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Title: “The European summer heatwave 2019 – a regional storyline perspective”

Authors: Tatiana Klimiuk, Patrick Ludwig, Antonio Sanchez-Benitez, Helge F. Goessling, Peter Braesicke, and Joaquim G. Pinto

Recommendation: [Major/Minor Revision]

GENERAL COMMENTS:

This article presents a storyline approach of the unfolding of European summer of 2019 on a regional scale with special focus on the heat wave end of July 2019. Next to assessing the outcomes for present-day conditions, corresponding to +1.4K global warming, the methodology is repeated to cooler pre-industrial conditions, and to warmer future climates projected at several levels of future global warming. Storylines are constructed from a GCM-RCM-CPM model chain where the GCM is spectrally nudged to ERA5 vorticity and divergence to enforce the GCM atmospheric circulation to stay close to observed circulation patterns. GCM states are subsequently used for downscaling at 12 km for the European domain and 3 km for a Central-European region encompassing Germany. A performance assessment of the present-day climate simulation indicates an improvement of representing 2-meter temperature by the RCM and even more so by the CPM compared to the GCM. A primary finding of the storyline approach is a doubling, and at some locations, almost a tripling of local warming rates relative to the background warming during the episode prior and during the heat wave whereas earlier in the season (late spring/early summer) this ratio tend to be much smaller.

The storyline perspective built from constraining the climate model state through spectral nudging to a quasi-observed state (followed by standard dynamical downscaling) provides an elegant method to isolate the thermodynamic response to anthropogenically induced climate change from the circulation response. That part of the work is already developed and described in the paper by Sanchez-Benitez et al. (2022).
The present article focuses on the subsequent downscaling steps and potential impact on a regional to local scale. Overall it is well written and of general interest, however a number of issues require attention before the manuscript is suitable for publication.

MAJOR POINTS:

1. What I found quite surprising to notice is that the authors seem not aware, at least nowhere in the manuscript any reference is made, of a widely used alternative approach, commonly referred to as Pseudo Global Warming (PGW), in which following a comparable methodology storylines are built from primarily the thermodynamic (or physical) responses to projected future global warming. Examples in literature include for example:
    - Schär et al., 1996 Surrogate climate-change scenarios for regional climate models Geophys. Res. Lett. 23 669–72

- Prein et al., 2017.: The future intensification of hourly precipitation extremes, Nat. Clim. Change, 7, 48–52, https://doi.org/10.1038/nclimate3168
- Aalbers et al., 2023 The 2018 West-Central European drought projected in a warmer climate: how much drier can it get? Nat. Hazards Earth Syst. Sci. 23 1921–46 https://doi.org/10.5194/nhess-23-1921-2023
- Brogli et al., 2023 The pseudo-global-warming (PGW) approach: methodology, software package PGW4ERA5 v1.1, validation and sensitivity analyses Geosci. Model Dev. 16 907–26 https://doi.org/10.5194/gmd-16-907-2023

Moreover, just two weeks after this manuscript was submitted a paper by H. de Vries et al., entitled "Western Europe's extreme July 2019 heatwave in a warmer world", appeared in Environmental Research: Climate (https://doi.org/10.1088/2752-5295/ad519f) in which the authors develop a storyline perspective built on the PGW-approach focusing on the very same event.

In my opinion, reference to the PGW-approach in the context of the application presented in this paper is required, and I would strongly encourage to include a discussion on the pro's and cons of applying the respective methods (spectral nudging and PGW) in this type of storyline development, focusing on events or episodes.

2. It is unfortunate that the region with highest temperatures during the heat wave episode is on the western edge of the ICON-GER-3 domain (see Figure 6). In particular, it makes the conclusion that the region of highest relative warming rates shifts to the east questionable. Comparing both panels from Fig. 9b it appears to me that because the region with highest warming rates in the GER-3 simulations is so near to the western edge of the CPM modelling domain, and according to the EUR-12 simulations this region is actually extending further west, the claim that the area with highest warming rates shifts to the east can, instead of being a genuine outcome, simply be an artefact induced by the proximity of the lateral boundary zone.

   Additionally, a further complication is that the role of internal variability can not be assessed here, because the authors have limited their downscaling experiments to one member based on the presumption that the ensemble spread in the GCM-experiments appeared is small enough during the heat wave episode. But without testing it is hard to make it plausible that this is a justifiable assumption.

