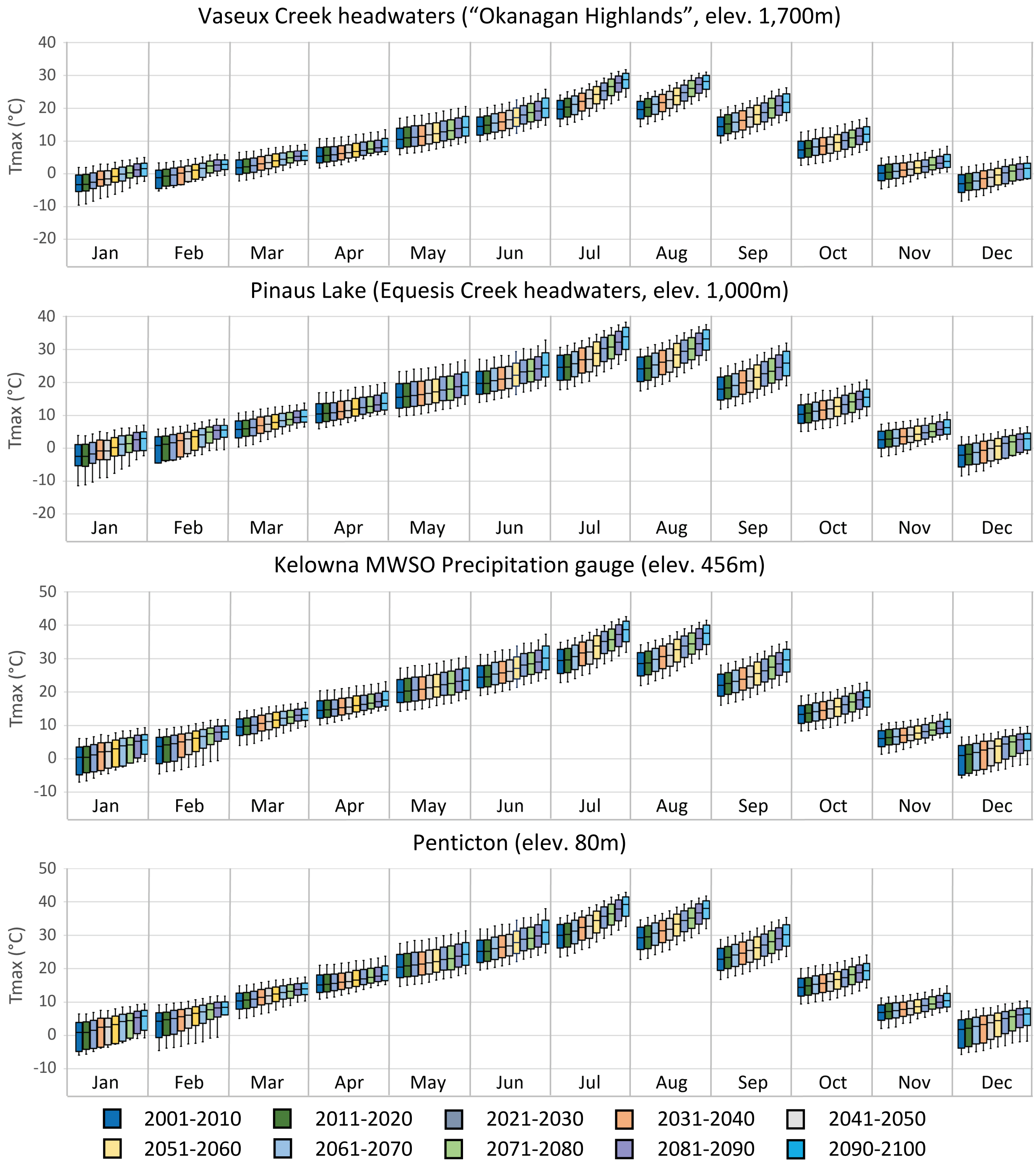

Figure 2-12 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four representative locations in the Okanagan basin, covering a range of elevations.

