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 significancy evaluation by using the FDR methodology.

Answers to the Reviewer 1

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.

General comments

The paper presents a 38-year quantification of the risks from heatwaves (HW) and coldwaves (CW) in the region of Trentino-Alto Adige in Italy. In precise, the authors try to quantify hazard, exposure, and vulnerability from HW and CW using the Heat Wave Magnitude Index daily/Cold Wave Magnitude Index daily, the Tweedie zero-inflated distribution, high-resolution maps of the population, and a set of eight socioeconomic indicators. They claimed that this new method for the calculation of human risk from HW and CW is applicable to other regions. The manuscript has an important aspect as it offers an additional contribution to understanding the spatio-temporal risk of HW / CW. Although, I have several comments on the methodology and the presented results. In general, the level of discussion is almost minimal, while most of the statements are too often very general, missing any proper citation and profound discussion that would put their results in a comparative context. My impression is that the paper is incomplete and can be improved. I, therefore, recommend that the paper goes a major revision, and the authors need to respond to the issues I list below before the paper can be accepted for publication in NHESS

We thank the Reviewer for the valuable and constructive feedbacks, which have been very much appreciated. The paper has undergone the suggested major revision in which all the suggestions have been included. Please see below the one-to-one answers to the reviewer comments.

Main comments

1. The abstract is very extended. It must be much shorter including only the key points of the manuscript.

Thank you for your feedback on this, it has been shortened and the key points are better highlighted.

The old abstract is:

Heat waves (HW) and cold waves (CW) can have considerable impact on people. Mapping risks of extreme temperature at local scale accounting for the interactions between hazard, exposure and vulnerability remains a challenging task. In this study, we quantify human risks from HW and CW at high resolution for theTrentino-Alto Adige region of Italy from 1980 to 2018. 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. We find a statistically significant increase in HW hazard and exposure, with 6.0-times more people exposed to extreme heat after 2000 compared to the last two decades of the previous century. CW hazard and exposure remained stagnant over the studied period in the region. 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. HW risk has risen practically everywhere in the region, indicating that the reduction in vulnerability in the smaller communities is outpaced by the increase in HW hazard. In the large cities, HW risk levels in the 2010s are 50% larger compared to the 1980s due to the rise in both hazard and vulnerability. Whereas in smaller communities, stagnant CW hazard and declining vulnerability results in reduced CW risk levels, the risk level in cities grew by 20% due to the increased vulnerability over the study period. The findings of our study are highly relevant for steering investments in local risk mitigation measures, while the method can be applied to other regions that have detailed information on hazard, exposure and vulnerability indicators.

The revised version abstract is below:

Heat waves (HWs) and cold waves (CWs) can have considerable impact on people. Mapping risks of extreme temperature at local scale accounting for the interactions between hazard, exposure and vulnerability remains a challenging task. In this study, we quantify risks from HWs and CWs for the Trentino-Alto Adige region of Italy from 1980 to 2018 at high spatial resolution. We use the Heat Wave Magnitude Index daily (HWMId) and the Cold Wave Magnitude Index daily (CWMId) as the hazard indicator. 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.

We find a statistically significant increase in HWs hazard and exposure while CWs hazard remained stagnant in the analyzed area over the study period. A decrease in vulnerability to extreme temperature spells is observed trough the region except in the larger cities where vulnerability has increased. HWs risk increased in 40% of the region, with it being stronger in highly populated areas. Stagnant CWs hazard and declining vulnerability result in reduced CWs risk levels, with exception of the main cities where it grew due to their increased vulnerabilities and exposures.

The findings of our study are relevant to steer investments in local risk mitigation, and this method can potentially be applied to other regions that have similar detailed data.

2. I would propose a reconstruction of the introduction. It does not have coherence, especially when going from one paragraph to another, and it is extended compared to the other sections. The novelty of the study is not being appropriately highlighted. Concerning novelty, the authors could also emphasize the advantages of applying specifically the form of Tweedie for the zero-inflated distribution. The limitations of this method should be accounted and properly included in the manuscript.

