

Projected Water Temperature and Exposure Indices for Adult Sockeye Salmon Migration in the Okanagan Watershed, 2010-2099

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ABSTRACT

Stiff, H. W., Thompson, P. L. 2026. Projected Water Temperature and Exposure Indices for Adult Sockeye Salmon Migration in the Okanagan Watershed, 2010-2099. Can. Tech. Rep. Fish. Aquat. Sci. 3793: viii + 102 p. <https://doi.org/10.60825/0jxx-3w53>

Rising river temperatures are increasingly constraining the upstream migration of adult salmon in interior Pacific Northwest rivers. This study quantifies projected changes in water temperature and the occurrence of migration-limiting thermal conditions along the terminal freshwater corridor of Okanagan Sockeye salmon (*Oncorhynchus nerka*) in the Okanagan–Okanogan River system (British Columbia, Canada; Washington State, USA). Daily mean water temperatures at three mainstem sites and the Similkameen River tributary were estimated using a generalized additive model relating air to water temperature, calibrated with observed data. Future projections were derived from statistically downscaled air temperatures from ten CMIP5 climate models under moderate (RCP4.5) and high (RCP8.5) emissions scenarios, and assessed for the June–September migration season relative to a 1971–2000 baseline.

Results show consistent warming across all sites, with higher summer mean temperatures, earlier onset of thermal stress, and a marked increase in the duration of conditions exceeding the 22 °C migration threshold. Thermal barriers have likely already advanced by about one week and are projected to occur several weeks earlier by mid- to late-century, especially under RCP8.5. Consequently, migration windows are compressing into early and late summer, with mid-summer passage increasingly limited. These trends suggest a shift from episodic to chronic thermal constraints, highlighting growing risks to migration success, survival, and long-term population resilience, and emphasizing the need for climate-informed management.

RESUMÉ

Stiff, H. W., Thompson P. L. 2026. Projected Water Temperature and Exposure Indices for Adult Sockeye Salmon Migration in the Okanagan Watershed, 2010-2099. Can. Tech. Rep. Fish. Aquat. Sci. 3793: viii + 102 p. <https://doi.org/10.60825/0jxx-3w53>

La hausse des températures des rivières limite de plus en plus la montaison des saumons adultes dans les rivières intérieures du nord-ouest du Pacifique. La présente étude quantifie les variations prévues de la température de l'eau et l'occurrence des conditions thermiques limitant la migration le long du corridor d'eau douce terminal du saumon rouge de l'Okanagan (*Oncorhynchus nerka*) dans le réseau hydrographique l'Okanagan–Okanogan (Colombie-Britannique, Canada; État de Washington, États-Unis). Les températures moyennes quotidiennes de l'eau à trois sites sur le cours principal et dans l'affluent de la rivière Similkameen ont été estimées à l'aide d'un modèle additif généralisé reliant la température de l'air à la température de l'eau, étalonné avec les données observées. Les projections sont issues de températures de l'air statistiquement extrapolées à échelle réduite, à partir de dix modèles climatiques CMIP5 selon des scénarios d'émissions modérées (RCP4.5) et élevées (RCP8.5); elles sont évaluées pour la saison de migration de juin à septembre par rapport à une base de référence de 1971 à 2000.

Les résultats montrent un réchauffement constant dans tous les sites, avec des températures moyennes estivales plus élevées, un début plus précoce du stress thermique et une augmentation marquée de la durée des conditions dépassant le seuil de migration de 22 °C. Les barrières thermiques ont probablement déjà avancé d'environ une semaine et devraient survenir plusieurs semaines plus tôt d'ici le milieu ou la fin du siècle, en particulier dans le cas du scénario RCP8.5. En conséquence, les périodes de migration se concentrent désormais au début et à la fin de l'été, et les passages au milieu de l'été sont de plus en plus limités. Ces tendances laissent entrevoir une évolution des contraintes thermiques, qui passent d'un caractère épisodique à un caractère chronique, ce qui souligne les risques croissants qui pèsent sur le succès des migrations, la survie et la résilience à long terme des populations, en plus de mettre en évidence la nécessité d'une gestion tenant compte des changements climatiques.

INTRODUCTION

Freshwater temperature and flow are among the most influential factors shaping salmon life-history outcomes. Temperature effects on adult Pacific salmon (*Oncorhynchus* spp.) during migration and spawning are well documented across the Pacific Northwest, with elevated river temperatures directly linked to migration delays, reduced upstream passage success, and increased pre-spawn mortality (Nelitz et al. 2007; Hinch and Martins 2011).

Optimal migration temperatures for adult Sockeye salmon (*O. nerka*) typically range from about 7–16 °C, with supra-optimal or stressful conditions emerging above ~17 °C (BC 2001). Thermal stress on the physiology of reproductively maturing salmon has been documented to begin at temperatures exceeding 17 °C, through accelerated metabolic processes, reduced aerobic scope and swimming capacity, heightened susceptibility to disease, increased en-route and pre-spawn mortality (Crozier et al. 2008; 2011). In migrants that survive to spawn, thermal stress negatively affects gonad development, gamete viability, egg size, and offspring abundance and performance (Crossin et al. 2008). Temperatures above ~21–22 °C consistently impede Sockeye adult migration (Hyatt et al. 2015; 2020), and water temperatures above 22 °C present a thermal barrier to Okanagan Sockeye². Exposure to temperatures exceeding 24 °C can be lethal for salmon species (Cooke et al. 2004; Crossin et al. 2008).

These biological thresholds define key markers for assessing the impacts of climate-driven changes in river water temperature on adult salmon during summer upstream migration, the life stage on which this study is focused.

Documented Regional Warming

Long-term climate observations show that air temperatures throughout the Pacific Northwest and British Columbia have increased steadily over the past century. Regional analyses indicate a warming trend of approximately 0.14 °C per decade through the 20th century, with accelerated rates of ~0.19 °C per decade since the 1950s (Zhang et al. 2000; Mote et al. 2003; Bush et al. 2014). Projections for the Pacific Northwest suggest continued warming of 1.5–3 °C in the next several decades, with summer warming of 4–5 °C by 2100 under high-emissions scenarios (Mote & Salathé 2009).

Warming in the Okanagan basin has occurred in all seasons during the past century (PCIC 2013). Historical data (1900–2009) indicate that approximately 1 °C of warming has already

² Pers. comm., E. McGrath (Okanagan Nation Alliance Fisheries Manager); C. Baldwin (Colville Confederated Tribes Fisheries Scientist). See also Strange (2010) for similar migration barrier thresholds found in the Klamath River basin for Chinook salmon.

occurred in the Okanagan watershed during the 20th century, with the maximum rate of change occurring since 1951 (Figure 1). Regional climate projection reports indicate substantial summer warming. The Regional District of Okanagan–Similkameen 2020 climate projections show that annual air temperatures are expected to rise by ~2 °C by the 2030s and ~4 °C by the 2060s under “business-as-usual” greenhouse gas emission trajectories, with the number of days above 30 °C projected to double by the 2030s and triple by the 2060s. The hottest summer days, historically ~30 °C, are expected to reach 34 °C (region-wide) and 36 °C (in the valley bottoms) by the 2050s (RDO 2020). Extreme hot-day temperatures (above the 95th percentile) are projected to rise from ~33–38 °C currently, to 37–44 °C (respectively) by mid-century (RDO 2020; Schira 2024).

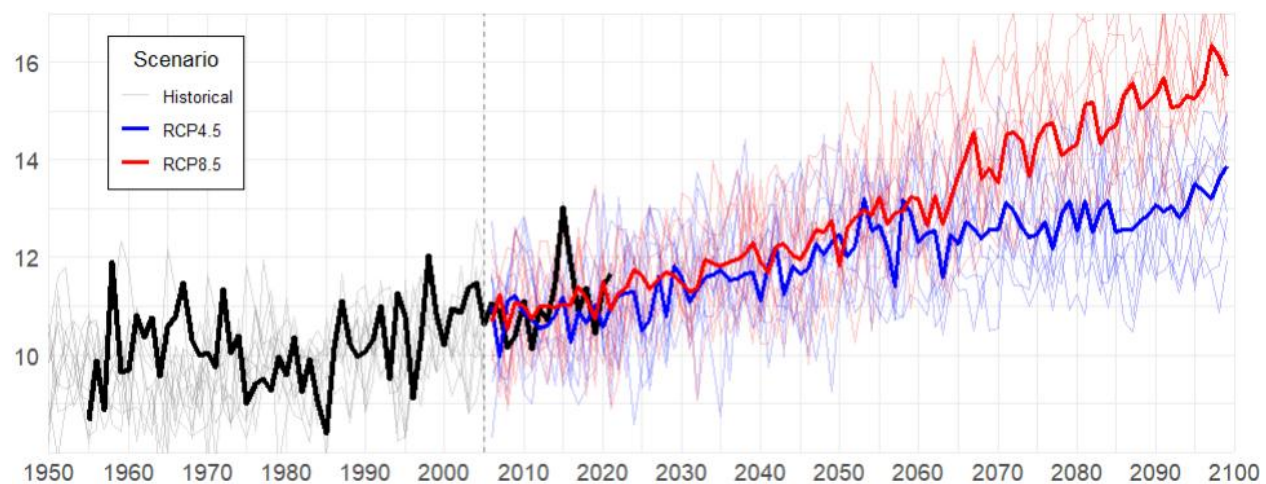


Figure 1. Mean annual air temperature for the Okanagan Region (black: observed; gray, red, blue: GCM projected).

Hydrologic and Watershed Scale Implications

Climate warming is expected to reshape the hydrology of the Okanagan River and its tributary watersheds by reducing snowpack, shifting nival (snowmelt-dominated) watersheds toward pluvial (rainfall-dominated), resulting in earlier peak flows and reduced late-summer discharge. Regionally, summer precipitation is projected to decline by ~14% and snow-derived inputs by ~25% by the 2050s (BC Climate Change Adaptation Program). Seasonal shifts toward warmer, drier summers and milder, wetter winters are indicated across multiple climate projection assessments (RDO 2020).

These hydrologic transitions – particularly declining late-summer flows – are expected to worsen warm-water conditions that already limit Okanagan salmon migration through the Columbia–Okanagan system. A key limiting reach along the route to spawning grounds in the Okanagan River, BC is the Okanogan River (note U.S. river name difference) in Washington State. Long-term monitoring shows that Okanogan River summer water temperatures have been rising since the 1970s–1990s, with more than 80% of dates during

peak migration (July–August) exceeding 20 °C ([Hyatt et al. 2020](#)). A major hydrological influence on water temperatures in the Okanogan River is the Similkameen tributary, which drains into the Okanogan River below Oroville, WA. It contributes 80-95% of lower Okanogan flows in May-June at the start of salmon migration season, driven largely by the influx of spring meltwaters from the Cascade mountain range in Canada, and largely defines the conditions for salmon migration in the lower 115 km of the Okanogan River.

A Critical Knowledge Gap: Projected River Temperatures

While the evidence for rising air temperatures in the Okanogan is substantial and supported by multiple regional climate assessments, much less work has been done to convert meteorological projections into expected river water temperatures, which are a direct determinant of adult salmon migration success.

Only a few studies – primarily focused on historical datasets rather than future projections – have quantified water-temperature responses or examined their impacts on adult Okanogan Sockeye salmon (e.g., [Hyatt et al. 2003](#); [2020³](#); [Fryer et al. 2017](#)). Thermal impact analyses show strong relationships between warm water years and significantly reduced migration success (e.g., an 8.5% survival rate for adult returns to spawners during the extreme warm year of 2015), but they do not provide watershed-specific thermal forecasts under 21st-century climate change scenarios, which represents a critical knowledge gap for fisheries managers. A number of other climate-related papers focus on hydraulic changes in Osoyoos Lake ([NHC 2025a](#); [2025b](#); [2026](#)) or hydrological changes in the Okanogan and Similkameen watersheds (e.g., [Leith and Whitfield 1998](#); [Rayne and Forest 2011](#); [Fleming and Barton 2015](#); [Mirmasoudi et al. 2019](#); [NHC 2021](#)), but do not address riverine water temperature changes during the adult salmon migration season. Without explicit river temperature projections, managers cannot fully evaluate the future risk to adult migrants or identify opportunities for mitigation, such as flow augmentation, habitat restoration, cold-water refugia identification and protection, and harvest management adjustments.

Purpose of this Report

Although atmospheric warming trends are well documented in regional and global climate assessments, there remains a lack of direct linkage between projected air temperature, altered hydrology, and resulting river thermal regimes. This limitation constrains the ability

³ Retrospective (historical) analyses of climate-related changes in water temperature and discharge (1920s - 2018) have been developed for the wild stock's Okanogan River (U.S.) migration corridor (June – September) and the lower Okanogan River spawning grounds (September - October) in British Columbia ([Hyatt et al. 2020](#)).

to assess climate vulnerability for adult salmon migration in the Okanagan/Okanogan river system. Developing such projections is essential for climate-informed fisheries management and long-term conservation planning in the Okanagan watershed. The purpose of this report is to characterize spatial and temporal patterns in water temperature along the terminal migratory pathway for the Okanagan Sockeye aggregate – which returns to the Okanagan watershed in British Columbia, Canada, via the Columbia River and Okanogan River tributary in Washington State, U.S.⁴

To address this objective, we “follow the fish” on their upstream journey through the Okanogan/Okanagan watershed, using existing water temperature monitoring sites at Malott (WA), Oroville (WA) and Oliver (BC) to represent key, distinct “reaches” of the lower and upper Okanogan mainstem in Washington and the lower Okanogan River in BC. Conditions in the lower Similkameen River (WA) were also examined to provide context for tributary influences, for reasons outlined below.⁵ Note that climate-related changes in river discharge, including projected reductions in flow under warmer and drier summer conditions ([RDO 2020](#)), were not explicitly evaluated in this analysis; however, these factors are recognized as important drivers of thermal conditions and may exacerbate the effects of warming trends described herein.

To track the trends in water temperature during the migratory season and associated thermal barrier events, we derive three climate change vulnerability indicators associated with the 22 °C migratory “thermal barrier” threshold for comparison between reference and future time periods:

1. the total frequency of dates when (estimated) daily mean water temperature exceeds 22 °C each year;
2. the duration of the longest annual continuous thermal barrier event (in days); and
3. the onset date of the longest annual thermal barrier event.

⁴ Due to similarities in freshwater life-history timing and geographical distribution, findings in this report likely equally apply to Okanagan summer/fall Chinook salmon populations.

⁵ Data for the upper reaches of the Okanagan River in BC, at Okanagan Falls and Penticton, which represent terminal portions of the migratory route for the Skaha and Okanagan Lake sub-stocks, were also reviewed, but excluded from GCM projection analyses to minimize redundancy, as water temperatures in these short reaches are statistically equivalent to conditions in the lower Okanagan River at Oliver, BC. See METHODS section *Okanagan River Site Comparisons* and RESULTS section *Okanagan River Site Comparative Analysis*.

Study Area

Terminal Migratory Route

The Okanagan Sockeye stock aggregate is comprised of “wild” natural-origin fish that spawn principally in the lower Okanagan River (near Oliver, B.C.) and whose offspring rear in Osoyoos Lake, and hatchery-origin fish⁶ that were released as fry to rear in Skaha Lake beginning in 2004 ([Wright and Smith 2003](#); [Alexander and Hyatt 2015](#)) and/or Okanagan Lake beginning in 2016 ([Bailey et al. 2025](#)). These fish (and their naturalized descendants) return to spawn in the mid- and upper Okanagan River and its tributaries below Okanagan Falls and Penticton (e.g. Shingle Creek)⁷.

Sockeye Salmon return to the Okanagan Basin to spawn after 1-3 years in the Pacific Ocean. On average, >80% of the population of returning adults are 4-year-old fish with the remainder being made up of 3- and 5-year-old fish. Okanagan Sockeye Salmon return to the mouth of the Columbia River in early June to commence the 986 km (about 613 mi) freshwater journey to their spawning grounds. Peak migration past Bonneville Dam occurs by late June/early July (CBR-DART). Travelling at 27-60 km/day in the lower river, and ~30-50 km/day in the mid-Columbia (Quinn et al. 1997; [Fryer et al. 2017](#)), Sockeye Salmon typically take two to three weeks to arrive at Wells Dam, arriving beginning the last week of June or the first week of July ([Hyatt et al. 2003](#)). Migration past Wells Dam generally peaks in mid-July, and continues into August. Fish may hold in the reservoir upstream of the Wells Dam (Lake Pateros, or “Wells Pool”) before migrating into the Okanogan River (Figure 2), particularly if temperatures in the Okanogan River exceed 20-21 °C ([Hyatt et al. 2003](#); [2020](#)).

Sockeye Salmon take 5-7 days to migrate from Wells Dam to Zosel Dam in Oroville (WA) located ~118 km (79 mi) up the 120-km Okanogan River, but migration into the Okanogan may be delayed by at least 2-4 weeks in warm years due to elevated Okanogan water temperatures (*ibid*; [Fryer et al. 2017](#)). Peak Okanogan River flows generally occur in May-June (mean: 250 m³/s; max: 350 m³/s) (Figure 5, top); high spring flow levels (> 200 m³/s) may temporarily delay early migrants ([Hyatt et al. 2020](#)). While snow-pack persists, the cooler waters of the Similkameen River tributary, fed by snow-melt from the east flank of the Cascade Mountain range, suppress water temperatures in the Okanogan River below

⁶ The *kt cpəlk'stim'* Fish Hatchery (Penticton, BC) was built in 2014, and has the capacity to rear and release eight million eggs annually.

⁷ Skaha Lake Sockeye contributions to aggregate Okanagan Sockeye returns in 2008-2021, as enumerated from dead-pitch surveys in all sections of the Okanagan River, ranged from ~4,000 - 54,000 fish, representing a weighted annual average of 26% (range: 6 - 72%) of total Sockeye counts on the spawning grounds ([Bailey et al. 2025](#)).

the Similkameen confluence usually into late June, and sometimes into late July (e.g., 2011), after which, Similkameen temperatures tend to rise rapidly. Temperatures above the confluence, in the last 5-7 km of the river up to Osoyoos Lake, can be 2-3 °C warmer than below the confluence. However, mild winters and/or low snow-pack levels can reduce the Similkameen freshet's cooling influence on lower Okanogan River temperatures (e.g., 2015). Adult migrant Sockeye salmon may take refuge in the slightly cooler Similkameen River when elevated Okanogan River temperature and low flow conditions prohibit movement upstream into Osoyoos Lake ([Fryer et al. 2017](#))⁸.

Once past Zosel Dam, Osoyoos Lake Sockeye salmon hold in the North Basin of Osoyoos Lake for three weeks to three months ([Hyatt and Stockwell 2003](#)), while Skaha Lake Sockeye and Okanogan Lake Sockeye generally continue to migrate upstream into the Okanogan River (BC).⁹

Okanogan Sockeye spawning and juvenile rearing occur exclusively in the Canadian portions of the Okanogan basin ([Bailey et al. 2025](#)). Spawning occurs from late September through October. The primary spawning areas for Osoyoos Lake Sockeye Salmon are a few kilometers upstream of Osoyoos Lake in the Okanogan River near the BC town of Oliver (Figure 2). Skaha Lake Sockeye spawn in the Okanogan River and Shingle Creek downstream of Penticton, BC, and the Okanogan Lake sub-stock spawns in various lake tributaries. Fry emerge the following spring, from late April to early May, and migrate downstream to their respective lakes (Osoyoos, Skaha, and Okanogan) where they rear for usually one, but sometimes two, years before migrating to sea in the spring ([Stockwell and Hyatt 2003](#); [Stockwell et al. 2020](#)).

Okanogan Valley, WA

Okanogan County, in north-central Washington below the Canadian border, has a continental, rain-shadow climate shaped by the Cascade Range to the west and interior plateaus and mountains to the east. The Okanogan Valley is among the driest area in Washington, and similar to the Okanogan region in BC, with warm to hot summers, low humidity, and cold winters featuring large diurnal and seasonal temperature ranges.

⁸ Chinook salmon may also take refuge and spawn in the lower reaches of the Similkameen River, below the Enloe Dam ([Davis et al. 2007](#)).

⁹ The upper channel between McIntyre Dam and Okanogan Falls at Skaha Lake was added to enumeration surveys in 2010 (partial season in 2009) when a retrofit of the water control gates at McIntyre Dam allowed Sockeye passage to the river above Vaseux Lake. Up to 5% of spawning occurs in the Okanogan River upstream of Vaseux Lake. Sockeye salmon that continue migration past Okanogan Falls Dam are considered to be either hatchery-origin or naturalized returns from the Skaha Lake reintroduction program (as of 2009) and the Okanogan Lake reintroduction effort (as of 2019), and are enumerated separately by biologists from the reintroduction program ([Alexander and Hyatt 2015](#)).

Summer daily mean air temperatures at Omak (WA) typically range from 22-24 °C, with maximums over 30 °C (Figure 3, bottom). Annual precipitation is least at low elevations, where semi-arid conditions prevail, and increases with elevation in surrounding uplands and mountain ranges (e.g., the Okanogan Highlands and eastern Cascades), where winter snowpack is substantial and spring snowmelt is a key hydrologic driver ([Washington State Climate Office n.d.](#)).

The Okanogan River in Washington is a snowmelt-dominated system, 127 km in length, with discharge characterized by a pronounced spring freshet driven by meltwaters from the Okanogan Highlands and upstream Canadian headwaters, but principally from the eastern Cascades via the Similkameen River. The Similkameen River provides ~75% of lower Okanogan River discharge volume during the spring freshet (April-May-June) (Figure 5). Peak flows typically occur between April and June, while summer and early autumn are characterized by low flows that are sensitive to interannual variability in the previous winter's snowpack and spring temperature conditions. Because the Similkameen is largely free-flowing and strongly snowmelt-driven, its hydrograph exerts a first-order control on the magnitude and timing of high flows in the middle and lower Okanogan River, influencing flood risk, sediment delivery, and ecological processes downstream, particularly during years of anomalously high or low snowpack. Seasonal discharge is further influenced by regulated outflows from Osoyoos Lake and upstream Canadian sources, as well as irrigation withdrawals and legally established minimum instream flows within Washington's Water Resource Inventory Area (WRIA).

Okanagan Valley, BC

The Okanagan watershed lies within the Okanagan Valley in the Okanogan Highlands. The watershed is bounded by the Cascade Mountains to the west and the Monashee Mountains to the east. The watershed is characterized by a series of lakes joined by rivers in a north-south chain along the valley bottom. At its southern end, Okanagan Lake drains into the Okanagan River which flows through Skaha Lake (1,960 ha), Vaseux Lake (290 ha), and then Osoyoos Lake (2,320 ha) (Figure 2). Osoyoos Lake, at the bottom of the chain, straddles the international border with the United States, and drains into the Okanagan River in WA, which joins the Columbia River, and flows 850 km to the Pacific Ocean near Astoria, Oregon.

The Okanagan region is the second driest in Canada outside of the Arctic. Most of the Okanagan watershed lies within the rain shadow of the Cascade Mountains to the southwest, resulting in a mild, relatively dry climate that varies depending on latitude. Areas in the north end of the valley receive more precipitation and cooler temperatures than areas south of Kelowna. Total annual precipitation may be 30-33 cm; the driest

months (Sep-Oct) contribute, on average, less than 2 cm per month, resulting in a desert-like xeric shrub-land ecosystem, unique in Canada. Dry forests of Ponderosa Pine and grasses can be found at higher elevations. The average daytime temperature in the southern region is about 10 °C (ECCC), which is the warmest in Canada, but slightly cooler than the Okanagan Valley (WA), with summer mean monthly temperatures ranging from 21-22 °C, and maximum daily temperatures of 28-30 °C (Figure 3, top).

The Okanagan watershed is a snowmelt-dominated system, with a spring freshet that occurs from April through June (Figure 5, bottom), accounting for as much as 90% of the annual inflows ([Dobson 2004](#)). By July, the freshet declines and inflows to the system remain very low for the summer, fall, and following winter. Because of the arid to semi-arid climate in the valley, most summer precipitation evaporates or soaks into the ground and does not contribute directly to surface water flow. The wide fluctuations between spring and summer flows are moderated by water regulation at a series of dams in the basin. Penticton Dam at the outlet of Okanagan Lake is the main control point; however, water levels and river flow can be manipulated to a minor extent by adjusting floodgates on dams at Skaha (Okanagan Falls Dam) and Vaseux lakes (McIntyre Dam). Zosel Dam, at the outlet of Osoyoos Lake, is controlled by the Washington Department of Ecology primarily to maintain seasonal target lake levels that are mandated by the International Joint Commission ([Bourget and Claman 1998](#)).

The Okanagan River has been significantly altered by widespread urban and agricultural land “development” and construction of numerous irrigation and flood control dams. Much of the river’s length has been straightened and largely confined to a flood control channel by dikes. Compared to their historic state (pre-1950’s), channel length and aquatic habitat area have been reduced by 53%, and associated wetland area has been reduced by 88% ([Bull et al. 2000](#); [Gaboury 2002](#)). Though environmental restoration and remediation efforts by the Okanagan Nation Alliance since 2000 have begun to mitigate or reverse some of the negative effects (e.g. [Rivard-Sirois 2014](#)), these developments still contribute to reduced flows (e.g., irrigation withdrawals), warmer stream temperatures (e.g., urban run-off, decreased shade) and fragmented aquatic habitat, making the watersheds in the Okanagan more sensitive to climate change impacts ([Nelson & Palmer 2007](#); [Warkentin et al. 2022](#)).

METHODS

Overview

This section describes the process used to translate downscaled global climate model (GCM) air temperature data into daily water temperature estimates at key sites in the watersheds associated with adult Okanagan Sockeye salmon summer migration (Figure 2). We developed a standardized workflow to estimate daily mean water temperature at four individual river monitoring sites and to summarize thermal conditions and trends across historical/reference period (1971-2000) and projected (2010-2099) time periods.^{10,11} For each water temperature site, the workflow:

- (i) downloads and compiles historical and future downscaled air temperature data for ten Global Climate Models (GCMs) and two Representative Concentration Pathways (RCPs) at a nearby meteorological station;
- (ii) additively applies site-specific monthly GCM-specific bias-corrections to the downscaled air temperature data based on overlapping observed air temperature data downloaded from US and Canadian meteorological stations;
- (iii) uses a multi-site generalized additive model (GAMM) to predict site-specific daily mean water temperature from air temperature for each GCM x RCP time-series for reference and future time-periods; and
- (iv) assembles season-specific air and water temperature projections datasets for trend analysis and comparisons among time-periods and emissions scenarios during the summer migration season (Jun-Sep).

Site Selection and Data Sources

Water Temperature (Observed)

Historical observed river temperature data were obtained for six locations from US Geological Survey (USGS) and Water Survey of Canada (WSC)¹² sources: two in the Okanogan River (WA), one in the Similkameen River at Nighthawk (WA), and three in the Okanagan River (BC) (Figure 2, Figure 6 - Figure 8). Following the upstream migration of the fish, the monitoring sites include:

¹⁰ All GCM data acquisition and projection analyses utilized R statistical software ([R Core Team 2025](#)).

¹¹ To promote transparency and reproducibility, all data and code are available at the GitHub repository [SiRE-P/ok_watertemp](https://github.com/sire-ok_watertemp) (https://github.com/sire-ok_watertemp).

¹² Maintained by the Water Survey of Canada (National Hydrologic Services, Environment and Climate Change Canada (ECCC)).

1. Malott (WA)¹³, which we consider representative of the lower 114 km (~95%) of the Okanogan River migratory corridor in Washington State, USA, from the Columbia River to the confluence of the Okanogan and its major tributary, the Similkameen River¹⁴, and which is directly related to adult migration interruptions when river temperatures exceed ~22 °C;
2. Oroville (WA)¹⁵, for the 4.5-km Okanogan River migratory corridor above the Okanogan-Similkameen confluence to Zosel Dam (WA)¹⁶, and beyond the dam to the outlet of Osoyoos Lake (1.5 km) for a total 6 km, which may be up to 4-5 °C warmer than the lower Okanogan;
3. Similkameen River near Nighthawk (WA)¹⁷, representing the lower Similkameen River, a major tributary to the Okanogan River (below Oroville, WA), which has historically contributed cool, snow-melt-driven spring freshets into the Okanogan River during May and June, when Sockeye begin to arrive in the Okanogan migratory corridor, and which often serves as a holding location for migrant Sockeye when temperatures in the “Oroville reach” exceed 22 °C (Hyatt et al. 2020).
4. Oliver (BC)¹⁸ in the lower Okanogan River in BC, downstream of the McIntyre Dam and upstream of Osoyoos Lake, which serves as:
 - a. a migration corridor in summer for hatchery-origin and naturalized Sockeye sub-stocks heading to Skaha and Okanagan lakes, and
 - b. as the principal spawning grounds for Osoyoos Lake Sockeye in the fall;
5. Okanagan Falls (BC)¹⁹ for the mid-Okanagan River (“Skaha Section”) between Okanagan Falls Dam and Vaseux Lake; and:

¹³ USGS gage 12447200 Okanogan River at Malott (WA): Gage datum: 239 m NGVD 1929.

¹⁴ “Lower” Okanogan River (“Malott Reach”) extends from 48.10°N x 119.72°W to 48.89°N x 119.42°W.

¹⁵ USGS gage 12439500 Okanogan River at Oroville (WA): Gage datum: 274 m NGVD 1929.

¹⁶ “Upper” Okanogan River (“Oroville Reach”) extends from from 48.89°N x 119.42°W to 48.93°N x 119.43°W.

¹⁷ USGS gage 12442500 Similkameen River near Nighthawk (WA). Gage datum: 347 m NGVD 1929. Similkameen River (197 km) mean annual discharge: 2,283 cubic feet per second (64.6 m³/s), with a recorded maximum of 45,800 cu ft/s (1,300 m³/s) and minimum of 65 cu ft/s (1.8 m³/s). Basin size: 7,600 km².

¹⁸ WSC station 08NM085 at Oliver, at 49.12°N x 119.57°W; Gage datum: 297 m.

¹⁹ WSC station 08NM116 at Okanagan Falls, at 49.50°N x 119.60°W; Gage datum: 343 m.

6. Penticton (BC)²⁰ for the upper Okanagan River section (“Penticton Channel”) between Skaha Lake and Okanagan Lake, which serves as a migratory corridor for hatchery-origin and naturalized Sockeye sub-stocks that reared in Skaha and Okanagan lakes.

Okanagan River Site Comparisons

Comparative analyses of June–September water temperatures at three Okanagan River sites (Oliver, Okanagan Falls, and Penticton) were conducted to assess whether minor spatial differences (< 35 km between sites; < 45 m elevation difference) in thermal conditions warranted site-specific GCM downscaling and projection analyses. In addition, available water temperature data at the Penticton site were limited to five years, of which only three provided complete coverage for the summer period (Figure 7).

To ensure temporal comparability, only dates with concurrent observations at all three sites were retained. Site–year–month combinations were required to include ≥ 25 days of observations to ensure adequate monthly representation (in fact, all 30–31 days of the month were available for the years and summer months analyzed). As a result of these filtering steps, June and July were represented across multiple years, whereas August and September data were limited to a single year.

Differences in mean water temperature among sites were evaluated using analysis of variance (ANOVA), beginning with a one-way model (site only), followed by models including month and site–month interaction. Interannual variability was incorporated by including year as a fixed effect. To account for year as a source of random environmental variation, a linear mixed-effects model was also fitted with site and month as fixed effects and year included as a random intercept.

Air Temperature (Observed)

Three meteorological stations (Figure 2) were queried for historical air temperature data and associated metadata for:

- Statistically-relating to observed water temperature data for derivation of the site-specific air-to-water temperature conversion model;
- Provision of geo-coordinates for station-based downscaling of GCM grid cell data;
- Monthly climatology data for comparison with downscaled GCM data for GCM-specific air temperature bias correction.

²⁰ WSC station 08NM050 at Penticton, at 49.48°N x 119.60°W; Gage datum: 345 m.

The three meteorological stations employed were all upstream of and within 85 km of the associated water temperature monitoring sites, and include:

1. For the lower Okanogan River (“Malott Reach”), daily air temperature data from Omak (WA)²¹ which is 18 km NE of Malott (WA), 1971-1980, 1992-present;
2. For the upper Okanogan River (“Oroville Reach”) and Okanagan River (BC), daily mean air temperature from the Adjusted and Homogenized Climate Change Data (AHCCD)²² for Oliver (BC)²³, 1971-present. Oliver (BC) is 28 km north of Oroville (WA) on the Okanogan River and within 5 km of the Okanagan River water monitoring site in Oliver (BC);
3. For the Similkameen River, AHCCD from Princeton (BC)²⁴ (1971-present), approximately 83 km northwest and upstream of Nighthawk (WA).

Daily mean air temperatures for each site were selected if provided or, alternatively, derived from the daily minimum and maximum air temperature values. Missing values were linearly interpolated for up to a maximum of three days of missing observations.

Global Climate Model Data

For each meteorological station listed above, statistically-downscaled daily minimum and maximum air temperature time-series (January 1, 1950 - December 31, 2099) were programmatically obtained for the associated grid-cell for each GCM²⁵ from the web data portal²⁶ hosted by the University of California (Merced, CA) Climatology Lab. This facility employs a modified Multivariate Adaptive Constructed Analogs (MACA) method for GCM data downscaling and initial bias-correction to convert the GCMs’ low-spatial-resolution outputs to a higher grid resolution on the ground (Abatzoglou and Brown 2012). A modification of the original MACA method (MACA-v2: Hegewisch & Abatzoglou) has been

²¹ NOAA/NCEI station [Omak USW00094197](#) at 48.46°N x 119.52°W; Elevation: 397 m. Station data exist from 1998-present, and were extended back to 1992 via linear relationship with station Omak USC00456123.

²² ENVIRONMENT AND CLIMATE CHANGE CANADA (ECCC) provide ADJUSTED AND HOMOGENIZED CANADIAN CLIMATE DATA (AHCCD), which incorporate a number of adjustments applied to the original station data to address non-climatological shifts related to changes in instruments and observation locations, conditions, or procedures, thus optimizing the use of these data for climate research (Vincent et al. 2012).

