Future flow and water temperature scenarios in an impounded drainage basin: Implications for summer flow and temperature management downstream of the dam

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Abstract

Water temperature is a key variable affecting fish habitat in rivers. The Sockeye salmon (*Oncorhynchus nerka*), a keystone species in north western aquatic ecosystems of North America, is profoundly affected by thermal regime changes in rivers, and it holds a pivotal role in ecological and economic contexts due to its life history, extensive distribution and commercial fishery. In this study, we explore the effects of climate change on the thermal regime of the Nechako River (British Columbia, Canada), a relatively large river partially controlled by the Skins Lake Spillway. The CEQUEAU hydrological-thermal model was calibrated using discharge and water temperature observations. The model was forced using the Fifth generation of ECMWF Atmospheric Reanalysis data for the past and meteorological projections (downscaled and bias-corrected) from climate models for future scenarios. Hydrological calibration was completed for the 1980-2019 period using data from two hydrometric stations, and water temperature calibration was implemented using observations for 2005-2019 from eight water temperature stations. Changes in water temperature were assessed for two future periods (2040–2069 and 2070–2099) using eight Coupled Model Intercomparison Project Phase 6 climate models and using two Shared Socioeconomic Pathway scenarios (4.5 and 8.5 W/m^2 by 2100) for each period. Results show that water temperatures above 20°C [an upper threshold for adequate thermal habitat for Sockeye salmon migration in this river] at the Vanderhoof station will increase in daily frequency. While the frequency of occurrence of this phenomenon is 1% (0-9 days/summer) based on 2005-2019 observations, this number range is 3.8-36% (0-62 days/summer) according to the ensemble of climate change scenarios. These results show the decreasing habitat availability for Sockeye salmon due to climate change and the importance of water management in addressing this issue.

Key Words

CEQUEAU model, Climate change, Nechako River, River temperature

1. Introduction

The aquatic systems are threatened by natural and anthropogenic pressures, including land cover change, flow regime change, and global climate change (Algera et al., 2022; Bosmans et al., 2022). Of all these threats, climate change may have the most prolonged and largest-scale impacts on various ecosystems, particularly in freshwater (Nash et al., 2017). Habitat loss already has severe consequences for aquatic life like salmonids (Carrington, 2020), with a 76% reduction in their global population and even more in some regions (93% in Europe) (Deinet et al., 2020). It remains unclear how much of this habitat loss is due to climate change. However, it has been shown that increased air temperature has changed North America's flow regime and water temperatures (Islam et al., 2019). The river reaches located downstream of dam facilities have managed flows, which can increase (via inadequate environmental flow prescriptions) or reduce (through water releases) the impact of climate change (Ahmad et al.; Algera et al., 2022; Fullerton et al., 2022; Sheedy, 2005; Sullivan and Rounds, 2021; Xiong et al., 2019). There are multiple ways to mitigate the impact of climate change through man-made efforts on the local scale. The analysis of dam operations as a potential mitigation method to counteract climate change impacts on juvenile salmon was conducted by Sullivan and Rounds (2021) and Stratton Garvin et al. (2022). They successfully utilized hydrodynamic models to demonstrate that changes in dam operations, particularly at the upstream dam, can effectively alter water temperatures released from the dam, with implications for seasonal temperature patterns and downstream river temperature variations. Climate change affects juvenile salmon through changes in water temperature, habitat availability, and food resources, influencing their growth and survival. Dam operation simulations aimed to investigate scenarios that can improve conditions for endangered anadromous fish by incorporating a temperature target.

A study conducted in the Nechako River watershed in Western Canada (Macdonald, 2019) focused on assessing the approaches to alleviate the challenges posed by reservoir operation and the resulting reduced water flows, both leading to unfavorable conditions for the Sockeye salmon population. River water temperature plays a crucial role in aquatic life, and previous studies have shown that temperature is one of the dominant factors influencing the Nechako River watershed's aquatic habitats (Macdonald et al., 2007) because water temperature significantly shapes the conditions essential for aquatic organisms' survival. It directly influences the metabolic rates of aquatic organisms, affecting their growth, reproduction, and overall physiological functions. Furthermore, temperature governs the solubility of gases in water, impacting oxygen levels vital for aquatic species' survival (Macdonald, 2019). For example, Islam et al. (2019) showed that summer water temperatures in the Fraser River watershed, which includes the Nechako River as a sub-watershed, rose by 1°C during 1950-2015. This rise in summer water temperature has doubled the number of days where the daily average water temperature exceeded 20°C. Therefore, previous studies related to Sockeye salmon (*Onchorhynchus Nerka*) habitat in the Nechako River resulted in a water temperature management protocol during the summertime (Macdonald, 2019).

The Summer Temperature Management Program (STMP) water release protocol was developed between 1980 and 1983 (Macdonald 2019) to mitigate water temperature increases downstream of the Skins Lake Spillway (SLS), the hydraulic structure to control the river flow downstream. Based on STMP, during the Sockeye salmon migration season, which lasts from mid-July to mid-August, the SLS owner/manager (Rio Tinto, the mining company that owns the Kenny Dam and SLS, also manages the water flow from SLS) releases volumes of water to maintain average daily water temperatures below 20°C at Finmoore town, approximately 35 km upstream of the confluence of the Nechako and Stuart rivers. Moreover, understanding the specific temperature ranges within which Sockeye salmon thrive is crucial. The known thermal tolerances for Sockeye salmon (Middleton et al., 2018; Robinson et al., 2015) are summarized in Table S1 in Online Resource (i.e., supplementary information, including detailed data in tables and graphs).

In recent decades, multiple models have been used to assess the impacts of climate change on river temperature, particularly on systems with salmonid populations around Canada (Ahmadi-Nedushan et al., 2007; Dugdale et al., 2018; Kwak et al., 2017b; Wilson et al., 2015). Existing water temperature models can be divided into three categories: (1) deterministic models (Dugdale et al., 2017a), (2) classic statistical models (Benyahya et al., 2007), and (3) artificial intelligence models as a subcategory of empirical models (Zhu and Piotrowski, 2020). Since deterministic models explicitly formulate physical processes, they are often considered a preferred tool for assessing possible shifts in water flow and temperature regimes under climate change scenarios (Ouellet et al., 2020).

CEQUEAU, a hydrological-thermal model, is specifically designed for forecasting water temperature at the watershed scale (Dugdale et al., 2017a; Ficklin et al., 2012). CEQUEAU is a flexible modeling tool that allows adding new modules (e.g., options for different evapotranspiration and snowmelt algorithms) (St-Hilaire et al., 2015), and the tool can be used jointly with modern algorithms to achieve model calibration or to conduct a sensitivity analysis (e.g., Khorsandi et al., 2022). CEQUEAU is also well-adapted for simulating dam release operations and thermal modeling of rivers. For the Nechako River watershed, CEQUEAU has been used for operational flow forecasting by Rio Tinto. Ouellet-Proulx et al. (2017a) studied ensemble water temperature forecasting using water temperature and flow assimilation. The model's source code for the evaporative heat loss module is improved (Ouellet-Proulx et al., 2019). However, deterministic modeling using CEQUEAU is still needed to assess the combined impact of flow regime change and climate change on the Nechako. Therefore, this study attempts to provide guidance on this need by simulating the impacts of climate change on the Nechako River in the context of STMP implementation with CEQUEAU. Therefore, this study aims to:

- Calibrate the CEQUEAU model hydrologically and thermally using the multisite water flow and temperature calibration method.
- Establish upstream boundary conditions by coupling CEQUEAU with other models that simulate reservoir temperature and those found in tributaries emptying in the reservoir (i.e., VIC-GL, RBO, and CE-QUAL-W2 models).
- Project future water temperatures using downscaled, bias-corrected meteorological data, upstream models outputs as boundary conditions, and the calibrated CEQUEAU model.
- Analyze these projected water temperatures, particularly focusing on compliance with the mandatory 20°C threshold at the Vanderhoof station.

2. Method

2.1. Study Area

The Nechako River watershed is located in the central part of British Columbia, Canada, with a 45,000 km^2 drainage area (Fig. 1). Downstream of Ootsa Lake (Fig. 1, the large lake immediately upstream of SLS), the flow of the river is fully regulated by the SLS between the Nechako Reservoir and its confluence with the Nautley River, after which the flows of the Nechako and Nautley rivers combine and continue past the town of Vanderhoof and eventually into the Fraser River. Three hydrometric stations measure the discharge (Environment and Climate Change Canada, https://www.canada.ca/en/environment-climate-change/, data access: May 2022). Those are at the SLS, the Nautley River (upstream of the confluence with the Nechako River), and the town of Vanderhoof (see Fig. 1). The SLS flows and temperatures provide the boundary conditions to the hydrological and thermal modules and are not used as target stations for hydrological calibration. Eight stations measure water temperature (Rio Tinto, data access: May 2022) in the watershed (Fig. 1). The study area and monitoring stations are explained in detail in Ouellet-Proulx et al. (2017a) and Khorsandi et al. (2022).

[Fig. 1 Here]

2.2. CEQUEAU Model

CEQUEAU is a hydrological-thermal model designed explicitly for hydrological and surface water temperature modeling (Morin and Couillard, 1990; St-Hilaire et al., 2015). The model has been extensively tested in multiple case studies (Dugdale et al., 2018; Dugdale et al., 2017b; Fniguire et al., 2022; Kwak et al., 2017a; Kwak et al., 2017b; Ouellet-Proulx et al., 2017a; Ouellet-Proulx et al., 2017b).

Land cover and topography are required physiographic input data for the CEQUEAU model (Dugdale et al., 2017b). We used the most up-to-date global land cover data, with a 10 m spatial resolution provided by Environmental Systems Research Institute (ESRI) and the European Space Agency (ESA)(Karra et al., 2021; Zanaga et al., 2021). We used the National Aeronautics and Space Administration (NASA) SRTM Digital Elevation Model (SDEM) with 30 m spatial resolution (Farr et al., 2007) to calculate elevations in the CEQUEAU's input structure.