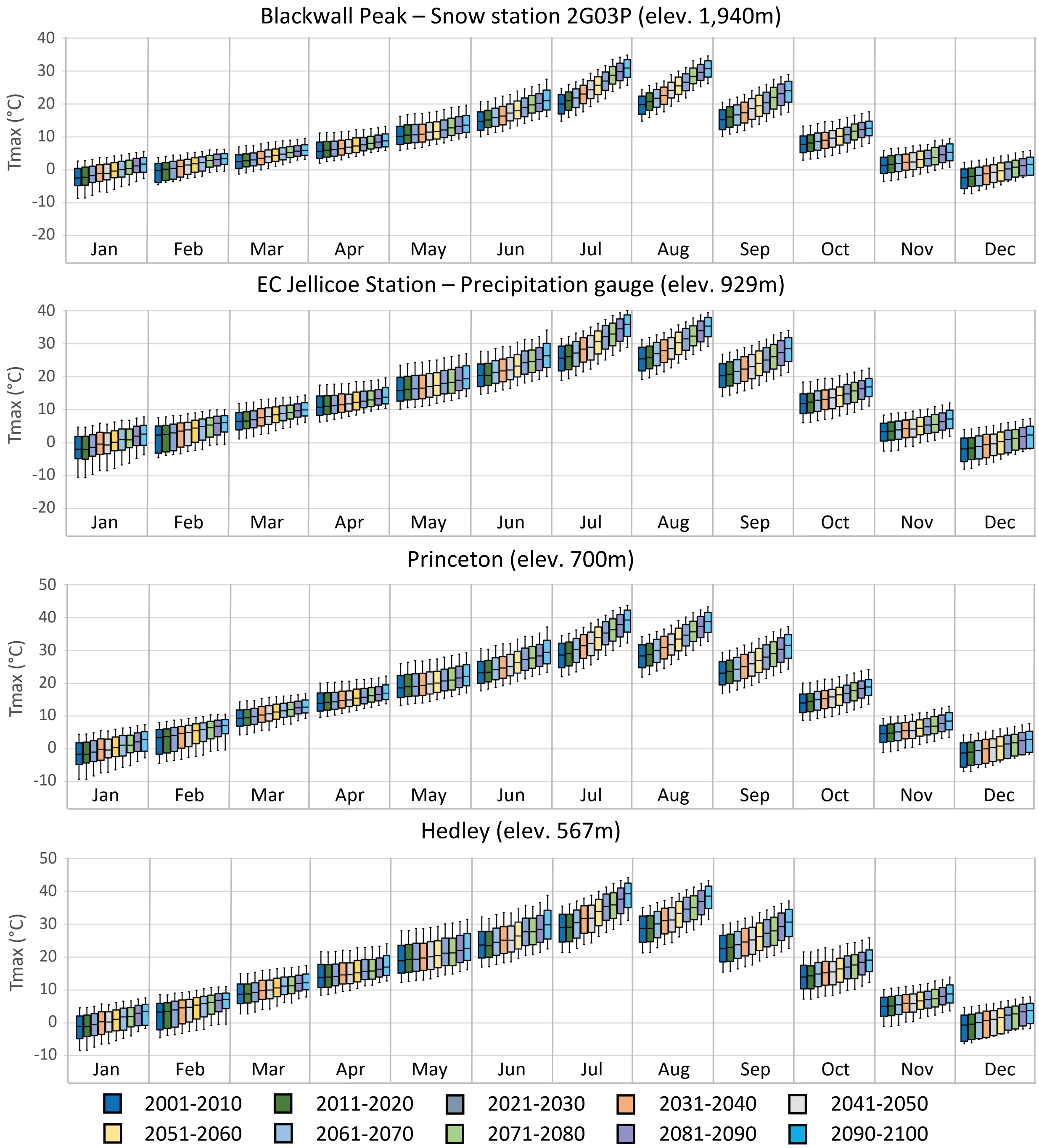

Figure 2-13 Statistical distribution of projected daily maximum temperature, Tmax, in each decade for four representative locations in the Similkameen basin, covering a range of elevations.

