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Te Whatu Ao

East Coast South Island salmon and the marine environment

Prepared for Central South Island and North Canterbury Fish and Game Councils

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Executive summary

Chinook salmon (*Oncorhynchus tshawytscha*), also known in New Zealand as quinnat or king salmon, and by Māori as Hāmana or Tāmana, have established self–sustaining wild populations, especially in the braided rivers of the east coast of Canterbury and north Otago. Sea–run (wild) populations of Chinook salmon are managed as a freshwater sports fishery by Fish and Game New Zealand, who have carried out salmon run surveys annually since the 1992/93 summer season. Surveys have indicated that numbers of wild Chinook salmon returning to breed in the Rangitata, Rakaia and Waimakariri rivers have declined by ~90% over the last 33 years. The present study is motivated by the desire to explore potential marine–based drivers for this decline in Chinook salmon numbers in these Canterbury rivers.

In North America, where Chinook salmon are native, warming of waters outside their optimal range (~13–16 °C) has correlated with decreases in spawning success. Chinook salmon also need high–water quality (including acceptable levels of dissolved oxygen, turbidity and pollutants) to live and breed in.

Earth Sciences New Zealand have assembled information describing environmental change in the Canterbury marine area: (1) oceanographic conditions, including sea surface temperature (SST), chlorophyll *a* concentrations (chl–a, as a proxy for primary production), suspended sediment concentrations and water clarity; (2) Southern Oscillation Index (SOI) which describes the El Niño (ENSO) climate variation; and (3) fish and fisheries data from Fisheries New Zealand (part of Ministry for Primary Industries). We also considered information on the abundances of Chinook salmon prey, predators and/or competitors (including fish, seabirds and marine mammals).

Our major findings were:

1. The Canterbury marine region warmed strongly between 1960 and 2025, with an SST increase of 1.3 °C over this period. The entire water column became hotter, but water near the seabed warmed less than at the surface. Summer warming was higher than in the winter. River mouths experienced similar warming to coastal waters.

2. In parallel with gradual ocean warming, the number of ocean "hot days" (where SST was greater than a certain temperature) per year increased. Between 1982 and 2025, the number of days per year hotter than 14.5 °C in the Canterbury marine region increased by 48% while the number of days hotter than 17 °C increased by 288%.

3. Both the overall increases in SST and the number of hot days were negatively and significantly correlated with salmon run numbers i.e. warmer ocean conditions co–occurred with poorer salmon runs in the Rangitata, Rakaia and Waimakariri rivers. It is important to note that these correlations do not attribute causality. The results do not imply that the ocean warming caused the decline in salmon numbers, but they are consistent with this hypothesis.

4. The Southern Oscillation Index is a relatively weak predictor of Canterbury SST, such that direct (satellite) observations of SST in the region should be preferred to describe oceanographic variability and change.

5. There were weak and varied trends in chlorophyll–a concentration, suspended sediment concentration and water clarity in the Canterbury marine region over the last few decades, and although these changes were sometimes correlated with salmon run numbers, the directions of the correlations were inconsistent with a causal link between salmon and these environmental changes.

6. Obtaining any insight into declines in Chinook salmon numbers from their predators and competitors using seabird or marine mammal observations will be difficult and uncertain because the data are limited and the potential connections within the oceanic food web complex and ambiguous.

7. Fisheries information covering a range of species was investigated. Overall, we found nothing in the fish or fishery data that had a strong correlation with the decline in salmon runs between the 1990s and the early 2000s. Sprats, a prey of Chinook salmon, may have declined after 2007 but this has high uncertainty. Kingfish numbers have recently increased, but the timing of the increase makes it unlikely this is linked to the salmon declines. Based on publicly–available information from Fisheries New Zealand, it is unlikely that salmon abundance is being directly impacted by marine commercial fisheries. Salmon are poorly sampled by current fisheries research surveys.

In conclusion, increases to SST in the Canterbury region were significantly correlated with changes in Chinook salmon run numbers in the Rangitata, Rakaia, and Waimakariri Rivers over the 33–year period between 1992/93 and 2024/25. The relationships between salmon run numbers and SST or number of hot days were non–linear and consistent with threshold effects. The values of these apparent temperature thresholds were broadly consistent with thermal tolerances of Chinook salmon reported for natural environments elsewhere. However, the fact that low salmon runs occurred in seasons with relatively cool seasonal indices (e.g. 2005/06, 2010/11) means that our results are inconsistent with ocean warming being the *only* factor affecting salmon run numbers. We emphasise also that while we found significant negative correlations with water temperature, no causality is indicated *per se*. It remains possible that salmon run numbers changed for reasons entirely disconnected from ocean warming in the Canterbury region.

1 Introduction

1.1 Motivation for this study

Chinook salmon (*Oncorhynchus tshawytscha*) are also known in New Zealand as quinnat or king or spring salmon, and by Māori as Hāmana or Tāmana. They are the largest of the Pacific salmon and can grow to 150 cm in length and up to 55 kg in weight, but typical length and weight of mature fish are about 90 cm and 7–10 kg, respectively. Chinook salmon are a cold-water fish and were successfully introduced to New Zealand in 1901 from eggs from California's McCloud River, followed by regular releases through 1907. These fish established self-sustaining wild populations, especially in the braided rivers of the east coast of Canterbury and north Otago. Chinook salmon are not managed under the New Zealand fisheries Quota Management System (QMS) and do not have dedicated stock assessments published in the annual Fisheries Assessment Plenary reports by Fisheries New Zealand. Instead, sea-run (wild) populations are managed as a freshwater sports fishery by Fish and Game New Zealand, and the species is commercially cultured via marine and freshwater aquaculture.

Surveys have indicated that numbers of wild Chinook salmon returning to breed in the Rangitata, Rakaia and Waimakariri rivers have declined by ~90% over the 33 years between the summer seasons of 1992/93 and 2024/25. This study is motivated by the desire of Central North Island and North Canterbury Fish and Game councils to explore potential reasons for this decline in Chinook salmon numbers in these Canterbury rivers.

1.2 Management

Fish and Game New Zealand (hereafter Fish and Game) has statutory responsibility under the Conservation Act 1987 for managing freshwater sport fishing and game-bird hunting. There are 12 fish and game councils with regional offices. The national council, with an office in Wellington, co-ordinates regional activities and lobbies government on behalf of anglers and hunters. Habitat protection work is a focus of Fish and Game's stewardship. Fish and Game has carried out stocking of Chinook salmon populations (and other species), but the major east coast river runs (like the Rakaia, Waimakariri and Rangitata) rely on natural spawning. Fish and Game have carried out salmon run surveys annually since the 1992/93 summer season.

1.3 Biology and ecology

Chinook salmon, like all salmon species, are anadromous. The eggs hatch in freshwater, the juveniles migrate to the sea to feed, grow for several years, then mature and return to their natal river/stream to reproduce. Eggs are laid in large redds (a gravel nest built by a female salmon to lay and fertilise her eggs), similar to those made by trout, but located in deeper and swifter river waters. In New Zealand, Chinook salmon are understood to spawn throughout catchments, most notably in stable spring-fed tributaries. Established spawning runs are found in the Rangitata, Opihi, Ashburton, Rakaia, Waimakariri, Hurunui and Waiau rivers on the east coast of Te Waipounamu South Island. There are also small runs in the Paringa, Taramakau and Hokitika Rivers on

the west coast of the South Island, but other records of Chinook salmon on the west coast are probably stray fish. A few land-locked stocks are also known from lakes along both the east and west coasts. Although juvenile fish have been caught in some Te Ika-a-Māui North Island rivers, indicating successful spawning had occurred, there are no known consistent runs of Chinook salmon documented in the North Island.

In New Zealand, Chinook salmon eggs hatch after two months in spring, and the young fish (parr) stay and feed in the same area for about three months. In late summer/autumn, the parr markings disappear and the fish (smolts), now silvery and about 10 cm long, migrate downstream and enter the sea. In some populations, a second downstream migration, consisting of individuals that have spent a year in freshwater, occurs the following spring.

Chinook salmon sexually mature between the ages of two and seven years and are typically three or four years old when they return to spawn (~65–80 cm, 4–10 kg). New Zealand Chinook do not grow as large as the North American Chinook, which commonly weigh up to 20 kg in Alaska. A 4-year-old New Zealand caught Chinook is more likely to average ~7 kg. The difference in size is largely attributed to the fact that North American Chinook salmon spend more years at sea (>6 years), whereas New Zealand salmon return at three to four years of age. Growth and length–weight relationships are well studied (e.g. Dougan, 1993; He et al., 2008). Upstream spawning migrations start in December in wild New Zealand populations and continue through February–April, with spawning generally in summer or early autumn (Paul, 1966). All Chinook salmon die after spawning.

At sea, salmon generally live in the upper layers of the water column, mostly staying within the top 30 to 50 metres, but their exact position is likely to vary based on light, temperature, and time of day (Holm et al., 2006). For example, based on data storage tags in the oceanic feeding and migration phase, Atlantic salmon stayed in the upper 5 m of the water column for 60% of the time, making occasional deep dives to ~280 m which could explain why there are occasional reports of considerable numbers of adult salmon taken in pelagic (midwater) and even demersal (bottom/near-bottom) fisheries (Holm et al., 2006). While at sea, Atlantic salmon seem to be distributed in scattered shoals both during feeding and migration (Jacobsen 2000; Hansen & Jacobsen 2003). The distribution of Chinook salmon off Canterbury is not well known but may follow a similar depth distribution as Atlantic salmon. Juvenile or young salmon tend to stay more coastal and occur very shallow (within the top 15 metres) whereas older salmon may venture further from the coast over deeper open ocean waters; though, even here, based on information from Atlantic salmon, they are likely to generally remain in surface layers (Holm et al., 2006).

Birds are known to eat smolt in the lower reaches of New Zealand rivers. In North America, marine mammals (such as killer whales and sea lions) and sharks eat adult Chinook salmon, and this is likely to also occur in New Zealand to some degree.

1.4 Diet

The diet of Chinook salmon in New Zealand coastal waters is described by James & Unwin (1996), based on 803 adult salmon taken by commercial bottom trawlers in depths of 40–70 m off the mid–Canterbury coast during three summers from 1991/92 to 1993/94, and 36 yearlings caught in a shallow coastal embayment in 1992 and 1993. Prey diversity was extremely low, both in terms of the number of species consumed (10), and the proportion of stomachs containing a single prey type (81%). With limited samples it is not clear whether this is normal. Diet showed no relationship to Chinook salmon size or geographical area.

Adult Chinook salmon were primarily piscivorous: stout sprat— *Sprattus muelleri* comprised 76% of the diet by weight (James & Unwin 1996). Pelagic swarming post–larval juveniles of the galatheid crab *Munida gregaria*, known as red krill, and juvenile hoki, *Macruronus novaezelandiae*, comprised 18% and 5% of the diet, respectively. The results are consistent with older New Zealand Chinook salmon that are reported as primarily feeding on small pelagic fish, such as sprat, smelt, whiting and mackerel (Paul, 1966).

Diets of yearling salmon consisted of several larval fish species and the mysid *Tenagomysis macropsis*. Therefore, both adult and yearling Chinook salmon appeared to feed opportunistically, but on a relatively narrow spectrum of pelagic prey, comprising small and juvenile fish and crustaceans.

1.5 Sensitivity to temperature

A substantial amount of research has been carried out on Chinook salmon in western North America, where their native range spans from Monterey Bay, California, north through Oregon and Washington, and all the way up the coast to the Chukchi Sea in Alaska. They have also been successfully introduced to the Great Lakes region. In Canada, they are abundant in the coastal waters and rivers of British Columbia and the Yukon Territory. Considerable research exists from North America on factors affecting Chinook salmon, including temperature (e.g. Bell, 1986; USEPA, 1999; WDOE, 2002; Howard & von Biela, 2023).

There is also concern that climate change and specifically warming of coastal and ocean areas occupied by Chinook salmon in New Zealand, could have affected adult survival and/or fish condition, and this may translate into reduced reproductive success or survival. Some information is available on relationships between environmental conditions and biological and ecological success. For example, considerable work has been carried out on temperature tolerances of Chinook salmon in North America (Carter, 2006 and references therein), and in New Zealand for farmed salmon (e.g. Butler et al., 2023; Symonds et al., 2024).

In North American populations, a radio tracking study on Chinook salmon in spring revealed that maximum annual temperatures of 21.1°C may present a thermal barrier to migration (USEPA 1999). Bell (1986) reviewed various studies and noted that, in spring, Chinook salmon migrated at water temperatures ranging from 3.3–13.3 °C, while in autumn they migrated at slightly warmer temperatures of 10.6–19.6 °C. Preferred

temperatures for North American Chinook salmon range from 7.2–14.5 °C (Bell, 1986). Based on a technical literature review, WDOE (2002) concluded that daily maximum temperatures should not exceed 21–22 °C during Chinook salmon migration. WDOE (2002) stated that where spring Chinook are holding over for the summer prior to spawning, the average daily water temperature should be below 13–14 °C and the maximum mean weekly temperature should be below 16–17 °C for optimal ecological success.

The Oregon Department of Environmental Quality (ODEQ 1995) reviewed numerous studies and recommended a temperature range of 5.6–12.8 °C for spawning Chinook salmon. A discussion paper and literature summary by WDOE (2002) noted a wider range of temperatures associated with Chinook salmon spawning (5.6–17.7 °C), although the majority of these temperature observations cited daily maximum temperatures below 14.5 °C. Recommended spawning temperature ranges for spring, summer, and autumn spawning Chinook salmon populations in the Pacific Northwest were 5.6–13.9 °C (Armour, 1991). When ripe adult spring Chinook salmon females experienced temperatures above 13–15.5 °C, pre-spawning adult mortality became pronounced (ODEQ, 1995). Additionally, there was decreased survival of eggs to the eyed stage and alevin development was inhibited due to the exposure of the ripe female to warm temperatures, even if the stream temperatures during the egg and alevin development were appropriate (ODEQ, 1995).

In a laboratory study, Marine & Cech (2004) studied the incremental effects of chronic exposure to three temperature regimes (13–16 °C, 17–20 °C, and 21–24 °C) on Chinook juveniles during rearing and smoltification. Their findings reflected that Chinook juveniles reared at the 17–20 °C and 21–24 °C temperature ranges experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared at 13–16 °C. A review of numerous studies led Bell (1986) to conclude that the upper lethal temperature for Chinook was 25 °C, consistent with later work by Myrick & Cech (2001).

In New Zealand, farmed Chinook salmon were negatively impacted when temperatures exceeded 17.0–18.0 °C for prolonged periods and marine heatwaves have resulted in reduced survival (Symonds et al., 2024). The optimal water temperature for farmed Chinook salmon is reported as 16–17 °C, although fish size, salinity, genetics, environmental factors and other stressors may alter this (Butler et al., 2023). In fresh water, the best performance is also at 16–17 °C, but fish continue to grow at 20°C, whereas in tank-based seawater challenge trials, larger fish have increased mortality at approximately 20 °C, whereas smaller fish stop feeding at 18–19 °C and mortalities increase at 23.5 °C (Butler et al., 2023).

In summary, if wild New Zealand Chinook salmon follow similar temperature tolerances to those in North America, they are likely to require water below ~21 °C to migrate (marine environment), ~14.5 °C to successfully spawn (river environment), and prior to spawning, female Chinook salmon may need temperatures below 16°C for successful egg maturation (ocean environment). In farmed salmon, optimum temperatures are somewhat lower than this, and tolerated maximum temperatures somewhat higher.

1.6 Water quality and habitat

Changes to riverine water quality and habitats are relevant to Chinook salmon ecology but are not the focus of this report and only a brief summary of the potential dependences is given here.

New Zealand research suggests that Chinook salmon have more stringent habitat requirements than indigenous freshwater species, needing very high–water quality and fast water flows to live and breed (Canning, 2018). Water quality factors that may affect salmon survival include dissolved oxygen, suspended sediment (turbidity), and pollutants (e.g. Lehman et al., 2017; Bell, 1986). Nutrient run off into rivers can impact water quality, for example by promoting algal blooms than can decrease water clarity and dissolved oxygen concentrations and can cause the death of sensitive aquatic species. Nutrients also impact macroinvertebrate species composition, with the potential to reduce food availability for juvenile salmon. These effects start to occur at nitrogen concentrations at above 0.5 mg/l, with nitrite being toxic, and fish being relatively indifferent to nitrate. Phosphates have no direct toxicity to fish but, like nitrates, can lead to a eutrophication problem (Bell, 1986).

Changes to habitat can affect temperature tolerance of Chinook salmon. Riparian foliage and biotic habitats also provide cover for smelts from bird predation, are related to riverine prey conditions (macro–invertebrates), contribute to dissolved oxygen levels, and provide river shading that affects water temperature. For example, from a North American study on stream and river water quality standards, reduced cover from large woody debris, and reduced resting pool area due to pool filling, increased the susceptibility of adult Chinook salmon to mortality from thermal effects (ODEQ, 1995). Changes in river conditions can affect marine conditions close to river mouths.

1.7 Objectives

This report focuses on the marine habitat of New Zealand Chinook salmon. The objectives of this work as agreed by Central South Island Fish and Game Council are:

- Report population estimates and trends (where available) for marine species comprising the bulk of the Chinook salmon diet. Key prey species will be identified based on findings from previous New Zealand Chinook salmon diet studies.
- Report on marine temperature changes using satellite–derived data and evaluate these changes in relation to established salmon temperature thresholds associated with growth and survival. Temperature thresholds will be derived from prior North American studies where applicable. There should be comment on the relationship between surface temperature estimates and deeper waters.
- Develop and supply a sea surface temperature record back to 1965.
- Analyse marine primary productivity estimates to determine whether significant changes have occurred over time and, if so, consider the

potential influence of those changes on salmon populations. Primary productivity will be assessed using satellite estimates of chlorophyll–*a* concentrations. There should be comment on the relationship between estimates of primary productivity at the surface and estimates in deeper waters, including stratification effects. This work should include consideration of nutrient availability where this information/data is/are accessible.

- Compare biophysical factors (including marine water temperature and chlorophyll–*a* concentrations) with historical and current salmon run estimates (provided by Fish and Game) for key salmon rivers to determine whether statistically significant relationships exist.
- Identify other structural changes in marine ecosystems that may be influencing salmon run size, including changes in predator and prey abundance. This will include consideration of observed shifts in species distributions, such as the southward movement of kingfish (likely predator on Chinook salmon), and evaluation of how such changes may affect salmon populations.

2 Methods

2.1 Study region

This study is focussed on the marine environment offshore of the three key salmon rivers in the Canterbury region: Rangitata, Rakaia and Waimakariri rivers. While salmon movements while at sea are not well known, Fish and Game suggested that salmon from these Canterbury rivers were likely to stay within the area bounded by the orange polygon, as outlined in Figure 2.1. This area contains the reported catches of salmon by James & Unwin (1996), who described salmon being caught by commercial bottom trawlers in depths of 40–70 m off the mid-Canterbury coast during three summers 1991/92 to 1993/94.

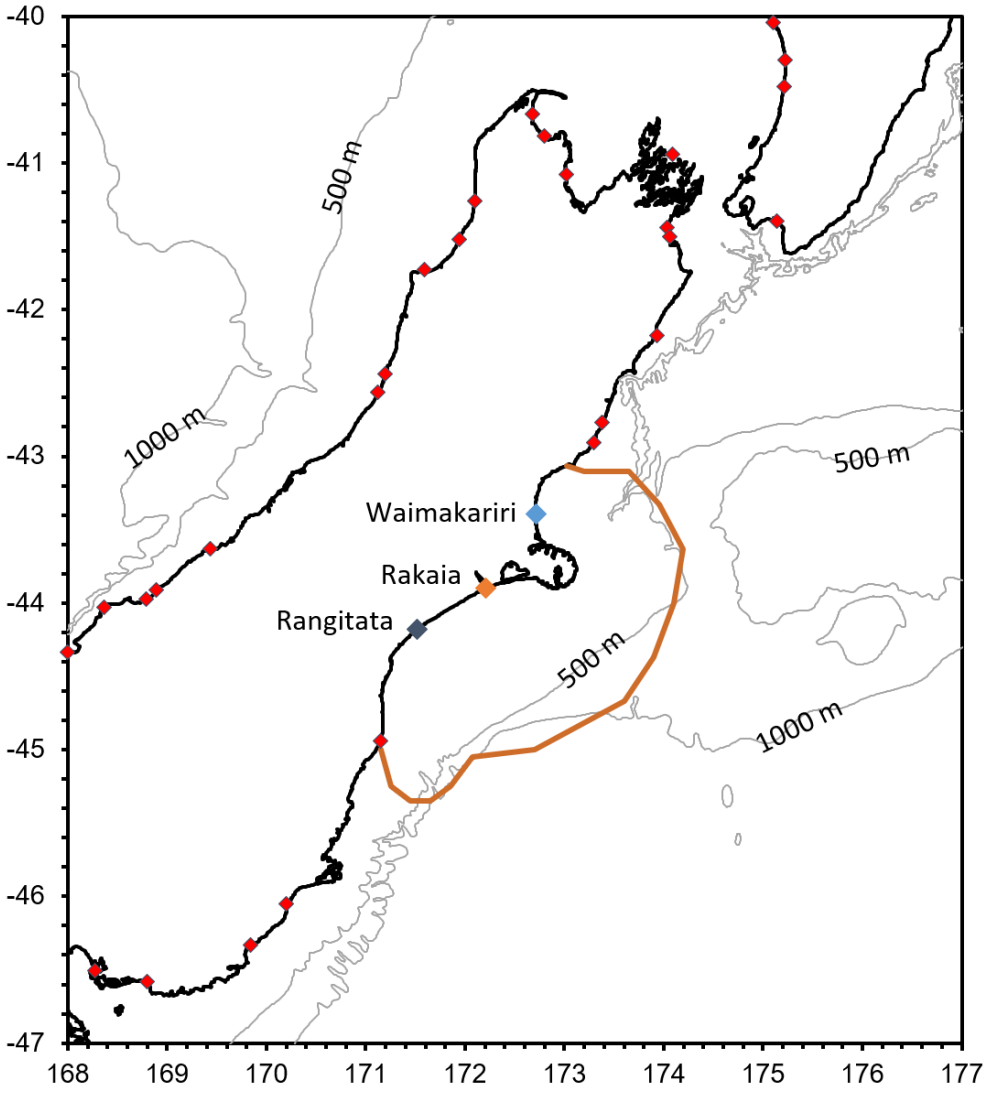

Figure 2.1: Study region off the east coast of Te Waipounamu South Island. The marine area considered to be used by adult salmon is shown bounded by the orange solid line. The terminal points of the three rivers of importance for salmon (Rangitata, Rakaia and Waimakariri rivers) are labelled and colour coded (black, orange and blue, respectively). Terminal points of other major river systems are shown as red diamonds. Bathymetric contours at 500 and 1000 m are shown in grey.

2.2 Salmon run counts

Since 1992, salmon in the Rangitata, Rakaia and Waimakariri rivers have been counted annually by Fish and Game using helicopter surveys. For each river, five surveys per season have been carried out starting in late March and finishing in early July (Figure 2.2). Salmon run anomalies were calculated for analysis by dividing the run counts by the mean and subtracting one, for consistency across the three rivers.

