

The paper went through a deep revision in which we: i) revised the language, ii) modified the paper structure (separating the discussion section from the result section, highlighting the main finding in the conclusion section), iii) improved the abstract, introduction, and methodology sections, iv) we changed and improved the figures' quality and captions.

Finally, we extended the level of discussion and we added more citation to justify and compare with our findings.

Moreover, we added the new analysis requested by the reviewer n1 and n. 2, specifically:

- a) As both the reviewer asked, we used the methodology of linear interpolation in time instead of the closest-year method presented in the original version of the paper
- b) to disentangle the effect of each single components of the risk on its total changes, changing in turn one by one each element (i.e. vulnerability, exposure and hazard) and keeping constant the other two
- c) finally we also improved our trend analysis and statistical significance evaluation by using the FDR methodology.

Answers to the Reviewer 2

General comments

This study investigates and quantifies hazard, exposure, and vulnerability to heat and cold extremes in the Italian region Trentino Alto-Adige for 1980-2018 and calculates the resulting combined risk. The structure of the paper is generally clear, and the presented results are mostly convincing. My main comments concern 1) the language, 2) a more precise estimation of the contribution of hazard, exposure, and vulnerability to the overall risk, 3) extending the figure captions, and 4) adjusting the p-values of the statistical significance tests to control for the false discovery rate.

We thank the reviewer for the revision and the useful comments and insights. We reviewed the paper according to the suggestions and below you can find a one-to-one answer. The answer to the reviewer comments are provided in red, the new revised sentences are provided in blue.

Main comments:

Although the manuscript is generally well comprehensible, the structure of some sentences and some of the terms that are used make some parts difficult to understand. I would thus recommend to carefully check the whole text again with a special focus on rephrasing cumbersome sentences (some examples are listed under “specific comments”)

We revised the manuscript and its organization as well as the results presentation, discussion, and conclusions. All the specific comments have been implemented in the revised paper.

I think that it would be possible to calculate the contribution of changes in hazard, exposure, and vulnerability to the overall changes in risk ratio (e.g. by keeping exposure constant while changing the other parameters, and similarly for the other parameters). I think this could provide a valuable insight into the importance of climate change vs population and socioeconomic changes.

We implemented the analysis requested by the reviewer, we provided a new figure summarizing the result of this analysis and we added the following new sentences in the revised paper.

The new figure is the following:

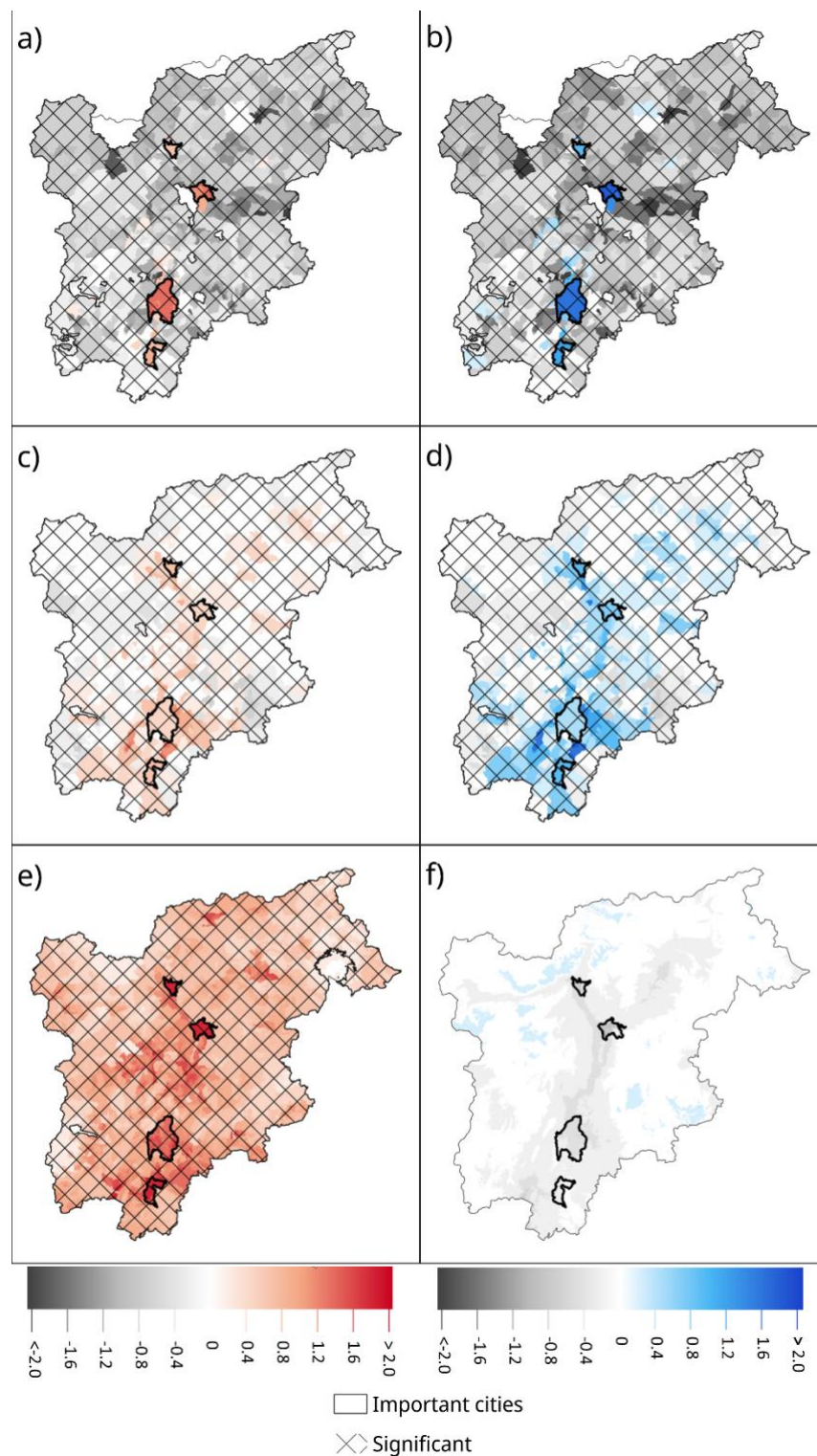


Figure 6: Trends of heat waves (and cold waves) risks due to changes in: a) (b) vulnerability only, c) (d) exposure only, and e) (f) hazard only. Trends found with the robust linear method, colors indicating an increase in the risk and grey a decrease, significance is indicated with the hashing, the yearly change being the robust linear model coefficient.