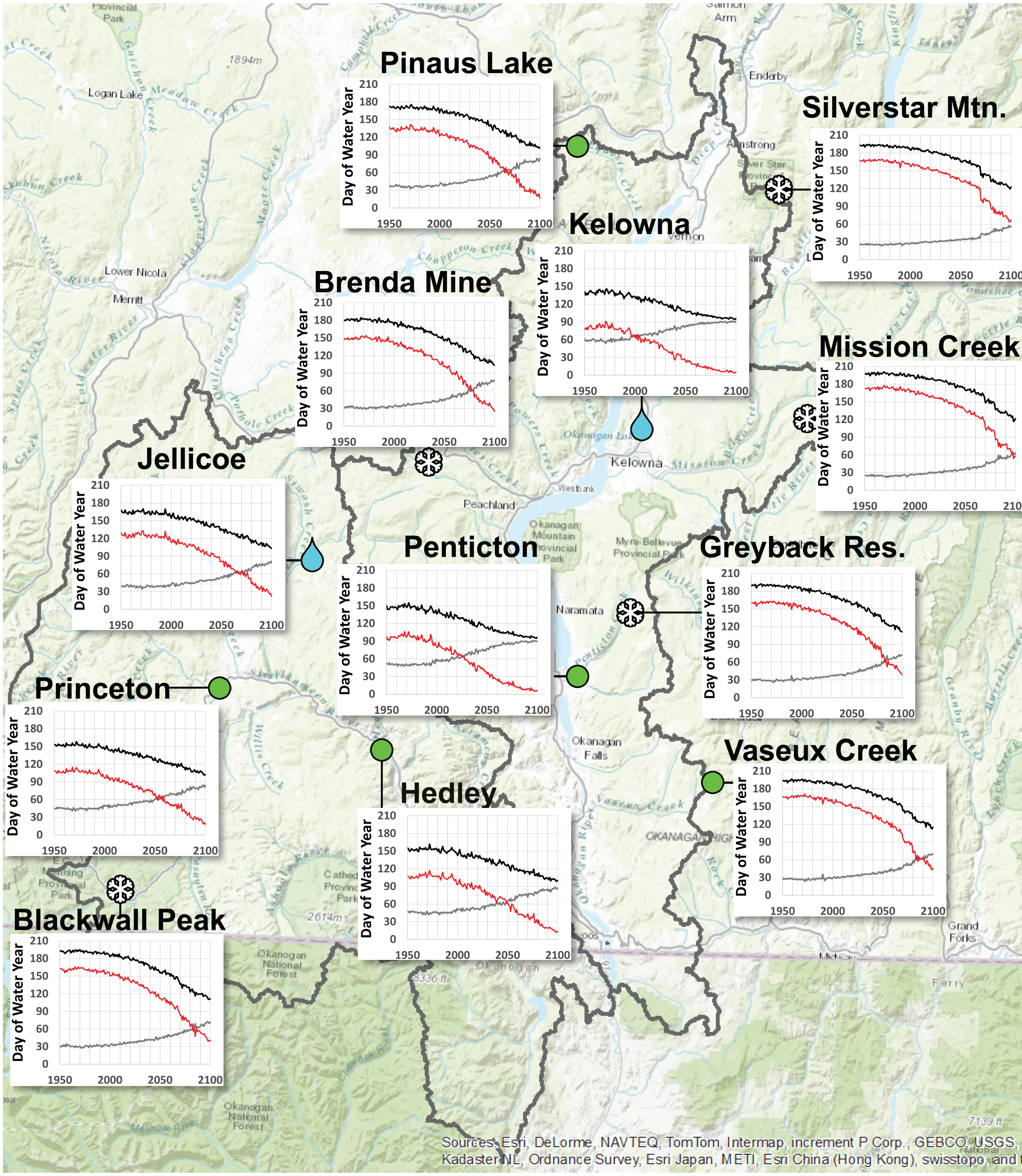

Figure 2-14 **Start of the freezing period (grey line), end of the freezing period (black line) and duration of the freezing period (red line, expressing the number of days separating the grey and black lines). Freezing period is defined by sub-zero (<0°C) daily mean temperatures. The curves represent annual averages for the downscaled 50 realizations of CanLEADv1.**