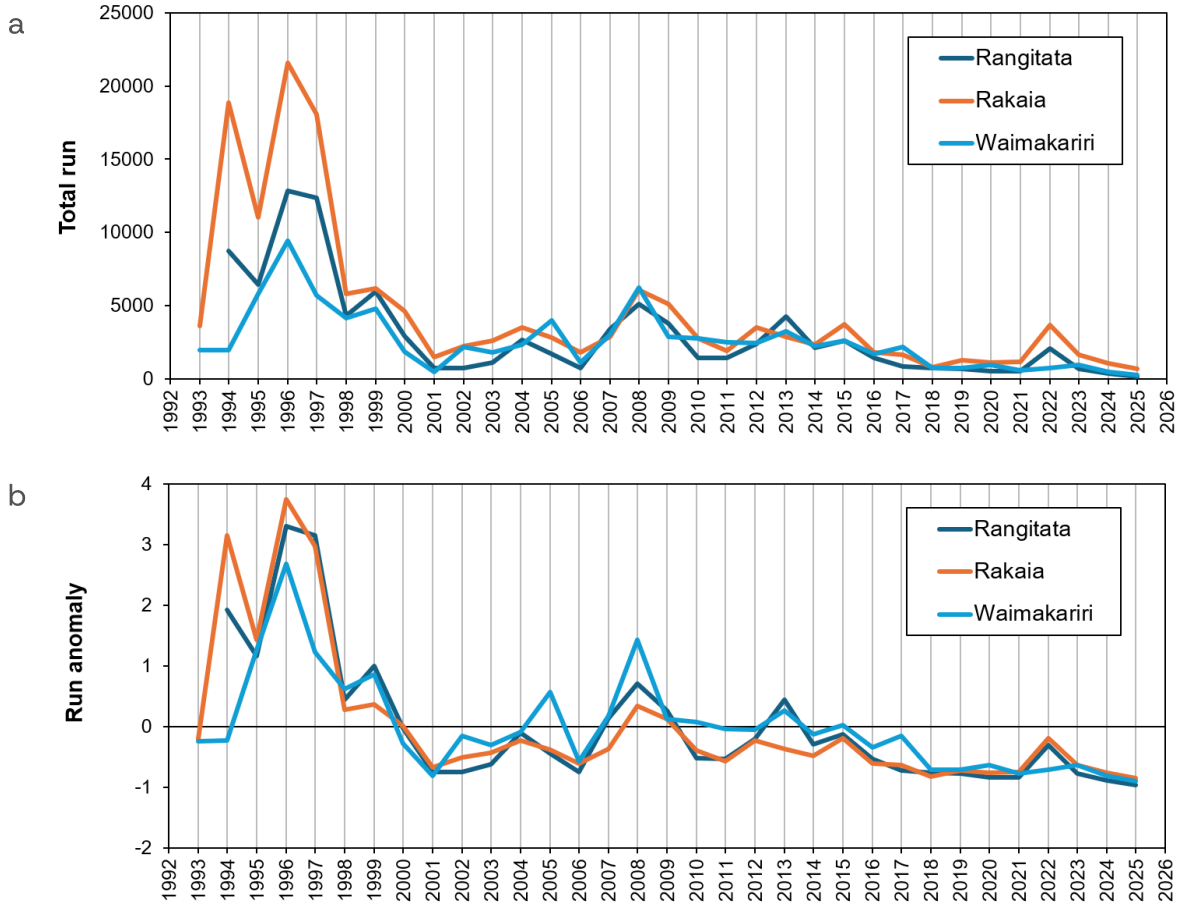

Figure 2.2: Chinook salmon counts in the three main Canterbury rivers. (a) Raw counts; (b) Salmon run anomaly obtained from dividing the run counts by the mean and subtracting one.

2.3 Environmental information and analysis

2.3.1 Satellite data sources

In our analysis, we predominantly used satellite products that align with previous environmental reporting in Aotearoa New Zealand (Pinkerton et al., 2018, 2024). However, we have also incorporated new satellite products into the analysis to explore the variability between different approaches and to extend the time-series of information on sea surface temperature (SST) into the pre-satellite era (see Table 2.1). Specifically, three measures of SST were used to provide different lengths of information and at different spatial and temporal resolutions. No new validation of satellite products using in situ measurements has been carried out in the present study as this is beyond the scope of the project deliverables.

The other satellite products used were: (1) surface chlorophyll-a concentration (chl-a), as an index of phytoplankton biomass and proxy for oceanic primary production) that might be related to food availability for Chinook salmon; (2) Suspended sediment (Total Suspended Solids, TSS) concentration as this might interfere with prey availability or visual hunting; (3) Underwater visibility (horizontal black disk visibility, Hvis), as a measure of how far a visual predator maybe be able to sight prey.

Table 2.1: Summary of satellite products. Below the data source we give the spatial resolution and period covered (month-year). SST = Sea surface temperature; OISST = Optimum Interpolation Sea Surface Temperature; SCENZ = Seas Coasts Estuaries New Zealand; MODIS-Aqua = Moderate Resolution Imaging Spectroradiometer; chl-a = chlorophyll-a concentration; SeaWiFS = Sea-Viewing Wide Field of View sensor; TSS = total suspended solids; HVIS = horizontal visibility.

Indicator	Primary dataset	Description	References
Daily ocean sea surface temperature (SST) (°C)	OISST v2.1 ¼° (~ 25 km), daily Sep 1981 – Dec 2025	Optimum Interpolation Sea Surface Temperature (OISST) version 2.1 blends satellite and *in situ* observations to produce a daily interpolated product	Reynolds et al., 2002; Huang et al., 2021
Monthly ocean SST (°C)	OISST v2.1 ¼° (~ 25 km) 9 km, monthly Sep 1981 – Dec 2025	Monthly-mean of daily OISST v2.1 data	Reynolds et al., 2002; Huang et al., 2021
Coastal SST (°C)	SCENZ v5.0 SST 500 m, monthly Jul 2002 – Jun 2026	MODIS-Aqua standard nighttime SST product, composited monthly and interpolated to 0.5 km	Pinkerton et al., 2019, 2023; Gall et al. 2022
Ocean primary productivity (chlorophyll-a concentration) (mg chl-a m^{-3})	MODIS-Aqua+SeaWiFS 9 km, monthly Sep 1997 – Dec 2025	Concentration of chl-a in the surface water as a proxy for phytoplankton biomass and ocean primary productivity	Pinkerton et al., 2019, 2023
Suspended sediment (Total Suspended Solids), TSS (g m^{-3})	SCENZ v5.0 TSS 500m, monthly Jul 2002 – Dec 2024	Gravimetric concentration of all particulates in the upper ocean from an inherent optical property inversion algorithm	Pinkerton et al., 2022; Gall et al. 2022
Underwater visibility, Hvis (horizontal visibility) (m)	SCENZ v5.0 HVIS 500m, monthly Jul 2002 – Dec 2024	Horizonal black-disk underwater sighting distance, which is relevant to visual foragers in the upper ocean	Gall et al. 2022

2.3.2 Model re-analyses: ORAS5

Because the earliest satellite observations of SST start in 1981 and there is interest in considering changes back to 1960, we sourced information from model re-analyses, specifically, ORAS5 (Copernicus Climate Change Service, Climate Data Store, 2021). ORAS5 (Ocean Reanalysis System 5) is a global ocean and sea-ice reanalysis dataset created by the European Centre for Medium-Range Weather Forecasts (ECMWF) that combines a numerical ocean model with global observations to provide a continuous, gap-free record of the historical ocean state from 1958 to present. The spatial and temporal resolutions of ORAS5 are relative coarse (¼°, ~25 km, monthly), but the data offer full-water depth resolution (surface to seabed) as opposed to surface-only information from satellites.

2.3.3 Monthly anomalies

Monthly anomalies for the satellite and ORAS5 model data were calculated as the average value for each month minus the long-term mean for that month (Equation 1). Here, $\delta_{y,m}$ is the anomaly for year *y*, month *m*; N_y is the total number of years of data, and $S_{y,m}$ is the satellite measure for year *y* and month *m*. For example, the monthly anomaly for January 2000 was calculated as the mean of January 2000 minus the long-term mean of every January in the time-series.

$$\delta_{Y,m} = S_{Y,m} - \frac{1}{N_y}\sum_y S_{y,m} \qquad \text{[Equation 1]}$$

The "reference period" is the time interval over which the "climatological" monthly averages are calculated. The choice of reference period is somewhat subjective, especially when there are multiple products spanning different time periods. Where there is a long-term trend, the choice of reference period affects the absolute values of the anomalies. In contrast, the seasonal patterns of anomalies and the trends derived from them are quite insensitive to the choice of reference period because the seasonal cycles of the variables considered here vary little over time.

For ORAS5 and OISST v2.1 we used the 30-year reference period January 1983 – December 2012 following that used for marine heatwaves (Hobday et al., 2016). For the chl-a, TSS, Hvis and SCENZ SST data (see Table 2.1), where the available time-series are shorter, we used a 20-year reference period July 2002 – June 2022 (following Pinkerton et al., 2024).

2.3.4 SST cross-validation

Because we are using three different data sources for SST, we carried out an intercomparison of the ORAS5 surface temperature re-analysis product, the OISST v2.1 product and the SCENZ-SST for the Canterbury region (Figure 2.3). The very close agreement between these SST products provides confidence in their robustness over the time-series.

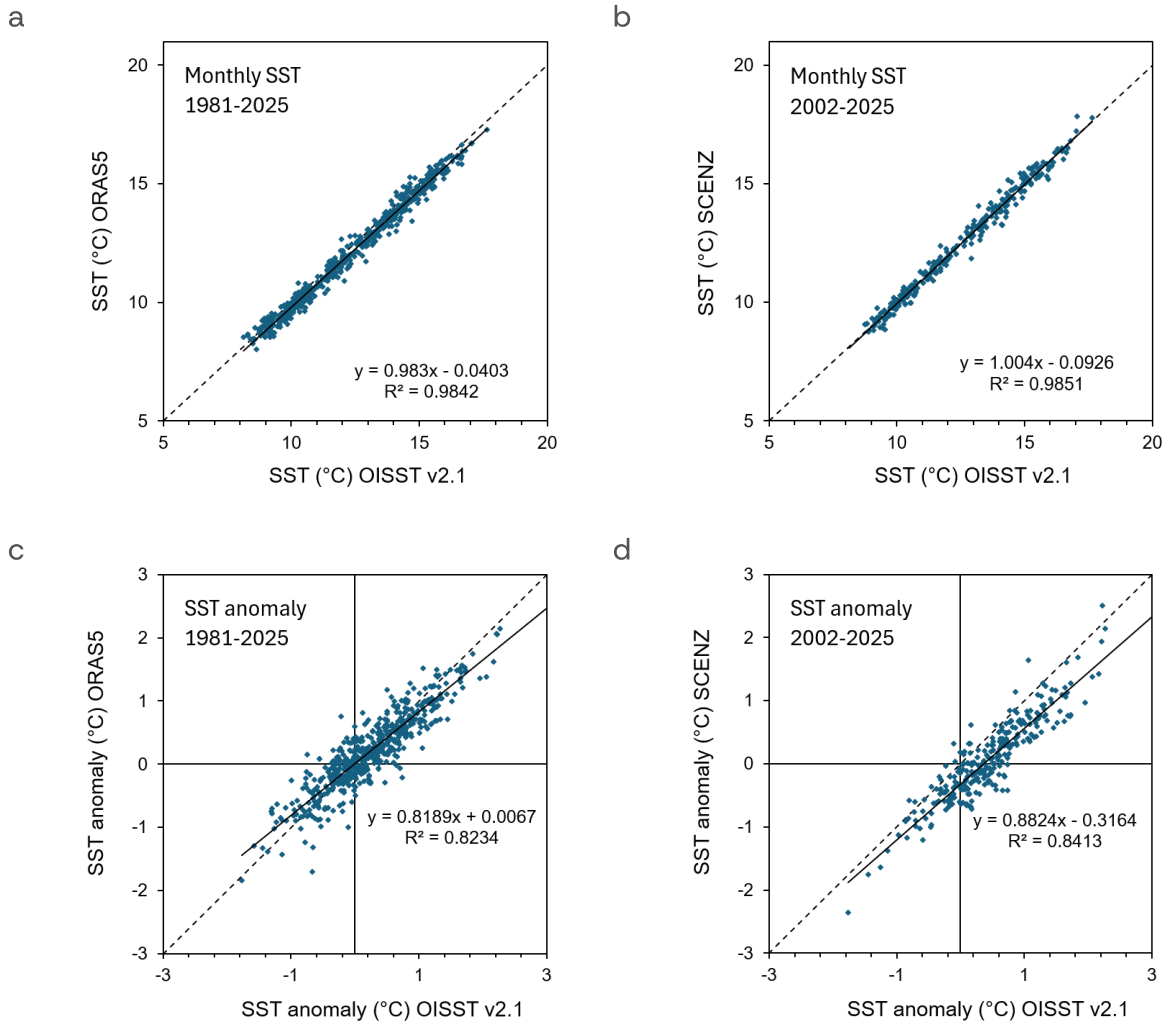

Figure 2.3: Cross-validation of metrics for sea surface temperature. a: OISSTv2.1 versus ORAS5 monthly data; b: OISSTv2.1 versus SCENZ monthly data; c: OISSTv2.1 versus ORAS5 monthly anomaly; d: OISSTv2.1 versus SCENZ–SST monthly anomalies. Equations are the y-on-x least squares regression results.

2.3.5 Daily SST analysis

We included daily OISST v2.1 satellite observations in the analysis because this allows us to consider short-term (i.e. sub-monthly) high temperature periods that may have a significant effect on Chinook salmon. The daily and monthly data come from the same source so that consistency is assured at the monthly scale (Figure 2.4a). An example (Figure 2.4b) shows the extra insight into short-term periods of surface warming (such as marine heatwaves) that the daily SST provides.

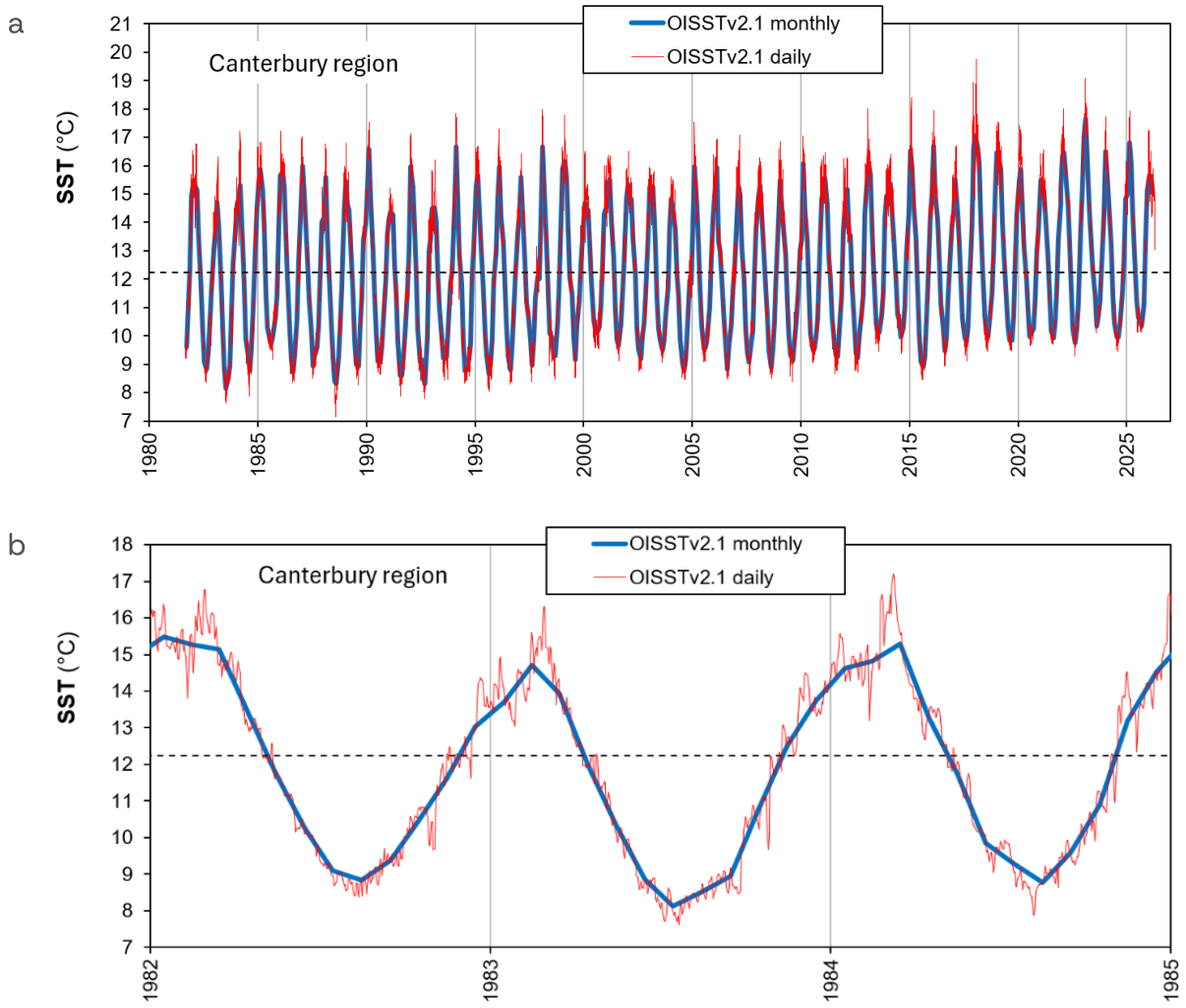

Figure 2.4: Comparison of daily and monthly Optimum Interpolation Sea Surface Temperature (OISST) v2.1. (a) Whole time series; (b) Example of three-year period showing the extra insight from the daily SST information.

To investigate whether periods of hot ocean days ("hot days") were related (correlated) with salmon run numbers, we calculated the number of days in each month when the daily SST was greater than a particular temperature threshold. A range of different temperature thresholds have been suggested as being ecologically important to Chinook salmon from North American research (see Section 1.5), and we don't know which (if any) SST threshold salmon in Canterbury will respond to. Hence, six SST thresholds were investigated at 0.5 °C intervals between 14.5 °C and 17 °C. The proportion of the month with hot days were then combined into seasons using the three season indices described in Section 2.3.8.

2.3.6 Effects of river water on SST

It is likely that the input of river water will affect water temperature close to the mouths of major river systems, and that this effect will be seasonal. We expect river water to be warmer than coastal water in summer, and cooler in winter because the land-surface will heat up and cool down faster than the coastal water. A method similar to that used to investigate onshore–offshore gradients in optical water quality (Pinkerton et al., 2026)

was used to check if the rivers were likely to be substantially hotter than the neighbouring coastal water.

Following Pinkerton et al. (2026), for each river, we selected a number of arcs at different distances from the nominal discharge point and averaged the high-resolution (500 m) satellite SST at these distances. The width of each arc was 1 km and we considered arcs from zero (the river mouth) to 20 km offshore. This approach corresponds closely with the "river radii" approach developed for investigating the effects of river discharge on coastal biogeochemical properties in Aotearoa New Zealand (Orchard et al., 2025a, b). Next, a LOWESS (Locally Weighted Scatterplot Smoothing) algorithm is fitted using a LOWESS order of 1 and width of 3 km. Finally, an Orthogonal Reduced Major Axis regression was fitted to the LOWESS results to represent the inshore-offshore gradient of the water property with distance from the river mouth.

2.3.7 Southern Oscillation Index (SOI)

El Niño and the Southern Oscillation, also known as ENSO, is a periodic fluctuation (every 2–7 years) in sea surface temperature and air pressure of the overlying atmosphere across the equatorial Pacific Ocean (Walker & Bliss, 1932). The presence of an El Niño, or its opposite – La Niña – sufficiently modifies the general flow of the atmosphere to affect normal weather conditions in many parts of the world, including in Aotearoa New Zealand. The Southern Oscillation Index (SOI) is a standardised measure of large-scale air pressure fluctuations between Tahiti and Darwin, Australia. It tracks the intensity of El Niño and La Niña episodes in the Pacific Ocean, with sustained negative values indicating El Niño, and sustained positive values indicating La Niña (Figure 2.5). In this study we used SOI anomalies from the National Oceanic and Atmospheric Administration (NOAA-NCEP, 2026) that are differences from the 30-year climatological reference period (1981–2010).

El Niño phases (negative SOI) often bring cooler regional anomalies to New Zealand waters, while La Niña phases (positive SOI) tend to increase sea and air temperatures in New Zealand (Holbrook & Bindoff, 1997; Shears & Bowen, 2017; Drake 2025). ENSO also influences precipitation patterns in New Zealand and hence has an impact on river flow and riverine/coastal water quality. The weather tends to be dryer in the summer during El Niño conditions in eastern South Island hence leading to lower river flows. It has often been noted, however, that relationships between SOI, weather patterns and ocean conditions (including SST) in the New Zealand are relatively weak, lagged, and variable, being modified by other climate variability such as the Southern Annular Mode (Thompson & Wallace, 2000), Pacific Decadal Oscillation (Mantua et al., 1997; Mantua & Hare, 2002), and possibly, the Indian Ocean Dipole (Tourre & White, 1997), as well as by local weather conditions. These variable influencing factors mean that we don't expect SOI to be an especially robust or accurate measure of year-to-year variations in New Zealand coastal conditions.

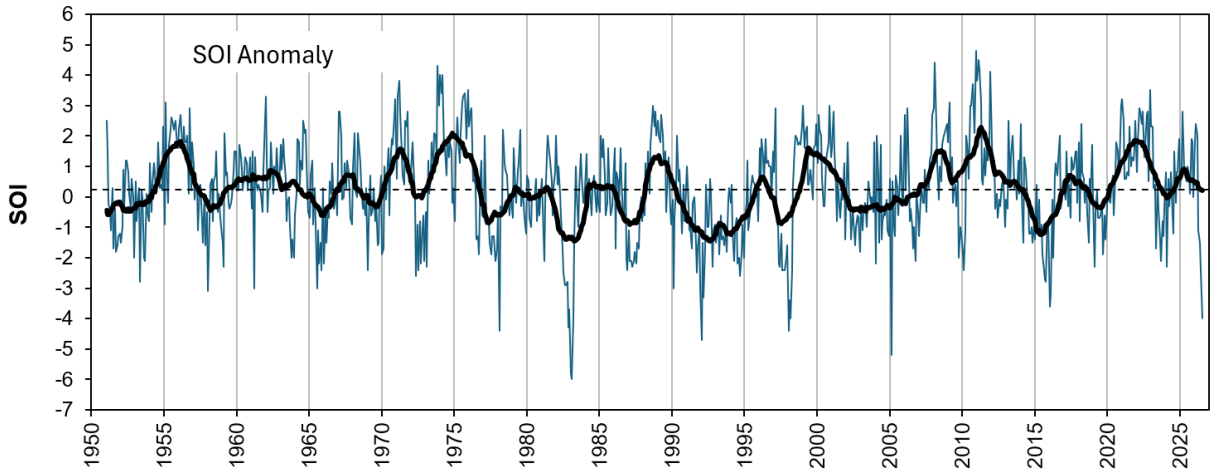

Figure 2.5: Southern Oscillation Index (SOI). The blue line gives the monthly SOI anomaly and the black line is the smoothed trend. Data were sourced from US NOAA (National Ocean and Atmospheric Administration), National Center for Environmental Information, cpc.ncep.noaa.gov/data/indices/soi.

2.3.8 Salmon-season environmental indices

To compare environmental information with salmon run numbers, we needed to combine the higher temporal resolution environmental information (monthly) with the run measurements (by season). First, months of environmental information were combined into a 1-year index by calculating the mean over a 12-month period starting from July and ending in June. The year was split in this way since salmon migrations typically occur over summer (December–March), so this covers the period when run data were collected. Because salmon may be sensitive to the hottest month in a year, for SST we also calculated indices based on the hottest month in the year ("SST-max") rather than the mean over 12 months. These annual indices were then combined to represent the factors that may have contributed to the changes in the measured salmon river run values. Because the dependencies and lags are not well known, we generated three different indices (Figure 2.6):

1-year lag index: This index is simply the seasonal environmental index one year before the run measurements, and will be appropriate if the number of salmon returning depends on short-term (within a year or two) environmental factors.

Natal index: In some areas, the salmon's first year at sea is reported as being the most critical for its survival to adulthood (Northwest Fisheries Science Center, 2024). If salmon in New Zealand are typically three or four years old when they return to spawn (Paul, 1966), we estimate a distribution of the natal years before a given season following a normal distribution with mean 3.5 year and nominal standard deviation of 1 year. This gives the "natal seasonal index", which represents the average conditions running salmon would have experienced in their first year at sea.

Cumulative index (or "C-index" in figures) represents the time-averaged conditions salmon starting the run would have experienced since entering the marine environment. It is produced by weighting the years of environmental data by the proportion of the salmon in the run that were present in the marine environment in that year. It was

estimated from estimated age–distribution of salmon returning to spawn as given above. This index would be appropriate if conditions over the whole of their time at sea affect how many salmon survive to form the seasonal run.

