Response to Referee #1 - inline annotations

Abstract

R1-1

RC: *[highlight on "observed daily water temperatures"] Mean daily?*

AC: We thank the reviewer. These are daily mean water temperatures. We will change the wording to "daily mean water temperatures" and ensure this explicit phrasing is used consistently on first mention.

R1-2

RC: *[highlight on "SSP scenarios"] This has not been defined yet in the abstract.*

AC: We will define the term on first use in the abstract. Following the revision to a single scenario, the abstract will refer to the Shared Socioeconomic Pathway SSP2-4.5 explicitly, with the acronym spelled out at first mention.

R1-3

RC: *[highlight on "…in warm and intermediately warm rivers"] This is a vague description, could it be omitted or the sentence rephrase?*

AC: We agree that the categorical qualifier is undefined at this point in the abstract. We will rephrase to ground the statement in a concrete descriptor rather than the as-yet-undefined thermal-group labels, e.g. "…and is accompanied by a pronounced redistribution of thermal exposure toward the 19–21 °C and 21–23 °C stress bands, most pronounced in the warmest, lower-altitude rivers."

Introduction & Figure 1

R1-4

RC: *This is a large component of the analysis and results interpretation. It would be more clearly presented and discussed in the Introduction. As I understand it, mainly the maximum and high temperature thresholds are addressed currently.*

AC: We agree. The cold-season component (autumn–winter and late-winter–spring warming affecting spawning, egg incubation, and fry emergence) is a core part of the analysis but is currently under-developed in the Introduction relative to the warm-season thresholds. We will expand the Introduction to introduce the ecological rationale for the cold-season thresholds (>10 °C ONDJ, >12 °C FMAM) and their relevance to early life stages, so the framing matches the weight these metrics carry in the Results.

R1-5

RC: *[Figure 1a] This figure provides a figure showing a decline in brown trout annual catches without providing supporting information regarding allowable catch rates, the presence or increase of adverse environmental conditions, etc. The additional context would be helpful to understand what the depicted trend represents.*

AC: We will retain panel (a) and add the source and the necessary context. The data are annual brown trout catch statistics compiled by the Czech Anglers Union (Český rybářský svaz, ČRS); the publicly available series (https://www.rybsvaz.cz/statistika-ulovku) covers 2019 onward, and the longer 2000–2024 record shown was provided by ČRS from their internal statistics (unpublished data), which we will cite in the caption. We will also add context clarifying that annual catches reflect angling pressure, stocking, and management practices in addition to environmental conditions, so panel (a) is presented as illustrative motivation rather than as direct evidence of a thermal effect.

R1-6

RC: *[Figure 1b] This panel of the figure shows analysis results, and would be better suited in the Results section or SI.*

AC: We agree that panel (b) presents results. We will relocate it to the Results (or Supplement) as part of the Figure 1 restructuring described under R1-8.

R1-7

RC: *[Figure 1c] The same comment applies to this statement as well. It is also unclear what the blue segments represent, as there appear to be more of them than the number of study streams supporting the model development. Please clarify what the blue segments represent.*

AC: The blue segments are the modelled river-network reaches (the full brown-trout-bearing network to which the global air–water model is applied), not the 35 monitoring profiles used for calibration. The apparent mismatch in number is expected: the 35 profiles are calibration points, whereas the mapped network covers all modelled reaches. We will state this explicitly in the caption and clarify the distinction between calibration profiles and modelled network reaches.

R1-8

RC: *[Figure 1] By and large this figure seems out of place here, as it presents results. A suggestion for an alternative Figure 1 is to provide a map of Czechia showing the distribution of the study reaches with map shading providing the ground elevation, and perhaps the current map of 2000 showing the distribution of water temperatures < 17 °C.*

AC: We appreciate this constructive suggestion and will restructure Figure 1 accordingly: a study-area map showing the distribution of the 35 monitoring profiles over the river network with elevation shading, retaining the observed 2000 water-temperature distribution (<17 °C) for orientation, while moving the projection/results panels (current panel b, and the 2030 projection in panel c) to the Results. Panel (a) is retained with the source and caveats added under R1-5. This provides a proper study-area figure up front and keeps results in the Results.