²³ [ECCC station 1125766 at Oliver \(BC\)](#): 49.18°N x 119.55°W; Elevation: 297 m

²⁴ [ECCC station 1126510 at Princeton \(BC\)](#): 49.46°N x 120.51°W; Elevation: 708 m

²⁵ The GCM data are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) analysis.

²⁶ [MACA Statistical Downscaling Method \(https://climate.northwestknowledge.net/MACA/index.php\)](https://climate.northwestknowledge.net/MACA/index.php)

shown to be preferable to other statistical methods which use interpolation for the downscaling in regions of complex terrain such as British Columbia and Washington (*ibid*).

The MACA-v2-LIVNEH²⁷ dataset ([Livneh et al. 2013](#)) was selected as climate forcing data, as this dataset encompasses the entire Columbia River Basin, and is downscaled from the coarse resolution of the native GCM to a high resolution of 16 km². Because GCM outputs employed in the MACA method are natively available at a daily time step, the downscaling procedure addresses spatial resolution and bias correction only, with no additional temporal downscaling necessary (e.g., disaggregation from monthly to daily time-steps).

To obtain a diversity of future climate projections for this study, an ensemble of ten GCMs was selected (Table 1), which account for projected climate change spanning 90% or more of the full set of CMIP5²⁸⁻³⁰ ensemble members for the Western North America (WNA) region²⁹ ([Cannon 2015](#)).

Downscaled minimum and maximum daily air temperature time-series were obtained for each GCM and RCP, and averaged to calculate daily mean air temperature, and organized by model, scenario, and date into 30-year time-blocks associated with a reference period (1971-2000) and three 21st century time-periods (2010-2039, 2040-2069, and 2070-2099). The multi-day moving average air temperature index is calculated from these daily values after GCM data bias-correction procedures (see below).

Model Name	Source	Model Agency	Resolution (Lon x Lat)	Ensemble
BNU-ESM	China	College of Global Change and Earth System Science, Beijing Normal University, China	2.8 deg x 2.8 deg	r1itp1
CanESM2	Canada	Canadian Centre for Climate Modeling and Analysis	2.8 deg x 2.8 deg	r1i1p1
CCSM4	USA	National Center of Atmospheric Research, USA	1.25 deg x 0.94 deg	r6i1p1
CNRM-CM5	France	National Centre of Meteorological Research, France	1.4 deg x 1.4 deg	r1i1p1
CSIRO-Mk3-6-0	Australia	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia	1.8 deg x 1.8 deg	r1i1p1
GFDL-ESM2G	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.5 deg x 2.0 deg	r1i1p1
inmcm4	Russia	Institute for Numerical Mathematics, Russia	2.0 deg x 1.5 deg	r1i1p1

²⁷ The dataset MACA-v2-LIVNEH was produced under the NORTHWEST CLIMATE SCIENCE CENTER (NWCSC) US Geological Survey Grant Number G12AC20495.

²⁸ Phase 5 of the COUPLED MODEL INTERCOMPARISON PROJECT (CMIP5: a framework for coupled ocean-atmosphere general circulation models and Earth system models) included a refined estimate for solar irradiation with corrections for scattering and diffraction ([Taylor et al. 2012](#)).

²⁹ The WESTERN NORTH AMERICA (WNA) region encompasses British Columbia and Washington State ([Giorgi and Francisco 2000](#), in: [PCIC 2014](#)).

Model Name	Source	Model Agency	Resolution (Lon x Lat)	Ensemble
MIROC5	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for	1.4 deg x 1.4 deg	r1i1p1
		Environmental Studies, and Japan Agency for Marine-Earth Science and Technology		
MRI-CGCM3	Japan	Meteorological Research Institute, Japan	1.1 deg x 1.1 deg	r1i1p1
NorESM1-M	Norway	Norwegian Climate Center, Norway	2.5 deg x 1.9 deg	r1i1p1

Table 1. Global Climate Models employed (Source: University of California (Merced) [Climatology Lab](#))

Representative Concentration Pathways

Representative Concentration Pathways (RCPs) are standardized greenhouse-gas (GHG) concentration trajectories developed by the Intergovernmental Panel on Climate Change (IPCC) to represent plausible future climate forcing outcomes driven by societal emissions.^{30,31} Climate forcings for both the historical (1950-2005) and future projections (2006-2099) were drawn from two RCPs³² that bracket the range of trajectories most relevant for contemporary planning ([Fuss et al. 2014](#); [IPCC 2022](#)). Consistent with recent assessments, RCP 4.5 is treated as the more policy-relevant scenario reflecting current emissions trends and mitigation efforts, while RCP 8.5 is retained as a high-end, low-probability bounding case to illustrate potential worst-case thermal exposure ([Hausfather and Peters 2020](#); [IPCC 2022](#)):

- RCP 4.5 – Represents a stabilization pathway under which emissions peak around mid-century and decline thereafter, consistent with a moderate level of global climate mitigation and broadly aligned with current policy trajectories ([Hausfather and Peters 2020](#)).
- RCP 8.5 – Represents a high-emissions pathway in which emissions continue to increase throughout the 21st century in the absence of effective climate policy,

³⁰ The IPCC uses four trajectories of atmospheric greenhouse gas concentration, known as REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) in its Fifth Assessment Report ([IPCC 2013](#)). The four RCPs (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) are named for the ensuing radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 Watts/m², respectively) and are used as input to climate models. For more information on CMIP5 and the RCPs, see: [van Vuuren et al. \(2011\)](#).

³¹ For CMIP6 in IPCC's Sixth Assessment Report (AR6), RCPs have been succeeded by Shared Socioeconomic Pathways (SSPs). RCP 4.5 aligns most closely with SSP2-4.5, a "middle-of-the-road" development pathway, while RCP 8.5 is broadly comparable to SSP5-8.5, which represents fossil-fuel-intensive growth and high emissions. Although CMIP6 models exhibit some differences in climate sensitivity and regional expression, comparisons indicate that CMIP5 RCP-based projections generally fall within the range of CMIP6 SSP outcomes for comparable forcing levels ([IPCC 2013](#); [IPCC 2022](#)). As a result, the qualitative findings and management implications derived here are expected to remain robust under a CMIP6 framework.

³² RCP 2.6 was *not* selected because it represents the range of lowest emissions scenarios – in which global GHG emissions peak between 2010-2020 and decline substantially thereafter. This pathway would have required implementation of stringent climate policies to limit emissions, which, as of 2026, are not feasible under current socio-political conditions. RCP 6.0 was also not selected, as associated projections would most likely be fully bracketed by projections for the two RCPs selected for downscaling in this study, i.e., RCP 4.5 and RCP 8.5.

retained here as a pessimistic but informative upper bound rather than a likely future ([ibid](#)).

Each river monitoring location was paired with the corresponding grid cell from the downscaled MACA GCM archive, for which two temporal categories of air temperature input data were configured:

1. Historical records of modelled daily minimum, mean, and maximum air temperature (1950–2005).
2. Future projections of daily air temperature (2010–2099) under two greenhouse-gas emissions pathways (RCP 4.5 and RCP 8.5).

To enable consistent year-over-year comparisons, leap-year dates were adjusted to form a uniform 365-day calendar (i.e., post-February records in leap years were shifted by one day to remove February 29 while preserving day-of-year continuity). Each daily record was then assigned to one of six analysis periods:

- 1950–1970, 2006–2009 (not used);
- 1971–2000 (historical Reference period, and bias-correction analysis);
- 2001–2005 (included in Omak air temperature bias-correction analyses to extend limited time-series);
- 2010–2039, 2040–2069, and 2070–2099 (future periods).

Air Temperature Bias-Correction

Because gridded GCM outputs can be systematically offset from local conditions, we applied site-specific monthly bias-correction factors specific to each climate model, based on monthly median air temperatures from observed station data. For each calendar month, the correction represented the median difference between modeled and observed daily mean air temperature during a calibration period fitted to the available time-series of station data. These included observed Omak (WA) air temperatures (NOAA/NCEI station USW00094197) from 1992–2005, Oliver (BC) AHCCD air temperature data (ECCC station 1125766) from 1971–2000, and Princeton (BC) AHCCD data (ECCC station 1126510) also for 1971–2000. The month- and model-specific bias correction is applied additively to the GCM's daily mean air temperature to produce a month-specific bias-adjusted daily mean air temperature for each site and climate model. Bias correction estimates are provided in Appendix Table A (Omak), Appendix Table B (Oliver) and Appendix Table C (Princeton).

Generalized Additive Model for Water Temperature

Derivation of Multi-Day Air Temperature Index

Since GCMs provide no water temperature projections, the downscaled, bias-corrected GCM air temperature outputs must be translated into daily mean water temperature with a temperature conversion model, based on observed air and water temperature time-series for each water monitoring site. To reflect the multi-day thermal forcing that governs waterbody heating, we first calculated a 7-day backward-looking rolling mean air temperature index (7d-BMAT) from observed air temperatures, representing cumulative thermal load leading up to each day. Hereafter, we refer to the 7d-BMAT index for *observed* data as T_a .

Site-Specific Air-to-Water Temperature Conversion Model

We modeled site-specific daily mean water temperature (T_w) using a Generalized Additive Mixed Model (GAMM) relating water temperature to (i) local rolling mean air temperature (T_a); (ii) seasonal timing (Julian “day of year”); and (iii) river site, fitted with the historic observations pooled across monitoring sites. For i individual observations, the fitted model can be written as:

$$T_{w,i} \sim \text{Gamma}(\mu_i, \phi)$$

$$\log(\mu_i) = \beta_0 + b_{\text{year}(i)} + f(T_{a,i}, \text{day}_i, \text{site}_i)$$

Where:

- μ_i is the expected daily water temperature for observation i ;
- ϕ is the dispersion (scale) parameter of the Gamma distribution, governing the degree of variability around μ_i ;
- β_0 is the overall intercept on the log scale;
- $b_{\text{year}(i)}$ is a year-specific random intercept capturing residual interannual variability shared across sites and not explained by air temperature or seasonal timing. Some of this variation may reflect other time-varying environmental drivers (e.g., snowpack) that were not explicitly modelled;
- $f(\cdot)$ is a three-dimensional tensor-product smooth, representing site-specific non-linear responses of water temperature to air temperature that vary smoothly over the annual cycle. The day-of-year term captures broad seasonal variation, including differences between spring warming and fall cooling dynamics. This formulation

assumes that the seasonal structure is stable with respect to calendar year, and therefore will not capture shifts in seasonal processes under future conditions.

The GAMM was fit using the `mgcv` R package (Wood 2017; 2024) using restricted maximum likelihood (REML), with a Gamma distribution and a log link. Inter-site heterogeneity in thermal regimes was accommodated using a tensor-product smooth that jointly models air temperature, seasonality, and site identity, allowing for nonlinear and interacting effects across these dimensions. “Day of year” was modeled with a cyclic smooth to enforce continuity at the annual boundaries. “Site” was incorporated within the tensor-product smooth using a random-effects basis, allowing the model to estimate site-specific nonlinear relationships between air temperature, seasonal timing, and water temperature, while enabling partial pooling across sites. Consequently, the model permits variation among sites in (i) baseline water temperature, (ii) sensitivity to recent air temperature forcing, and (iii) seasonal phasing and amplitude. A moving air temperature index based on a seven-day window was used, as this was found to be the most strongly correlated with river temperature while still retaining day-to-day variability (e.g., Mohseni et al. 1998; Hyatt et al. 2015; 2020; Stiff et al. 2015a; 2015b; 2015c). By integrating air temperature over preceding days, this approach smooths short-term variability and approximates the lagged thermal response of water, thereby implicitly representing short-term thermal inertia without explicitly including a lagged water temperature (e.g., Sohrabi et al. 2017; Ulaski et al. 2023). A second smooth was included as a random-effect year term to represent interannual anomalies (e.g., basin-scale climate variability, snowmelt timing, drought) that are not otherwise modeled. This avoids conflating site effects with year-specific departures. The tensor-product smooth used basis dimensions of $k = 9$ for air temperature, $k = 9$ for day of year, and $k = 5$ for site identity. Basis adequacy was verified using standard diagnostic checks.

Model selection

This model was selected from a suite of alternative GAMM structures, which differed in how they accounted for site specificity, treatment of seasonality, and inclusion of random effects. Candidate models included: (i) hierarchical formulations with site-specific smooths of air temperature (factor-smooth interactions), with and without additional seasonal effects represented as categorical interactions; (ii) models allowing fully site- and season-specific smooths via interaction terms; and (iii) an alternative formulation based on a tensor-product smooth of air temperature and day-of-year, with site incorporated as a random-effect modifier of the smooth. Models were also fit with and without a year-

specific random intercept to capture interannual variability. Models were compared using restricted maximum likelihood (REML) and Akaike's Information Criterion (AIC).

In addition to AIC-based comparison of alternative GAMM structures, we evaluated the potential influence of residual temporal autocorrelation by refitting the selected model with an AR(1) correlation structure. Although residual autocorrelation was detected, accounting for autocorrelation did not materially alter the estimated smooth structure or substantive inference. This was assessed based on a comparison of residual autocorrelation functions, visual inspection of the estimated smooth terms, and consistency of the fitted relationships. Given the added complexity of the AR(1) formulation and the absence of meaningful changes in results, the simpler model was retained for subsequent analyses.

Prediction of Daily Mean Water Temperature

For each site, GCM, RCP, and date, the GAMM was applied to the 7-day backwards moving average *projected* GCM air temperature index ($\hat{G}_a$) and day-of-year to generate predicted daily mean water temperature ($\hat{G}_w$) for the historical period and both future RCP scenarios. Predictions honour the site-specific thermal behavior (degree and pattern of warming) learned during model calibration and reflect the multi-day air temperature forcing and seasonal phase for each day. Site-specific depictions of the GAMM-modelled $\hat{G}_w$ as a function of $\hat{G}_a$ can be found for Okanogan River at Malott in Appendix Figure 1; for Okanogan River at Oroville in Appendix Figure 2; for Similkameen River at Nighthawk in Appendix Figure 3; and for Okanogan River at Oliver in Appendix Figure 4.

Climate Change Vulnerability Indicators

Because warm-season conditions are most consequential for adult migration, a seasonal analysis subset was extracted for the months of June to September across the four principal temporal windows (Reference Period: 1971-2000; and Future Periods: 2010–2039 [a.k.a. the “2020s”]; 2040–2069 [or “2050s”]; and 2070–2099 [or “2080s”]). For each climate model and year, mean summer air and water temperature were calculated, which were subsequently averaged across all GCMs to provide the projected ensemble mean summer temperature with model range for lower and upper bounds to illustrate overall summer trends. While the effects of ambient air temperature on salmon health, survival, and reproduction are largely indirect, air temperature projections are included here as they are directly available from GCM downscaling, and provide a trend indicator that is independent of site-specific air-to-water temperature conversion errors. Water temperatures were similarly summarized, but by month, to better reflect timing of

temperature changes, as summer averages mask within-season variation and depress seasonal highs.

Since GCMs do not provide reliable projections for individual years due to internal variability and are typically interpreted over multi-decadal periods (IPCC 2013), GCM outputs were grouped, summarized and tabulated by site, month, RCP and 30-year time-block to provide GCM ensemble median and interquartile range statistics for reference and future period time-blocks.

Thermal Barrier Exposure Indicators

A threshold value of 22 °C was used to denote the occurrence and timing of “thermal barrier events”, which are associated with complete adult salmon migration stoppages. Annual thermal barrier event *frequency*, *duration* and *onset timing* were summarized by site across GCMs to review yearly trends and summarized by 30-year time-block to summarize periodic changes in tables and boxplots. A river temperature threshold of 17 °C was also demarcated on site water temperature plots to indicate potential onset of thermal stress to adult salmonids, but was not statistically evaluated.

The thermal barrier *frequency* index is a simple tally of the annual number of dates during the adult migration period (Jun-Sep) when daily mean temperatures exceeded the threshold.

The thermal barrier *duration* index refers to the annual length in days of the longest continuous run when water temperatures exceeded the threshold. This index provides information beyond a simple tally of exceeded dates across the season, as the latter does not account for ‘breaks’ in the weather pattern and associated water temperature conditions that may be conducive to resumption of migration.

Thermal barrier *onset timing* refers to the annual start date (Julian) of the longest thermal barrier event to track changes in how early in the season migration blockages may occur under projected climate change, relative to the historic period.

Though highly inter-correlated, these indices reflect different aspects of thermal stress impacts on adult migrant Sockeye, in particular how often, how long, and how early in the summer river water temperatures exceed a biologically critical threshold.

RESULTS

Observed Air Temperatures

Summer (Jun-Sep) minimum, mean, and maximum air temperatures (1971–2000) show pronounced warming at Omak (WA), moderate increases at Oliver (BC), and little change at Princeton (BC) (Figure 4). Trends are strongest at Omak, particularly in maximum ($+1.55\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.002$) and mean ($+0.79\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.002$) temperatures, while Oliver exhibits moderate warming in mean temperature ($+0.43\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.01$); trends at Princeton are weak and non-significant (Figure 4A).

Linear trends ($^{\circ}\text{C decade}^{-1}$) in minimum, mean, and maximum temperature indices confirm strong warming at Omak (for maximum and mean; $p < 0.01$), moderate but largely non-significant increases at Oliver, and negligible or slightly negative trends at Princeton (Figure 4B). Warming at Omak appears greatest for maximum air temperatures, while warming at Oliver appears highest for minimum temperatures. However, it should be noted that the Omak air temperature time-series for the reference period (1971-2000) is incomplete, with observations limited to 1971-1980, 1992-1994, 1996-2000), which may influence trend analysis.

Observed Water Temperatures

Okanogan River at Malott, WA

Monthly mean observed water temperatures in the “lower” Okanogan River near Malott, WA (downstream of the Similkameen River confluence) ranged from $16 \pm 3\text{ }^{\circ}\text{C}$ (mean $\pm$ standard deviation [SD]) in June to $23 \pm 3\text{ }^{\circ}\text{C}$ in July and August for the years 2008-2021 (Table 2; Figure 5, top). Peak stream flows generally occur in May-June (mean: $250\text{ m}^3/\text{s}$; max: $350\text{ m}^3/\text{s}$), driven largely by the influx of spring meltwaters from the Similkameen River tributary, which contributes up to 80-90% of lower Okanogan flows at this time of year (Figure 5). An evident temperature-suppression effect from the cool meltwaters of the Similkameen spring freshet on Okanogan River water temperatures below the confluence is therefore apparent in May and June in the Okanogan River’s thermal climatology (Figure 8, top), in contrast to the upper Okanogan River at Oroville, above the Similkameen confluence (Figure 8, middle). As a result, the lower Okanogan River appears to be significantly cooler in May and June than other Okanogan/Okanogan mainstem stations in this study (Figure 9).

Okanogan River at Oroville, WA

The aquatic thermal climatology of the “upper” Okanogan River at Oroville (located upstream of the Similkameen River confluence) contrasts distinctly with the lower Okanogan River at Malott (downstream of the Similkameen River confluence) in May and June (Figure 6, middle), and the pattern of warming/cooling more closely resembles the thermographs of the lower Okanogan River in Canada (Figure 8). Due to receiving the warm surface outflows of Osoyoos Lake, the Okanogan River at Oroville tends to be the warmest river location in the study area. Upper Okanogan water temperatures are 3-4 °C warmer than the lower Okanogan in June, and can be 1-2 °C warmer in July, August, and September (Figure 9).

Monthly mean observed water temperatures in the upper Okanogan River at Oroville ranged from 17-22 °C in June (mean 19.9 ± 2.2 °C) and ranged from 23-26 °C in July and August (mean 23.5 ± 1.8 °C) for the years 2005-2021 (Table 7). Mean water temperatures in July in recent ‘hot years’ of 2014, 2015, and 2021 exceeded 25 °C. Mean monthly water temperatures in September remain warm in most years, ranging from 18-21 °C (mean 19.5 ± 1.8 °C), before falling to more optimal temperatures of 13-15 °C in October.

Similkameen River at Nighthawk, WA

Observed temperature data in the lower Similkameen River data (2014-2021; Figure 6) reflect the seasonal variation in monthly mean water temperatures due to the spring freshet effect (Figure 8). Monthly mean Similkameen River temperatures ranged from 11-17 °C in June (mean 14.0 ± 3.0 °C), while temperatures in July and August, after the freshet has subsided, ranged from 17-22 °C (mean 19.5 ± 2.0 °C) (Table 12). By September, water temperatures fall back to 14-16 °C (mean 15.6 ± 2.0 °C).

Okanagan River at Oliver, BC

Monthly mean observed water temperatures in the lower Okanagan River near Oliver, BC ranged from 17-22 °C in June (mean 18.1 ± 2.5 °C) and ranged from 20-25 °C in July and August (mean 22.3 ± 1.7 °C) for the years 2008-2021 (Figure 7, top; Table 17). Mean water temperatures in July in recent ‘hot years’ of 2014, 2015, and 2021 exceeded 23-24 °C (Table 17). Mean monthly water temperatures in September remain warm in most years, ranging from 17-20 °C (mean 18.1 ± 1.8 °C), before falling to more optimal ranges of 11-14 °C for salmon in October.

Okanagan River at Okanagan Falls, BC

Monthly mean temperatures for the mid-Okanagan River (or “Skaha Section”) ranged from 17-22 °C in June (mean 18.1 ± 2.4 °C) and ranged from 20-24 °C in July and August (mean

22.3 ± 1.5 °C) for the years 2003-2016 and 2019-2021 (Figure 7, middle; Table 22). Mean water temperatures in July in ‘hot years’ of 2014, 2015, and 2021 exceeded 23-24 °C. Mean monthly water temperatures in September remain warm in most years, ranging from 17-20 °C (mean 18.5 ± 1.8 °C), before falling to more optimal ranges of 11-14 °C for spawning in October (mean 13.1 ± 2.0 °C).

Okanagan River at Penticton, BC

Limited water temperature data were available (2016, 2018-2021) for the upper Okanagan River at Penticton (i.e., “Penticton Channel”). Annual thermographs indicate that daily mean temperatures at this location are influenced by Penticton Dam operations (Figure 7, bottom).

Monthly mean Penticton Channel temperatures for available data ranged from 16-20 °C in June (mean 17.7 ± 2.8 °C), with highs in 2019 (mean 20.2 ± 1.8 °C). and ranged from 20-24 °C in July and August (mean 22.3 ± 1.5 °C) for the years 2003-2016 and 2019-2021 (Table 23). Mean water temperatures in July in recent ‘hot years’ of 2014, 2015, and 2021 exceeded 23-24 °C. Mean monthly water temperatures in September remain warm in most years, ranging from 17-20 °C (mean 18.5 ± 1.8 °C), before falling to more optimal ranges of 11-14 °C for spawning in October (mean 13.1 ± 2.0 °C).

Okanagan River Site Comparative Analysis

ANOVA results based on coincident dates of observed daily mean water temperature indicated significant differences between months for all Okanagan River sites (Oliver, Okanagan Falls, and Penticton; $p < 0.001$): temperatures increased from June to peak conditions in July–August and declined in September (Table 24). Interannual variation was also significant ($p < 0.001$), indicating differences in thermal conditions among years. In contrast, there was no consistent evidence of differences in mean temperature among lower, mid- and upper Okanagan River sites after accounting for seasonal and interannual effects ($p > 0.05$). The site–month interaction was weak overall ($p > 0.11$), although a mixed-effects model identified a modest increase in August temperature at Penticton relative to upstream sites ($p < 0.02$; Table 25).

This late-summer effect was not consistent across months and is based on observations from a single year (2020; Table 24), and therefore should be interpreted cautiously. Potential factors contributing to this localized increase include year-specific hydrological and weather conditions, and/or operational influences associated with Penticton Dam leading to differences in residence time and solar exposure in the forebay and upper river reach. In particular, regulation of outflows from Okanagan Lake may alter proximate thermal conditions by modifying flow volume, timing, and water source depth, with effects

that can vary among years depending on lake stratification and prevailing climatic conditions. These factors may amplify warming during peak summer periods in certain years but do not appear to drive consistent spatial differences among sites.

Overall, results indicate that seasonal and interannual variation are the primary drivers of temperature patterns in the study area, with only limited and episodic spatial differentiation among sites.

These findings indicate that thermal conditions in the lower, mid- and upper Okanagan River are largely consistent across sites when evaluated over comparable time periods, and that observed differences are primarily driven by seasonal and interannual variability rather than persistent spatial gradients. Because observed temperatures are spatially uniform across reaches, projections for the mid- and upper Okanagan River can reasonably be assumed to be equivalent to those for the lower reach, with no expected difference in resulting biological exposure or response under future climate scenarios. As a result, there is limited justification for developing separate GCM downscaling and projection analyses for the mid- and upper Okanagan River reaches located within 35 km of each other, and GCM projection analyses were not performed for these reaches.

Air-Water Temperature Conversion GAMM

Overall goodness of fit was high for the selected air-water temperature GAMM, explaining 86.5% of the deviance in daily mean water temperature (adjusted $R^2 = 0.98$; $N = 1,538$). The tensor-product smooth had an effective degrees of freedom of approximately 76, indicating substantial data-driven flexibility that remained well within the imposed basis constraints.

GCM Projections

Okanogan River at Malott (WA)

The median air temperature projection for the Omak/Malott region indicates ~1-1.4 °C warming to the present period (2010–2039), ~2.4-3.1 °C by mid-century, and ~3.2 °C (RCP4.5) to ~5.7 °C (RCP8.5) by late century across Jun–Sep, with August warming the most (Table 3; Figure 10, top; Figure 11A). This pattern is consistent with stronger summer warming and a growing divergence between emissions pathways later in the century.

Consequently, minimum, median, and maximum summer water temperatures in the lower Okanogan River at Malott have risen by about +0.8 to +1.1 °C to the current period, and are projected to increase roughly +1.5 to +3.0 °C by mid-century, and about +1.8 to +2.9 °C by late-century under RCP4.5 versus +3.0 to +5.8 °C under RCP8.5 (Table 4; Figure 10, bottom; Figure 11B). The largest increases generally occur in July/August, for which the model

maximums increase the most – reaching +5-6 °C by late-century under RCP8.5 – indicating hotter peaks and a higher likelihood of very warm river conditions.

Models suggest, on average, water temperatures in June should not rise much above 17 °C until late in the century, especially if society can limit emissions to the RCP 4.5 scenario, or better (Figure 12). However, on average, water temperatures in July will likely exceed the 22 °C threshold for most of the month by the 2040s, which is already occurring for most of August now (Table 4).

With rising temperatures, the frequency of summer dates when mean daily water temperature exceeds 22 °C has also risen (Figure 14A). In the lower Okanogan, the frequency in June has been historically low, and remains low, on account of the temperature suppression effect from Similkameen River spring freshet (Figure 14, top). After Similkameen inflows subside however, 30-50% of the months of July and August have historically exhibited temperatures exceeding the 22 °C threshold (Figure 14, middle) – and future projections indicate a rising trend to the point where, depending on RCP trajectory, 75-100% of the dates in July and August will be in exceedance.

GCM outputs indicate that the thermal barrier onset date at Malott has shifted earlier relative to the Reference period. Historically the median onset date was July 25; it has advanced by ~5 days to the present, and possibly ~9–13 days by mid-century (July 11 – July 7), depending on RCP trajectory (Figure 13C). By late-century, the onset date could commence ~July 12 (RCP4.5) and ~July 3 (RCP8.5), with earliest years occurring in late June under RCP8.5 (Table 5; Figure 15A).

The longest annual thermal barrier events in the lower Okanogan typically lasted ~21 days (three weeks) in the Reference period (range 16-27 days) (Table 6; Figure 13B). In the current time period (2010-2039), the median event length is ~34 days (approx. 5 weeks), and is expected to rise to 41-50 days by the 2050s (6-7 weeks), depending on RCP pathway. Under the worst case RCP 8.5 scenario, 50% of GCM models indicated thermal barriers would last 66-81 days (9-12 weeks) (Figure 15B).

Okanogan River at Oroville (WA)

Projected air and water temperatures in the upper Okanogan River near Oroville, WA likewise show a clear warming trend through the 21st century, with summer (June-September) air temperatures increasing by roughly +1 to +1.5 °C in the early-century period, rising to +2 to +3 °C by mid-century, and reaching +4 to +6 °C under RCP8.5 by late-century, with the largest warming in July and August (Table 8; Figure 16 (top); Figure 17A).

Water temperatures in this lake-influenced reach – already warm historically (22–23 °C in midsummer) – correspondingly rise steadily, increasing by +0.4 to +0.8 °C in early-century, +1.1 to +2 °C by mid-century, and +1.5 to +4 °C by late-century depending on the emissions scenario, with the strongest warming again in late summer months (Table 9; Figure 16 (bottom); Figure 17B).

Projected water temperature changes follow the same trend as at Malott, but the upper reach of the Okanogan at Oroville is relatively warmer in all months, particularly in June (Figure 18), because it does not benefit from the moderating influence of the cooler Similkameen River during the spring freshet (see Figure 8). While baseline (1971-2000) water temperatures near Malott are ~14 °C, June water temperatures at Oroville are ~19 °C, approximately 4-5 °C warmer (*cf.* Table 4 vs. Table 9). The magnitude of seasonal warming is similar between the two locations, but absolute water temperatures near Oroville start higher earlier in the season (Figure 18; Table 9). The upper reach remains substantially warmer in all future periods, causing adverse thermal conditions (≥ 22 °C) to occur earlier, more frequently, and persist longer in the upper reach than in the lower river as the climate warms (Figure 19ABC; Figure 20).

Historically (1971–2000), the median onset date of the thermal barrier in the Oroville reach was 16 July (Table 10; Figure 21A). Under climate change:

- 2010–2039: Median onset advances to 10 July (RCP4.5) and 9 July (RCP8.5) – a shift of about one week earlier.
- 2040–2069: Median onset shifts to 3 July (RCP4.5) and 1 July (RCP8.5).
- 2070–2099: Median onset reaches 4 July (RCP4.5) and 22 June (RCP8.5), with earliest model years starting as early as 11–16 June.

This shows a clear shift of the thermal barrier into late June, more than two weeks earlier than the historical baseline, unless the emissions trajectory can be limited to RCP 4.5 or better (Figure 19C).

During the reference period, the median duration of the longest continuous thermal barrier events at Oroville was 36 days (Table 11; Figure 21B). Future projections show further lengthening, with median durations roughly doubling relative to the reference period by the end of the century between RCPs 4.5 and 8.5 (Figure 19B):

- 2010–2039: 50 days (RCP4.5) and 51 days (RCP8.5);
- 2040–2069: 62 days (RCP4.5) and 68 days (RCP8.5);

- 2070–2099: 65 days (RCP4.5) and 85 days (RCP8.5), with extreme years reaching 105 days.

Similkameen River at Nighthawk (WA)

The Similkameen River is the coolest river of its size in the Okanogan watershed, especially in June, when water temperatures range from 13-16 °C (2010-2039; Table 14), approximately 4-5 °C cooler than the Okanogan at Oroville (*cf.* Table 9). Post-freshet, waters can exceed thermal stress levels for salmon, however: July and August median estimates currently reach 19-20 °C, and are anticipated to increase by +1-2 °C by the 2050s, depending on RCP pathway (Figure 22B; Figure 23B).

Thermal barriers have not, heretofore, been an issue for Okanogan-bound salmon migrants forced to hold in the lower Similkameen. Historically, temperatures exceeding 22 °C have not generally occurred until mid-August, and then only for 3 or 4 days (Table 15; Figure 24), by which time the thermal barrier at the mouth of the Okanogan has been set up for weeks (*cf.* Table 5). GCM projections suggest that by the 2050s, thermal barrier events in the Similkameen may become more common in July/August, and, by the 2080s, prevalent in those months under the RCP8.5 scenario (Figure 25, top; Figure 26).

Despite that, the median onset date for the annual longest continuous thermal barrier event has advanced more than 10 days, relative to the reference period, into the first week of August (though with wide variance), and is anticipated to advance another week by the 2050s under either emissions scenario, and yet another 10-14 days earlier by the 2080s under RCP 8.5 (Figure 25C; Figure 27A). The maximum duration of thermal barrier events, currently about 7-9 days, will approach (RCP 4.5) or exceed (RCP 8.5) two weeks by the 2050s (Table 16; Figure 25B; Figure 27B). Should the worst-case scenario unfold, temperatures inhospitable to Sockeye salmon may occur in the first week of July, and last more than a month, reinforcing the importance of preserving hospitable Similkameen conditions during June for brief holding periods.

Okanagan River at Oliver (BC)

Historical summer conditions (1971–2000) in the lower Okanagan River (BC) allowed salmon to migrate – on average – through June and early July, with median mid-summer water temperatures of ~21.4-21.7 °C, i.e., warm but – on average – below the 22 °C migration-blocking threshold (Table 18; Table 19; Figure 28B).

By the current period (2010–2039), summer warming has already crossed a critical threshold. July–August median temperatures have reached 22.2–22.4 °C under both RCP 4.5 and RCP 8.5, exceeding the 22 °C barrier frequently enough to impair adult migration (Figure 30). By mid-century (2040–2069), July–August medians will reach

~23.0±1.0 °C (regardless of RCP), maintaining temperatures above the migration-blocking threshold for prolonged periods (Table 19). June and September currently remain tolerable for migration. June median temperatures remain in the 17–18 °C range across scenarios – below high stress levels – while September temperatures generally fall to < 20–21 °C as the month proceeds.

While slightly cooler than the Okanogan River at Oroville (WA), the lower Okanogan River at Oliver in BC also warms steadily from June onwards. As regional climate warms, thermal conditions adverse to migration (≥ 22 °C) will occur more frequently, and persist longer, and develop sooner in the season (Figure 31ABC; Figure 32).