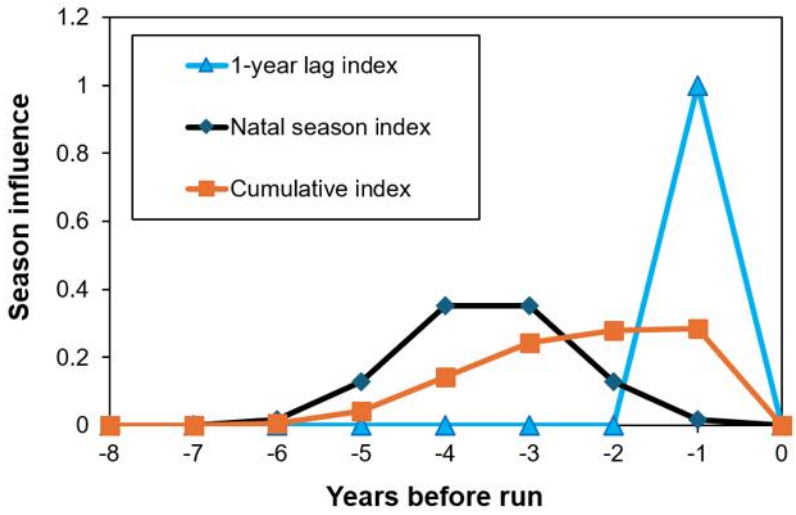

Figure 2.6: Seasonal indices. Three ways were used to combine environmental data from different years to provide an average of what salmon entering the run might have experienced while in the marine domain. (1) The "1–year lag" index is simply the seasonal environmental index one year before the run measurements. (2) The "Natal index" assumes they are particularly affected by conditions in the first year in the marine domain. (3) The "cumulative index" assumes survival is affected by conditions over the whole period they are at sea.

Rank correlation analysis was used to analyse correspondence between salmon run numbers and environmental indices. A t–test was used to assess significance of the rank correlation.

2.4 Fisheries information

Information from research fishing was obtained from publicly available sources, primary being surveys completed by NIWA/Earth Sciences New Zealand under contract to Fisheries New Zealand (Ministry for Primary Industries). These data are available from the Trawl Survey Information Portal (TSIP[1]). The portal provides access to the main inshore (especially relevant here is East Coast South Island) and deepwater trawl surveys (including the Chatham Rise trawl survey series), giving information on abundance (biomass) trends, species distributions, catch rates, size frequencies, and biological data for over 100 species.

The east coast South Island research trawl survey covers the adjacent marine area from 10 m depth to the shelf edge (400 m) and is a primary source of fish abundance information in this region (Figure 2.7). The survey uses a bottom trawl towed at about 3 knots (MacGibbon et al., 2024). Because the survey uses a bottom trawl towed relatively slowly, it is not considered a good sampling method for small and/or pelagic fishes that are either above the net or able to fit through the net meshes, nor for faster–swimming species which are able to evade the net. The extent to which Chinook salmon

[1] https://tsip-uat.niwa.co.nz/

are vulnerable to bottom trawls is not well known (James & Unwin, 1996). We are not aware of any scientific midwater trawling being done in this region.

Information on catches of chinook salmon by commercial fishers was obtained from the Fisheries New Zealand Infosite (Fisheries New Zealand, 2026b).

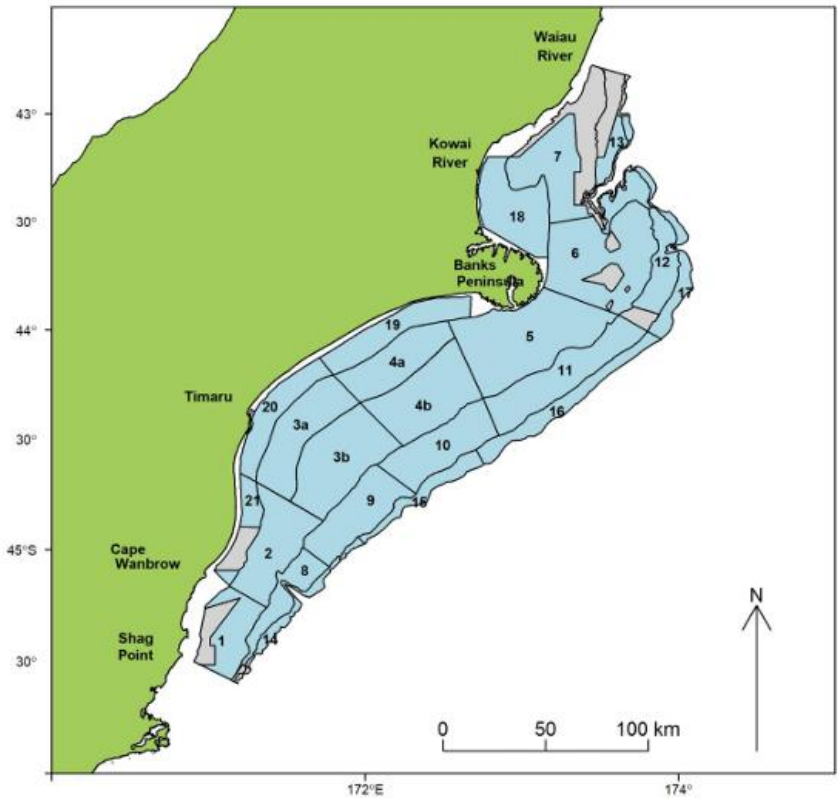

Figure 2.7: Area and strata, used in the East Coast South Island research trawl survey. The "core" survey has strata extending from 30–400 m depth and are labelled 1–17. The core plus shallower strata (labelled 18–21) form the "all" series and cover 10–400 m depth. Grey areas are foul ground (trawling was not possible).

2.5 Seabirds

More than 70 seabird species utilise waters off the Canterbury region (Taylor, 2000a, b; Pinkerton, 2014), but the assemblage is likely dominated by ~12 species, including sooty shearwater (*Puffinus griseus*), red-billed gull (*Larus novaehollandiae scopulinus*), southern black-backed gull (*Larus dominicanus dominicanus*), Hutton's shearwater (*Puffinus huttoni*), Australasian gannet (*Morus serrator*), white-fronted tern (*Sterna striata striata*), spotted shag (*Stictocarbo punctatus*), Otago shag (*Leucocarbo chalconotus*), white-flippered penguin (*Eudyptes minor albosignata*), southern blue penguin (*Eudyptula minor minor*), yellow-eyed penguin (*Megadyptes antipodes*), and black shag (*Phalacrocorax carbo novaehollandiae*). In rivers, seabirds like terns and shags may feed on concentrated aggregations of salmon smelt. At sea, some species of seabirds are highly mobile predators, and can exploit food resources over relatively large spatial scales and may feed on salmon or their prey. It is possible that information on seabirds can help in understanding factors driving changes in Chinook salmon numbers.

For the purposes of this study, we searched for long time–series of information on seabird numbers and foraging in the Canterbury region, and report on the best dataset found: Allen et al. (2011) which measured breeding success in white–flippered penguins.

2.6 Marine mammals

2.6.1 Cetaceans

There are a number of species of toothed whales and dolphins that are likely to have the Canterbury marine region in their living range (e.g. Gaskin, 1982; Baker, 1990; Pinkerton 2014), and which may affect salmon populations as predators. These animals may be dominated (in terms of biomass) by pilot whales (*Globicephala melas, G. macrorhynchus*), common dolphins (*Delphinus delphis*), killer whales (*Orcinus orca*), dusky dolphins (*Lagenorhynchus obscurus*), bottlenose dolphins (*Tursiops truncatus*) and Hector's dolphins (*Cephalorhynchus hectori*).

These toothed whales primarily consume fish in the water column, and, given the suitability of the size and habitat of salmon in the Canterbury region, it is highly likely that most of these toothed whales and dolphins would consume Chinook salmon in New Zealand. For example, in North America, salmon are the primary prey for southern resident killer whales (Ford et al., 1998). The proportions of Chinook salmon consumed in New Zealand by cetaceans, however, are not well known, and, unlike in North America, abundances of salmon in the Canterbury region seem likely too low for this species to be a major target prey item for any cetacean in New Zealand.

2.6.2 Pinnipeds (seals and sealions)

Two species of eared (otariids) and earless (phocids) seals are present in the Canterbury region: New Zealand fur seal (*Arctocephalus forsteri*) and Hooker's (New Zealand) sealion (*Phocarctos hookeri*) (Pinkerton, 2014). Although southern elephant seals (*Mirounga leonine*) have been seen in the New Zealand region, this species is unlikely to reach as far north as Canterbury on a regular basis. Similarly, leopard seals (*Hydrurga leptonyx*) are now present in New Zealand but their numbers are low.

Recent estimates of the fur seal population of the Otago coast are 20,000–30,000, whereas it is likely that there are far fewer sealions in the region, maybe just a few hundred (Pinkerton 2014). Both species primarily consume small and medium–sized pelagic fish, as well as squid, and could predate on salmon while foraging at sea.

2.6.3 Sources of information for marine mammals

We note that information on marine mammal numbers in the New Zealand region is available from a number of sources, including:

- New Zealand Marine Mammal Database[2]. This database holds historical records of over 21,500 sightings covering 57 different taxa;

[2] https://www.dragonfly.co.nz/publications/richard_sightings_2024/

- Fisheries Observer Reports: Recent datasets add thousands of new observation events, detailing interactions and numbers for dolphins, whales, and pinnipeds (Richard & Berkenbusch, 2024);
- Department of Conservation Stranding Records: More than 5,000 whale and dolphin strandings have been logged along the whole New Zealand coast since 1840, with an average of 85 incidents recorded each year (Department of Conservation, 2026).

The quantitative analysis of these marine mammal data is likely be complex given that the data are from a variety of sources, often non–systematically or scientifically collected, and cover a wide range of species with very different ecological connections. Because of this, and as there are many different ways in which changes to the abundance of salmon and marine mammals could be related, we think it unlikely that this analysis will be very useful for understanding why the salmon runs have declined, whether this trend is likely to continue in the future, and if any action can improve the situation for salmon. For this reason, and discussed in greater detail in the Discussion, we have not obtained or analysed marine mammal time–series data in this report, focussing instead on the environmental and fisheries analyses.

3 Results

3.1 Sea surface temperature

3.1.1 Monthly SST

Based on the three sets of SST information, the surface ocean in the Canterbury marine region has been warming since 1965 (Figure 3.1a) although there have also been many intermittent periods of cooling (1971–1973, 1982–1983, 1985–1987, 1990–1992, 2001–2004, 2014–2016, 2019–2020, 2023–2025). Overall, ocean surface temperatures are about 1.3 °C warmer today than in 1960. Based on ORAS5 SST reconstructions, extracted close to the mouths of the Rangitata, Rakaia and Waimakariri rivers (Figure 3.1b), there was a decade of very rapid warming between 1965–1975 when SST rose by more than 2 °C. The difference between this rapid coastal warming and the average of the ocean warming is suspicious, especially given the coarse spatial nature of the ORAS5 data. Further analysis would be needed before it is known if these data can be trusted and, in the meantime, we are sceptical of their validity.

This issue is not important for the purposes of the present report, however, because between 1980 and 2026, the changes in SST near the river mouths and in the wider Canterbury marine area are consistent, and this interval completely spans the period over which we have salmon run data. Our results are consistent with previous work in New Zealand (e.g. Pinkerton et al., 2018) showing that the OISST product is consistent with the higher spatial resolution (500 m) information from SCENZ in the New Zealand coastal zone. January–March were the warmest months in terms of SST in the Canterbury marine region (Figure 3 1c) and warming over the 1960–2025 period has been higher in these warm months than in those in winter, i.e. the summers are getting hotter faster than the winters. Mean February SSTs have risen from about 15 °C to ~16.5 °C during this period.

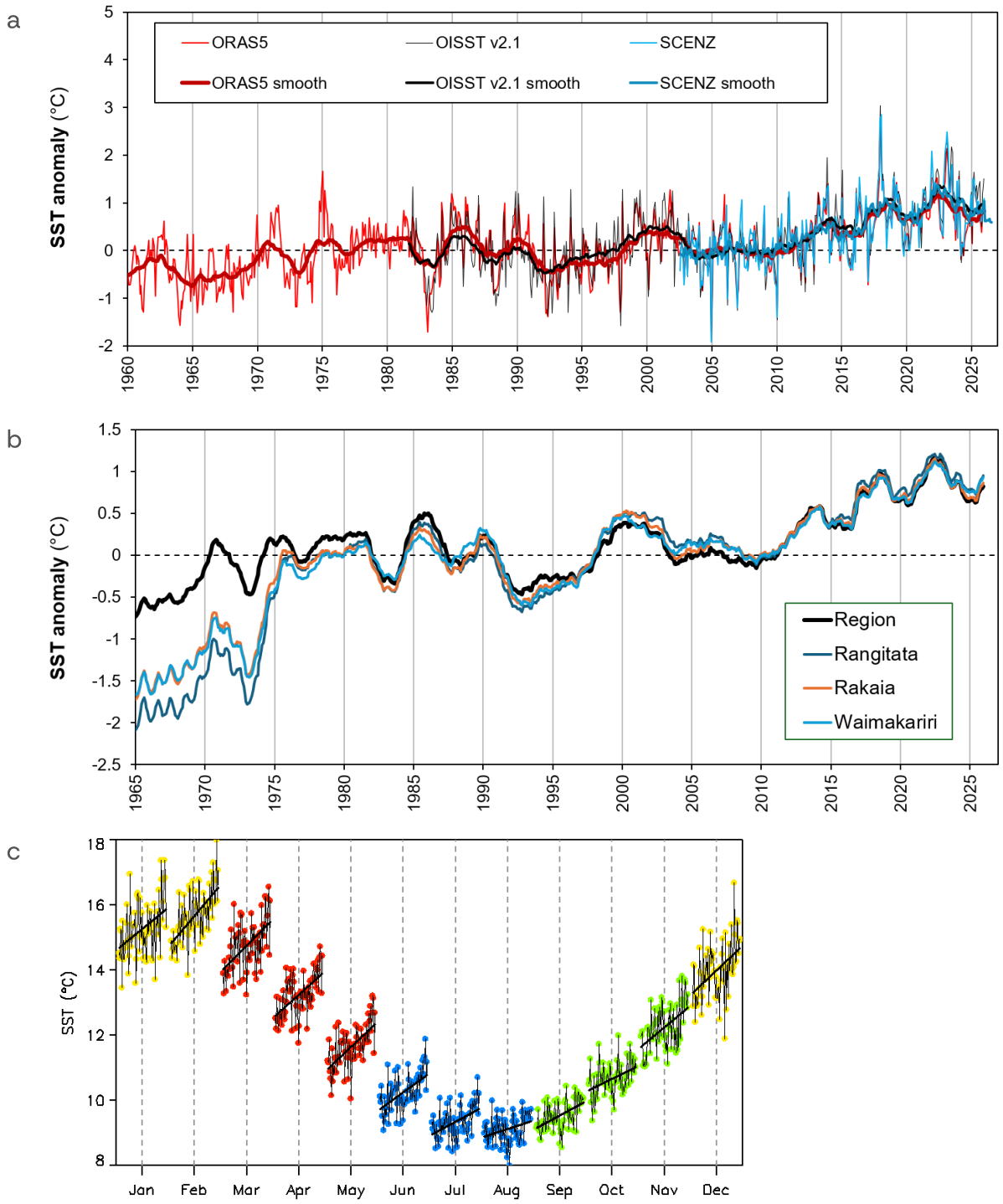

Figure 3.1: Sea surface temperature (SST) time series. (a) SST anomalies 1965–2026 for the Canterbury marine region from three data sources: ORAS5 (Ocean Reanalysis System 5; orange), OISST v2.1 (Optimum Interpolation Sea Surface Temperature; black) and SCENZ (Seas, Coasts and Estuaries, New Zealand; blue), with monthly data and the 5-year smoothed trend shown for each. (b) ORAS5 SST anomalies for the three river mouths (Rangitata, Rakaia, Waimakariri) compared to the larger Canterbury marine region (black line "Region"); (c) Seasonal changes to SST based on ORAS5, where each year is shown as a symbol grouped by month, with colours showing seasons (summer, yellow; autumn, red; winter, blue; spring, green) and black lines indicating within-month trends (least-squares linear regressions).

Rising annual mean surface temperatures corresponded with the decreasing salmon run figures, irrespective of whether the SST was based on ORAS5 or OISST (Figure 3.2). Rank correlations between run anomalies and SST (using the cumulative index) were all negative (higher SST corresponds to lower run numbers) and statistically significant for all rivers ($p<0.001$), with coefficients 0.75–0.86 (Section 3.6). In the correspondence plots, there was evidence of a non-linear relationship, where salmon run numbers were lower where mean annual surface temperature were >12°C. We repeated the analysis using the maximum (summer) SST (Figure 3.3). For ORAS5, salmon run numbers were consistently low when surface water temperatures were 15.5 °C. The relationship was similar, but less well pronounced using OISST. Two things are important to note. First, there were very low salmon run numbers in years with colder waters; statistically, warm water implies poor runs, but cool water does not imply good runs. Second, these relationships are not necessarily causal, i.e. the different runs are not necessarily due to the different water temperatures.

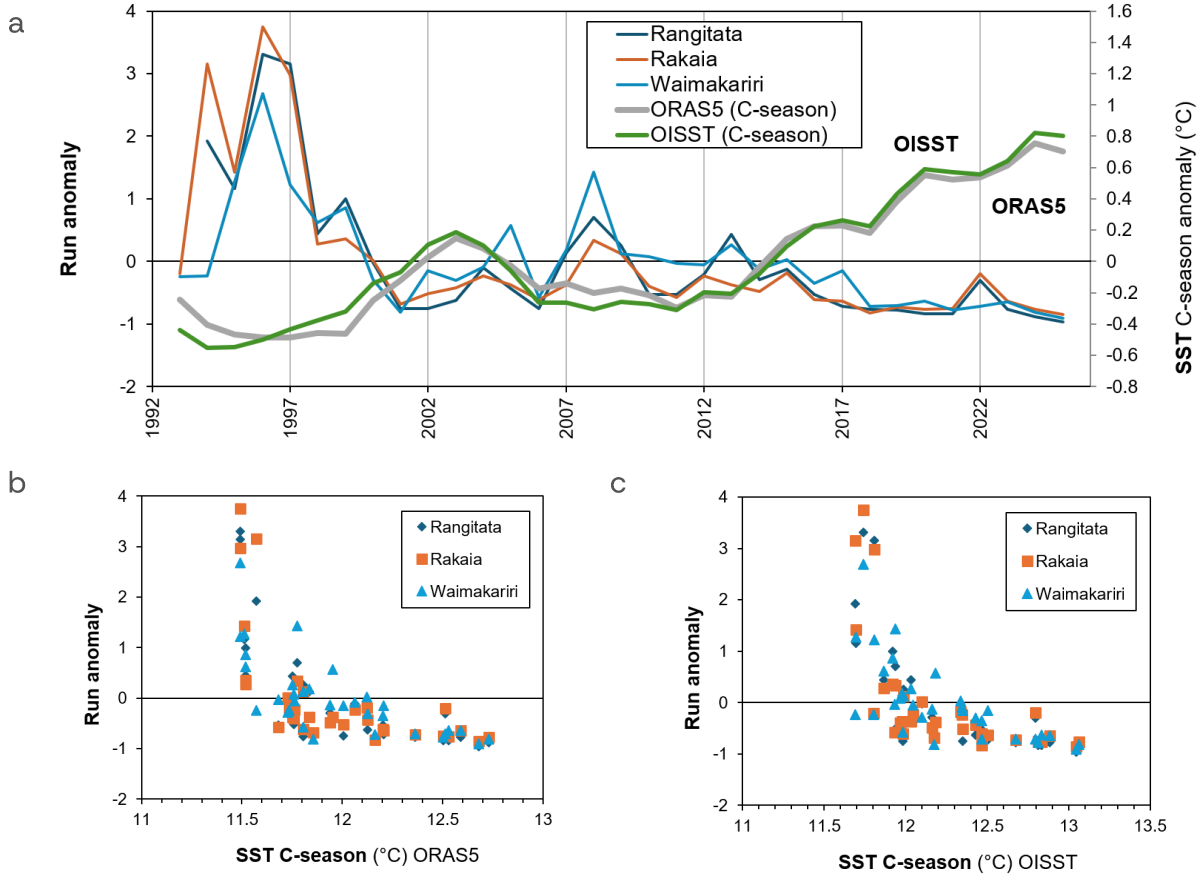

Figure 3.2: Comparing season-average SST and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and season-average SST (using cumulative season mean); (b) Annual-average SST correspondence plot by season for each river based on ORAS5 (Ocean Reanalysis System 5); (c) As in (b) but based on OISST (Optimum Interpolation Sea Surface Temperature) v2.1.

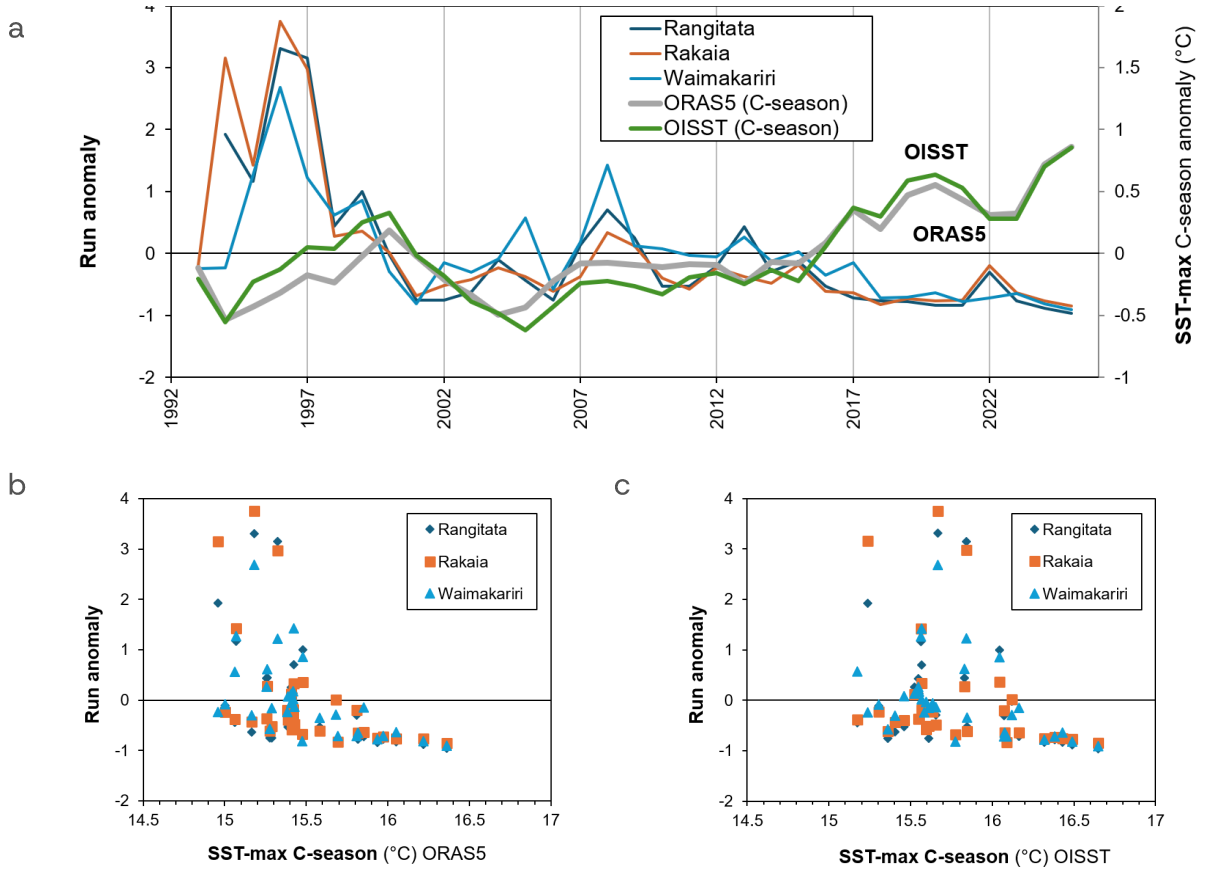

Figure 3.3: Comparing season-average SST-max and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and annual maximum SST index (SST-max, using cumulative season mean); (b) SST-max correspondence plot by season for each river based on ORAS5 (Ocean Reanalysis System 5); (c) As in (b) but based on OISST (Optimum Interpolation Sea Surface Temperature) v2.1.