The CEQUEAU model conceptualizes a drainage basin as an interconnected network of hydrological response units called partial squares (CP; based on the French acronym in the CEQUEAU manual), delineated as sub-components of square grid cells (Fig. 2a). For each CP, the hydrological module calculates a simplified hydrological budget using a production function (PF) that simulates water routing into the surface runoff, interflow, and groundwater. Then a hydrological transfer function (TF) applies a routing scheme on the available surface water to calculate the water volume routed to the downstream CP (Fig. 2d). The PF uses precipitation and air temperature (minimum and maximum) as meteorological inputs (Fig. 2b). The hydrological module includes 26 global (i.e., one value for all CPs) parameters and then produces the output, i.e., simulated discharge (Fig. 2d).

[Fig. 2 Here]

2.3. Modeling Upstream Boundary Conditions

Flow and temperature at the SLS are the boundary conditions for the CEQUEAU model. These data are observed values at SLS (Environment and Climate Change Canada, https://www.canada.ca/en/environment-climate-change/, data access: May 2022) for the calibration period. In terms of temperature, one sensor is installed immediately downstream of SLS. The data for this sensor has been available since 2017. Therefore, for the calibration period, similar to previous studies on the Nechako using the CEQUEAU model (Ouellet-Proulx 2018, Ouellet-Proulx et al. 2017b, Ouellet-Proulx et al. 2017a), we calculated the average water temperature for each day of the year (DOY) using the observed data from 2017 to 2021.

A coupled hydrologic model simulates upstream boundary conditions for flow and temperature at SLS for future horizons (2040-2069 and 2070-2099): the Variable Infiltration Capacity (VIC-GL) (Liang et al., 1996, 1999; Schnorbus, 2018), the River Basin Model (RBM) (Larabi et al., 2022), the STMP reservoir operation program, and the CE-QUAL-W2 hydrodynamic model (Cole and Wells, 2006) (Fig. 2). The coupled modeling platform aims to simulate the governing processes of water flow and temperature feeding the reservoir and reservoir hydrodynamics. The modeling platform allows for consideration of changes in timing and volume of water availability to simulate reservoir thermal stratification and temperature of water released at SLS.

The VIC-GL is an upgraded version of the VIC model, a spatially distributed land surface model that accounts for glacier processes (Schnorbus, 2018). The VIC-GL model was implemented at the upstream area of the Nechako Reservoir. The stream temperature model, RBM, is a gridded physically-based model that uses a one-dimensional mixed Eulerian-Lagrangian approach to simulate water temperature based on local air-water surface heat exchange and advected heat flux from upstream. VIC-GL was coupled with RBM to simulate discharge and water temperature at the main tributaries feeding the Nechako Reservoir (Larabi et al., 2022). Both models were calibrated against observed discharge and water temperature at the six main tributaries of the Nechako Reservoir as identified by Canada Water Survey stations. They used input meteorological data for 1945-2018 at a 3-hour timestep for which both observed water flow and water temperature data are available for different periods depending on the station (Larabi et al., 2022). These models (VIC-GL, RBM, and CE-QUAL-W2) did not need upstream conditions since each model provided upstream conditions for the next one. Therefore, the calibration and validation were performed using partial time series data availability and daily time steps for water flow and temperatures.

CE-QUAL-W2 is a mechanistic hydrodynamic model for water quality modeling (Cole and Wells, 2006). This model uses a two-dimensional scheme to differentiate water bodies along the river (longitudinal) and depth (vertical). This scheme makes this model suitable for studying water flow and quality studies in large water bodies like dam reservoirs (Afshar et al., 2011; Kim and Kim, 2006). The model assumes water is laterally well mixed but can be vertically stratified. CE-QUAL-W2 can model water velocity and flow at different time scales with the hydraulic sub-model. Also, these variables are input for the water quality sub-model, which simulates temperature, dissolved oxygen, and multiple other variables required to study aquatic life. The model requires meteorological data as well as boundary conditions of inflows and outflows. Using VIC-GL and RBM to provide inflow boundary conditions and historical powerhouse intake and water release at SLS, the CE-QUAL-W2 model was first calibrated against historical reservoir water elevation for the period spanning 1986-2017. Then, the model was calibrated against water temperature profiles at Kenney Dam (See Fig. 1, in the Nechako River) and Natalkuz Lake (Upstream of Kenny Dam, Fig. 1) for the summer of 1994, as well as outlet water temperature at SLS for the summer of 2016-2017 (See Fig. 1). The deployment and calibration of the integrated modeling platform are discussed in detail by Larabi et al. (2022).

Implementing the Summer Temperature Management Program (STMP) represents a crucial facet of water flow regulation at the Nechako Reservoir (see Fig. 2c). As a response to the significant influence of reservoir regulation on water quantity and quality in the Nechako River, the STMP was introduced in 1983 with the primary objective of ameliorating conditions for Sockeye salmon migration. The STMP focuses on mitigating elevated water temperatures during the critical migration period from July 20 to August 20 at Finmoore. This program involves augmenting water releases at the SLS during the migration period, effectively curbing the frequency of water temperatures exceeding 20°C. The average water release is approximately 32 m^3/s at SLS during fall and winter to support Sockeye salmon. The water release is increased during summer to a maximum limit (approximately 450 m^3/s) in response to warming trends. By orchestrating these controlled releases, the STMP plays a pivotal role in preserving the ecological integrity of the Nechako River and sustaining the migratory patterns of vital salmon species (Macdonald, 2019; Larabi et al., 2022).

To simulate future scenarios of temperatures and flows at SLS, the VIC-GL/RBM/CE-QUAL-W2 combination of models is forced with future climate model outputs using two Shared Socioeconomic Pathways (SSPs). These future hydrologic scenarios are then used as input to the reservoir operation model (e.g., STMP) provided by Rio Tinto to simulate associated scenarios of powerhouse intake and SLS discharge (Fig. 2b,c).

2.4. Fifth Generation of ECMWF Atmospheric Reanalysis Data

There is a need for complete meteorological data to calibrate and validate the hydrological model for the historical period as the baseline to be compared with future scenarios. However, there is no complete observed meteorological dataset for the basin in the past that can be used as a reference dataset. Therefore, an alternative is to use climate reanalysis products, as Gatien et al. (2022) suggested.

In addition to precipitation and air temperature, the CEQUEAU water temperature module (Fig. 2d) requires wind speed, water vapor pressure, and net solar shortwave radiation. These meteorological variables are provided by the European Center for Medium-Range Weather Forecasting (ECMWF) through their European Reanalysis 5th generation (ERA5) (Hersbach et al., 2020), with the exception of vapor pressure which was calculated using ERA5 dew point temperature at 2 m height and with Teten's equation (Monteith and Unsworth, 2013; Murray, 1967). These gridded-based input data (with 30 × 30 km resolution) were interpolated to all basin whole squares using the built-in CEQUEAU interpolator based on the nearest neighbors approach (Ouellet-Proulx et al., 2019). ERA5 and climate models had three hours of temporal time steps. After downscaling and bias correction for climate models, we converted these data to daily time steps for running the CEQUEAU model.

2.5. Model calibration and implementation

This study uses multisite model calibration, using the maximum available information to provide the best set of parameters for the whole watershed (Arsenault et al., 2018; Bérubé et al., 2022; Shen et al., 2022). This study uses data from all available hydrometric (2) and water temperature stations (8). First, the hydrological module with 26 parameters was calibrated using the data from two hydrometric stations for June-September, which is the high-temperature period of the year (Online Resource Table S2). Then, using the calibrated hydrologic module outputs, the thermal module with eight parameters was calibrated using the data from eight water temperature monitoring stations for the same period.

2.5.1. Covariance Matrix Adaptation Evolution Strategy calibration algorithm

This study uses the Covariance Matrix Adaptation Evolution Strategy (CMA-ES; Hansen and Ostermeier, 1996) to find the optimal set of parameters for both hydrological and thermal modules for CEQUEAU during model calibration. CMA-ES is an evolutionary algorithm developed as a global optimization method (Hansen, 2016). This algorithm is frequently used for hydrological model calibration (Elshall et al., 2015; Smaoui et al., 2018; Yu et al., 2012;

Zouhri et al., 2021). Arsenault et al. (2014) showed the superiority of CMA-ES in finding global optima and convergence speed compared to nine other well-known optimization algorithms used to calibrate hydrological models. Khorsandi et al. (2022) showed the efficiency of this method for thermal calibration of the CEQUEAU model for the Nechako watershed. This method can be summarized in four steps, which are explained in detail by Hansen (2016) and Khorsandi et al. (2022).