   For the authors interest, the results from de Vries et al. (2024) do not indicate an eastward shift of the area with highest warming rates relative to the area with highest temperatures in the present-day simulation (their Figs 8 and S6).

OTHER POINTS:

1. Line 87,146,156: Replace the word "*validation*" by "*evaluation*". A model result cannot be validated.
2. Section 2.1: I found the description somewhat confusing as if the spectral nudging is a feature of the AWI-CM1 GCM. I think though it should be considered an extension to enforce simulations in free climate mode to be constrained by ERA5-reanalyses. I suggest to remove the two words "spectral nudged" from line 92, and rephrase line

100 as “In the storyline experiments the evolution of the AWI-CM1 large-scale atmospheric circulation is constrained by spectrally nudging the model vorticity and divergence …”

3. Line 64: “at resolutions *of less* than 4 km” →“at resolutions *finer* than 4 km”
4. Line 120: “the spread” → “the inter-member spread”
5. Line 122-123: Please explain the meaning of R12B5 and R13B7 resolution,
6. Figure 1: Are the shown EUR-12 and GER-3 domains, the respective modelling domains including or excluding the lateral boundary zone? Please mention in the caption
7. Line 138: What does “*vn*” stand for?
8. Line 141-145: It is unclear how the soil information from ERA5 is used to adjust the forcing in the respective storyline, specifically at which stage of the model chain does it enter the computations.
9. Also the way the 4-layer temperature and soil moisture from ERA5 is mapped onto the soil mesh of either of the three models (AWI-CM1 and/or ICON-EUR-12 and/or ICON-GER-3) is unclear, in particular for soil moisture this is not a trivial mapping given the role of soil type in the ERA5 hydrological module HTESSEL. Please, clarify.
10. The remark “the temperature of the lowermost soil level (T_CL) was adjusted” sounds worrying in this context, why adapting a climate related prognostic variable, the simulation itself should keep track of an appropriate evolution.
11. Line 157: “model’s output” → “model output” (and everywhere else)
12. Line 187-188: “However, as our study is focused on Central Europe, the model performance in the most western and eastern part of the domain is found to be acceptable” . According to Fig 4 and Fig S3, there is a considerable cold bias in ICON-EUR-12 maximum 2-m temperature compared to EOBS-12 with hatched areas in most of Germany, the eastern part of France, and Sweden/Norway. On the one hand, why do the authors consider the size of the bias acceptable, given the purpose of the paper, on the other hand what is the relevance of this bias, given that they are primarily interested in the heat wave response under different storylines.
13. Line 189: “indicating “ is too strong phrasing, use “suggesting”.
14. Figure 4: The authors might check what part of the temperature biases (right column) in ICON-EUR-12 originates from the AWI-CM1 driving fields by carrying out the RCM simulation directly driven by ERA5. Has such a simulation been conducted?
15. Lines 197-200: I recommend to omit statements like “indicating a further added value of out approach”, since “added value” of high-resolution computations wrt courser-resolution has a somewhat different framing than in the context of evaluation. Also, in my perception the result from ICON-GER-3 wrt ICON-EUR-12 yields only an improvement for maximum 2-m temperature, and not for mean and 2-meter minimum temperature.
16. Line 201: “improved topography” →”refined topography”
17. Figure 6: Please use a different colour indicating the 40C line, e.g. green or black.
18. Line 242: What is meant by “individual”?
19. Line 248: “… which occurs in late August when the temperature again increase during summer.” Why is this happening? Please, expand on the possible mechanism behind this behaviour.

20. Line 255: “in spring and early summer.” And also in September?
21. Line 260: refer to “goodness of fit” instead of R2
22. Line 268: “in line with the finding” Presumably, this is just an expression of the same finding, not an independent confirmation of it.
23. Line 271-273: Likely also because the British Isles are surrounded by sea.
24. Line 299: “to the west of it”. Presumably, “to the east of it” is what is meant.
25. Line 309: avoid using “observed”, but use “derived warming rate” instead
26. Line 310: “temporal”? The authors refer to intra-seasonal variations?
27. Line 315: “extending” → “an extension of” (or “an increase of”)
28. Lines 328-329: this statement is very speculative.
29. Line 336: “ … we addressed here for the first time …” I am afraid this statement no longer holds, see de Vries et al. (2024) for an analysis of the heat wave of 2019, and Aalbers et al. (2023) for a comparable type of analysis of the drought episodes and heat wave of 2018.