The new sentences added in the result section are the following:

“Figure 6 shows the marginal effect of the driving factor behind the trends in HWs and CWs risks. Figure 6-a, Figure 6-c, and Figure 6-e (Figure 6-b, Figure 6-d, and Figure 6-f) show the trend in HWs (CWs) risks with only vulnerability, only exposure, and only hazard changing, respectively.

The results in Figure 6-a and Figure 6-b show the same patterns as well as Figure 6-c and Figure 6-d because exposure and vulnerability are the same for both HWs and CWs and hazard is the only differing variable.

Figure 6-a (Figure 6-b) show increasing trends in risk (due to change in vulnerability only) in the main cities and nearby areas. Decreasing trends are found for most of the remaining region.

Figure 6-c (Figure 6-d) show increasing trends in risk (due to change in exposure only) in/near urban areas and decreasing trends in zones at high elevations and far from the urban centers.

Figure 6-d show that the hazard is the main driver of risk for HWs, with statistically significant increasing trends, more evident in and around highly populated areas. Finally, Figure 6-e show no significant trends in CWs risk (due to change in hazards only).”

The new sentences added in the discussion section are the following:

The analysis of the trends of risk while changing only one of its three variables and keeping constant the remaining two shows that hazard and vulnerability are the main driving factor of the HWs risk. The changes in HWs risk due to hazard also highlights the presence of urban heat island in the most populated cities of the region (in Figure 6-e these are the zones of the highest increasing trends in risk). This has also been found in other in urban areas (e.g. Morabito et al., 2021). The changes in CWs risk is mainly explained by the demographic and vulnerability changes, which are increasing in/around urban areas and decreasing elsewhere. The changes found in HWs and CWs risk due to changes in exposure or vulnerability only is partially explained by rural-urban migration and an aging population, which is presented in other studies such as (Reynaud and Miccoli, 2018).

The captions of the figures are currently very short and contain insufficient information to fully understand the associated figures. A caption should be written such that it is possible to understand a figure and its main message only from watching the figure and reading its caption (i.e., without the need to read the main text). I would thus recommend extending the captions such that they explain the figures and the displayed features more comprehensibly.

Thank you, this has been considered and the captions have been rewritten accordingly.
Please, see also the specific comments where we show the modification.

Many of the figures contain estimates of statistical significance. As the multiple statistical tests (which I presume are conducted independently for each grid cell) may cause to overestimate the statistical significance (Wilks, 2016, <https://doi.org/10.1175/BAMS-D-15-00267.1>), I would suggest adjusting the p-values by controlling for the false discovery rate as proposed by Wilks (2016).

Thank you for this suggestion, all the figures have been remade with this suggestion, their significance corresponds to the FDR significance. Moreover, we added the following new section in which we explained the methodology we used.

The new sentence is:

The trends are analyzed using the robust regression technique (Huber, 2011). This method is often used throughout the literature for natural hazards (Formetta and Feyen, 2019; Kishore et al., 2022).

The trends are analyzed using the robust regression technique (Huber, 2011). This method is often used throughout the literature for assessing trends in natural hazards (Formetta and Feyen, 2019 for multiple hazards and Kishore et al., 2022 specifically for HWs). To confirm the statistical significance of the trends the false discovery rate (FDR) methodology is used according to Wilks (2016) and Leung et al. (2019), with a significance level $\alpha=0.05$. The FDR is defined as the statistically expected fraction of null hypothesis test rejections at the grid cell for which the respective null hypotheses are actually true (Wilks 2016).

Specific comments:

- 1 Lines 15-16 (and generally for the description of the Tweedie distribution): I think it would make sense to first mention that HWMId and CMWId are normalized to the interval (0, 1)

to combine them with the exposure and vulnerability metrics, and only then write that the Tweedie distribution is used for this purpose.

Thank you this has been adjusted. The old sentence was:

We use the Heat Wave Magnitude Index daily (HWMId) and a Cold Wave Magnitude Index daily (CWMId) as temperature-based indicators and apply a Tweedie zero-inflated distribution to derive hazard intensities and frequencies. The hazard maps are combined with high-resolution maps of population, for which the vulnerability is quantified at community and city level using a set of eight socioeconomic indicators.

The new sentence is:

To obtain HWs and CWs risk maps we combined: i) occurrence probability maps of the hazard, ii) normalized population density maps, and iii) normalized vulnerability maps based on eight socioeconomic indicators. The occurrence probability of the hazard is obtained using the Tweedie zero-inflated distribution. The methodology allowed us to disentangle the effects of each component of the risk to its total change.

2 Line 17: Maybe better “which are used to derive vulnerability”

Thank you for this suggestion, this sentence has been rephrased entirely as part of the changing of the abstract. See the sentence above.

3 Line 18 ff: I am wondering how the increased resilience is determined? Maybe the factors causing the increased resilience could be mentioned here (same for CW)

We thank the reviewer for the suggestion, the sentence was actually removed in order to make the abstract shorter per the other reviewer’s request, only the trends in vulnerability are now mentioned.

The old sentence was: “We observe a general trend towards increased resilience to extreme temperature spells over the region. In the larger cities of the region, however, we find that vulnerability has increased due to an ageing population and more single households.”

The new revised sentence is:

“A decrease in vulnerability to extreme temperature spells is observed trough the region except in the larger cities where vulnerability has increased.”

4 Line 36 (and other occasions): I think that the text would be easier to read if an “s” would be added to the acronyms for the plural forms of “heat wave” and “cold wave” (i.e., HWs, CWs).

We thank the reviewer for the suggestion, we adjusted it throughout the entire text.

5 Line 38: In which direction do they change? Increasing or decreasing?

We thank the reviewer for the question. We revised the section. The old section “With global warming, heat and cold wave intensities and durations are expected to change (Perkins-Kirkpatrick and Gibson, 2017; Russo et al., 2015; Smid et al., 2019), which could increase the risks to society.”

The new revised sentence is:

“With global warming, HWs intensities and durations are expected to increase while those of CWs are expected to decrease (Perkins-Kirkpatrick and Gibson, 2017; Russo et al., 2015; Smid et al., 2019), which would change their risks to society.”

6 Line 42: How are heatwaves defined in this study? Based on percentiles? Or is it HWMld?

We thank the reviewer for the question. Heatwave in that study are defined as 3days above the 90th percentile temperature. This is now mentioned in our article and the new sentence is: “In Europe, recent high intensity HWs events (2003 and 2018, where HWs are defined as 3 days over 90th temperature percentile of the 1980-2010).”

7 Line 43-44: This part of the sentence about GCP losses is a bit difficult to understand. I would suggest rephrasing it.