2.5.2. *Hydrological Model Calibration*

The objective function for the optimization algorithm is the Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) coefficient, which is in Equations (1-5). The objective function in the calibration process shows the goodness of fit between simulated and observed data. Since every efficiency metric has its own strengths and limitations, presenting only one metric may be biased or may not accurately reflect the calibration's success. In addition to KGE, the Bias and Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) metrics were also calculated as follows:

$$KGE_j = 1 - ED_j \tag{1}$$

$$ED_j = \sqrt{(r_j - 1)^2 + (\alpha_j - 1)^2 + (\beta_j - 1)^2} \tag{2}$$

$$r_j = \frac{\sum_{i=1}^{N}\left(O_{i,j} - \bar{O}_j\right)\left(S_{i,j} - \bar{S}_j\right)}{\sqrt{\sum_{i=1}^{N}\left(O_{i,j} - \bar{O}_j\right)^2}\sqrt{\sum_{i=1}^{N}\left(S_{i,j} - \bar{S}_j\right)^2}} \tag{3}$$

$$\alpha_j = \frac{\sigma_{S\,j}}{\sigma_{O\,j}} \tag{4}$$

$$\beta_j = \frac{\bar{S}_j}{\bar{O}_j} \tag{5}$$

$$Bias_j = \bar{O}_j - \bar{S}_j \tag{6}$$

$$NSE_j = 1 - \frac{\sum_{i=1}^{N}\left(S_{i,j} - O_{i,j}\right)^2}{\sum_{i=1}^{N}\left(O_{i,j} - \bar{O}_j\right)^2} \tag{7}$$

where KGE_j, $Bias_j$ and NSE_j are the metrics for the j^{th} station; $O_{i,j}$ and $S_{i,j}$ respectively are observed and simulated values for the j^{th} station at the i^{th} time step; N is the number of time steps (measurements); r_j is the pearson correlation coefficient between observed and simulated values; α_j is the ratio of the standard deviation of simulated values to the standard deviation of observed values; β_j is the ratio of the mean of simulated values to the mean of observed values; $\sigma_{S\,j}$ and $\sigma_{O\,j}$ are the standard deviation of simulations and observations for the j^{th} station, and $\bar{S}_j$ and $\bar{O}_j$ are the mean of simulated and observed values. As previously recommended by Arsenault et al. (2018) and Shen et al. (2022), all the available data and stations were used for model calibration, which means that no data was reserved for validation.

2.5.3. *Thermal Model Calibration*

The eight thermal model parameters (Online Resource Table S3) - were adjusted using Root Mean Square Error (RMSE) as the objective function and the CMA-ES algorithm for optimization. The RMSE efficiency metric was used as recommended in the literature (Ouellet-Proulx et al., 2017a; Ouellet-Proulx et al., 2019).

$$RMSE_j = \sqrt{\frac{\sum_{i=1}^{N}\left(S_{i,j} - O_{i,j}\right)^2}{N}} \tag{8}$$

where $RMSE_j$ is the metric for the j^{th} station.

As with the hydrological calibration, all stations and all observed data were used for thermal model calibration. Both hydrological and thermal calibrations were completed in a two-step process. First, lower and upper boundaries for the model parameters were examined manually to ensure that the simulations stayed within realistic limits when the parameter had a physical meaning. Following this manual calibration, the CMA-ES optimization algorithm was used to refine the model parameter values of the hydrological and thermal modules. These steps are explained in detail by Khorsandi et al. (2022).

2.6. Future Model Projections

Following calibration, the calibrated CEQUEAU model was used to simulate water temperature over the Nechako watershed for two future periods, 2040-2070 and 2070-2100, using eight CMIP6's General Circulation Models (GCM) (Online Resource Table S4). The 4.5 and the 8.5 W/m^2 radiative forcing scenarios show the range of possible changes for the two future periods compared to the baseline period (for 1980-2019, using the ERA5 dataset). We selected the 4.5 and the 8.5 W/m^2 scenarios based on Shared Socioeconomic Pathways (SSP) terminology agreed upon in CMIP6 (Online Resource Table S5), with 8.5 w/m^2 being the more pessimistic scnenario. . The water temperature simulations resulted in metrics for the river's thermal regime. From all CMIP6 models, these eight models were selected to conduct this study because they had all the required variables at sub-daily time steps. We used the sub-daily time steps for bias correction, similar to Gatien et al. (Personal communication) for inter-model comparison studies.

Each global climate model using SSP forcings provided all meteorological data to run the model, which were bias-corrected using the N-dimensional Multivariate Bias Correction algorithm (MBCn) algorithm (Cannon, 2018) with the ERA5 data as the reference dataset for two radiative forcing scenarios (4.5 and 8.5 W/m^2). Eight climate models were used, as presented in Online Resource Table S4. The bias correction at the sub-daily timestep better represents the meteorological data's diurnal cycle and improves the daily averages (Gatien et al., 2022).

The MBCn algorithm is a novel approach in climatology that addresses limitations in traditional bias correction methods. While many existing algorithms focus on univariate time series and disregard the interdependencies between different variables, MBCn introduces a multivariate perspective. Inspired by an image processing technique, it leverages the N-dimensional probability density function transform to correct climate model projections of multiple climate variables. MBCn generalizes quantile mapping, preserving the entire observed continuous multivariate distribution in the corresponding climate model distribution. This adapted technique accurately maintains the quantile changes between historical and projection periods (Cannon, 2018).

Considering that the CEQUEAU model simulates water temperature at daily time steps, the sub-daily variables were aggregated to generate daily meteorological time series (by averaging for most variables and summing for precipitation). Finally, the daily meteorological projections were forced into CEQUEAU, and the model simulated future discharge and water temperature projections for the two periods mentioned above. Each GCM has a different gridded network, which was interpolated for the CEQUEAU grid points using the nearest neighbors approach (Ouellet-Proulx et al., 2019).

2.7. Duration Curve Method

All inputs and outputs for the CEQUEAU model have daily time steps in this study. For the simulation outputs, temperature duration curves (TDC) were used to show and analyze the daily water temperature simulations for the past and future periods. TDC plots the probability of the exceedance of the observed value from multiple thresholds in a continuous manner (Karakoyun et al., 2018). This study identified the probability of exceedance of the critical environmental threshold of 20°C [an upper threshold for adequate thermal habitat for Sockeye salmon migration in this river at Finmoore; Macdonald (2019)] on TDC curves. The TDC curves in this study show the probability of exceedance for water temperatures higher than 5°C. The temperatures above the 5°C threshold was selected because the CEQUEAU model is not designed to model low (close to zero) water temperatures (e.g., there is no ice-formation algorithm in CEQUEAU).

3. Results

3.1. Hydrological module calibration and parameters

Fig. 3 shows the simulated and observed discharge values for Vanderhoof and Nautley stations during the calibration period.

[Fig. 3 Here]

Performance indicators were excellent for the Vanderhoof station (KGE = 0.94, NSE = 0.88) (Fig. 3a), and the KGE value was acceptable for the Nautley station (KGE = 0.54, NSE = 0.4) (Fig. 3b). Online Resource Table S2 shows the 26 calibrated hydrological parameters using the multisite approach using these two observation stations. However, the simulated values at the Nautley station show overestimations for high flows. This Bias for high flows is likely due to the presence of two large lakes upstream of the station. The current version of the CEQUEAU model conceptualizes the lake storage effect by using a single reservoir and a modified transfer coefficient. However, a single calibrated value for CVMAR (Lakes and marshes drainage coefficient in a CP) and HMAR (Lakes and marshes drainage threshold in a CP), the two parameters associated with lake water storage, is likely not well-adapted to the lake cascade configuration in the Nautley sub-watershed (See online resources Table S2). On the other hand, for the Nautley station, high flows are not the priority in this study. As explained by Khorsandi et al. (2022), high flows tend to occur in May and June, while the main focus of this research is on the warm July-August period, for which the simulations for the Nautley station show acceptable efficiency metrics (KGE = 0.61) with unbiased flow estimations (Bias = 1.19m^3/s, relative Bias = 0.03).

3.2. Thermal Model Calibration

Online Resource Table S3 shows the thermal module parameter values using eight stations and a multisite approach for calibration. The simulated time series versus observed values are shown in Fig. 4 for eight stations using the calibrated values for thermal calibration.

[Fig. 4 Here]

For the stations with more extended observation periods and without water bodies upstream, the CEQUEAU model can provide low Bias simulations with RMSE < 2°C and Bias < 0.8°C (Stations 1, 2, 3, 4, and 5). However, three of the eight stations (Stations 6, 7, and 8) show Bias metrics higher than 1.5°C and RMSEs greater than 2°C. Again, this Bias is likely due to the presence of large water bodies upstream of these stations. Large water bodies increase the contact surface, which, during the summer period, has a warming effect on surface water outflow. The current version of CEQUEAU does not consider this lake effect, which may explain the underestimation of simulated water temperature. The impact of large lakes on the CEQUEAU temperature simulations is further discussed by Khorsandi et al. (2022). The Vanderhoof station (Station 2) is of higher importance because it is the closest station with longest observation period to the location identified in the STMP (Finmoore), where the average daily water temperature must remain ≤ 20°C during the Sockeye salmon migration.

The simulated results for the Vanderhoof station for the baseline period show RMSE = 1.27°C and Bias ≈ 0°C, which are acceptable results when using a hydrological model at the watershed scale. Although the simulated values are generally unbiased (Fig. 4), there is a slight underestimation of the yearly number of days above 20°C (Fig. 5).

Fig. 5a shows that the average simulated temperatures matched the observed values for the July-August period for each year. These simulated values use ERA5 data (one dataset) for the 1980-2019 baseline period, and each boxplot shows the simulated water temperature range in a year. Fig. 5b shows the number of days above 20°C for both observed and simulated data. Fig. 5b shows that the number of days above 20°C is not perfectly matched. Fig. 5b shows that the error (observed - simulated) in the number of days above 20°C for simulated time series ranges from -5 to +9 days. Hence, there are summers during which the model overestimates the number of days above 20°C; and there are summers during which the model underestimates the number of days above 20°C. These differences in the simulated versus the observed number of days should be considered when interpreting climate change simulations. The observed data show that the maximum number of days above 20°C that occurred in a year is nine days (during the July-August of 2019 in Fig. 5b). Simulations indicate that the highest historical number of exceedances of 20°C is nine days (2016; Fig. 5b). The STMP aims to regulate elevated water temperatures during sockeye salmon migration in the Nechako River by manipulating the timing and volume of reservoir water releases from SLS (Bond, 2017). The management plan focuses on maintaining average daily water temperatures at or below 20°C in the Nechako River at Finmoore (30 km downstream of Vanderhoof), upstream of the Stuart River confluence, during the critical migration period from July 20 to August 20. Cooler water temperatures are essential for the survival of Sockeye salmon during its migration. The program employs a comprehensive approach involving field data collection, weather forecasts, temperature predictions, and flow release decisions. By analyzing trends in observed and predicted water temperatures, Rio Tinto determines when to increase or decrease the release of water from SLS, aiming to achieve optimal conditions for salmon migration. This protocol enhances the resilience of the Nechako River ecosystem and contributes to the conservation of Sockeye salmon populations. The program also employs a decision protocol to adjust SLS releases between 14.2-453 m^3/s based on observed and forecasted water temperature trends, ensuring that the water temperature remains below the critical threshold for salmon survival. Additionally, the release of water from SLS is carefully managed to maintain flow below Cheslatta Falls (Fig. 1) between 170 m^3/s and 283 m^3/s.