Thank you for your suggestion on this, your constructive feedback has been taken into account, the introduction has been shortened and has been rearranged with a better emphasis on the point mentioned. The Introduction of the revised paper is structured as follows:

1) importance of HWs and CWs from a global to the local scale
2) definition of the HWs and CWs risk as product of hazard, exposure, and vulnerability
3) how the single risk components have been computed in different studies and what are the main challenges in defining them as well introducing Tweedie as a possible solution to one of these challenges, i.e., accounting for zero inflation.
4) The need to move to a high-resolution risk analysis and goals and objectives of our study

The advantages and limitations of using a tweedie methodology has been highlighted as well and is present both in the introduction as well as in the new limitation section of this study. This has been done with the following new sentences:

The main advantage of the Tweedie distribution is the possibility of considering many distributions for the continuous and semi-continuous domain such as: normal, Gamma, Poisson, Compound Gamma-Poisson, and Inverse Gaussian (Bonat and Kokonendji, 2017; Rahma and Kokonendji, 2021; Shono, 2008; Temple, 2018). Moreover, for some of these distributions (i.e. Poisson mixtures of gamma distributions) it explicitly enables the fitting of zero-inflated data. Tweedie distribution main limitation is the complex distribution's fitting methodology and the difficulties to compare it to other models via information criteria such as the Akaike's information criterion (Shono, 2008)

3. Lines 153-160. The used gridded temperature dataset includes uncertainties due to the interpolation of the observed data. Have the authors considered how these uncertainties may impact the results of their study?

We thank the editor for the comment. We added into the revised paper a more detailed description of the interpolation methods that Crespi et al. (2021) used and a quantification of the errors they obtained in a leave one out cross validation framework. The new sentence is reported here:

"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)."

Although the dataset is based on a state-of-the-art approach and the errors found in cross validation as relatively small, we added a new sentence in the conclusion section of the paper where we underline the importance of reducing the uncertainty in interpolating temperature data in orographically complex area. The new sentence is reported here:

"The hazard analysis presented in this paper rely on the Crespi et al. (2021) air temperature database. Although it is based on a state-of-the-art interpolation approach and it represents the best product for the area, more attention should be given to measuring meteorological variables in orographically complex area and at high elevation. This will in turn reduce the uncertainty in spatial interpolation and improve the quantification of impacting hazards such as HWs and CWs."

4. In line 165, it is not clear how the cumulative indices are calculated and how someone can interpret these indices. I assume that the HWMId is the sum of the daily magnitude of the most severe heatwave in each year, something that is not clear in the manuscript.

We thank the reviewer for the comment. We have re-organized the section of the hazard definition according to the reviewer suggestions. Moreover, we also gave a practical example to explain what the index value means. The new sentence is:

"To quantify the hazard we used the HWMId (Russo et al., 2015) and the CWMId (Smid et al., 2019). These indices represent a way of measuring extreme temperature events while considering their durations, intensity, and taking in account the site-specific historical climatology (30years).

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. The magnitude of a HW is the sum of the daily heat magnitude $\mathrm{HM_d}$ of all the consecutive days composing the HW (Equation 1):

$$\mathrm{HM_d}(\mathrm{T_d}) = \begin{cases} \dfrac{\mathrm{T_d} - \mathrm{T_{30y25p}}}{\mathrm{T_{30y75p}} - \mathrm{T_{30y25p}}} & \text{if } \mathrm{T_d} > \mathrm{T_{30y25p}} \\ 0 & \text{if } \mathrm{T_d} \leq \mathrm{T_{30y25p}} \end{cases} \tag{1}$$

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). The interquartile range (IQR, i.e. the difference between the T_{30y75p} and T_{30y25p} percentiles of the daily temperature) is used as the heatwave magnitude unit and represents a non-parametric measure of the variability of the temperature timeseries. Therefore, a value of $\mathrm{HM_d}$ equals to 3 means that the temperature anomaly on day d with respect to T_{30y25p} is 3 times the IQR. Finally, for a given year HWMId corresponds to the highest sum of magnitude (HMd) over the consecutive days composing a heatwave event (with only days with HMd > 0 considered). Analogously to the HWMId, CWMId is defined as the minimum magnitude of the CWs in a year (Smid et al., 2019). A CW occurs when the air temperature is below a daily threshold for more than three consecutive days. The threshold is set to the 10th percentile of the temperature data of the day and the window of 15 days before and after throughout the reference period 1981-2010.