The sentence about the GDP has been removed in our attempt to make the introduction a bit shorter and straightforward as suggested by both reviewers.

8 Line 71-73: Rephrase, as the last part reads rather cumbersome.

We thank the reviewer for the suggestion. The sentence has been rephrased. The old sentence was:

“Most of these studies have found increasing trends in exposure to HW and for the studies that also analyzed CW, found decreasing trends for them.”

The new sentence is:

“These studies found increasing trends in HWs (Chambers, 2020; Dosio et al., 2018) and decreasing trends in CWs in their period of analysis (Oldenborgh et al., 2019, Smid et al., 2019).”

References were added as per the other reviewer's request.

9 Line 99: Maybe “are most exposed to” instead of “affect”

We thank the reviewer for the question, we revised the sentence. The old sentence was:

“In Korea at the county level, Kim et al. (2017) found that elderly living alone, agricultural workers and unemployed affect vulnerability to heat wave days and tropical nights”

The new revised sentence is:

“In Korea at the county level, Kim et al. (2017) found that elderly living alone, agricultural workers, and unemployed are the most significant vulnerability factors to extreme temperatures.”

10 Line 113-114: What does “normalized population” mean? Can this be shortly explained here?

We thank the reviewer for the question, and we revised the sentence. Russo et al., 2019 normalized the population density maps in order to have values between 0 and 1 and therefore consistent with the hazard (between 0 and 1) and the vulnerability (between 0 and 1) in the risk equation.

The old sentence was: “where the exposure is the normalized population”.

The new sentence is: “where the exposure is the population density normalized in [0;1] based on its maximum, minimum values;”

11 Line 134: Remove “for the”

We thank the reviewer for the suggestion, and we removed it.

The old sentence was:

“The aim of this article is to solve some of these previous limitations while quantifying heat and cold waves hazards, the human exposure, vulnerability, and risk for the at the high-definition city scale for the Trentino-Alto-Adige region over the period 1980-2018”

The new revised sentence is:

“The aim of this article is to solve some of these previous limitations while quantifying HW and CW hazards, the human exposures, vulnerabilities, and risks at the high-definition (i.e. city-scale) over the period 1980-2018, for the Trentino-Alto-Adige region”

12 Lines 141-143: Something with the reference to Figure 1 is wrong

We thank the reviewer for the comment. We have addressed revising the sentence. The old sentence was:

“The Trentino Alto-Adige region (**Error! Reference source not found.**) is a mountainous region in northern Italy, which borders Austria”

The new revised sentence is:

“The Trentino Alto-Adige region (Figure 2) is a mountainous region in northern Italy, which borders Austria”

13 Lines 145-146: I think it would be good to exactly state the population of Trento, Bolzano, Merano and Rovereto

We thank the reviewer for the suggestion. We revised the sentence accordingly. The old sentence was: “Its most populous cities are the two provincial capitals -Trento and Bolzano - as well as minor cities Merano and Rovereto (both have a population of over 30000)”

The new revised sentence is

Its most populous cities (population for 2022 in parenthesis) are the two provincial capitals, Trento (118509) and Bolzano (107025), as well as minor cities such as Merano (40994) and Rovereto (39819).

14 Lines 157-160: I think it would be good to shortly explain which variables are used for the extrapolation of the temperature dataset (e.g. height, land cover, something else?)

We thank the reviewer for the question. We revised this section including more information on the interpolation schema (and on the geomorphological variables used in the interpolation).

The old sentence was:

“The dataset is obtained with the anomaly-based approach taking into account elevation of the local station observations; the dataset has undergone a quality analysis and control against the stations’ observations (Crespi et al. 2021).”

The new revised sentence is:

“This dataset is based on more than 200 station daily records which have been quality controlled and homogenized. The interpolation method is based on a combination of 30-year temperature climatology (1981–2010), daily anomalies and explicitly accounts for topographic features (i.e. elevation, slope) which are crucial in orographic complex areas such as the Trentino Alto-Adige. The leave one out cross validation presented in Crespi et al. (2021) finds mean correlation coefficient higher than 0.8 and mean absolute errors of around 1.5 degree Celsius (on average across months and stations used for the interpolation).”

15 Lines 164ff: What is the reference period for calculating HWMId? I would also explicitly mention that data are pooled from a window of 15 days before and after each day (currently this is not entirely clear).

We thank the reviewer for the question. We revised the sentence better specifying the reference period for calculating HWMId. The old sentence was:

For HWMId, from the temperature time series in each grid cell, we select the days where the temperature is above the 90th percentile of the dataset Ad (Equation 1):

$$A_d = \bigcup_{y=1981}^{2010} \bigcup_{i=d-15}^{d+15} T_{y,i}$$

(1)

where y corresponds to the year, i to the day, and $T_{y,i}$ correspond to the temperature of the corresponding year and day and the dataset A_d corresponds to the temperature data for 30 years, centered on a 31-day window for the day in question. Three consecutive days above this threshold correspond to a HW.

The new revised sentence is:

According to Russo et al. (2015), HWMId is defined as the maximum magnitude of the HWs in a year. A HW occurs when the air temperature is above a daily threshold for more than three consecutive days. The threshold is set to the 90th percentile of the temperature data of the day and the window of 15 days before and after throughout the reference period 1981-2010.

16 Line 175: I think rather “daily heat magnitude”

We thank the reviewer for the suggestion. We revised the sentence accordingly.

The old sentence was: “to the heat daily magnitude.”

The new revised sentence is: “the daily heat magnitude.”

17Line 176: Are the percentiles calculated from the temperature distribution or from the yearly maximum temperatures? (the latter is done in the original publication by Russo et al.).

We thank the reviewer for the question. We used the yearly maximum temperatures, and we revised the sentence accordingly.

The old sentence was:

“where $HM_d(T_d)$ corresponds to the heat daily magnitude, T_d the temperature of the day in question and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile temperature for the 30 years used as a reference”

The new revised sentence is:

where $HM_d(T_d)$ corresponds to the daily heat magnitude, T_d the temperature of the day in question and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile of the yearly maximum temperature for the 30 years of the reference period (1981-2010).

18Line 178: I would write “only consecutive days with HM_d above 0”

We thank the reviewer for the suggestion. We modified the sentence (and the entire paragraph to describe the $HWMId$ in a more clear way). The old sentence was:

“The highest cumulative magnitude is retained for each year and only consecutive days above 0 are considered when calculating it”.