3.1.2 Daily SST

A greater number of ocean "hot days" – where SST exceeded a set of different temperature thresholds – generally corresponded with lower numbers of salmon. Using the 16 °C threshold as an example, if more than 8% of the season (about one month a year) was hotter than this in the Canterbury marine region, all the run anomalies were negative (Figure 3.4). Note that this correlation does not imply causality. There is a general trend of decreasing run anomalies over time when the ocean water has also been warming. This means that a negative correlation between run numbers and SST will be obtained even if the decline in salmon is not caused by warming. We also note that many years with negative run anomalies had less than a month hotter than 16 °C. For example, 2005/06 had a very low mean run anomaly (8th worst) but only six days were hotter than 16 °C. So, many hot days correspond with low run numbers, but few hot days don't correspond to high runs. Overall, rank correlations between run anomalies and hot days (using the cumulative index) were all negative (more hot days corresponded to lower run numbers) and usually statistically significant ($p<0.001$) with coefficients between 0.41–0.81 (Section 3.6).

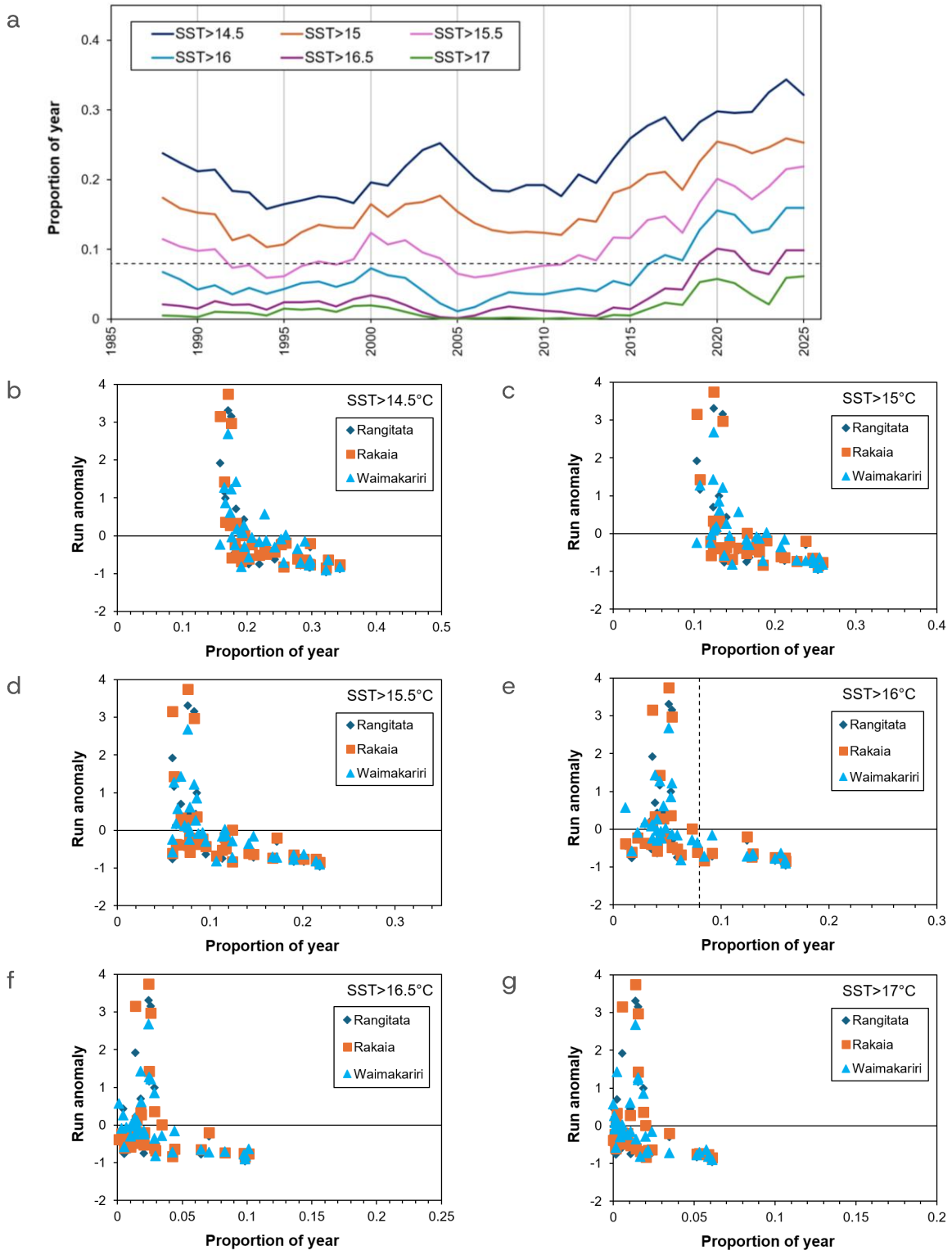

Figure 3.4: Proportion of year that temperatures at the river mouths are above a certain value. (a) The proportion of time in the Canterbury marine region that is hotter than different SST thresholds (14.5–17 °C) by season using the cumulative season index; (b)–(g) Salmon run anomalies for the Rangitata, Rakaia and Waimakariri rivers versus the "hot" proportions of the season (cumulative index). The dashed lines in (a) and (e) are a nominal example, showing that for seasons where more than 8% of the days are hotter than 16 °C, all salmon run anomalies were negative. We note that there were also many negative salmon run anomalies in seasons with lower proportions of hot days.

3.1.3 Effects of river run off on SST

Our analysis showed a seasonal difference in surface water temperature at river mouths compared to the coastal receiving environment (Figure 3.5), at least for the Rangitata and Waimakariri rivers; the differences were less clear for the Rakaia. In general, this is evidence of the river water being warmer than the coastal water in summer and cooler in winter. The effect on salmon is likely to be low, however, because these seasonal differences are small: less than 0.05 °C/km implying a difference of less than 0.25 °C over the 5 km of the near–coast transition zone. Of course, it is possible that river temperatures are much higher than coastal temperatures higher upstream of the nominal discharge point (but we didn't have data for this), although this seems unlikely based on these results. We suggest the coastal SST values are representative of the conditions that salmon experienced in the lower reaches of these rivers on average over a year, but that rivers are ~0.25 °C warmer than the coastal zone in summer and ~0.25 °C cooler in winter.

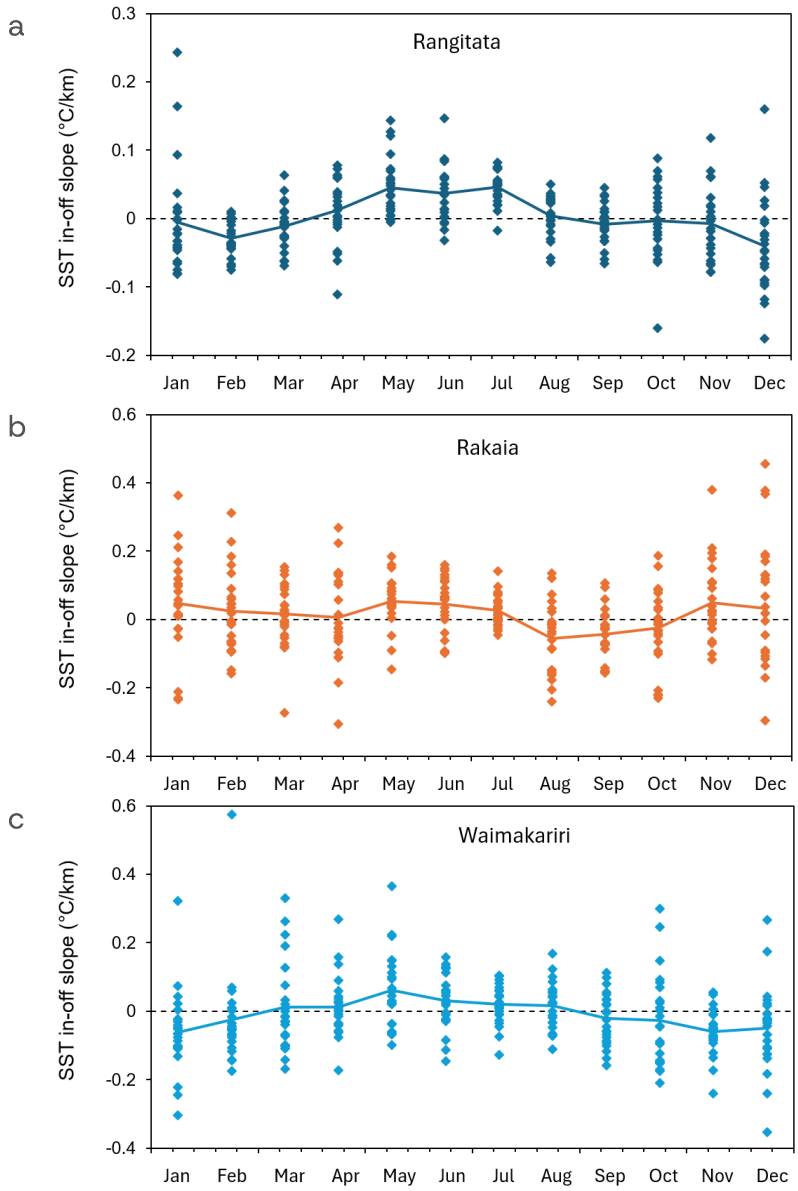

Figure 3.5: Seasonal effects of river discharge on surface temperature at river mouths. (a) Rangitata; (b) Rakaia; (c) Waimakariri rivers. Values on the y-axis are the inshore–offshore spatial gradient of SST (°C per km of linear radial distance away from the river mouth). The plots showing the effects of river run off on SST at the river mouth, where positive values indicate the river water being colder than the coastal receiving environment and vice versa.

3.1.4 Temperature at depth

Based on the ORAS5 depth-resolved hindcast model, the seawater near the seabed in the Canterbury marine region is an average of 2.4 °C colder than at the surface, and the seasonal temperature range at the seabed is about half that at the surface (Figure 3.6). The warming pattern over the 65-year period (1960–2025) at the seabed and sea surface are similar, but there was only 0.8 °C warming at the seabed over this time compared to warming of 1.3 °C at the surface. Because there are no major differences in patterns of temperature change over time, and because salmon are understood to spend most of their time in the surface mixed-layer (see Sections 1.5 and 1.6), we did not carry out further analysis of these seabed temperatures.

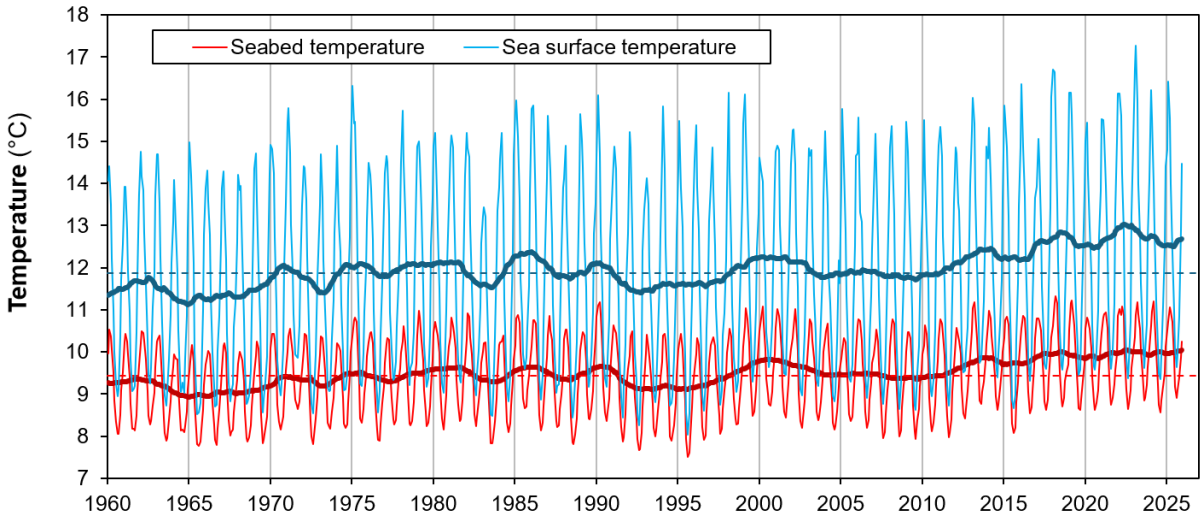

Figure 3.6: Temperature through the water column. Based on ORAS5, the sea surface (blue) and seabed temperatures (red), and their trends (thick line) and mean values (dashed lines) are compared.

3.2 Southern Oscillation Index

Consistent with other studies (e.g. Figure 14 in Drake 2025,), we found only weak correlation between SOI and SST in the Canterbury marine region, with correlation, R~ 0.2 at a one–month lag. Here, our analyses agree very closely (Figure 3.7) with a weak positive correlation at 1–month lag, and correlation coefficients of 0.23 (OISST v2.1) and 0.22 (ORAS5). We found negligible correlations between SOI anomaly and anomalies in chl–a, TSS and Hvis (<0.1 in all cases; data not shown). SOI was weakly related to changes in salmon run numbers (Figure 3.8); rank correlations with the SOI cumulative index were between −0.32 and −0.41 and generally non–significant (p>0.01; Section 3.6).

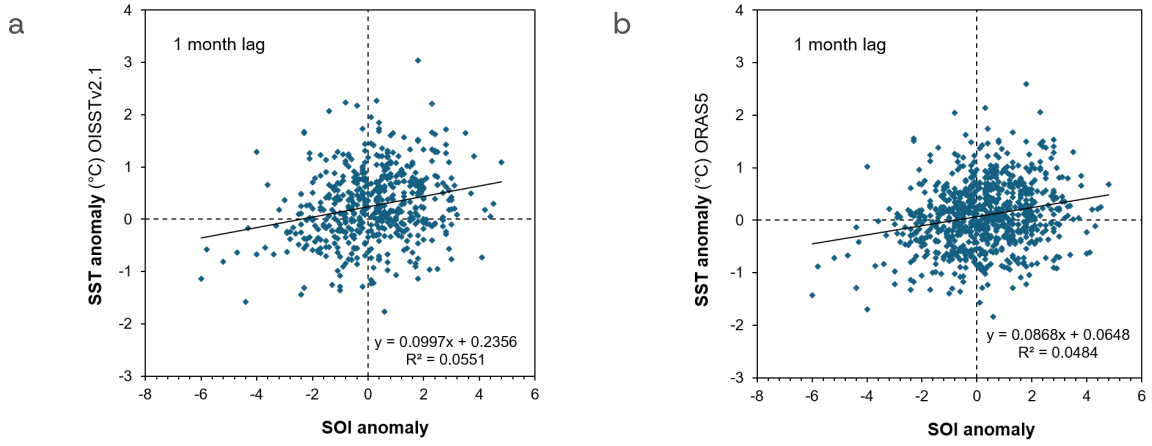

Figure 3.7: Correspondence between Southern Oscillation Index (SOI) anomaly and sea surface temperature (SST) in the Canterbury marine region. (a) OISST v2.1; (b) ORAS5 SST. The SST anomalies are lagged by 1 month as in Drake (2025).

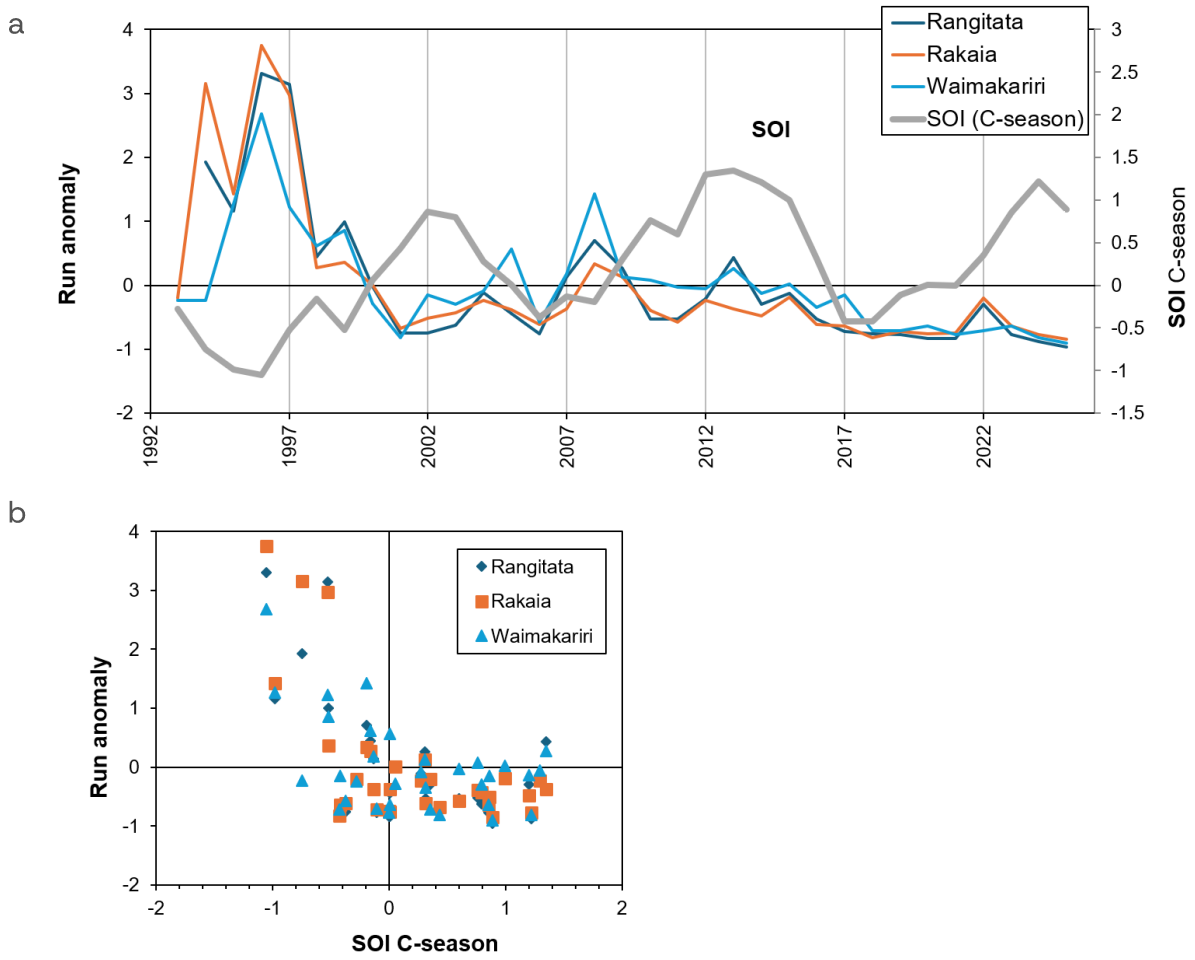

Figure 3.8: Comparing season-average indices of SOI and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and season-average SOI (Southern Oscillation Index; using cumulative season mean); (b) Correspondence plot between variables.

3.3 Ocean productivity (chlorophyll-a)

Changes in surface chl-a increased by a small amount in the Canterbury region since satellite observations started in 1997 (Figure 3.9), although the trend was smaller than the month-to-month variability. Chl-a values near the mouths of the three rivers of interest were higher than for the Canterbury marine area as a whole (as expected). The seasonal pattern of chl-a in the Canterbury region was relatively weak, with values similar in all months. Trends in chl-a in all months except January and February were positive over the period 1997–2025, consistent with warming stabilising the water column and increasing mean light intensity in the surface mixed-layer (Pinkerton et al., 2023). Rank correlations between run anomalies and chl-a (using the cumulative index) were not statistically significant for any river (Figure 3.10; $p>0.05$, Section 3.6). Overall, we found no substantial reduction or increase in chl-a (as a proxy for oceanic primary production in the Canterbury region) that could explain reductions in salmon run numbers.

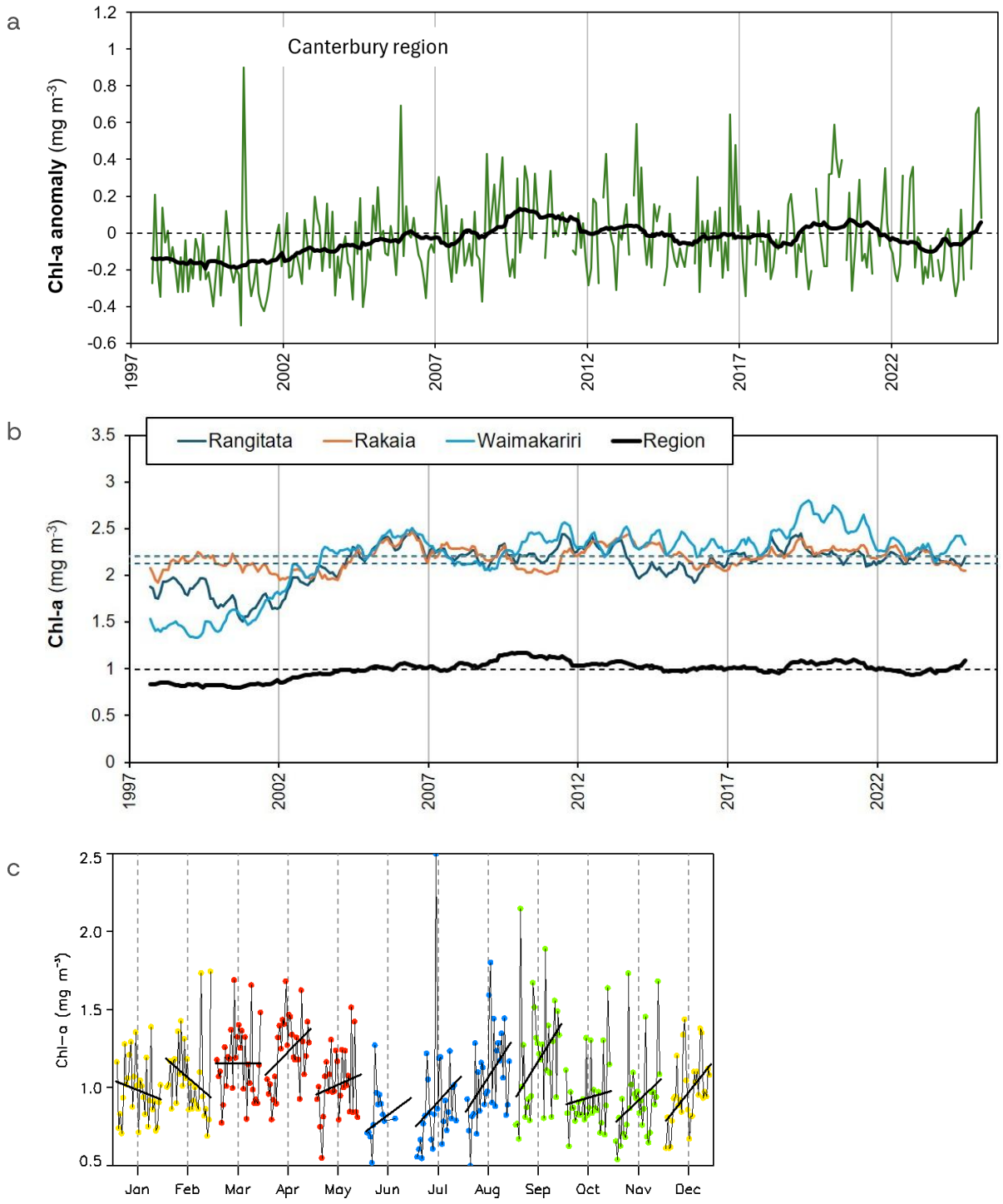

Figure 3.9: Chlorophyll-a concentration (chl-a) time series. (a) Anomalies 1997–2025 for the Canterbury marine region, showing the monthly data (green) and the smoothed trend (black). (b) Anomalies for the three river mouths (Rangitata, Rakaia, Waimakariri) compared to the larger Canterbury marine region (black line "Region"), where the horizontal dashed lines show means; (c) Seasonal changes, with colours showing different seasons (summer, yellow; autumn, red; winter, blue; spring, green) and black lines indicating within-month trends.

