2021-2022
ANNUAL REPORT

PACIFIC CLIMATE IMPACTS CONSORTIUM

The Pacific Climate Impacts Consortium

The Pacific Climate Impacts Consortium (PCIC) is a regional climate service centre at the University of Victoria. PCIC conducts quantitative studies on the impacts of climate change and climate variability and provides climate information and data focused on the needs of its user base in British Columbia and beyond. PCIC's research is organized around three interrelated themes: Regional Climate Impacts, Hydrologic Impacts and Climate Analysis and Monitoring. The Regional Climate Impacts theme works to determine the effects of global climate variability and change at the regional and community scales, using downscaling methods to derive regional information from global climate model projections. The Hydrologic Impacts theme examines the effects of climate variability and change on water resources using hydrologic models that simulate the flow of water through and on the landscape, as well as, in some cases, examining water temperature. The Climate Analysis and Monitoring theme collects, analyzes and applies quality control measures to historical and near real-time climate data from PCIC's partner networks. These three themes are supported by PCIC's Operations team who manage PCIC's staffing, finances and logistics, and PCIC's Computational Support Group, who develop PCIC's online tools and manage PCIC's computational resources. Because of the integrated nature of PCIC's themes and the fact that projects often require expertise from more than one theme, the stories that follow are not organized by theme, but rather by broad topic.

CONTENTS

Message From Corporate Leadership

In 2021-2022 PCIC continued to fulfill its important role as a provider of high-quality climate services for regional and national users, in support of their climate adaptation planning and decision-making processes.

Extreme weather events in 2021 had profound impacts on BC and surrounding regions. The extreme heat event that occurred in the summer resulted in the loss of hundreds of lives in the province. The extreme rainfall, high stream flow and subsequent flooding in November resulted in highway washouts that had devastating impacts on communities in the interior and lower mainland, and for a while left Vancouver and sections of the Lower Mainland entirely cut off by all means of ground transportation from the rest of Canada. The magnitude of the impacts from these extreme weather events highlighted the ever more urgent need to both better understand and better prepare for events like them. PCIC responded immediately, starting as the events were occurring, by contributing its expertise to the development of two rapid attribution studies that have enhanced our understanding of the extreme weather events that BC is facing.

To support the continued attainment of PCIC's service objectives and strategic goals, PCIC has updated its 5-year Strategic Plan for the 2021-2025 period. This plan articulates a spectrum of activities, ranging from direct data delivery to user-specific interpretation and training, that will help PCIC continue to develop in its role as the authoritative climate service provider in the region. This report will highlight the many achievements over the past fiscal year that contribute to achieving these strategic goals.

During the 2021-2022 fiscal year, PCIC has deployed the latest climate model projections from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), contributed to the growth of the Pacific Climate Data Set (with 55 million observations added over the last year alone), expanded PCIC's station data portal to provide service to Canada's Western Arctic, and released a new analysis tool, the Design Value Explorer, which provides civil engineers with information to support their planning in a changing climate. In collaboration with its partners, PCIC continues to improve its hydrologic modelling capacity and efficiency, as well as advance its hydrologic modelling projects, which will aid in the management of salmon habitat and migration routes and support highway engineering in the context of a changing climate. PCIC continues to actively share its research findings and contribute to the broader scientific discourse. All this and more was accomplished during the ongoing difficult circumstances that the globe and our region continue to face. We would like to express our sincere gratitude to all our staff and partners for their hard work and continued efforts in providing climate data, science, and training of the very highest quality to meet the needs of our many users.

Dr. Francis Zwiers,
PCIC Director

PCIC Staff, Fiscal Year 2021-2022

Top row, left to right: Md. Shahabul Alam, Mohamed Ali Ben Alaya, Faron Anslow, Matthew Benstead, Charles Curry, Rod Glover, James Hiebert, Shelley Ma

Middle row, left to right: Trevor Murdock (on secondment), Stacey O'Sullivan, Dhouha Ouali, Markus Schnorbus, Arelia (Werner) Schoeneberg, Michael Shumlich, Stephen Sobie, Qiaohong Sun

Bottom row, left to right: Travis Tai, Kari Tyler, Pei-Ling Wang, Francis Zwiers

Not pictured: Johnathan Helfrich, Tom Kunkel, Samah Larabi, Nigus D. Melaku, Teresa Rush, Ada Sungar, Kai Tsuruta, Kathy Veldhoen, Eric Yvorchuk, Lee Zeman


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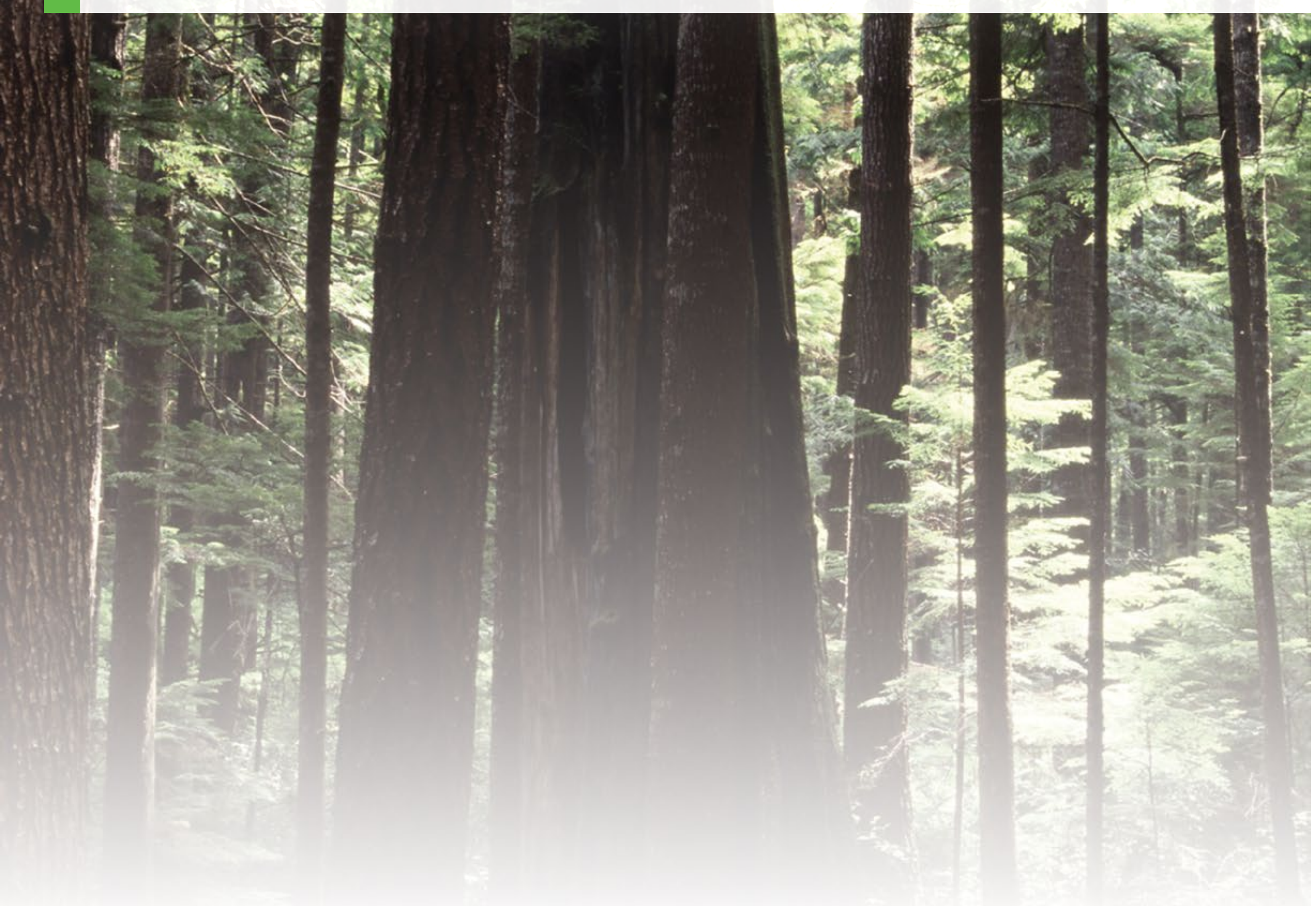
Francis Zwiers, Director, Pacific Climate Impacts Consortium

ANALYZING CLIMATE EXTREMES

The changing climate is affecting the frequency and magnitude of certain climate extremes. These events are of great concern because of their potential for significant societal impacts. PCIC's research team is working to better understand the interplay of climate change and extreme weather events in BC and to develop methods for the detection and attribution of climate extremes more broadly.



The Rapid Attribution of Climate Events

Purpose: To better understand and contextualize the extreme weather events that BC faces, so that planners can have the necessary information to understand the causes of recent events and prepare for future events.

PROJECT PARTNERS

Environment and Climate Change Canada

World Weather Attribution Initiative

PCIC's team worked collaboratively with the broader climate science community over the past year to perform two rapid attributions of extreme weather events that had severe impacts on British Columbia and surrounding areas. This work showcases the synergies between the work supported by PCIC's partners. Drawing on research from multiple areas allows for a comprehensive level of analysis to emerge.

The first event occurred in June of 2021, when Western North America was gripped by an extreme heat wave (Figure 1). This was caused by a strong high-pressure system, often referred to as a "heat dome," which diverted atmospheric moisture from the region while trapping hot air at the surface, resulting in the shattering of many long-standing temperature records across the region (by 4 °C in Greater Vancouver), the loss of 619 lives in the province, and impacts across multiple sectors. The authors of the attribution study[18] that PCIC participated in found that: (1) the event was exceedingly rare, given the historical climate of the region and (2) a heatwave of this magnitude is at least 150 times more likely under human-induced climate change and will occur with increasing frequency under further global warming. The report, released by the World Weather Attribution initiative, was covered widely by the international press.

The second event occurred in November of the same year, when a powerful atmospheric river event struck the province, breaking at least 20 rainfall records across southern BC. The devastating event

left 200,000 homes without power, forced more than 17,000 to evacuate their homes, and caused Vancouver and several other communities to be completely cut off by land travel from the rest of Canada due to extensive damage to BC's surface transportation system. As the event unfolded, PCIC's team was already working to understand it with colleagues from Environment and Climate Change Canada (ECCC). In the resulting publication[10], they found that atmospheric rivers of the magnitude of the November event can be expected to occur, on average, once every ten years in the current climate and that such events are at least 60% more likely due to the human influence on the climate system. In terms of the amount of precipitation that fell, the researchers found that the event was about a one in 50-to-100 year event and that the probability of such events has increased by about 50% due to

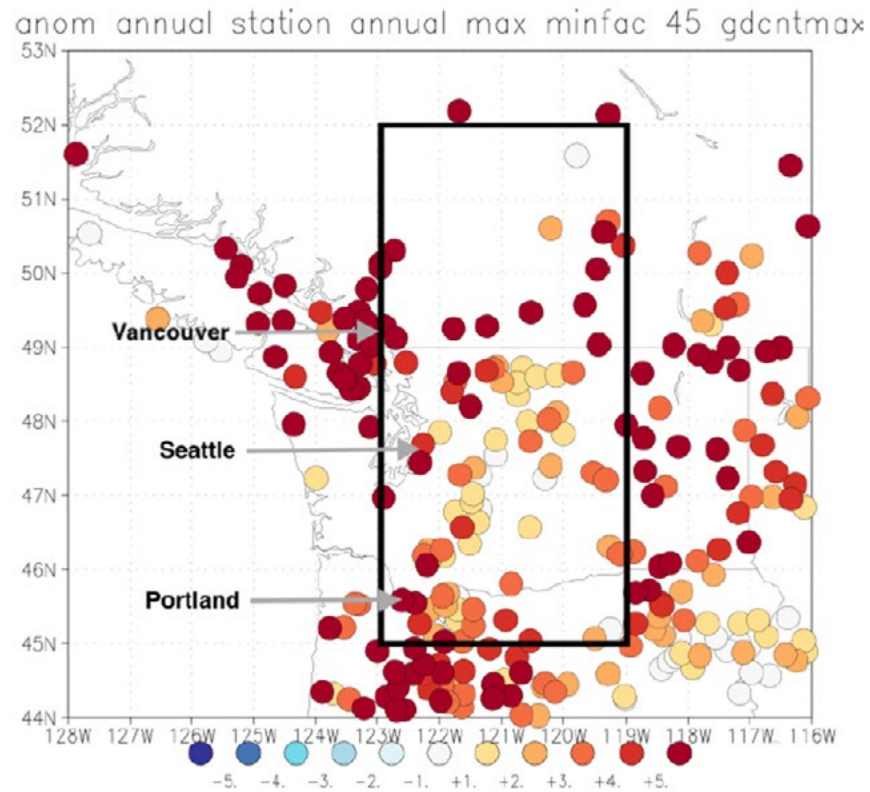


Figure 1: This figure shows the anomalies of the 2021 highest daily maximum temperature (TXx) relative to the period of 1900-2019 over the study region (shown in the black box).

human-induced climate change. The authors estimated that the probability of the extreme streamflow events of the magnitude that were seen in November are now two to four times as large as they were in the 1950s, as a result of human-induced climate change.