R1-9

RC: *[on "profile"] I am not sure I understand what is meant by 'profile' in this case. Is it a cross-section? Or does it refer to a river reach (i.e., a short length of river where a temperature sensor can be reasonably assumed to provide representative observations)?*

AC: The reviewer's second interpretation is correct. A "profile" is a river reach at a monitoring location = a short river segment where the temperature sensor provides representative observations, not a cross-section. We will define the term explicitly at first use and use it consistently thereafter.

Methods & Table 1

R1-10

RC: *The earliest year listed in Table 1 is 2004. Please rectify this inconsistency.*

AC: Thank you. The text stating an observational period from 2002 is inconsistent with Table 1, where the earliest record begins in 2004. We will correct the text so the stated start year matches the data (2004).

R1-11

RC: *Please provide units either in the table heading or in the caption.*

AC: We will add the units (°C for the temperature statistics; m a.s.l. for altitude) to the Table 1 headings and caption.

R1-12

RC: *Suggest specifying 'upper percentiles (P75, P95, P99) of water temperature.'*

AC: We will adopt this wording in the caption, specifying "upper percentiles (P75, P95, P99) of water temperature."

R1-13

RC: *I suggest moving this information to the Results section. Additionally, I suggest including a table, either in the Results or in the S.I., which provides the range of site-specific estimated coefficients. Those values are useful and can provide additional interpretation on which streams / regions in Czechia may be more resilient/susceptible to warming, due to the inference regarding groundwater contributions that may be obtained from the site-specific estimated coefficients.*

AC: We agree and will add a table reporting the site-specific estimated coefficients for all 35 profiles to the Supplementary Material, with the range summarised in the main text. We will also add a brief interpretation noting that lower air-water sensitivity (a shallower slope) is consistent with a stronger groundwater influence and hence greater potential thermal resilience, providing a regional indication of which reaches may be more buffered against warming. The descriptive text currently in the Methods that reads as a result will be moved to the Results accordingly.

R1-14

RC: *GCM has not yet been defined in the main text.*

AC: We will define "global circulation model (GCM)" at its first occurrence in the main text (the abstract definition does not carry over), and check acronym definitions throughout.

R1-15

RC: *It is not clear how the site-specific model coefficients were applied to produce the gridded national-scale river temperature data set. Were the population-level coefficients applied to the gridded air temperature (i.e., the slope of 0.69 and intercept of 2.91)? Please provide more details on how the gridded river temperature data were produced.*

AC: We will clarify this in the Methods. The gridded national-scale water temperature was produced using the global model - the single population-level relationship (slope 0.69, intercept 2.91) applied to the gridded air temperature at each 500 × 500 m cell. The site-specific coefficients were not used for the gridded product; they exist only at the 35 monitoring profiles and are used for the profile-level analyses. We will make this division explicit so the two models' roles are unambiguous.

R1-16

RC: *Can you please provide literature references to support these thresholds?*

AC: Yes. We will add the supporting literature for the biological thresholds: Elliott & Elliott (2010) and Réalis-Doyelle et al. (2016) for the cold-season incubation/emergence thresholds (10 °C, 12 °C); Jonsson (2023) and Borgwardt et al. (2020) for the growth-related thresholds (17 °C, 19 °C); and Vornanen et al. (2014) for the 21–23 °C and >23 °C cardiac limits.

R1-17

RC: *The results provide heat wave metrics as well, but the definitions of heat waves or their consideration is absent from the Methods section here. I suggest incorporating them. Regarding the quantification of heat waves, I am curious to know if there is value in also considering acute heatwaves where there is a threshold river temperature increase (e.g., +3 °C) over previous conditions, in addition to the definition used in the results (>3 days, >23 °C).*

AC: We will move the heat-wave definition into the Methods (water temperature ≥ 23 °C for ≥ 3 consecutive days), where it is currently absent, together with its rationale and references. On the reviewer's suggestion of a relative (anomaly-based) definition (an increase of e.g. +3 °C over antecedent conditions) we agree this is a valuable complementary approach and will discuss it. We deliberately retain an absolute, fixed threshold here because our assessment targets a single species with a defined physiological limit (cardiac failure in brown trout at approximately 23.5 °C; Vornanen et al., 2014); an absolute threshold therefore maps directly onto biological risk, whereas a relative threshold captures local thermal anomalies that need not reach physiologically critical levels. We will note the relative/anomaly-based definition as a promising direction for future work, particularly for multi-species or cross-regional comparisons where acclimation to local baselines matters.