[Fig. 5 Here]

Fig. 6a compares TDC for observations with simulated values (for values greater than 5°C). Fig. 6a shows the probability of exceedance for water temperatures higher than the 5°C since the CEQUEAU model is not designed to model low water temperatures. Fig. 6b shows the timing of interannual averaged values for each DOY from 1980 to 2019 for observed and simulated values during the warm months (from June to September). Fig. 6b shows that the simulated values mostly follow the same timing pattern as the observed values. Although simulated temperatures lag a few days behind observed ones, the observed values fall within the lower and upper boundaries of simulated water temperatures. Fig. 6b also shows that in long-term management through STMP implementation (adjusting SLS releases between 14.2-453 m^3/s at SLS from July 20 to August 20), STMP decreases the water temperature at the Vanderhoof and the DOY average during the warm season is below the 20°C threshold, as confirmed by observed water temperature values.

[Fig. 6 Here]

Fig. 4 (for the Vanderhoof station in higher resolution, see Fig. S1 in Online Resource) shows that for Vanderhoof Station on a short-term daily basis, the CEQUEAU model can accurately reproduce high-temperature days. Fig. 6b shows this ability in the long term over the years through DOY averaged values. Therefore, the CEQUEAU simulated values for future climate change scenarios can provide reliable insight into the timing and extent of changes in high water temperatures.

3.3. Future projections

The selected climate scenarios data were used as inputs to the CEQUEAU model (Fig. 2b). In addition, simulated water flow and water temperature at the SLS using CE-QUAL-W2 were used as boundary conditions for the CEQUEAU model for future scenarios. Figures S2-S5 in Online Resource show the simulated temperature results for the Vanderhoof station for the

SSP2-4.5 2040-2069, SSP2-4.5 2070-2099, SSP5-8.5 2040-2069, and SSP5-8.5 2070-2099 horizons, respectively.

Fig. 7 for the Vanderhoof station shows an increase in summer water temperature compared to the baseline period (Fig. 6a). Fig. 6a shows TDC for the baseline, while Fig. 7 provides TDC at the Vanderhoof station for all climate change scenarios. Figures S2-S5 in Online Resource also show this increase in water temperature for future horizons compared to the baseline (Fig. 4 and Fig. S1 in Online Resource) for daily simulations. The range of the yearly increase range can be seen in Online Resource Figures S6-S9.

Fig. 7 shows TDC for all eight climate models for all four climate change scenarios. As expected, these scenarios show a higher probability of exceedance for 20°C compared to the baseline period. The increasing probability of occurrence can be seen by moving from SSP4.5 to SSP8.5 and by going further in the time horizon. The exceedance probability starts from 3.8% for SSP2-4.5 (2040-2069 horizon) as the lowest value using MPI-ESM1-2-HR model data, and the highest exceedance value is 36% for SSP5-8.5 (2070-2099 horizon) using CMCC-ESM2 model data.

[Fig. 7 Here]

Fig. 8 shows the change in the timing of high temperatures for future time horizons. When compared to Fig. 6b, it can be seen that August remains the warmest month, but September is warming more than July. Fig. 6b indicates that the crucial time of year for warming is mid-July to mid-August, which corresponds to the STMP period. This crucial warming period will become longer and warmer in the future. The future warm summers are expected to start in early July and last until early September. Considering the STMP fixed period (July 20 to August 20), we calculate the onset and end temperature for STMP using the interanuual average data for the baseline period. This onset-end threshold equals 17°C (by using Fig. 6b for July 20 to August 20 period). Fig. 8 shows future scenarios for which June 8 to June 27 is the range for the future 17°C onset and September 12 to 25 is the end of the 17°C threshold (Table 1), which means more prolonged periods of warm days above these thresholds.

[Table 1 Here]

[Fig. 8 Here]

Fig. 9 shows the mean and median temperature for the July-August period on a yearly basis, along with the number of days above 20°C per year. This figure provides a better understanding of the potential frequency and duration of thermally stressful events for Sockeye salmon in future scenarios compared to the past (shown in Fig. 5).

[Fig. 9 Here]

The number of days above 20°C during summer each year differs between the four situations. Figures S6-S9 in Online Resource show this variability among models. The four situations (SSP4.5 and SSP8.5 for the 2040-2069 and 2070-2099 periods) show an increasing maximum number of days above 20°C during summer, ranging from 38 to 62 days, which is above the model uncertainty of nine days for this criterion. The SSP8.5 for the 2070-2099 period shows that the daily average water temperature for the STMP period is above 20°C. Future water temperature scenarios consistently show higher annual numbers of threshold exceedances than the maximum level that occurred during the baseline period, which was nine days.

4. Discussion

4.1. Hydrothermal modeling

The CEQUEAU calibration metrics are satisfactory (KGE and NSE ≥ 0.6), comparable or better than those provided in previous studies on the Nechako (Online Resource Table S6) (Islam et al., 2019; Kwak et al., 2017b; Ouellet-Proulx, 2018; Ouellet-Proulx et al., 2017b; Ouellet-Proulx et al., 2019). Even though simulated flows and temperatures are comparable to or better than in previous studies on Nechako (Ouellet-Proulx et al., 2017b; Ouellet-Proulx et al., 2019; Ouellet et al., 2020), the hydrological calibration for the Nautley station shows weaker performance metrics than at Vanderhoof. It is suspected that the weaker model performance at this station is related to the impact of relatively large lakes upstream of the station. The CEQUEAU model can conceptually account for the slower water routing through lakes, but it is somewhat limited since it considers flow routing in a simplified and conceptual form. Given that little is known about the water residence time in those lentic habitats, this could be revisited if additional information is gathered. Khorsandi et al. (2022) also showed that simulated water temperature is positively biased downstream of large water bodies in the Nechako River watershed (e.g., the CEQUEAU simulations are underestimating the observed temperature values downstream of the large water bodies). Lake surfaces provide a large area exposed to solar radiation, leading to warming surface water. Stations 6-8 in Fig. 4 show this Bias (underestimation in water temperature) for the stations upstream of the Nautley confluence. However, this Bias does not spread downstream since the water temperature is mainly controlled by local meteorological forcings (Khorsandi et al., 2022; Gatien et al., 2022). As a result, the simulations at the Vanderhoof station are unbiased. Therefore, we can say the future projections at the Vanderhoof station are unbiased too.

For stations 6-8, part of this Bias may be due to water temperature boundary conditions at SLS. Synthetic time series were produced using DOY averages for the reference period. Gatien et al. (2022), using the HEC-RAS hydraulic model for the reaches of the Nechako River between the SLS and Vanderhoof, showed that the impact of upstream boundary conditions on the simulated temperature at Vanderhoof is insignificant. Khorsandi et al. (2022) also showed that local meteorological variables have a more significant impact than upstream conditions in the Nechako, especially at Vanderhoof. However, since CEQUEAU does not include a complex hydraulic water routing scheme like HEC-RAS, upstream boundary conditions may impact the stations upstream of the Nautley confluence (Stations 6-8), which may partly explain the presence of thermal simulation biases.

4.2. Future Upstream Boundary Conditions Impacts on Downstream Water Temperature

This study used the CE-QUAL-W2 outputs for water temperature at the SLS based on using current reservoir operations (STMP) to constrain the upstream boundary condition. The current reservoir operation model defines powerhouse water intake and SLS outputs. This assumption is based on a business-as-usual operation based on STMP by Rio Tinto and considers the water temperature stratification inside the reservoir due to climate change impacts. Although CE-QUAL-W2 resolves water stratification inside the reservoir, water is only released at SLS from the surface layer of the reservoir, and reservoir management cannot provide cold water to the Nechako River unless the water is taken from deeper layers. However, both flow and temperature may experience regime shifts due to the impact of climate change on reservoir stratification and climate change mitigations by Rio Tinto (e.g., future updated STMP or installing a new water release facility). Currently, there is no facility to manage water temperature downstream at the Nechako Reservoir directly. Therefore, testing other reservoir management rules that explicitly consider water temperature downstream to reduce the exceedance of the 20°C threshold is required. Further studies can analyze the implications and efficiency of these changes on the upstream boundary conditions under climate change scenarios.

4.3. Future Water Temperature Simulation under Climate Change Impacts

The results emphasize a projected increase in water temperature at the Vanderhoof station during the 2040 to 2100 period. Past observed water temperature data and historical simulations at Vanderhoof show similar exceedances of the 20°C threshold (1% for observations and simulations; observations exist from 2005-2019). Islam et al. (2019) modeled temperatures for the 1950-2015 historical period and found that the number of days above 20°C in the summertime doubled over 65 years for the whole basin, and the whole Fraser River basin's average summer temperature rose by 1°C during this period.

They reported that during the summer periods of 1960 to 2000 there was a three days decrease in 20°C exceedances for the Vanderhoof station. This small reduction in 20°C exceedances for Vanderhoof station while reporting warmer water at the Fraser basin may be explained by the implementation of the STMP protocol by Rio Tinto, which focused on the Vanderhoof station to keep the average temperature below the 20°C threshold.