The onset timing of thermal barriers has advanced at least 5 days to 18 July (RCP 4.5) and 14 July (RCP 8.5) (Figure 31C), with median length of thermal barrier increasing from ~20 days historically to 32–35 days currently (Table 20; Table 21; Figure 31B). These changes already render much of July–August impassable to migrating salmon (Figure 32). By the 2050s, median onset timing will shift another minimum five days earlier into the first two weeks of July and persist 6–7 weeks. Under RCP 8.5, late-century warming may shift thermal barriers into late June with median durations of ~72 days (range 53–96 days; Table 21), creating near-complete blockage of the summer migration corridor (Figure 33AB).

DISCUSSION

System-wide Patterns In Projected Thermal Change

Results from this GCM analysis indicate a common warming signal over the 21st century along the adult salmon migratory route in the Okanogan–Okanagan system mainstem and its major tributary, the Similkameen River. The projected trends are directionally consistent with observed historical warming in the Okanogan basin over the 20th century (~1 °C rise, accelerating since the 1950s; [PCIC 2013](#)). Although absolute temperatures and timing differ among river sites, projected changes exhibit a shared structure: summer air temperatures increase progressively through the century, with the largest warming occurring in July and August, and these changes translate into the aquatic environment as elevated river temperatures, earlier development of thermally stressful conditions, and earlier onset and longer durations of thermal barriers to upstream migration.

Throughout this report, projections under RCP 4.5 are emphasized as representing the most policy-relevant and plausible near- to mid-term emissions trajectory, while RCP 8.5 is presented as a low-likelihood, high-impact scenario to illustrate the upper bound of potential thermal risk. Differences between scenarios are modest in the early part of the

century but diverge substantially by mid- to late-century, particularly for peak summer temperatures and thermal barrier duration.

Interpreting results in this way helps distinguish those changes that are already emerging or likely within current planning horizons from those that would occur only under sustained high-emissions futures, while still acknowledging the risks associated with delayed or ineffective climate mitigation. Our additive bias-correction factor assumes that bias between GCM and air temperatures does not change over time. We could not fully assess this in the historical dataset because of decadal-scale natural variability and the relatively short time series.

Spatial Gradients and the Role of Basin Structure

Our analyses highlight a strong spatial structure in thermal vulnerability within the Okanogan/Okanagan river system. Upper reaches influenced mainly by lakes are consistently warmer than downstream riverine segments in the “lower” Okanogan – below the Similkameen confluence – and display adverse thermal conditions earlier in the season. Historically, downstream reaches benefited from cooling associated with the Similkameen tributary inflows, particularly during the spring freshet. These inputs delayed the onset of high summer temperatures and moderated thermal conditions in the lower 95% of the Okanogan River during early summer migration periods.

However, projections suggest that the buffering role of Similkameen inflows is temporally limited. As summer progresses and freshet contributions subside, the downstream reaches of the Okanogan River warm rapidly and increasingly resemble thermal conditions in the “upper” Okanogan above the Similkameen confluence. Under future climates, this seasonal convergence is projected to intensify, reducing spatial heterogeneity and limiting the availability of cooler downstream passage corridors during mid-summer. Hydro-climatological modelling undertaken on the Similkameen River basin ([NHC 2021](#)) forecasted a shift from a system dominated by the spring freshet, with low flows in winter and late summer, to a mixed hydrologic regime, with a diminished freshet, higher winter flows and lower late summer flows.

Temporal Shifts in Migration Opportunity

A key finding from these GCM projections is the systematic advancement of thermal barrier onset and the lengthening of thermal barrier duration at all sites considered. Historically, adult salmon migration through the system was generally feasible through much of June and early July, with thermal barriers to migration developing later in summer and persisting for shorter periods.

Across the Okanogan/Okanagan main stem, the onset of thermally restrictive conditions for adult salmon migration has advanced by approximately one week on average between the Reference Period and the current period (2010–2039), with site-specific advances ranging from about 5 to 9 days. This relatively modest but consistent shift indicates that earlier seasonal establishment of migration barriers is already underway, even prior to the larger advances in onset timing projected for mid- and late-century periods. Notably, the barrier onset timing in the upper Okanogan “Oroville reach” above the Similkameen confluence is setting up 10 days earlier than in the lower Okanogan, with June water temperatures up to 3-4 °C warmer than below the confluence, adding significant thermal stress to migrants or presenting an impassable barrier at elevated temperatures, forcing fish to delay and stray into the Similkameen for thermal refuge.

Projected warming results in three related changes:

1. Earlier onset of mainstem conditions exceeding established migration thresholds, both in the lower and upper Okanogan reaches, generally shifting from late July into early July or late June;
2. Substantial increases in the duration of continuous thermal barrier events, particularly under higher GHG emissions scenarios; and
3. Delayed seasonal relief, such that cooling sufficient to permit migration is increasingly confined to September.

Collectively, these trends indicate a compression of the effective migration window, with progressively less opportunity for migration during mid-summer and correspondingly greater reliance on early- and late-season passage, likely leading to the development of a bi-modal return pattern. Sustained differences in timing across generations could ultimately produce two distinct run-timing sub-populations, with implications for genetics, management, and harvest ([Hinch and Martins 2011](#); [Martins et al. 2012](#)).

Increasing Prevalence of Chronic Thermal Stress

In addition to changes in timing, the results indicate a transition from predominantly episodic thermal exceedances to more persistent and widespread exposure to elevated temperatures. Future summers are characterized not only by higher mean temperatures but also by more extreme peaks and a greater proportion of days exceeding biologically relevant thresholds.

From a biological perspective, this shift increases the likelihood that adult salmon will experience chronic thermal stress, rather than brief exposure that may have been tolerable under historical conditions. Persistent exposure at or above stress thresholds has been

found to elevate metabolic costs, reduce aerobic scope, increase susceptibility to disease, and negatively impact reproductive success, particularly when combined with other stressors such as low flows or crowding in holding areas ([Lee et al. 2003](#); [Farrell 2009](#); [Crossin et al. 2008](#); [Burnett et al. 2014](#)). These effects are expected to increase in frequency and severity over time, especially under higher emissions pathways ([van Vuuren et al. 2011](#); [IPCC 2022](#)).

Tributaries as Conditional Thermal Refugia

The Similkameen River emerges as a vital cooling component of the system, particularly during early summer, and thus retains critical importance as both a temperature-suppression driver for the lower 95% of the Okanogan River and a short-term holding or staging area for migrants. [Leith and Whitfield \(1998\)](#) documented a historical trend in the Similkameen toward earlier onset of snowmelt runoff followed by low summer flows between 1973-1995. Though projections suggest that this tributary will continue to provide comparatively favorable migration conditions in the lower Okanogan River during June for at least part of the century, the Okanogan's vulnerability to climate warming may be foretold by the river's hydro-thermal conditions in 2015, when a mild winter and low snowpack in the region resulted in a reduced Similkameen spring freshet, corresponding to elevated temperatures and thermal blockages in the lower Okanogan in mid-June – and Sockeye survival from Wells Dam to the Okanogan spawning grounds was 8.5% ([Fryer et al. 2017](#); [Hyatt et al. 2020](#)).

The GCM analysis further indicates that the thermal refuge function of the Similkameen is neither static nor guaranteed. Under warmer future climates, elevated temperature events are projected to occur more frequently and earlier in the season in the Similkameen as well, reducing the temporal reliability of the Similkameen refuge, and its moderating effect on temperatures in the lower Okanogan. Thus, by late century under high emissions scenarios, conditions inhospitable to migration in the lower Okanogan may develop substantially earlier and persist longer than observed historically. Furthermore, the Similkameen refugium serves no purpose if conditions in the tributary warm beyond thermally-stressful thresholds before the Okanogan cools enough to allow passage. This possibility underscores the importance of preserving early-season thermal conditions and minimizing additional thermal loading.

Implications for Adult Salmon Migration and Population Viability

Taken together, these projections suggest several implications for adult salmon migrating through the Okanogan–Okanogan system. First, successful migration is likely to become increasingly dependent on early-season timing, with reduced tolerance for delayed entry

(Cooke et al. 2004; Salinger and Anderson 2006; Hinch and Martins 2011; Farrell 2009). Second, prolonged periods of thermal blockage may increase the need for holding behavior in Okanogan mainstem thermal refugia (of currently unknown frequency and location) or tributary habitats, potentially increasing density-dependent stress, disease risk, and pre-spawn mortality (Hinch and Bratty 2000; Crossin et al. 2008; Hinch and Martins 2011; Burnett et al. 2014). Third, selective pressures against later-migrating phenotypes may intensify, with potential negative consequences for life-history diversity and population resilience (Schindler et al. 2008; McDaniels et al. 2010; Martins et al. 2012). Sustained compression of migration periods into June and September could promote bi-modal run timing (Schindler et al. 2008; Hyatt et al. 2020, Potapova et al. 2025), with potential long-term consequences for genetic structure, harvest management, and population resilience – transforming a behavioural response into a demographic and evolutionary outcome (Schindler et al. 2008; McDaniels et al. 2010; Martins et al. 2012).

Under higher emissions scenarios, up-river segments are projected to experience near-continuous thermal barriers through much of the summer, effectively transforming portions of the migration corridor from seasonally restrictive to functionally impassable during critical periods. In contrast, more moderate scenarios indicate that, while constraints still increase, early-season migration opportunities and localized refugia should persist longer, suggesting some scope for adaptive management.

Implications of Thermal Barriers for Canadian Sockeye Harvest

Earlier and increasingly persistent thermal barriers in the Okanogan River have the practical effect of reducing or eliminating viable Sockeye salmon harvest opportunities in Canadian waters for Indigenous Food, Social, and Ceremonial (FSC) and recreational fisheries. Climate-driven delays in upstream passage through the U.S. migration corridor increasingly shift arrivals into the Okanogan River (BC) from mid-summer into late summer or early autumn (Hyatt et al. 2020), precluding access during historically important harvest periods and effectively reducing realizable harvest independent of run size (e.g., 2015, 2021, 2025 (unpub. Data: K. Ryde, DFO Fish. Mgr.)).

Fish that eventually arrive in the fall are often in advanced stages of maturation or have experienced prolonged thermal exposure and holding, resulting in degraded condition and reduced suitability for brood-stock egg-takes (pers. comm. R. Benson, ONA Fish. Biol., ONA) and harvest (Cooke et al. 2004; Fryer et al. 2017). Under the Wild Salmon Policy (DFO 2005), this represents a climate-driven reduction in effective productivity and access that should be considered a systematic source of uncertainty rather than an episodic anomaly (Irvine 2024). Consistent with the Precautionary Approach (DFO 2009), projected climate-driven losses of realizable harvest opportunity should be treated as an additional,

non-stationary source of uncertainty when evaluating conservation risk, productivity benchmarks, and harvest planning assumptions.

Uncertainty, Assumptions and Management Implications

Model Uncertainty and Interpretation of Projections

Projected changes in thermal barrier onset and duration reflect several interacting sources of uncertainty related to climate variability, climate model divergence, and model structure.

At near-term horizons (2010–2039), uncertainty is driven primarily by interannual climate variability, including fluctuations in summer weather patterns, discharge, and the timing of freshet recession ([Whitfield 2001](#); [Fleming and Whitfield 2010](#); [Mantua et al. 2010](#)). While ensemble median trends are consistent across models and sites, individual years may diverge substantially from projected conditions. For this reason, summaries over 30-year periods provide a more robust and interpretable representation of system behaviour than year-specific outputs ([Taylor et al. 2012](#); [Cannon 2015](#)).

At mid- to late-century time horizons, uncertainty increasingly reflects differences among global climate models and emissions pathways, as well as their interaction with hydrological processes ([Giorgi and Francisco 2000](#); [van Vuuren et al. 2011](#); [IPCC 2022](#)). Projected changes in snowmelt timing, summer low-flow development, and tributary cooling effects – none of which are explicitly resolved in the modelling framework – can amplify divergence among model outputs ([Mote and Salathé 2010](#); [Zwiers et al. 2011](#)). Small differences in projected air temperature or discharge timing can therefore translate into substantially larger differences in estimated thermal barrier onset. Accordingly, projections are best interpreted as plausible ranges of future conditions, with greater confidence placed on the direction and relative magnitude of change than on precise timing for any given year.

Model Structure and Key Assumptions

This analysis assumes that the empirical relationship between air and water temperature remains stationary over time. The GAMM framework captures nonlinear responses to air temperature and seasonality and accounts for site- and year-level variability, but it does not explicitly represent key physical drivers such as discharge, groundwater exchange, channel morphology, or reservoir operations. In regulated salmon-bearing rivers typical of British Columbia, these processes strongly influence thermal regimes by controlling heat fluxes, flow, and spatial heterogeneity through hyporheic exchange and floodplain connectivity ([Poole and Berman 2001](#)). Consequently, they are only indirectly represented

through historical correlations, which may limit model transferability under changing hydrologic or management conditions.

If these relationships shift—for example, due to declining snowpack, earlier freshet, or altered flow regulation—projected water temperatures may be biased. Discharge is a key control, as streamflow modulates thermal sensitivity to air temperature ([Toffolon and Piccolroaz 2015](#); [Leach and Moore 2019](#)): lower flows tend to amplify warming, whereas higher flows buffer temperature extremes ([Caissie 2006](#); [van Vliet et al. 2013](#)). Reservoir operations can further modify these effects by altering the volume and temperature of downstream releases, effectively resetting thermal boundary conditions ([Olden and Naiman 2010](#); [Daniels and Danner 2020](#)). Accordingly, changes in flow regime and regulation may either amplify or dampen projected warming, depending on how future conditions diverge from the historical record.

Spatial Representation and Scaling

Additional uncertainty arises from the spatial representation of both climate forcing and river temperature. Air temperature inputs are derived from meteorological stations located up to ~85 km from river sites (i.e., between Princeton BC and Nighthawk WA), while water temperature observations are treated as representative of broad migration corridors (e.g., water temperatures from Malott WA representing Okanogan River conditions from the Columbia River up to the Similkameen confluence). This approach does not resolve fine-scale spatial heterogeneity, including localized cold-water refugia or reach-specific warming patterns. Future research should prioritize identifying the mainstem and tributary sources of these localized influences to enhance our understanding of the fine-scale spatial heterogeneity in river temperature dynamics.

The use of a 7-day rolling mean air temperature index further assumes a consistent thermal response timescale across sites and future conditions. While this improves representation of cumulative atmospheric forcing, it may dampen short-term variability and underestimate acute thermal extremes that can still be biologically important.

These limitations may be particularly important in systems such as the Similkameen River, where upstream source regions and local climatic conditions are not well captured by available station data ([McKenney et al. 2011](#)). Similarly, projections for mid- and upper Okanogan River reaches in BC are assumed to be equivalent to the lower reach at Oliver based on observed similarity. While supported by historical data, this assumption may not hold if future hydrologic or operational changes alter longitudinal thermal gradients.

Bias Correction and Climate Forcing Assumptions

Uncertainty is also introduced through bias correction of GCM air temperature data. Monthly additive corrections assume that biases estimated over the historical period remain constant through time, a standard approach in statistical climate analyses ([Cannon et al. 2015](#); [Teutschbein and Seibert 2012](#)). While this improves representation of historical means, it does not account for non-stationarity in model biases or changes in variability and extremes, potentially leading to underestimation of both mean warming and the frequency and intensity of extreme temperature events.

Additional uncertainty arises because the observational records used for calibration exhibit positive temperature trends and decadal climate variability (e.g., PDO/ENSO), which are not explicitly represented in the GCM projections. Their implicit incorporation during bias correction may therefore introduce inconsistencies in projected warming trajectories. Consequently, projections should be interpreted as conservative, particularly with respect to extreme conditions.

Biological Thresholds and Interpretation

Thermal barrier metrics in this analysis are based on daily mean temperature and a fixed threshold of 22 °C, representing a biologically meaningful indicator of migration impairment. However, this simplification does not account for sub-daily temperature peaks, behavioural thermoregulation, or potential variation in thermal tolerance among populations ([Hinch and Martins 2011](#)). Consequently, actual biological responses may vary around these threshold-based indicators.

CONCLUSIONS

Although uncertainty remains regarding the precise magnitude and timing of thermal change at individual sites in the Okanagan/Okanagan river system, projections should be interpreted as scenario-based indicators of increasing risk rather than precise forecasts of future conditions. Nevertheless, the consistency of warming trends across models, sites, and emissions scenarios provides strong evidence that earlier onset, increased frequency, and longer duration of thermally stressful conditions are highly likely. These patterns indicate that climate change is already influencing adult salmon migration timing, holding behaviour, and survival conditions across the Okanagan–Okanogan system ([Hyatt et al. 2020](#); [PSC 2023](#); [Ogden et al. 2025](#)), at spatial and temporal scales directly relevant to population performance and management decision making.

Within the Wild Salmon Policy (WSP; [DFO 2005](#)) framework, these changes should be viewed not as episodic stressors but as systematic alterations to core life history processes that define Conservation Unit (CU) productivity and survival ([Schindler et al. 2008](#); [McDaniels et al. 2010](#); [Hunter et al. 2015](#)). Migration timing, cumulative thermal exposure, and prespawn survival are fundamental determinants of CU status, and projected shifts in these processes therefore warrant explicit consideration in risk assessment and management planning. More broadly, climate-driven thermal constraints should now be treated as a persistent and progressively early-season driver of migration risk, rather than the occurrence of rare or anomalous events.

From a management perspective, this supports a precautionary, forward-looking approach in which projected changes are treated as early warning signals of increasing migration constraint. Harvest strategies based on historical run timing are increasingly likely to underestimate total mortality as environmental baselines shift ([Hague and Patterson 2007](#)). Thermal constraints now function as a cumulative, system-wide source of stress, increasing the likelihood of prolonged holding in the Columbia River and associated exposure to physiological stress, disease, and fisheries-related mortality. Under the Precautionary Approach ([DFO 2009](#)), this evolving exposure regime represents an additional mortality pathway that should be explicitly incorporated into harvest planning and decision rules, consistent with WSP guidance to account for uncertainty and changing productivity ([Schindler et al. 2008](#); [Hague and Patterson 2007](#); [Hinch and Martins 2011](#)). Waiting for empirical confirmation of these conditions risks delayed response in systems where ecological thresholds may be crossed rapidly.

Consistent with the “safe operating space” framework for salmon watersheds ([Moore et al. 2025](#)), maintaining access to suitable thermal conditions across time and space is central to sustaining population resilience under climate change. In this context, management actions that identify and protect thermal refugia, sustain summer discharge, and align flow regulation with migration timing represent the most effective local levers for mitigating increasing thermal risk. Integrating these considerations into harvest planning, migration timing assessments, and habitat management provides a proactive strategy for maintaining CU diversity, resilience, and long-term sustainability under a warming climate.

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TABLES

Okanogan River at Malott, WA

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2008	30	14.5	2.4	31	21.9	1.2	31	22.3	2.0	30	17.6	1.6
2009	30	16.2	2.0	31	23.2	1.8	31	22.8	2.1	30	19.1	2.3
2010	30	14.2	1.8	31	21.1	2.5	31	22.7	1.9	30	17.5	1.3
2011	30	12.3	1.0	31	16.0	1.6	31	21.3	0.9	30	18.3	1.9
2012	30	13.0	1.7	31	20.2	2.3	31	22.7	1.3	30	17.6	1.1
2013	30	15.4	1.3	31	22.2	1.6	31	22.7	1.3	30	18.7	2.8
2014	30	14.0	1.3	31	20.7	1.8	31	22.8	0.8	30	18.4	1.1
2015	30	21.4	2.7	31	25.0	1.4	31	22.4	2.4	30	17.1	1.3
2016	30	18.6	2.0	31	21.9	1.5	31	22.8	1.1	30	17.6	1.5
2017	30	16.3	2.4	31	23.2	0.7	31	22.9	0.9	30	18.1	2.6
2018	30	16.2	1.5	23	23.2	2.3	31	21.5	2.6	27	17.3	1.5
2019	30	19.5	1.9	31	22.4	1.2	31	23.0	1.1	30	18.5	3.0
2020	9	13.1	1.0	5	24.2	0.6	31	22.9	1.2	30	18.6	2.2
2021	30	17.0	3.3	31	24.0	0.8	31	22.1	1.6	30	17.8	2.0

Table 2. Okanogan watershed observed monthly mean water temperature (°C) statistics at Malott, WA (Source: NOAA/NCEI).

Projected Air Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	17.5 (16.6–18.3)	22.1 (20.8–22.5)	21.7 (20.7–22.5)	16.0 (15.1–16.9)
RCP45	2010-2039	18.5 (17.9–20.1)	23.3 (22.2–24.0)	23.2 (22.4–23.9)	17.5 (15.9–18.3)
RCP85	2010-2039	18.8 (17.7–20.3)	23.5 (22.3–24.3)	23.3 (22.4–23.7)	17.4 (15.9–18.2)
RCP45	2040-2069	19.8 (18.6–21.6)	24.5 (23.3–25.8)	24.5 (23.2–26.5)	18.2 (16.8–19.8)
RCP85	2040-2069	20.1 (19.3–22.7)	25.2 (24.0–27.9)	25.4 (24.0–26.8)	19.0 (17.2–20.6)
RCP45	2070-2099	20.2 (18.6–22.4)	25.3 (23.6–27.7)	25.5 (24.0–27.4)	19.0 (17.5–20.4)
RCP85	2070-2099	22.6 (20.3–25.1)	28.2 (26.0–32.1)	28.2 (26.1–31.5)	21.2 (19.2–24.8)

Table 3. Projected regional monthly median air temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Omak (WA) for Malott (WA).

Projected Water Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	14.3 (13.8–14.8)	20.7 (19.7–21.2)	21.9 (21.3–22.5)	17.6 (16.9–18.1)
RCP45	2010-2039	14.9 (14.3–16.0)	21.7 (21.0–22.4)	23.0 (22.4–23.2)	18.5 (17.3–19.0)
RCP85	2010-2039	14.9 (14.4–16.0)	22.0 (21.2–22.6)	23.0 (22.6–23.3)	18.5 (17.6–19.3)
RCP45	2040-2069	15.7 (14.9–17.0)	22.8 (21.6–23.7)	23.7 (23.1–24.8)	19.1 (17.9–20.2)
RCP85	2040-2069	16.1 (15.2–17.7)	23.3 (22.1–25.0)	24.2 (23.4–25.0)	19.6 (18.2–20.7)
RCP45	2070-2099	16.0 (15.0–17.6)	23.3 (21.9–24.8)	24.3 (23.5–25.2)	19.6 (18.6–20.5)
RCP85	2070-2099	17.7 (16.0–20.6)	25.1 (23.4–27.4)	25.8 (24.7–27.6)	21.5 (19.8–24.2)

Table 4. Projected Okanogan River monthly median water temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Malott (WA).

Projected Thermal Barrier Onset and Duration

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	20-Jul	25-Jul	25-Jul	27-Jul	28-Jul
RCP45	2010-2039	15-Jul	18-Jul	20-Jul	23-Jul	24-Jul
RCP85	2010-2039	14-Jul	17-Jul	20-Jul	21-Jul	25-Jul
RCP45	2040-2069	07-Jul	11-Jul	16-Jul	18-Jul	21-Jul
RCP85	2040-2069	02-Jul	07-Jul	12-Jul	14-Jul	18-Jul
RCP45	2070-2099	01-Jul	09-Jul	12-Jul	17-Jul	21-Jul
RCP85	2070-2099	23-Jun	26-Jun	03-Jul	07-Jul	10-Jul

Table 5. Projected Okanogan River annual thermal barrier onset date (day of year) statistics across ten GCMs by period and RCP at Malott (WA).

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	16	20	21	22	27
RCP45	2010-2039	29	31	34	35	40
RCP85	2010-2039	27	33	35	37	44
RCP45	2040-2069	36	38	41	52	57
RCP85	2040-2069	39	47	50	60	68
RCP45	2070-2099	38	45	51	57	68
RCP85	2070-2099	58	66	70	81	93

Table 6. Projected Okanogan River annual thermal barrier duration (days) statistics across ten GCMs by period and RCP at Malott (WA).

Okanogan River at Oroville, WA

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2005	27	20.2	1.5	31	22.6	1.4	31	23.2	1.3	30	18.8	1.7
2006	30	19.4	1.5	31	24.9	1.4	31	22.4	0.8	30	19.6	1.7
2007	30	19.9	1.0	31	24.4	1.3	31	22.5	1.4	30	19.1	1.8
2008	30	19.6	1.4	30	24.1	0.5	31	22.8	1.7	30	18.6	1.1
2009	30	21.8	0.9	31	24.0	1.3	31	23.6	1.7	30	20.2	1.6
2010	30	18.8	1.9	31	23.0	1.5	31	23.5	2.0	30	18.2	0.9
2011	30	16.9	1.1	31	20.6	0.8	31	23.4	0.8	30	20.3	2.1
2012	30	17.4	1.2	31	23.0	1.7	31	24.1	1.4	30	20.2	0.9
2013	30	19.0	1.1	31	23.9	1.6	31	24.3	1.1	30	21.1	2.3
2014	30	20.5	1.1	31	25.0	1.5	31	24.6	1.4	30	19.6	1.3
2015	30	23.4	1.8	31	25.1	1.2	31	23.4	1.7	30	18.3	1.2
2016	30	20.8	1.8	31	22.9	1.5	31	23.6	1.1	30	19.3	1.3
2017	30	18.8	1.2	31	23.1	0.7	31	23.6	0.5	30	20.0	2.4
2018	30	19.1	1.4	31	23.3	1.7	31	23.2	2.2	30	18.7	1.1
2019	30	21.5	1.3	31	23.0	1.0	31	23.8	0.8	30	20.5	2.2
2020	30	18.7	1.7	31	22.3	2.0	31	23.5	0.9	30	20.3	1.5
2021	30	21.8	3.0	31	26.0	1.2	31	23.2	1.8	30	19.2	1.6

Table 7. Okanogan watershed observed monthly mean water temperature (°C) statistics at Oroville, WA (Source: NOAA/NCEI).

Projected Air Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	18.5 (18.5–18.5)	21.8 (21.8–21.8)	21.4 (21.4–21.4)	16.3 (16.3–16.3)
RCP45	2010-2039	19.4 (18.4–21.2)	23.2 (22.1–24.5)	22.7 (21.9–24.0)	17.5 (16.4–18.7)
RCP85	2010-2039	19.7 (18.8–20.5)	23.7 (22.1–24.7)	22.8 (21.9–24.0)	17.5 (16.8–18.8)
RCP45	2040-2069	21.2 (19.4–23.2)	24.6 (22.7–26.5)	24.0 (22.6–26.0)	18.8 (16.8–19.9)
RCP85	2040-2069	21.6 (20.0–23.1)	25.2 (23.5–28.7)	25.1 (23.4–27.2)	19.7 (17.5–20.9)
RCP45	2070-2099	21.7 (19.7–23.5)	25.2 (23.4–28.6)	25.0 (23.4–27.1)	19.3 (17.8–21.0)
RCP85	2070-2099	23.7 (21.1–26.1)	28.3 (25.4–33.0)	28.2 (25.7–32.3)	22.0 (19.3–25.0)

Table 8. Projected regional monthly median air temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Oliver (BC) for Oroville (WA).

Projected Water Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	19.0 (18.9–19.0)	22.4 (22.3–22.5)	22.8 (22.6–22.9)	19.1 (19.0–19.3)
RCP45	2010-2039	19.4 (18.9–20.1)	23.2 (22.6–23.9)	23.6 (23.1–24.4)	19.6 (19.3–20.2)
RCP85	2010-2039	19.5 (19.0–20.0)	23.4 (22.7–23.9)	23.6 (23.2–24.3)	19.7 (19.2–20.3)
RCP45	2040-2069	20.2 (19.4–21.2)	24.0 (23.0–25.1)	24.2 (23.7–25.2)	20.3 (19.3–21.1)
RCP85	2040-2069	20.5 (19.5–21.2)	24.4 (23.3–26.4)	24.9 (23.9–26.0)	20.8 (19.5–21.5)
RCP45	2070-2099	20.5 (19.6–21.3)	24.3 (23.3–26.2)	24.8 (24.0–26.0)	20.7 (19.8–21.6)
RCP85	2070-2099	21.8 (20.1–23.3)	26.0 (24.4–28.7)	26.3 (25.1–28.4)	22.5 (20.7–24.3)

Table 9. Projected Okanogan River monthly median water temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Oroville (WA).

Projected Thermal Barrier Onset and Duration

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	14-Jul	15-Jul	16-Jul	16-Jul	17-Jul
RCP45	2010-2039	02-Jul	07-Jul	10-Jul	12-Jul	15-Jul
RCP85	2010-2039	03-Jul	06-Jul	09-Jul	09-Jul	16-Jul
RCP45	2040-2069	25-Jun	30-Jun	03-Jul	08-Jul	11-Jul
RCP85	2040-2069	22-Jun	25-Jun	01-Jul	04-Jul	09-Jul
RCP45	2070-2099	20-Jun	27-Jun	04-Jul	04-Jul	09-Jul
RCP85	2070-2099	11-Jun	16-Jun	22-Jun	25-Jun	01-Jul

Table 10. Projected Okanogan River annual thermal barrier onset date (day of year) statistics across ten GCMs by period and RCP at Oroville (WA).

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	34	35	36	38	39
RCP45	2010-2039	44	47	50	53	65
RCP85	2010-2039	44	50	51	58	62
RCP45	2040-2069	48	57	62	66	76
RCP85	2040-2069	51	62	68	77	82
RCP45	2070-2099	53	59	65	74	84
RCP85	2070-2099	69	81	85	96	105

Table 11. Projected Okanogan River annual thermal barrier duration (days) statistics across ten GCMs by period and RCP at Oroville (WA).

Similkameen River at Nighthawk, WA

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2014	30	11.2	1.1	31	17.1	1.7	31	19.6	0.5	30	16.2	0.8
2015	30	17.1	2.5	31	20.9	1.2	31	19.7	1.5	30	14.8	1.2
2016	30	15.0	2.1	31	18.0	1.6	31	19.7	1.1	30	15.0	1.3
2017	30	13.5	2.5	31	20.6	1.0	31	20.5	0.8	30	16.0	2.5
2018	30	13.3	2.5	31	19.5	2.2	31	18.6	2.2	30	14.7	1.3
2019	30	16.2	1.9	31	18.8	1.3	31	20.3	1.1	30	16.4	3.1
2020	30	11.4	1.7	31	16.9	2.9	31	19.5	1.2	30	16.3	2.2
2021	30	14.5	3.6	29	21.7	0.7	31	19.8	1.8	30	15.6	2.0

Table 12. Similkameen River observed monthly mean water temperature (°C) statistics at Nighthawk, WA (Source: NOAA/NCEI).

Projected Air Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	14.5 (14.5–14.5)	17.7 (17.7–17.7)	17.6 (17.6–17.6)	13.2 (13.2–13.2)
RCP45	2010-2039	15.2 (14.5–17.6)	19.1 (17.8–20.7)	18.8 (18.1–20.2)	14.2 (13.4–15.5)
RCP85	2010-2039	15.6 (14.6–16.5)	19.2 (17.7–20.2)	18.8 (18.1–19.8)	14.2 (13.4–15.4)
RCP45	2040-2069	17.3 (15.4–19.4)	20.4 (18.5–22.5)	20.3 (19.0–22.4)	15.7 (13.5–16.8)
RCP85	2040-2069	17.7 (15.9–19.4)	21.0 (19.0–24.8)	21.2 (19.6–23.3)	16.6 (14.3–17.7)
RCP45	2070-2099	17.8 (15.5–20.1)	21.4 (19.3–24.8)	21.3 (19.6–23.5)	16.2 (14.7–18.0)
RCP85	2070-2099	19.9 (17.2–22.1)	24.3 (21.0–29.2)	24.6 (22.1–28.9)	19.1 (16.3–21.8)

Table 13. Projected regional monthly median air temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Princeton (BC) for Similkameen River (WA).

Projected Water Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	13.5 (13.2–13.6)	18.4 (18.3–18.7)	19.3 (19.1–19.4)	15.6 (15.4–15.8)
RCP45	2010-2039	13.9 (13.3–15.6)	19.3 (18.6–20.6)	20.1 (19.6–21.0)	16.3 (15.6–16.9)
RCP85	2010-2039	14.0 (13.4–14.7)	19.6 (18.6–20.0)	20.0 (19.7–20.7)	16.3 (15.7–17.0)
RCP45	2040-2069	15.4 (14.0–17.1)	20.4 (19.1–21.8)	20.9 (20.2–22.3)	17.2 (15.9–18.0)
RCP85	2040-2069	15.7 (14.4–16.3)	20.8 (19.6–22.9)	21.6 (20.4–23.0)	17.7 (16.2–18.4)
RCP45	2070-2099	15.6 (14.2–17.1)	20.8 (19.5–22.8)	21.6 (20.6–23.1)	17.7 (16.7–18.6)
RCP85	2070-2099	17.3 (15.1–19.0)	22.6 (20.8–25.0)	23.5 (22.0–26.3)	19.7 (17.7–21.4)

Table 14. Projected monthly median water temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP for Similkameen River at Nighthawk (WA).

Projected Thermal Barrier Onset and Duration

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	13-Aug	16-Aug	17-Aug	18-Aug	28-Aug
RCP45	2010-2039	31-Jul	01-Aug	05-Aug	06-Aug	21-Aug
RCP85	2010-2039	26-Jul	01-Aug	07-Aug	08-Aug	16-Aug
RCP45	2040-2069	19-Jul	25-Jul	30-Jul	03-Aug	16-Aug
RCP85	2040-2069	14-Jul	22-Jul	26-Jul	31-Jul	10-Aug
RCP45	2070-2099	14-Jul	22-Jul	27-Jul	31-Jul	06-Aug
RCP85	2070-2099	04-Jul	08-Jul	16-Jul	19-Jul	29-Jul

Table 15. Projected thermal barrier onset date statistics (minimum, median, and maximum) across ten GCMs by month, period, and RCP for Similkameen River at Nighthawk (WA)

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	1	3	3	4	4
RCP45	2010-2039	3	7	8	9	14
RCP85	2010-2039	4	6	7	8	13
RCP45	2040-2069	4	12	13	18	26
RCP85	2040-2069	9	16	19	25	39
RCP45	2070-2099	8	13	19	27	39
RCP85	2070-2099	19	30	42	53	69

Table 16. Projected thermal barrier duration statistics (minimum, median, and maximum) across ten GCMs by month, period, and RCP for Similkameen River at Nighthawk (WA).