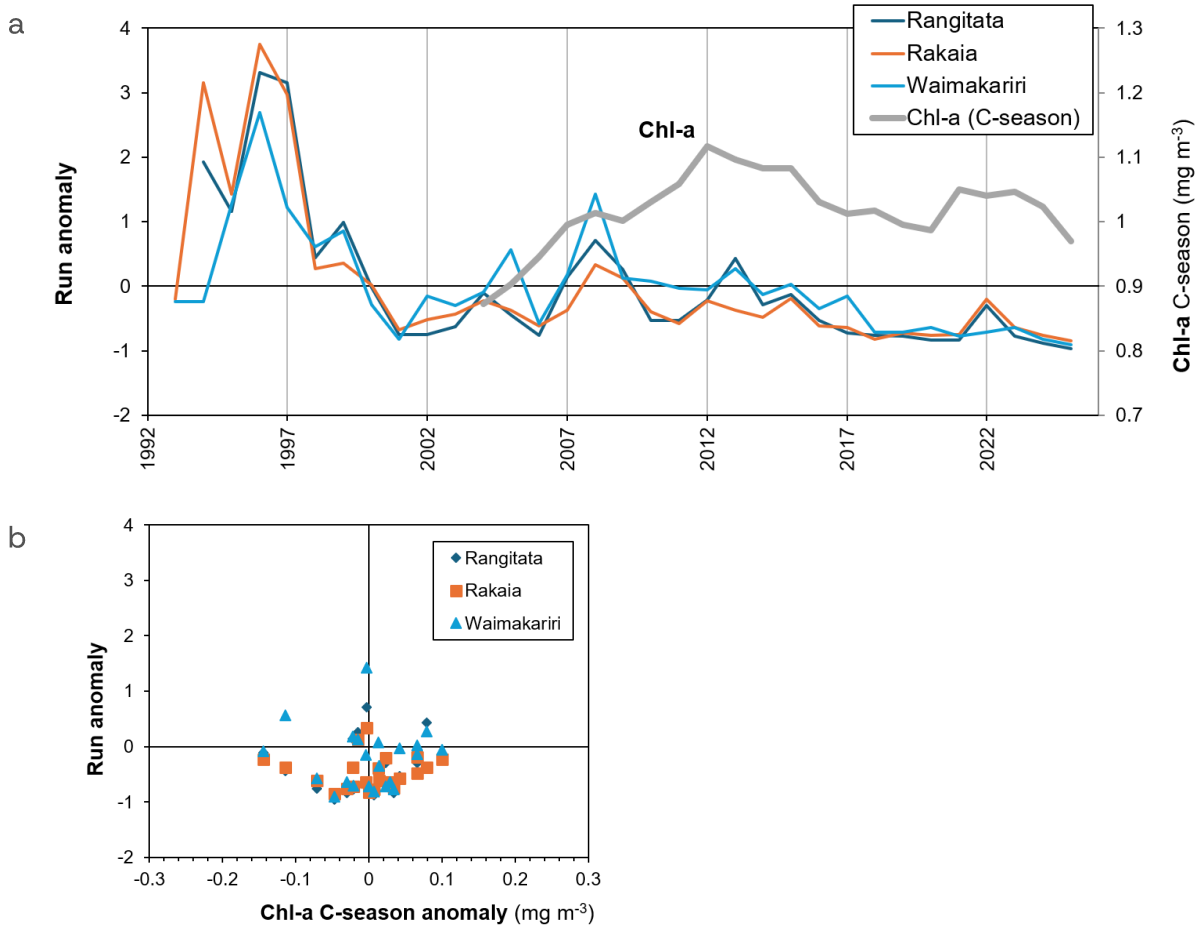

Figure 3.10: Comparing season-average indices of chlorophyll-a concentration (chl-a) and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and season-average chl-a (using cumulative season mean); (b) Correspondence plot between variables.

3.4 Suspended sediment concentrations

There were no substantial trends in TSS in the Canterbury marine region nor near the mouths of the major rivers over the period of moderate-resolution satellite observations that started in 2002 (Figure 3.11). At the monthly scale, suspended sediment concentrations were consistently highest in the Rakaia and lowest in the Waimakariri. Seasonally, TSS was highest in the winter and lowest in summer, with highest change in July (increasing) and August (decreasing) possibly due to a trend of earlier rainfall in the winter. Overall, there was no indication of a change in suspended sediment in the Canterbury region that corresponded to salmon run numbers (Figure 3.12). Rank correlations between run anomalies and TSS (using the cumulative index) were all positive (higher TSS corresponded to higher run numbers) and generally not statistically significant ($p>0.001$, Section 3.6).

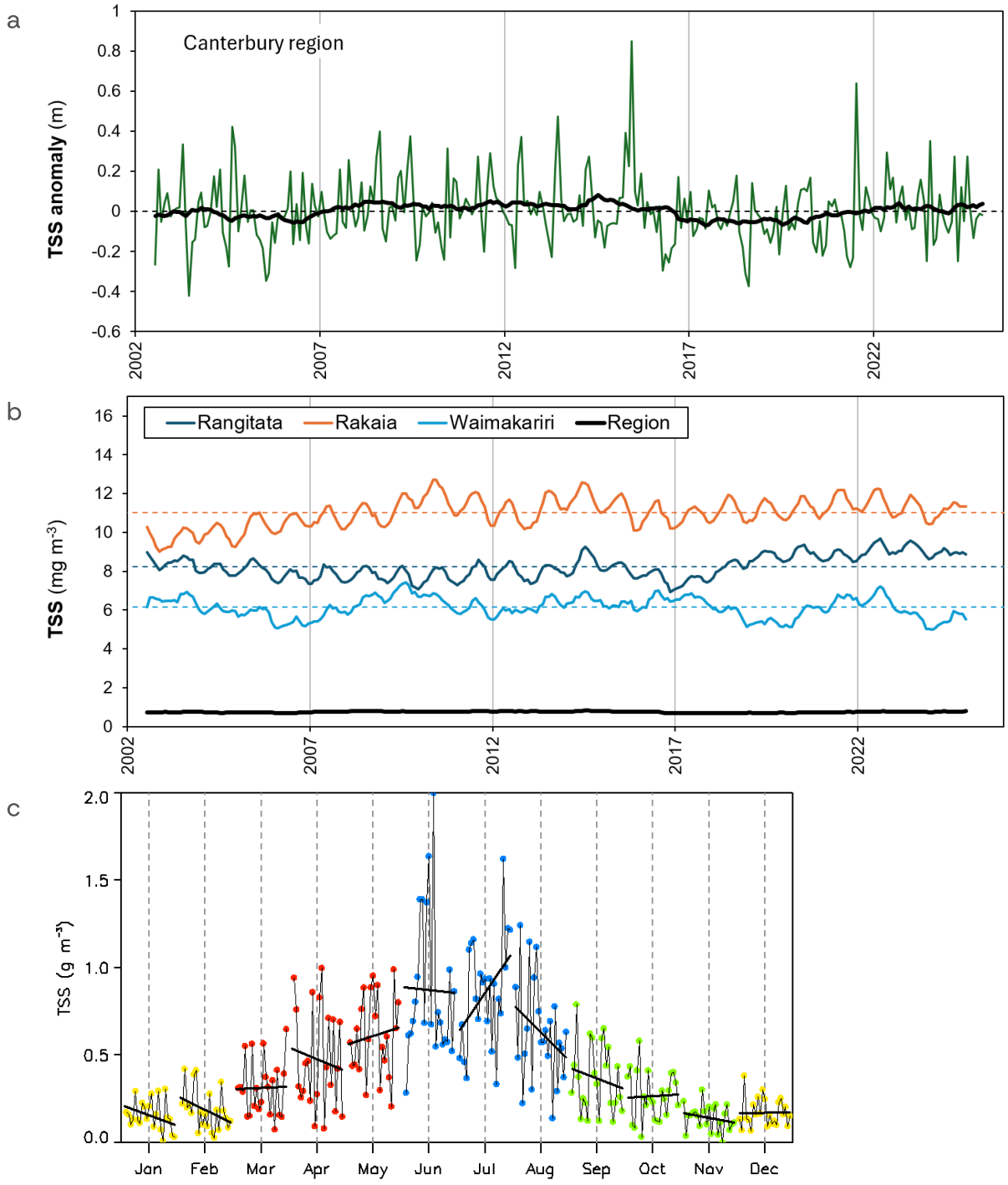

Figure 3.11: Total suspended solids (TSS) time series. (a) Anomalies 2002–2025 for the Canterbury marine region from SCENZ, showing the monthly data (green) and the smoothed trend (black). (b) Smoothed TSS for the three river mouths (Rangitata, Rakaia, Waimakariri) compared to the larger Canterbury marine region (black line "Region"). The coloured dashed lines show means; (c) Seasonal changes, with colours showing seasons (summer, yellow; autumn, red; winter, blue; spring, green) and black lines indicating within-month trends.

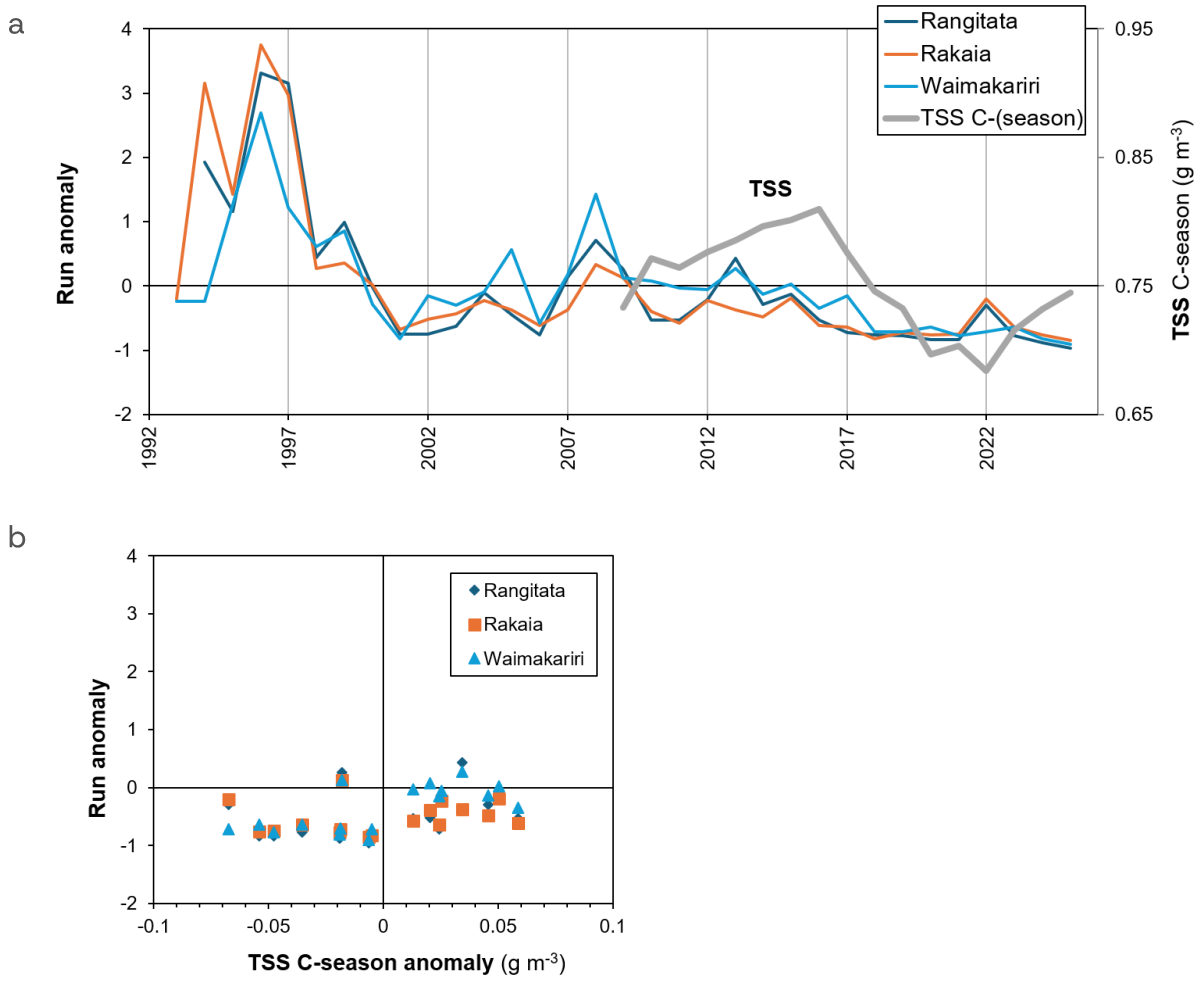

Figure 3.12: Comparing season-average indices of total suspended solids (TSS) and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and season-average TSS (using cumulative season mean, "C-season"); (b) Correspondence plot between variables.

3.5 Water clarity (horizontal visibility)

Horizontal visibility, a measure of water clarity, was highly variable across the Canterbury region, being lower close to the coast due to higher suspended sediment and phytoplankton, and higher offshore in optically clearer, more oceanic waters (Gall et al., 2022). Since 2002, there were no substantial trends in water clarity, either at the larger Canterbury region scale, or close to the river mouths (Figure 3.13). Water clarity was greatest at the mouth of the Waimakariri and lowest in the Rakaia. The satellite data showed that water clarity was highest in autumn and lowest in summer. Overall, there was an indication of an increase in water clarity in the Canterbury region towards the end of the time-series from 2009 onwards (Figure 3.14). Rank correlations between run anomalies and Hvis (using the cumulative index) were all negative (higher Hvis or less turbid water corresponds to lower run numbers). The relationships were often statistically significant ($p<0.01$) with coefficients between 0.54 – 0.74 (Section 3.6).

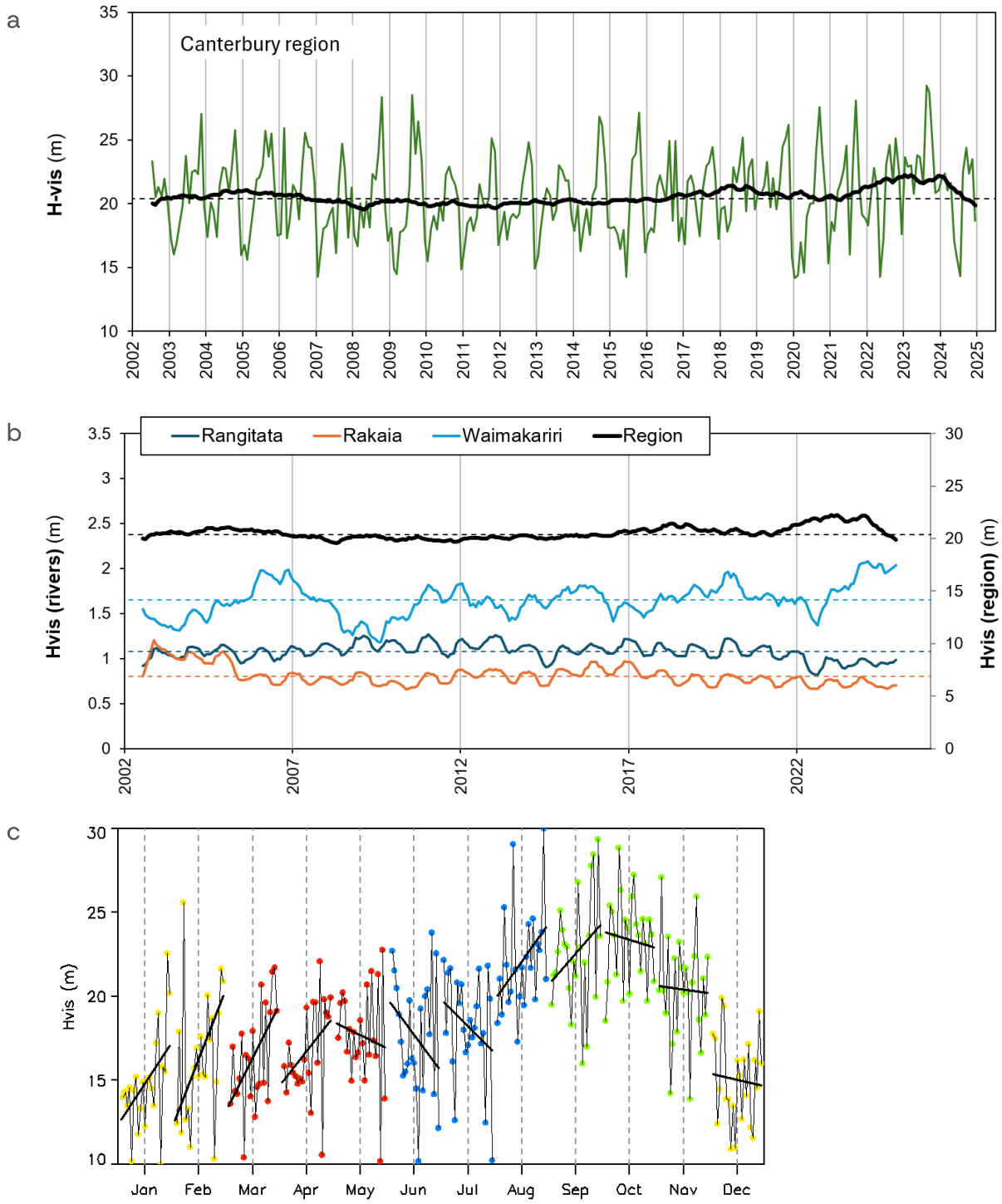

Figure 3.13: Horizontal visibility (Hvis) time series. (a) Anomalies 2002–2025 for the Canterbury marine region from SCENZ, showing the monthly data (green) and the smoothed trend (black). (b) Values for the three river mouths (Rangitata, Rakaia, Waimakariri) compared to the larger Canterbury marine region (black line "Region"), where dashed lines show the long-term means; (c) Seasonal changes, with colours showing seasons (summer, yellow; autumn, red; winter, blue; spring, green) and black lines indicating within-month trends.

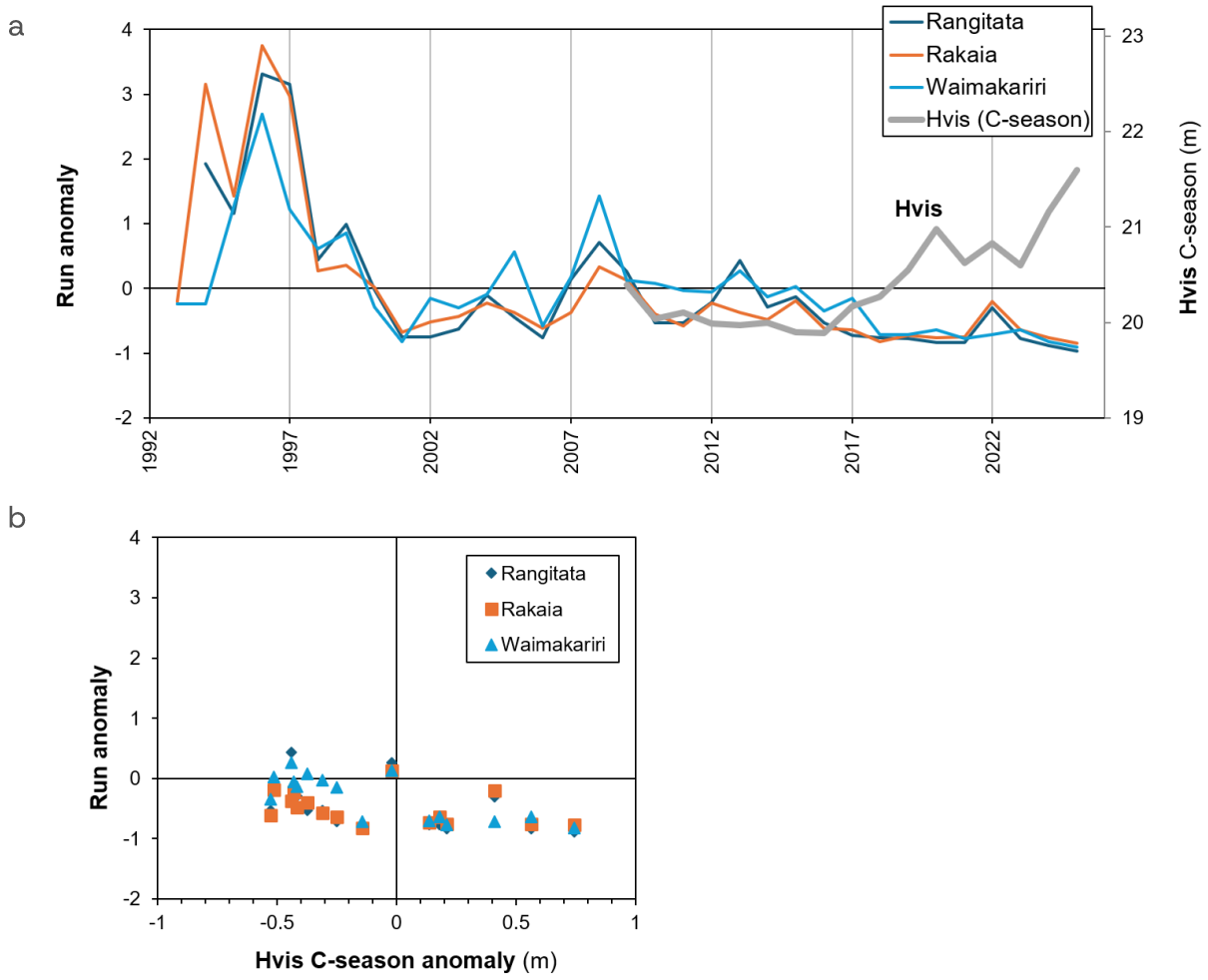

Figure 3.14: Comparing season-average indices of horizontal visibility (Hvis) and salmon runs. (a) Time-series of salmon run anomalies (Rangitata, Rakaia, Waimakariri) and season-average Hvis (using cumulative season mean, "C-season"); (b) Correspondence plot between variables.

3.6 Summary of environmental correlations

The correlations between salmon river run number and environmental conditions are shown below for the three seasonal indices: previous-season index (Table 3.1), natal season index (Table 3.2) and cumulative index (Table 3.3). Correlations with no asterisks are not statistically significant ($p>0.05$). Those with the most asterisks (*** $p<0.001$) have the strongest (most significant) correlation. Negative correlations imply that smaller salmon run number corresponded with higher values for the environmental parameters (for example, warmer water). Overall, the correlations were strongest for the cumulative index, and weakest for the previous-season index, but the patterns were fairly consistent across all three different season indices.

Table 3.1: Correlations between salmon run numbers in three rivers and environmental factors using the "previous-season" metric. Variables marked "SST>" are the proportion of time when the daily SST is greater than the value in °C. N (seasons) = number of seasons for Rakaia and Waimakariri rivers (Rangitata is one less than this because the 1992/93 run numbers are missing). Values are the rank correlation coefficients and the significance is shown: *** p<0.001; ** p<0.01; and * p<0.05. Highest correlations for each river are shown in bold. See text for information on response variables.

Season metric	Variable	N (seasons)	River		
			Rangitata	Rakaia	Waimakariri
Previous season index	SST-ORAS5	33	-0.68***	-0.62***	-0.63***
	SST-OISST	33	**-0.71*** **	**-0.69*** **	**-0.65*** **
	SST-max-ORAS5	33	-0.37*	-0.35*	-0.25
	SST-max-OISST	33	-0.19	-0.20	-0.32
	SOI	33	-0.19	-0.16	-0.20
	Chl-a	22	+0.15	+0.17	+0.20
	TSS	17	+0.44	+0.31	+0.44
	Hvis	17	-0.57*	-0.54*	-0.59*
	SST>14.5 °C	33	-0.42*	-0.33	-0.39*
	SST>15 °C	33	-0.41*	-0.35*	-0.40*
	SST>15.5 °C	33	-0.38*	-0.32	-0.35*
	SST>16 °C	33	-0.40*	-0.38*	-0.35*
	SST>16.5 °C	33	-0.39*	-0.42*	-0.31
	SST>17 °C	33	-0.32	-0.33	-0.23

Table 3.2: Correlations between salmon run numbers in three rivers and environmental factors using the natal index. Other information as Table 3.1.