Picketts et al. (2017) reported an increasing trend in water temperature for the Nechako watershed during summertime using climate change impact assessments. Warmer summers mean limiting conditions for Sockeye salmon, their migration, and spawning time upstream of Vanderhoof station (Macdonald, 2019). Our simulations for exceedance of 20°C in near climate horizons (2040-2069) show 0-36 days for SSP 4.5 and 0-58 days for SSP 8.5, which is a significant increase. Picketts et al. (2017) mentioned a water temperature increase of around 2°C for this horizon using regional studies. Results for far future horizons (2070-2099) show even higher exceedance frequencies for the 20°C threshold. Our estimations indicate 3-62 days for SSP2-4.5. The SSP5-8.5 scenario simulations show 53-62 days beyond the 20°C threshold. These simulations resulted from considering natural or at least historic flow rules based on STMP. However, it may be possible to modify SLS water releases to target longer and more frequent heat waves to mitigate the increase in temperatures.

4.4. Ecological Implications of Nechako River Water Temperature Warming

Sockeye salmon is one of the most vulnerable species to rising water temperatures, with 100% mortality beyond 21°C in water temperature after 72 hours following exhaustive exercise (Middleton et al., 2018; Robinson et al., 2015). Scatter plots of the daily average temperature from July-August for each year of the baseline period (Fig. 5) indicate some years with nine days above 20°C, with a rising trend in the number of days.

All four projections (SSP2-4.5 and SSP5-8.5 for 2040-2069 and 2070-2099) show an increasing water temperature and an increased frequency of days with > 20°C water temperature. While for the past period, the maximum number of exceedance days is 9 for each summer, for these four combinations, the maximum number of 36, 62, 58, and 62 days is expected based on daily simulations using eight climate models. Considering the lethal threshold for Sockeye salmon (Online Resource Table S1), the number of days with a temperature of more than 20°C is a severe and alarming signal for this species' habitat (Carrington, 2020).

4. Conclusion

This study provided water temperature simulations for the historical baseline period of 1980-2019, for the near future (2040-2069), and far future (2070-2099) for the Nechako River in British Columbia, Canada. The study used CMIP6 climate models and SSP2-4.5 and SSP5-8.5 climate change scenarios. The CEQUEAU model was forced with ERA5 data for the past and eight CMIP6 climate models for the future. The study's main finding was the ability of the model to accurately simulate water temperatures during the summer at all eight observation sites. The CEQUEAU model provided reliable water flow and temperature values for the entire Nechako River watershed. The results of the study provide ensemble estimations of water temperature under climate change scenarios, which are necessary for decision-makers in the Nechako River watershed. Climate change scenarios indicate that there will be 3.8-36% more days with water temperatures higher than 20°C, which may pose a severe threat to the Sockeye salmon population due to changes in the Nechako River's thermal regime. The frequency of days with an average water temperature of more than 20°C is expected to be 0-62 days during July-August, compared to 0-9 days in the past. The water temperature simulation results indicated a relatively high probability of exceeding the 20°C thermal limit at Vanderhoof in the Nechako River. Scenarios indicate that potentially highly stressful conditions for cold-water species like Sockeye salmon during high-temperature events will likely occur more frequently. Future studies are needed to assess the possible impact of dam operation as an adaptation strategy to tackle this and to implement other solutions as mitigation for increasing water temperature.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Data Availability

Data will be made available on request.

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Table 1 The onset and end dates for the 17°C thermal threshold (Fig. 6b) based on the STMP period (July 20 to August 20)

Scenario	Onset date (for 17°C)	End date (for 17°C)	Duration (days)
Baseline-ERA5, 1980-2019	July 20	August 20	32
SSP2-4.5, 2040-2069	June 27	September 12	78
SSP2-4.5, 2070-2099	June 16	September 14	91
SSP5-8.5, 2040-2069	June 16	September 16	93
SSP5-8.5, 2070-2099	June 8	September 25	110

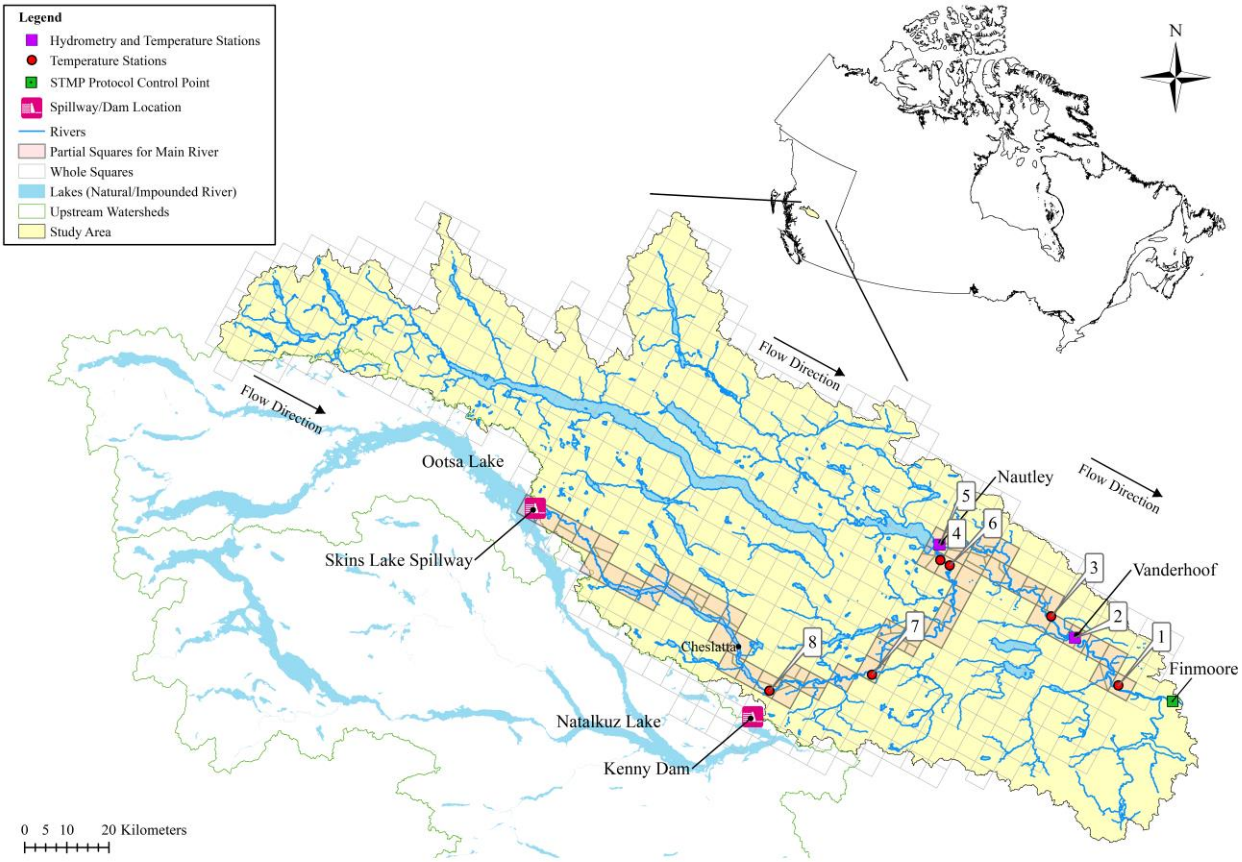

Fig. 1 Nechako River watershed study area. The hydrometry/temperature stations are numbered 1 to 8 from downstream to upstream. Station 2 (Close to Vanderhoof town) is labeled Vanderhoof. Station 5 (labeled as Nautley) is just upstream of the confluence on the Nautley River. The yellow area shows the modeled region using CEQUEAU from Skins Lake Spillway (SLS) to Station 1. The computational units in CEQUEAU are "Whole Squares or CE" and "Partial Squares or CP." Each CE, a square grid cell, can be divided into a maximum of four CPs by overlapping CEs and sub-watershed boundaries. The CPs are hydrologic response units in CEQUEAU and are shown for the main river from SLS to Station 1. The Ootsa Lake is impounded part of the Nechako River due to Kenny Dam construction which SLS controls its flow downstream, and Natalkuz Lake is the impounded part of the Nechako River immediately upstream of Kenny Dam.