R1-18

RC: *It may be easier for consistency and interpretation to have panels e) through h) labelled with the centre of the period, like it is for the historical periods.*

AC: We agree and will relabel the future panels (e–h) using the period centre year, consistent with the labelling of the historical panels, so the time reference is uniform across the figure.

R1-19

RC: *This is not specific, suggest referring to the colours directly (red, blue).*

AC: We will revise the wording to refer to the colours directly (red and blue) rather than the current indirect phrasing, so the reader can map the description onto the figure unambiguously.

R1-20

RC: *I suggest removing the inset table and providing it as a stand-alone table in the main text.*

AC: We agree and will remove the inset table, providing it as a stand-alone table in the main text. (This is consistent with the figure-legibility improvements we are making throughout, including increased font sizes.)

R1-21

RC: *I suggest including the baseline period as well, prior to 2020s.*

AC: We agree. In the revised Figure 4 the baseline period (1961–2024) is included as the leftmost box in each panel, so the projected decadal changes are shown relative to the historical reference rather than beginning in the 2030s. The caption will be updated accordingly.

R1-22

RC: *The manuscript earlier states there are 35 stations. Please ensure that the correct value is provided throughout the manuscript.*

AC: Thank you, the correct number of profiles is 35. We will audit the manuscript and ensure this value is stated consistently throughout, correcting any instance that reports a different count.

R1-23

RC: *The point size in the legend for 10, 20, 30, and 40 are all very similar and difficult to differentiate. Can the legend point scaling please be revised to reflect the point sizes in the map? Additionally, is it ≤10, ≤20, etc?*

AC: Point size encodes the annual number of days per year with water temperature exceeding 23 °C; the legend values 10, 20, 30, and 40 are representative day counts, not "≤" bins. We will (i) clarify this directly in the legend so the meaning is explicit, and (ii) revise the point scaling so these reference sizes are clearly differentiated and match the symbol sizes rendered in the map. The square-root scaling that currently compresses the larger classes will be adjusted to improve differentiation.

R1-24

RC: *The same comment for Figure 5 also applied here.*

AC: We will apply the same legend revision (differentiated, correctly scaled point sizes and explicit class definitions) to this figure as well.

Discussion

R1-25

RC: *It is unclear to me, after reading the Methods, where or how the Czechia-wide river network spatial data was obtained.*

AC: The river network is based on the watercourse-axis layer (*Osy vodních toků*) obtained from the official Central Register of Watercourses (*Centrální evidence vodních toků*, CEVT) of the Czech Republic, administered by the Ministry of Agriculture and the Ministry of the Environment (2025 version). As a vector dataset it has no raster spatial resolution; the source data correspond to an approximate map scale of 1:10,000. For the mapped outputs, the watercourse-axis layer was processed in QGIS — individual reaches were merged as needed and clipped to the boundaries of the designated brown-trout fishing districts. We will add this description to the Methods.

R1-26

RC: *[on "a small fraction of river length"] Can you please provide a value?*

AC: We will replace the qualitative "small fraction" with the projected value. Under the SSP2-4.5 median projection, thermally suitable habitat (≥ 350 days < 17 °C) declines to below 5 % of river length by 2085. The sentence will be revised to state this figure explicitly.

R1-27

RC: *Related to my first comment on this line, how did you convert from the gridded model output of river temperature to linear spatial features?*

AC: Water temperature was computed on the 500 × 500 m grid via the global air–water model, and each river reach of the CEVT network was then attributed the value of the grid cell it intersects. The linear features therefore inherit the gridded model output through a spatial join, rather than being modelled as lines directly. We will state this explicitly in the Methods.

R1-28

RC: *What is the current day and/or historical distribution of brown trout across Czechia? This detail should be provided in the Introduction [...] no mention of the implicit subject of the study, brown trout, in Czechia.*

AC: We agree. The Introduction currently establishes the thermal and physiological context but does not describe the study species' distribution in the Czech Republic. We will add a short passage on the current and historical distribution of brown trout across Czech rivers, its association with the upper, cooler reaches of the network and the designated brown-trout fishing districts used to define our study domain, with appropriate references. This also provides context for the catch data in Figure 1a.

R1-29

RC: *Is this primarily where spawning and early life stages of brown trout occur? I am less familiar with this species than I am with Pacific salmon species and behaviours.*

AC: Yes. The cool, well-oxygenated upper reaches that our analysis identifies as persistent thermal refugia are also the principal spawning and early-development habitat for brown trout, which spawn in autumn–winter in gravel-bed headwater and upper-reach sections. We will make this connection explicit in the text and add a supporting reference, so the ecological significance of these reaches is clear.