Okanagan River at Oliver, BC

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2003	30	18.3	2.2	31	22.3	1.1	31	22.8	3.0	30	18.0	4.0
2004	30	20.1	2.6	31	23.6	1.1	31	24.1	1.3	30	18.8	1.5
2005	30	19.1	1.5	31	22.5	0.9	31	22.8	1.1	30	18.6	1.6
2006	30	19.7	2.1	31	24.5	0.8	31	22.5	0.6	30	19.7	1.2
2007	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2008	30	17.4	2.0	31	22.3	0.6	31	21.5	1.2	30	17.4	1.2
2009	30	19.5	1.0	31	22.8	1.5	31	22.3	1.6	30	19.0	1.6
2010	30	16.6	2.4	31	21.7	1.6	31	22.2	1.4	30	17.3	1.1
2011	30	15.2	1.4	31	20.1	0.9	31	21.9	0.7	30	18.6	1.6
2012	30	15.4	1.4	31	21.9	2.0	31	22.7	1.1	30	18.5	0.9
2013	30	17.7	1.4	31	22.9	1.2	31	22.8	1.2	30	19.5	2.4
2014	30	18.7	1.5	31	23.1	1.2	31	23.0	1.2	30	17.9	1.1
2015	30	21.9	1.7	31	23.7	1.0	31	21.9	1.5	30	16.8	1.2
2016	30	19.2	1.8	31	21.9	1.1	31	22.1	0.8	30	18.0	1.5
2017	30	17.1	1.4	31	22.2	0.7	31	22.4	0.6	30	18.3	2.6
2018	30	17.6	1.4	31	22.0	1.6	31	21.0	2.0	30	17.0	1.1
2019	30	19.9	1.1	31	21.7	0.7	31	22.2	0.8	30	19.1	2.3
2020	30	17.2	2.0	31	21.3	1.9	31	22.5	1.2	30	18.9	1.7
2021	30	20.3	3.3	31	24.6	1.0	31	21.9	1.7	30	17.5	1.6

Table 17. Observed monthly mean water temperature (°C) statistics for lower Okanagan River at Oliver, BC (Source: WSC).

Projected Air Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	18.5 (18.5–18.5)	21.8 (21.8–21.8)	21.4 (21.4–21.4)	16.3 (16.3–16.3)
RCP45	2010-2039	19.4 (18.4–21.2)	23.2 (22.1–24.5)	22.7 (21.9–24.0)	17.5 (16.4–18.7)
RCP85	2010-2039	19.7 (18.8–20.5)	23.7 (22.1–24.7)	22.8 (21.9–24.0)	17.5 (16.8–18.8)
RCP45	2040-2069	21.2 (19.4–23.2)	24.6 (22.7–26.5)	24.0 (22.6–26.0)	18.8 (16.8–19.9)
RCP85	2040-2069	21.6 (20.0–23.1)	25.2 (23.5–28.7)	25.1 (23.4–27.2)	19.7 (17.5–20.9)
RCP45	2070-2099	21.7 (19.7–23.5)	25.2 (23.4–28.6)	25.0 (23.4–27.1)	19.3 (17.8–21.0)
RCP85	2070-2099	23.7 (21.1–26.1)	28.3 (25.4–33.0)	28.2 (25.7–32.3)	22.0 (19.3–25.0)

Table 18. Projected regional monthly median air temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Oliver (BC).

Projected Water Temperatures

Scenario	Period	Jun	Jul	Aug	Sep
Reference	1971-2000	17.2 (17.1–17.4)	21.4 (21.3–21.5)	21.7 (21.5–21.7)	17.6 (17.6–17.9)
RCP45	2010-2039	17.8 (17.2–18.9)	22.2 (21.6–22.9)	22.4 (21.9–23.0)	18.2 (17.8–18.8)
RCP85	2010-2039	18.0 (17.4–18.7)	22.4 (21.6–22.9)	22.4 (22.0–22.9)	18.4 (17.8–18.9)
RCP45	2040-2069	19.0 (17.9–20.4)	22.9 (22.0–23.8)	22.8 (22.4–23.6)	18.9 (17.8–19.7)
RCP85	2040-2069	19.5 (18.1–20.3)	23.3 (22.4–24.7)	23.3 (22.6–24.1)	19.5 (18.1–20.2)
RCP45	2070-2099	19.4 (18.2–20.4)	23.2 (22.3–24.6)	23.3 (22.6–24.1)	19.3 (18.4–20.2)
RCP85	2070-2099	21.0 (19.0–22.5)	24.5 (23.3–26.3)	24.3 (23.5–25.6)	21.0 (19.4–22.5)

Table 19. Projected Okanagan River monthly median water temperature statistics (minimum - maximum) across ten GCMs by month, period, and RCP at Oliver (BC).

Projected Thermal Barrier Onset and Duration

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	21-Jul	22-Jul	22-Jul	23-Jul	24-Jul
RCP45	2010-2039	12-Jul	14-Jul	18-Jul	21-Jul	23-Jul
RCP85	2010-2039	11-Jul	13-Jul	14-Jul	17-Jul	21-Jul
RCP45	2040-2069	01-Jul	06-Jul	11-Jul	17-Jul	19-Jul
RCP85	2040-2069	27-Jun	01-Jul	09-Jul	10-Jul	16-Jul
RCP45	2070-2099	24-Jun	03-Jul	10-Jul	13-Jul	17-Jul
RCP85	2070-2099	15-Jun	20-Jun	26-Jun	01-Jul	10-Jul

Table 20. Projected Okanagan River thermal barrier onset date statistics (minimum, median, and maximum) across ten GCMs by month, period, and RCP at Oliver (BC).

Scenario	Period	Min	P25	Median	P75	Max
Reference	1971-2000	17	20	20	21	22
RCP45	2010-2039	25	28	32	35	45
RCP85	2010-2039	26	32	35	38	44
RCP45	2040-2069	31	37	42	51	61
RCP85	2040-2069	36	46	49	62	71
RCP45	2070-2099	36	40	49	59	71
RCP85	2070-2099	53	65	72	84	96

Table 21. Projected Okanagan River annual thermal barrier duration (days) statistics across ten GCMs by period and RCP at Oliver (BC).

Okanagan River at Okanagan Falls, BC

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2003	30	19.6	1.5	31	22.4	1.2	31	22.3	1.0	30	18.6	1.8
2004	30	19.2	3.1	31	22.7	1.0	31	23.7	1.4	30	18.2	1.8
2005	30	18.1	1.4	31	21.1	1.1	31	22.3	1.0	30	18.2	1.6
2006	30	17.7	2.1	31	23.3	1.1	31	21.8	0.7	30	19.0	1.6
2007	30	18.0	1.4	31	22.3	1.5	31	21.5	1.2	30	18.0	1.7
2008	30	16.6	1.6	31	21.8	0.7	31	21.3	1.4	30	17.8	1.0
2009	30	18.4	1.3	31	22.0	1.5	31	22.6	1.3	30	19.2	1.6
2010	30	17.0	2.2	31	21.1	1.3	31	22.1	1.3	30	17.4	1.2
2011	30	15.2	1.4	31	19.5	0.9	31	21.9	0.6	30	19.1	2.0
2012	30	15.2	1.0	31	21.2	1.9	31	22.7	1.1	30	19.3	0.7
2013	30	17.4	1.3	31	22.7	1.4	31	23.3	1.0	30	19.7	2.8
2014	30	18.9	1.4	31	23.2	1.2	31	23.3	0.9	30	18.7	1.4
2015	30	21.5	1.5	31	24.0	0.9	31	22.3	1.6	30	17.3	1.1
2016	30	18.7	1.7	31	21.4	1.1	NA	NA	NA	NA	NA	NA
2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2018	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2019	30	19.4	1.3	31	21.2	0.8	NA	NA	NA	NA	NA	NA
2020	30	17.0	2.2	31	21.0	1.9	31	22.5	0.9	30	19.4	1.8
2021	30	19.2	3.5	28	24.5	0.6	31	22.5	1.7	30	17.5	2.3

Table 22. Observed monthly mean water temperature (°C) statistics for “Middle” Okanagan River at Okanagan Falls, BC (Source: WSC).

Okanagan River at Penticton, BC

Observed Water Temperatures

Year	June			July			August			September		
	N	Mean	Std	N	Mean	Std	N	Mean	Std	N	Mean	Std
2016	30	18.7	1.7	31	21.4	1.1	NA	NA	NA	NA	NA	NA
2018	30	15.7	1.6	31	21.9	2.2	31	22.9	1.9	30	18.4	1.0
2019	30	20.2	1.8	31	22.2	1.3	31	23.0	0.7	30	19.6	2.5
2020	30	16.3	3.3	31	21.4	2.2	31	23.5	0.8	30	18.9	4.4

Table 23. Observed monthly mean water temperature (°C) statistics for “Upper” Okanagan River at Penticton, BC (Source: WSC).

Okanagan Site Water Temperature Comparisons

Year	Month	Oliver	Ok Falls	Penticton
2016	6	19.2	18.7	18.7
2016	7	21.9	21.4	21.4
2019	6	19.9	19.4	20.2
2019	7	21.7	21.2	22.2
2020	6	17.2	17.0	16.3
2020	7	21.3	21.0	21.4
2020	8	22.5	22.5	23.5
2020	9	18.9	19.4	18.9

```
> # control for year
> anova_model3 <- aov(mean_water_temp ~ site * month + factor(year))
> summary(anova_model3)
              Df Sum Sq Mean Sq F value Pr(>F)
site           2   10.7      5.4   1.493  0.225
month          3 1992.1    664.0 185.144 <2e-16 ***
factor(year)    2  281.2    140.6  39.208 <2e-16 ***
site:month       6   37.0      6.2   1.718  0.114
Residuals      718 2575.1      3.6
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 24. ANOVA results comparing Okanagan River (BC) sites' mean water temperature (above, left) incorporating a site-month interaction term and interannual variability via year as a fixed effect. While month and year were significant factors, site was not found to be significant by itself, or as an interaction term with month.

```
> library(lme4)

> model_mixed <- lmer(mean_water_temp ~ site * month + (1 | year),
+                      data = subset_data)

> summary(model_mixed)
Linear mixed model fit by REML. t-tests use Satterthwaite's method [
lmerModLmerTest]
Formula: mean_water_temp ~ site * month + (1 | year)
Data: subset_data

REML criterion at convergence: 3017.8

Scaled residuals:
    Min       1Q   Median       3Q      Max
-6.2192 -0.6026 -0.0229  0.6338  2.1299

Random effects:
 Groups Name Variance Std.Dev.
 year   (Intercept) 0.7488  0.8653
Residual              3.5865  1.8938
Number of obs: 732, groups: year, 3

Fixed effects:
              Estimate Std. Error      df t value Pr(>|t|)
(Intercept)    18.78808    0.53801  2.55401  34.921 0.000172 ***
site5_OK_Falls -0.40523    0.28231  718.00000  -1.435 0.151606
site6_Penticton -0.37505    0.28231  718.00000  -1.328 0.184438
monthJul        2.84993    0.28003  718.00000  10.177 < 2e-16 ***
monthAug        4.68724    0.41021  719.83473  11.426 < 2e-16 ***
monthSep        1.04049    0.41489  719.81583   2.508 0.012365 *
site5_OK_Falls:monthJul -0.01844    0.39602  718.00000  -0.047 0.962865
site6_Penticton:monthJul  0.42298    0.39602  718.00000   1.068 0.285843
site5_OK_Falls:monthAug  0.35372    0.55775  718.00000   0.634 0.526165
site6_Penticton:monthAug  1.34975    0.55775  718.00000   2.420 0.015768 *
site5_OK_Falls:monthSep  0.93846    0.56462  718.00000   1.662 0.096929 .
site6_Penticton:monthSep  0.41859    0.56462  718.00000   0.741 0.458715
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 25. Further results comparing mean water temperature between Okanagan River sites in BC. To account for year as a source of random environmental variation, a linear mixed-effects model was also fitted with site and month as fixed effects and year included as a random intercept. The mixed-effects model identified a modest increase in August temperature at Penticton relative to upstream sites ($p = 0.016$). However, comparisons involving the months of August and September were based on limited observations in one year, 2020.

FIGURES

Maps

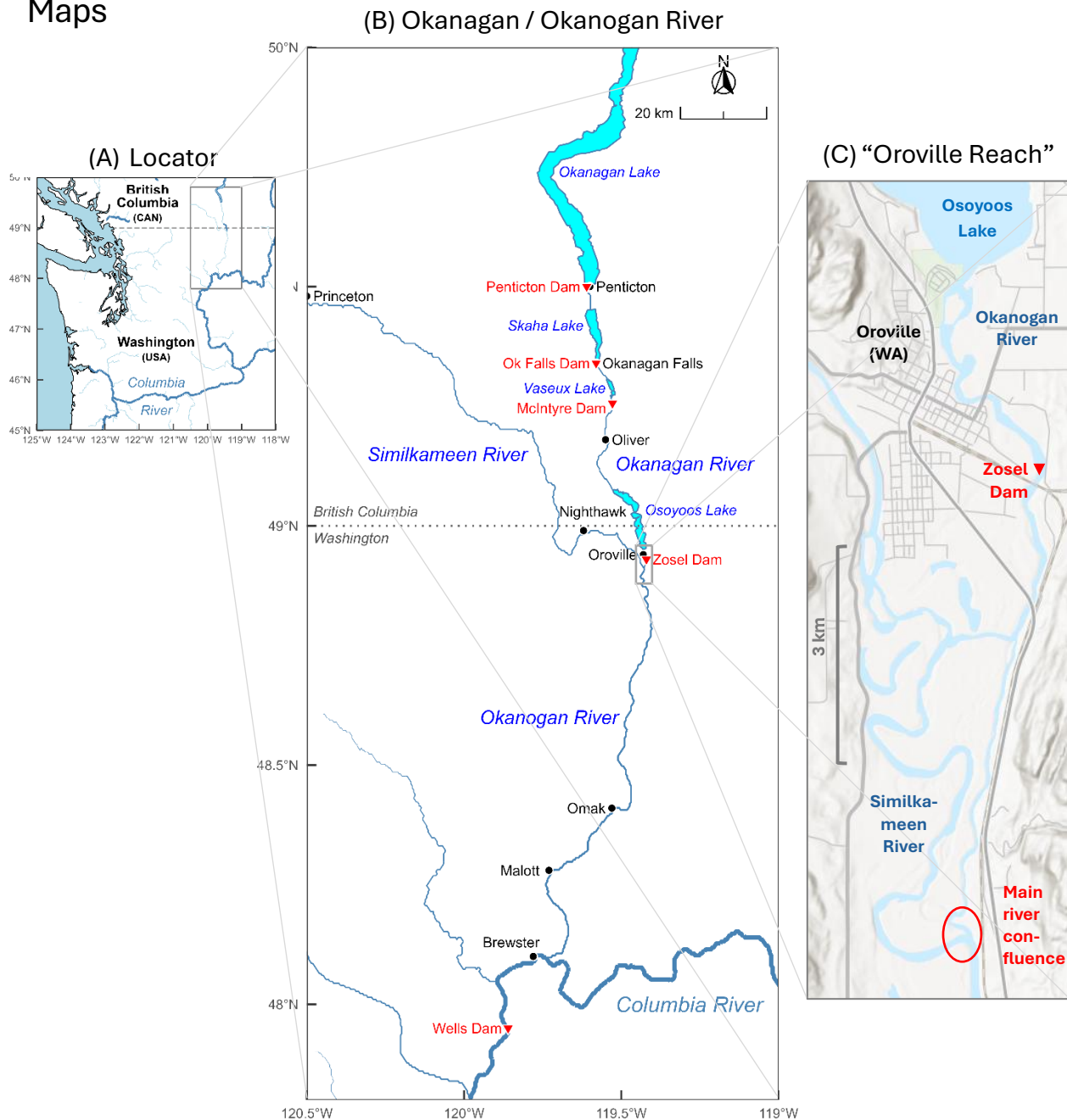


Figure 2. Principal air and water temperature monitoring sites in the Okanogan watershed, including the "lower" Okanogan River at Malott (WA), the "upper" Okanogan River at Oroville (WA), the Similkameen River at Nighthawk (WA), and the Okanogan River at Oliver (BC). Meteorological sites for air temperature observations and downscaled GCM data include: Omak (WA) for the Okanogan River at Malott; Princeton (BC) for the Similkameen River at Nighthawk (WA); and Oliver (BC) for the Okanogan River at Oliver (BC) and the Okanogan River at Oroville (WA). Upper left inset map locates the Okanogan/Okanogan River system as a tributary in the mid-Columbia River. Lower right inset map shows the "Oroville Reach" of the "upper" Okanogan River (WA), from the outlet of Osoyoos Lake to the main confluence with the Similkameen River, approximately 6 km downstream. Data Sources: (A) and (B): HydroBASINS, HydroRIVERS, HydroLAKES. <https://www.hydrosheds.org/> downloaded on 01-Jun-2026 © HydroSHEDS. Maps A & B designed in R packages: ggplot2 (Wickham 2016); sf (Pebesma 2018); ggspatial (Dunnington 2018)); (C) BCRFC 2026.

Climatology

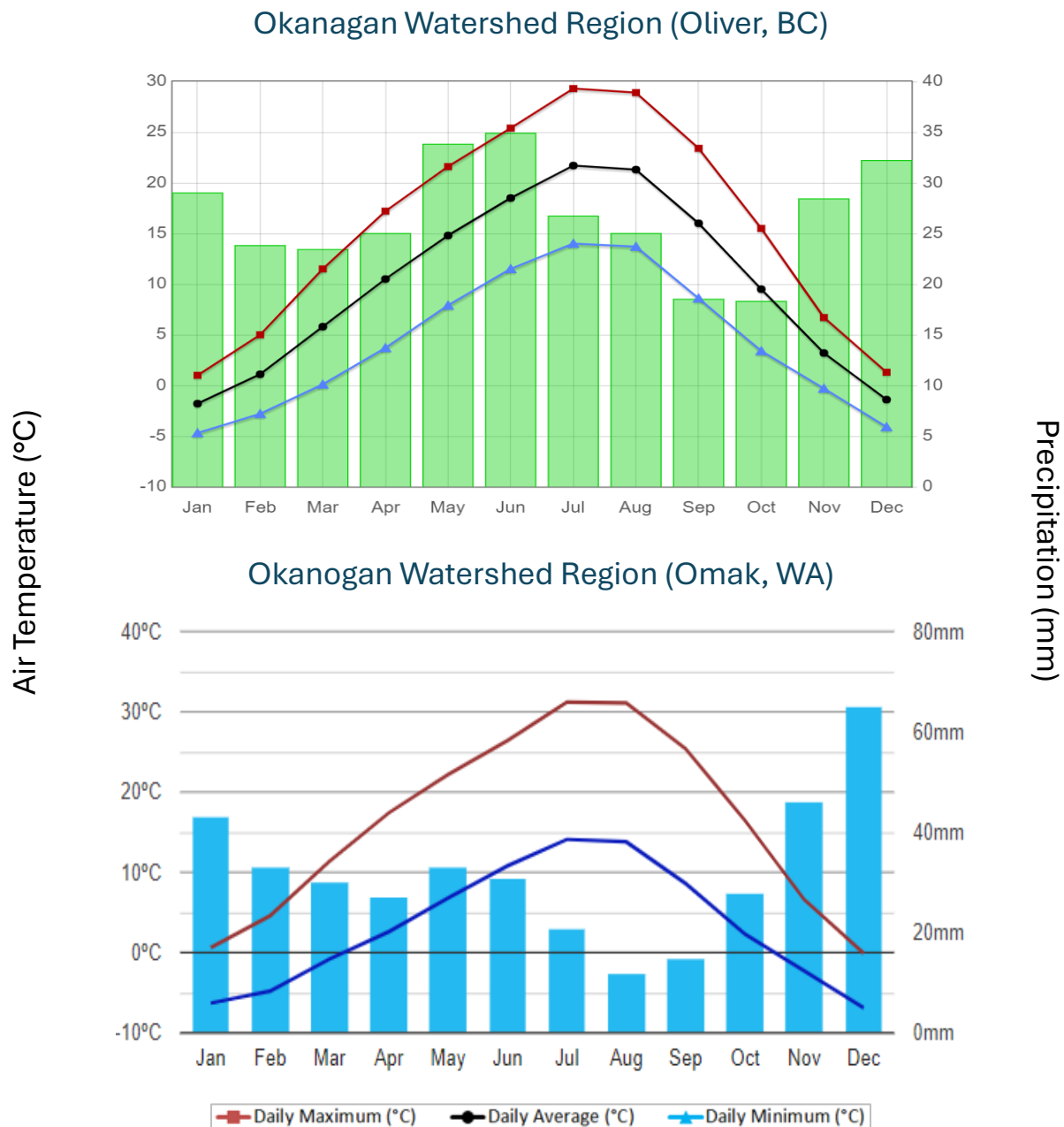


Figure 3. Monthly climatology from regional meteorological stations in the Okanagan watershed (bars represent precipitation (mm)).

1. Top: Environment Canada (ECCC) station at Oliver, BC, 1971-2000 (Station 1192340; 49.10°N x 119.32°W; Gage datum: 297 m); source: [Climate normals data, 1971-2000, Env Canada and Climate Change](#)).
2. Bottom: US National Center for Environmental Information (NCEI) station at Omak, WA, 1981-2010 (Station GHCND:USW00094197; 49.46°N x 119.52°W; Gage datum: 397 m); (Source: [Climate Omak - Washington and Weather averages Omak \(usclimatedata.com\)](#)).

Air Temperature Time Trends

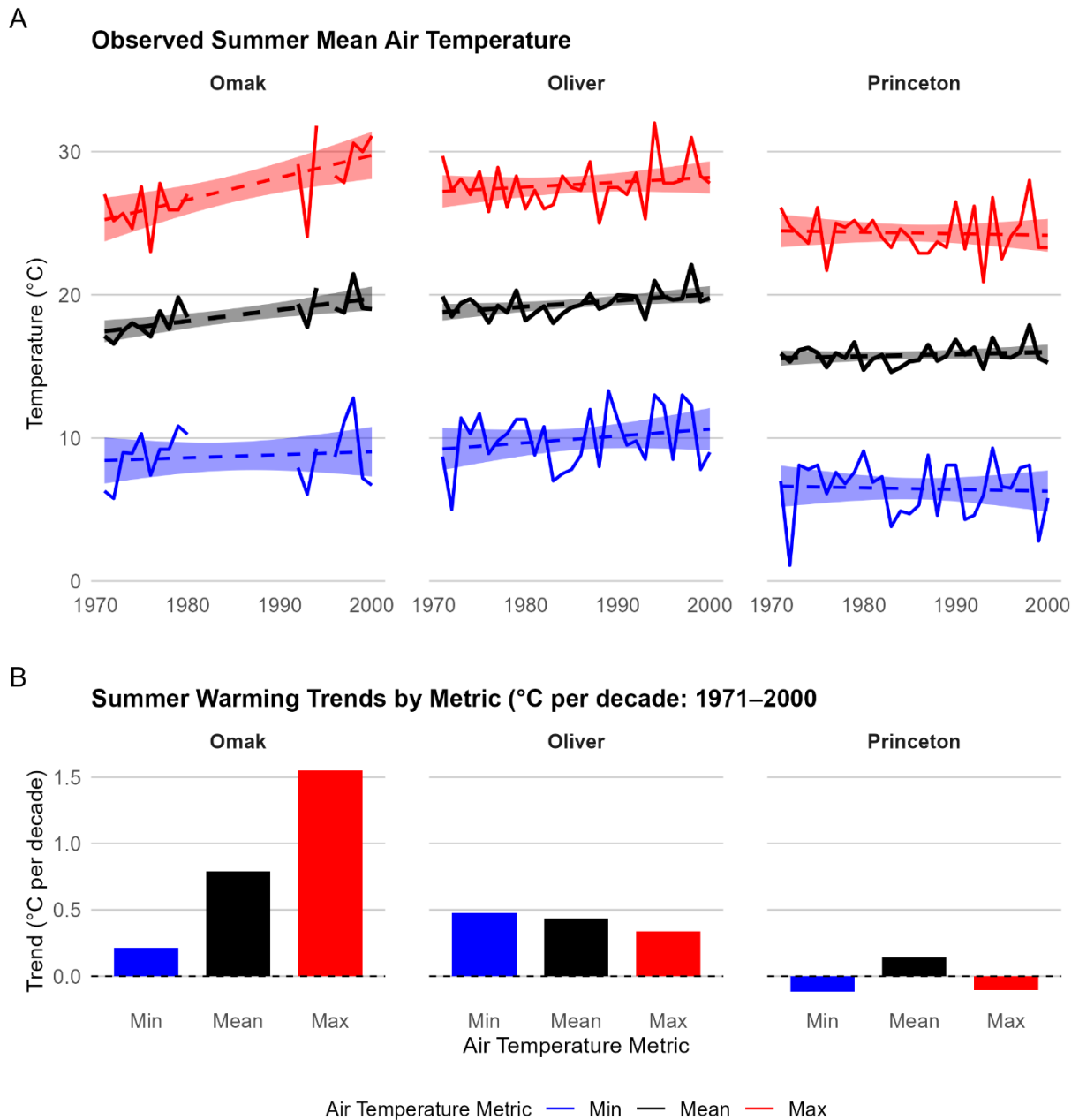


Figure 4A: Summer (Jun-Sep) minimum, mean, and maximum air temperatures (1971–2000) show pronounced warming at Omak (WA), moderate increases at Oliver (BC), and little change at Princeton (BC). Trends are strongest at Omak, particularly in maximum ($+1.55\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.002$) and mean ($+0.79\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.002$) temperatures, while Oliver exhibits moderate warming in mean temperature ($+0.43\text{ }^{\circ}\text{C decade}^{-1}$; $p = 0.01$); trends at Princeton are weak and non-significant. Figure 4B: Linear trends ($^{\circ}\text{C decade}^{-1}$) confirm strong warming at Omak (maximum and mean; $p < 0.01$), moderate but largely non-significant increases at Oliver, and negligible or slightly negative trends at Princeton. Warming is generally greatest in maximum temperatures, though this pattern is driven primarily by Omak, which is characterized by least number of years of data.

River Discharge

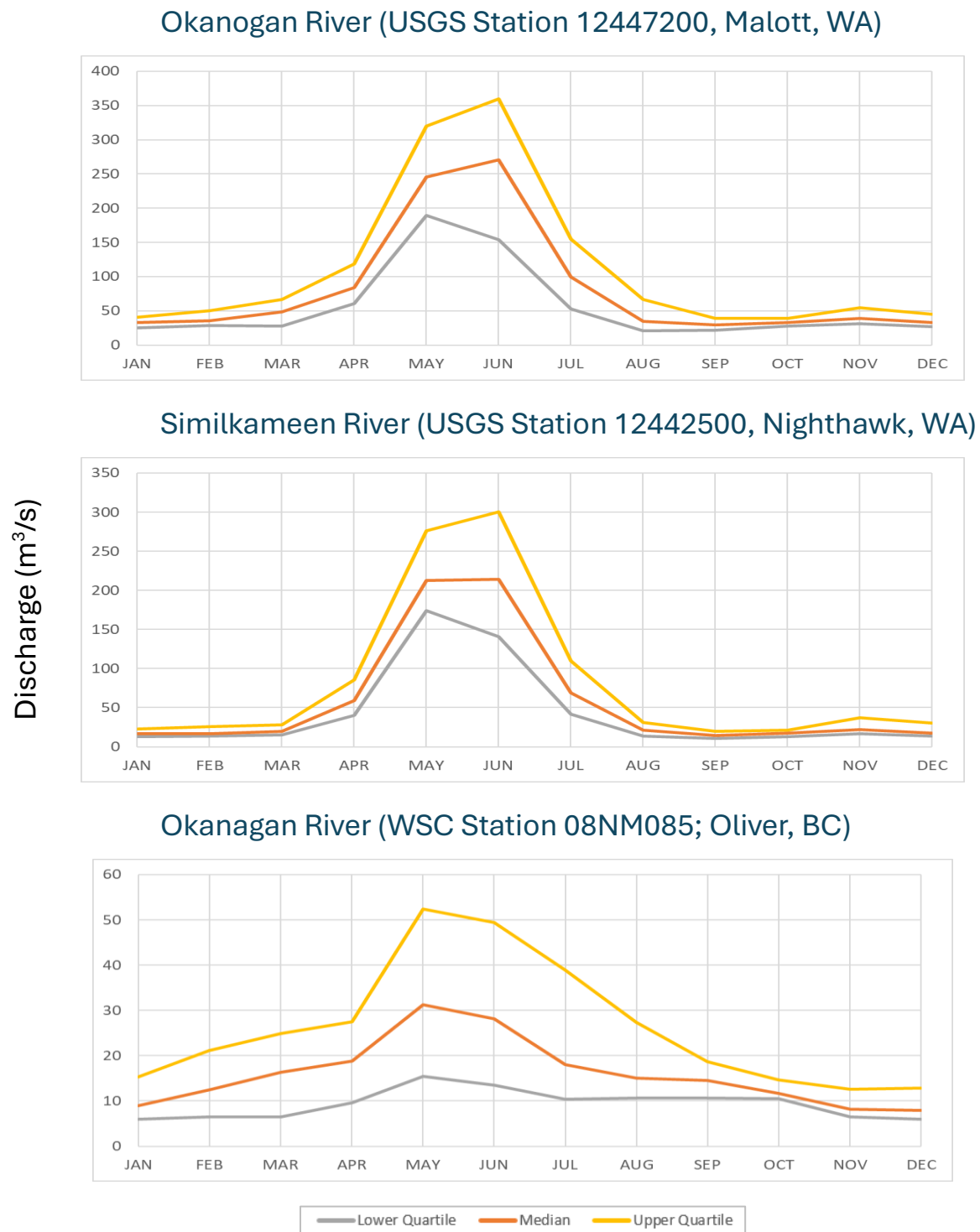


Figure 5. Monthly discharge statistics (m^3/s ; 1971-2021) in the Okanogan/Okanagan River migration corridor at [Malott \(WA\)](#) (top) and [Oliver \(BC\)](#) (bottom), and major tributary [Similkameen River \(WA\)](#) (center). Oroville discharge not available. (Sources: USGS, WSC Wateroffice). The Similkameen River provides up to 90% of lower Okanogan River discharge volume during the spring freshet (April-May-June). Note y-axis scales are not equivalent.

River Temperature Time-Series

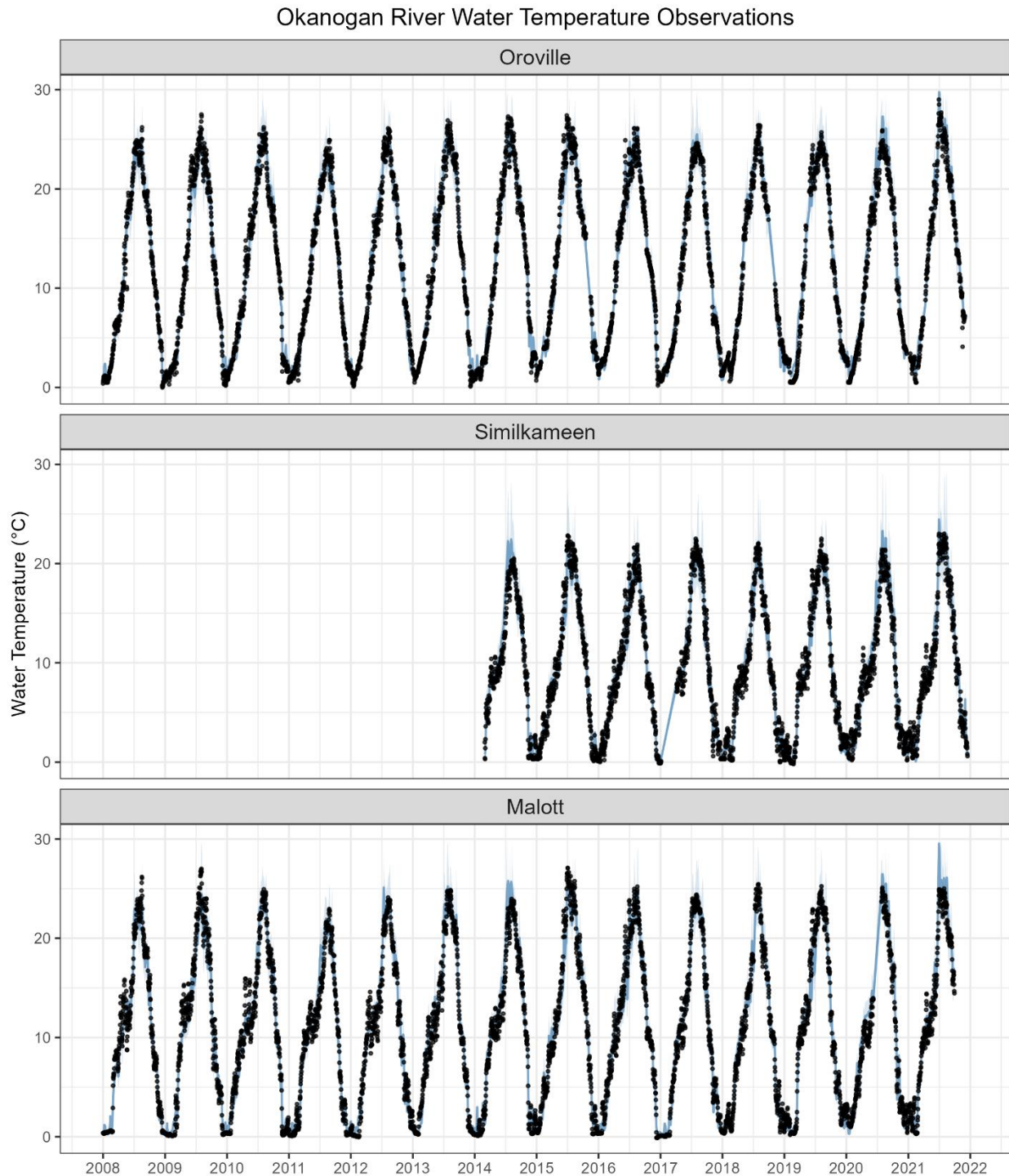


Figure 6. Time-series of observed daily mean water temperature for the upper Okanogan River at Oroville, WA (top); Similkameen River at Nighthawk, WA (middle); and the lower Okanogan River at Oroville, WA (bottom). Shaded bands represent 95% confidence intervals for the predicted mean daily water temperature, illustrating uncertainty in the fitted GAMM relationship with the 7-day rolling mean air temperature index and seasonal timing.