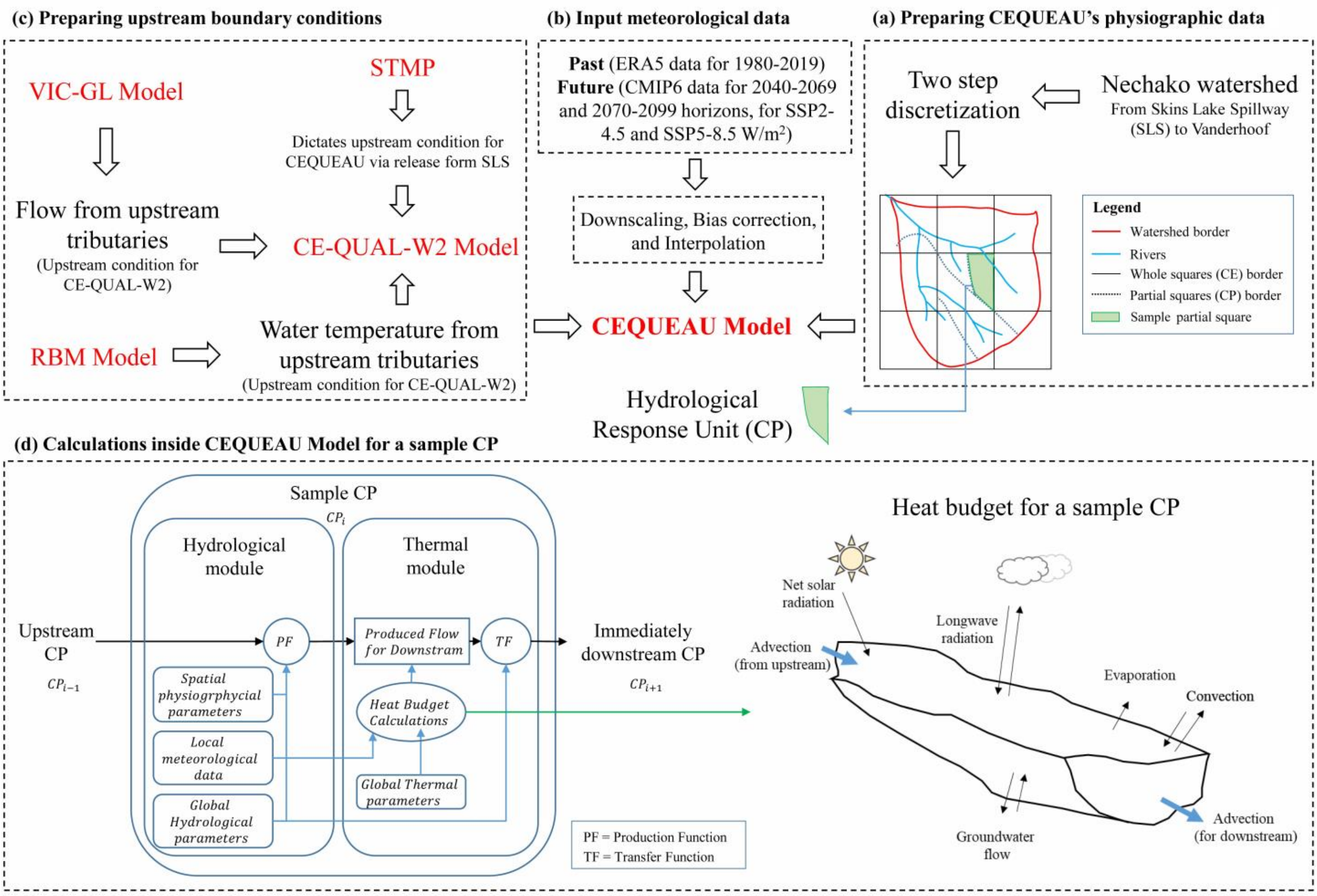

Fig. 2 Schematic representation of steps, concepts, and models to set up the CEQUEAU model in this study, including (a) physiographical data for the watershed, whole squares, and partial squares; (b) input meteorological data (precipitation, min and max air temperature, vapor pressure, cloud cover, net solar shortwave radiation), (c) the models incorporated to prepare upstream boundary condition for CEQUEAU; (d) structure of a sample partial square (CP) which is a hydrological response unit for which both hydrological and thermal budgets are computed. The core of the hydrological module is the Production Function (PF) and Transfer Function (TF), which calculates available water inside each CP and subsequent routing downstream. The thermal module calculates the heat budget using available water inside each CP.

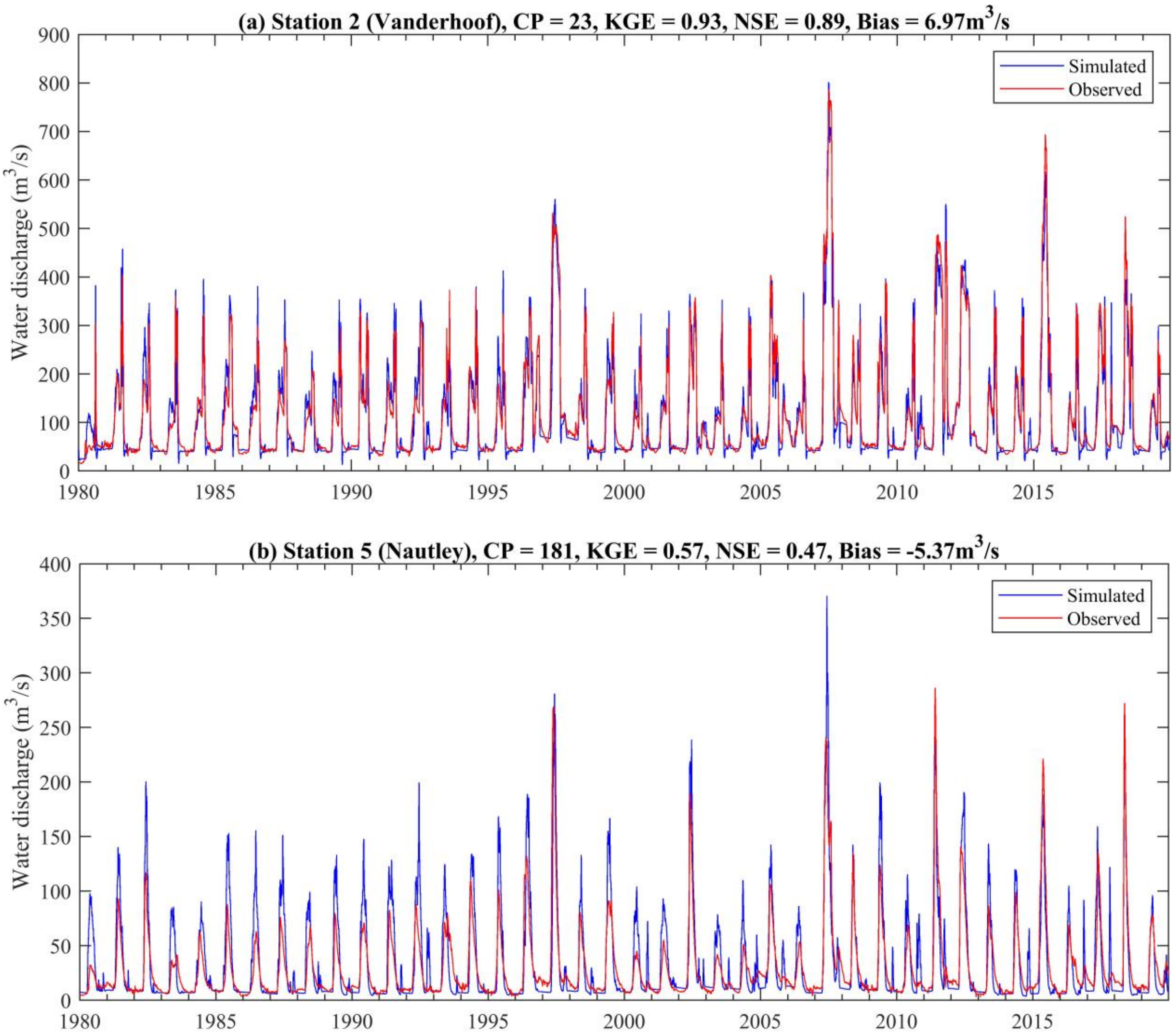

Fig. 3 Simulated and observed flows using the calibrated model for Vanderhoof and Nautley stations for the June-September period

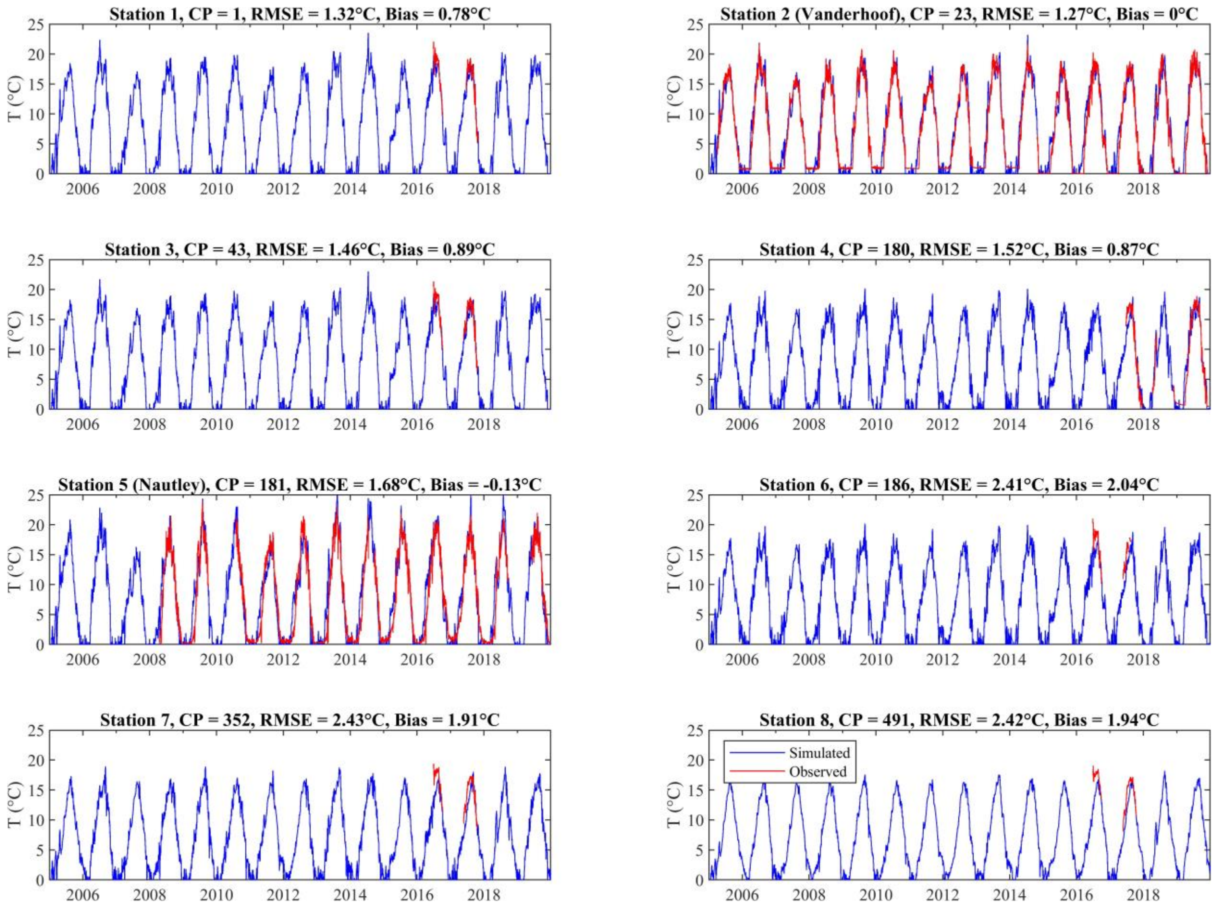

Fig. 4 The simulated (blue) and observed (red) water temperature time series for each station using the multisite calibration approach for the June-September period