This work allowed PCIC to contribute its expertise and resources to better understand and contextualize the extreme weather events that BC faces, so that planners can have the necessary information to prepare for future events. It also allowed for the further development and refinement of attribution techniques that serve the climate science community more broadly. In addition, these studies illustrate how multiple threads of research supported by PCIC's partners can be woven together. For instance, the rapid-attribution analysis of the November flooding events drew upon the existing large-ensemble simulations of the Fraser basin supported by BC Hydro and extreme streamflow analyses of these simulations, supported by the BC Ministry of Transportation and Infrastructure that are discussed later in this report (see the story *Providing Peak Streamflow Information* on page 32).

Figure 2: This photograph shows the flooding that occurred in the City of Merritt immediately following the November 2021 atmospheric river event. Photo credit: the British Columbia Ministry of Transportation and Infrastructure.

Analyzing Climate Extremes

PROJECT PARTNERS

Global Water Futures

University of Saskatchewan

This project was undertaken thanks in part to funding from the Canada First Research Excellence Fund

Purpose: Improve our understanding of extreme events, which are of interest because of their destructive power.

Researchers at PCIC have been analyzing the properties of extreme precipitation and wind speed events. Their work has improved our understanding of these extreme events, which are of immense interest due to their destructive power and the need to quantify and characterize them for designing infrastructure. Over the past year, this research, supported by the Global Water Futures program, has focused on the detection and attribution of extreme precipitation events and the characterization of extreme wind speed events. The detection and attribution research[21] found that human influence on extreme precipitation is observable at the global scale, at the continental scale in Asia, Europe, and North America, and in several smaller regions (Figure 3). It found that anthropogenic influence has made extreme precipitation events more frequent, such that extreme one-day events that would have only occurred, on average, once every 20 years in the 1950's, are now occurring once every 16 years. The intensification of these events is in line with physical theory regarding the increasing amount of water vapour that the atmosphere can hold as it warms. The research on extreme wind speed events focused on how to characterise events with long return periods, of up to 3000 years, when only 10-50 years of data are available at many locations. This research found that while a standard extreme value analysis method provides reasonable estimates for events with return periods of 100 years or less, it may underestimate the magnitude of very long (1000-year-plus) return-period events. This ongoing work targets important, unresolved questions that have implications for engineering applications, but also contributes to the body of knowledge regarding extremes in climate science more broadly.

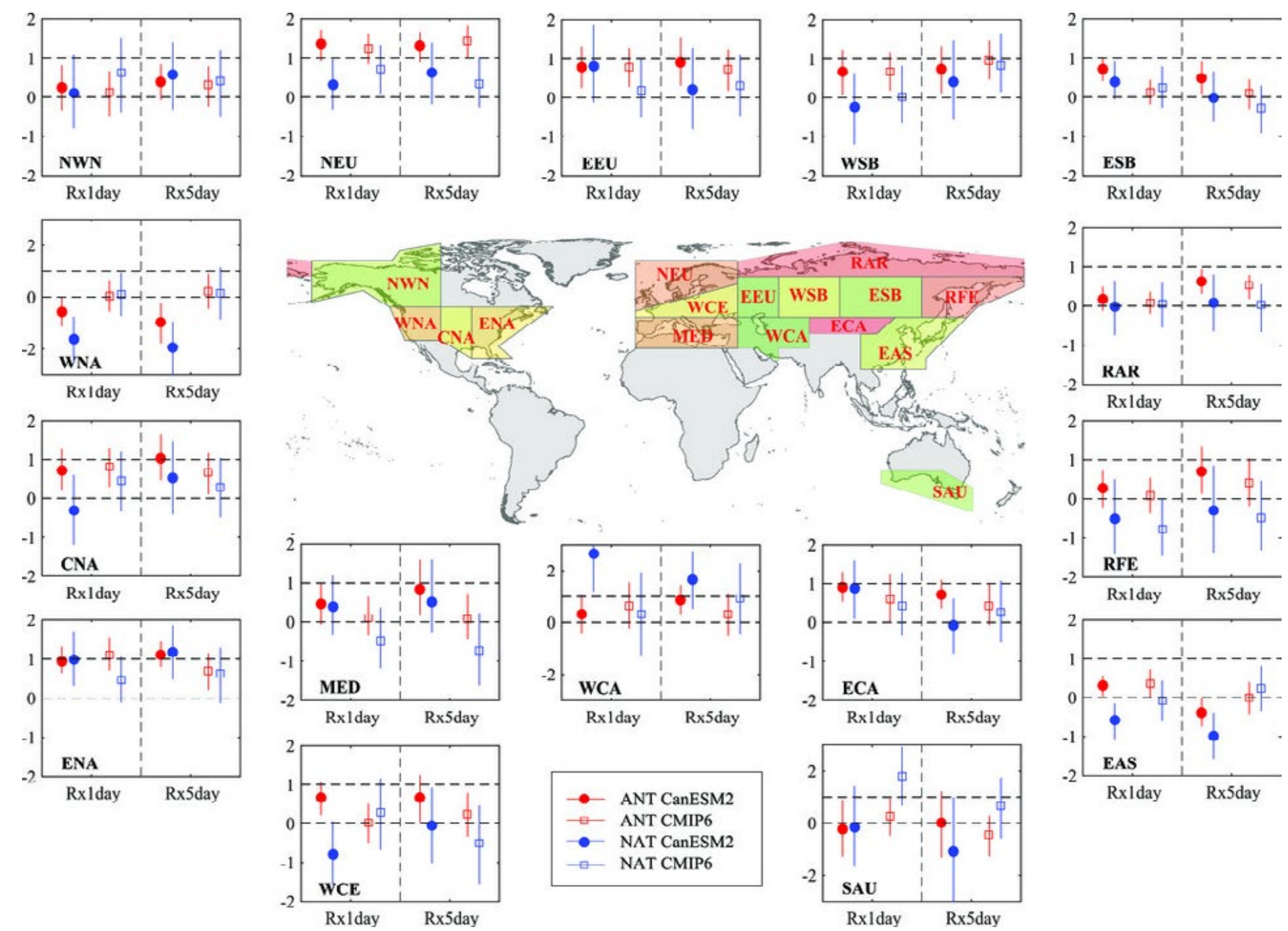


Figure 3: Estimates of the scaling factors that describe how well the expected effects of external forcings (signals) can be detected in observed changes in extreme precipitation. Results are shown for signals obtained from two sets of climate model simulations, where each set of simulations included model runs that considered anthropogenic (red) and natural (blue) external forcings of the climate. The method searched for these signals in observations of the annual maxima of 1-day (Rx1day) and 5-day (Rx5day) precipitation amounts over the 1950–2014 period in each of the 16 land regions used in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6). Solid boxes indicate results using signals in Rx1day and Rx5day obtained from the Canadian Earth System Model version 2 (CanESM2) and outlined boxes show corresponding results when using a group of ten models participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The bars indicate 5%–95% uncertainty ranges of the scaling factors. If these overlap with 1 but do not overlap with 0, it indicates that the forcing signal for that type of precipitation extreme can be detected.

THE NEXT GENERATION OF CLIMATE MODEL PROJECTIONS

The global climate science community is now using projections from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) that were the basis for much of the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report. These projections come from the current generation of climate models with updated representations of the various parts of the Earth's climate system. PCIC has begun analyzing and downscaling the latest climate model projections and integrating them into PCIC's Data Portal and online tools, in order to provide its users with the most current climate projections available. PCIC is also working on refining the methods of downscaling that we use so that our users can glean the most useful information possible for their regions from GCM output.

Evaluating and Downscaling CMIP6 Model Output

Purpose: Provide our users with the latest climate model output, downscaled for regional-scale application, to inform impacts assessments and decision making.

PROJECT PARTNER

Environment and Climate Change Canada

PCIC scientists have analyzed global climate model (GCM) output from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) across Canada and compared it to earlier projections from CMIP5. Our researchers found that higher temperatures are projected for most seasons across the country in CMIP6 compared to CMIP5. For instance, comparing the projected changes in summer maximum temperatures by the 2050s over British Columbia only (Figure 4, upper panels), the CMIP6 projections show more warming than in CMIP5 across the whole province, but less warming in winter minimum temperatures (not shown). The differences in projected precipitation between CMIP5 and CMIP6 are smaller. PCIC's team also found that, for specified levels of global temperature change, the regional responses of temperature and precipitation are quite similar between CMIP5 and CMIP6, meaning that similar information is available from both CMIP ensembles (Figure 4, lower panels). The improved understanding gained through this analysis allows PCIC to provide better guidance to decision makers in their planning. This work was also shared with the broader scientific community through a paper[21] published in the journal *Atmosphere-Ocean*.

PCIC has produced downscaled and bias-corrected versions of simulations over Canada from a large collection of CMIP6 climate models and has made them freely available through its Statistically Downscaled Climate Scenarios Data Portal page. These downscaled scenarios have also been incorporated into the PCIC Climate Explorer, are being incorporated into the Plan2Adapt tool, and will serve as

the basis for future hydrologic projections. The new downscaled CMIP6 scenarios that PCIC has produced use a univariate downscaling method, Bias Correction/Constructed Analogues with Quantile mapping, version 2, (BCCAQv2), which treats only one variable at a time. Consequently, relationships between minimum temperature, maximum temperature, and precipitation amount are not taken into account. PCIC's team evaluated several recently developed multivariate techniques that account for the interdependence between variables and found that the Multivariate Bias Correction algorithm (MBCn) performed best, giving single-variable results that were very similar to those from BCCAQv2, and also providing a substantially improved representation of climate indices composed of two or more vari-

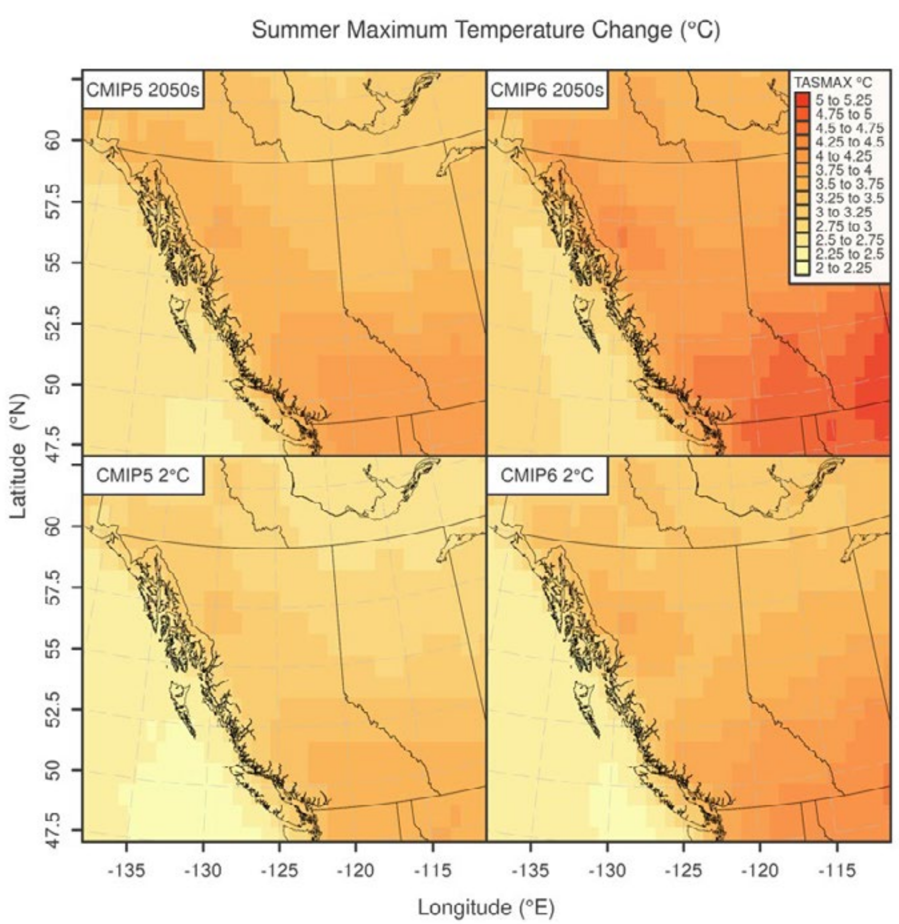


Figure 4: The change in summer mean daily-maximum temperature over BC and surrounding areas over the 2050s (top panels) and for an average global warming of 2°C (bottom panels). Two high-emissions scenarios are used here: in the left panels, CMIP5 RCP8.5 ensemble mean results for the 2050s are contrasted with those from CMIP6 SSP5-8.5 in the right panels. All changes are relative to a 1971-2000 baseline period. As a group, when comparing models at 2°C of global warming, the CMIP6 models project about 0.4°C more warming in summer maximum temperatures over BC, on average.

ables. Using this improved downscaling method, our team is currently producing downscaled CMIP6 scenarios across Canada, which will be made available on PCIC's Data Portal. It is expected that certain applications, such as hydrological modelling, will benefit from the multivariate approach.