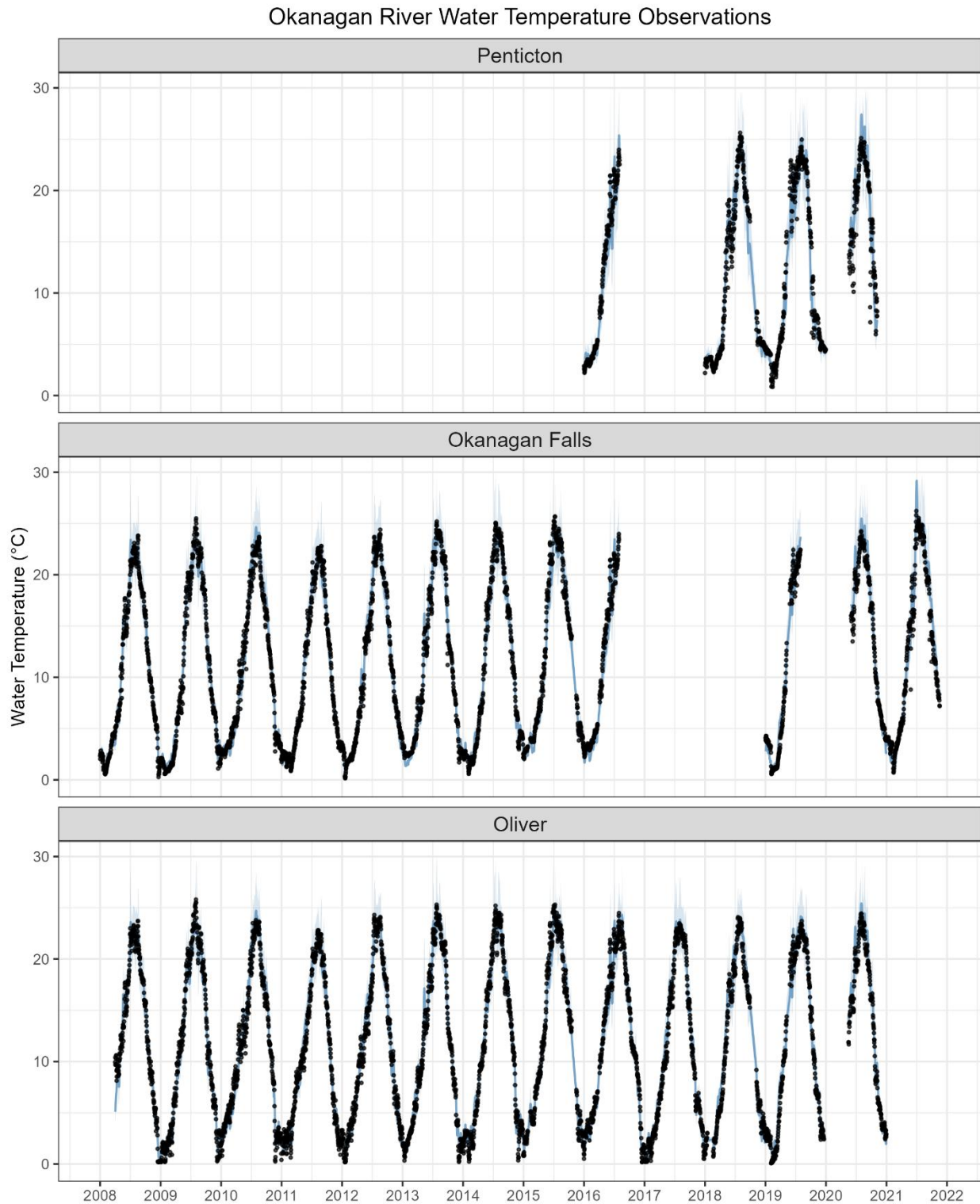


Figure 7. Time-series of observed daily mean water temperature for upper Okanagan River at Penticton, BC (top); middle Okanagan River at Okanagan Falls, BC (middle); and lower Okanagan River at Oliver, BC (bottom). Shaded blue bands represent 95% confidence intervals for the predicted mean daily water temperature, illustrating uncertainty in the fitted GAMM relationship with the 7-day rolling mean air temperature index and seasonal timing. Note that daily mean temperatures at Penticton are influenced by Penticton Dam operations affecting flow volumes.

River Thermographs

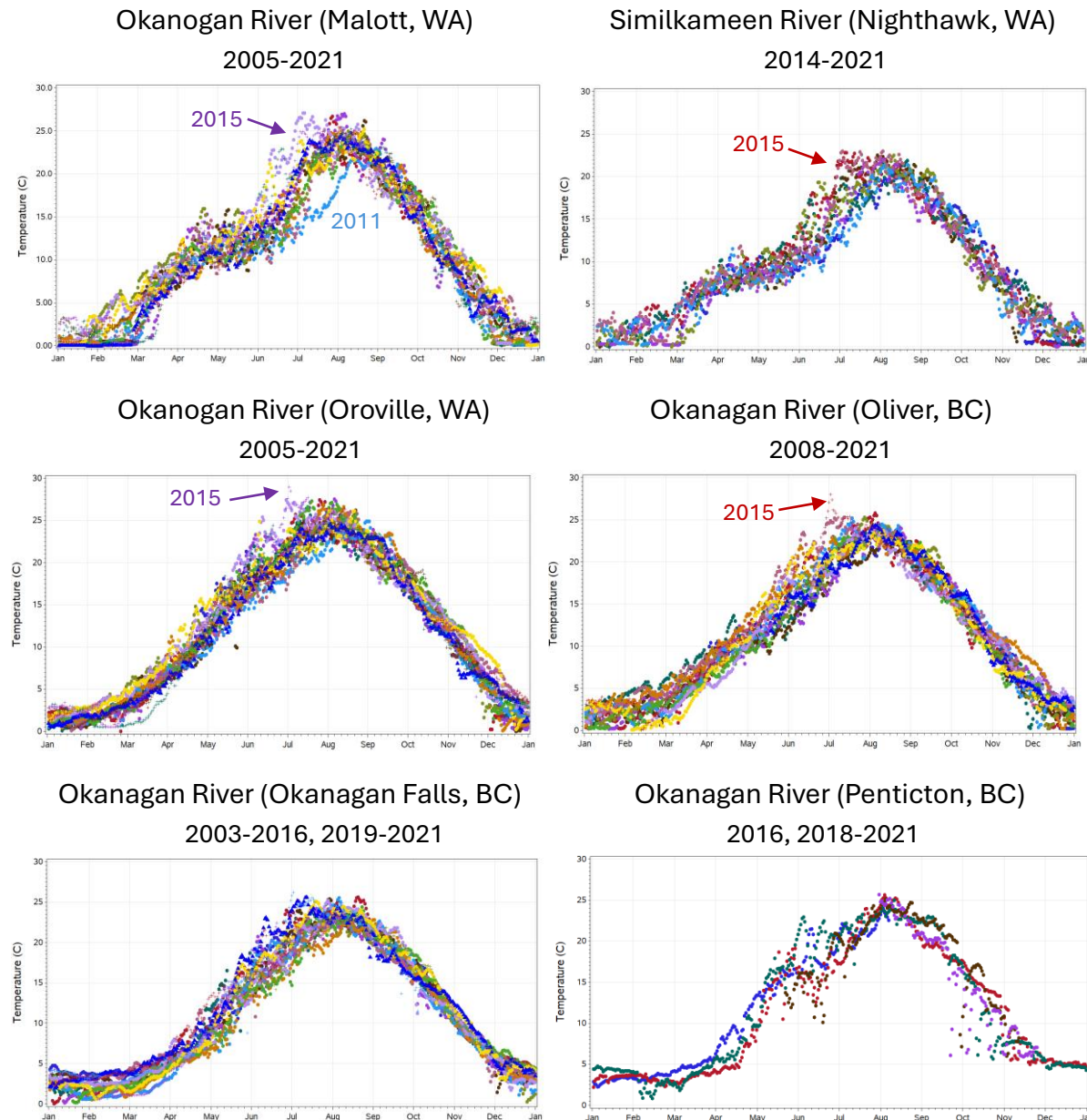


Figure 8. Annual thermograph of daily mean water temperature observations for the lower Okanogan River at Malott WA (top left); the Similkameen River at Nighthawk WA (top right); the upper Okanogan River at Oroville WA (middle left); the lower Okanogan River at Oliver BC (middle right); the mid-Okanogan River at Okanagan Falls, BC (bottom left); and the upper Okanogan River at Penticton, BC (bottom right).

The Okanogan River's vulnerability to climate warming may be foreseen by conditions in 2015, when a mild winter and low snowpack resulted in a reduced spring freshet, corresponding to elevated temperatures and thermal blockages in the lower Okanogan in mid-June (Hyatt et al. 2020). Conversely, 2011 was characterized by a cool, wet spring, when high flows out of the Similkameen (not shown; data not available) inhibited Okanogan temperature increases until early August (ibid).

Site Thermal Comparisons

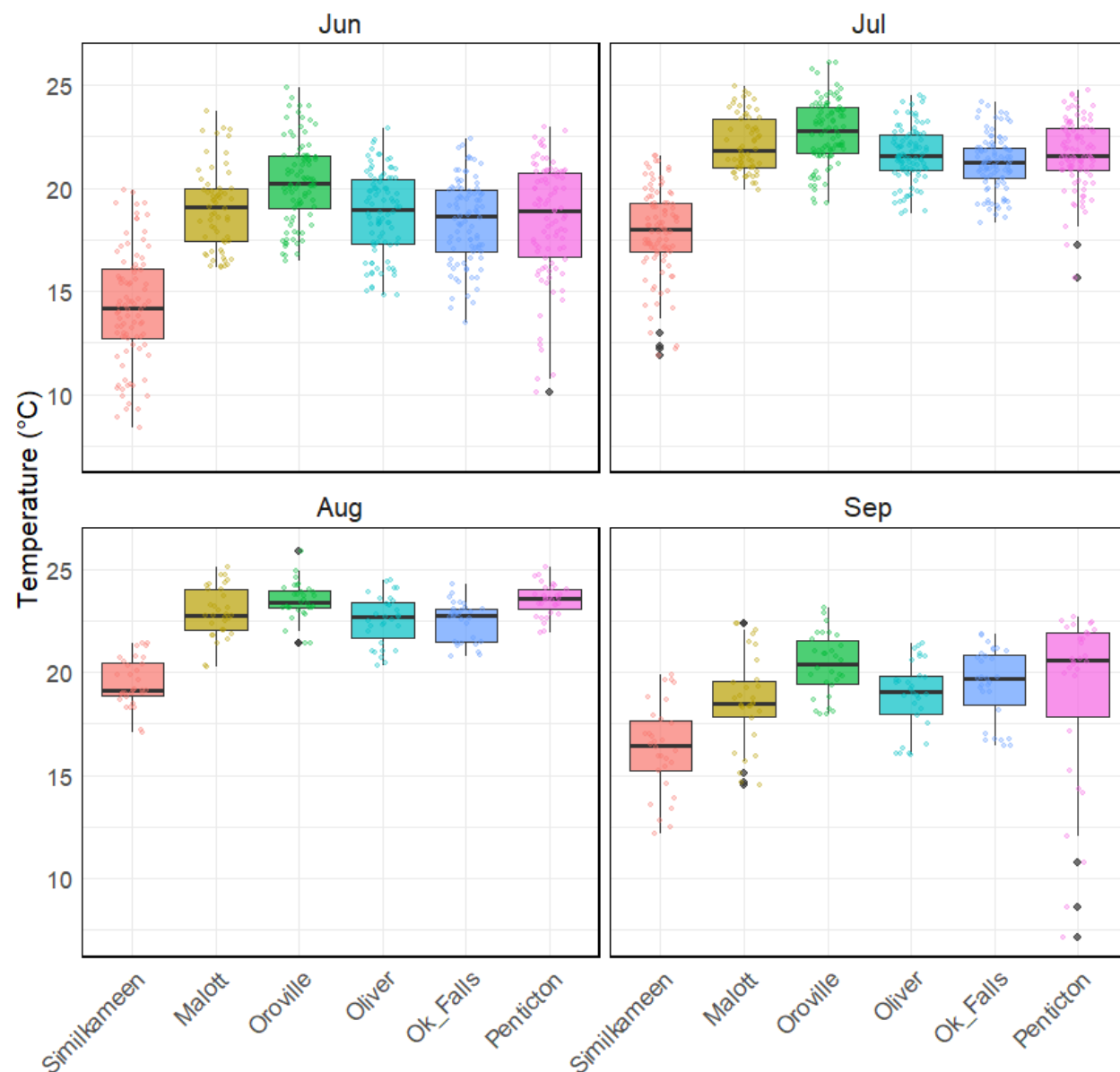


Figure 9. Comparison of observed daily mean water temperature in the Okanagan/Okanogan watershed, by location and month, for dates where complete monthly temperature data are available at all sites (2016, 2019, 2020). The Okanagan River at Oroville (WA) (green) is the site of the warmest water in June and July. The Okanagan River at Malott (WA) (gold) is at its coolest in June and September (when Similkameen discharge (red) asserts a cooling effect).

While temperatures at Penticton (upper Okanagan River) appear warmer than other Okanagan River sites (i.e., Oliver and Okanagan Falls) in August and September, data common to all three locations in these months were limited to 2020, and may not be representative. Statistical analyses based on ANOVA and mixed-effects models indicated no consistent evidence of differences in mean temperature among Okanagan (BC) sites at Oliver (cyan), Okanagan Falls (blue) and Penticton (pink) after accounting for seasonal and interannual effects ($p > 0.05$).

GCM Projections

Okanogan River at Malott, WA

Okanogan River at Malott (WA)

Projected Mean Daily Temperature

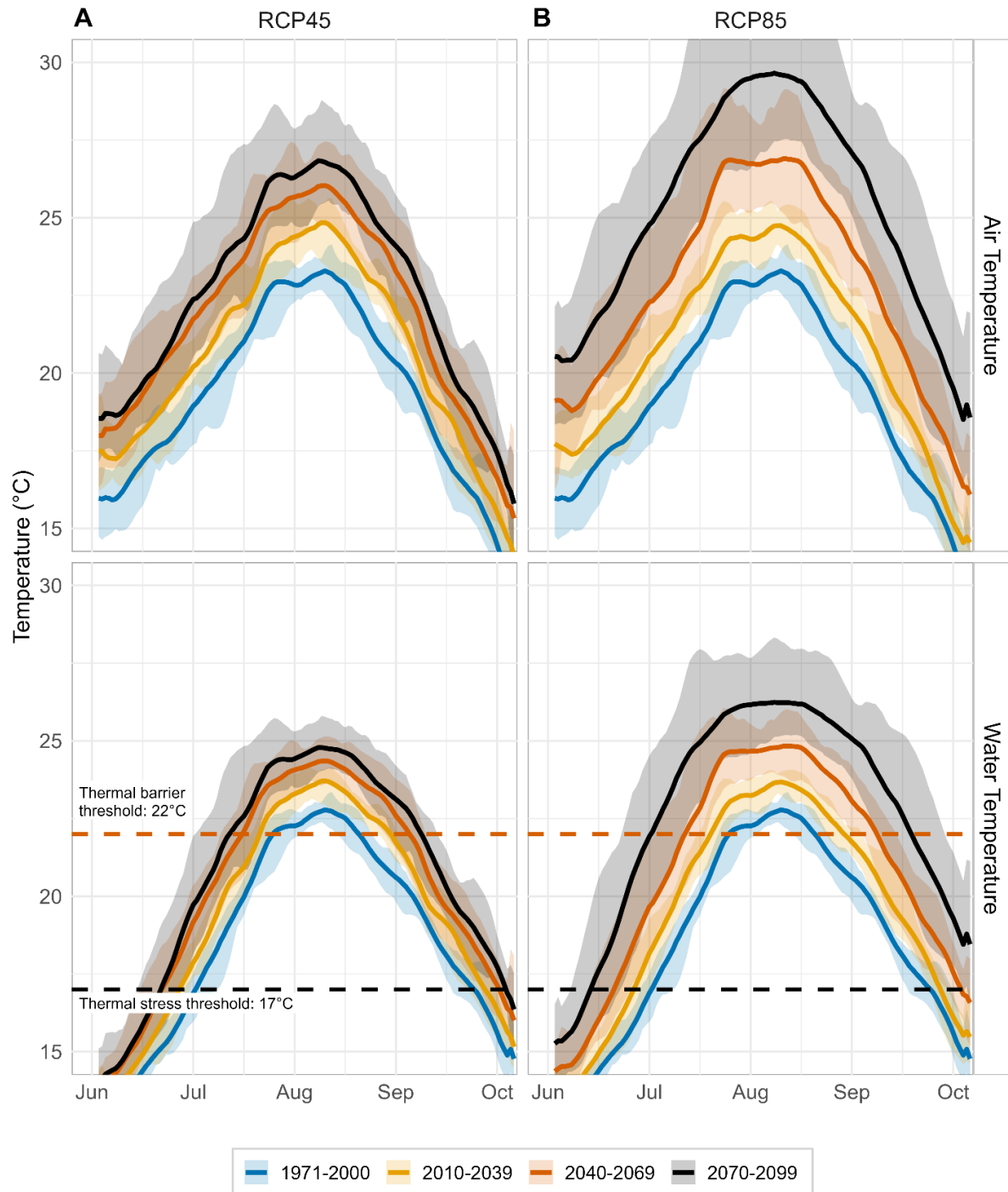


Figure 10. GCM projections in mean daily air temperature (top) and mean daily water temperature (bottom) for Okanogan River at Malott (WA), by RCP and 30-year time-block. Ribbons reflect min-to-max variation across the 10 GCMs.

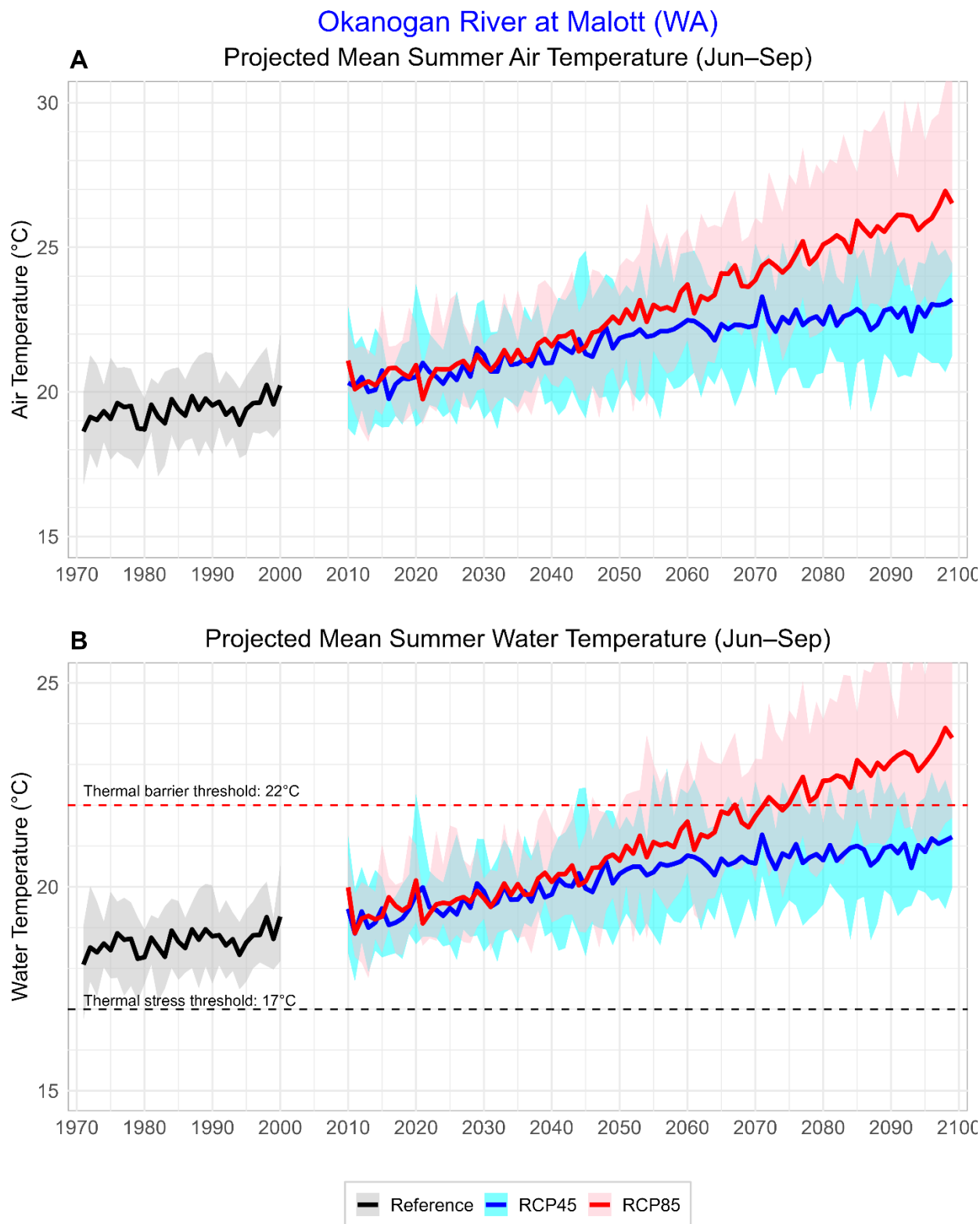


Figure 11. Annual GCM projections in mean summer (Jun–Sep) air temperature (A) and water temperature (B) for Okanogan River at Malott (WA), by year and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

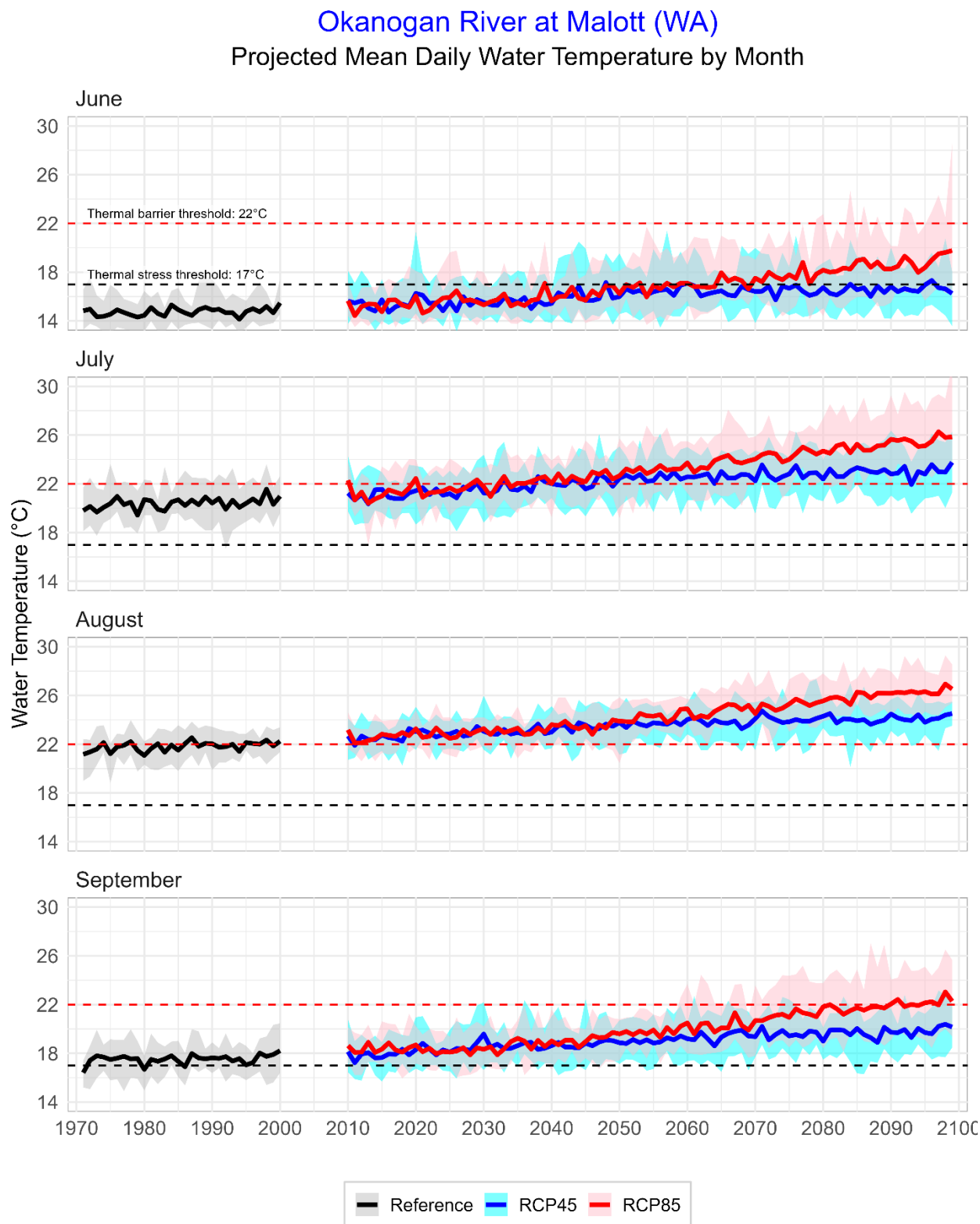


Figure 12. Annual GCM projections in mean water temperature for Okanogan River at Malott (WA), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

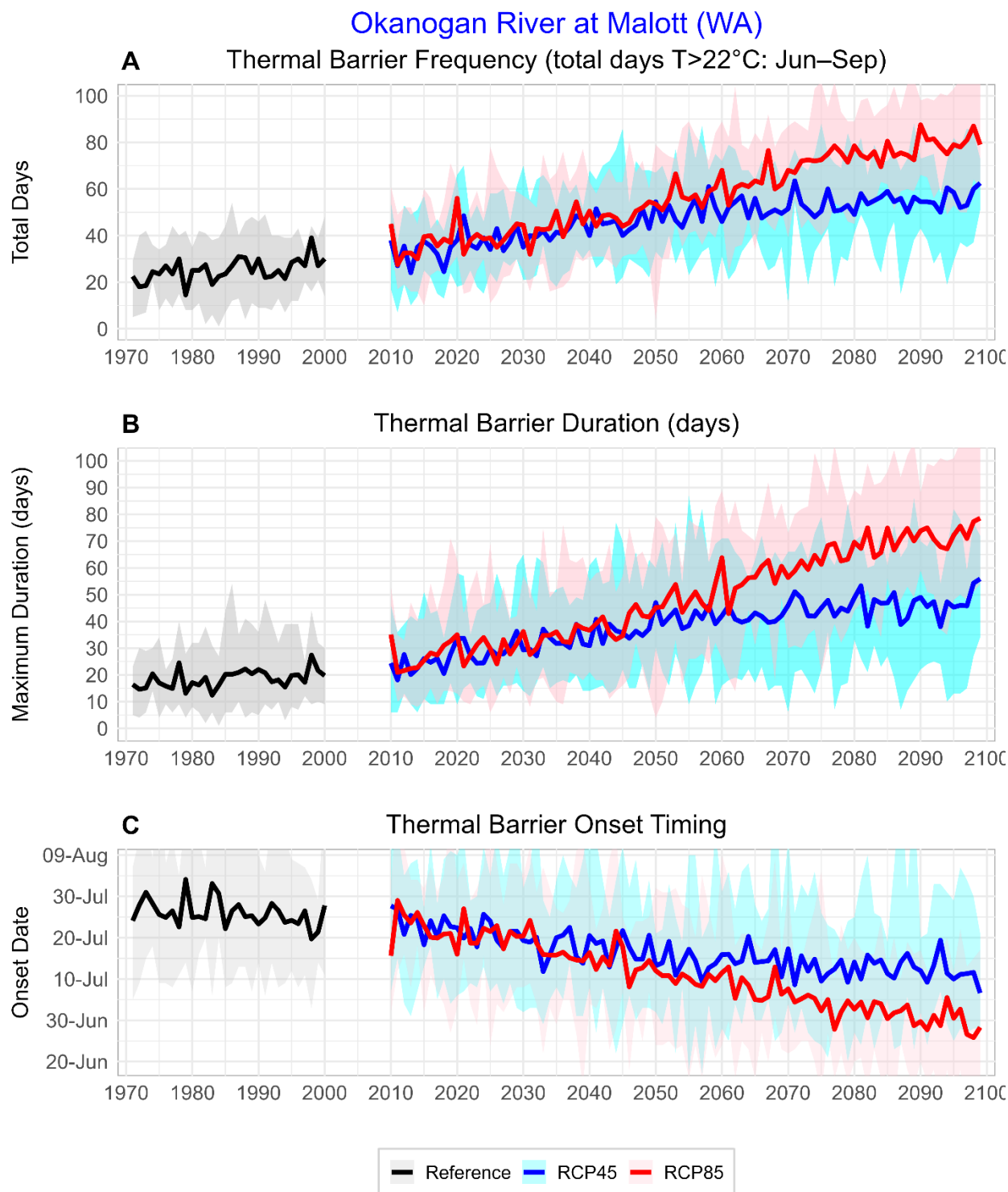


Figure 13. Annual GCM projections in (A) thermal barrier frequency (total days), (B) duration (continuous days), and (C) onset timing (date) for Okanogan River at Malott (WA), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

Okanogan River at Malott (WA)

Monthly Thermal Barrier Frequency

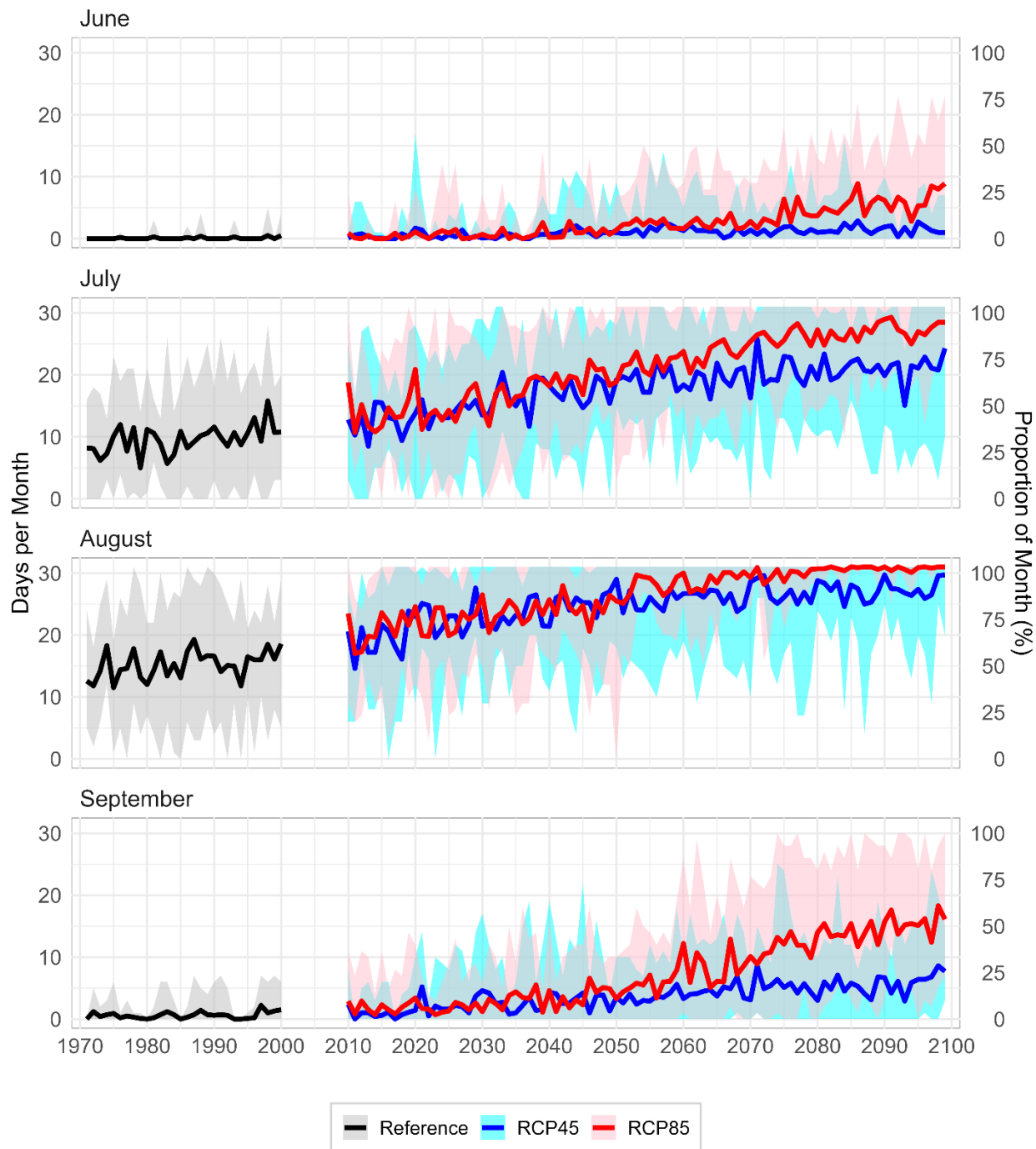


Figure 14. Annual GCM projections in thermal barrier frequency (total days) for Okanogan River at Malott (WA), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

Okanogan River at Malott (WA)

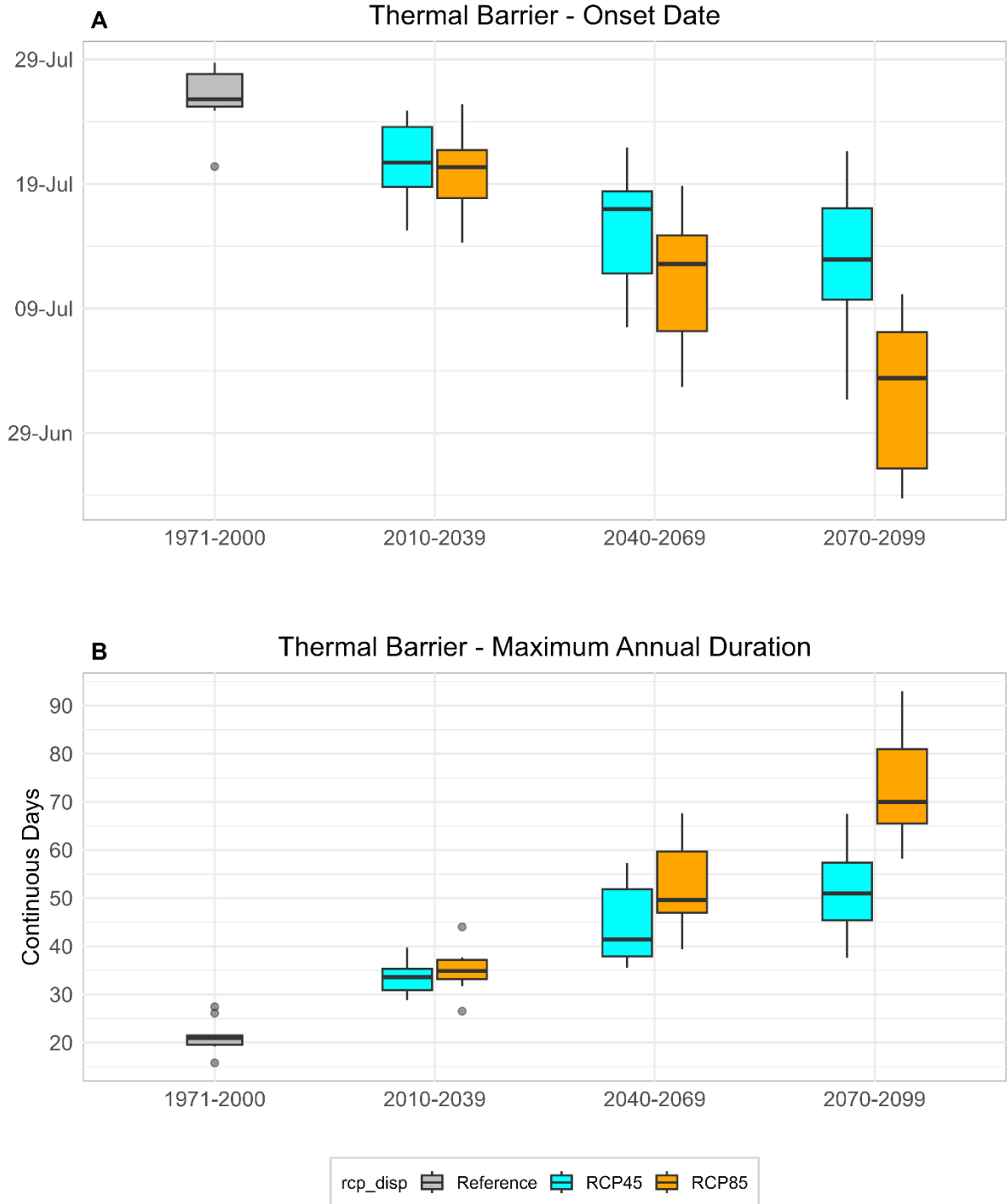


Figure 15. GCM boxplot projections in (A) onset timing (date) and (B) duration (continuous days) of annual thermal barrier events for Okanogan River at Malott (WA), by RCP and 30-year time-block. Boxes reflect quartiles and whiskers min-to-max range across the 10 GCMs.