R1-30

RC: *Are elevated 'cold season' temperatures ecologically relevant in the same manner as elevated 'warm season' temperatures, where the number of consecutive days above a temperature threshold matters more, perhaps, than occasional, non-consecutive days above the threshold?*

AC: This is an important distinction and we will address it explicitly. The two seasons act through different mechanisms, which is why we use different metrics. Warm-season stress is largely acute: consecutive days above a physiological limit matter, which is why heat waves are defined as runs of consecutive days (≥3 days > 23 °C). Cold-season effects on spawning, incubation, and emergence are instead cumulative and developmental — embryonic development integrates temperature over the incubation window — so total (not necessarily consecutive) exceedance days above the cold-season thresholds (>10 °C in ONDJ, >12 °C in FMAM) is the more appropriate measure of exposure. We will clarify this rationale in the Methods and Discussion and support it with the incubation/emergence literature (Elliott & Elliott, 2010; Réalis-Doyelle et al., 2016).

R1-31

RC: *[on "Even infrequent exceedances may disrupt thermal stability during incubation."] Can you please provide a reference to support this?*

AC: We will add a supporting reference. The sensitivity of embryonic development to temperature during the incubation window is documented by Réalis-Doyelle et al. (2016) and Elliott & Elliott (2010), which we will cite here.

R1-32

RC: *[on "thermal niche narrowing" or similar] Is it the niche that's narrowing, or the temporal window of suitable thermal conditions?*

AC: The reviewer is right that the wording is imprecise. The species' thermal niche (its physiological tolerance range) is fixed; what contracts under warming is the temporal window (and spatial extent) of conditions falling within that niche. We will rephrase accordingly, referring to a contraction of the window of thermally suitable conditions rather than a narrowing of the niche itself.

R1-33

RC: *[on "...a structural collapse of the continuous trout zone within the Czech river network."] This is not entirely clear and is not specific, can you please rephrase this?*

AC: We will rephrase to a specific, data-grounded statement and remove the dramatic wording. The revised sentence will read, e.g.:

"The spatial analysis (Fig. 3) shows a progressive loss of continuously cold-water reaches: the network fraction maintaining ≥ 350 days per year below 17 °C declines from near-complete coverage historically to below 5 % by 2085, with the remaining suitable conditions increasingly confined to high-altitude headwaters."

R1-34

RC: *Related to comments in section 4.2, it is unclear how the river network and river length was obtained.*

AC: As described under R1-25, the network derives from the CEVT watercourse-axis layer (Ministry of Agriculture / Ministry of the Environment, 2025; ~1:10,000), clipped in QGIS to the designated brown-trout fishing districts. River-length metrics are computed directly from this vector network. We will ensure the Methods describe the source and processing so the length calculations are traceable.

R1-35

RC: *This is a smaller contraction, it seems, that the results of this study. Can you provide further context to compare these findings? How do the results of the submitted manuscript compare to the results of Borgwardt et al., 2020? Is there any available explanation for why they are so different?*

AC: We will add a paragraph placing our results in the context of Borgwardt et al. (2020) and explaining why the two contraction estimates differ. The difference reflects methodological choices rather than a genuine discrepancy in the projected direction or severity of warming:

- **Different suitability metric.** Borgwardt et al. quantify habitat loss from the annual 95th-percentile of daily mean water temperature (WTQ95, effectively the ~18 hottest days) against thresholds for diminished growth (≥ 19.5 °C) and cardiac dysfunction (≥ 23.5 °C). Our metric is the number of days per year below 17 °C (≥ 350 days defining suitable habitat). A whole-year cold-persistence criterion is inherently more sensitive to warming than a summer-peak percentile, so a larger apparent contraction is expected from our metric even under identical warming.
- **Different thermal reference.** Their thresholds target summer maxima and acute risk; our framework is built around chronic sub-lethal exposure and the erosion of continuously cold conditions, which our results identify as the dominant driver of habitat loss. The two studies therefore measure related but distinct facets of thermal risk.
- **Different scenario and horizon.** Their headline contraction figures are reported under RCP8.5 for the far future (2071–2100), whereas our main analysis uses SSP2-4.5; direct numerical comparison is limited by this difference in forcing.
- **Different region and resolution.** Their analysis covers Austria on 5 km reaches (n = 5,985) with 1 km climate data and river-type-specific regressions by Strahler order, versus our Czech network on a 500 m grid. Regional hydrography and network composition differ.