PCIC researchers also evaluated several potential downscaling training datasets, and settled on a blended dataset that has better performance in the mountainous west than the competitor datasets that were considered. PCIC scientists are now using this blended training dataset in combination with the MBCn downscaling method. In addition, PCIC's team investigated the length of the training datasets that are used to tune the parameters of the downscaling methods that they use. This research is ongoing and PCIC's team are working to determine whether BCCAQv2 (and MBCn) can be trained successfully with observational datasets that are shorter (down to 15 years) than the training sets that PCIC has employed in the past, which were about 60 years long. The interim results of this work suggest that, under some circumstances, moderately shorter training sets can give results comparable to the longer data sets. This could allow for a wider range of possibilities for the use of new observational datasets. One of these, the Regional Deterministic Reforecast System version 2.1 (RDRSv2.1) reanalysis of historical surface meteorological conditions, recently produced by ECCC and spanning 1980-2018, is a promising candidate data set for use at PCIC.

REGIONAL CLIMATE SERVICES

PCIC's team works to determine the effects of global climate variability and change at the regional and community scales needed to support our users' planning and decision-making, using downscaled GCM projections. The following projects show how PCIC uses these to deliver regional climate information in a comprehensive way to meet the diverse needs of our user base.

Supporting Regional Climate Service Delivery

Purpose: Support regional climate service delivery across Canada.

PCIC has contributed its experience to the coordination of Canada's regional climate services and applied its expertise to inform national best practices in user engagement and training in climate science, train climate educators, and support electronic climate service delivery across Canada. To aid in aligning the efforts of Canada's regional climate service providers, PCIC has continued to participate directly in the Canadian Centre for Climate Services' Regional Coordination Committee, coordinating the efforts of existing climate service centres and supporting provinces in establishing new centres for regions that do not yet have them. PCIC has been participating in the CCCS Support Desk Working Group, augmenting the Support Desk's capacity to provide information to Canadian climate information users and to direct them to the appropriate tools for their needs. PCIC's user engagement team has also been participating in the Training Sub-Group, helping to train the trainers and develop instructional materials. PCIC has also been providing presentations, guiding workshops, developing user needs assessments, and aiding in the focus groups that test the modules on ClimateData.ca, to ensure that they meet user needs and to iteratively improve them. To support electronic climate service delivery across Canada, PCIC's team has also coordinated with the Centre de Recherche Informatique de Montréal (CRIM) and Ouranos to share downscaled output from GCMs participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6).

PROJECT PARTNER

Canadian Centre for Climate Services

Supporting Canadian Decision Makers: ClimateData.ca

PROJECT PARTNERS

Computer Research Institute of Montréal

Canadian Centre for Climate Services

Purpose: Contribute resources to help decision makers incorporate climate change into their decision-making processes.

PCIC is part of a national collaboration that is working to provide Canadians with high-resolution climate data, together with context and guidance on its use, through an online portal called ClimateData.ca. PCIC contributed the data (based on CMIP5) that is accessed through the portal, and helped develop the portal's Analyze section, its Buildings and Transportation sector modules, and outreach materials for the site. The downscaled CMIP6 scenarios that PCIC recently produced have also been provided to ClimateData.ca and are currently being incorporated into the site. Its Analyze section allows users to access climate indices generated from PCIC's downscaled GCM output for their region of interest. Users can also specify custom thresholds for certain climate indices at the level of a health region, census division, and watershed or sub-watershed scale, for a past or future period. The Transportation and Buildings sector modules provide context for the use of climate data in planning for Canadian transportation systems and the built environment, respectively, to help users in making decisions that take projected climate changes into account. The Buildings sector module links to PCIC's national Weather Files Data Portal page, and highlights its application in a case study. Both modules provide users with in-depth case studies, education and engagement resources, and a list of the relevant variables for each sector.

Contributing to Improved Floodplain Risk Assessments

Purpose: Improve floodplain mapping and prediction via the provision of innovative downscaling techniques and high-quality calibration data.

Flooding results in the most financially costly impacts out of all of the extreme weather events that Canada faces. Climate change is likely to alter the magnitude and frequency of flooding events. Canada's floodplain maps are roughly 25 years old and the Earth's climate has changed significantly in that time. In order to help decision makers across Canada in their assessment of floodplain risk, PCIC has contributed its expertise in climate model downscaling and observational data assessment. As an initial step in this project, PCIC conducted a preliminary evaluation of a new reanalysis product for North America, the second version of the Regional Deterministic Reforecast System (RDRSv2), comparing key variables from RDRSv2 with those from both global reanalysis products, such as the European Centre for Medium-Range Weather Forecast Reanalysis, version 5 surface variables product (ERA5-Land) and gridded observational datasets for the region. RDRSv2 is a potential target dataset for the downscaling and hydrologic modelling connected to the floodplain risk assessment, but it is presently only 39 years in length, which could be a limitation for the Multivariate Bias Correction for n variables (MBCn) downscaling method used by PCIC. PCIC therefore also conducted a study on the robustness of the MBCn-downscaled results to the length of a target dataset, concluding that the benefit of using an improved, albeit shorter duration target dataset likely outweighs the potential losses from a shorter calibration period.

PROJECT PARTNER

Environment and Climate Change Canada

Supporting Planning and Energy Modelling in Calgary

PROJECT PARTNER

The City of Calgary

Purpose: Provide future-adjusted weather files and climate data review for the City of Calgary to aid in energy modelling and built environment planning and policy.

PCIC recently provided future-adjusted weather files, engineering design variables, and a climate data review for the City of Calgary, in order to aid in their built environment planning and policy development (Figure 5). These were designed to support engineers and decision-makers as they plan for buildings and infrastructure projects with the changing climate in mind. PCIC's team provided weather files suitable for energy modelling for the current climate and the projected future climate, to allow for an analysis of how heating and cooling demands will be affected as the region warms in step with global warming. Our team also provided historical and future-projected values for variables used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). PCIC staff also made recommendations for the incorporation of the future-shifted weather files and future design values in planning, and provided a review of the City's existing climate projections data, drawing upon PCIC's previous experience with multiple partners in these domains.

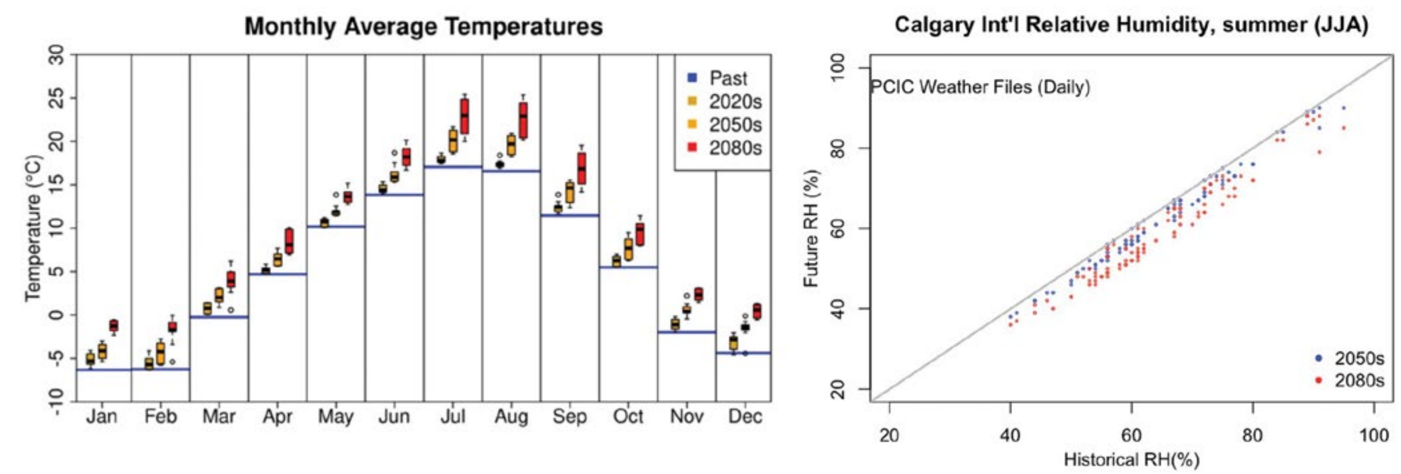


Figure 5: Monthly average temperatures for the City of Calgary for the past (1998-2014), and simulated temperatures for the 2020s, 2050s and 2080s (left), and the projected summer relative humidity for the Calgary International Airport for the 2050s and 2080s (right). All simulations were made using the RCP8.5 high emissions scenario.

Supporting Canadian Forestry Management

PROJECT PARTNER
FPInnovations

Purpose: Support Canadian forestry management by providing climate indices for integration into a forestry management tool.

In order to support Canadian forestry management in the face of a changing climate, PCIC partnered with FPInnovations (FPI) to provide data on historical trends in selected climate indices (Figure 6), along with assistance in interpreting these data to help with future applications. PCIC produced gridded, historical trend results over Canada's land area for eight climate indices of interest to FPI and their user base. These data, along with future climate projections for the same indices delivered in a previous collaboration, are now being integrated into a sustainable forestry management tool under development at FPI, intended to support the planning of forestry service roads. Our team worked with FPI to provide clear interpretations of the data and to explain its limitations for the intended purpose. In addition, via a collaborative online workshop with FPI targeted towards its engineering user group, PCIC shared the results of recent in-house work on leveraging the known physical relationship between temperature and rainfall to develop an approximate change factor for scaling Intensity, Duration and Frequency (IDF) curves as a function of the amount of local warming. Using our newly-developed Design Value Explorer online tool, PCIC researchers illustrated the variation of these change factors across BC. All of these results will be available to support engineers as they develop the infrastructure to manage water in and around forest service roads.

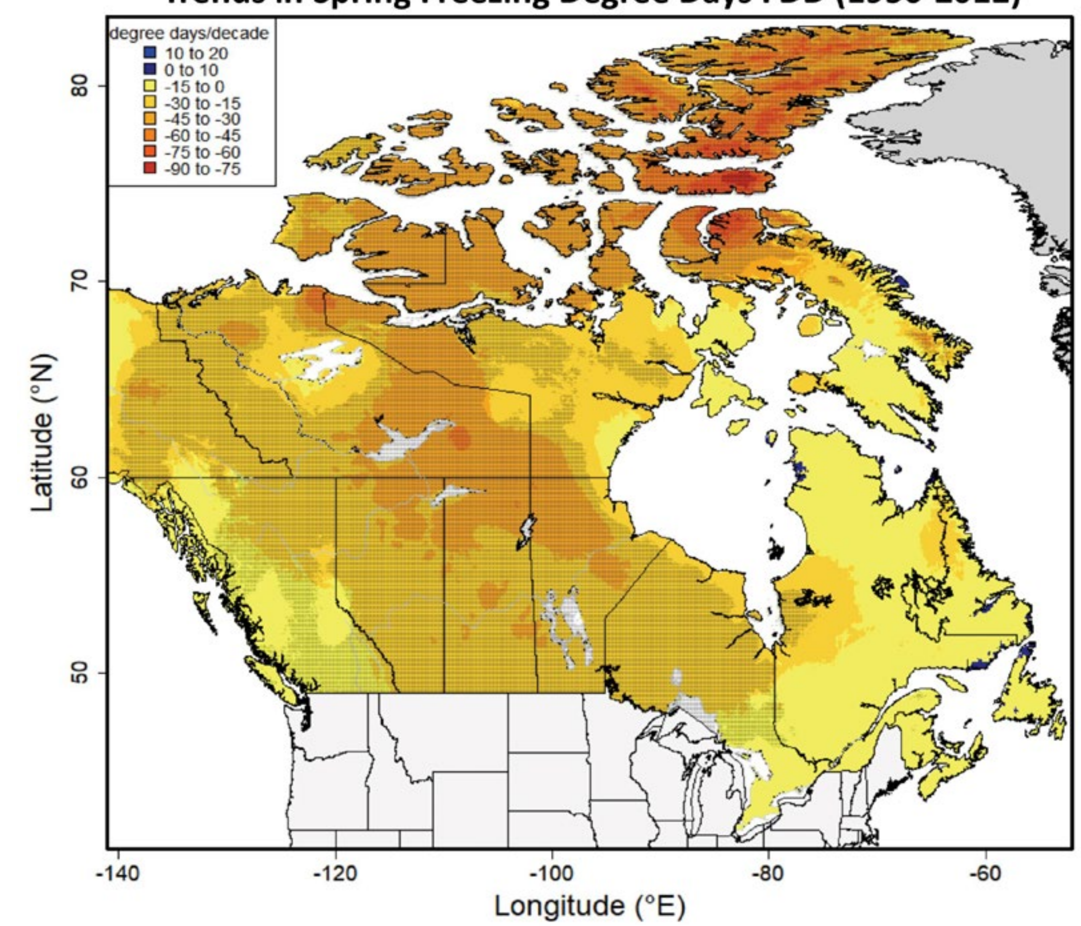


Figure 6: The trend in Freezing Degree Days (FDD) per decade over the 1950-2012 period from the recently developed PCIC-Blend gridded observational dataset. Stippling indicates where trends are statistically significant at the 5% level. Significant decreasing trends in FDD as derived from PCIC-Blend are seen in all seasons throughout Canada, except in Quebec and the Atlantic provinces. The largest decreases are seen in the northwest and also in the Arctic Archipelago in winter. The decreases in FDD found in this work are consistent with the pervasive decrease in frost days over the last 7 decades, as reported earlier in *Canada's Changing Climate Report* (2019).