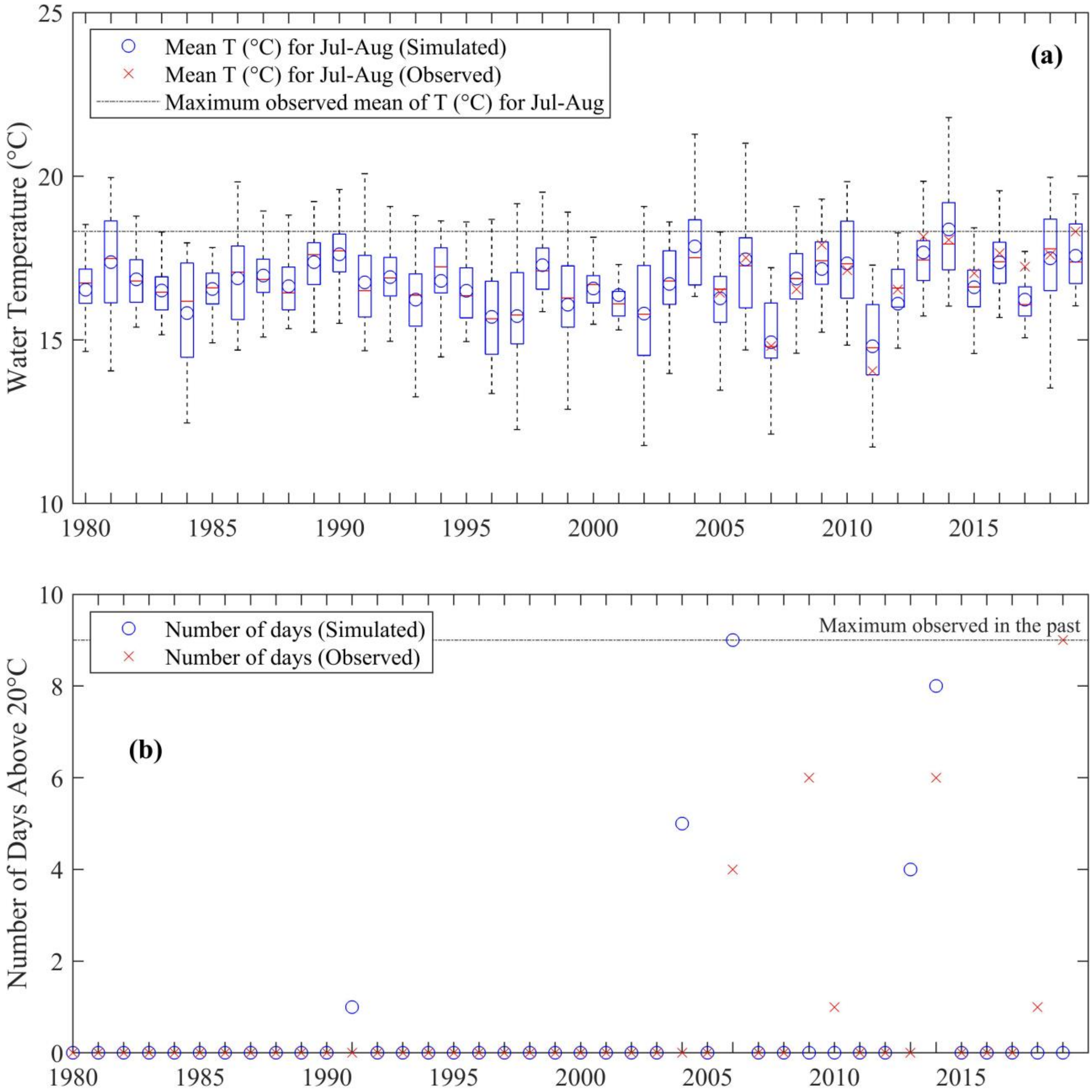

Fig. 5 (a) The yearly range [for July-August only] of simulated water temperature variability is shown using boxplots for the Vanderhoof station's baseline period 1980-2019. The red line represents the median value, and the blue circles show the mean simulated value. The upper and lower limits of the boxes show the 25th and 75th percentiles, respectively, and the whiskers show the most extreme data. The mean annual temperature of the observed data is shown with the red crosses (x) (2005-2019 only). (b) Red crosses and blue circles show the annual number of days on which the mean daily temperature exceeds the critical limit of 20°C for simulated and observed time series, respectively. The horizontal dotted line shows the maximum number of observed days above 20°C in a year, equal to 9 days

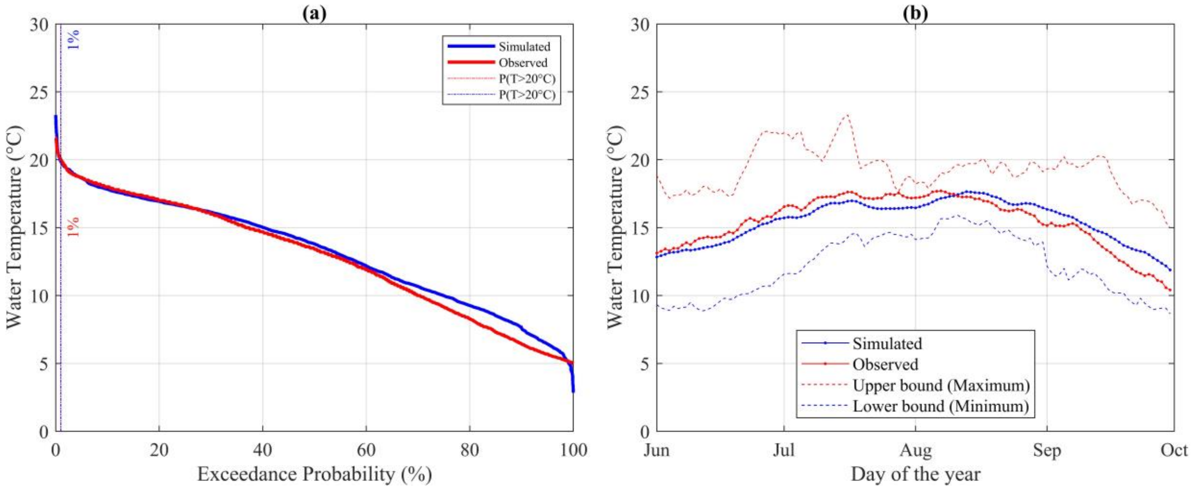

Fig. 6 (a) Duration curve of baseline (1980-2019) simulated data and observed water temperatures at the Vanderhoof station (b) Water temperature timing for the warm season (June-September) for observed and simulated time series together with the lower and upper boundary of simulated values

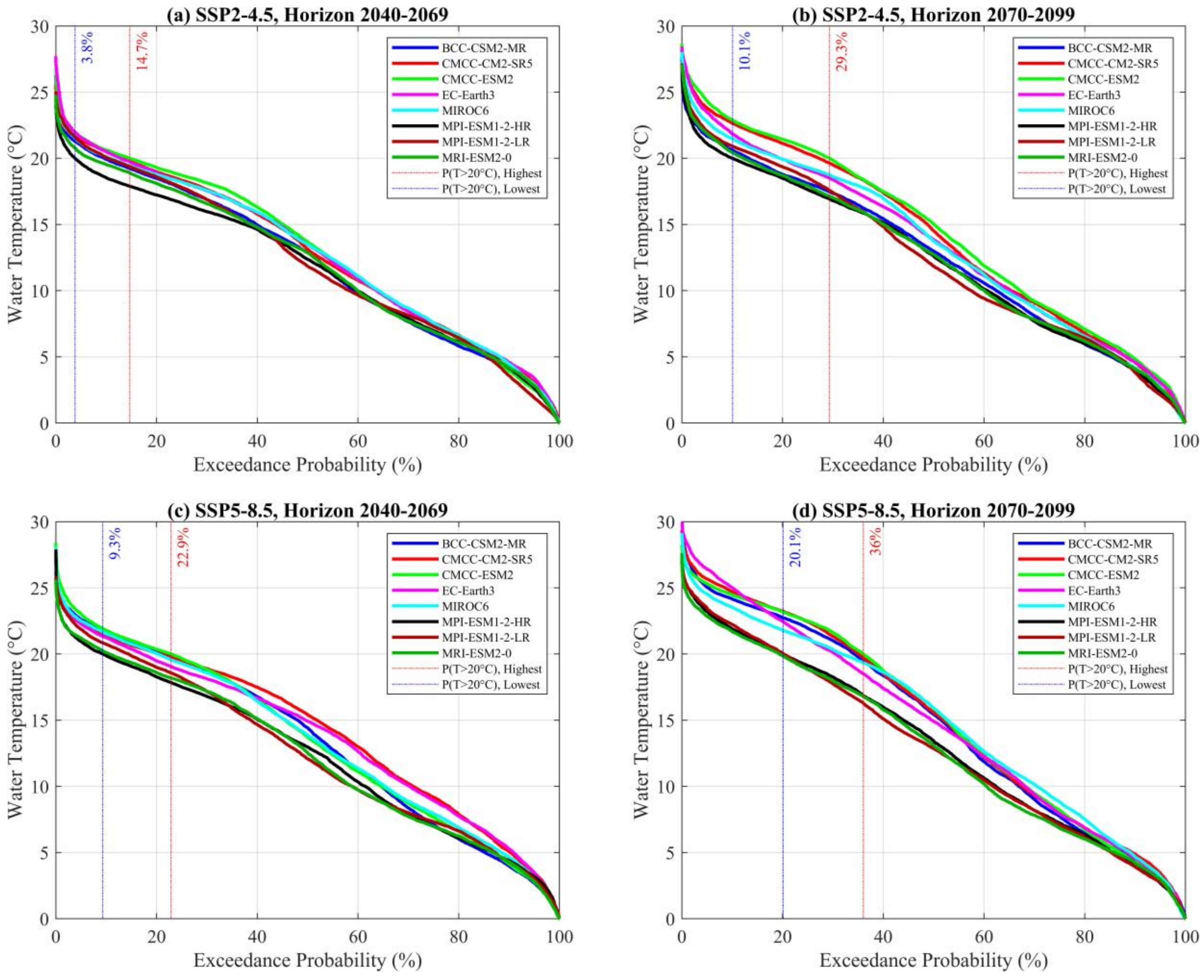

Fig. 7 Duration curve of simulated data using eight climate models and their median for SSPs 4.5 and 8.5W/m^2 and for the 2040-2069 and 2070-2099 time horizons at the Vanderhoof station. The models with the lowest and highest exceedance probabilities were used to calculate the minimum and maximum exceedance probabilities depicted on the graphs.