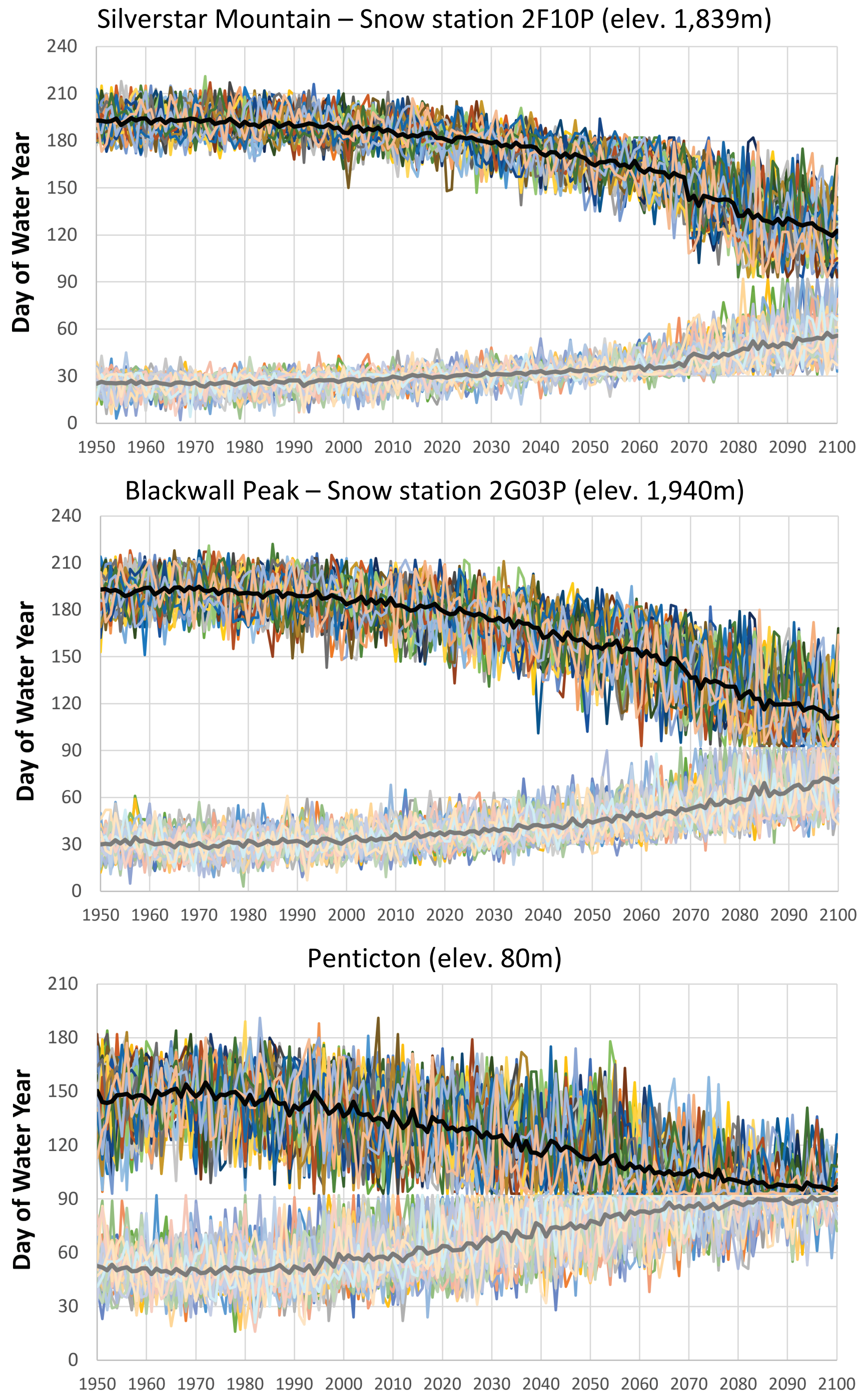

Figure 2-15 Start and end date of the freezing season. Each of the 50 climate model realizations is plotted in color. The average date of freezing season start in each year is represented by the thick grey line; the average date of end of the freezing season is represented by the thick black line. The freezing season's duration declines over time, due to a trend toward later starting dates and earlier ending dates (the latter trend being especially strong).

2.6.2 Precipitation, Snowfall, Rainfall Intensity, and Storm Duration

Precipitation is also projected to increase. Figure 2-16 through Figure 2-18 display the projected changes in the statistical distribution of daily precipitation for each of the 12 months and each decade of the 21st century, at representative locations. The distribution includes all 50 CanLEADv1 realizations pooled together. The boxplots summarize the statistical distribution by marking the median (central horizontal line), the 25th and 75th percentiles (lower and upper box boundary), and the 10th and 90th percentiles (whiskers). Hovering above the boxplots are plotted the maxima, i.e., the largest daily precipitation value of the decade.

At all locations in Figure 2-16 through Figure 2-18, significant precipitation increases are projected for October through May. These changes accentuate the existing contrast between wetter winters and drier summers at Silverstar Mountain, Brenda Mine and Blackwall Peak; and they introduce seasonality in the historically more uniform seasonal cycle such as at Mission Creek and Greyback Reservoir. Increases in the 75th percentile are larger than increases in the median and increases in the 90th percentile are even larger. Increases seen in the maxima are often large, especially for the winter months.

In Figure 2-19, the grey lines represent, for each month, the average rainstorm duration across the decades of the 21st century, while the funnel plots represent the distribution of values. Duration is the number of consecutive days with rain, calculated from daily rainfall, hence having the minimum value of 1 day. The average duration is in the vicinity of 2 days for all months. Increases in the rainstorm duration is apparent in the figure for winter months December, January, and February. The width of the funnel plots is proportional to the number of occurrences, which is greatest for 1 day, followed by 2 days, etc. All 50 realizations of downscaled CanLEADv1 were pooled together. The points highlight the maximum value simulated by any of the 50 realizations in each decade.

Snowfall is projected to decline due to rising temperatures, despite projected precipitation increases. However, high-elevation locations may experience an increase in average snowfall in December and January towards the mid-century, in some cases followed by a decline from mid-century to end-century. This can be seen in Figure 2-20.