Developing a New High-Resolution Climatic Data Set

PROJECT PARTNER

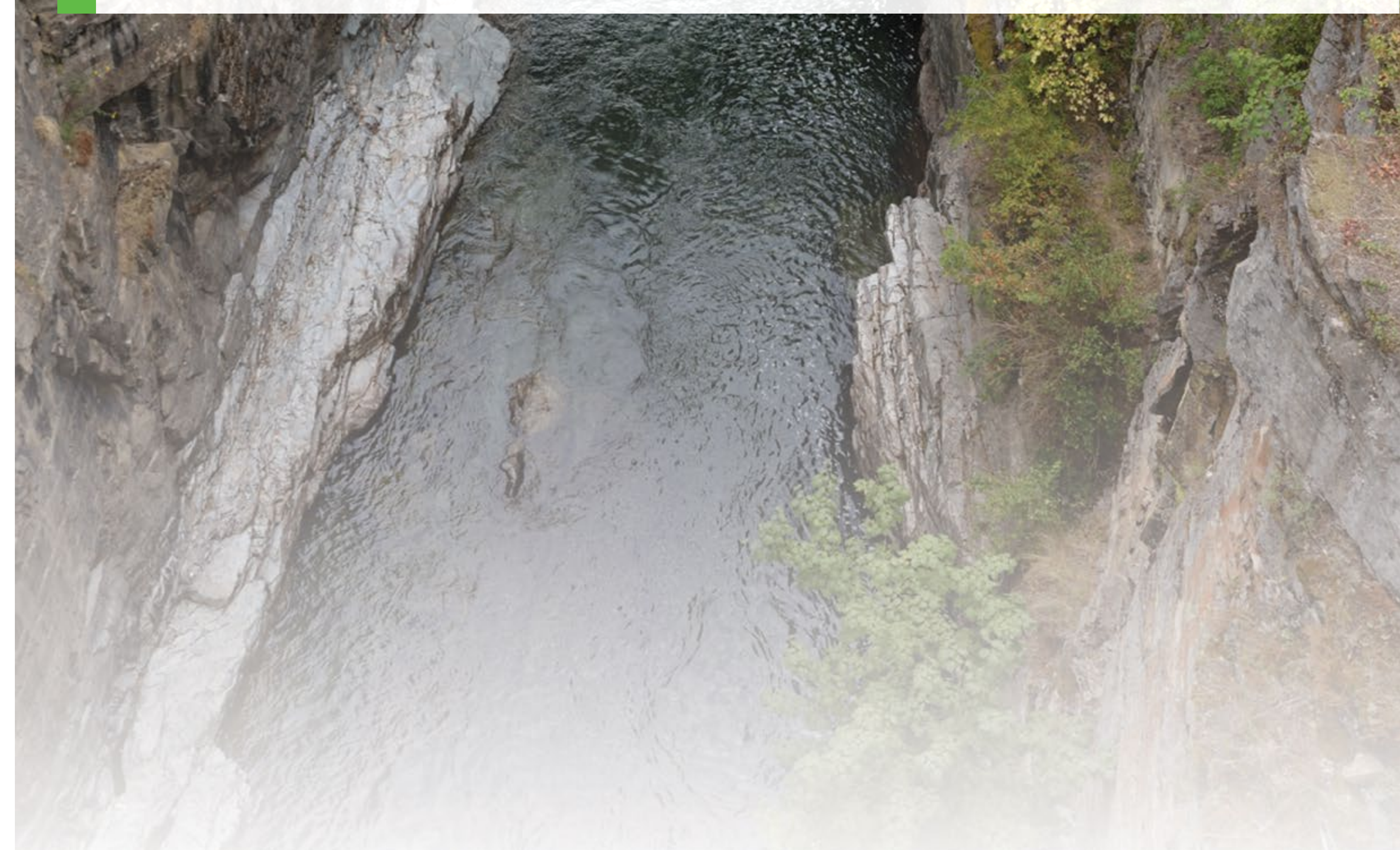
British Columbia Ministry of Forests

Purpose: To develop a high spatial resolution climatic dataset based on daily data, to better capture climatic extremes.

PCIC partnered with the BC Ministry of Forests, Lands, Natural Resource Operations & Rural Development during the last fiscal year to help scope an initiative to create a new high-resolution climatic dataset for British Columbia and the surrounding area, provisionally referred to as ClimatEx. While high-resolution (of the order of one-kilometre) monthly climatological data are currently available via PCIC's BC Parameter Regression on Independent Slopes Method (PRISM) Data Portal or the ClimateBC tool, there is an unfilled need for a similarly fine-scale product based on daily data, and also one that extends beyond the BC provincial boundaries. This product would initially be used to study climate change impacts and adaptation measures for the region's forests, but would also have applications to many other areas of interest.

CUTTING-EDGE HYDROLOGIC MODELLING

Water is a critical resource for British Columbia's communities and ecosystems. Just under 90% of the province's electricity comes from hydroelectric sources. As the climate changes, it will impact the hydrology of the province, affecting water availability, the timing and magnitude of streamflow events, as well as extreme events such as flooding and drought. PCIC's team continues to develop, test and apply the latest advances in hydrologic modelling to examine the effects of climate variability and change on water resources in BC.



PROJECT PARTNER
BC Hydro

BC Hydro's Support Continues to Improve Hydrologic Modelling for the Province

Purpose: Support utility planning and decision making by developing hydrologic projections for all of the watersheds that BC Hydro manages, accompanied by an analysis of streamflow and extremes.

BC Hydro has been PCIC's close partner for 17 years, with BC Hydro present at the meeting at which the PCIC concept was first envisioned in 2005. This relationship is based on their shared interest in ensuring that the province's energy supply, distribution, and transmission networks anticipate the impacts of the changing climate. The ongoing support of BC Hydro has allowed for a substantial body of work, in particular hydrological modelling of the province and the US Columbia Basin at various scales, and hydrologic projections for all of the watersheds that BC Hydro manages and relies upon for operations. BC Hydro's support has also allowed for the ongoing development of a new hydrological modelling framework called Raven and updates to tools and datasets, such as the PCIC Climate Explorer.

This year, with the support of BC Hydro, PCIC hydrologists continued their work to deploy the Raven model across the watersheds that BC Hydro manages. Taking advantage of Raven's ability to couple to a glacier model, researchers at PCIC examined what effect melting glaciers would have on streamflow in the Cheakamus and Mica River basins - of particular interest because they are glaciated basins that contain reservoirs and power generation infrastructure operated by BC Hydro. They found that the Mica basin simulations project an increase in springtime (April–June) flow and a decrease in summer (July–September) flow, with the end of century decreases in August and September being similar in magnitude to the decrease in glacier flow. The expected shift in the Mica Basin's annual hydrograph may lead to challenges for dam operators who are motivated to maintain high water levels during the spring/early summer to meet the relatively large late summer demands, while simultaneously being obliged to mitigate any spill risks (in which the dam exceeds capacity and water must be released from the reservoir into the spillway and subsequently into the river downstream).

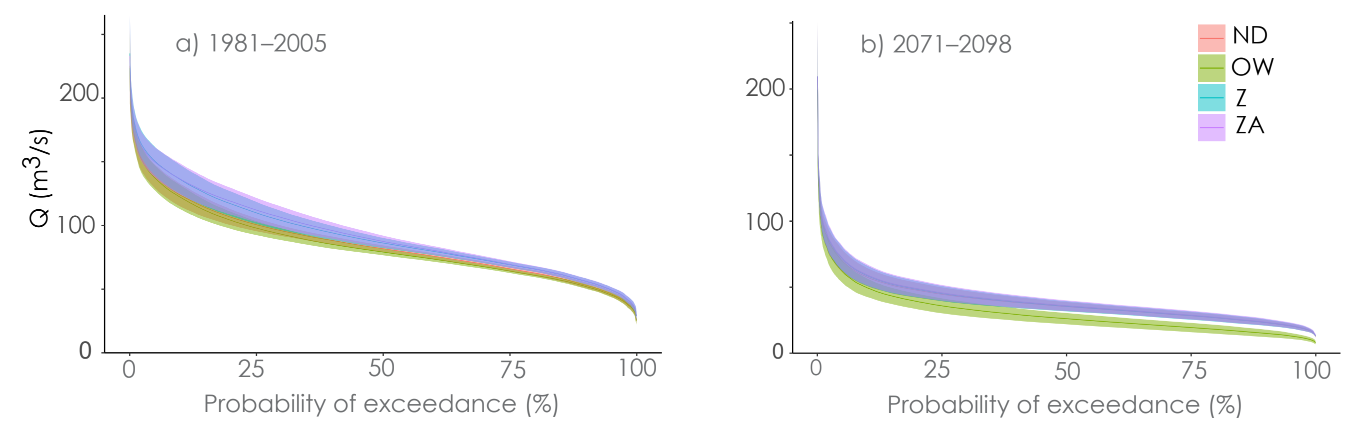


Figure 7: Flow duration curves (the percentage of time that flow exceeds a specific magnitude) for summer (July-August) flows in the Cheakamus basin comparing a) the 1981-2005 period to b) the 2071-2098 period, assuming a high greenhouse gas emissions scenario. The influence of glacier loss is seen as a reduction in summer flow. For example, during 1981-2005, summer flow exceeds ~100 cubic metres per second (m^3/s) 50% of the time. At end-century, a flow of ~100 m^3/s will only be exceeded <5% of the time. Although the general trend is of declining summer flow, the details are dependent upon how the coupled model is calibrated (where ND, OW, Z, and ZA represent alternative ways of calibrating glacier mass balance and melt rates).

In the Cheakamus basin, projected summer streamflow will be reduced as the glaciers feeding the Cheakamus River become depleted of ice (Figure 7). However, the details of how that will happen over time are still highly uncertain because of challenges in calibrating glacier mass balance in the coupled model. Nevertheless, these findings will still allow dam operators to include credible estimates of changes in seasonal streamflow into their planning. Raven's ability to represent physical processes with different levels of complexity makes it well suited to explore how the likely shrinking of BC's glaciers due to global warming will affect streamflow in these rivers.

Improving Large Domain Model Parameterization

PROJECT PARTNERS

Global Water Futures

University of Saskatchewan

University of Waterloo

This project was undertaken thanks in part to funding from the Canada First Research Excellence Fund

Purpose: PCIC is doing cutting edge hydrologic modelling, determining the best way to model large domains, in order to benefit our users while contributing to the advancement of hydrologic modelling.

PCIC's hydrologic modelling team are working on ways to make hydrologic modelling over large domains more efficient. To do this, they are tackling the most computationally expensive part of the hydrologic modelling process: model calibration. During model calibration, a set of mathematical parameters that appear in approximations of land surface processes are adjusted for as a hydrologic model is set up to run over a given area. These approximations are required because the necessary detailed process knowledge may not be available or because the computational expense of representing these processes explicitly may be prohibitively high. By identifying which of these parameters have the largest effect on model performance, future calibration efforts may be focused on these "sensitive" parameters. PCIC's team used a screening method to identify the sensitive parameters using sub-basins across the Pacific Northwest region that are representative of different hydrologic regimes. They also assessed whether parameter sensitivity can be inferred from the climate and terrain of the basins, which would allow suitable parameters to be chosen in a general way in the future, so that sensitivity analysis does not need to be repeated on each new domain to be modelled. They found that the degree of dryness of the climate (aridity), the amount of snow (snow index), and the glacier area for a given basin are strong predictors of model sensitivity for streamflow, evaporation, and snow cover (Figure 8). Ongoing work focusses on how to use the results of the sensitivity analysis to improve the model calibration process.