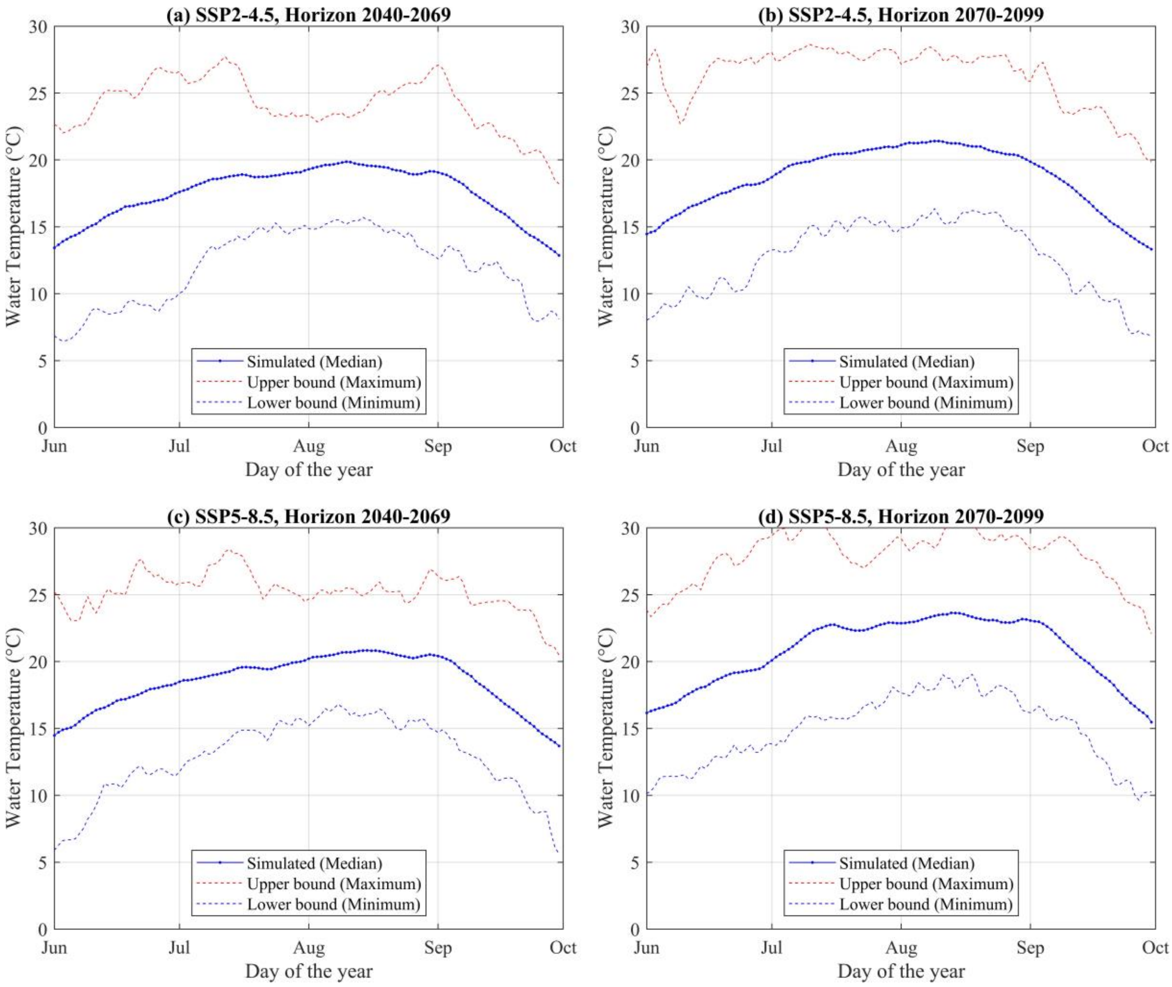

Fig. 8 High water temperatures timing for the June-September period for the simulated time series in the future, together with the lower and upper boundary of simulated values

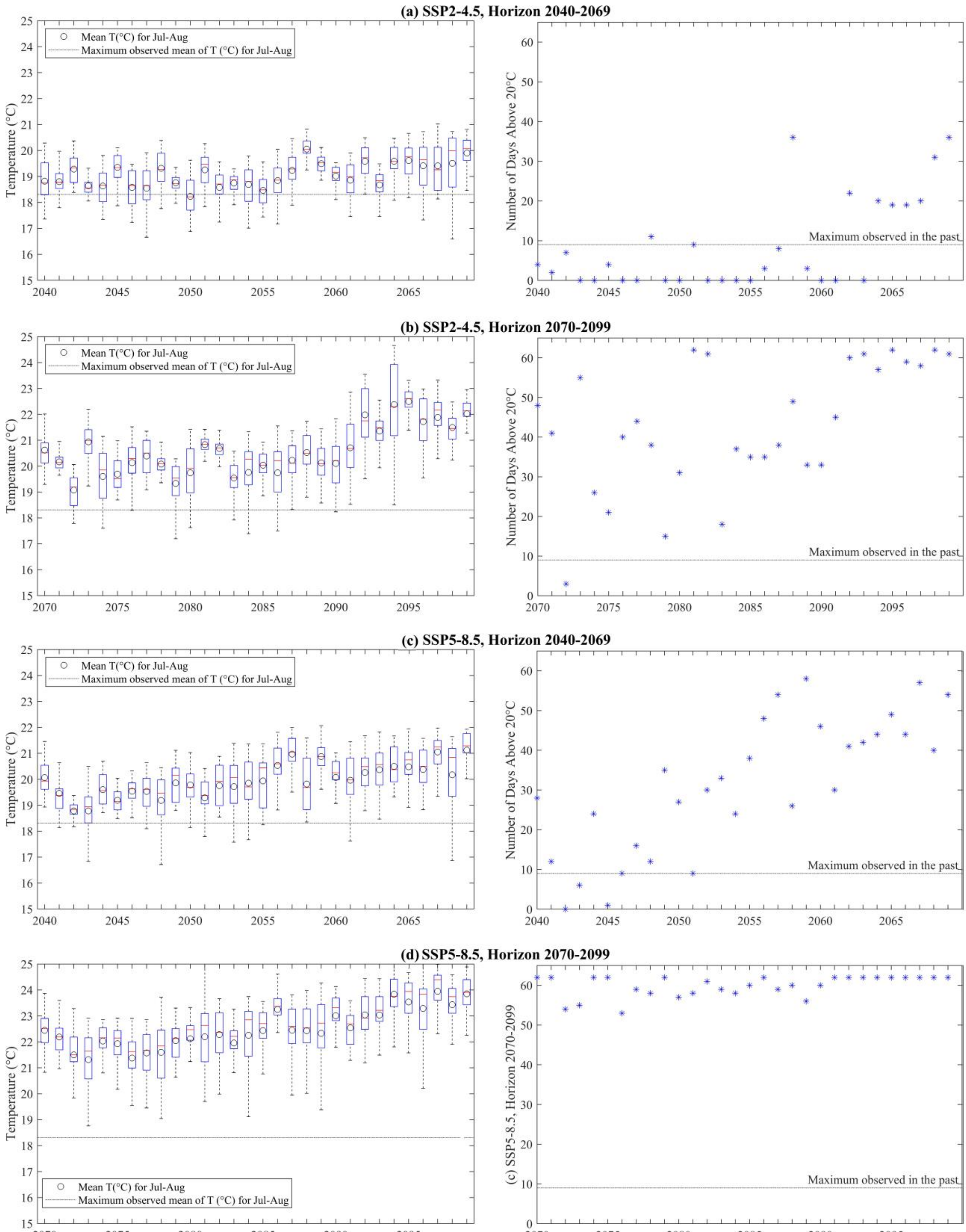

Fig. 9 The yearly range of water temperature variability is shown using boxplots for two-time horizons and two SSPs. The red line represents the median multi-model value, and the black circles show the mean multi-model simulated value. The upper and lower limits of the boxes show 25th and 75th percentiles, respectively, and the whiskers show the most extreme data. The horizontal dotted line on the left panels shows the maximum observed mean of temperatures for July-August months in the past. Blue asterisks on the right-side plots show the annual number of days on which the temperature exceeds the critical limit of 20°C for simulated and

observed time series using multi-model median values. The horizontal dotted line shows the maximum number of observed days above 20°C in a year, which occurred during the 2005-2019 period and is equal to 9 days.

Supplementary Files

- 6SupplementaryInformation22082023.docx