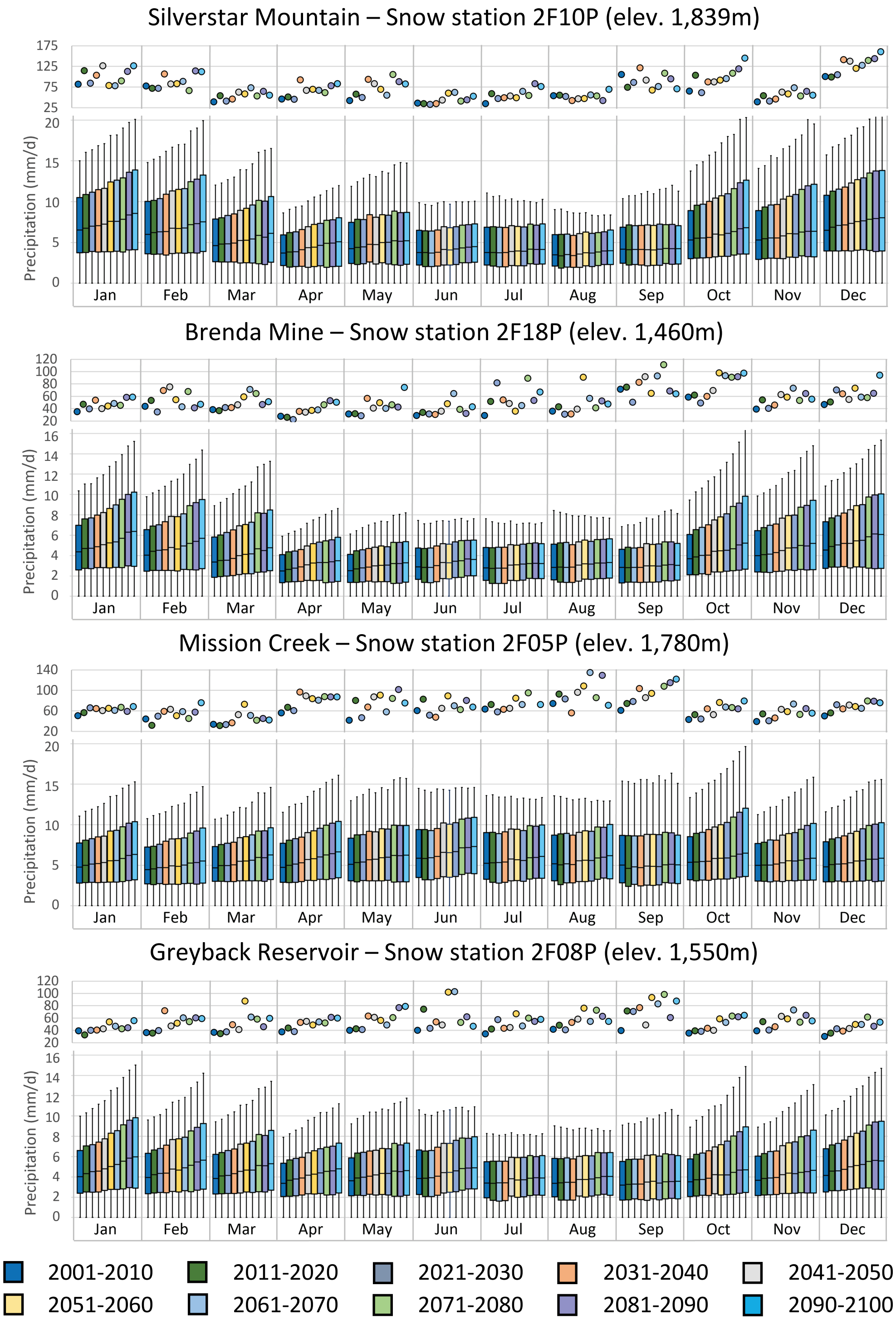

Figure 2-16 Statistical distribution of projected daily precipitation in each decade for four snow stations in the Okanagan basin. The vertical axis scale is different for the plots of maximum points above the boxplots.