The daily cold magnitude corresponds to (Equation 2):

$$\mathrm{CM_d}(\mathrm{T_d}) = \begin{cases} \dfrac{\mathrm{T_d} - \mathrm{T_{30y75p}}}{\mathrm{T_{30y75p}} - \mathrm{T_{30y25p}}} & \text{if } \mathrm{T_d} < \mathrm{T_{30y75p}} \\ 0 & \text{if } \mathrm{T_d} > \mathrm{T_{30y75p}} \end{cases} \tag{2}$$

where $CM_d(T_d)$ corresponds to the cold daily magnitude, T_d the daily temperature and T_{30y25p} and T_{30y75p} correspond to the 25th and 75th percentile yearly temperature for the 30 years used as a reference. 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 <T 0, its absolute values are retained for its values to be on a positive interval (similar to HWMId)."

5. Line 215. What are exactly the outcomes of the Tweedie distribution? I assume it is only the return period. Please be more clear in the manuscript.

We thank the reviewer for the question. We add a new section where we specify the outcomes of the Tweedie distribution and the functions we used in the paper. This is connected to the next comment (6). The new sentence is:

“It provides distribution density, distribution function, quantile function, random generation for the Tweedie distributions. The Tweedie parameters (i.e. mean, power, and dispersion) have been estimated by the “tweedie.profile” function (Dunn, 2015) using the maximum likelihood as described by Dunn (2015) and Dunn and Smyth (2005).”

6. Lines 213-219. These lines need more analysis as they are essential for the computation of the return period. Also, the authors must include abbreviations for the legends in the Fig S-1

We thank you for the suggestion. We added the following new section to specify better how we fitted the Tweedie distribution and performed parameter estimation:

“It provides distribution density, distribution function, quantile function, random generation for the Tweedie distributions. The Tweedie parameters (i.e. mean, power, and dispersion) have been estimated by the “tweedie.profile” function (Dunn, 2015) using the maximum likelihood as described by Dunn (2015) and Dunn and Smyth (2005).”

Further we modified the figure S1, shortening the legends as requested by the reviewer and being more explicit in the caption to clarify the abbreviations used in the figure.

Old figure and caption:

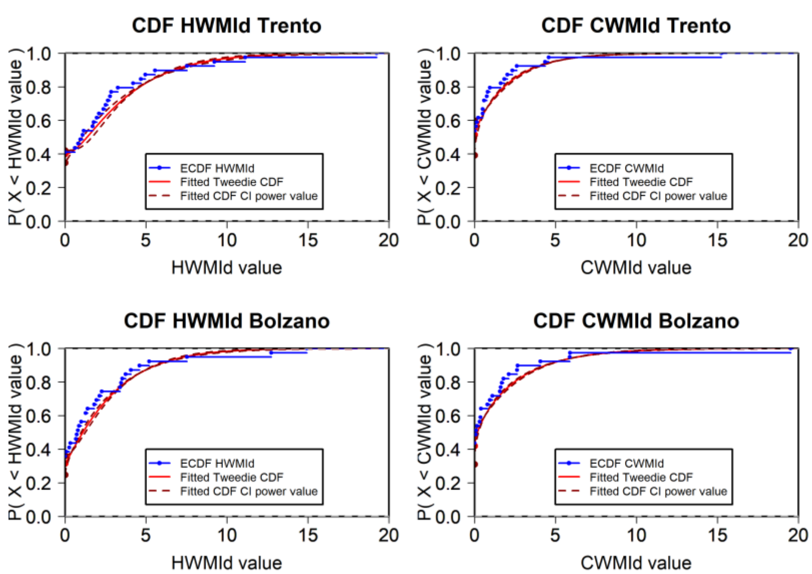

Figure S - 1: Cumulative distribution functions for both HWMId / CWMId at the location of the cities of Bolzano and Trento

The new figure and the new caption is reported below:

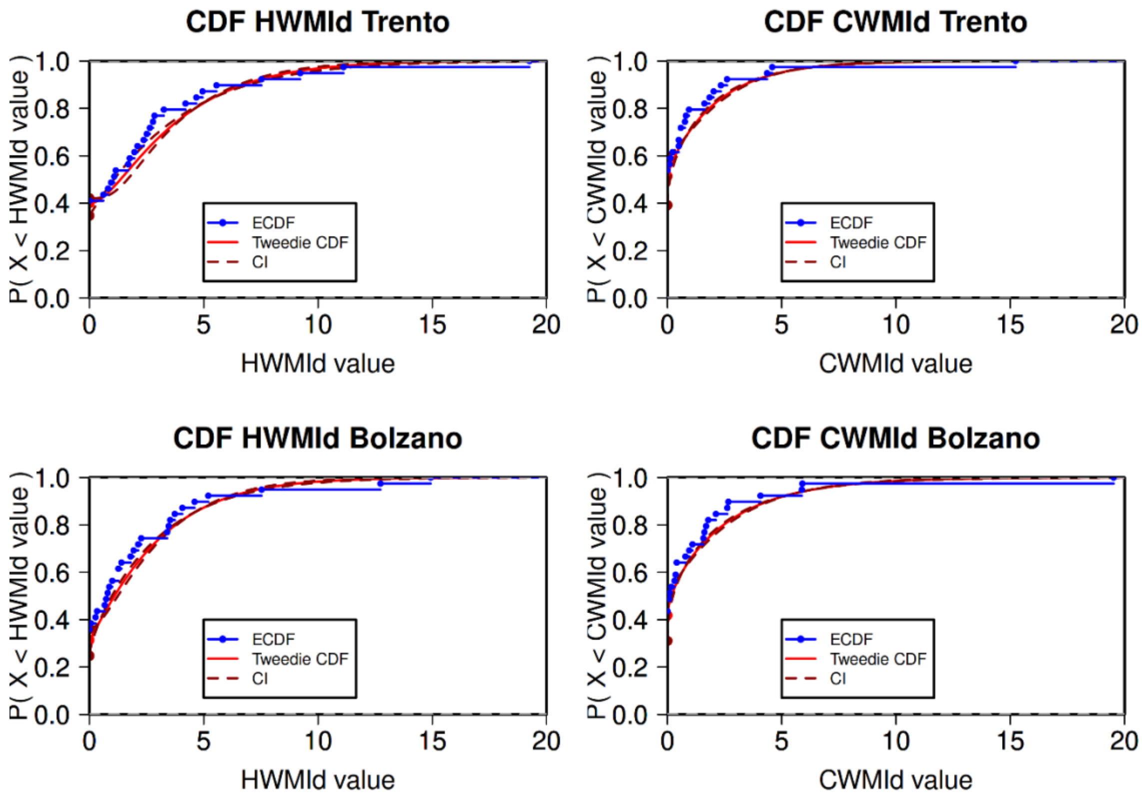

Figure S2: Cumulative distribution functions (CDF) for both HWMId / CWMId at the location of the cities of Bolzano and Trento, displaying the probability (P) showing the empirical cumulative distributions (ECDF) for these locations as well as the confidence interval (CI) of the power value of the Tweedie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

7. Lines 218-219. Why have the authors chosen to keep only 5 and 10 return periods? Most extreme episodes may fall into a higher return period (e.g. 20 or 30 return years)

We thank the reviewer for the comment. We choose 5 and 10 years return period for accounting of both the length of the analyzed return period (39 years) and the type of hazards we are analyzing (the HWs and CWs usually doesn’t occur every year). Higher return periods estimations could be affected by higher extrapolation effects and more uncertainty.
We add the following sentence in the paper to clarify this point. The new sentence is:

“This choice aims to account for of both the length of the analyzed period (39 years) and the type of hazards we are analyzing (HWs and CWs usually doesn’t occur every year). Higher return level estimations would be affected by extrapolation effects and higher uncertainty.”

8. In line 253, the authors claim that the vulnerability is computed only for precise years while exposure has been calculated for each year. In line 275 the authors said that the computation of the risk was made based on the closest year. This limitation must be highlighted in the results (line 370 and further). Also, why the authors have chosen to use the “closest year” and not to interpolate the data?

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."

9. Line 280. This section must be divided into subsections in an organized structure in order to be more clear and effective when presenting the findings of the paper. Also, the discussion section must be clearer in order to defend your research and to emphasize the significance of your research.