The new revised sentence is:

Finally, for a given year $HWMId$ corresponds to the highest sum of magnitude (HM_d) over the consecutive days composing a heatwave event (with only days with $HM_d > 0$ considered).

19Line 189-190: I think it would be good to explicitly write that based on the definition used in this paper, CM_d is always < 0

We thank the reviewer for the question. We revised the sentence according to the suggestion.

The old sentence was:

“Similarly, the lowest cumulative magnitude is retained for each year and only consecutive days below 0 are considered when calculating it. For both the values of $HWMId$ and $CWMId$

to be positive and on the same interval, the absolute values of CWMId are retained from this point on.”

The new revised sentence is:

Inversely to HWMId, the lowest cumulative magnitude sum is retained for each year and with only consecutive days with $CM_d < 0$ considered to calculate it. CWMId being always < 0 , its absolute values are retained for its values to be on a positive interval (similar to HWMId).

20 Lines 210-212: This is partly a repetition, maybe shorten it?

We thank the reviewer for the suggestion, we have removed the sentence accordingly.

Line 220ff: I would suggest writing more specific what the KS test has been used for in this paper (“statistical fit verification” sounds rather generic)

We thank the reviewer for the suggestion. We modified the sentence accordingly.

Old sentence: “For statistical fit verification, the Kolmogorov–Smirnov (KS) test on two samples is used with one sample being the found HWMId or CWMId values, and the other sample being a randomly generated sample using the fitted distribution value.”

New revised sentence.

“The goodness of fit of the Tweedie distribution fitted to the HWMId/CWMId data for every pixel have been tested by means of a Kolmogorov-Smirnov test of hypothesis. The test is performed using two samples, with the first being the data and the other being a randomly generated sample using the fitted distribution parameters.

21Line 230: “population data”

We thank the reviewer for the suggestion. We modified the sentence accordingly.

Old sentence: “To quantify the population exposed to HW and CW we use time-varying population from the Global Human Settlement Layer (GHSL) (Schiavina et al., 2019). The data is available at a resolution of 250m for the following years: 1975, 1990, 2000 and 2015:”

New revised sentence: “To quantify the population data exposed to HWs and CWs, we use time-varying population data from the Global Human Settlement Layer (GHSL) (Schiavina et al., 2019). The population data is available at a resolution of 250m for the following years: 1975, 1990, 2000 and 2015”.

22Lines 254-256: This sentence is not clear to me. Could it be explained a bit more in detail how this was done and why this approach was chosen?

We clarified better this concept in the revised paper. Equation 8 and 9 have been added as well as paragraph mentioning why this methodology was picked.

The old sentence was: “The methodology to quantify vulnerability uses the equal weight analysis (EWA) with the indicators being standardized between 0 and 1 prior to aggregation according to Liu et al, (2020).”

The new revised sentence is:

The methodology to quantify vulnerability uses the equal weight analysis (EWA, e.g. Liu et al, 2020). Firstly, the individual indicators are standardized between 0 and 1, prior to aggregation (their sum); the standardization is done at the city level for all the years of record (1991, 2001, 2011) based on Equation 7:

$$\text{Standardized Indicator } (t) = \frac{\text{Indicator}(t) - \min(\text{Indicator}_{1991,2001,2011})}{\max(\text{Indicator}_{1991,2001,2011}) - \min(\text{Indicator}_{1991,2001,2011})} \quad (7)$$

Secondly, the EWA is performed according to Equation 8:

$$\text{Vulnerability } (t) = \frac{\sum \text{Standardized indicator}(t)}{\text{number of indicators}} \quad (8)$$

This approach was chosen as it is the simplest method for weighing the vulnerability indicators and it is commonly applied in the literature with regards to HWs and CWs (e.g. Buscail et al., 2012; Buzási, 2022).

Finally, we created yearly varying vulnerability maps for the period 1980-2018 following the same approach we used for the population.

23 Lines 274-279: Another approach could be the temporal linear interpolation of the exposure and vulnerability variables.

We thank the reviewer for this question. We intensively revised this part of the paper. To account for the reviewer suggestion, we interpolated the data in time and removed the approximation of using the closest year (when possible) for all the variables (i.e. hazard, vulnerability and exposure).

The exposure data (i.e. population) are available for the years 1975, 1990, 2000 and 2015. We created yearly varying population maps following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018.

The vulnerability data are available for the years 1991, 2001, 2011. We created yearly varying vulnerability maps following the same approach we used for the population: we interpolated the data in time for the period 1991-2011 (assuming a constant rate in between available years) and we used the closest year for the period 1980-1990 and 2012-2018.

We added the following sentence in the section of the exposure:

“To more accurately model exposure, we created yearly varying population maps for the period 1980-2018 following the methodology presented in other studies (e.g. Formetta and Feyen, 2019; Neumayer and Barthel, 2011). We linearly interpolated the data in time for the period 1980 to 2015 (assuming a constant rate in between available years) and we used the closest year for the period 2016-2018..”

We added the following sentence in the section of the vulnerability:

“Finally, we created yearly varying vulnerability maps for the period 1980-2018 following the same approach we used for the population.”

24Line 303: Here, does HW mean the yearly HWMId values or something else? Could that be specified?

We thank the reviewer for the suggestion. Yes it is correct and we modified the sentence accordingly. Old sentence: “statistically significant positive trends are found for HW in most pixels of the region (Figure 2)”

New revised sentence: “Fitting the robust linear model to the HWs values, statistically significant positive trends are found for HWs (i.e. HWMId > 0) and HWs with a magnitude larger than the 5-year event (HWMId > HW5Y) in most pixels of the region (Figure 2).”

25Line 305-306: If I understand correctly, there should only be 3-4 values for HW10Y in each pixel, given that a period of 39 years is used. I am not sure whether a trend can be deduced from such few data points.

We agree with the reviewer comment. We used the robust regression method and the FDR method to evaluate the trend in a more robust way. For very extreme heatwave hazard in the revised paper we obtain as result no statistical significance (with FDR).

26Line 312: Maybe “that was” instead of “and”?

Thank you, this sentence has been removed in the revised paper.

27Lines 324-328: I would add “event” after HW and CW.

Thank you, we modified accordingly. However this section is now in the discussion section.