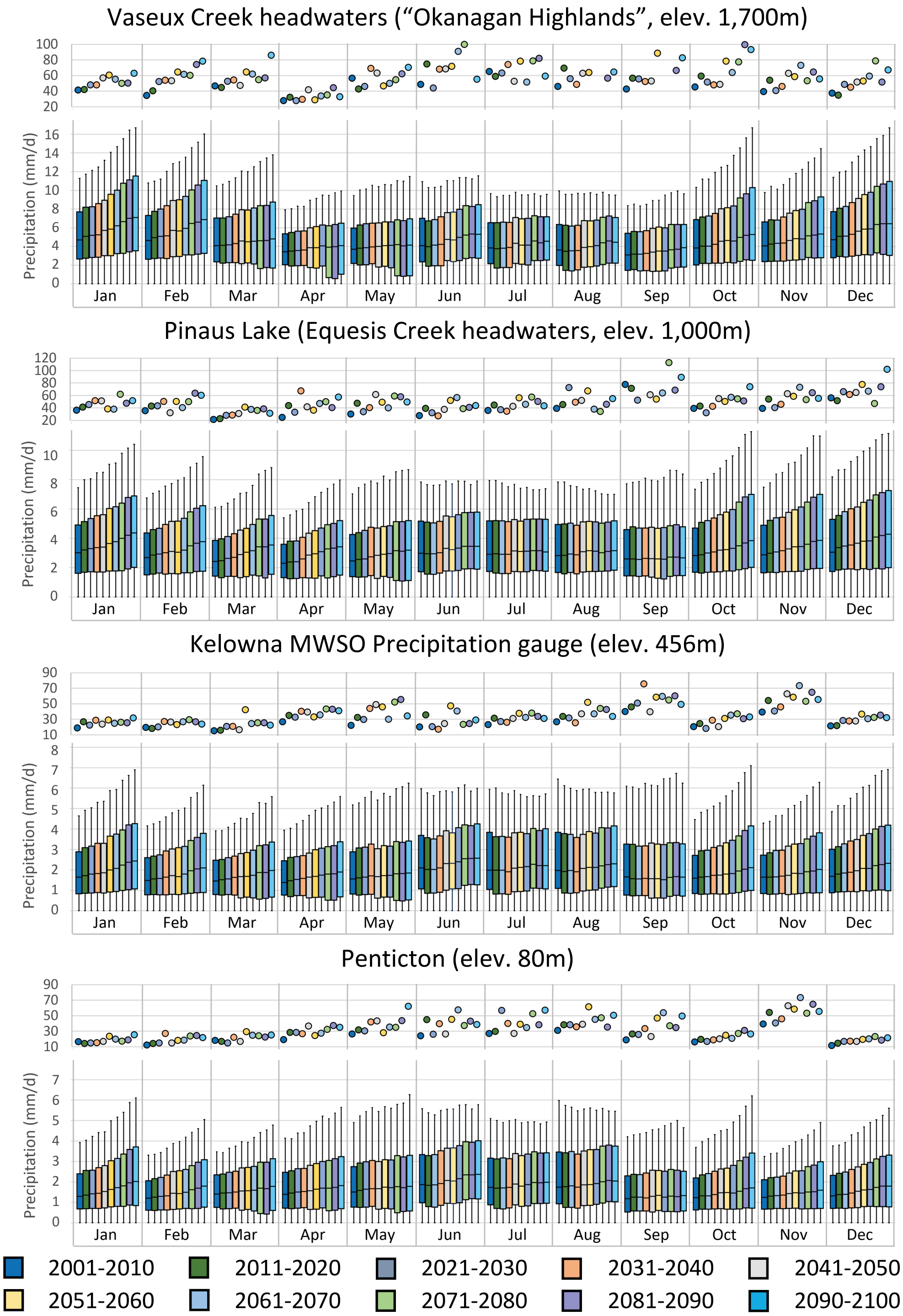

Figure 2-17 Statistical distribution of projected daily precipitation in each decade for four representative locations in the Okanagan basin, covering a range of elevations. The vertical axis scale is different for the plots of maximum points above the boxplots.