Okanogan River at Oroville, WA

Okanogan River at Oroville (WA)

Projected Mean Daily Temperature

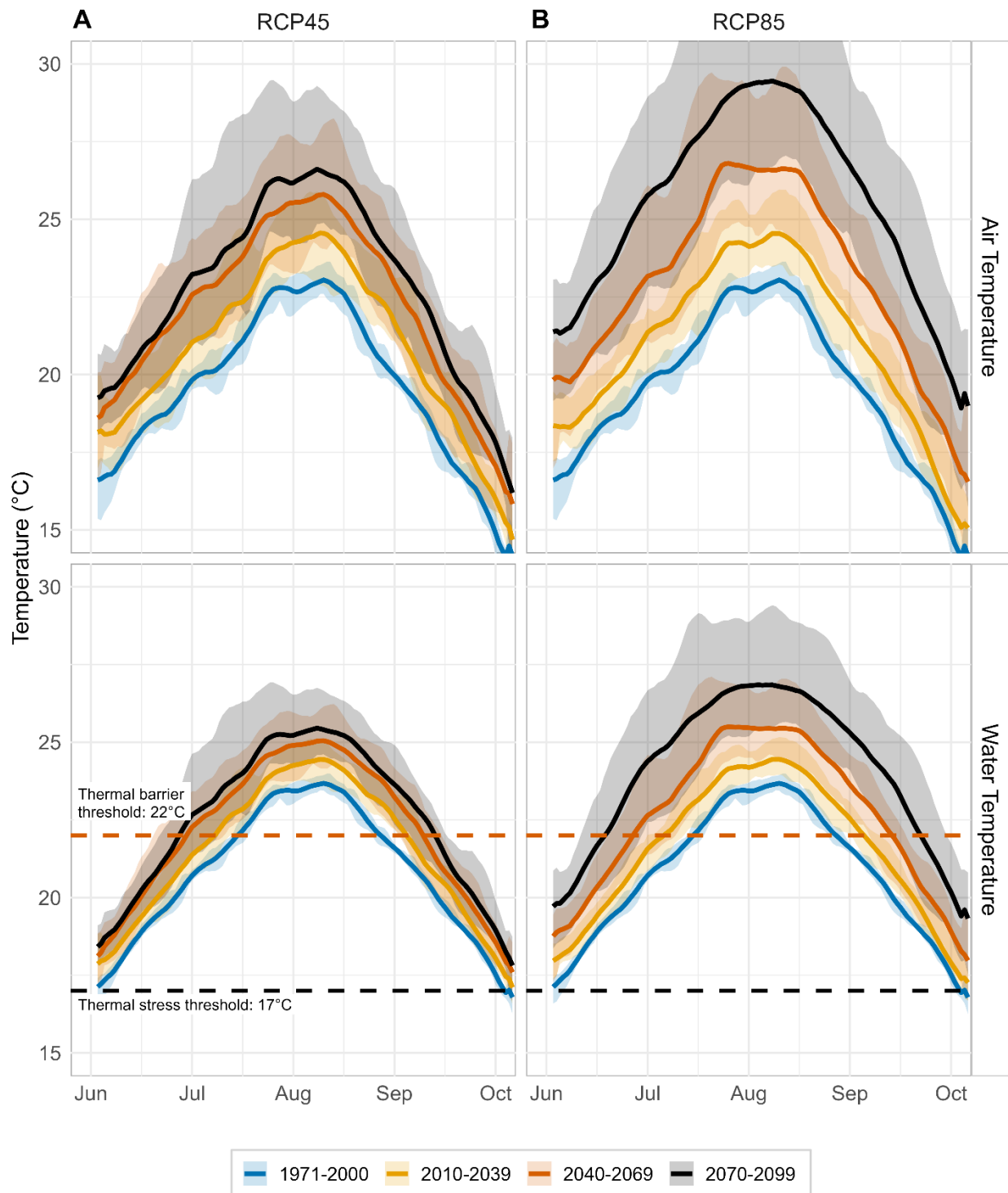


Figure 16. GCM projections in mean daily air temperature (top) and mean daily water temperature (bottom) for Okanogan River at Oroville (WA), by RCP and 30-year time-block.

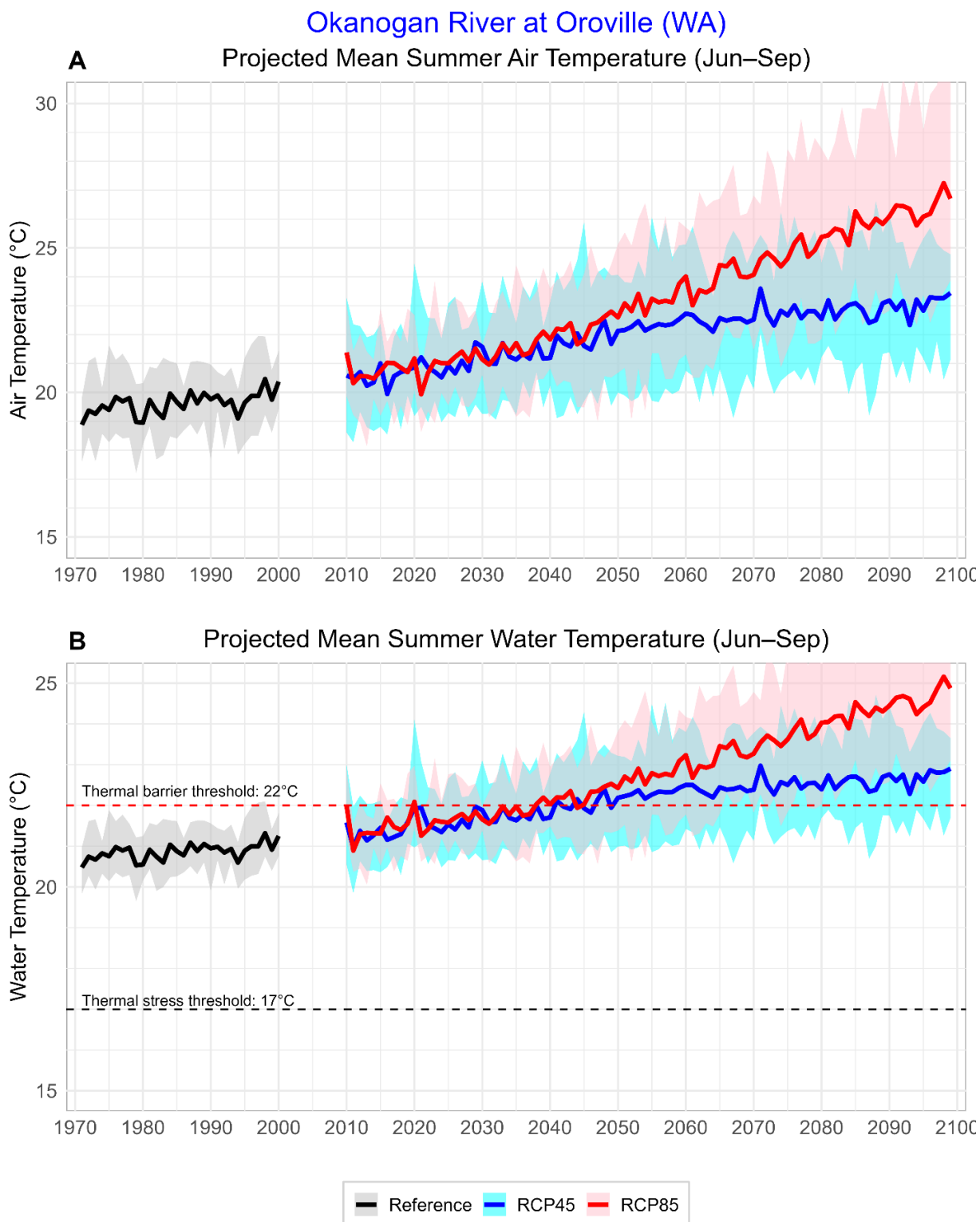


Figure 17. Annual GCM projections in mean summer (Jun–Sep) air temperature (A) and water temperature (B) for Okanogan River at Oroville (WA), by RCP and 30-year time-block. Ribbons reflect min-to-max variation across the 10 GCMs.

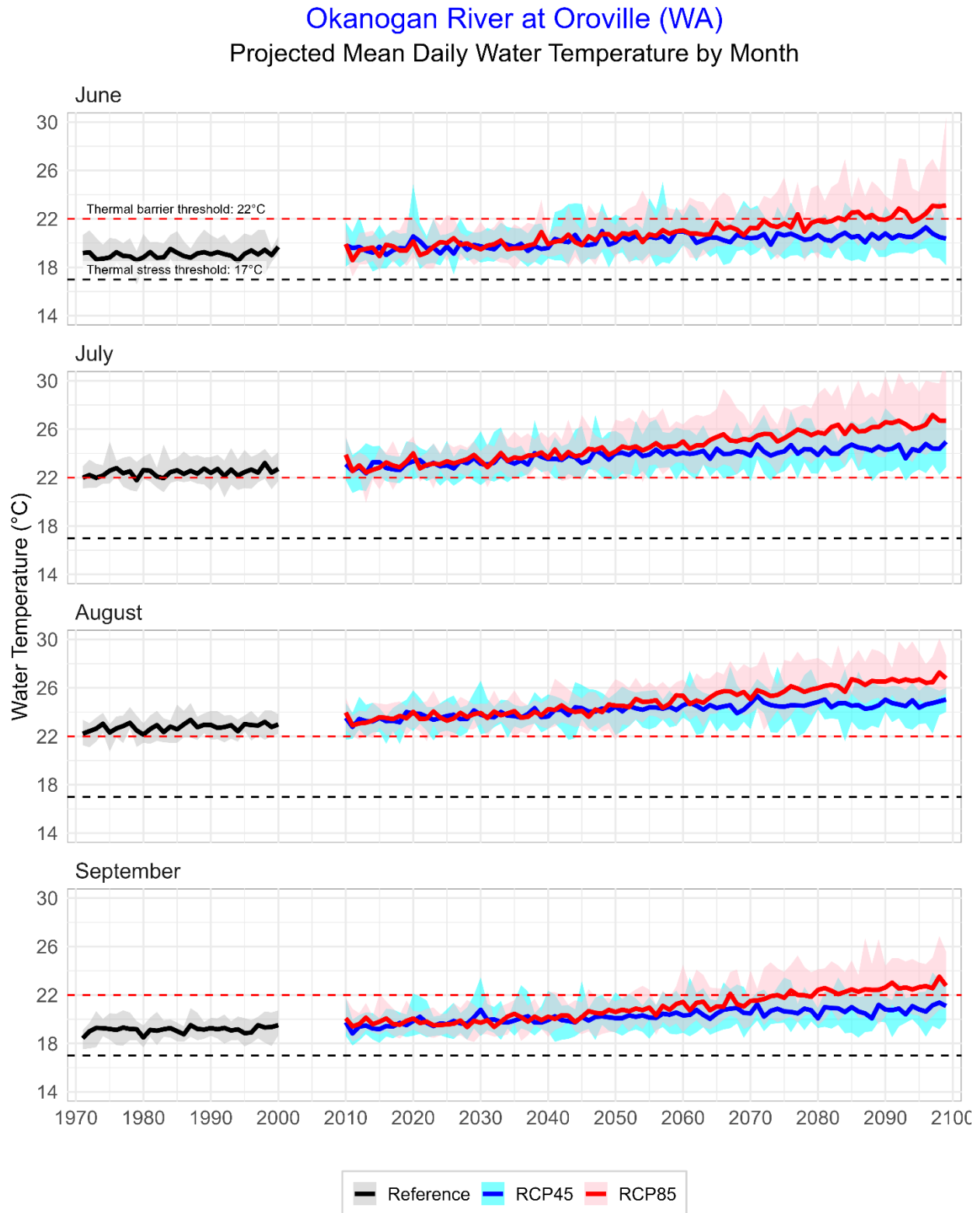


Figure 18. GCM projections in summer mean summer water temperature for Okanogan River at Oroville (WA), by month, year and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

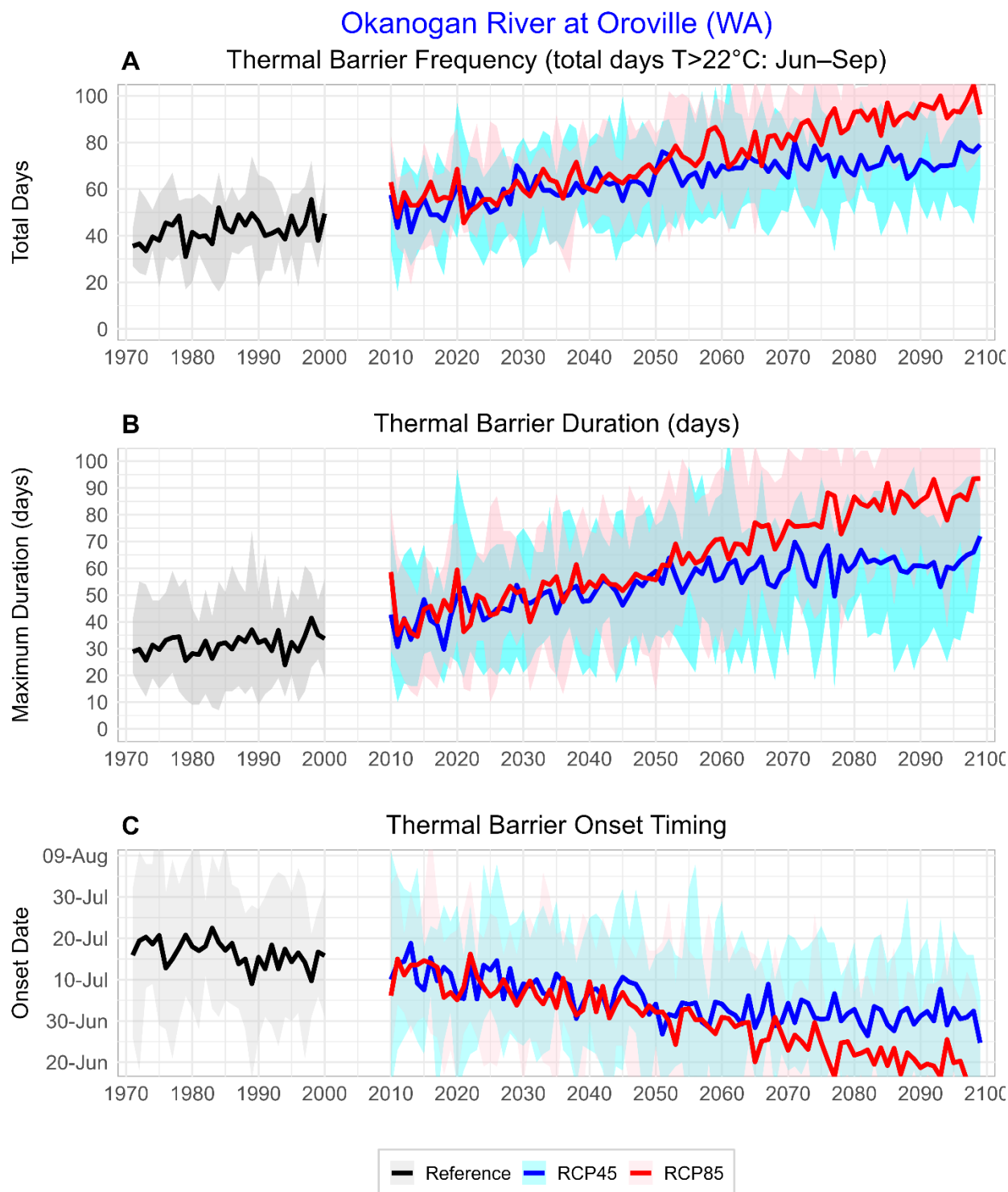


Figure 19. Annual GCM projections in (A) thermal barrier frequency (total days), (B) duration (continuous days), and (C) onset timing (date) for Okanogan River at Oroville (WA), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

Okanogan River at Oroville (WA)

Monthly Thermal Barrier Frequency

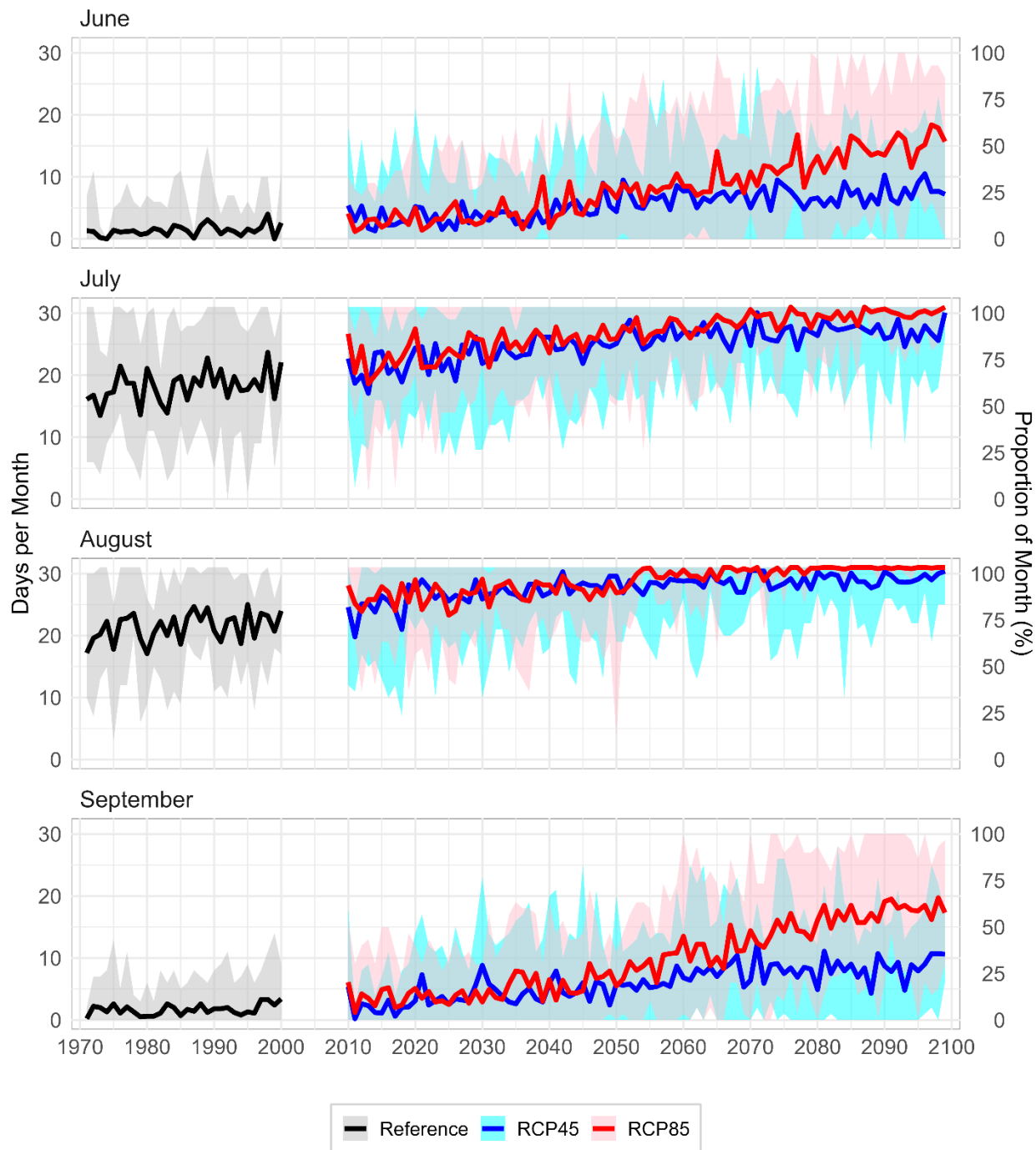


Figure 20. Annual GCM projections in thermal barrier frequency (total days) for Okanogan River at Oroville (WA), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

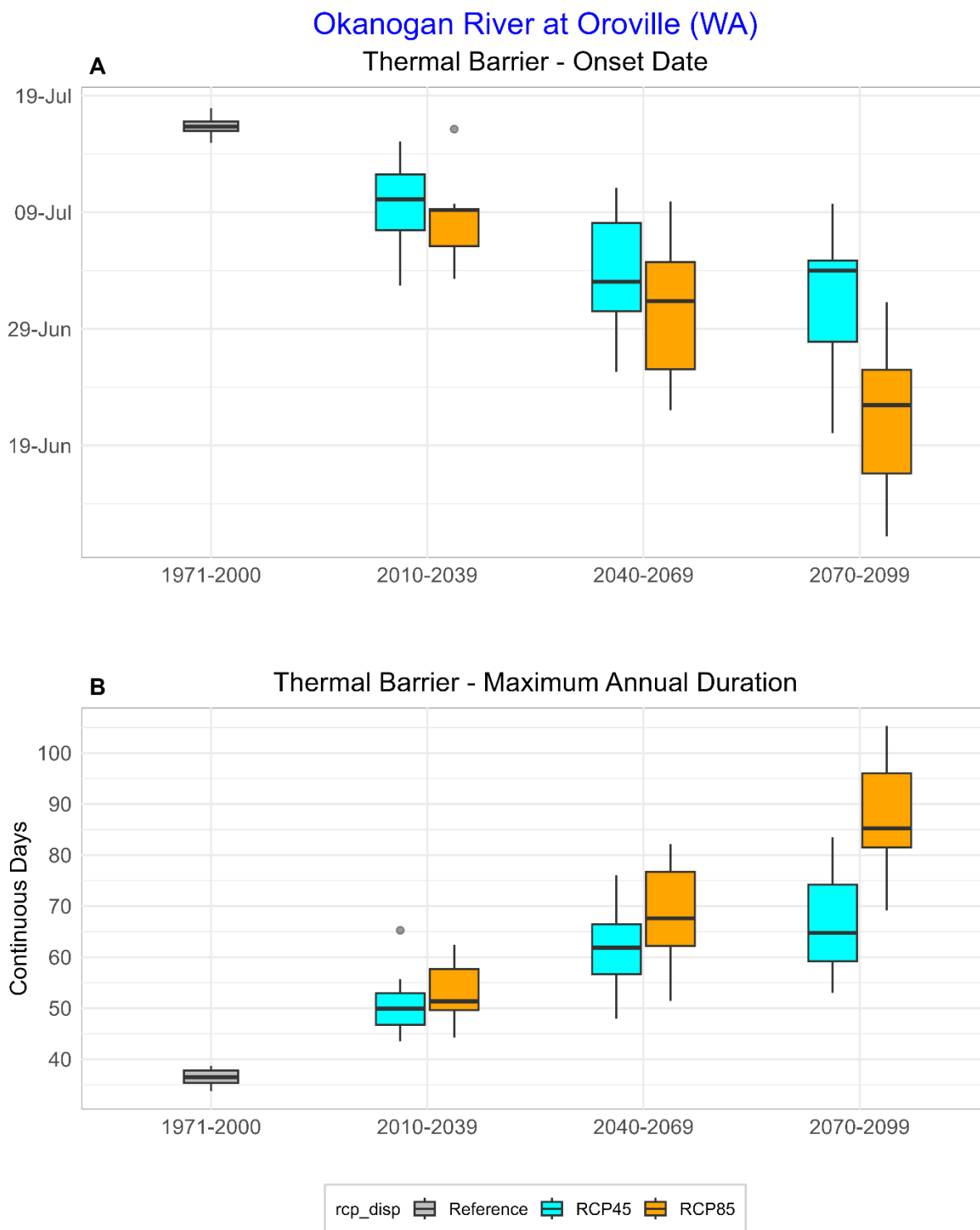


Figure 21. GCM boxplot projections in (A) onset timing (date) and (B) duration (continuous days) of annual thermal barrier events for Okanogan River at Oroville (WA), by RCP and 30-year time-block. Boxes reflect quartiles and whiskers min-to-max range across the 10 GCMs.

Similkameen River at Nighthawk, WA

Similkameen River at Nighthawk (WA)

Projected Mean Daily Temperature

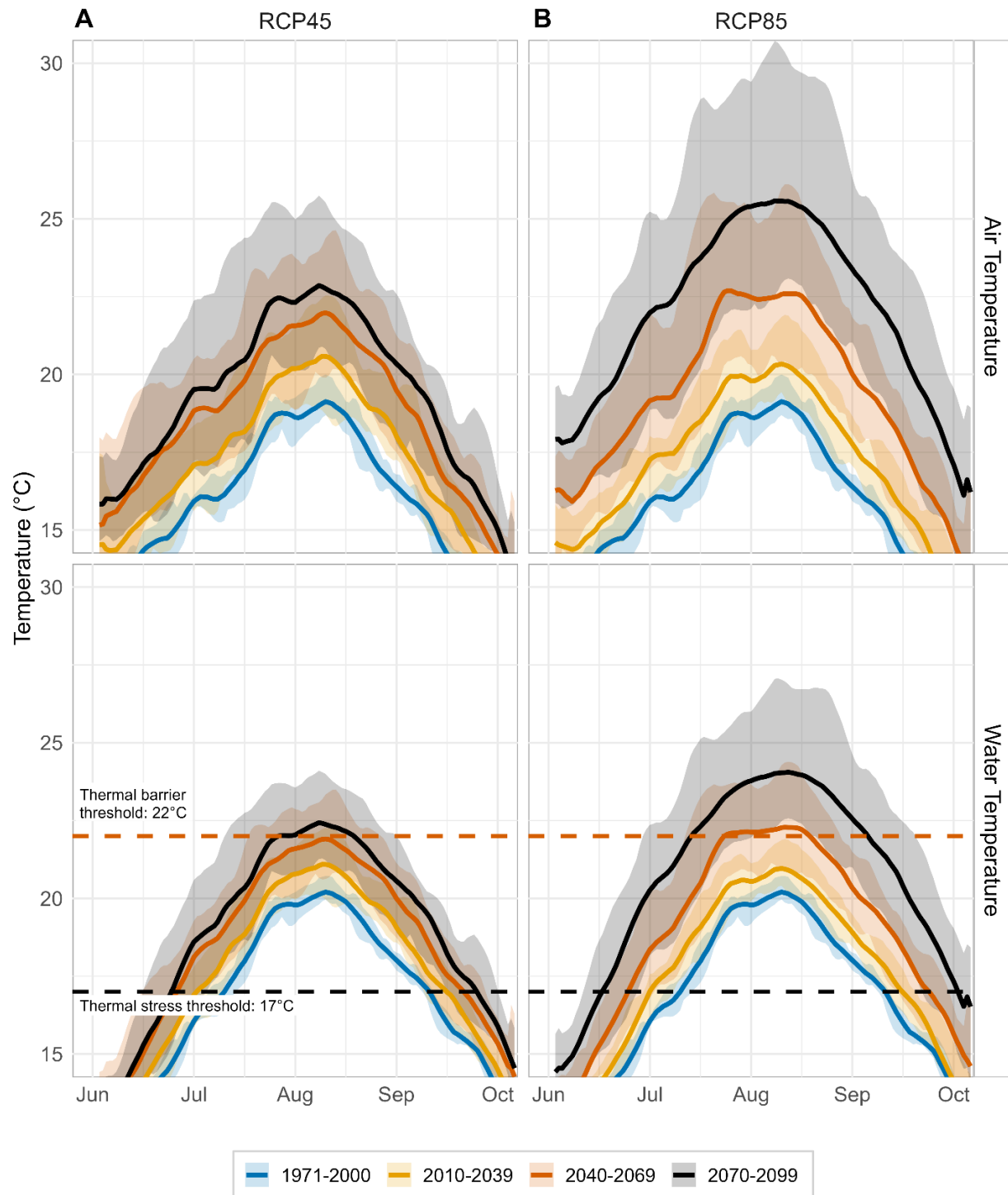


Figure 22. GCM projections in mean daily air temperature (top) and mean daily water temperature (bottom) for Similkameen River at Nighthawk (WA), by RCP and 30-year time-block.