Season metric	Variable	N(seasons)	River		
			Rangitata	Rakaia	Waimakariri
Natal season index	SST–ORAS5	33	–0.77***	–0.70***	**–0.72*** **
	SST–OISST	33	–0.79***	**–0.73*** **	–0.70***
	SST–max–ORAS5	33	–0.62***	–0.56***	–0.69***
	SST–max–OISST	33	–0.60***	–0.48**	–0.71***
	SOI	33	–0.31	–0.30	–0.30
	Chl–a	22	–0.04	–0.14	–0.08
	TSS	17	+0.32	+0.07	+0.37
	Hvis	17	–0.29	–0.08	–0.40
	SST>14.5 °C	33	–0.80***	–0.76***	–0.71***
	SST>15 °C	33	**–0.81*** **	–0.77***	–0.74***
	SST>15.5 °C	33	–0.78***	–0.72***	–0.79***
	SST>16 °C	33	–0.60***	–0.54**	–0.68***
	SST>16.5 °C	33	–0.51**	–0.41*	–0.62***
	SST>17 °C	33	–0.44*	–0.34*	–0.61***

Table 3.3: Correlations between salmon run numbers in three rivers and environmental factors using the cumulative index. Other information as Table 3.1.

Season metric	Variable	N(seasons)	River		
			Rangitata	Rakaia	Waimakariri
Cumulative season index	SST–ORAS5	33	–0.83***	–0.79***	–0.75***
	SST–OISST	33	**–0.86*** **	**–0.83*** **	**–0.78*** **
	SST–max–ORAS5	33	–0.64***	–0.63***	–0.62***
	SST–max–OISST	33	–0.51**	–0.46**	–0.65***
	SOI	33	–0.41*	–0.41*	–0.32
	Chl–a	22	+0.19	+0.17	+0.08
	TSS	17	+0.56*	+0.32	+0.62**
	Hvis	17	–0.72**	–0.52*	–0.74***
	SST>14.5 °C	33	–0.81***	–0.76***	–0.71***
	SST>15 °C	33	–0.75***	–0.71***	–0.69***
	SST>15.5 °C	33	–0.69***	–0.66***	–0.71***
	SST>16 °C	33	–0.56***	–0.53**	–0.63***
	SST>16.5 °C	33	–0.46**	–0.41*	–0.55***
	SST>17 °C	33	–0.47**	–0.42*	–0.59***

3.7 Fisheries information

3.7.1 Bycatch of Chinook salmon in commercial fisheries

Chinook salmon were caught as bycatch in commercial fisheries in the Canterbury region but since 1991, in response to concerns about excessive numbers of chinook salmon being taken by commercial bottom trawlers off Canterbury, large bottom trawlers (> 23 m registered length) operating off the east coast of the South Island have been subjected to various controls designed to minimise the salmon by-catch. These include the Banks Peninsula salmon conservation area, a 7-nautical-mile-wide marine exclusion zone established to protect migrating salmon from large commercial trawlers[3].

The Fisheries New Zealand Infosite[4] (Fisheries New Zealand, 2026b) indicates near-zero commercial fishery catches of Chinook salmon over the last five years, inconsistent with the hypothesis that salmon abundance was being impacted directly (i.e., caught as bycatch in significant numbers) by commercial marine fisheries.

Providing information on total commercial fishing *effort* relevant to salmon would need a specific fisheries data extract from Fisheries New Zealand and analysis; given the low reported catches of salmon, we suggest this is unlikely to provide much additional insights.

3.7.2 Salmon in the ECSI research survey

The few Chinook salmon that the East Coast South Island (ECSI) survey has managed to capture were in the northern survey Stratum 7 (Figure 3.15, Figure 3.16), and then from 2014 were no longer caught there but occasionally in the 10–30 m strata (Figure 3.17, see Figure 2.7 for strata locations). All salmon caught were in depths less than 50 m. Most fish were less than 50 cm length (Figure 3.17) but because salmon are not a native species, little further detailed sampling of their biology was done. In winter surveys, only three fish were sampled for details of their biology, being 49 and 58 cm long in 2012 (1 male, 1 female) and 58 cm (2.4 kg) in 2021 (male). In summer surveys, 102 salmon were sampled, ranging between 12 cm and 93 cm in length and 315 g to 5.1 kg, and most were male (where sexed, 18 of 22 were male). Note that the summer surveys were discontinued after 2000, after which we only have the winter surveys.

The salmon biomass trend from the survey tends to suggest more were caught in the sampling series in the 2000s compared to the 1990s (Figure 3.18). However, catches have been sporadic, which is why the uncertainty is large, so it is probably best to draw no strong conclusions other than "the survey sometimes catches salmon" off eastern South Island.

[3] https://www.legislation.govt.nz/secondary-legislation/pco-drafted/1986/219/en/2008-04-01/sections/DLM110348/
[4] https://fs.fish.govt.nz/

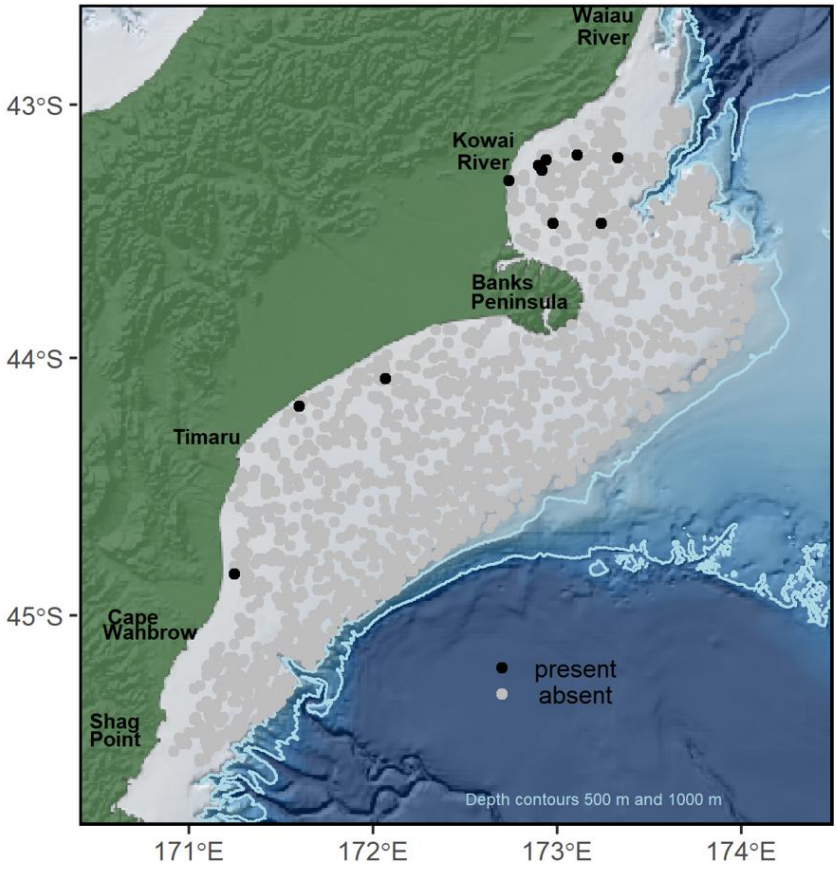

Figure 3.15: Location of salmon catches in the east coast South Island trawl survey, for all years combined. Black dots show where salmon was caught, and grey dots where salmon were not caught. See Figure 3.18 for the survey years.

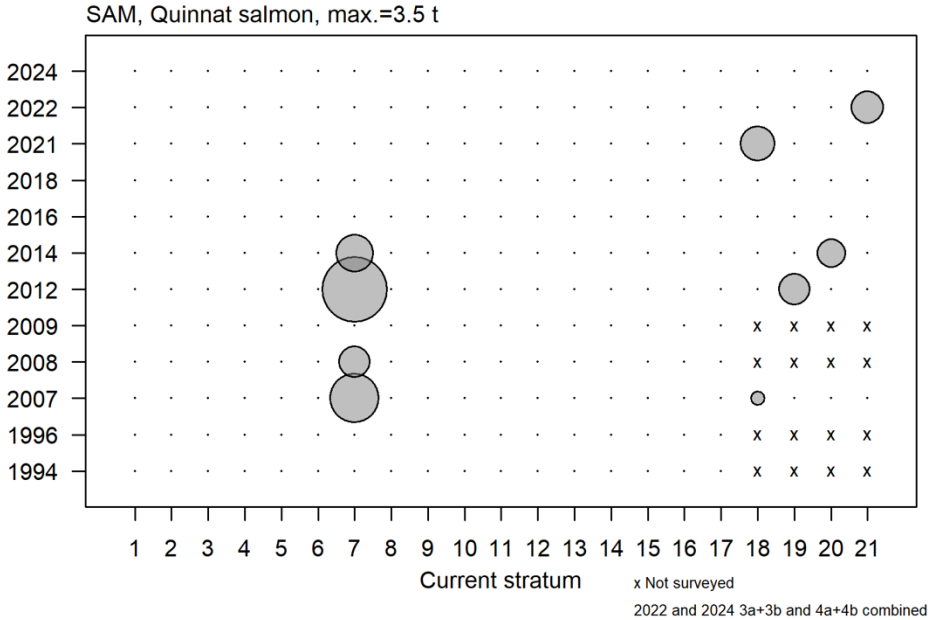

Figure 3.16: Size of salmon catches in the east coast South Island trawl survey by stratum. See Figure 2.7 for the stratum locations. Crosses indicate the stratum was not part of the survey at that time. Bigger circles mean bigger catches, and no circle means zero catch. The largest catch in any survey was 3.5 tonnes (t). "SAM, Quinnat salmon" is the Fisheries New Zealand code for Chinook salmon.

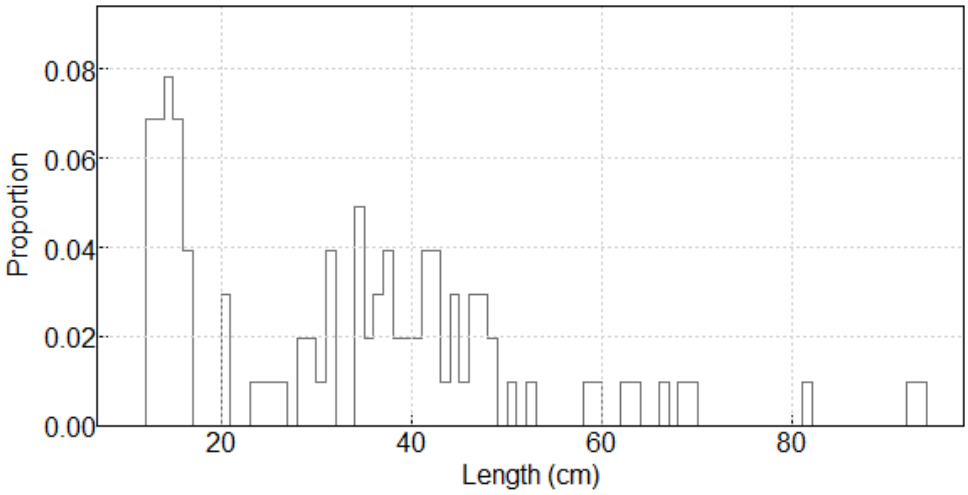

Figure 3.17: Salmon length frequencies from the east coast South Island research trawl surveys. Data are for all surveys combined (although most data were from the summer survey series which ran annually from 1996 to 2000).

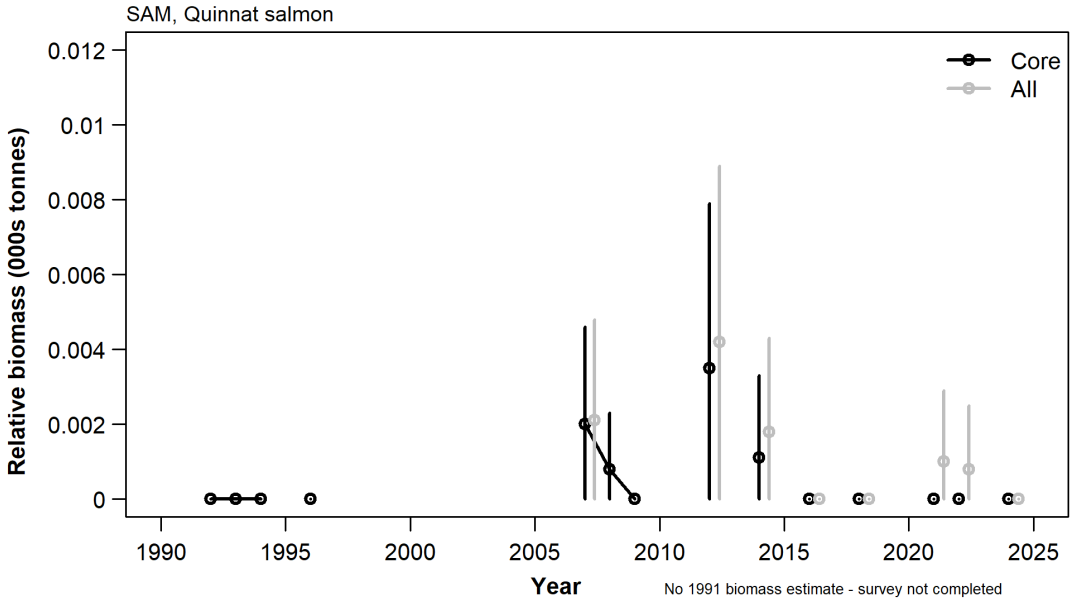

Figure 3.18: Salmon biomass estimates from the east coast South Island research trawl surveys. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012. "SAM, Quinnat salmon" is the Fisheries New Zealand code for Chinook salmon.

3.7.3 Salmon prey in the research survey

There are limited scientific data on the trophic ecology (diet) of salmon at sea. James & Unwin (1996) found salmon mostly eating sprats, with some squat lobsters and hoki. Sprat eggs were found off the Canterbury Bight in the mid–1970s, suggesting sprat were spawning in that area, mainly between June and November (Colman, 1979). There are two species of sprat, the "slender sprat", *Sprattus muelleri* (Fisheries New Zealand species code SPM) which was the one observed in the salmon diet (James & Unwin, 1996), and the "stout sprat", *Sprattus antipodum* (code SPA). The species are not

always distinguished in the survey catches, so we have added all sprats together to show the biomass trend (Figure 3.19). The survey does suggest a declining trend in sprats after 2007, but there is high uncertainty so this trend remains tentative.

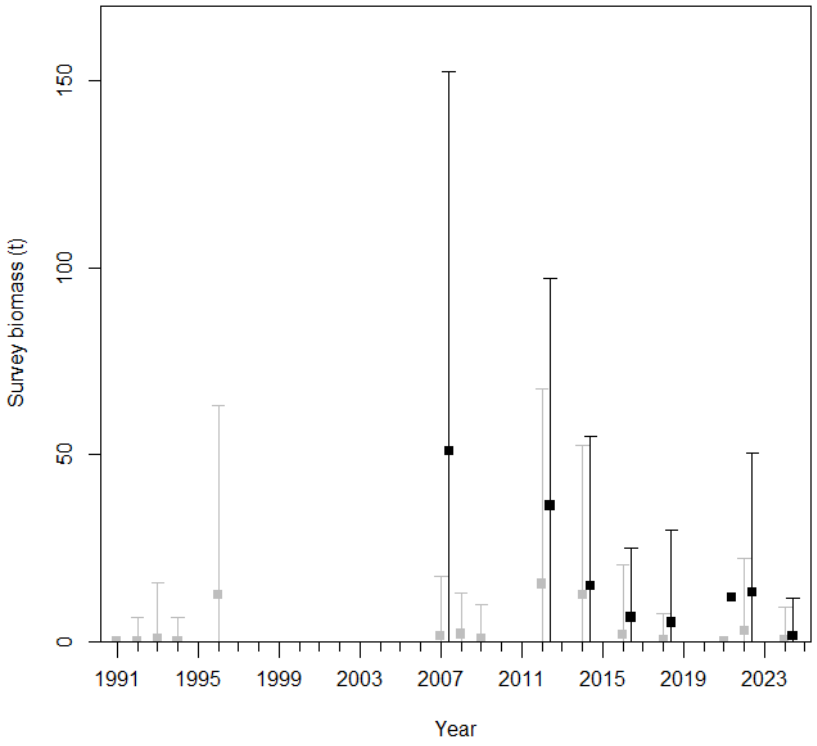

Figure 3.19: Biomass estimates of all sprats in the east coast South Island research trawl survey. The black dots are estimates for 10–400 m water depths, and the grey dots the estimates for 30–400 m (note this is the reverse of the colouring in Figure 3.18). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals).

A few other small pelagic species are caught by east coast South Island research trawl survey. Silverside (*Argentina elongata*) were more abundant through the 2000s than in the 1990s, with a possible peak in abundance around 2016 (Figure 3.20a). Jack mackerel (*Trachurus declivis*) were relatively abundant during the 1990s, with no trend in abundance through the 2000s (Figure 3.20b).

No catches of pilchards or smelt have been recorded in the east coast South Island research trawl survey.

The New Zealand offshore research trawl surveys do generate a time–series of acoustic backscatter, which is a measure of bait fish and similar smaller animals in the water column. Although similar data are collected on the inshore surveys, they have not yet been analysed for this purpose (and the interpretation of these data would be more complex compared to the offshore data). As a result, we do not currently have further information on the trends in abundance of "bait fish" as a whole.

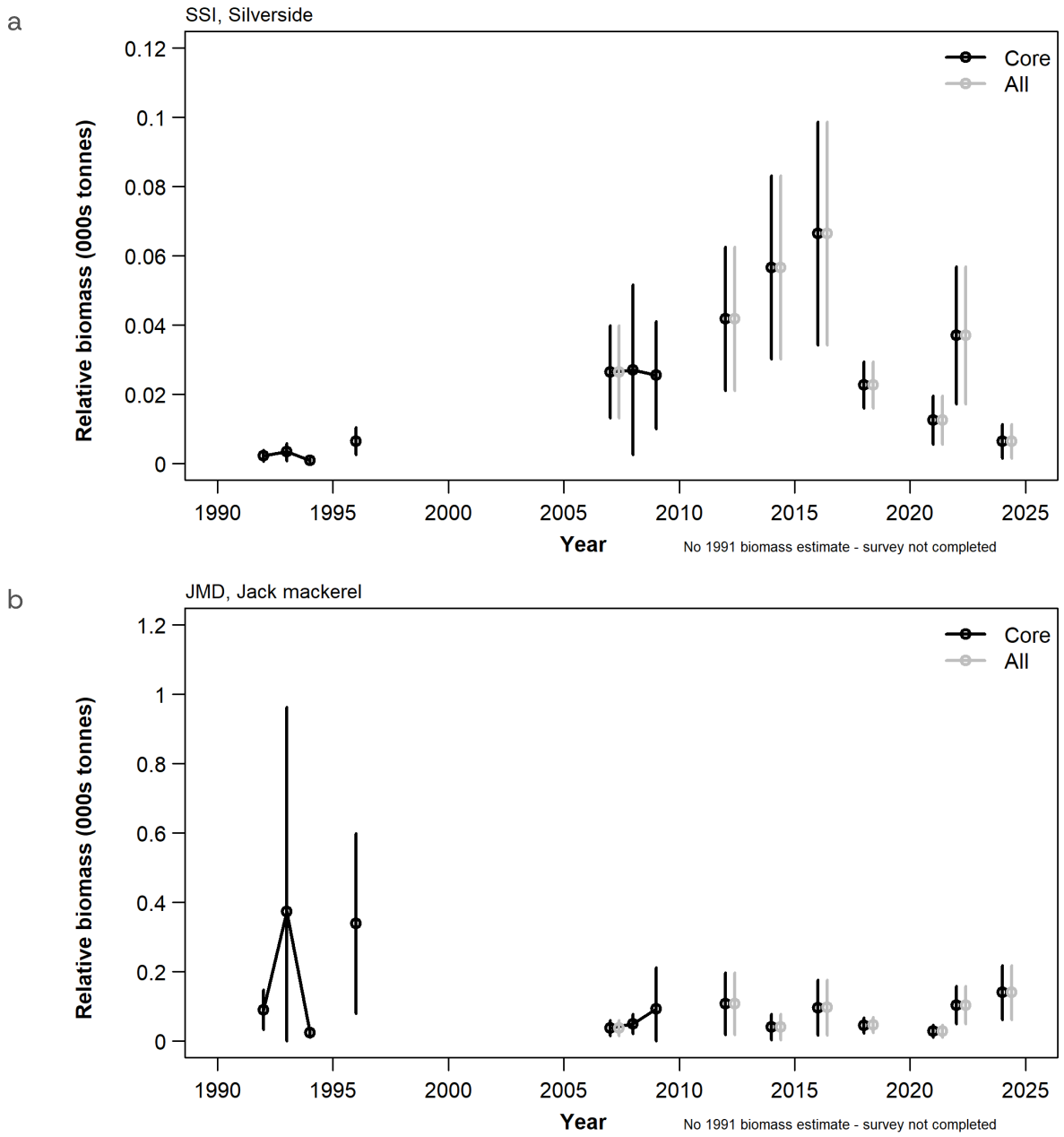

Figure 3.20: Biomass estimates for other small pelagic fishes in the Canterbury area. Biomass estimates for (a) silverside and (b) jack mackerel from the east coast South Island research trawl survey. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012.

3.7.4 Salmon prey: Information on juvenile hoki abundance

Hoki spawn during July and August, primarily to the north in the Cook Strait region, with small juveniles then widespread in coastal waters before they eventually move to more offshore waters on Chatham Rise (Fisheries New Zealand 2026a). The east coast South Island research trawl survey suggests no material change in the abundance of hoki (Figure 3.21), and in these areas, the populations are dominated by juveniles. Hoki is

subject of a comprehensive scientific stock assessment (McGregor–Tiatia & Langley 2026). The estimates of hoki recruitment from this assessment suggest the smallest (juvenile) hoki may have been less abundant during the late 1970s and early 1980s, but otherwise their numbers show variability but with no trend over time (Figure 3.22).

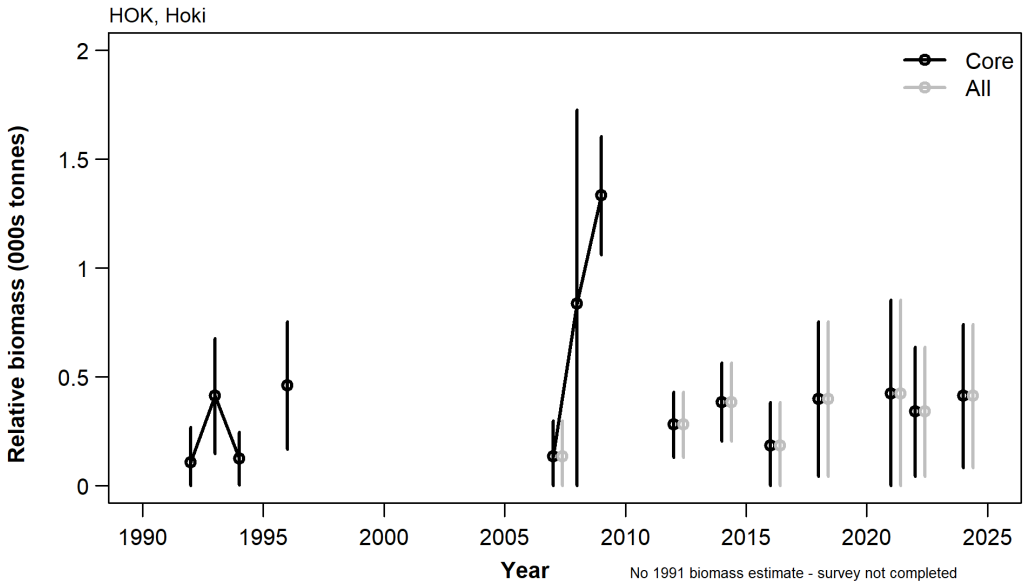

Figure 3.21: Biomass estimates for hoki from the east coast South Island research trawl survey. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012.