We thank you very much for this constructive feedback. To properly respond to this suggestion, we have re arranged the structure of the paper. We subdivided the results section in four specific subsections: 4.1) Hazard quantification and trends 4.2) Population exposure 4.3) Vulnerability quantification and 4.4) Risk quantification.

Finally, the discussion section has been separated from the result section and deeply reviewed to better emphasize as per the reviewer's comment. The new discussion section is:

The years found with the greatest HWs for the region agree with those of Russo et al. (2015), who found very high HWs in 1983, 2003 and 2015 in their analysis of the ten greatest HWs in Europe since 1950. The fact that four of the six largest HWs occurred in the last decade suggests that climate change is already influencing the intensity and frequency of HWs in the Trentino Alto-Adige region. With regards to CWs, Jarzyna & Krzyżewska, (2021), have also found cold spells in the years 1985 and 2012 using different methodologies for other locations throughout Europe. Similarly, other studies have found 1985 to be a year of an exceptional CW in Europe (Spinoni et al., 2015; Twardosz and Kossowska-Cezak, 2016).
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 Acquaotta 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). The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016).

The two driving factors behind the increase in vulnerability (elderly population and isolation) have also been found as some of the main factors for vulnerabilities in other regions of Europe (López-Bueno et al., 2021; Poumadère et al., 2005). 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.

Our findings related to the increase in HWs risks are consistent with Smid et al., (2019), which showed an increase of risk in both current and the future period for European capitals; the same study highlights a future decrease in CWs risk for these same cities. We found that CWs risk is still increasing for the main cities of our study. This is also the case for other cities in mountainous regions, such as highlighted by López-Bueno et al. (2021) for the city of Madrid, where the urban area was found to be the more at CWs risk compared to the rural area.

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).

Specific and minor comments:

1. Please insert the proper citations in lines 71-72.

Thank you for the comment. We added the new references. The old sentence in the paper 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 revised sentence reads:

"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)."

2. Line 76: Is there an advantage to defining hazards by return period? Please add the information at the introduction or the methodology section.

We thank the reviewer for the question. We used the return period because it is a standard way to express extreme events intensity. The main novelty is that for the first time, we used the Tweedie zero inflated distribution to quantify the cumulative distribution function of the HWMId and CWMId, which are indeed zero inflated data.

3. There is a piece of misleading information in the citations in lines 136 and 162

We thank the reviewer for the comment. The sentence has been modified according to the reviewer's suggestion and is now consistent:

Old sentence: "The quantification of the hazard and its return period will be performed using the Heatwave magnitude index HWMId and its cold wave counterpart CWMId (Russo et al., 2014, 2015) "

New sentence:

1) Quantify HWs and CWs hazards and their return level at a very high spatial resolution (250m) by combining for the first time i) the indicators proposed by Russo et al., (2015) and Smid et al., (2019), together with ii) the Tweedie distribution;

4. Line 178. Please revise the sentence

We thank the reviewer for the suggestion. We revised the sentence according the reviewer suggestion. The new sentence has to be read in the context of the answer to the general comment 4.

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

The new sentence is:

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

5. Lines 189-190. Please revise the sentence

We revised the sentence according to the reviewer’s suggestion.

Old sentence:

“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.”

New sentence:

“CWMId being always lower than zero, its absolute value is retained for its values to be on a positive interval (similar to HWMId).”

6. Lines 235-237. Please clarify better this sentence

We revised the sentence according to the reviewer’s suggestion.

Old sentences: “Following recent studies (King and Harrington, 2018; Russo et al., 2019), for each year of the time period a pixel is considered exposed if the HW/CW hazard (measured by HWMId or CWMId) is greater than zero or a specified return level value. For that year, the population exposed in the region is the sum of all exposed pixels in the region. The percentage of population exposed is obtained dividing the population exposed by the total population in the region at that time. The results for the percentage of population exposed are calculated on annual basis over the study period (1980-2018).

New sentences:

Following recent studies (King & Harrington, 2018; Russo et al., 2019), for each year, a pixel is considered exposed to HW/CWs hazard (or to a 5 or 10 year return-period HWs/CWs) if for that year the HWMId/CWMId of the pixel is greater than zero (or greater than the corresponding return level HW5Y/CW5Y or HW10Y/CW10Y, respectively).This is the exposition factor, and it is a binary value (0 meaning not exposed or 1 meaning exposed). The percentage of population exposed are calculated on annual basis over the study period (1980-2018) with the help of population data linearly interpolated from 1980 to 2018.