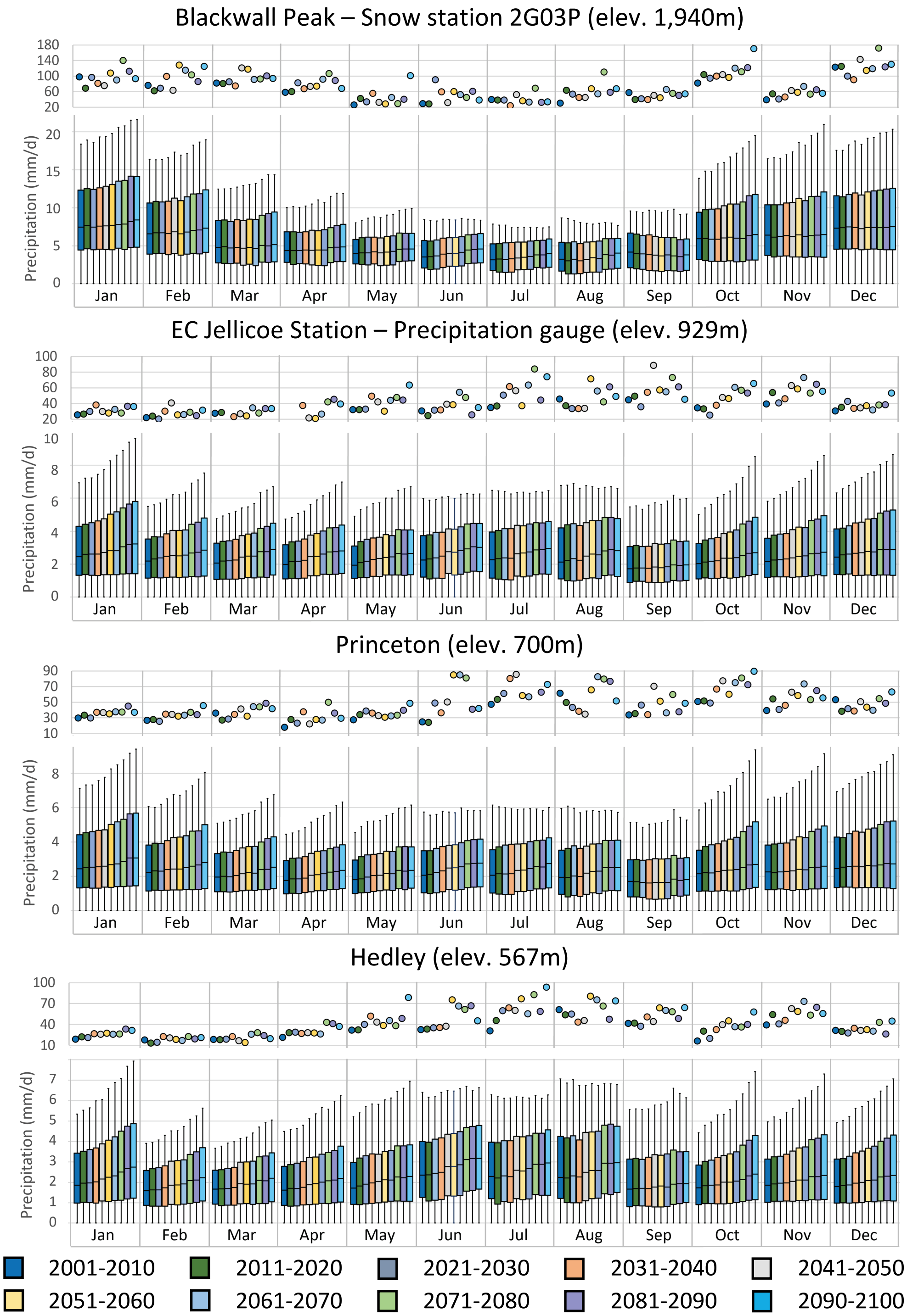

Figure 2-18 Statistical distribution of projected daily precipitation in each decade for four representative locations in the Similkameen basin, covering a range of elevations. The vertical axis scale is different for the plots of maximum points above the boxplots.