The old sentence was: “The significant increasing trend for HW that we find are consistent with literature that reported increasing HW trends in Europe over the last decades (Perkins-Kirkpatrick and Lewis, 2020; Piticar et al., 2018; Serrano-Notivoli et al., 2022; Spinoni et al., 2015 Zhang et al., 2020). The lack of trend in CW is also in agreement with previous research that could not detect any trend in extreme cold spells (Jarzyna and Krzyżewska, 2021; Piticar et al., 2018)”

The new revised sentence is: “The significant increasing trend we found in HWs events are consistent with other studies in Europe over the last decades (e.g. Perkins-Kirkpatrick and Lewis, 2020; Piticar et al., 2018; Serrano-Notivoli et al., 2022; Spinoni et al., 2015; Zhang et al., 2020). The location of our highest increasing trends in HWs events are concordant to those of the higher increase in temperatures found at higher elevations by Acquafredda et al., (2015) in north-west Italy. Our results for HWs are also in line with the finding of Bacco et al., (2021) that analyzed trends in temperature extremes over northeastern regions of Italy (including Trentino Alto-Adige) based on homogenized data from dense station networks. They also found widespread warming, with significant positive trends in maximum-related mean and daytime temperature extremes. The lack of trend in CWs events is also in agreement with previous research that could not detect any trend in extreme cold spells (Jarzyna and Krzyżewska, 2021; Piticar et al., 2018).”

28Lines 329-331: But Figure 3 does not present a separation of both effects! It shows the combined effects of changes in HWs and of changes in population. I think that for disentangling both effects, one of them would need to be kept constant (see also main comment above)

We implemented this change in the revised paper. See the main comment above to view the new figure and new sentences added in result and discussion sections.

29Line 350: Not sure that “extreme age” is the right term.

We thank the reviewer for the suggestion, we modified accordingly. Old sentence:

“The increase in these cities’ vulnerability relates to the extreme age indicator and social status,”

New revised sentence: “The increase in these cities’ vulnerability relates to the older age indicator and social status”

30 Line 360: I would delete “somehow”

We thank the reviewer for the suggestion, and we modified that sentence accordingly from:

The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province.

The new sentence is: The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province.

31Lines 362-365: Does this refer to the study by Frigerio & De Amicis?

We thank the reviewer for the comment, and have clarified this aspect in a clearer way. This refers to the difference between the two (our study and theirs) and has been specified. This part is now in the discussion. The old sentence was:

Old sentence was:

“The results of our vulnerability analysis somehow contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province. This likely relates to the use of different indicators (employment, social-economic status, family structures, race/ethnicity, and population growth) and a different methodology for calculating the vulnerability. Notably in Frigerio & De Amicis (2016) the normalization of indicators is applied across all of Italy as opposed to only over the Trentino Alto-Adige region in this study, which may better characterize local vulnerability.”

The new revised sentence is:

“The results of our vulnerability analysis contrast with the findings of Frigerio & De Amicis (2016), who report increasing vulnerabilities for municipalities of the Bolzano province and slightly decreasing to steady vulnerabilities in the Trento province. This contrast, between our finding and theirs, is related to the use of different indicators (employment, social-economic status, family structures, race/ethnicity, and population growth) and a different methodology for calculating the vulnerability where the normalization of indicators is applied across all of Italy in their study, as opposed to only over the Trentino Alto-Adige region in this study, the latter characterizing better local vulnerability. The selection of different indicators and methodology might yield different results.”

32Lines 368-372: These results cannot easily be seen in the figures. I would suggest to change the figures to make this better visible (see my comments to Figure 5 below)

We thank the reviewer for the comment and have remade the figure in order to make the results more evident. The difference is shown in the comment about the figure below.

33 Lines 377-380: What are the main factors? Can they be identified, and can their contribution be quantified? (see also my main comment above)

Following your main comment a further analysis has been conducted and the results are discussed in the appropriate section and are visible in Figure 6. See also the reply to the main comment above

34Line 407: Mainly “normalized” instead of “sized”

We thank the reviewer for the suggestion. We use hazard quantification. The new sentence is:

“The hazard probability of occurrences are then quantified by fitting a Tweedie distribution to the HWMId and CWMId values, explicitly accounting for zero values in their time series”

35Line 409: I do not really understand the meaning of this sentence.

We thank the reviewer for the comment and have revised the sentence accordingly.

Old sentence: “Exposure is be found using the different fitted hazard levels.”

New sentence: “Two types of population exposure are found using the different hazard levels (5 years and 10 years return level).”

36Line 428: Are there any proofs/studies showing that this is the case “likely also in many other regions”? Otherwise this statement should be deleted.

We thank the reviewer for the comment, and we deleted the sentence accordingly.

Figures:

1. Figure 1: I think it would be good to have some more information in the caption, e.g. that Merano, Bolzano, Trento, and Rovereto are the main cities in the region and what the colors mean.

We thank the reviewer for the comment we added more information as requested. The old caption was: Figure 1: The Trentino Alto-Adige region

The new caption is: Figure 2: The Trentino Alto-Adige region and its most populated cities (Trento, Bolzano, Rovereto and Merano); the colors indicating the elevations, river network, and lakes.

”

2. Figure S-1: The abbreviations used in the legends and the titles should be explained in the caption.

Thank you, we modified the figure and the caption accordingly.