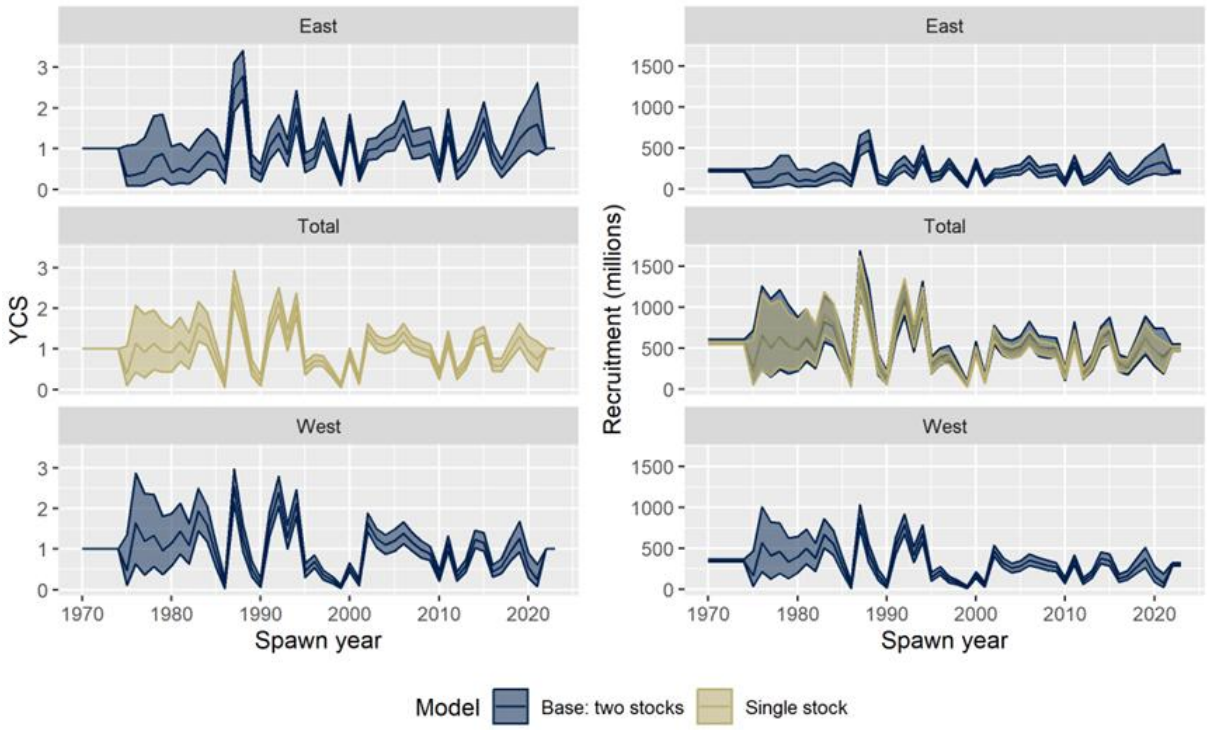

Figure 3.22: Estimates of hoki abundance from a stock assessment model. The hoki stock assessment model results are shown as a relative trend (year class strength (YCS), left panels) or alternatively in absolute numbers (recruitment, right panels). The plots show the average (middle line) and the uncertainty in the estimates (shaded area between the top and bottom lines) The "Base: two stocks" and "Single stock" are alternative assessment model assumptions. The panels to focus on here are in the top row, for the eastern stock. Reproduced from McGregor-Tiatia & Langley (2026).

3.7.5 Salmon prey: Commercial catches

The direct impact of commercial fishing on salmon prey is likely to be small. There are no reported anchovy catches (ANC3), and annual catches less than one tonne of pilchard (PIL3) and sprat (SPR3) (Fisheries New Zealand 2026a). These fishery management areas cover the whole Subantarctic part of the New Zealand Exclusive Economic Zone so commercial catches of salmon prey in the Canterbury marine area will be small.

3.7.6 Fish potentially competing with Chinook salmon

There are substantial historical samples of fish diet, and we see occasional sprats that are eaten by a few fish species (Stevens et al., 2011), other than salmon. These species might compete for prey with salmon, but judging from the relatively low occurrence of sprat in their diets we would suggest competition is likely to be trivial. Of the species identified as eating sprats, none shows substantive biomass changes between the 1990s and 2000s that might correspond with the decline in salmon numbers in Canterbury rivers (Figure 3.23). We do note abundance of hake has been especially low after 2016.

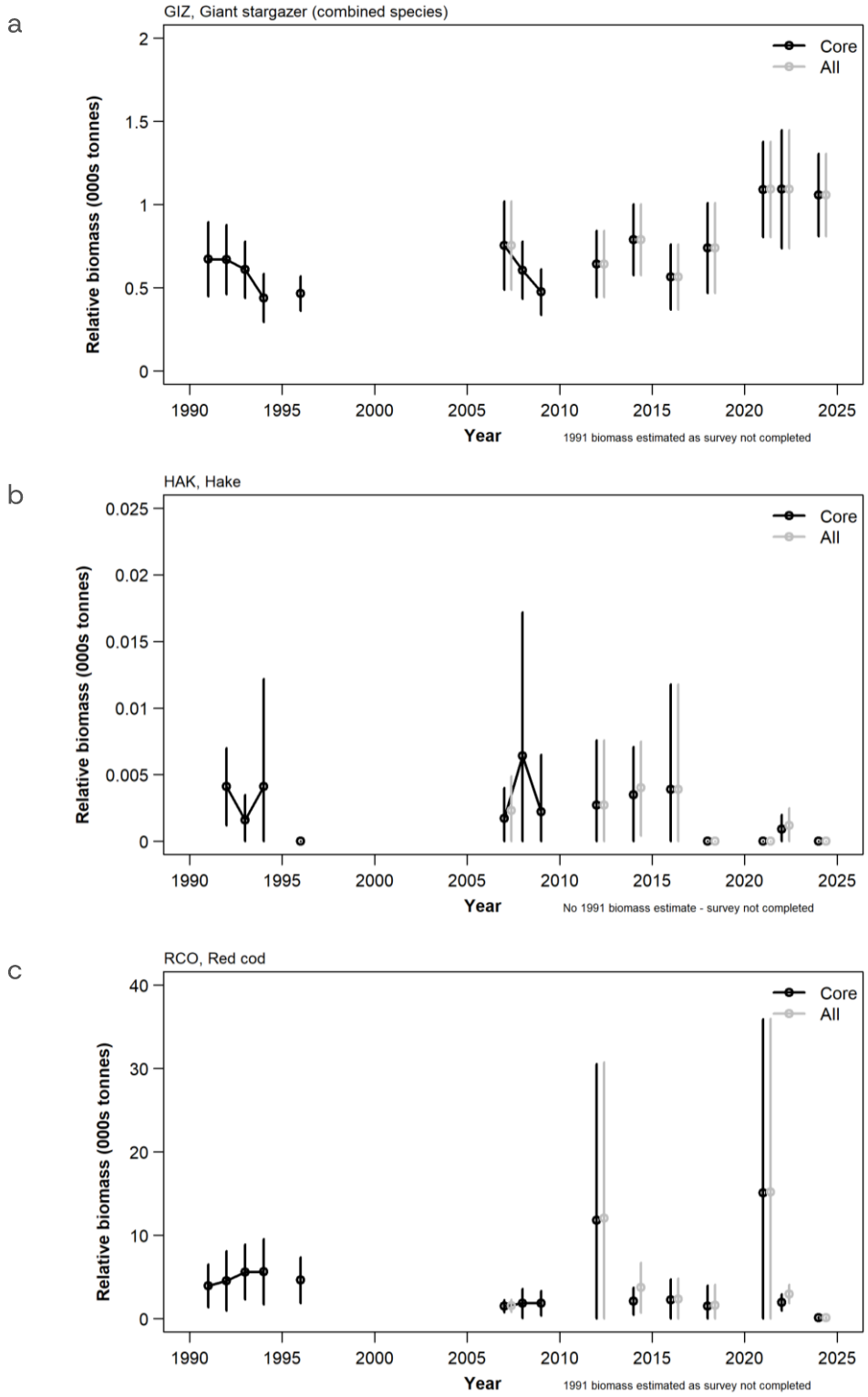

Figure 3.23: Potential fish competing with salmon. Biomass estimates for (a) giant stargazer (*Kathetostoma giganteum*); (b) hake (*Merluccius australis*); and (c) red cod (*Pseudophycis bacchus*), from the east coast South Island research trawl survey. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012.

3.7.7 Potential fish predators of Chinook salmon

There are a few large predatory fishes which might predate on Chinook salmon, and/or compete for the same prey as Chinook salmon. The selection of species of interest is inferred from their size and habits because we currently have little scientific data on their diets.

Both gemfish (*Rexea solandri*) and kingfish (*Seriola lalandi*) have substantially increased in abundance within the last 10 years (Figure 3.24, Figure 3.25), although the kingfish increase is better shown in the commercial catch records rather than the trawl survey biomass estimates (where kingfish are rarely caught). Most gemfish probably occur deeper than salmon, as they have a preference for depths greater than 100 m. Barracouta (*Thyrsites atun*) and school sharks (*Galeorhinus galeus*) are other potential salmon predators or competitors, but the former has shown a decline (contrary to kingfish and gemfish), and the latter has shown little trend over time (Figure 3.26).

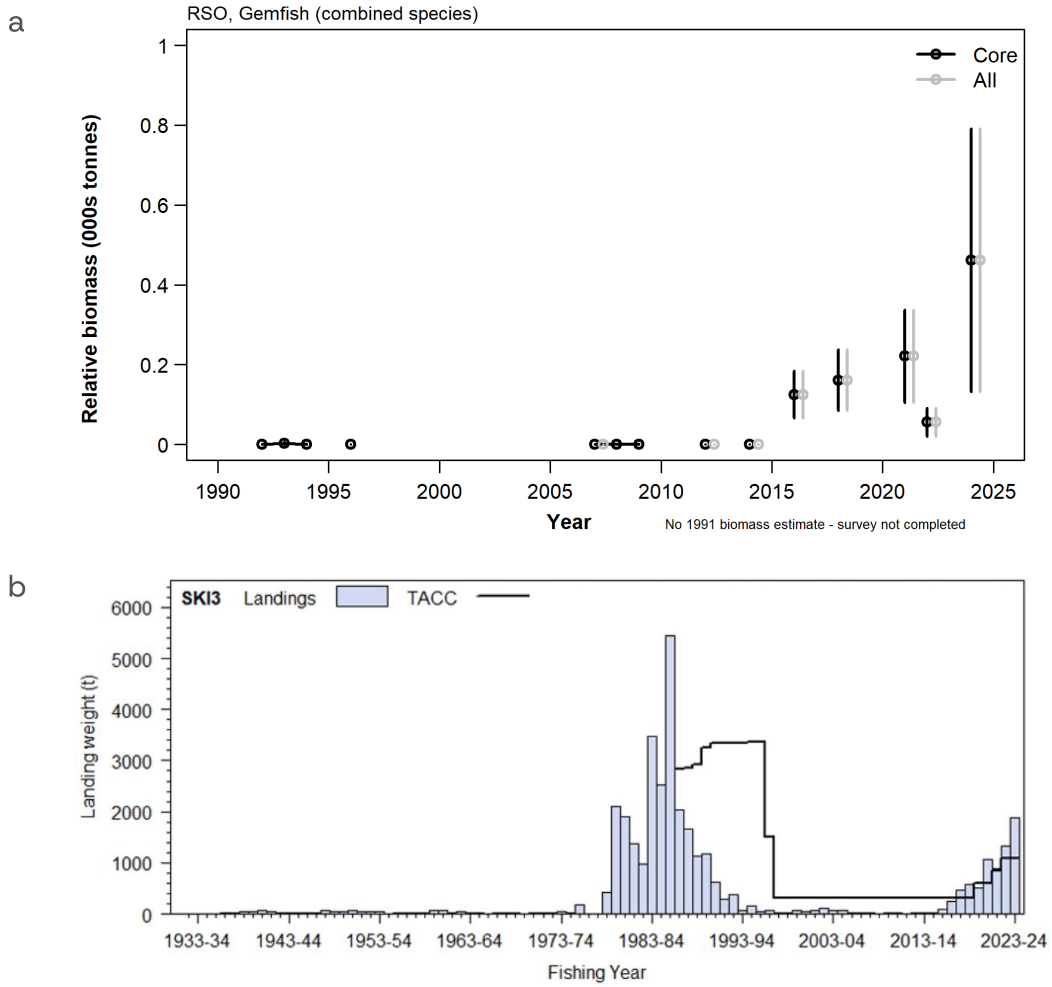

Figure 3.24: Gemfish as a potential predator of salmon. (a) Gemfish biomass estimates from the east coast South Island research trawl survey. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012. (b) Gemfish commercial landings and Total Allowable Commercial Catch (TACC) for gemfish in SKI3 (the area that covers eastern and southern South Island plus the Campbell Plateau). Plot reproduced from Fisheries New Zealand (2026a).

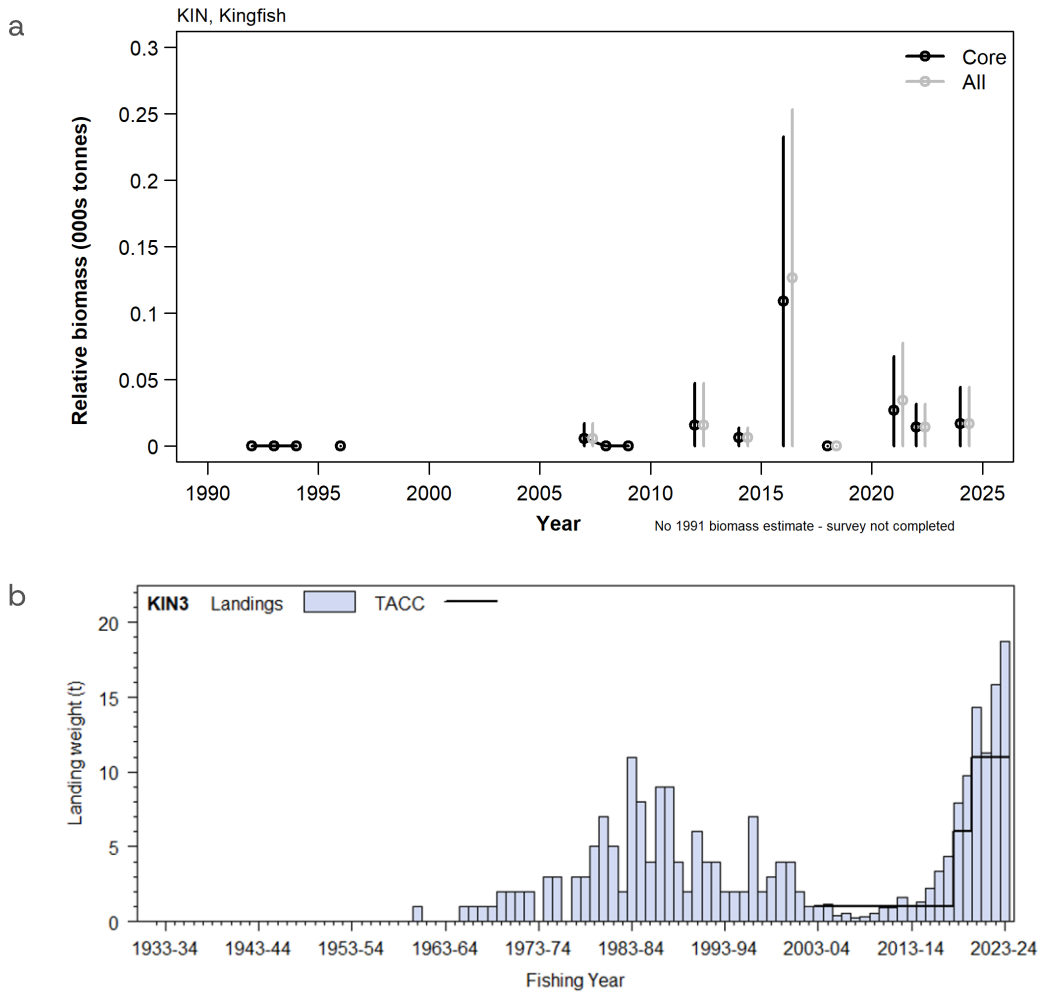

Figure 3.25: Kingfish as a potential predator of salmon. (a) Kingfish biomass estimates from the east coast South Island research trawl survey. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012. (b) Kingfish commercial landings and Total Allowable Commercial Catch (TACC) for gemfish in KIN3 (the area that covers eastern and southern South Island plus the Campbell Plateau). Plot reproduced from Fisheries New Zealand (2026a).

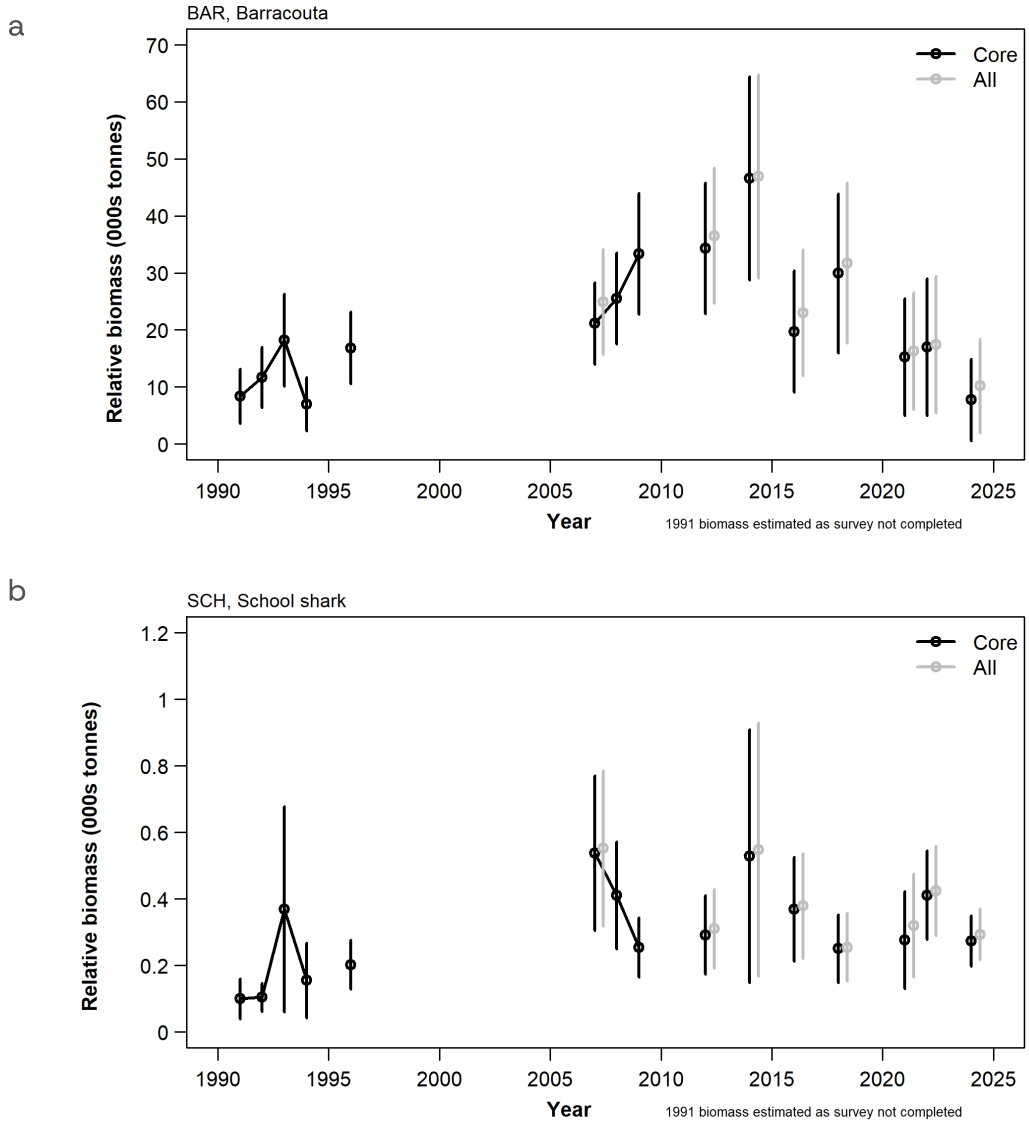

Figure 3.26: Barracouta and school shark as potential predators of salmon. Biomass estimates from the east coast South Island research trawl survey for top, barracouta, and bottom, school shark. "Core" covers 30–400 m water depths (black dots), and "All", 10–400 m (grey dots). The dots show the best estimate, and the vertical lines the range of uncertainty in that estimate (95% confidence intervals). The 10–30 m strata were not always sampled before 2012.

3.7.8 Information from commercial fisheries

There are many fish stocks in the Canterbury region with large trends in catches and catch rates over time but compiling these data, and then importantly synthesising and understanding the patterns in relation to Chinook salmon, was beyond the scope of the present study. To do so would require time–consuming, stock–specific analyses and careful treatment of Fisheries New Zealand data, for example, due to the various changes in catch and effort reporting over time, which vary by location and fishery. However, we are aware that catches of stocks such as elephant fish and red gurnard have substantially increased after the late 1990s, while others such as red cod have decreased (Fisheries New Zealand 2026a). It would seem hard to see any direct link between these commercial fisheries and salmon, but it is possible these species are responding to the same environmental factors.

3.8 Seabirds

Relatively poor at-sea conditions, including when seabird prey abundance and availability are reduced, are likely to manifest as relatively low breeding metrics, such as poor chick growth rates or lowered breeding success. Allen et al. (2011) measured three metrics of breeding success in white-flippered penguins (*Eudyptula minor albosignata*) at Flea Bay, Banks Peninsula, between 1996/97 and 2008/09 and showed that breeding success varied between 50% and 80% over this time period (Figure 3.27). The study only just overlapped with the period of change in salmon run numbers, but there was no clear or obvious temporal trend or inflection point over this time.

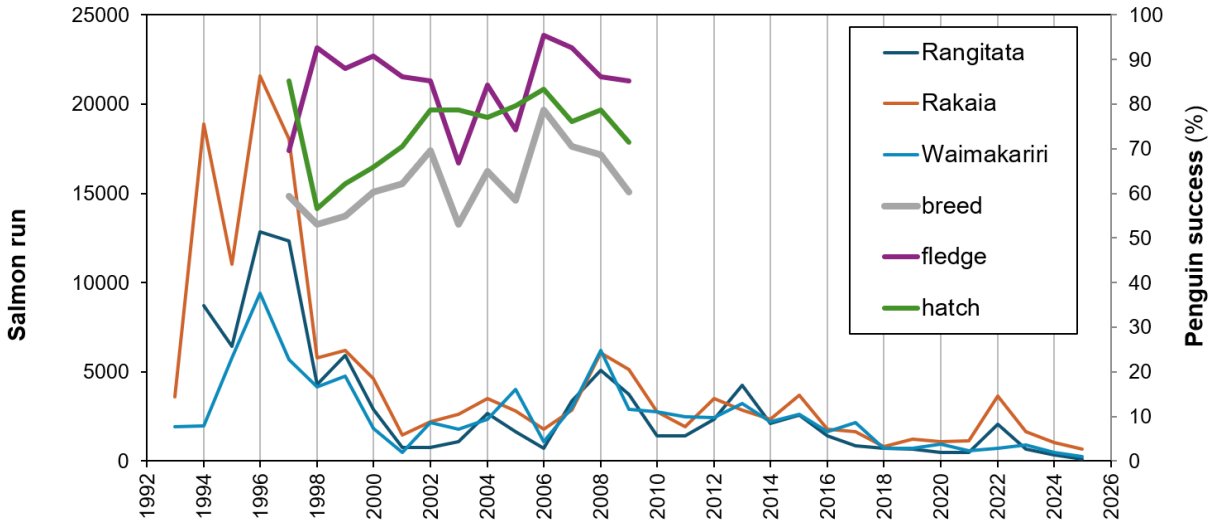

Figure 3.27: Breeding success of white-flippered penguins compared to salmon run numbers. Three metrics of breeding success in white-flippered penguins (*Eudyptula minor albosignata*) in monitored nest boxes at Flea Bay, Banks Peninsula (from Allen et al., 2011) compared with salmon run numbers in three Canterbury rivers (Rangitata, Rakaia, Waimakariri).

4 Discussion

This report has considered marine environmental factors that may influence Chinook salmon populations in the Canterbury marine area, with a focus on oceanographic conditions, prey, predators, and broader ecosystem changes. Declining numbers of salmon in the three main Canterbury rivers (Rangitata, Rakaia, Waimakariri) have been noted in Fish and Game surveys carried out annually since the 1992/93 summer season. In particular, these surveys note a substantial reduction in Chinook salmon numbers between 1995/96 and 1997/98, and a variable pattern but overall trend showing a slow decline in salmon numbers after 2007/08. These changes over time are consistent across all three rivers considered. There is a desire to understand what has caused these changes.