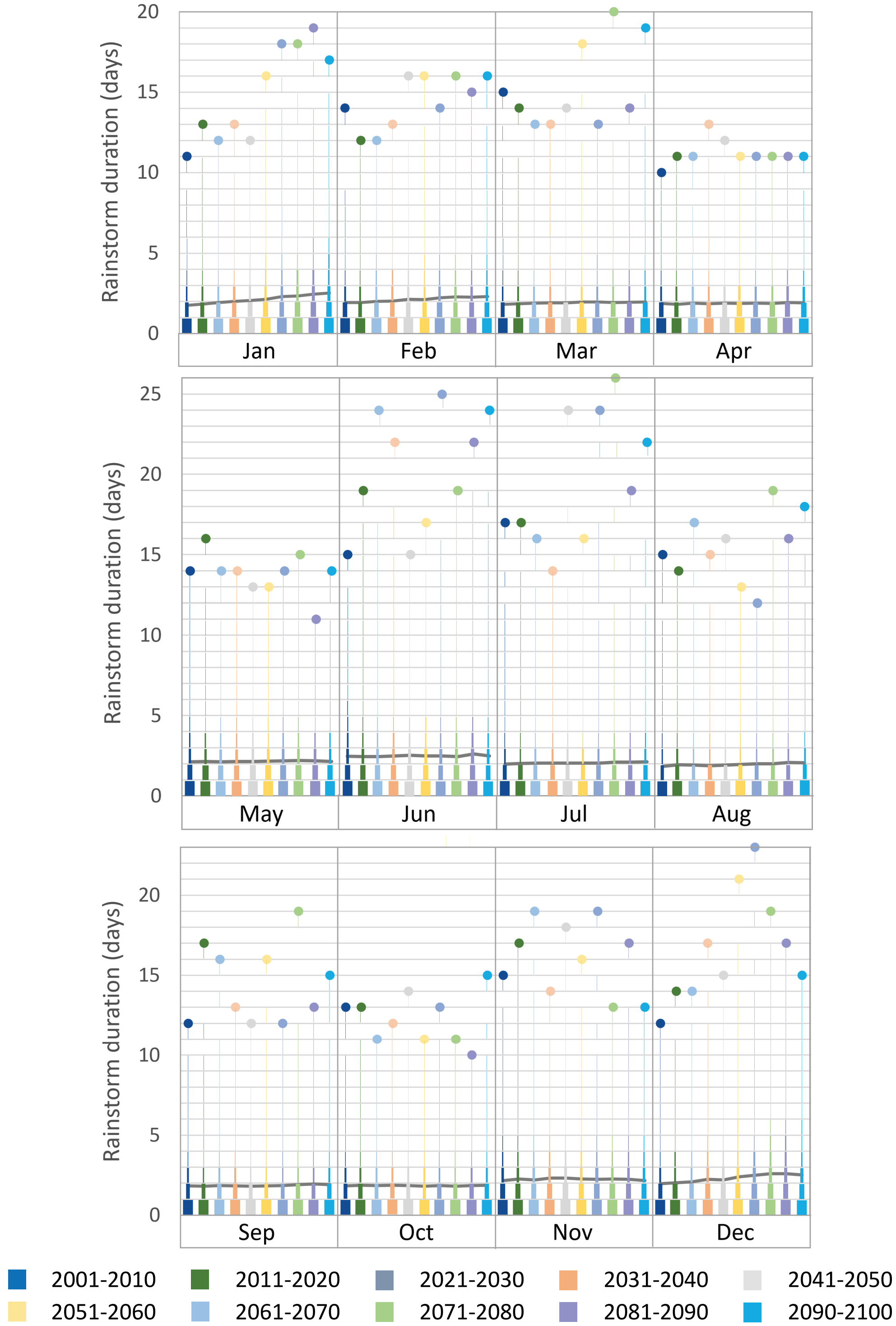

Figure 2-19 Distribution of rainstorm duration per month and decade. The grey line represents the average duration, while the funnel plots show the distribution of values and the points mark the maxima.

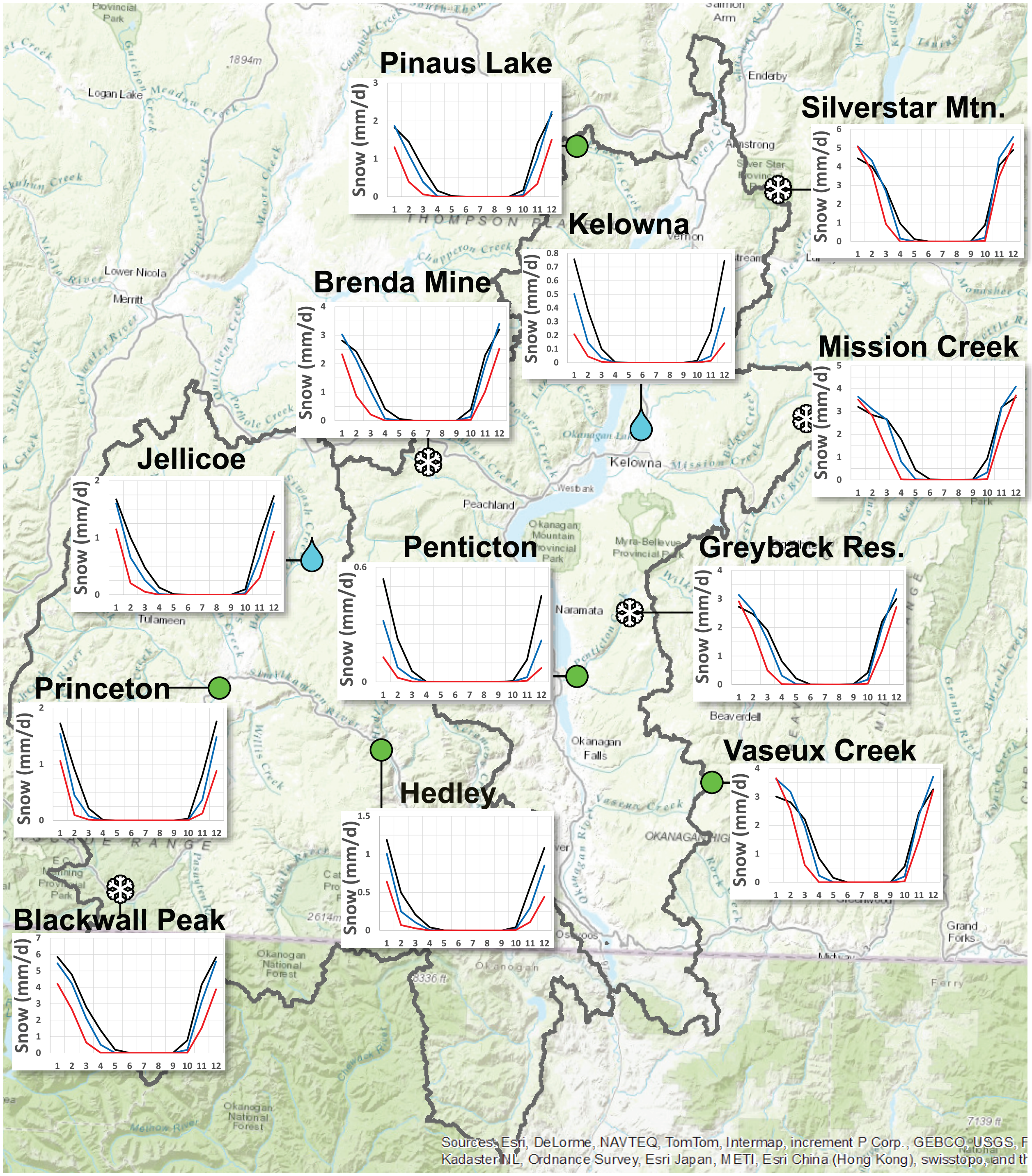

Figure 2-20 Average monthly snowfall, in mm of water equivalent per day, in decade 2001-2010 (black line), 2051-2060 (blue line) and 2091-2100 (red line).