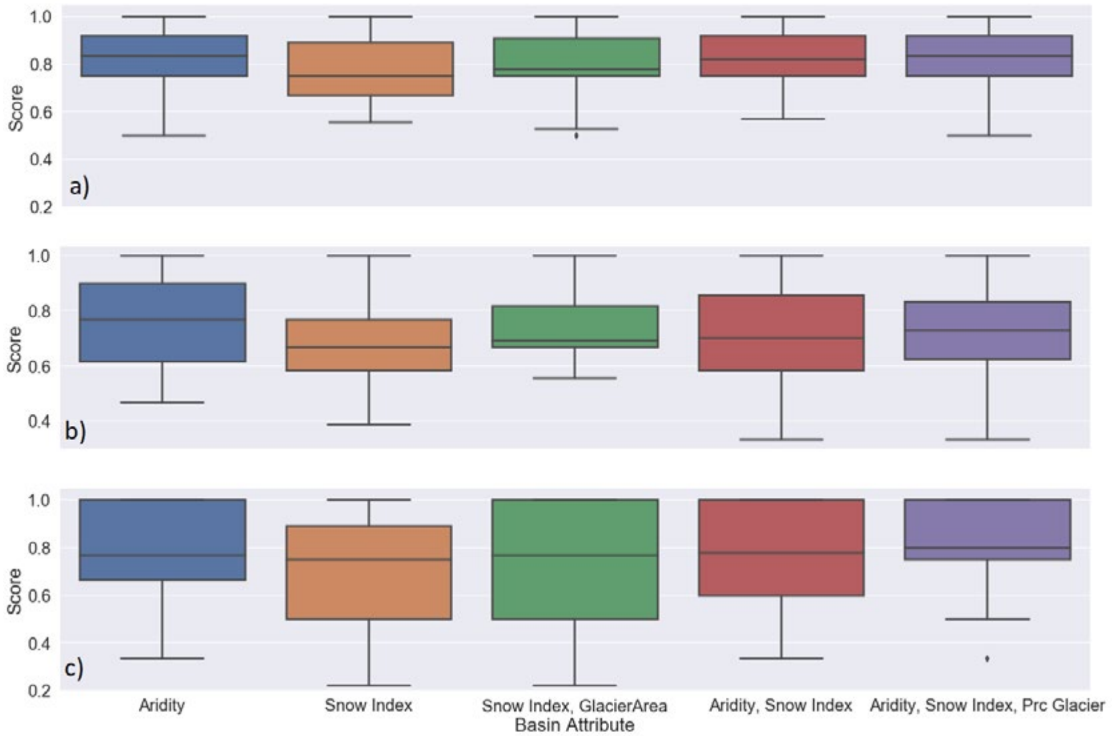


Figure 8: This figure shows the extent to which informative hydrologic model parameters for a) streamflow, b) evapotranspiration, and c) snow water equivalent can be accurately identified based on physical similarity of basin attributes – i.e., the unknown parameter sensitivity for a given basin is predicted using a different donor basin that has similar physical attributes. These results derive from analysis of 25 sub-basins spanning a large range of climates and hydrologic regimes (e.g. primarily snow-fed, primarily rain fed) throughout the Peace, Fraser, and Columbia basins. Results show the success by which sensitive parameters for each sub-basin can be identified from the most physically similar donor basin. The findings are presented as "box and whiskers" plots, which show the results and associated uncertainties. The median value is indicated by the line within the box, the upper 75th and lower 25th percentiles of the projections are given by the upper and lower boundaries of the box, respectively, and the full range of the projections (or 1.5 standard deviations, whichever is less) is given by the upper and lower 'whisker' marks at the end of the lines above and below the box. The ideal value of the score is 1, which would mean that all sensitive parameters are correctly identified. Results confirm that basins with similar aridity, amount of snow (snow index), and glacier area have near-identical sensitive parameters for streamflow and similar sensitive parameters for evaporation, and snow cover. These results could greatly improve the efficiency with which sensitive parameters are screened and identified for large-domain models.

Providing Peak Streamflow Information

PROJECT PARTNER

British Columbia Ministry of Transportation and Infrastructure

Purpose: To provide tools and projected future streamflow data to support highway engineering in the context of a changing climate.

To understand changes in peak streamflow, PCIC hydrologists have modelled the entire Fraser River and estimated future design flow values for the region. These design flows are hypothetical peak flows used in engineering design that are typically associated with a specific hazard level, such as a probability of occurrence. Our team has already modelled peak streamflows in the Upper Fraser, which are available through the Extreme Streamflow tab on PCIC's Climate Explorer, and is doing so for the remainder of the Fraser basin, a region that encompasses 232,000 square kilometers. The output is spatially continuous, allowing users to pick locations that are relevant for their project and receive the streamflow for those areas. In addition, when users pick a point, the tool indicates the upstream drainage area, so that users can see the basin they are getting runoff from. This data will also be made available through an application programming interface, so that the BC Ministry of Transportation and Infrastructure will be able to use it in their internal tools. This project is providing engineers with projected future design flow values for the Fraser for streamflow events with return periods from two to 200 years. These design flow values for various return periods will be available on a gridded domain, with a grid resolution of 1/16th of a degree, or about 25-30 square kilometres, depending on the latitude. The projections were made from downscaled output from a large ensemble of 50 hydrologic model simulations, each of which was driven by a different downscaled simulation from the second version of the Canadian Earth System Model (CanESM2) that was run using a high greenhouse gas emissions scenario.

HYDROLOGIC MODELLING TO SUPPORT FISH HABITAT MANAGEMENT

British Columbia's River ecosystems are habitat for multiple species of fish during different stages in their lifecycles and these ecosystems will be affected by changes in hydrology brought on by anthropogenic climate change. PCIC's team are performing hydrologic modelling on rivers in the province and developing a risk assessment tool to support the management of these habitats.

Supporting BC Salmon Habitat Management

PROJECT PARTNERS

Fisheries and Oceans Canada, British Columbia Salmon Restoration and Innovation Fund

Purpose: To develop exposure indicators and a risk-assessment tool to help decision makers manage BC's salmon habitats.

Pacific salmon are culturally, ecologically, and economically important in British Columbia. Their habitats are expected to be impacted by anthropogenic climate change. To address this, in partnership with researchers from the Department of Fisheries and Oceans Canada (DFO), and with the support of the British Columbia Salmon Restoration and Innovation Fund (BCSRIF), PCIC is developing exposure indicators that will support the regional management and planning of freshwater salmon habitats that considers climate change. PCIC researchers are simulating streamflow and water temperature under present and future climate conditions in virtually all of BC's gauged river basins that drain to tide water, representing an area of ~427,000 square kilometres. Preliminary findings show projected increases in the water temperature of salmon habitat and migration routes in both low and high emissions scenarios, with warming larger under the high emissions scenario (Figure 9). Our team have also developed a prototype risk-assessment framework for salmon conservation units in the Fraser River basin. The methods and indicators for this framework will be used to support BC-wide assessment of all wild salmon species by conservation unit - a unit of measure that refers to a group of wild salmon that are sufficiently isolated from other groups. The results of the hydrologic modelling and exposure indicator work will be delivered to fisheries managers and the public via a collection of online tools that will inform science-based policies and decisions in support of wild salmon conservation.

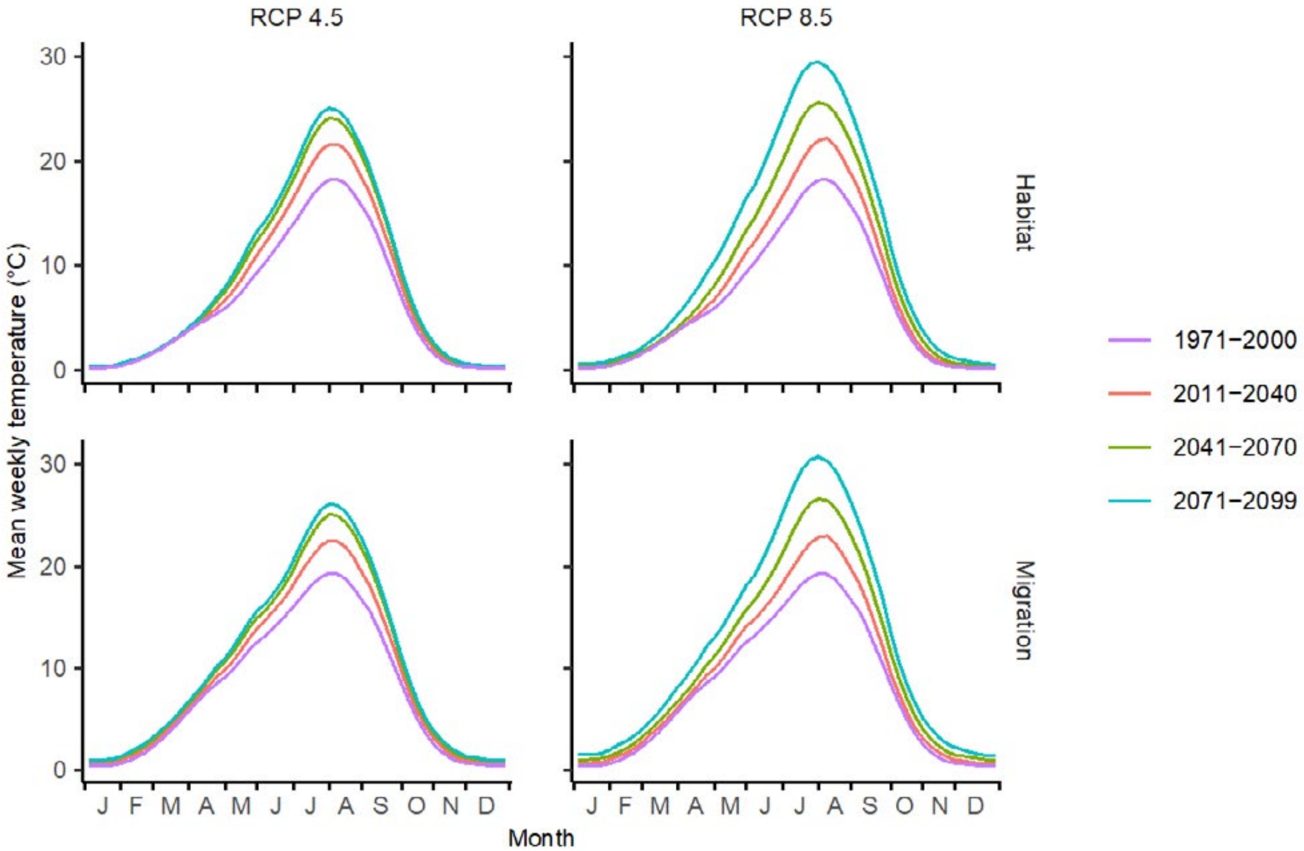


Figure 9: Mean weekly water temperature (the average is given by the solid lines and the associated standard error ranges are shaded) across all 62 salmon Conservation Units (CU) of the Fraser River basin. Data are presented for four 30-year time periods, and under medium (Representative Concentration Pathway 4.5, RCP 4.5) and high (RCP 8.5) greenhouse gas emissions scenarios. Values for each CU are averaged across a multi-model ensemble (six GCM projections per emissions scenario).