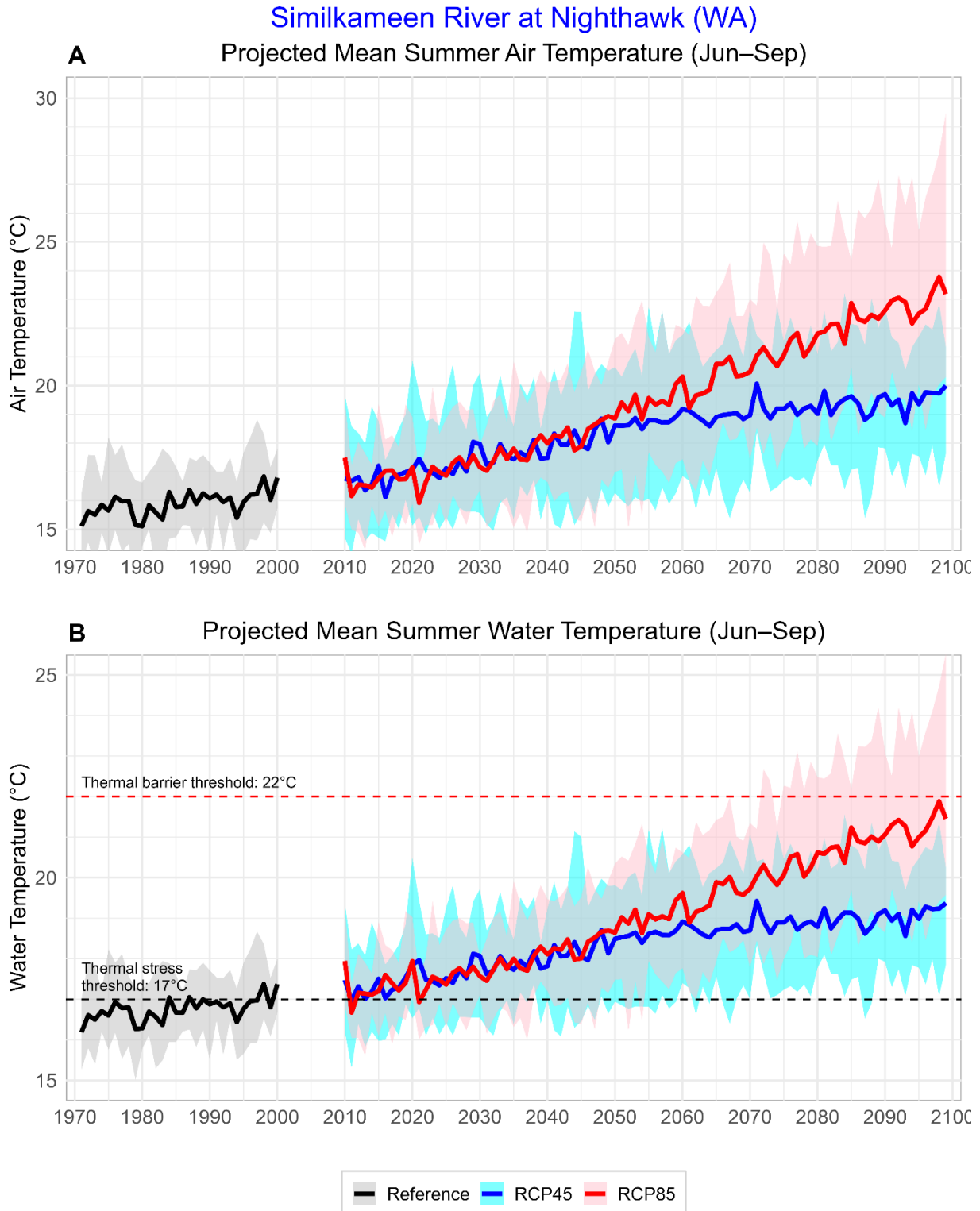


Figure 23. Annual GCM projections in mean summer (Jun–Sep) air temperature (A) and water temperature (B) for Similkameen River at Nighthawk (WA), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

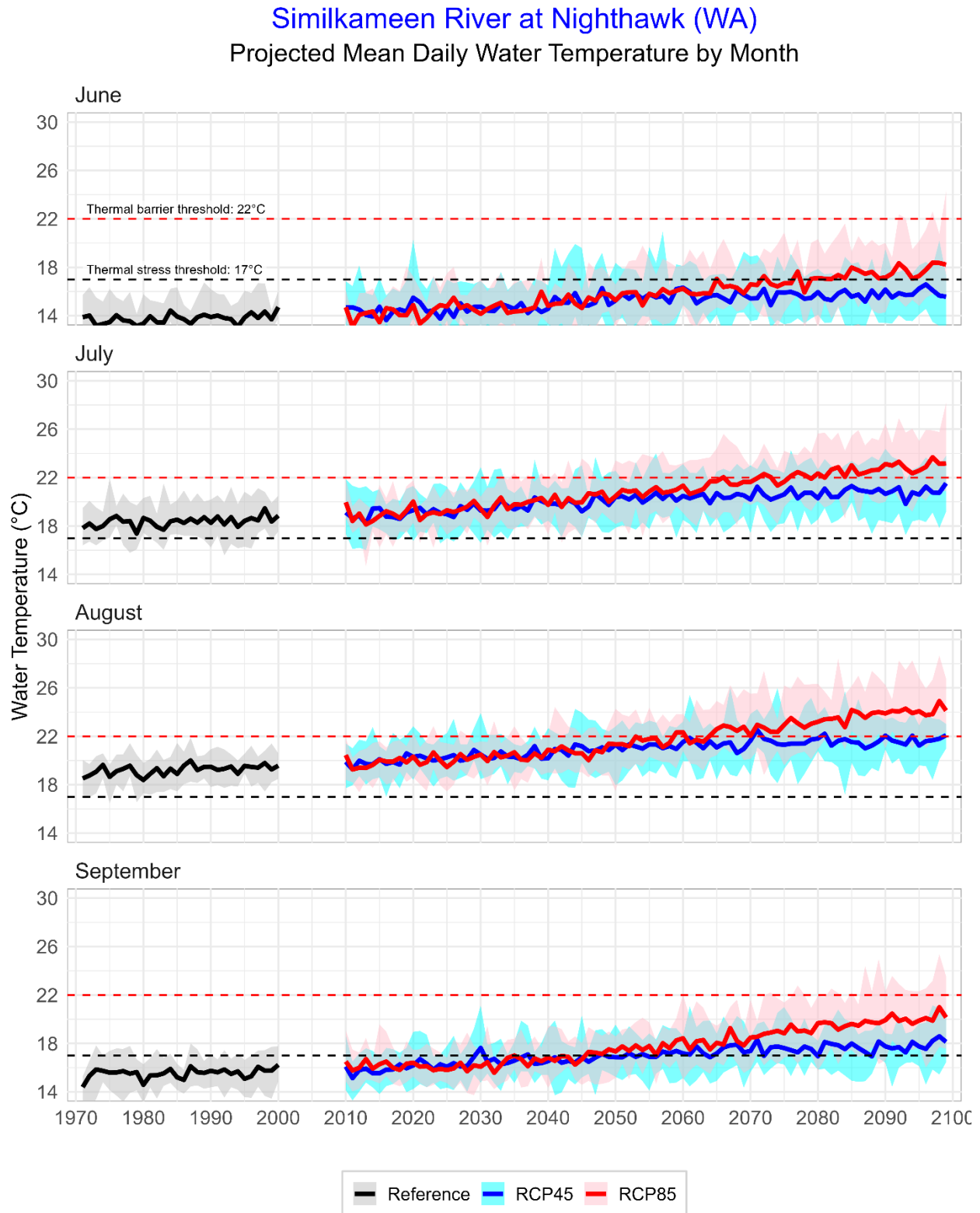


Figure 24. Annual GCM projections in mean summer water temperature for Similkameen River at Nighthawk (WA), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

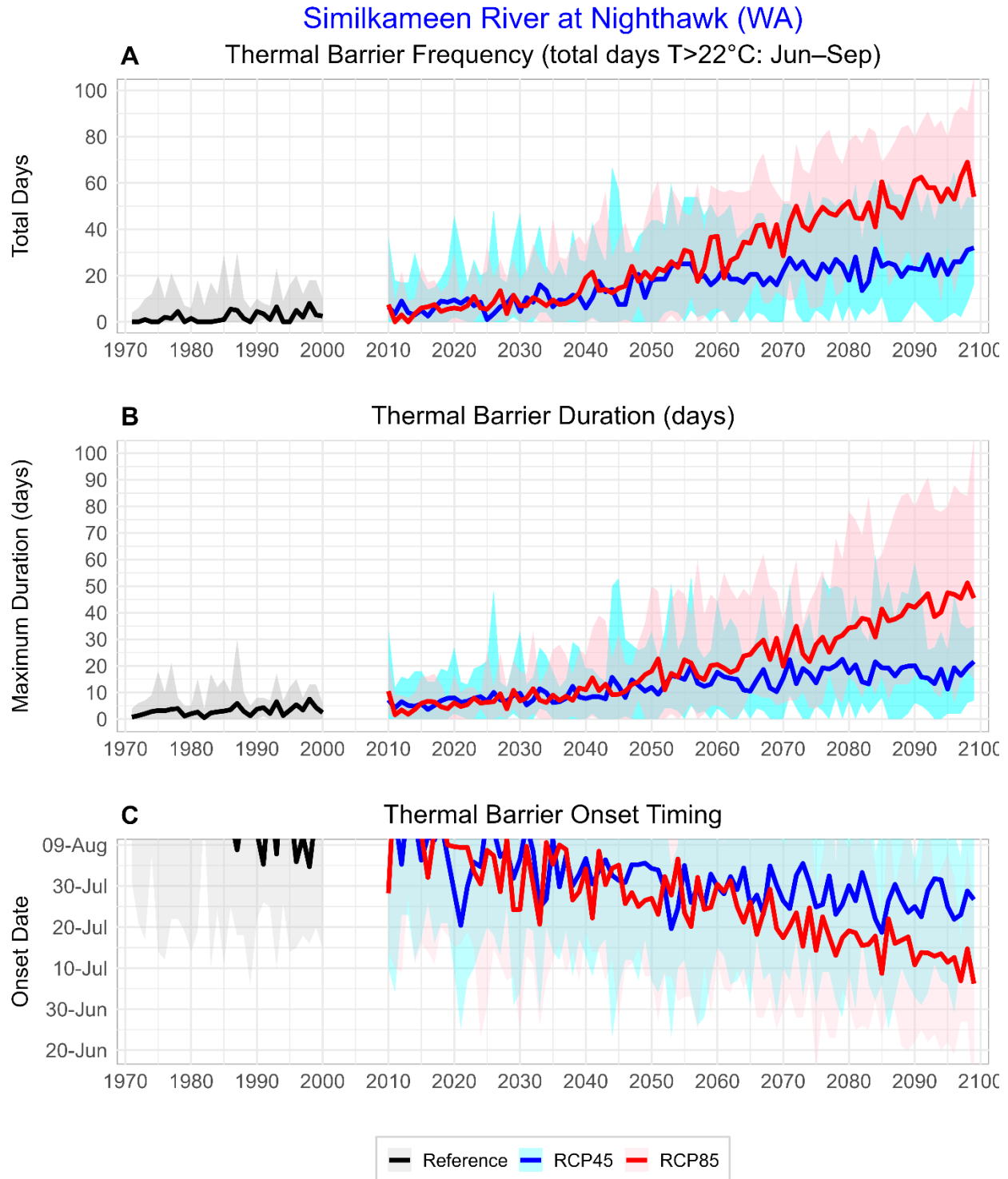


Figure 25. Annual GCM projections in (A) thermal barrier frequency (total days), (B) duration (continuous days), and (C) onset timing (date) for Similkameen River at Nighthawk (WA), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs. Y-axis maximum in Figure 25C is limited (at 09-Aug) to period when thermal barrier onset timing is a major factor in adult upstream migration success; after mid-August, water temperatures progressively decrease. Projections show that although temperature conditions in the Similkameen have not historically been an issue for Sockeye holding in the tributary, conditions may become increasingly limiting to July migrants.

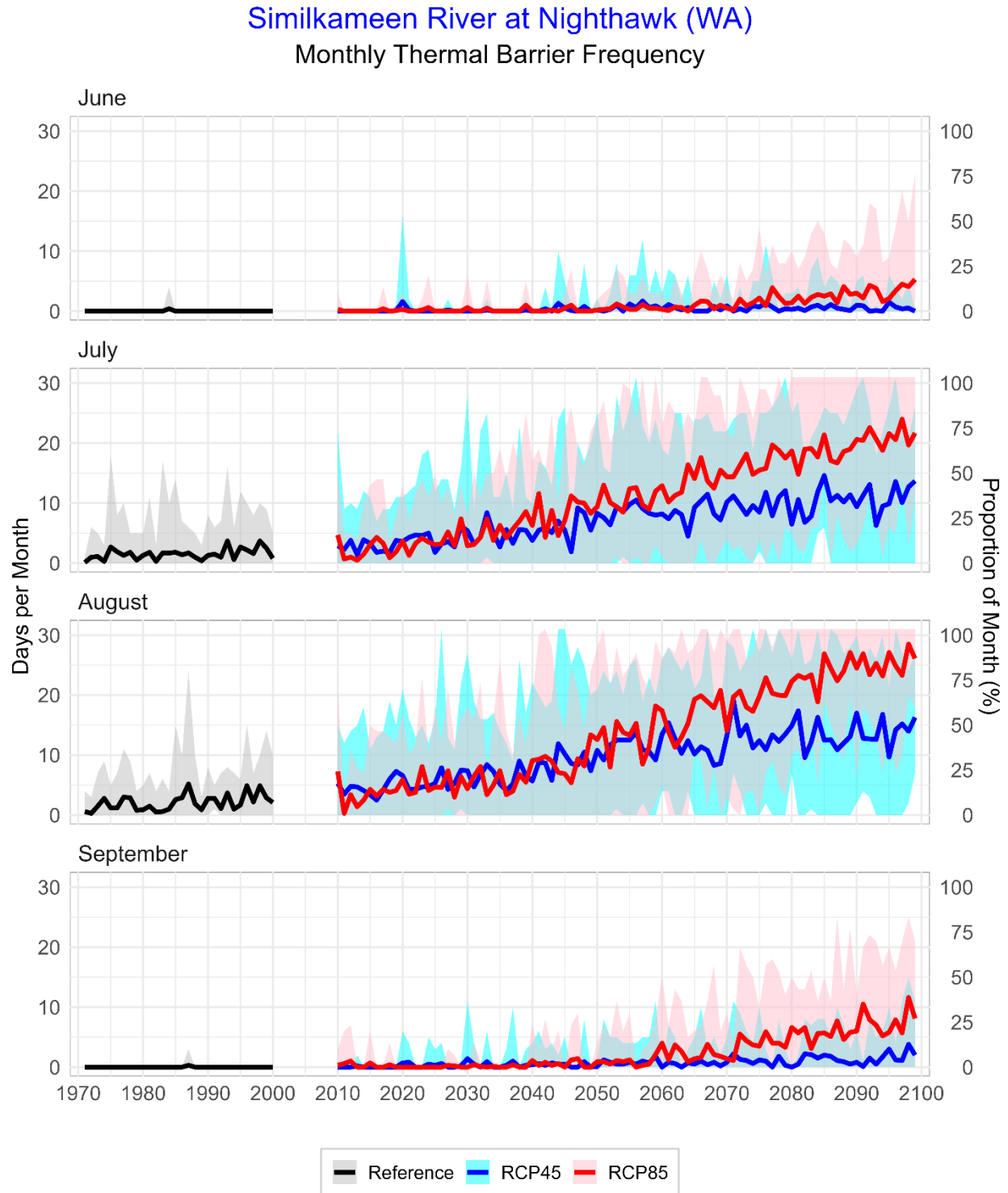


Figure 26. Annual GCM projections in thermal barrier frequency (total days) for Similkameen River at Nighthawk(WA), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

Similkameen River at Nighthawk (WA)

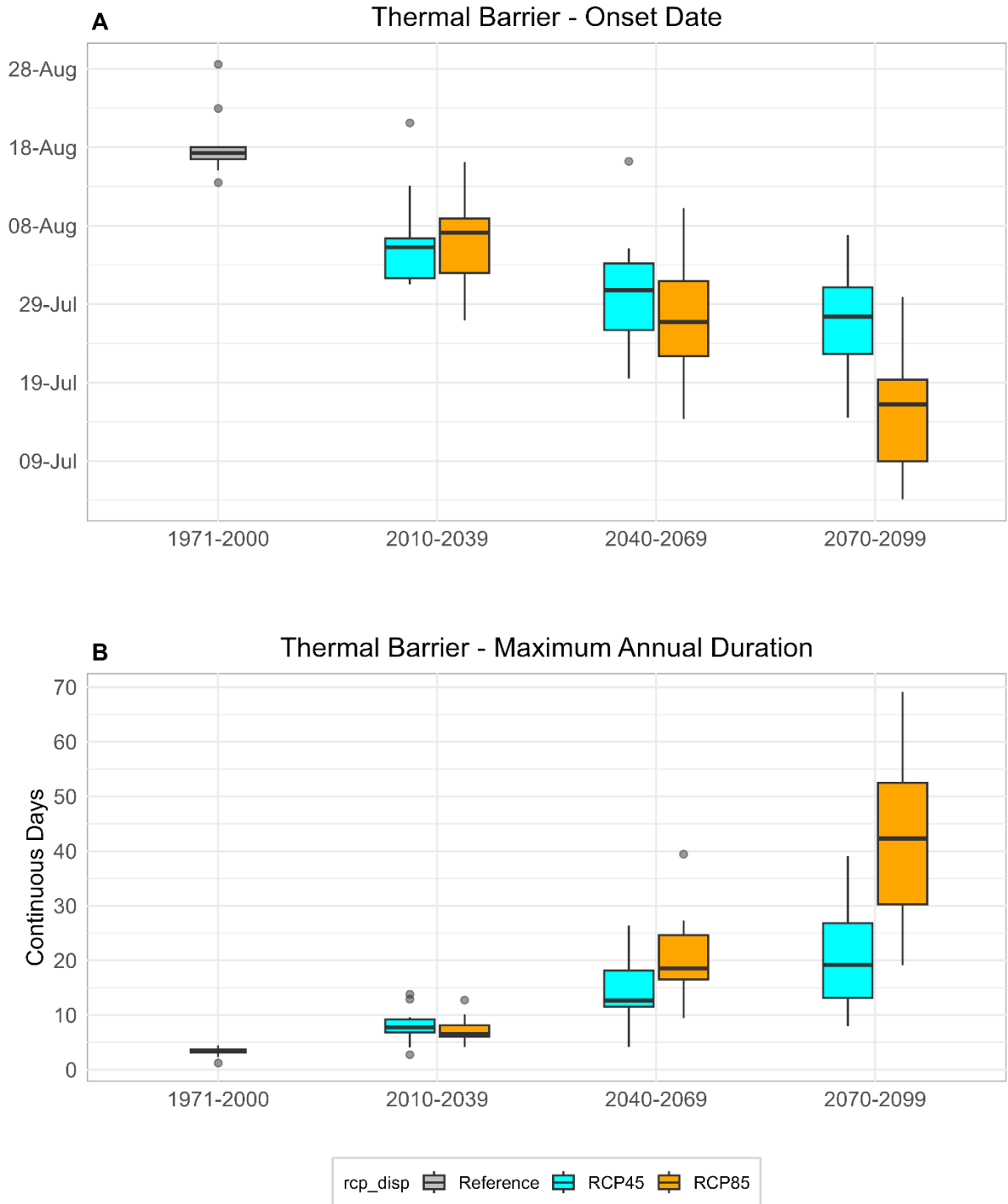


Figure 27. GCM boxplot projections in (A) onset timing (date) and (B) duration (continuous days) of annual thermal barrier events for Similkameen River at Nighthawk (WA), by RCP and 30-year time-block. Boxes reflect quartiles and whiskers min-to-max range across the 10 GCMs.

Okanagan River at Oliver, BC

Okanagan River at Oliver (BC)

Projected Mean Daily Temperature

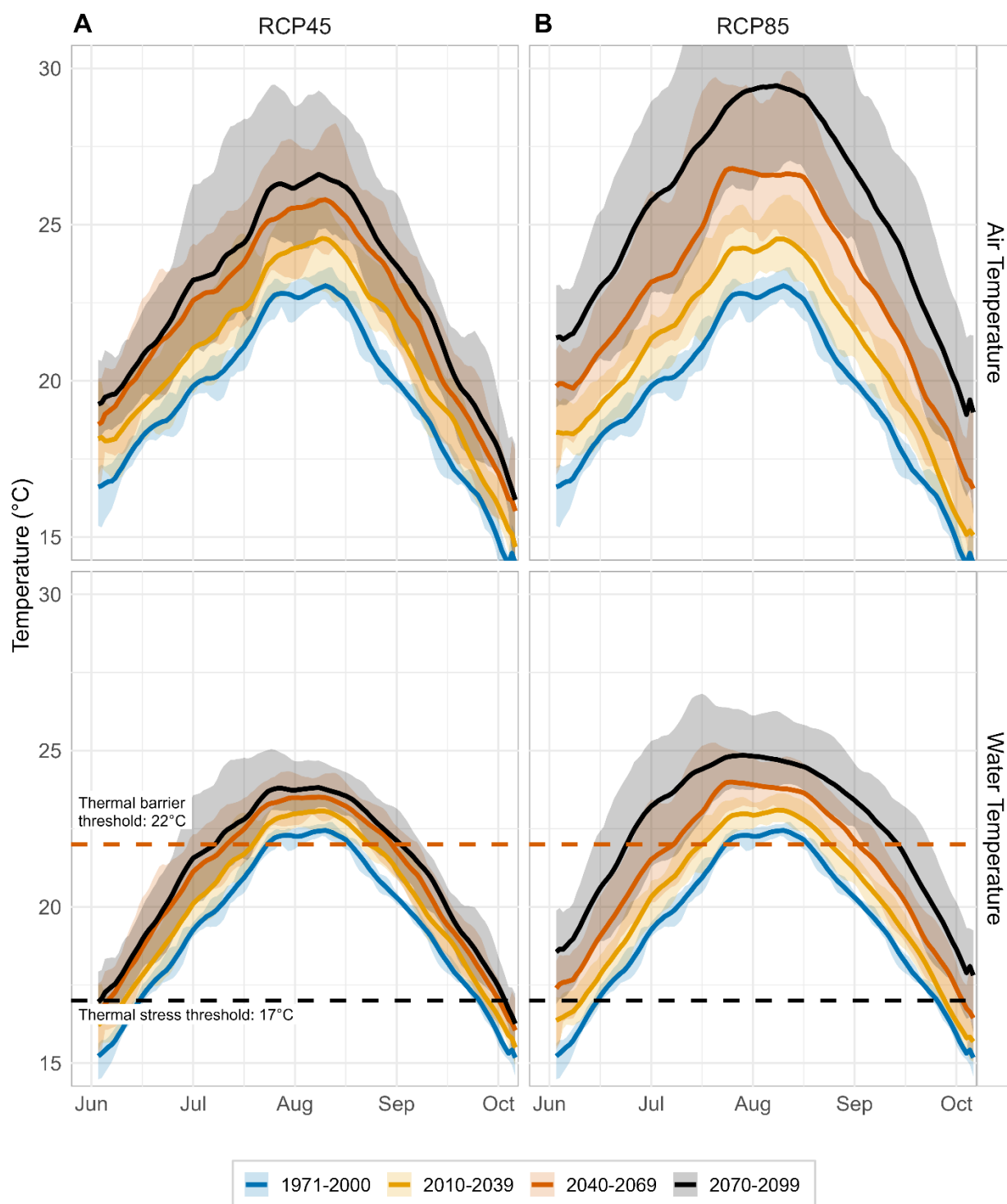


Figure 28. GCM projections in mean daily air temperature (top) and mean daily water temperature (bottom) for Okanagan River at Oliver (BC), by RCP and 30-year time-block.

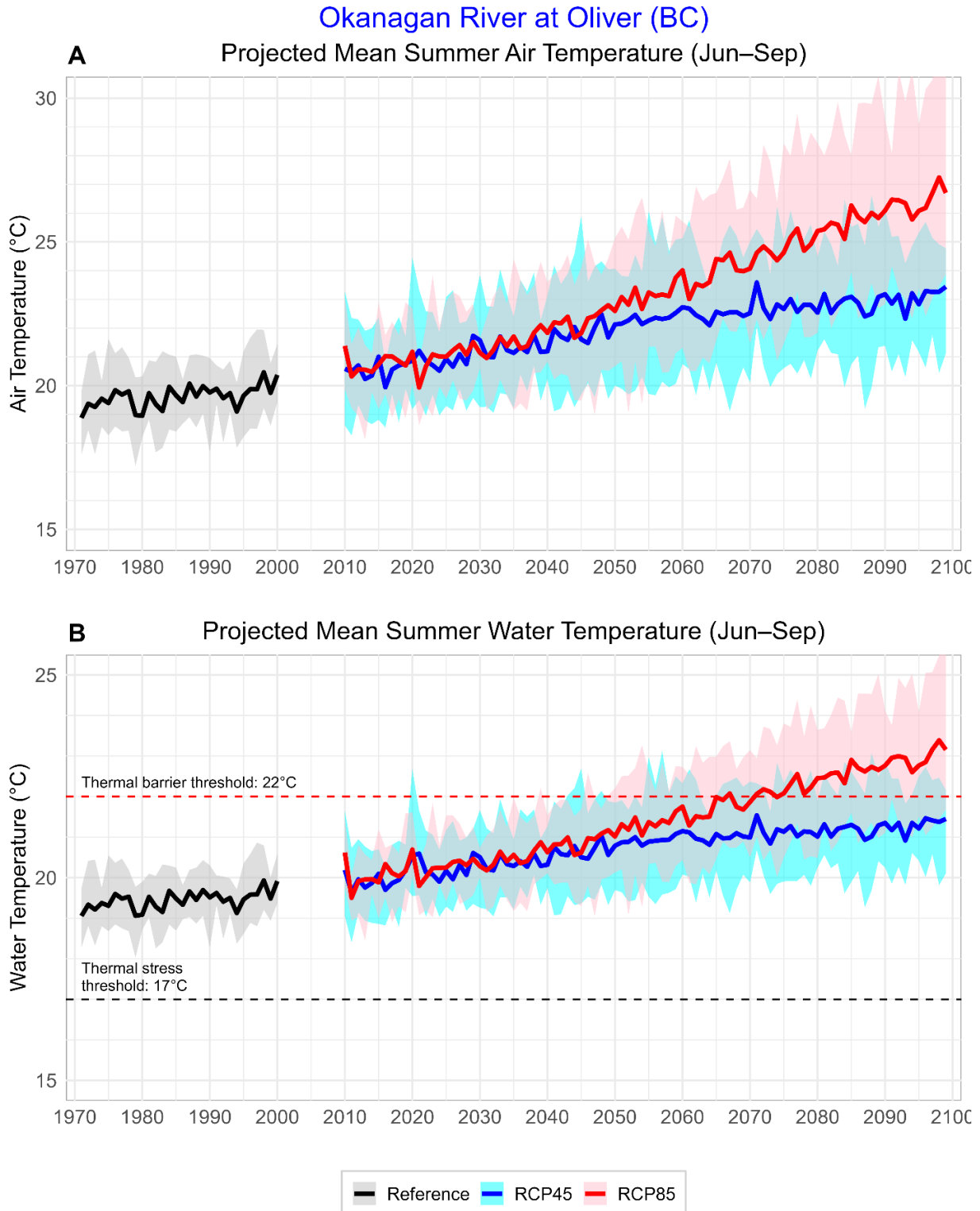


Figure 29. Annual GCM projections in mean summer (Jun–Sep) air temperature (A) and water temperature (B) for Okanagan River at Oliver (BC), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

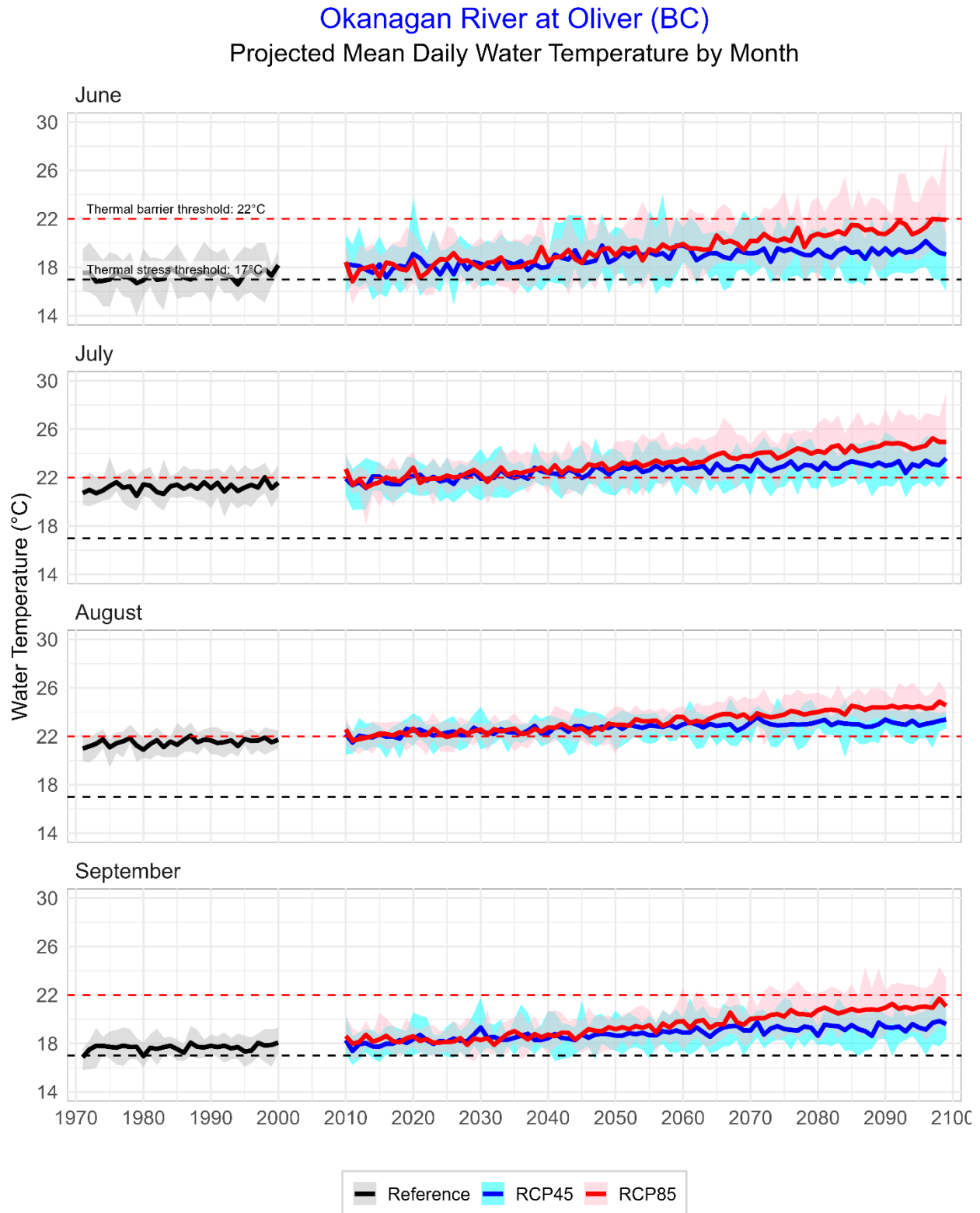


Figure 30. Annual GCM projections in mean summer water temperature for Okanagan River at Oliver (BC), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

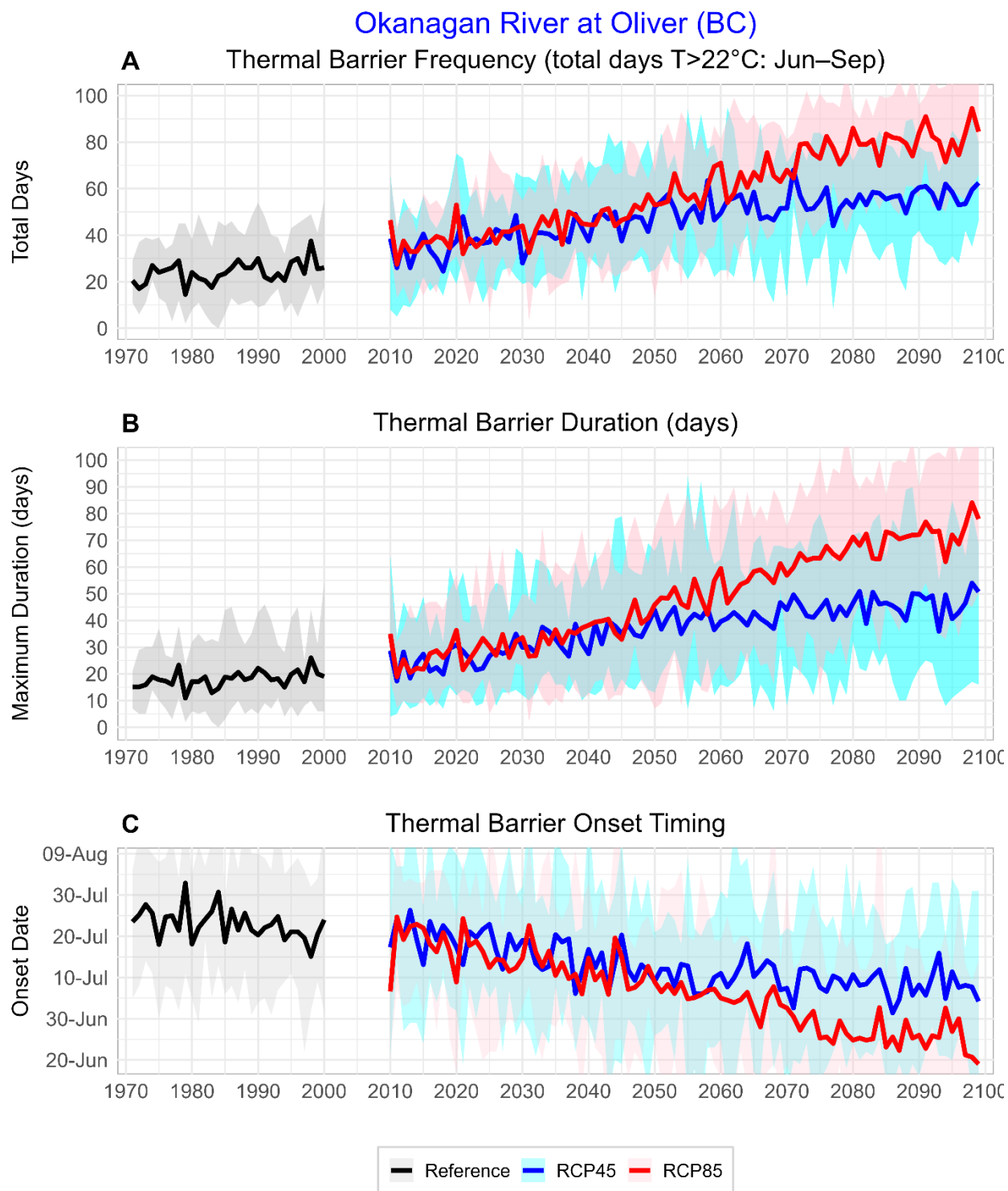


Figure 31. Annual GCM projections in (A) thermal barrier frequency (total days), (B) duration (continuous days), and (C) onset timing (date) for Okanagan River at Oliver (BC), by RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

Okanagan River at Oliver (BC)

Monthly Thermal Barrier Frequency

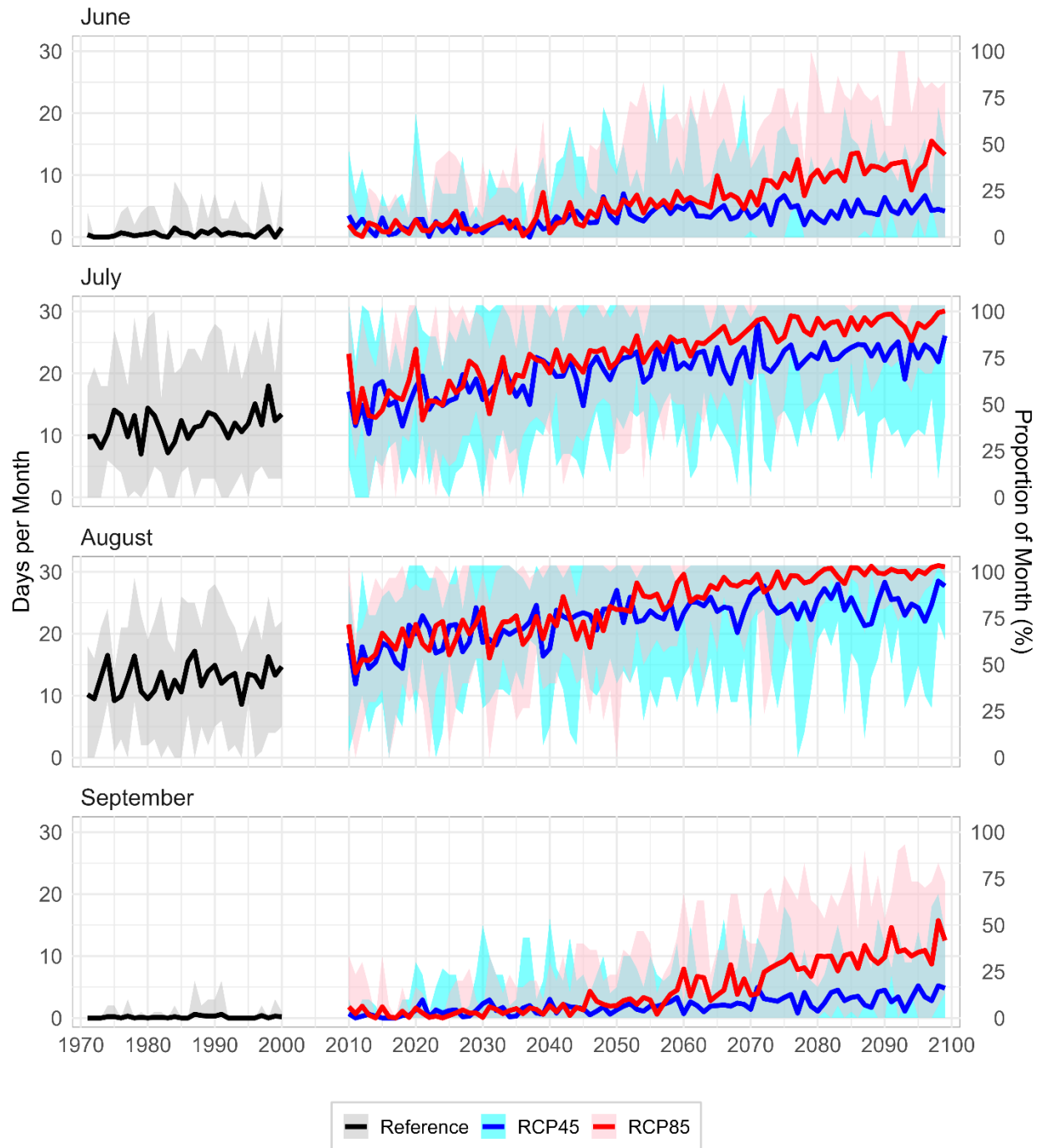


Figure 32. Annual GCM projections in thermal barrier frequency (total days) for Okanagan River at Oliver (BC), by month and RCP. Ribbons reflect min-to-max variation across the 10 GCMs.