Taken together, the two studies are consistent in projecting substantial loss of thermally suitable brown trout habitat under continued warming; the larger contraction in our study follows directly from a whole-year cold-persistence metric rather than a summer-percentile threshold, not from a stronger warming signal.

R1-36

RC*: It may be helpful to provide statistics on the number or percentage of Czech rivers that are regulated, or perhaps the length of unregulated river vs. high elevation river length that may be unaccessible due to flow regulation obstructions.*

AC: We agree this is a relevant dimension, but data on flow-regulation structures and migration barriers were not part of our analysis, and we do not have a barrier dataset to quantify the regulated versus unregulated (or accessible versus inaccessible) river length. Rather than provide an unsupported figure, we will frame this explicitly as a limitation, linked to our treatment of connectivity: our analysis quantifies the thermal suitability and length of river reaches but not their physical accessibility, which depends on migration barriers and flow-regulation structures not resolved here. We will note the quantification of barrier-constrained access to high-elevation refugia as a priority for future work.

R1-37

RC*: [on "low flows reduce thermal inertia"] It is not intuitive that low flows reduce thermal inertia. Could this be rephrased to something more clear and specific?*

AC: We will rephrase for clarity. The intended mechanism is that reduced discharge means a smaller water volume and thus a smaller heat capacity, so water temperature responds more rapidly to atmospheric forcing and reaches higher maxima. The sentence will be revised to, e.g.: *"During low-flow periods the reduced water volume has a lower heat capacity, so the* *river warms (and cools) more rapidly in response to air temperature, amplifying summer temperature extremes."*

R1-38

RC: *Is it possible to provide a range of stream widths to more precisely define this?*

AC: Channel-width data are held by the Czech Hydrometeorological Institute but were not available within our dataset, and obtaining them through the formal request process was not feasible within the revision. Rather than state an unsupported range, we will rephrase the statement qualitatively so it does not imply a quantified width, describing the reaches in terms of their position in the network (upper, headwater reaches) rather than by channel width.

R1-39

RC: *Providing the thermal sensitivity values of the study streams may help identify the rivers which may have greater resilience to warming due to increased groundwater contributions. [...] other stream temperature models such as PASTA [...] utilize sinusoidal relationships between air temperature and stream temperature, and provide several coefficients which can be interpreted to represent various aspects of groundwater contributions to rivers. It may be worthwhile to incorporate a brief discussion of these kinds of analyses [...]*

AC: We appreciate this suggestion, which we address in two ways. First, we now report the site-specific air–water sensitivity (the slope of each profile's model) for all 35 profiles in a new Supplementary table (per our response to the comment on site-specific coefficients), and we interpret lower slopes as indicating weaker air–water coupling consistent with stronger groundwater buffering and greater potential thermal resilience, providing exactly the regional resilience indication the reviewer describes. Second, we will add a brief discussion of process-oriented approaches such as PASTA, whose sinusoidal air–water formulation yields coefficients interpretable in terms of groundwater contribution, noting these as valuable tools for identifying resilient reaches and as a direction for future work. We are careful to frame our slope as an indicative proxy rather than a direct measure of groundwater input.

R1-40

RC: *My understanding is that Copernicus publications generally require data to be openly accessible. If the data are not able to be made publically accessible, an explanation as to why would be warranted.*

AC: We agree and will make the processed data and analysis code openly available. Where specific input datasets cannot be redistributed we will state this explicitly and provide the source and access conditions rather than the raw data themselves.

R1-41

RC: *[on a reference] Should not be all capital*

AC: We will correct the capitalisation of the flagged reference (removing the all-capital styling) and check for similar cases in the list.

R1-42

RC: *[on "Journal of fish biology" in the Elliott & Elliott 2010 reference] Fish Biology*

AC: We will correct the journal name in the Elliott & Elliott (2010) reference to its proper form, "Journal of Fish Biology", and check that all journal names in the reference list are correctly capitalised.

R1-43

RC: *This is Title Case, whereas the bulk of the references are Sentence case. I suggest the authors thoroughly proofread the reference list and format them for consistency*.

AC: We will thoroughly proofread the reference list and standardise the formatting, converting Title Case entries to sentence case, so the style is consistent throughout.