Modelling Nechako River Fish Habitat

PROJECT PARTNERS

Institut national de la recherche scientifique

University of British Columbia

L'Université du Québec à Montréal

Natural Sciences and Engineering Research Council of Canada

Rio Tinto

Ouranos

École de Technologie Supérieure

Purpose: To support water temperature management in the

Rio Tinto operates the Nechako Reservoir, created by the presence of the Kenney Dam, a hydrologic dam at the start of the Nechako River in northwestern British Columbia. Rio Tinto releases water from the reservoir to ensure the river's water temperature is safe for migrating fish during the salmon migration season. This has led to an ongoing project to (1) learn more about the fish and their temperature tolerances and (2) examine how current water release strategies will control water temperature in the future. The first of these objectives is being undertaken at the University of British Columbia. Working on the second objective, PCIC researchers have developed and used a linked hydrological, hydrodynamic, and water quality model to understand the potential impact of climate change on river temperatures. This will aid in reservoir management operations on the Nechako River system. The model has so far been driven with data from the 1986 to 2017 period to better understand the dynamics of the watershed. They found that 84% of the total inflow into the Nechako Reservoir originates from watersheds draining the eastern slopes of the Coast Mountains. The model simulations also show that tributaries flowing into the north arm of the Nechako Reservoir supply cooler water than those flowing into the southern arm. Prior research has identified a 20°C water temperature threshold for the safety of sockeye salmon. In order to reliably keep downstream water below this 20°C threshold, water released at the Kenney Dam must be kept below 10°C. To determine the availability of cold water for regulating the temperature of the Nechako in the reaches below

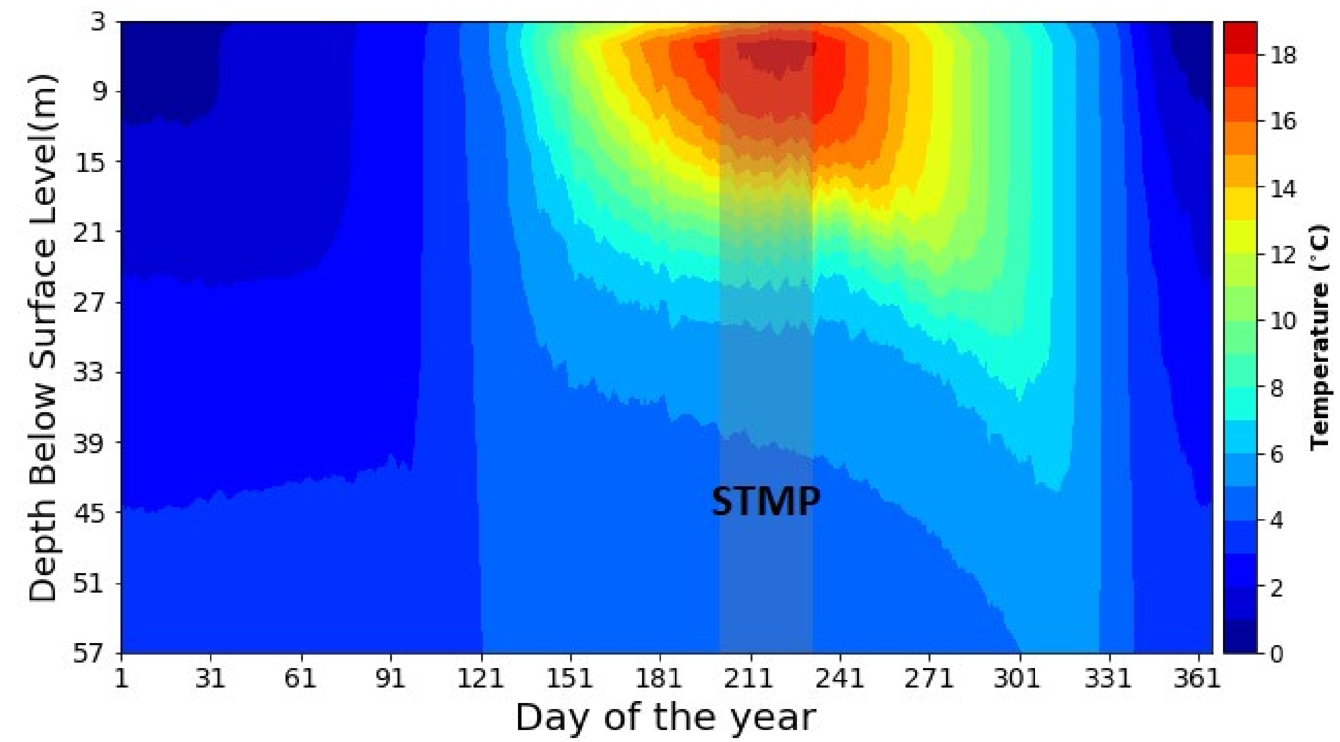


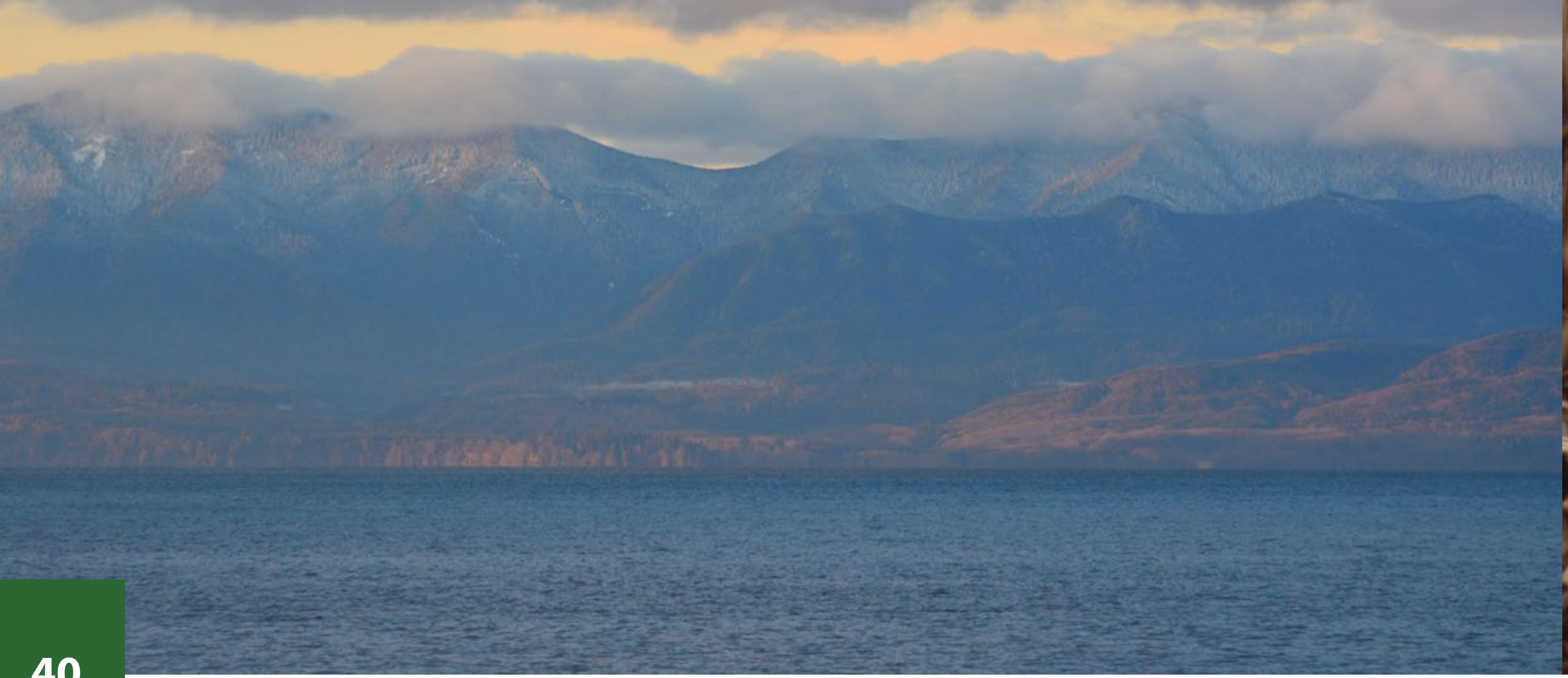
Figure 10: Simulated daily mean water temperature at Kenney Dam over the 1987-2017 period. The shaded area corresponds with the Summer Temperature Management Program (STMP) period of July 20th to August 20th, which is the period during which water is released into the Nechako River to maintain water temperature at levels acceptable for migrating salmon.

the Kenney Dam, the team modelled water temperatures in the Nechako Reservoir at the Kenney Dam (which feeds the Nechako River) at different depths. They found that the surface water temperature is uniform across the reservoir during the winter, spring, and fall (Figure 10). From May through September, there is a weak temperature gradient between the west-end of the reservoir and its eastern end. Surface water is typically warmer at Kenney Dam than elsewhere in the reservoir during the summer months due to the absence of water circulation at this location. They found that the temperature of deep water remains between 4°C to 5°C year-round. During the ice season, the surface water temperature is at 0°C. It then

warms up and mixes with the deep water following the disappearance of surface ice after about 40 days. The surface water temperature continues increasing with the warming air temperature and reaches a maximum of 18°C during the salmon migration period. The summer stratification starts in late spring and lasts until early November. Then, surface water mixes again with the deeper water due to increased wind and low surface water temperature. During the period of the Summer Temperature Management Program (STMP), the thermocline layer (between the mixed surface water and cooler water below) lies at a depth of between 10 metres and 30 metres. Water temperatures below 10°C are available, on average, at depths below 20 metres. The eventual understanding that is developed from this work will aid in the planning of future water release regimes for controlling downstream water temperatures.

MAKING THE MOST OF METEOROLOGICAL DATA IN BC AND BEYOND

PCIC's team works to make high-quality meteorological data for BC and the surrounding regions available for research and to support decision making. To do this, we gather, apply quality control measures to, and analyze data from our partner networks and make this data available through our analysis tools and data portal.



Pacific Climate Data Set Continues to Grow

PROJECT PARTNERS

British Columbia Ministry of Environment and Climate Change Strategy

British Columbia Ministry of Agriculture and Food

British Columbia Ministry of Forests

British Columbia Ministry of Transportation and Infrastructure

Rio Tinto

BC Hydro

Environment and Climate Change Canada

Metro Vancouver

The Capital Regional District

Pacific Climate Impacts Consortium

Purpose: To maintain, augment and curate this valuable BC-wide, multi-source station data archive that users can access via a single, convenient online portal.

The Pacific Climate Data Set (PCDS) continues to grow, with 55 million observations added over the last year alone. Users can access the PCDS through PCIC's BC Station Data portal. The data are also used to create PRISM climate maps and the annual State of the Ocean Report published by Fisheries and Oceans Canada, in addition to serving as the basis for some of PCIC's seasonal analysis and research. The PCDS serves as the most comprehensive record of longitudinal meteorological information in BC. The PCDS records span the entire spatial extent of BC, date from the 1870s to present, and are updated hourly from many different sources.

In addition, work has been initiated to prepare for the development of updated very high resolution "climate normals" maps for BC created with the PRISM methodology. These 800 m resolution maps are the foundation of many other PCIC products, including its high quality gridded daily dataset for the Pacific Northwest region known as PNWNAmet. The World Meteorological Organization defines two sets of 30-year historical averages of meteorological conditions, called "climate normals," that provide information about the current climate and baseline periods against which climate change can be measured. One set is updated every 30 years and is used as a reference period (currently 1961-1990) for global climate studies. A second set is updated every ten years, to account for the rapid changes that are occurring in the Earth's climate system. This second set (currently being updated from the 1981-2010 period to 1991-2020) is valuable for planning and operational purposes for climate sensitive sectors and industries.

Moving Toward Daily PRISM Maps

Purpose: To explore the possibility of providing very high resolution gridded daily temperature observations for the province.

PCIC is studying whether it would be possible to provide very high resolution gridded daily temperature observations for the entire province. PCIC currently uses PRISM to provide 30-year climate normals and monthly time-series maps. PRISM brings together information about the physical aspects of a landscape, such as elevation, along with expert knowledge to estimate the values of variables, such as temperature and precipitation, at locations in between station observations, creating a seamless and consistent dataset over a large area. This research seeks to determine whether reliable daily PRISM maps can be produced for BC given the station data resources available in the Pacific Climate Data Set.

Expanding the Coverage of PCIC's Meteorological Data Portal

PROJECT PARTNER

Government of Northwest Territories

Purpose: Provide service to Yukon and the Northwest Territories by expanding PCIC's Station Data portal.

In partnership with the Government of Northwest Territories, work at PCIC continues on the development of a station data portal for Canada's Western Arctic, serving the regions of Yukon and the Northwest Territories. This year, a new user interface was developed and added to the beta version of the portal to improve user experience (Figure 11). The new interface allows for stations to be filtered by a subset of variables and networks. Revised base maps were also made, which improve the quality of the presentation for Western Arctic users by using a map projection (Yukon Albers) that better represents the region's geography. The amount of data has also increased, with about 700 stations and almost 300 million observations (increasing daily) now available, which has enabled the finalization of station climatologies for the entire region. The new station data portal is expected to be released in the fall of 2022.

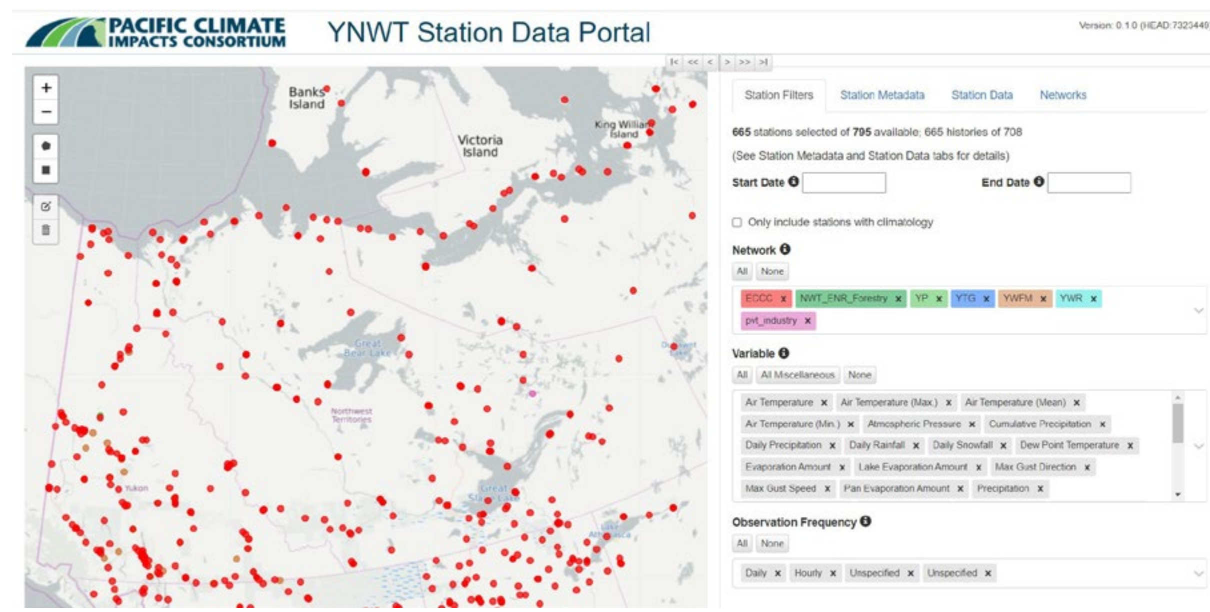


Figure 11: The user interface for the new station data portal for Canada's Western Arctic region.

NEW DATASET AND ONLINE TOOL DEVELOPMENT

PCIC's team develops and maintains a Data Portal and a suite of analysis tools to support users requiring different levels of climate information, from data to purpose-built technical tools with varying features and degrees of interpretation.

A New Tool for Canada's Engineers and Infrastructure Planners

Purpose: Provide infrastructure professionals with information about how climate-related design values may change in the future.

This year PCIC released a new analysis tool, the Design Value Explorer (DVE), which provides information for Canada's building professionals about the environmental conditions that their projects will be exposed to today and over the lives of these structures. The new tool supplies historical and projected future design values, which are indices used in building and bridge design that provide information about temperature, wind, precipitation, and moisture for all of Canada. The design values in the DVE update those found in the National Building Code of Canada (2015) and the Canadian Highway Bridge Design Code (2014), by using data from the last decade. The Design Value Explorer builds upon earlier work for the Climate-Resilient Buildings and Core Public Infrastructure Initiative that was supported by Infrastructure Canada through the National Research Council of Canada and developed in partnership with Environment and Climate Change Canada (ECCC). The DVE represents the culmination of three years of research and applied science efforts. In prior years, PCIC created a database of over two billion meteorological observations from across Canada, drawing together weather stations and manual snow surveys that were subjected to quality-control. Our researchers developed a novel spatial interpolation scheme that blends information derived from station observations with that from climate model output to allow for the design values to be made available anywhere across Canada, as well as at the specific locations tabulated in the National Building Code of Canada. PCIC's team then used their substantial experience in developing online climate service delivery platforms to create a versatile tool that allows for easy

PROJECT PARTNERS

National Research Council Canada

Environment and Climate Change Canada

access to these design values. The DVE allows users to view maps of these values, zoom in on regions of interest, and to display and download the values at any location of interest, including specific locations listed in the National Building Code of Canada. It also provides projections of how historical design values change at different levels of future global warming. This work was made possible through partnerships and collaboration with multiple organisations. In particular, PCIC gratefully acknowledges Infrastructure Canada and the National Research Council of Canada for funding and support, colleagues at the Climate Research Division of ECCC for fruitful collaboration, and ECCC's Meteorological Service of Canada for the provision of meteorological station data from across Canada.

The Development of Sharable Climate Analysis Infrastructure

Purpose: Build software and hardware infrastructure to enable Canadian climate service providers to analyse climate data where that data resides.

PCIC's team has continued to contribute to the Data Analytics for Canadian Climate Services (DACCS) project with the addition of more computational resources, the improvement of tools already developed, and the creation of a new tool for inclusion in the DACCS library of analysis tools. The DACCS project brings together the computational resources and tools to handle climate data analytics requests and store massive amounts of data. The ultimate objective of this is to create a distributed system that enables practitioners to analyze data using a library of established procedures without having to move that data from the location where it is stored to the location where it will be analyzed. Having the computational nodes near the data storage systems saves teams from having to move huge amounts of data between institutions and from doing duplicate work preparing this data for use. It also makes climate analytics more accessible, by allowing researchers broad access to the data and the tools. This year, PCIC has brought into operation a dedicated 64-core DACCS server that will serve as part of the national network. The web processing tools that the DACCS project uses are called "birds." The birds developed at PCIC include: Thunderbird, which creates temporal climatological summaries of high-resolution data, while maintaining the original spatial scale; Osprey, which runs a streamflow routing model; Sandpiper, which performs the functions of Plan2Adapt's rule engine for impacts analyses; Chickadee, which does statistical downscaling; and Quail, which computes climate extremes indices. PCIC's team has also developed a web service that encapsulates Os-

PROJECT PARTNERS

Canada Foundation for Innovation

British Columbia Knowledge Development Fund

University of Toronto

Ouranos

Computer Research Institute of Montréal

McGill University

Concordia University

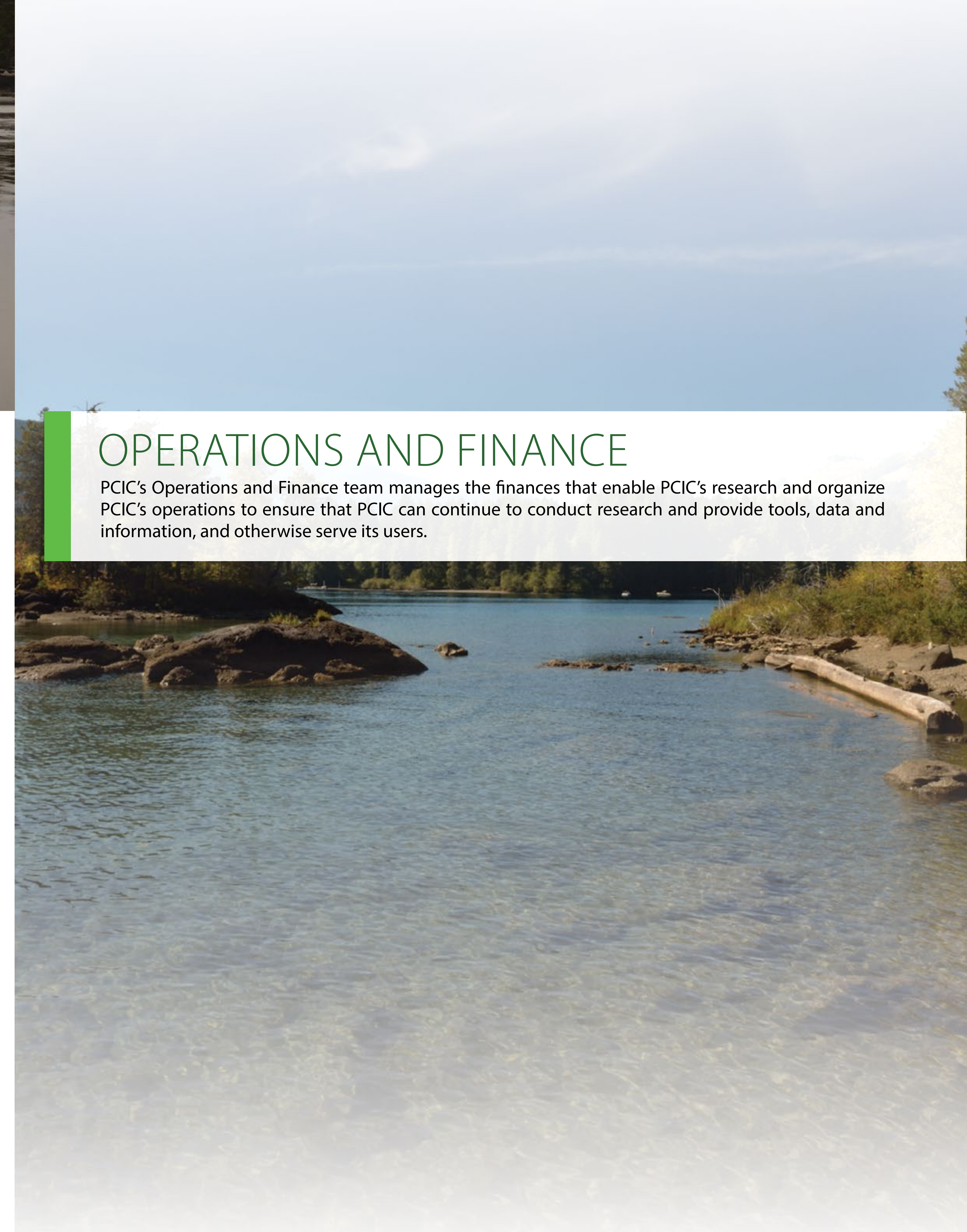
prey and pre-configures it with the hydrologic model output that is available from PCIC. This new web service allows a user to select a hydrologic simulation according to the climate model that provided the driving data for the simulation, outlets where streamflow is desired, and a time range. As is often the case for projects at PCIC, the code and tools developed for this project will also serve PCIC's users in another form, as our team is developing an on-demand routed streamflow data portal using the DACCS back end. This will allow users to calculate streamflow for the river outlets in their regions of choice. PCIC's participation in the DACCS project has been made possible by a grant from the Canada Foundation for Innovation Cyberinfrastructure Initiative and the BC Knowledge Development Fund. PCIC is grateful for the support of our partners at the University of Toronto, Ouranos, CRIM, McGill University, and Concordia University.

COMMUNICATIONS

PCIC shares the findings of its team and updates on projects through reports, peer-reviewed research, and the PCIC Update newsletter. In addition, PCIC publishes brief extension notes on research relevant to PCIC's users. Our team also presents their work at conferences and workshops.

Purpose: Deliver multiple forms of communication and outreach with our users and share important research findings.

To keep PCIC's users up-to-date with the latest findings from the research literature, PCIC delivers multiple forms of communication and outreach. PCIC's researchers also actively share their findings with the broader scientific community. The work PCIC shares with its users includes important research findings from PCIC's team and the broader scientific community. These include high-level written discussions and presentations of various levels of technical detail, delivered both virtually and in-person. Over the past fiscal year, PCIC delivered seminars on topics including the attribution of the June 2021 extreme heat event and November flooding, to using storylines as a way of bringing meaning to climate change projections. We also released three Science Briefs on: trends in Canadian snow cover, the RCP 8.5 emissions scenario, and the human climate niche. PCIC's team presented at multiple workshops and conferences, sharing their knowledge with the public, planners, and the broader scientific community.



OPERATIONS AND FINANCE

PCIC's Operations and Finance team manages the finances that enable PCIC's research and organize PCIC's operations to ensure that PCIC can continue to conduct research and provide tools, data and information, and otherwise serve its users.

Operations and Finance

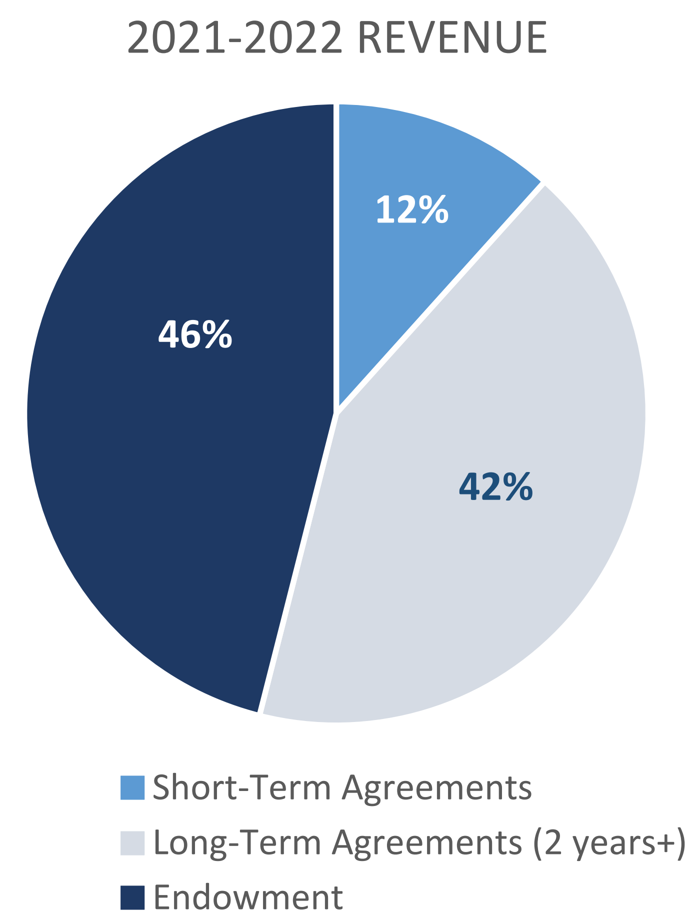
Purpose: Maintain a strong financial position that will allow PCIC to continue growing and serving the needs of its users.

In fiscal year 2021-2022, PCIC continued to enjoy a stable funding and operational environment in support of its programs and service delivery. PCIC managed over 20 active agreements related to user-commissioned projects, externally funded research grant programs and other projects. Nine new contracts were signed with local governments, BC ministries and federal agencies. Short-term and long-term agreements with our partners provided 54% of our revenue, with the balance provided by an endowment administered by the University of Victoria.