4.1 Ocean warming

Over this 33–year period, the reconstructed time–series of sea surface temperature (SST) and the satellite–based observation of SST indicated overall warming of the Canterbury marine region. There were periods of cooling in SST (lasting a few years sometimes), but overall, the sea surface water in the Canterbury region warmed by about 1.3°C between 1960 and 2025, or by about 0.8 °C between 1981 and 2025. This significant surface warming was paralleled by warming near the seabed, but the warming at depth was lower (+0.8°C over 65 years). Given that salmon likely spend most of their time at sea in the surface mixed–layer, we suggest that the trend in surface warming is more relevant to salmon population dynamics than temperature changes at depth. Shorter–term and higher resolution satellite temperature change showed that warming near river mouths was consistent with warming in the wider Canterbury marine area. We detected a seasonal change in surface water temperature near river mouths due to differential heating of the land and coastal water, but this difference was quite small (~ 0.2 °C).

The general pattern of ocean surface warming has led to salmon experiencing more often "hot days", where the SST has above a certain threshold. Between 1982 and 2025, the number of days per year hotter than 14.5 °C in the Canterbury marine region increased by 48% while over the same period, the number of days hotter than 17 °C increased by 300%.

Three different methods were developed to compare salmon run numbers at the seasonal scale with environmental changes measured at the monthly scale. These methods assumed that salmon run numbers were influenced by conditions: (1) the preceding year from the run, (2) at the time the salmon entered the marine environment, or (3) cumulatively over each year at sea. The results were qualitatively consistent irrespective of which index was used, but overall, the cumulative index gave the strongest correlations. The cumulative index assumes that salmon are equally affected by environmental conditions throughout their time at sea whatever their age. We found that the annual–average SST, the maximum monthly SST, and the number of

hot days per year, were negatively (higher temperatures corresponded with lower salmon runs) and significantly ($p<0.001$) correlated with salmon run numbers in all three rivers, with correlations as high as 0.86.

We stress that the relationships presented show correlations and this does not test nor imply a causal link. The results are partially consistent with the suggestion that Canterbury salmon are being affected by rising temperatures in the ocean. Our analysis shows evidence of a non–linear correspondence between SST and salmon run numbers. When the average SST over the year was higher than about 12 °C, or the maximum annual SST was greater than about 15.5 °C, we found that salmon runs were low in all three rivers. A summer coastal temperature of 15.5 °C is likely to correspond to ~15.75 °C in the river mouth because temperature in the terminal part of the river system is likely be about 0.25 °C warmer on average than the coastal water. If this represents a maximum temperature threshold for Chinook salmon in New Zealand it is comparable with information from wild populations in North America, where Chinook salmon are likely to require water below ~14.5 °C to successfully spawn and below ~16 °C for egg maturation. However, the correlations were stronger with mean annual SST rather than maximum annual SST which is counter to this possible connection. Also, there were very low salmon run numbers in years with colder waters, i.e. warm water implied poor runs, but cool water did not imply good runs. The fact that low salmon runs occurred in seasons with relatively cool seasonal indices (e.g. 2005/06, 2010/11) means that our results are inconsistent with ocean warming being the *only* factor affecting salmon run numbers.

4.2 Southern Oscillation Index

The Southern Oscillation Index (SOI) which measures the major ENSO pattern of the equatorial Pacific Ocean was weakly related to SST in the Canterbury region, and only weakly correlated with salmon run numbers. If SST has an effect on salmon off Canterbury, this is better measured using actual observations of SST rather than via a climate index such as SOI.

4.3 Ocean productivity and turbidity

Other environmental variables considered here (chl–a, TSS, Hvis) using satellite observations were generally not significantly correlated with salmon run numbers or correlated in a way which seems inconsistent with a plausible effect on salmon. For example, more sediment and lower water clarity tended to occur with higher salmon numbers whereas we would have expected the effects to be negative. We hence consider these correlations, where significant, likely to be spurious.

4.4 Seabirds

Seabirds in New Zealand could be predators of smelts in rivers, and of juvenile salmon in the years immediately after salmon enter the marine environment at ~10 cm length. Seabirds may also compete with larger salmon for prey when the salmon are large enough to feed on small pelagic fish. Both as direct predators and as competitors for

resources with salmon, changes to seabird abundances may hence be expected to show negative correlations with salmon run numbers. However, if the abundance of small fish prey is primarily affected by a third-party driver (for example, environmental change, or alterations to the abundances of a different predator of small fish), both seabirds and salmon numbers could be affected together, leading to positive correlations in their numbers.

Examination of the relationship between changes in seabird numbers and changes to salmon numbers is difficult because of the paucity of good information on seabird abundances and seabird ecology over the last three decades, and the complexity of the factors involved. In order to be able to link seabird population trajectories or breeding performance with at-sea conditions, including prey abundance and availability, long-term data sets (of seabird population size, adult and juvenile survival rates, breeding success, for example) spanning decades would be necessary. For many seabirds breeding in Aotearoa New Zealand, such data sets are lacking.

Also, seabird ecology is complex so unpicking drivers of changes in seabirds is usually ambiguous or cryptic. Seabirds tend to be relatively long-lived, late-maturing, and produce relatively few offspring per breeding attempt. These characteristics mean that under challenging environmental conditions, seabirds tend to maximise adult survival over other life-history parameters (such as breeding or chick-rearing). Hence, seabird populations are effectively 'buffered' against short-term periods of sub-optimal environmental conditions, and their population size, at least over the short-term, will be relatively unaffected by changes in prey abundance. For these reasons, using seabirds to understand changes affecting salmon populations is not likely to be useful.

4.5 Marine mammals

Various relations between marine mammals and Chinook salmon in the Canterbury area are possible. For example, marine mammals may: (1) directly prey on salmon; (2) compete with salmon for prey, especially small pelagic fish; (3) respond to changes in the abundance of trophic competitors or predators of salmon that are caused by other factors (such as climate variability or environmental change); (4) predate on trophic competitors or predators of salmon; and (5) respond to changes in the abundance of the prey of salmon.

Some of these potential relationships are causal and some are purely correlative. For example, if marine mammals predate more heavily on salmon, this will lead to fewer salmon entering the river to breed in the future (i.e. this relationship is causal). However, if climate change leads to a reduction in prey availability, the numbers of both marine mammals and salmon in the area might decrease but the changes in salmon populations does not derive from the changes in marine mammals (i.e. this relationship is correlative and non-causal). Furthermore, some relationships (as in points 1-3 above) would imply a negative correlation between mammal and salmon numbers whereas the others imply a positive correlation (points 4-5). The abundances of different species of marine mammals in the Canterbury region might also change for reasons that are entirely uncorrelated with changes in salmon run numbers.

Practically, there is a complex and poorly understood assemblage of marine mammals in the Canterbury region. Although data exist on many marine mammals, the relatively scant and non–systematic nature of these data, coupled with the fact that salmon are a minor species in the ecosystem, makes linking changes in marine mammals to changes in salmon populations very challenging. Overall, we considered it unlikely that any insights that are useful to understanding changes in Chinook salmon run numbers could be gained from the further effort required to analyse marine mammal observations and focussed instead on environmental and fishery–related factors. However, this could be attempted in the future if desired.

4.6 Fisheries information

Fisheries information has some potential to shed light on changes to changes to salmon populations in the study region because the information is more systematically collected and because different fish may be informative in contrasting or complementary ways. The present study used a range of fish species and different fisheries data to probe aspects of marine ecological change that may be affecting salmon.

A limitation of the available catch data for salmon is that the east coast fisheries survey of the South Island has rarely caught Chinook salmon. Salmon are likely to spend most of their time at sea in the surface mixed–layer, only occasionally making deep dives for feeding, which makes their availability to benthic trawl gear variable and means that benthic trawl surveys are an unreliable sampling method for salmon.

Sprats, which are likely an important prey for salmon, may have declined during the 2000s. It is unclear whether this was a decline from historically higher abundance levels or was part of a longer–term cycle in abundance. The other noted prey fish for Chinook salmon, hoki, does not seem to have materially changed in abundance in the region. We have no information on the relative abundance over time of the *Munida* (squat lobster) prey. Commercial fishery catches of key salmon prey have been negligible. Based on these data, we conclude that the changes in salmon abundance seem relatively unlikely to be attributed to changes in the abundance of their prey.

Some potential piscine competitors with, and/or predators of, salmon have recently increased in abundance in the region, in particular kingfish. The timing suggests it was not relevant to the changes observed for salmon in the 1990s and 2000s, but the timing does coincide with especially low salmon abundance since the late 2010s. The hypothesis of increased predation on salmon within the last decade is plausible but remains speculative, however, because data to evaluate this hypothesis are incomplete or lacking (such as time–series of wild kingfish diet).

Salmon can also be caught in commercial fishing gear as bycatch but such catches of Chinook salmon over the last five years are reported as zero by Fisheries New Zealand; the Canterbury part of the Chinook salmon distribution is within areas closed to set net fishing and trawls are restricted to having a relatively low headline height (both as measures for dolphin conservation). Therefore, at this stage we consider the hypothesis that salmon abundance is being directly impacted by marine commercial fisheries to be unlikely.

Overall, we see nothing obvious in the fish or fishery data that has a strong relationship with the decline in salmon runs between the 1990s and the early 2000s.

4.7 Other environmental factors

Other changes with the potential to affect Chinook salmon in the Canterbury region have occurred alongside ocean warming. For example, the area of dairy farming in Canterbury has been increasing over the last 30 years (Pangborn & Woodward 2011; Infometrics, 2026). Various land use activities have the potential to affect river water and habitat quality through introduction of agricultural nutrient run–off, effluent, and suspended sediment (Parliamentary Commissioner for the Environment, 2012), and modification of riparian zones. Changes to land use in the Canterbury region may hence effect freshwater, anadromous and coastal marine species, including Chinook salmon, and a combination and accumulation of pressures on river environments may have contributed to the decline in run numbers over time.

4.8 Final comments

Changes to SST (measured as the mean or maximum surface seawater temperature or in terms of the number of hot days) in the Canterbury marine region had highly significant and negative rank correlations with the changes in salmon run numbers in the Rangitata, Rakaia and Waimakariri rivers over the 33 year period from 1992/93 to 2024/25. The relationships between salmon run numbers and SST or number of hot days were non–linear and consistent with threshold effects. The values of these apparent temperature thresholds were broadly consistent with thermal tolerances of Chinook salmon reported for natural environments elsewhere. It is hence plausible that ocean warming over the last few decades has caused or contributed to the observed declines in salmon numbers in Canterbury. However, we emphasise that we found correlations, and no causality is implied *per se*. It is entirely possible that salmon run numbers changed for reasons disconnected from ocean warming. For example, salmon are known to be affected by changes to physical river habitats, physical barriers to migration, genetic degradation of the wild stock and reductions in river water quality. Examining these factors was beyond the scope of this study. Finally, we note that special caution is warranted in drawing causal connections between salmon and warming because the rise in ocean temperature and the reduction in salmon run numbers have essentially been changing monotonically over time, so any factor that has either been increasing or decreasing fairly consistently over the last few decades will correlate significantly with changes to salmon numbers.

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6 References

Allen, W.J., Helps, F.W., Molles, L.E. (2011) Factors affecting breeding success of the Flea Bay white-flippered penguin (*Eudyptula minor albosignata*) colony. *New Zealand Journal of Ecology,* 35: 199–208.

Armour, C.L. (1991) Guidance for evaluating and recommending temperature regimes to protect fish. U.S. Fish and Wildlife Service Biological Report 90(22). 13 pp.

Baker, A.N. (1990) Marine mammals. In: Glasby, G.P. (Ed.), Antarctic sector of the Pacific. Elsevier Oceanogr. Ser. 51, Amsterdam, pp 241–262.

Bell, M.C. (1986) Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program. U.S. Army Corps of Engineers. 209pp.

Butler, J.R.A., Cradock-Henry, N.A., Behrens, E., Cummings, V.J., Davidson, I., Knight, B., Major, R., Symonds, J.E., Vennell, R. (2023) Adaptation pathways for the seafood sector: salmon aquaculture. Nelson: Cawthron Institute. Cawthron Report 3993. Prepared for The Aotearoa Circle. 50 p.

Canning A.D. (2018) Predicting New Zealand riverine fish reference assemblages. PeerJ, 6: e4890.Carter, K. (2006) The Effects of Temperature on Steelhead Trout, Coho Salmon, and Chinook Salmon Biology and Function by Life Stage. California Regional Water Quality Control Board, North Coast Region. Available[Sep 2026): https://coastcoho.org/wp-content/uploads/2022/03/Carter-2005.pdf

Colman, J.A. (1979) Spawning of the sprat, *Sprattus antipodum* (Hector), round the South Island of New Zealand. *New Zealand Journal of Marine & Freshwater Research,* 13: 263–272.

Copernicus Climate Change Service, Climate Data Store (2021) ORAS5 global ocean reanalysis monthly data from 1958 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.67e8eeb7 (Accessed on 01/08/2026)

Department of Conservation (2026) Marine mammals strandings. Available online (Sep 2026]: https://www.doc.govt.nz/nature/native-animals/marine-mammals/marine-mammal-strandings/

Dougan, M.C.R. (1993) Growth and development of Chinook salmon, *Oncorhynchus tshawytscha*: effects of exercise training, and seawater transfer. Phd Thesis, University of Canterbury. Available online [Sep 2026]: https://ir.canterbury.ac.nz/

Drake, J.F. (2025) Variability and Predictability of Sea Surface Temperatures in the Southwest Pacific. Master of Science thesis, University of Auckland. Accessed (August 2026): https://researchspace.auckland.ac.nz/items/ff5c4902-1567-40be-94e1-097649b7078b

Fisheries New Zealand (2026a) Fisheries Assessment Plenary, May 2026: stock assessments and stock status. Compiled by the Fisheries Science Team, Fisheries New Zealand, Wellington, New Zealand. 1990 p.

Fisheries New Zealand (2026b) *Fisheries Infosite*, https://fs.fish.govt.nz/.

Ford, J.K.B., Ellis, G.M., Barrett-Lennard, L.G., Morton, A.B., Palm, R.S., Balcomb, K.C. (1998) Dietary specialization in two sympatric populations of killer whales (*Orcinus orca*) in coastal British Columbia and adjacent waters. *Canadian Journal of Zoology*, 76, 1456–1471. Full Text.

Gall, M.P., Pinkerton, M.H., Steinmetz, T., Wood, S. (2022) Satellite remote sensing of coastal water quality in New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 56:3: 585–616, DOI: 10.1080/00288330.2022.2113410.

Gaskin, D.E. (1982) The ecology of whales and dolphins. Heinemann, London, 459 pp.

Hansen, L.P., Jacobsen, J.A. (2003) Origin, migration and growth of wild and escaped farmed Atlantic salmon, *Salmo salar* L., in oceanic areas north of the Faroe Islands. *ICES Journal of Marine Science,* 60 (1): 110–119.

He, J.X., Bence, J.R., Johnson, J.E., Clapp, D.F., Ebener, M.P. (2008) Modeling variation in mass length relations and condition indices of lake trout and Chinook salmon in Lake Huron: a hierarchical Bayesian approach. *Transactions of the American Fisheries Society*, 137:801–817.

Hobday, A.J., Alexander, L.V., Perkins, S.E; Smale, D.A., Straub, S.C., Oliver, E.C., Wernberg, T. (2016) A hierarchical approach to defining marine heatwaves. Progress in *Oceanography,* 141: 227–238.

Holbrook, N.J., Bindoff, N.L. (1997) Interannual and Decadal Temperature Variability in the Southwest Pacific Ocean between 1955 and 1988. *Journal of Climate,* 10(5), 1035–1049. https://doi.org/10.1175/1520-0442.

Holm, M., Jacobsen, J.A., Sturlaugsson, J., Holst, J.C. (2006) Behaviour of Atlantic salmon (Salmo salar L.) recorded by data storage tags in the NE Atlantic – implications for interception by pelagic trawls. ICES ASC CM 2006/Q:12.

Howard, K.G., von Biela, V. (2023) Adult spawners: A critical period for subarctic Chinook salmon in a changing climate. Global Change Biology, 29, 1759–1773. https://doi.org/10.1111/gcb.16610

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., Smith, T., Zhang, H.M. (2021) Improvements of the daily optimum interpolation sea surface temperature (DOISST) version 2.1. Journal of Climate, 34: 2923–2939.

Infometrics (2026) Regional Economic Profile, Canterbury region 2026. Online resource, available [Sep 2026] at: https://regions.infometrics.co.nz/canterbury-region/economy/dairy?compare=kaikoura-district,mackenzie-district

Jacobsen, J.A. (2000) Aspects of the marine ecology of Atlantic salmon (*Salmo salar* L.). Ph. D. thesis at the University of Bergen, May 2000.

James, G.D., Unwin, M.J. (1996) Diet of Chinook salmon (*Oncorhynchus tshawytscha*) in Canterbury coastal waters, New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 30:1, 69–78, DOI: 10.1080/00288330.1996.9516697.

Lehman, B., Huff, D.D., Hayes, S.A., Lindley, S.T. (2017) Relationships between Chinook Salmon Swimming Performance and Water Quality in the San Joaquin River, California. *Transactions of the American Fisheries Society*, 146: 349–358.

MacGibbon, D.J., Beentjes, M.P., Escobar-Flores, P. (2024) Inshore trawl survey of Canterbury Bight and Pegasus Bay, April–June 2024 (KAH2402). New Zealand Fisheries Assessment Report 2024/87. 150 p.

Mantua, N.J., Hare, S.R. (2002) The Pacific Decadal Oscillation. Journal of Oceanography, 58(1), 35–44. https://doi.org/10.1023/A:1015820616384

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C. (1997) A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production*. Bulletin of the American Meteorological Society, 78(6), 1069–1080. https://doi.org/10.1175/1520.

Marine, K.R., Cech, J.J. (2004) Effects of high water temperature on growth, smoltification, and predator avoidance in juvenile Sacramento River Chinook salmon. *North American Journal of Fisheries Management,* 24:198–210.

McGregor-Tiatia, V.L., Langley, A.D. (2026) Assessment of hoki (*Macruronus novaezelandiae*) in 2025. New Zealand Fisheries Assessment Report 2026/04. 241 p.

Myrick, C.A., Cech Jr., J.J. (2001) Temperature Effects on Chinook Salmon and Steelhead: a Review Focusing on California's Central Valley Populations. Calif. Water Environ. Model. Forum. Available (September 2026): https://www.noaa.gov/sites/default/files/legacy/document/2020/Oct/07354626150.pdf

NOAA –NCEP (2026) Southern Oscillation Index from the National Oceanic and Atmospheric Administration – National Centers for Environmental Information, sourced [August 2026]: cpc.ncep.noaa.gov/data/indices/soi.

Northwest Fisheries Science Center (2024) Salmon and Steelhead Research in the Pacific Northwest. NOAA Fisheries online, https://www.fisheries.noaa.gov/west-coast/science-data/salmon-and-steelhead-research-pacific-northwest. Updated October 28, 2024; Accesses September 2026.

Orchard, S., Thoral, F., Pinkerton, M., Battershill, C.N., Ohia, R., Schiel, D.R. (2025a) River Radii: A Comparative National Framework for Remote Monitoring of Environmental Change at River Mouths. *Remote Sensing*, 17, 1369. https://doi.org/10.3390/rs17081369.

Orchard, S., Thoral, F., Pinkerton, M.H., Battershill, C.N., Ohia, R., Schiel, D.R. (2025b) Proximity–Based Monitoring of Coastal River Mouths. *Geoinformation Geostatics*: *An Overview*, 13, Volume 3.

Oregon Department of Environmental Quality (ODEQ). 1995. Temperature: 1992–1994 Water quality standards review. Final Issue Paper. 122pp.

Pangborn, M.C., Woodford, K.B. (2011) Canterbury dairying – a study in land use change and increasing production. 18th International Farm Management Congress IFMA18 – Theme 3, Methven, Canterbury, New Zealand. Available: [Sep 2026] https://www.researchgate.net/profile/Keith-Woodford/publication/277128474_Canterbury_dairying_-_a_study_in_land_use_change_and_increasing_production/links/55a4e72208ae5e82ab1f6a29/Canterbury-dairying-a-study-in-land-use-change-and-increasing-production.pdf

Parliamentary Commissioner for the Environment (2012) Water quality in New Zealand: Understanding the science. Available [Sep 2026]: https://pce.parliament.nz/publications/water-quality-in-new-zealand-land-use-and-nutrient-pollution/

Paul, L.J. (1966) Salmon, Quinnat. In: An Encyclopaedia of New Zealand, edited by A. H. McLintock, originally published in 1966., and accessed as part of Te Ara – the Encyclopedia of New Zealand, August 2026, https://teara.govt.nz/node/24482.

Pinkerton, M.H., Atwood, E.C., Whiteside, A., Pearson, R., Tilstone, G. (2026) SeaSTAR–EO4NZ: Potential drivers of SEdiment loAdS from caTchment to coAst using EO data foR New Zealand. Prepared for UK Research and Innovation, c/o Plymouth Marine Laboratory. ESNZ report, pp 61, March 2026.

Pinkerton, M.H., Gall, M., Thoral, F., Sutton, P., Wood, S. (2024) Monitoring ocean health: Satellite indicators for surface temperature, productivity and

suspended solids. NIWA report 2023217WN_rev2, for Ministry for the Environment, July 2024. Pp 141. DOI: 10.13140/RG.2.2.29646.27208

Pinkerton, M.H., Sutton, P., Wood, S. (2018) Satellite indicators of phytoplankton and ocean surface temperature for New Zealand. *NIWA Client Report* 2018180WN, Prepared for Ministry for the Environment, December 2018. Pp 87.

Pinkerton, M.H. (2014) Ecosystem Modelling of the Chatham Rise. NIWA research report prepared 2014, *NIWA Client Report* WLG2013-17. Pp 183.

Reynolds, R.W., Rayner, N.A., Smith, T.M., Stokes, D.C., Wang, W. (2002) An improved in situ and satellite SST analysis for climate. *Journal of Climate,* 15: 1609-1625.

Richard, Y., Berkenbusch, K. (2024) Sightings of marine mammals in New Zealand waters by government fisheries observers. (Technical report prepared for Department of Conservation (Project INT2022-06)). Retrieved from https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/202223-annual-plan/int2022-06_marine-mammals-sightings-final-report.pdf

Shears, N.T., Bowen, M.M. (2017) Half a century of coastal temperature records reveal complex warming trends in western boundary currents. *Scientific Reports,* 7(1), 14527. https://doi.org/10.1038/s41598-017-14944-2

Stevens, D.W., Hurst, R.J., Bagley, N.W. (2011) Feeding habits of New Zealand fishes: A literature review and summary of research trawl database records 1960 to 2000. New Zealand Aquatic Environment and Biodiversity report No. 85.

Symonds, J.E., Scholtens, M.R., Dodds, K.G., Costilla, R., Clarke, S.M., Arinez, J., Kenny, N.J., Walker, S.P., Waddington, Z. (2024) Fast-tracking farmed king salmon climate change adaptation. *Proceedings of the Association for the Advancement of Animal Breeding and Genetics,* 26: 130-133.

Taylor, G.A. (2000a) Action Plan for Seabird Conservation in New Zealand. Part A: Threatened Seabirds. Threatened Species Occasional Publication 16. 234 p.

Taylor, G.A. (2000b) Action Plan for Seabird Conservation in New Zealand. Part B: Non-Threatened Seabirds. Threatened Species Occasional Publication 17. 201p.

Thompson, D.W.J., Wallace, J.M. (2000) Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *Journal of Climate,* 13(5), 1000-1016.

Tourre, Y.M., White, W.B. (1997) Evolution of the ENSO Signal over the Indo-Pacific Domain. *Journal of Physical Oceanography,* 27(5), 683-696.

U.S. Environmental Protection Agency (USEPA) 1999. A review and synthesis of effects of alternation to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. Region 10, Seattle, WA. EPA 910–R–99–010. 279pp.

Walker, G., Bliss, E. (1932) World Weather V. Mem. Roy. Meteor. Soc, 4, 53–84.

Washington State Department of Ecology (WDOE) (2002) Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards: Temperature Criteria (Draft Discussion Paper and Literature Summary, Part II). Publication compiled by Mark Hicks. Olympia, WA.