Using this population data, percentage of population exposed are then calculated using the following equation (Equations 5 and 6):

$$Population\ exposed(t) = \sum_i EF_i * \ population_i(t)$$

(5)

$$Percentage\ of\ population\ exposed\ (t) = \frac{Population\ exposed(t)}{Total\ population\ (t)}$$

(6)

where i corresponds to the pixels, t to the year being analyzed, EF to the exposition factor mentioned above (binary).

7. Line 255. Please elaborate on this

We thank the reviewer for the suggestion. We extended the sentence and modified it according to the reviewer's comment.

Old sentence:" The methodology to quantify vulnerability uses the equal weight analysis (EWA, e.g. Liu et al, 2020)"

New sentence:

"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:

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

(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)."

8. Line 269. It is not clear in the manuscript how the hazard is defined

We revised according to the reviewer suggestion.

The old sentence was:

"Hazard is the probability of HWMId/CWMId derived from the Tweedie distribution"

The new sentence is:

"The hazard is computed as the probability of occurrence of HWs/CWs by using the fitted Tweedie distributions probability function for each pixel."

9. Line 282. Why have the authors chosen the median and not the mean for the intensity of the HW?

The median was chosen to avoid the possibility of a particular high or low intensity area affecting the overall result.

10. Line 343. The authors must comment on the uncertainty in increasing and decreasing values found for vulnerability. Also, they must highlight that these trends are not statistically significant.

We thank the reviewer for the suggestion we added the following sentence to the discussion section:

The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016).

11. Fig 4. The vulnerability is calculated for hw or cw?

The vulnerability is calculated for extreme temperatures so both hw and cw Several other studies used the same approach, see for example the methodology used in Nwoko (2016) and Török et al. (2021).

Nwoko, D. S. V. I. for E. T. R. in N.: Developing social vulnerability index for newcastle extreme temperatures, Msc Thesis, Durham University, 68 pp., 2016.

Török, I., Croitoru, A.-E., and Man, T.-C.: Assessing the Impact of Extreme Temperature Conditions on Social Vulnerability, Sustainability, 13, 8510, https://doi.org/10.3390/su13158510, 2021.

12. Line 413. “HW have occurred more frequently and have become more intense”. This sentence is not properly justified in the results section.

We agree with the reviewer comment, and we rephrased the sentence.

The sentence old sentence was: HW have occurred more frequently and have become more intense.

The new sentence is: “HWs, i.e. HWMId>0, (and extreme HWs, i.e. HWMId>HW5Y) showed increasing trends in most of the region, with 98% (70%) being statistically significant.”

13. Line 417. Please rephrase in order to highlight the limitations of this result

We thank the reviewer for the comment. In the new revised paper this part have been moved in the discussion section and it has been rephrased according to this comment.

The old sentence was:

“In general, vulnerability is decreasing over time in the Trentino Alto-Adige region. However, in the larger cities of the region, vulnerability is increasing due to an ageing population and more single households. It should be noted that the socioeconomic indicators of vulnerability are only available for three points in time, which does not allow to do a proper trend analysis of vulnerability”

The new sentence in the discussion section is:

“The trends in vulnerability and their absence of statical significance strongly depend on the available data. In our case they are the output of specific national census carried out every ten years and aggregated at the city spatial scale. From the other side, these data represent a freely available option to quantify the vulnerability to natural hazards, which is a crucial component for the risk quantification (e.g. Formetta and Feyen, 2019, Frigerio & De Amicis, 2016)."

14. Line 428. Why "will be exposed"? This work is not a future projection analysis

We revised the sentence according to the reviewer suggestion. The old sentence was:
"The findings of this work shows that municipalities and cities in the Trentino Alto-Adige region, but likely also in many other regions, will be exposed especially to more frequent and intense heat, while potentially still experiencing the same levels of cold wave hazard"
The revised sentence is:
"The findings of this work shows that municipalities and cities in the Trentino Alto-Adige region have been seen increasing trends in HWs risk over the timeframe 1980-2018, while potentially experiencing the same levels of CWs risk."