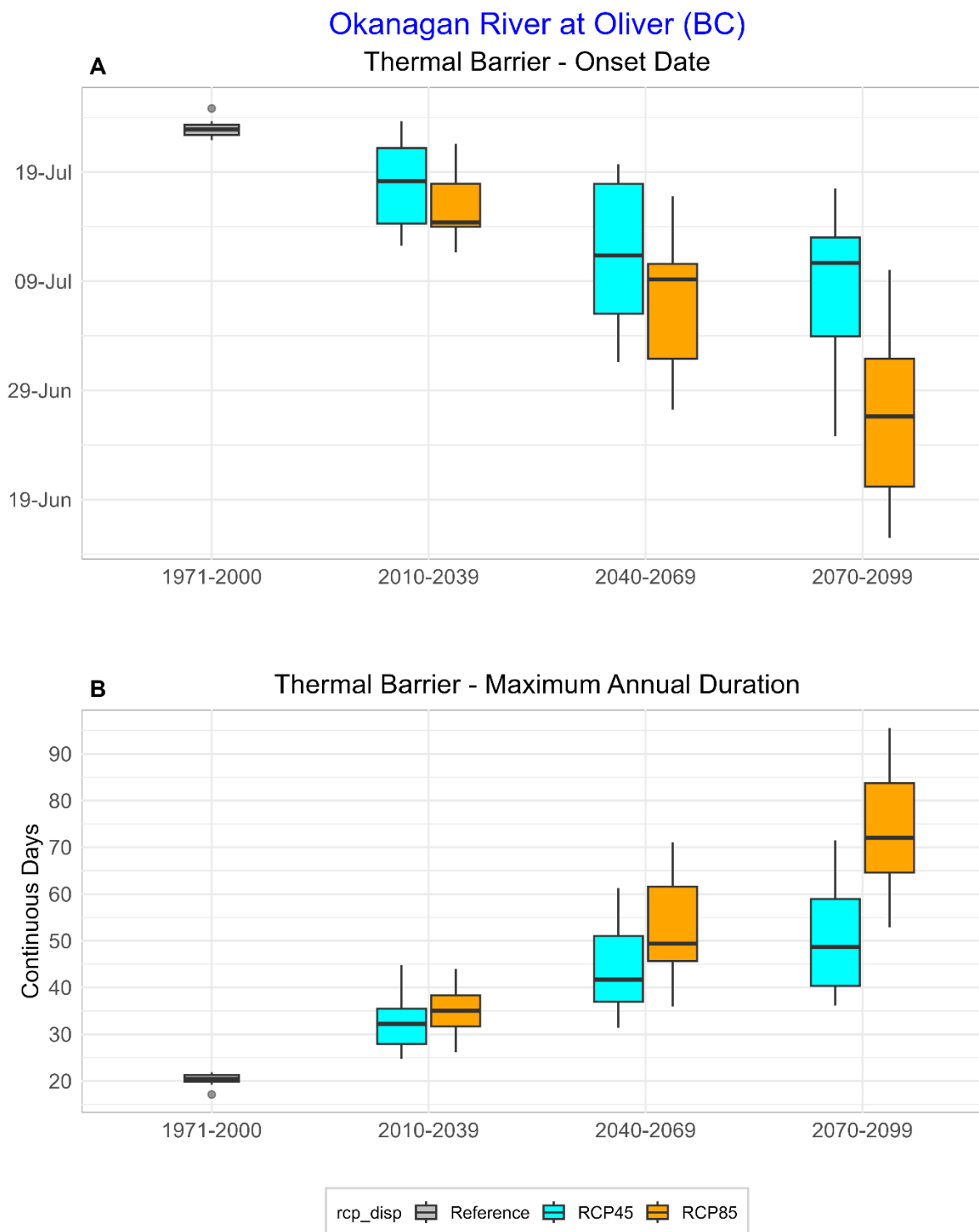


Figure 33. GCM boxplot projections in (A) onset timing (date) and (B) duration (continuous days) of annual thermal barrier events for Okanagan River at Oliver (BC), by RCP and 30-year time-block. Boxes reflect quartiles and whiskers min-to-max range across the 10 GCMs.

APPENDICES

GCM Air Temperature Bias Correction

Omak, WA

Station	Omak
Start	1992
End	2005

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
BNU-ESM	6	Jun	18.22	17.70	-0.52
	7	Jul	22.99	22.41	-0.58
	8	Aug	23.25	22.27	-0.98
	9	Sep	16.85	16.42	-0.43
BNU-ESM Total			20.33	19.70	-0.63
CanESM2	6	Jun	19.44	17.70	-1.74
	7	Jul	24.02	22.41	-1.61
	8	Aug	23.28	22.27	-1.01
	9	Sep	17.43	16.42	-1.01
CanESM2 Total			21.04	19.70	-1.34
CCSM4	6	Jun	19.52	17.70	-1.82
	7	Jul	23.34	22.41	-0.93
	8	Aug	22.80	22.27	-0.53
	9	Sep	17.28	16.42	-0.86
CCSM4 Total			20.73	19.70	-1.04
CNRM-CM5	6	Jun	19.32	17.70	-1.63
	7	Jul	23.54	22.41	-1.13
	8	Aug	22.78	22.27	-0.52
	9	Sep	17.67	16.42	-1.25
CNRM-CM5 Total			20.83	19.70	-1.13
CSIRO-Mk3-6-0	6	Jun	18.73	17.70	-1.03
	7	Jul	23.46	22.41	-1.05
	8	Aug	22.20	22.27	0.06
	9	Sep	17.37	16.42	-0.96
CSIRO-Mk3-6-0 Total			20.44	19.70	-0.74
GFDL-ESM2G	6	Jun	18.11	17.70	-0.41
	7	Jul	22.78	22.41	-0.37
	8	Aug	21.83	22.27	0.43
	9	Sep	17.28	16.42	-0.86
GFDL-ESM2G Total			20.00	19.70	-0.30

Station	Omak
Start	1992
End	2005

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
inmcm4	6	Jun	18.51	17.70	-0.81
	7	Jul	22.35	22.41	0.06
	8	Aug	22.30	22.27	-0.04
	9	Sep	17.38	16.42	-0.96
inmcm4 Total			20.14	19.70	-0.44
MIROC5	6	Jun	18.51	17.70	-0.81
	7	Jul	22.26	22.41	0.15
	8	Aug	22.14	22.27	0.13
	9	Sep	16.98	16.42	-0.56
MIROC5 Total			19.97	19.70	-0.27
MRI-CGCM3	6	Jun	18.06	17.70	-0.36
	7	Jul	22.66	22.41	-0.25
	8	Aug	22.17	22.27	0.10
	9	Sep	17.02	16.42	-0.60
MRI-CGCM3 Total			19.98	19.70	-0.28
NorESM1-M	6	Jun	19.90	17.70	-2.20
	7	Jul	22.41	22.41	0.00
	8	Aug	22.66	22.27	-0.40
	9	Sep	18.07	16.42	-1.65
NorESM1-M Total			20.76	19.70	-1.06

Appendix Table A. Derivation of GCM- and month-specific air temperature data bias-correction based on comparison of monthly median GCM estimates for Omak, WA with observed station data.

Oliver, BC

Station	Oliver
Start	1971
End	2000

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
BNU-ESM	6	Jun	18.23	18.50	0.27
	7	Jul	21.75	21.80	0.05
	8	Aug	21.04	21.35	0.31
	9	Sep	15.73	16.30	0.57
BNU-ESM Total			19.19	19.49	0.30
CanESM2	6	Jun	18.14	18.50	0.36
	7	Jul	21.36	21.80	0.44
	8	Aug	20.29	21.35	1.06
	9	Sep	15.65	16.30	0.66
CanESM2 Total			18.86	19.49	0.63
CCSM4	6	Jun	18.10	18.50	0.40
	7	Jul	21.46	21.80	0.34
	8	Aug	20.58	21.35	0.77
	9	Sep	15.31	16.30	0.99
CCSM4 Total			18.86	19.49	0.62
CNRM-CM5	6	Jun	18.51	18.50	0.00
	7	Jul	21.42	21.80	0.38
	8	Aug	20.61	21.35	0.74
	9	Sep	14.85	16.30	1.45
CNRM-CM5 Total			18.84	19.49	0.64
CSIRO-Mk3-6-0	6	Jun	17.85	18.50	0.65
	7	Jul	21.33	21.80	0.47
	8	Aug	20.54	21.35	0.81
	9	Sep	15.14	16.30	1.16
CSIRO-Mk3-6-0 Total			18.71	19.49	0.77
GFDL-ESM2G	6	Jun	17.99	18.50	0.51
	7	Jul	21.23	21.80	0.57
	8	Aug	20.72	21.35	0.63
	9	Sep	15.29	16.30	1.01
GFDL-ESM2G Total			18.81	19.49	0.68
inmcm4	6	Jun	17.94	18.50	0.56
	7	Jul	21.38	21.80	0.42
	8	Aug	20.52	21.35	0.83
	9	Sep	15.42	16.30	0.88

Station	Oliver
Start	1971
End	2000

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
inmcm4 Total			18.82	19.49	0.67
MIROC5	6	Jun	17.38	18.50	1.12
	7	Jul	21.08	21.80	0.72
	8	Aug	20.47	21.35	0.88
	9	Sep	15.14	16.30	1.16
MIROC5 Total			18.52	19.49	0.97
MRI-CGCM3	6	Jun	18.13	18.50	0.37
	7	Jul	21.14	21.80	0.66
	8	Aug	20.39	21.35	0.96
	9	Sep	15.91	16.30	0.39
MRI-CGCM3 Total			18.89	19.49	0.59
NorESM1-M	6	Jun	18.04	18.50	0.46
	7	Jul	20.98	21.80	0.82
	8	Aug	20.73	21.35	0.62
	9	Sep	15.19	16.30	1.11
NorESM1-M Total			18.74	19.49	0.75

Appendix Table B. Derivation of GCM- and month-specific air temperature data bias-correction based on comparison of monthly median GCM estimates for Oliver, BC with observed station data.

Princeton, BC

Station	Princeton
Start	1971
End	2000

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
BNU-ESM	6	Jun	15.19	14.50	-0.69
	7	Jul	18.80	17.70	-1.10
	8	Aug	18.22	17.60	-0.62
	9	Sep	13.52	13.20	-0.32
BNU-ESM Total			16.43	15.75	-0.68
CanESM2	6	Jun	14.96	14.50	-0.46
	7	Jul	18.26	17.70	-0.56
	8	Aug	17.42	17.60	0.18
	9	Sep	13.61	13.20	-0.41
CanESM2 Total			16.06	15.75	-0.31
CCSM4	6	Jun	15.03	14.50	-0.53
	7	Jul	18.53	17.70	-0.83
	8	Aug	17.70	17.60	-0.10
	9	Sep	13.21	13.20	-0.01
CCSM4 Total			16.12	15.75	-0.37
CNRM-CM5	6	Jun	15.46	14.50	-0.96
	7	Jul	18.28	17.70	-0.58
	8	Aug	18.11	17.60	-0.51
	9	Sep	12.68	13.20	0.52
CNRM-CM5 Total			16.13	15.75	-0.38
CSIRO-Mk3-6-0	6	Jun	14.95	14.50	-0.45
	7	Jul	18.24	17.70	-0.54
	8	Aug	17.71	17.60	-0.11
	9	Sep	13.08	13.20	0.12
CSIRO-Mk3-6-0 Total			16.00	15.75	-0.25
GFDL-ESM2G	6	Jun	14.94	14.50	-0.44
	7	Jul	18.10	17.70	-0.40
	8	Aug	18.02	17.60	-0.42
	9	Sep	12.98	13.20	0.22
GFDL-ESM2G Total			16.01	15.75	-0.26
inmcm4	6	Jun	14.96	14.50	-0.46
	7	Jul	18.44	17.70	-0.74
	8	Aug	17.72	17.60	-0.12
	9	Sep	13.24	13.20	-0.04

Station	Princeton
Start	1971
End	2000

			Median Monthly Air Temperature		
GCM Model	Month	Month	GCM	Station	Bias Correction
inmcm4 Total			16.09	15.75	-0.34
MIROC5	6	Jun	14.10	14.50	0.40
	7	Jul	17.97	17.70	-0.27
	8	Aug	17.68	17.60	-0.08
	9	Sep	12.96	13.20	0.24
MIROC5 Total			15.68	15.75	0.07
MRI-CGCM3	6	Jun	14.91	14.50	-0.41
	7	Jul	18.11	17.70	-0.41
	8	Aug	17.70	17.60	-0.10
	9	Sep	13.80	13.20	-0.60
MRI-CGCM3 Total			16.13	15.75	-0.38
NorESM1-M	6	Jun	14.77	14.50	-0.27
	7	Jul	17.85	17.70	-0.15
	8	Aug	18.09	17.60	-0.49
	9	Sep	13.05	13.20	0.15
NorESM1-M Total			15.94	15.75	-0.19

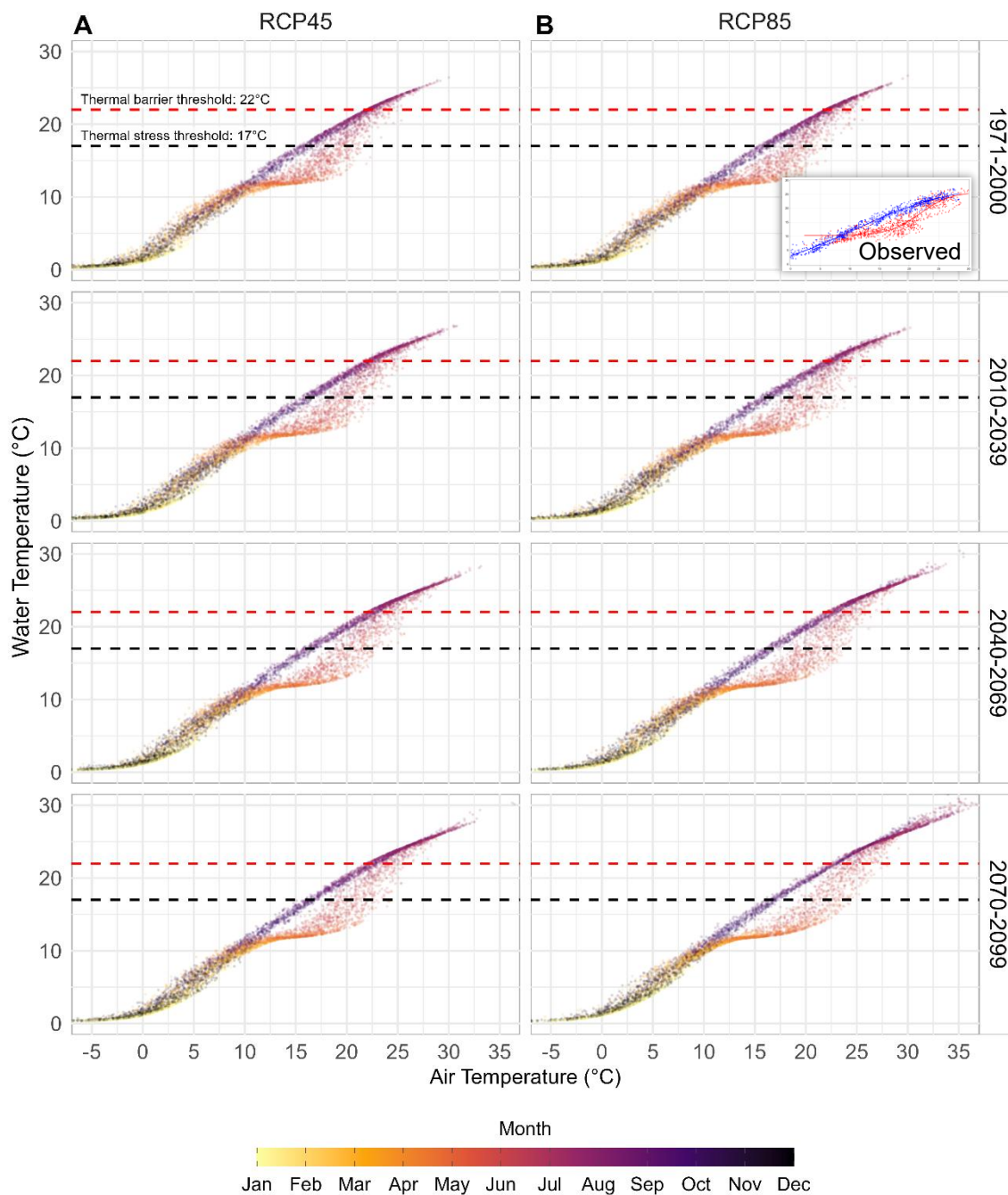
Appendix Table C. Derivation of GCM- and month-specific air temperature data bias-correction based on comparison of monthly median GCM estimates for Princeton, BC with observed station data.

Site Air-Water Temperature Relations (GAMM Outputs)

Okanogan River at Malott (WA)

Okanogan River at Malott (WA)

Water Temperature as a Function of Projected Air Temperature

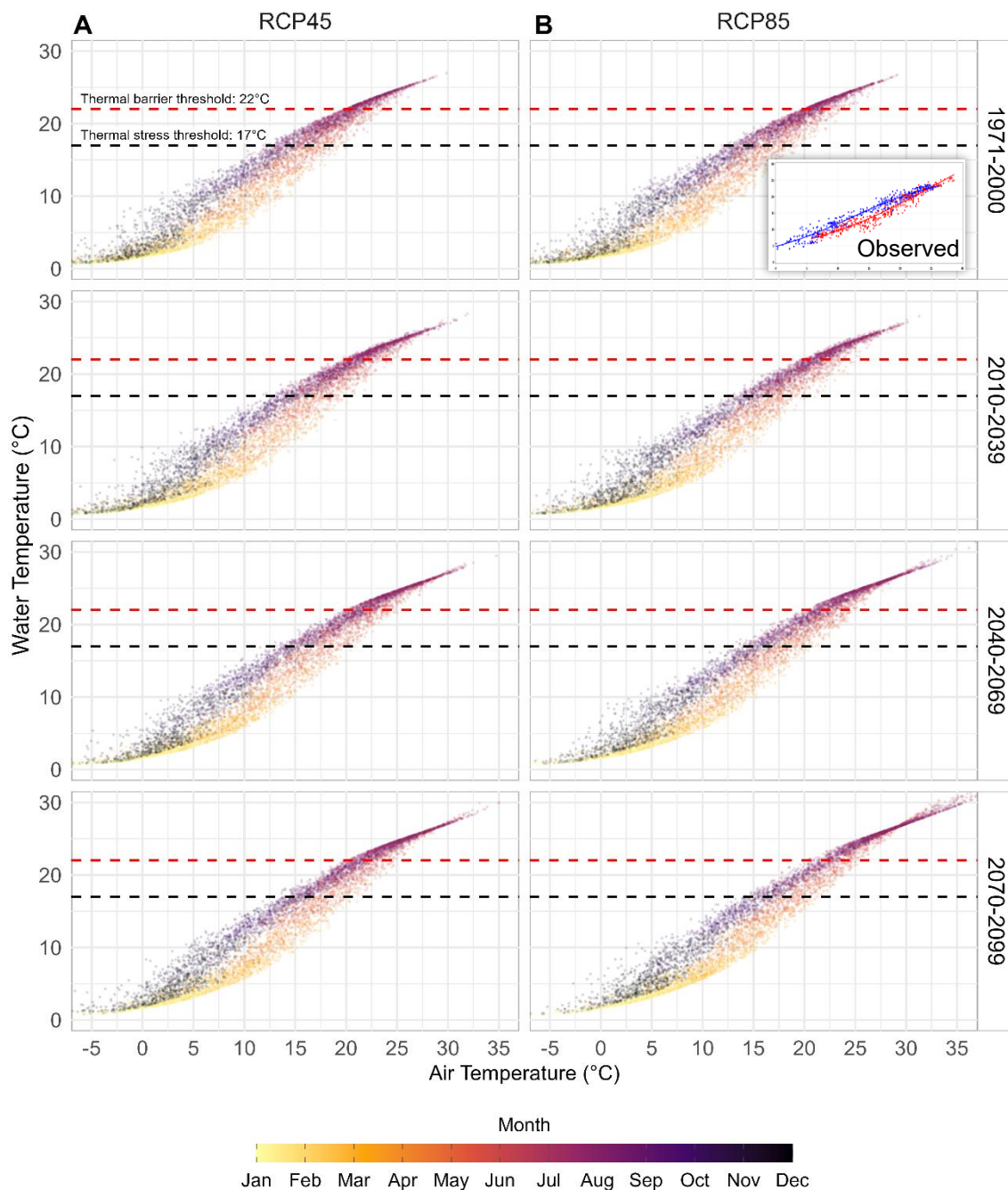


Appendix Figure 1. GAMM-modelled daily mean water temperature ($\hat{G}_w$) as a function of GCM daily mean 7-day backwards moving average air temperature index ($\hat{G}_a$) for Okanogan River at Malott (WA), by RCP and climate period. Inset shows observed data, where 'warming season' dates from Jan-to-mid-August are in red, and 'cooling season' dates from mid-August to December are in blue.

Okanagan River at Oroville (WA)

Okanagan River at Oroville (WA)

Water Temperature as a Function of Projected Air Temperature

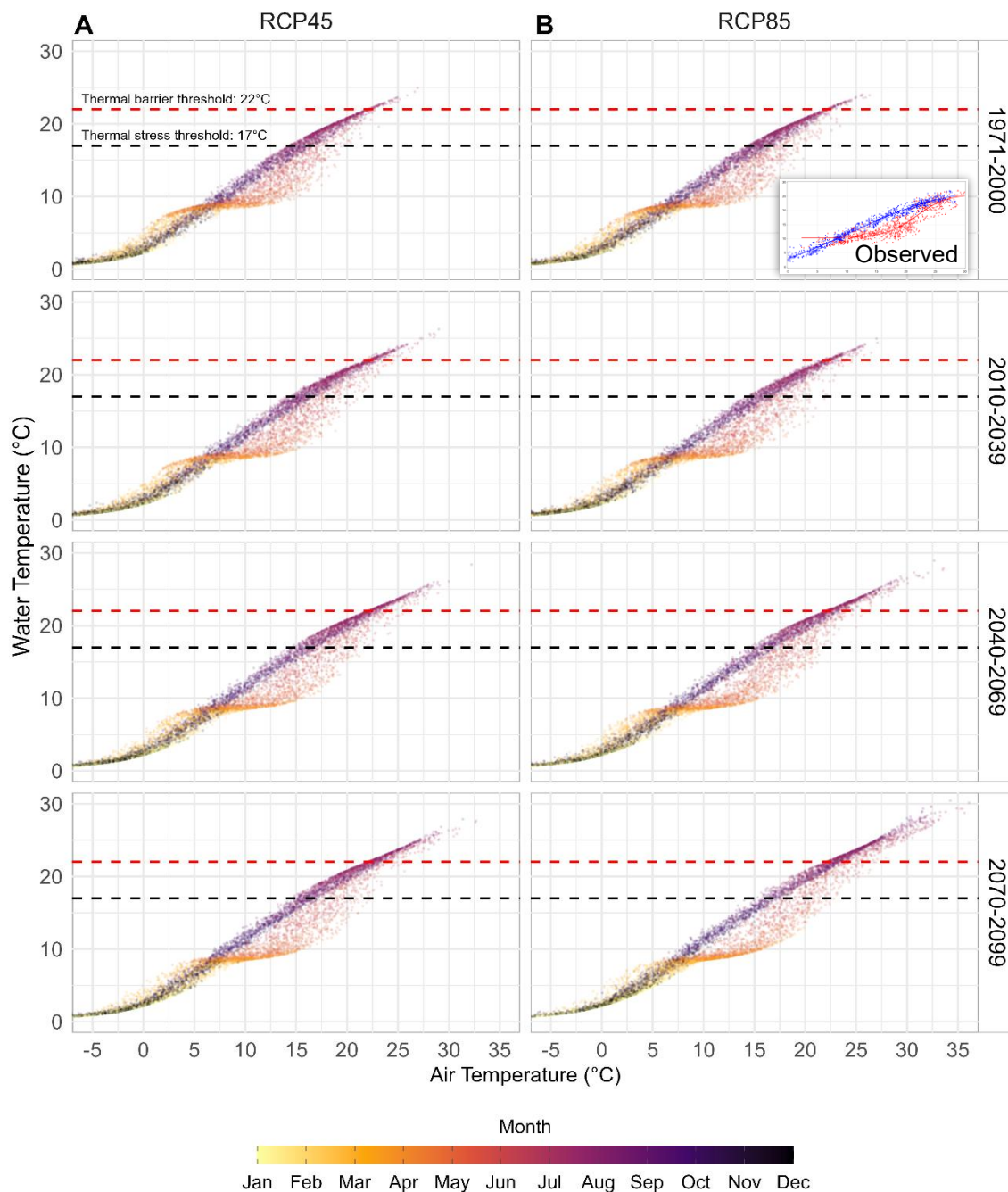


Appendix Figure 2. GAMM-modelled daily mean water temperature ($\hat{G}_w$) as a function of GCM daily mean 7-day backwards moving average air temperature index ($\hat{G}_a$) for Okanagan River at Oroville (WA), by RCP and climate period. Inset shows observed data, where 'warming season' dates from Jan-to-mid-August are in red, and 'cooling season' dates from mid-August to December are in blue.

Similkameen River at Nighthawk (WA)

Similkameen River at Nighthawk (WA)

Water Temperature as a Function of Projected Air Temperature

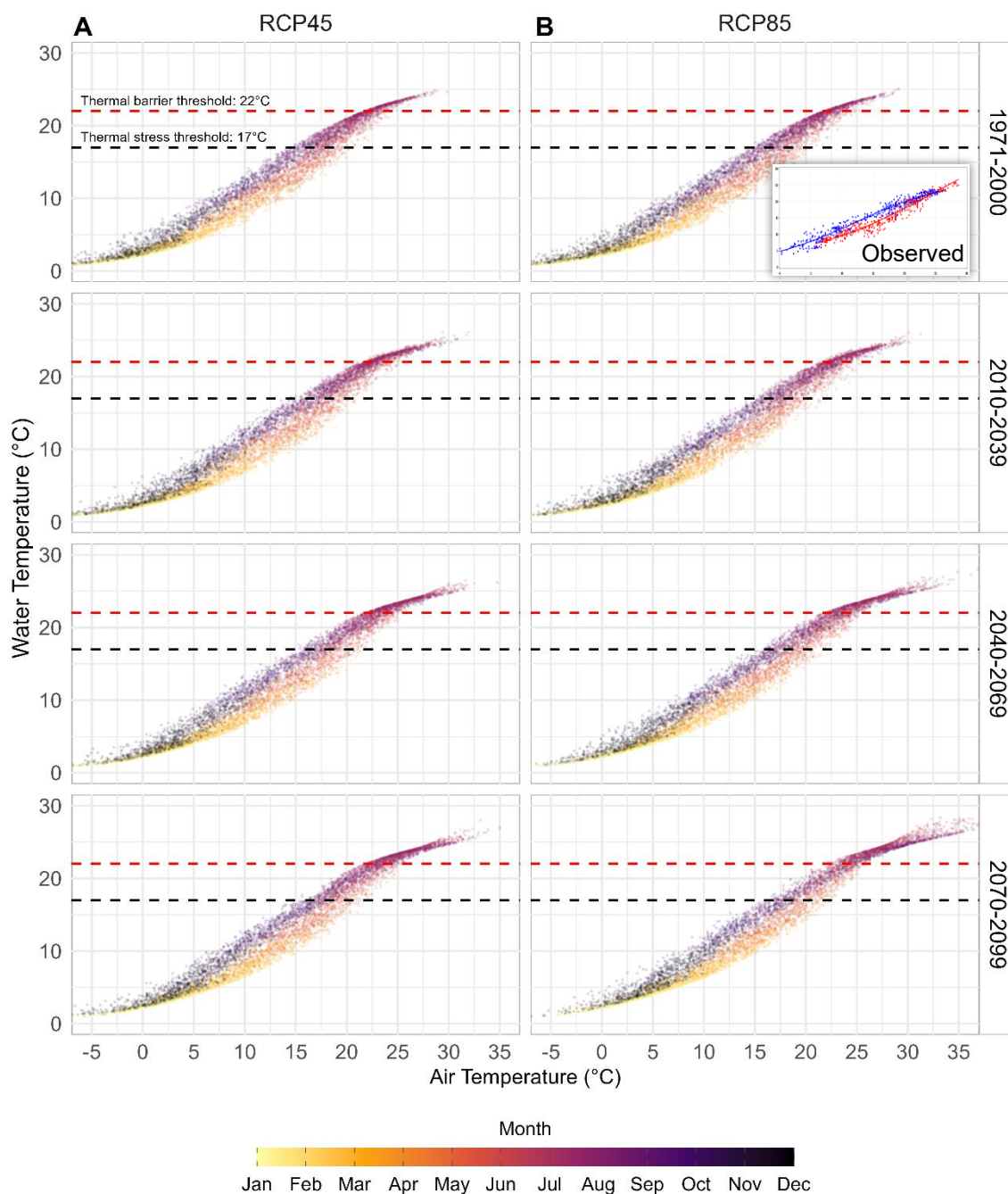


Appendix Figure 3. GAMM-modelled daily mean water temperature ($\hat{G}_w$) as a function of GCM daily mean 7-day backwards moving average air temperature index ($\hat{G}_a$) for Similkameen River at Nighthawk (WA), by RCP and climate period. Inset shows observed data, where 'warming season' dates from Jan-to-mid-August are in red, and 'cooling season' dates from mid-August to December are in blue.

Okanagan River at Oliver (BC)

Okanagan River at Oliver (BC)

Water Temperature as a Function of Projected Air Temperature



Appendix Figure 4. GAMM-modelled daily mean water temperature ($\hat{G}_w$) as a function of GCM daily mean 7-day backwards moving average air temperature index ($\hat{G}_a$) for Okanagan River at Oliver (BC), by RCP and climate period. Inset shows observed data, where 'warming season' dates from Jan-to-mid-August are in red, and 'cooling season' dates from mid-August to December are in blue.