With its most important resource always being its staff, 96% of PCIC's expenditures supported the salaries of 26 staff members. The remaining expenses supported operational expenses such as computing resources, financial and auditing services, and staff professional development.

In the last quarter of the fiscal year, PCIC staff transitioned to a more flexible working environment that allowed them to work at PCIC's office or remotely under various remote working arrangements. Our staff continued to work productively and collaboratively within PCIC and with our partners. We express our sincere appreciation for the dedication, hard work and teamwork of our very talented staff, the University of Victoria's excellent supporting infrastructure and the ongoing commitment of our partners.

In keeping with its strategic goal to achieve and maintain operational and managerial excellence under its 2021-2025 Strategic Plan, PCIC will continue to commit to long-term financial sustainability by managing the resources entrusted to it efficiently and to the greatest possible benefit of users and stakeholders.



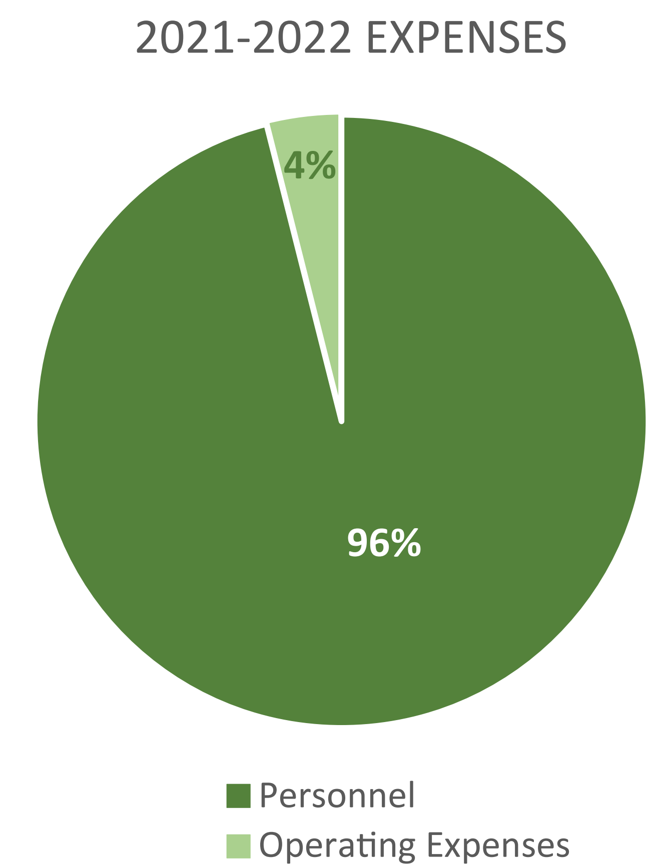
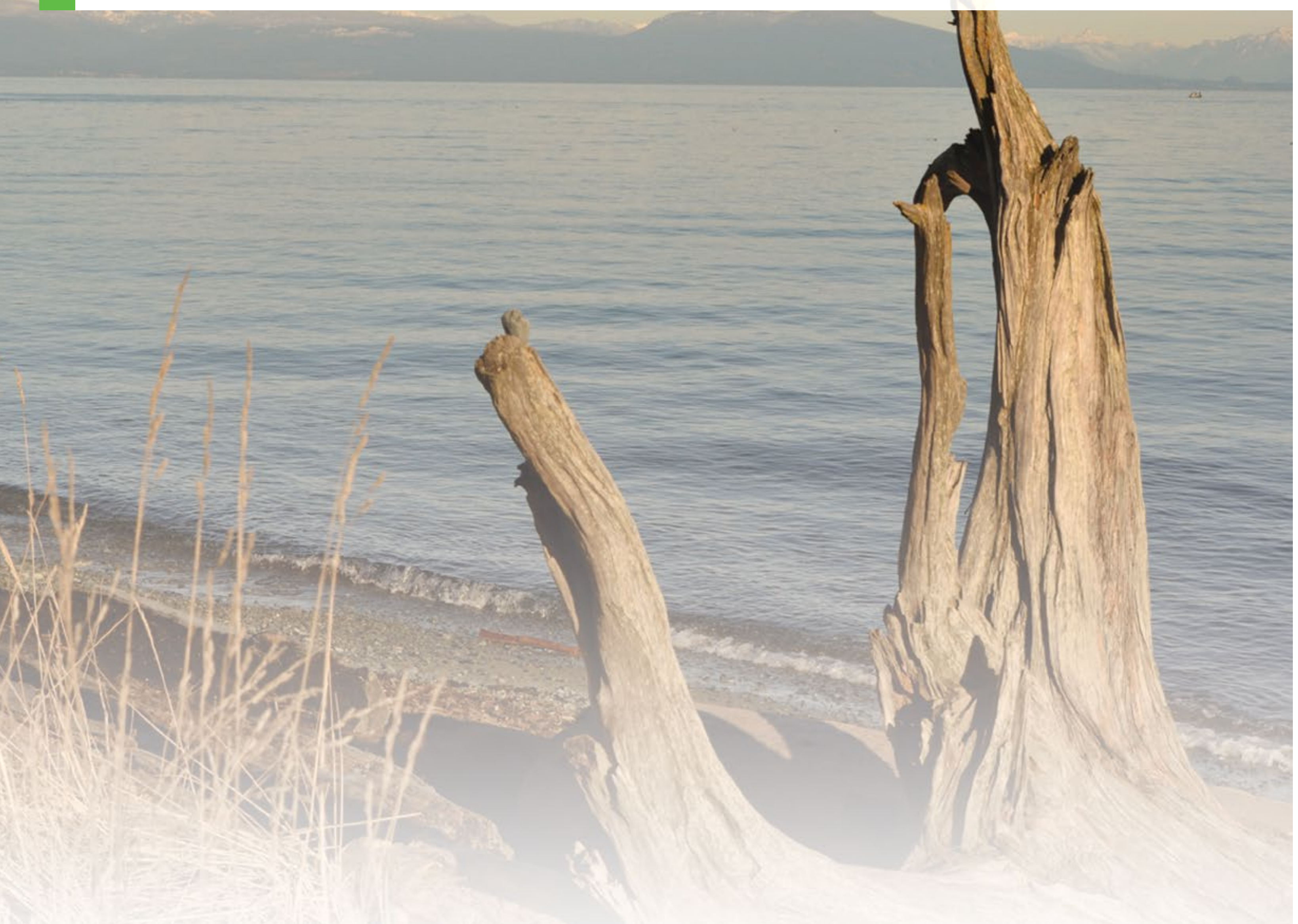


Figure 12: A breakdown of PCIC's sources of revenue and expenses for the 2021-2022 fiscal year.

PUBLICATIONS

In order to communicate with our users, share knowledge with the scientific community, and allow our methods to undergo scrutiny and refinement, PCIC actively publishes material ranging from reports, newsletters, and extension notes to peer-reviewed publications.



PCIC Publications

In addition to three newsletters, PCIC has released the following PCIC publications.

1. **The Pacific Climate Impacts Consortium**, 2022: *Pacific Climate Impacts Consortium Strategic Plan 2021-2025*. The Pacific Climate Impacts Consortium, Victoria, BC, 19 pp.
2. **The Pacific Climate Impacts Consortium**, 2022: *PCIC Primer: Understanding Future Climate Scenarios*, The Pacific Climate Impacts Consortium, Victoria, BC, 2 pp.
3. **The Pacific Climate Impacts Consortium**, 2022: *PCIC Science Brief: Should the RCP 8.5 Scenario Represent Business as Usual?*, The Pacific Climate Impacts Consortium, Victoria, BC, 4 pp.
4. **The Pacific Climate Impacts Consortium**, 2022: *PCIC Science Brief: Trends in Canadian Snow Cover Over Recent Decades*, The Pacific Climate Impacts Consortium, Victoria, BC, 5 pp.
5. **Schnorbus, M.A.** and **Q. Sun**, 2022: *Future Design Flood Values in the Fraser River Basin Using the CanESM2-LE*, Final Report to "Revision and Expansion of Extreme Streamflow Design Value Projection Online Tool." The Pacific Climate Impacts Consortium, Victoria, BC, 45 pp.
6. **Schoeneberg, A.T.** and **M.A. Schnorbus**, 2021: *Exploring the Strength and Limitations of PCIC's CMIP5 Hydrologic Scenarios*. Report prepared for Ministry of Forests, Lands, Natural Resource Operations and Rural Development, and Ministry of Environment and Climate Change Strategy, Victoria, BC, 42pp.


7. **Ben Alaya, M.A.**, **F.W. Zwiers** and X. Zhang, 2021: On estimating long period wind speed return levels from annual maxima. *Weather and Climate Extremes*, **34**, 100388, doi:10.1016/j.wace.2021.100388.
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13. Li, C., **F.W. Zwiers**, X. Zhang, G. Li, Y. Sun and M. Wehner, 2021: Changes in Annual Extremes of Daily Temperature and Precipitation in CMIP6 Models. *Journal of Climate*, **34**, 9, 3441-3460, doi:10.1175/JCLI-D-19-1013.1.
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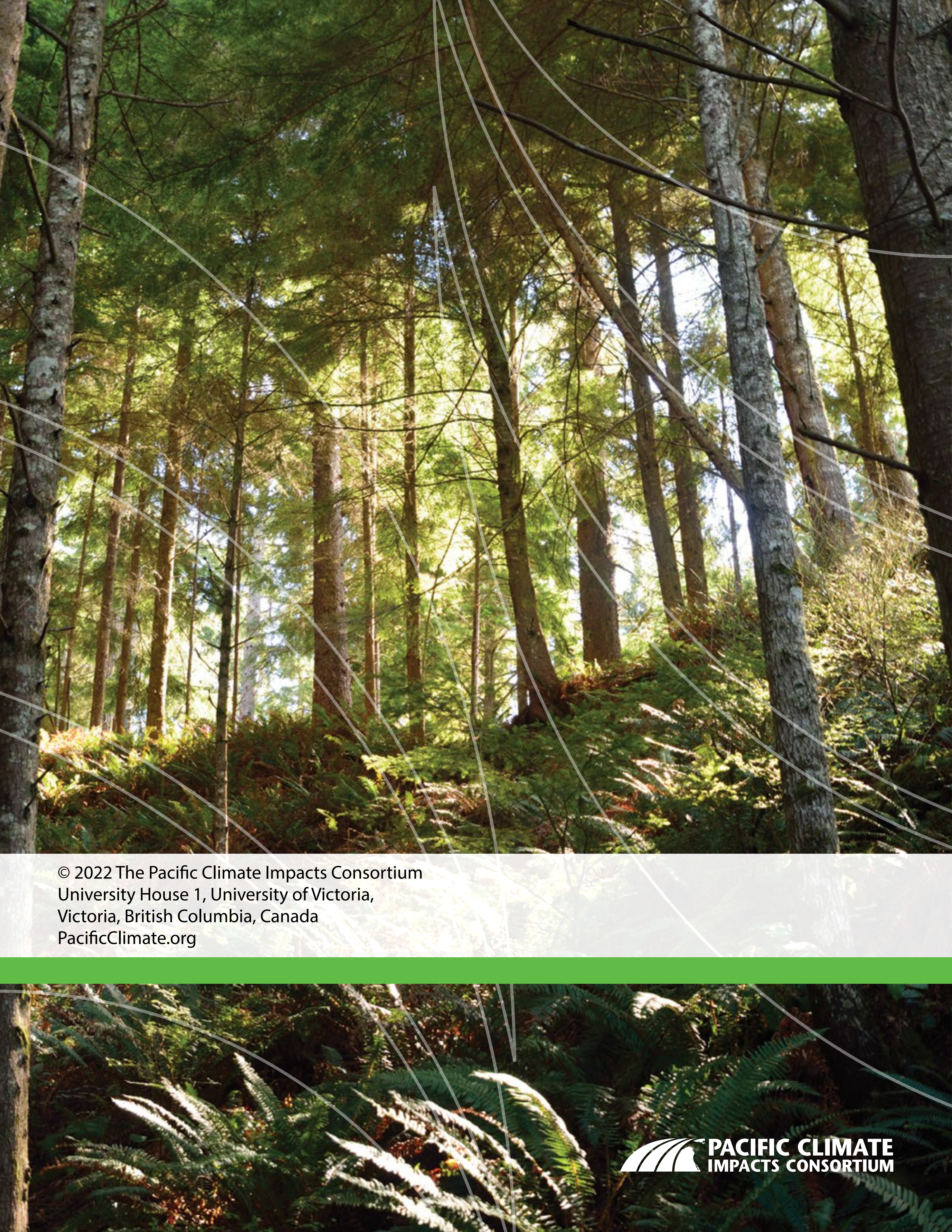

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