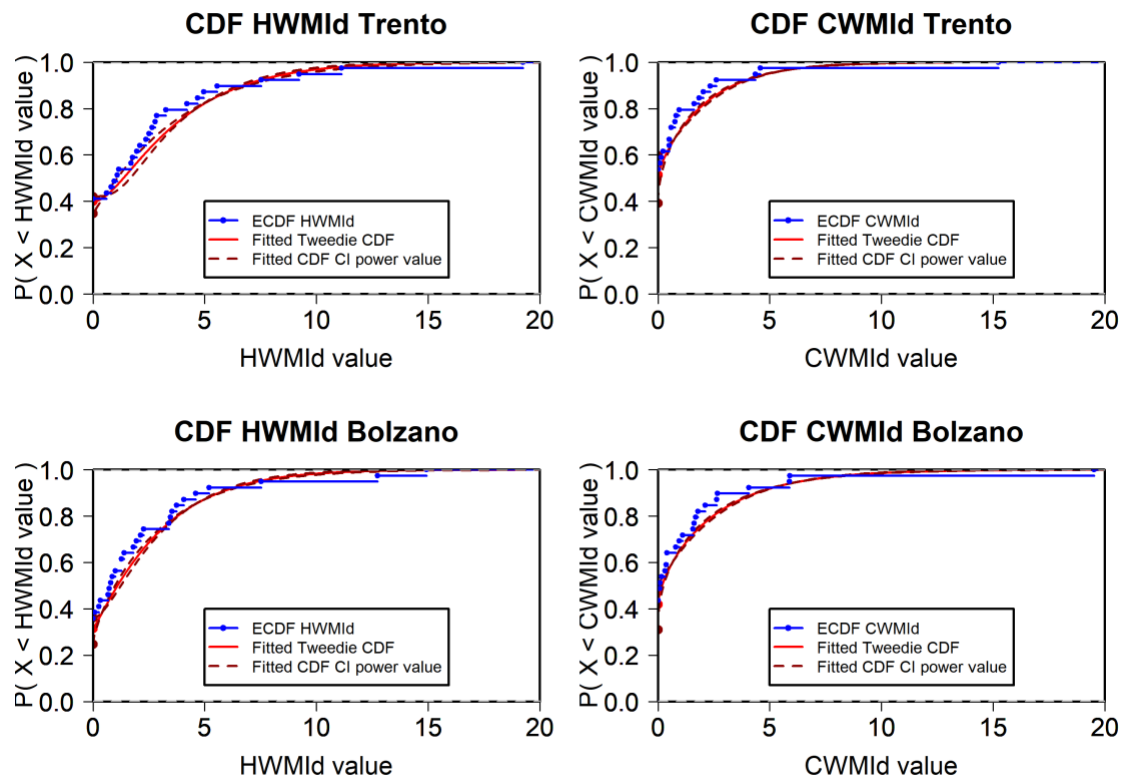


Figure S - 1: Cumulative distribution functions for both HWMId / CWMId at the location of the cities of Bolzano and Trento

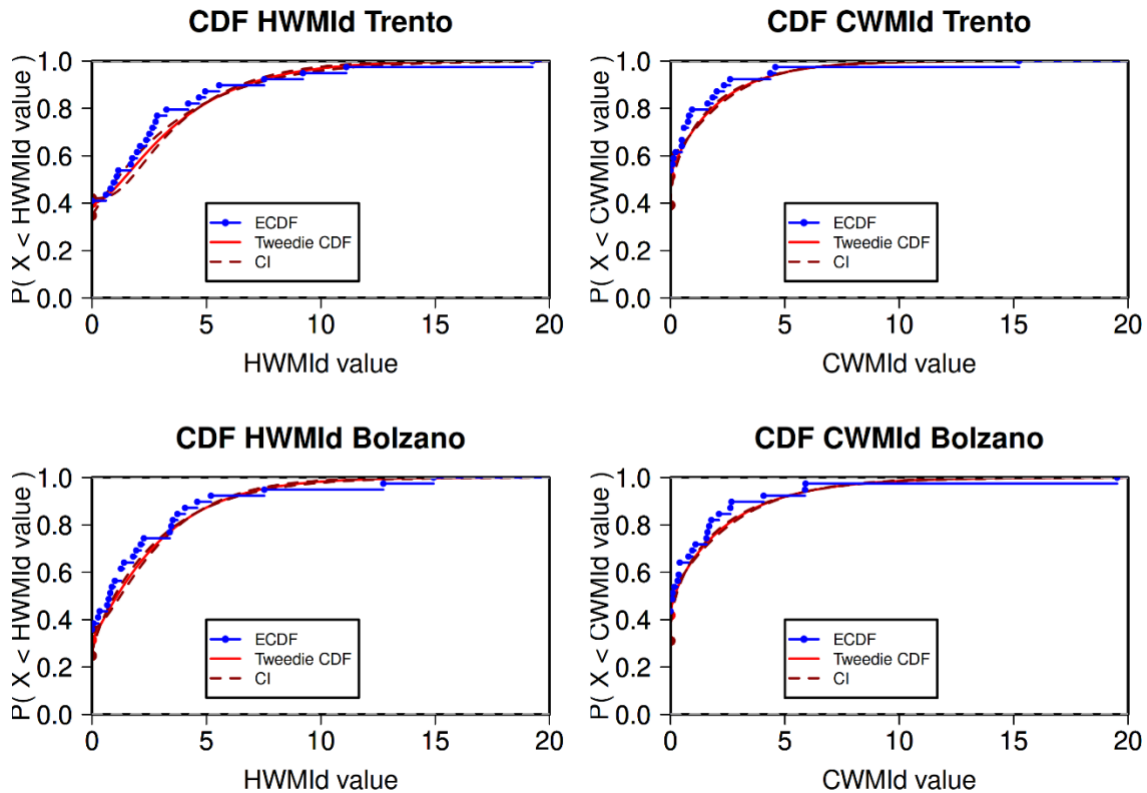


Figure S2: Cumulative distribution functions (CDF) for both HWMI / CWMI at the location of the cities of Bolzano and Trento, displaying the probability (P) showing the empirical cumulative distributions (ECDF) for these locations as well as the confidence interval (CI) of the power value of the Tweedie distribution.

3. Table 1: What are the exact definitions of “population living in at risk housing” and “population with low income”? Could you be more specific? And does the diploma/degree for “population with low education” refer to school or university degrees?

Thank you for the comment, we added more specific information in the table. Old table:

Table 1: Vulnerability indicators used (after Ho et al., 2018)

Category	Indicator	Definition
Extreme Age	Older Age	Population over 55 years old
	Infants	Population under 5 years old
Household physical characteristics	People in old houses	Number of household living in housing built prior to 1960

	People in poor living condition	Population living in at risk housing
Social Status	Low education population	Population with low education (no diploma or degree)
	People living alone	Number of single-person households
Economic Status	Low-income population	Population with low income
	Unemployed	Unemployment rate

New table:

Table 2: Vulnerability indicators used (after Ho et al., 2018)

Category	Indicator	Definition
Extreme Age	Older Age	Population over 55 years old
	Infants	Population under 5 years old
Household physical characteristics	People in old houses	Percentage of household living in housing built prior to 1960 (corresponding to when better insulation started being implemented)
	People in poor living condition	Percentage of household living in other type of housing not meant for inhabitation (cellar, attics)
Social Status	Low education population	Population with low education (no middle-school diploma)
	People living alone	Number of single-person households
Economic Status	Low-income population	Population in a household with children and no money-earning members
	Unemployed	Unemployment rate

4. Why has the year 1960 been used for the category “people in old houses”? Is this an arbitrary choice or are there reasons to choose this year?

The year is not arbitrary, 1960 is first of all used in the study on which the indicators are based from (Ho et al, 2018). Second, the implementation of insulation dates from the 1960s, this has been specified in several studies about building insulations in several locations such as Austria or Italy (Mukati, 2021; De Angelis et al., 2020) and the first building energy regulation in Italy is from 1973 (Carrosio, 2015; Magnani et al., 2020), therefore it can be assumed that some building in an alpine region in Italy bordering Austria had insulations.

Carrosio, G.: Politiche e campi organizzativi della riqualificazione energetica degli edifici, *Sociol. URBANA E RURALE*, <https://doi.org/10.3280/SUR2015-106002>, 2015.

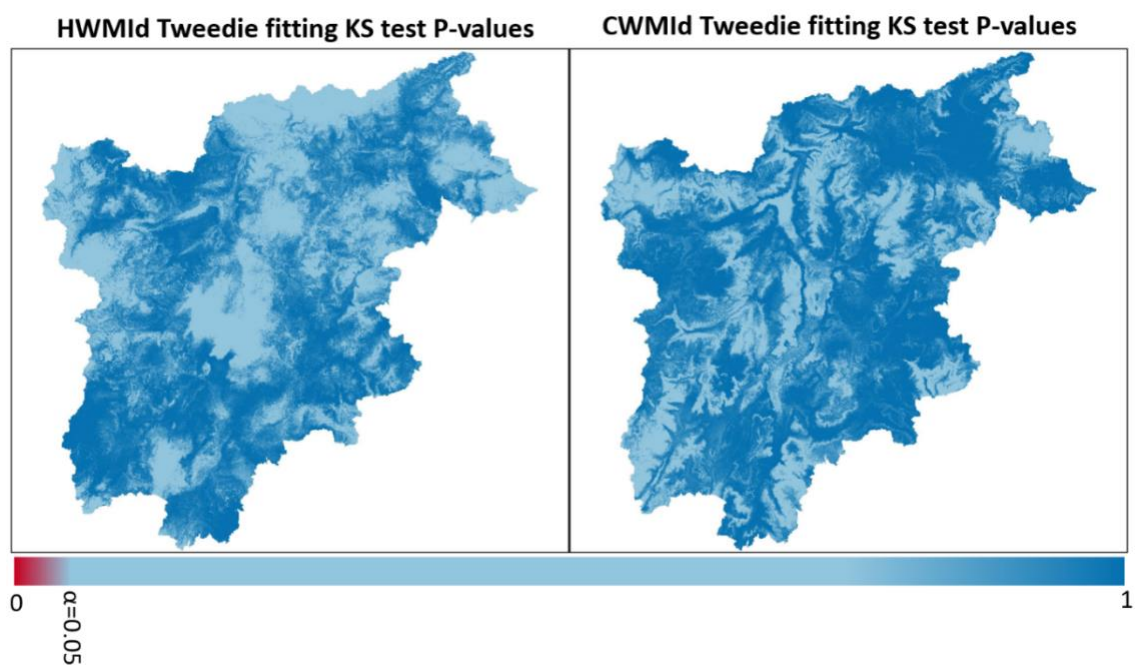
De Angelis, A., Ascione, F., De Masi, R. F., Pecce, M. R., and Vanoli, G. P.: A Novel Contribution for Resilient Buildings. Theoretical Fragility Curves: Interaction between Energy and Structural Behavior for Reinforced Concrete Buildings, *Buildings*, 10, 194, <https://doi.org/10.3390/buildings10110194>, 2020.

Magnani, N., Carrosio, G., and Osti, G.: Energy retrofitting of urban buildings: A socio-spatial analysis of three mid-sized Italian cities, *Energy Policy*, 139, 111341, <https://doi.org/10.1016/j.enpol.2020.111341>, 2020.

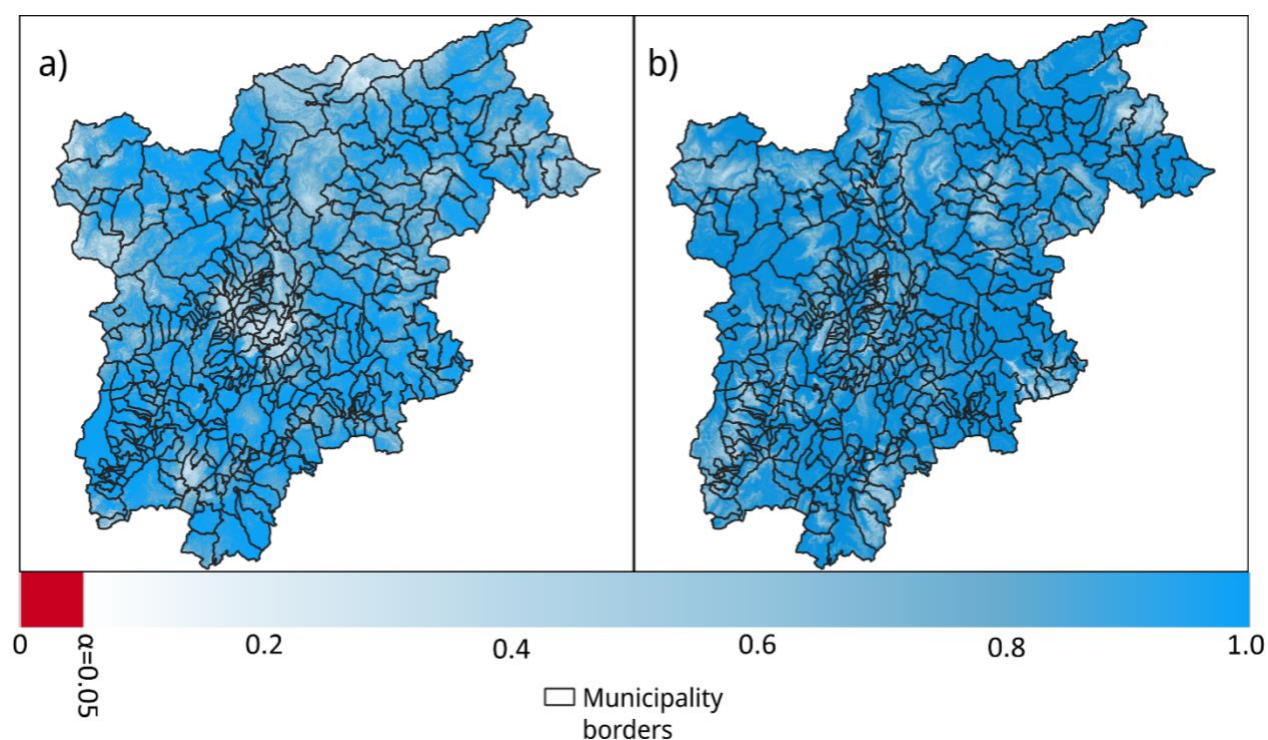
Mukati, A.: Effect of Heatwaves on the Cooling Demand of Austrian Residential Buildings, 2021.

5. Figure S-3: I wonder whether it would make sense to add the borders of the municipalities/districts shown in Figure 4 also to this figure. Moreover, I would suggest to use a linear color scale between 0.05 and 1 and add more ticks to the colormap (not just 0, 0.05, and 1)

The figure was remade to account for the reviewer comment. The old figure was:



the new revised figure is.



6. Figure 4: I think it would be good to add a figure (or a subplot) that shows the evolution for the four cities as it is impossible to identify them and to see their changes just from the maps. Also, what do the black borders in the figures depict? Is it municipalities or districts? This should be added in the caption.

We thank the reviewer for the comment we created a new figure and placed in the supplementary material according to the suggestion. The new added figure is:

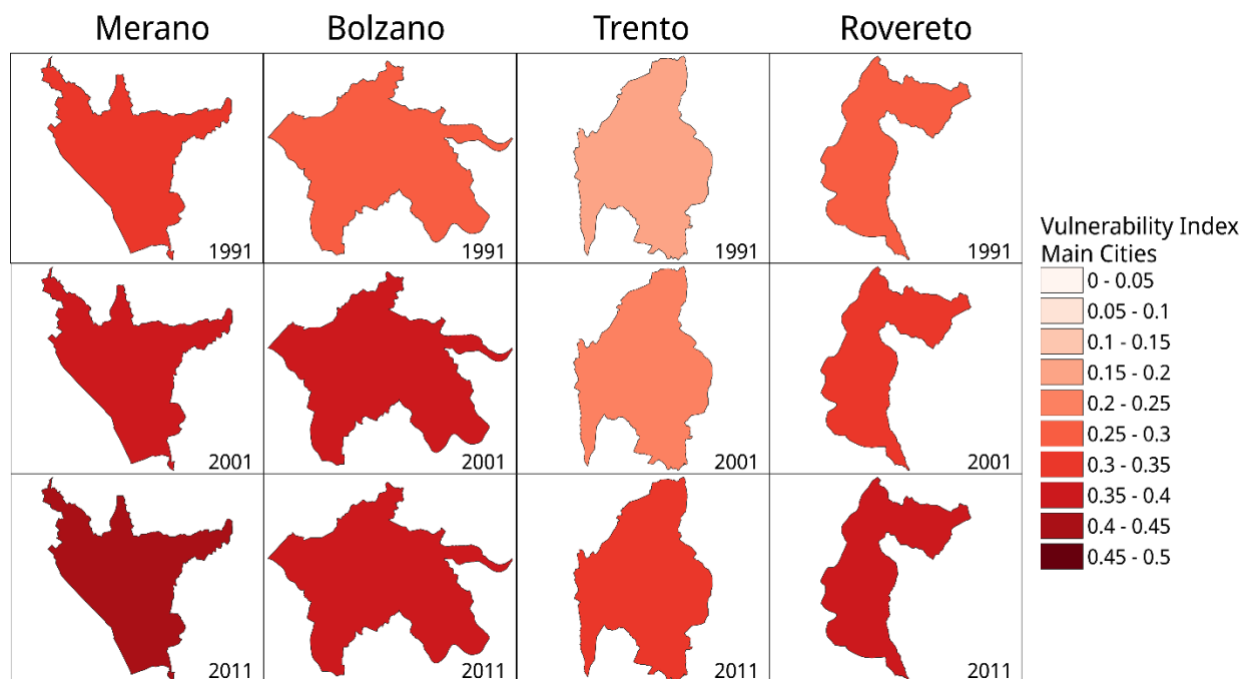


Figure S5: Evolution of the vulnerabilities of the 4 large cities of the region (Merano, Bolzano, Trento and Rovereto).

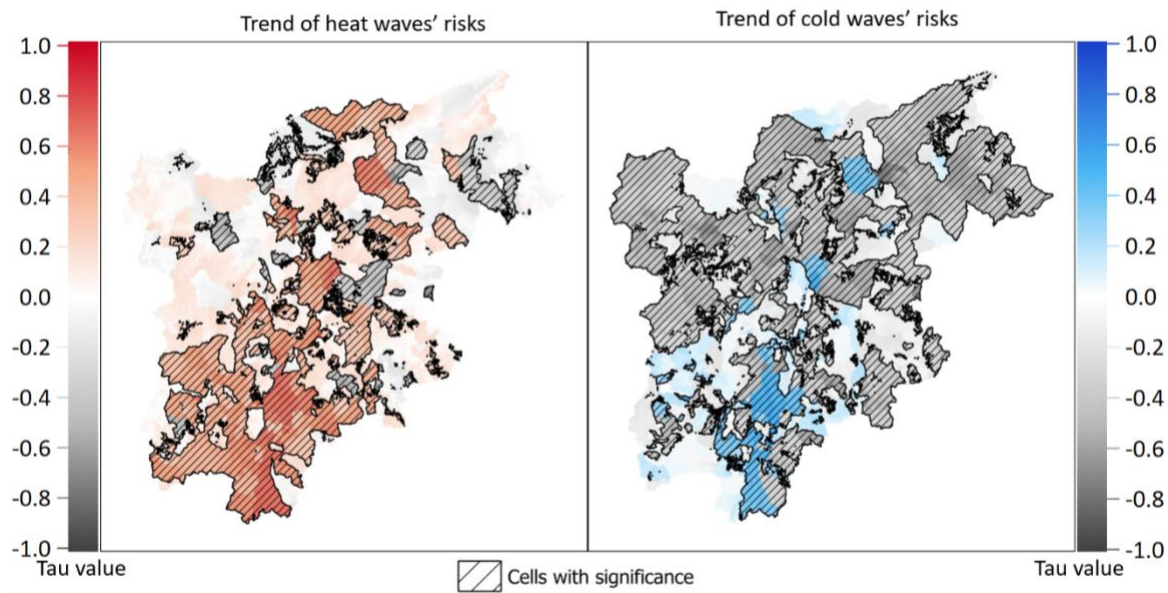
Moreover, the black borders are municipality, and this was added in the caption of the revised figure. The old caption was Figure 3: Calculated vulnerability index for the three years of the census records (1991, 2001, 2011)

The new caption is:

Figure 4: Calculated extreme temperatures vulnerability index for the three years of the census records (1991, 2001, 2011) with the borders of the municipalities in black.

7. Figure 5: The trends are difficult to see due to the many hatching lines. I would suggest having only fewer hatching lines (like in Figure 2). Also, how is it possible to see that a trend is positive or negative? (the tau values are positive both for HWs and CWs). Like for Figure 4, I'd suggest adding a separate panel showing the results for the four cities.

The Figure was remade, the cities were added directly on it and are visible. The old figure was:



The new figure is:

