Dear Dr Fuchs et al,
It was my pleasure to review this manuscript, which is well-written, interesting, and covers an important topic. The manuscript describes the first known multi-hazard exposure assessment using building-level data, and offers sufficient detail to allow replicating in other geographies where such data exists.
Whereas the methodologies to assess changing exposure using building-level data are not fully novel, the new case study and multi-hazard perspective justifies the research and publication thereof. Although I therefore feel that this paper should eventually be published, there are a number of shortcomings in the current version that need to be addressed before publication. The comments are a mix of major and minor issues, with some specific minor details at the end.

Dear Dr Jongman,
We kindly would like to acknowledge your detailed and insightful comments on our manuscript. In the following we will answer these comments as well as your concerns and suggestions step-by step. In red, you will find comments while in blue we included suggestions to improve the current version on the manuscript. Once the NHESSD interactive discussion is closed by the Editor, and we will have the permission to revise the manuscript, these parts will be used to improve the manuscript.

- Page 2421, L11-13: Looking at the 10-year average (grey line) in Figure 1, I can only see this decrease for the period 1975 – 2000 (instead of 1960-2000), and the trend jumps back up after 2000 to higher levels than ever seen before (as the authors briefly note later). I would suggest to be more nuanced about this temporary decline and any implications it would have for the effectiveness of disaster risk reduction measures.

This suggestion is absolutely understandable since so far the description is a bit narrow. In a revised version we will shift this statement to a more detailed comment, see below.

> In Fig. 1, the annual number of damage-causing mountain hazards occurring in the Eastern European Alps (Republic of Austria) is shown. The underlying event documentation focused on the hazard processes but no further detailed information on individual losses is provided. The data for the period 1900-2014 is describing snow avalanches, torrential flooding, landslides and river flooding, as well as the 10 years moving average of the total amount per year. While between 1900 and 1959 an increase in the annual number of hazard events of around a factor of four can be concluded – presumably also due to an increased event observation – between 1960 and 1964 a decrease of around 50 % is traceable, followed by an increase due to the excessive events in 1965 and 1966. Since then, the 10 years moving average is steadily decreasing again, which is in line with the increasing efforts into technical mitigation measures since the mid-1960s (Holub and Fuchs, 2009). Due to the high number of events in 1999, 2002, 2005 and 2009, however, the curve is again increasing to around 440 events per year. This shape is in clear contrast to the trends repeatedly shown for world-wide data and indicating an exponential increase in the number of events since the 1950s (e.g., Keiler, 2013). Apart from hazard dynamics (the natural frequency and magnitude of events), decreasing dynamics in mountain hazard losses may result from (a) increased efforts into technical mitigation (Keiler et al., 2012), (b) an increased awareness of threats being consequently considered in land-use planning (Wöhrer-Alge, 2013; Thaler, 2014), both leading to less exposure, and (c) a decline in vulnerability (Jongman et al., 2015) which will not be further considered in the following sections. During the period of investigation, specific years with an above-average occurrence of individual hazard types (…)

- Page 2421, L26: what about spatial and temporal dynamics of vulnerability? I understand quantifying this is more difficult, but it should at least be mentioned. See e.g. Mechler and Bouwer (2014) and Jongman et al. (2015) for recent studies on the global scale and some references to more local studies.

We will include this statement in the previous comment since the focus of the manuscript is not explicitly on the dynamics of vulnerability.

> Apart from hazard dynamics (the natural frequency and magnitude of events), decreasing dynamics in mountain hazard losses may result from (a) increased efforts into technical mitigation (Keiler et al., 2012), (b) an increased awareness of threats being consequently considered in land-use planning (Wöhrer-Alge, 2013; Thaler, 2014), both leading to less exposure, and (c) a decline in vulnerability (Jongman et al., 2015) which will not be further considered in the following sections.

Moreover, Fig. 1 shows the annual number of hazardous events in Austria which were documented because they caused any kind of damage (infrastructure, buildings, citizens, agricultural land, etc.). Nevertheless, the data does not allow for any further detailed information on loss generation, which in turn does not allow for a sound deduction of vulnerability patterns. We will change the Figure caption to:

> Figure 1. Annual number of documented mountain hazard events causing damage. (…)

- The introduction is not fully clear on the scope of the paper. Is it to produce an accurate understanding of building-level exposure in Austria; or rather the methodological advance of using building level data for national level exposure assessment; or both? If it is the first, the introduction should include a few more lines outlining the current knowledge regarding exposure in Austria, the methods applied in those study, and the precise gaps that the authors see. If it is the latter, the authors should more clearly indicate how the approach relates to earlier such analyses. In the current version of the Introduction, the authors say (Page 2422, L27): "Because of the limited data availability, comprehensive object-based and therefore spatially explicit analyses have thus not been extended beyond the regional level". Only in the conclusions do the authors write that "The presented method together with the results may be used for similar assessments in other European countries, such as already available for the Netherlands (Jongman et al., 2014), and beyond, in order to get a more precise over view on exposure and possible losses." Similar studies as indicated here should be discussed in the introduction, and used to put this new study in context, to better highlight the innovation.

We agree and will provide a clearer and more accessible introduction in the revised version. The scope of this paper is to produce a nation-wide understanding of object-based exposure in Austria based on the recently available data set on buildings within the country. Moreover, temporal and spatial dynamics will be discussed.

> Focusing on exposure, the effectiveness of natural hazard risk management depends on the availability of data and in particular an accurate assessment of elements at risk (Jongman et al., 2014), which also requires a temporal and spatial assessment of their dynamics. It has been repeatedly claimed with respect to flood hazards in Europe that the main driver of increases in observed losses over the past decades is increased physical and economic exposure (Bouwer, 2013; Hallegatte et al., 2013; Jongman et al., 2014). Until now, however, in mountain regions of Europe such conclusions remain fragmentary since property data has only been available on the local scale as a result of individual case studies. These – often conceptual – studies related to the temporal dynamics of exposure to mountain hazards include both the long-term and the short-term evolution. Long-term changes were found to be a result from the significant increase in numbers and values of properties endangered by natural hazard processes, and can be observed in both rural and urban mountain areas of Europe (Keiler, 2004; Fuchs et al., 2005; Keiler et al., 2006a; Shnyparkov et al., 2012). Short-term fluctuations in elements at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of people in endangered areas and of vehicles on the road network (Fuchs and Bründl, 2005; Keiler et al., 2005; Zischg et al., 2005). These results suggest that the spatial occurrence of losses is not so much dependent on the occurrence of specifically large

events with high hazard magnitudes but more a result of an increased amount of elements at risk in endangered areas (Fuchs et al., 2012). Most of the recent works, however, rely on local object-based studies (Zischg et al., 2004; Fuchs et al., 2012) or aggregated land use data (Bouwer et al., 2010; de Moel et al., 2011; Cammerer et al., 2013), leading to substantial uncertainties if up-scaled to a larger spatial entity (de Moel and Aerts, 2011; Jongman et al., 2012a). Because of the limited data availability, comprehensive object-based and therefore spatially explicit analyses have thus not been extended beyond the local level (Kienberger et al., 2009; Huttenlau et al., 2010; Zischg et al., 2013), and studies focusing on the national level in mountain regions using such data remain fragmentary (Fuchs et al., 2013).
To contribute to this gap, we show how detailed property level data can be used to improve the understanding of trends in hazard exposure on a national level. We will explicitly focus on dynamics in elements at risk, neglecting (a) any changes in the natural process dynamics due to underlying changes in the natural system including the effects of climate change, (b) any shifts in exposure due to the implementation of technical mitigation measures, and (c) any changes in vulnerability. This allows for the assessment of dynamics in property exposure, and will provide insights in the impact elements at risk may have on changing risk in mountain environments leaving other risk-contributing factors constant.

- Page 2423, L18: “Hazard maps usually refer to an individual community, and depict the area affected by a design event with a return period of 1 in 150 years (Republik Österreich, 1976).” The reader may understand that the underlying hazard data has been published 4 decades ago – is this the case? The authors should fully extend on the nature, source and year of production of the hazard data, as well as on the resolution, geographical coverage and other details. A map showing the various hazard layers would be very helpful. The quality of the hazard mapping should be incorporated throughout when interpreting the findings. How would the results change if other hazard data were used?

We will include this information in a revised version (see below). Nevertheless, due to the protection of privacy we are not supposed to show a detailed (local) map with red and yellow hazard zones. The readers may wish to have a look at eHORA where this data is shown in a more aggregated way.
The combination of hazard maps for mountain hazards and information from eHORA for river flooding is due to the fact that (a) for mountain hazards, no nation-wide modelling is available in Austria and (b) for river flooding, no nation-wide compilation of hazard maps is available since in contrast to mountain hazards river flooding lies within the competency of the individual Federal States. As a result, we cannot assess the results using “other hazard data”.

> Hazard information was compiled from two different sources. For mountain hazards, available local-scale hazard maps were used, and for river flooding, the results of a nation-wide flood modelling were available. This method of data combination was chosen because (a) for mountain hazards, no nation-wide modelling is available in Austria and (b) for river flooding, no nation-wide compilation of hazard maps is available so far since in contrast to mountain hazards, river flooding lies within the competency of the individual Federal States.
In Austria, the method for hazard mapping is regulated by a national legal act (Republik Österreich, 1975) and an associated decree (Republik Österreich, 1976). The implementation of these regulations is assigned to the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and administrated by the governmental departments of the Austrian Service for Torrent and Avalanche Control (WLV). Since the mid-1970s, these governmental departments had been progressively compiling hazard maps for the communities affected by mountain hazards based on available data and information on hazards as well as modelling exercises (Holub and Fuchs, 2009). These hazard maps are mostly compiled on a detailed local scale of 1:2,000 to 1:10,000 in order to decide whether or not individual plots are affected by the different hazard types. Hazard maps usually refer to individual catchments within individual communities, and depict the area affected by a design event with a return period of 1 in 150 years. So far, 92 % of all

communities with an obligation for hazard mapping in Austria do have a legally valid hazard map. According to the Decree on Hazard Zoning (Republik Österreich, 1976), red hazard zones indicate those areas where the permanent utilisation for settlement and traffic purposes due to the exposure to the design event is not possible or only possible with extraordinary efforts for mitigation measures. Yellow hazard zones indicate those areas where a permanent utilisation for settlement and traffic purposes is impaired by the design event. Red and yellow hazard zones of different catchments and multiple hazard types may overlap, and as a result elements at risk may be exposed to more than one hazard type (multi-exposure, Kappes et al. 2012a,b). While in some catchments there may be a temporal separation of processes (snow avalanches during winter and torrential processes in summer) affecting the same elements at risk, in other catchments there may be a temporal overlap of different processes occurring in the same period of time (debris flows from the tributary and flooding in the receiving channel, both affecting the same elements at risk). The available red and yellow hazard zones were provided digitally by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management in March 2013 in order to select exposed property.

- Similarly to the previous point, the relationship between the individual perils should be discussed in more detail. Are they mutually exclusive (i.e. flash floods do not happen in avalanche prone areas?) Any other innovative insights we can learn from this multi-hazard perspective?

As you may see from Tables 1-3, the perils are not “exclusive”, a certain amount of buildings is exposed to more than one hazard type (multi-exposure) which means that in some areas (depending on the geology, geomorphology, hydrology, etc.) flash floods and snow avalanches may occur in the same catchment, taking the same transit path and affecting the same run-out area. We will include a clarification in the revised version of the manuscript (see above).

- Page 2424, L5: In what sense is this data ‘unique in Europe’? Is it different from any other inundation model?

We will change the wording to avoid confusion. The uniqueness is related to the fact that Austria was one of the first countries to provide online information on river flooding exposure, based on a public-private partnership between the administration and the Austrian Insurance Association. Due to the implementation of the European Floods Directive, however, other European countries meanwhile have similar information available (e.g., ZÜRS in Germany and the assessment of the UK Environment Agency).

> For river flooding data from the digital eHORA platform (http://www.hochwasserrisiko.at/) was used. This platform provides information on the exposure to river flooding using web-GIS techniques, and has been jointly implemented by the Federal Ministry of Agriculture, Forestry, Environment and Water Management and the Austrian Insurance Association in terms of a public-private partnership on more than 25,000 of a total of 39,300 river kilometres (Stiefelmeyer and Hlatky, 2008). By using a hydrological model probabilistic runoff data for a 1 in 30, 100, and 300 year event was computed and converted into water levels and flood zones based on a nation-wide DEM and a digital slope model. Following an ongoing discussion on the harmonisation of hazard mapping in Austria (Rudolf-Miklau and Sereinig, 2009), the 1 in 100 year event was provided by the Austrian Insurance Association in terms of a vector representation of flood plain boundaries and taken for our analysis.

- Tables 1, 2, 3: it is not clear whether the data in these tables are the result of this research or based on existing data. The tables are included in the Results section, but their caption reads “[Exposure] according to the Federal States. Data source: Fuchs and Zischg (2013)”. How much of this table contains new findings, and how much presents existing knowledge? Please clarify and improve caption.

We will improve the captions accordingly. Even if the underlying preliminary but original study was done by Fuchs and Zischg (2013), the Tables in their present form contain new data and therefore we deleted this information.

> Tab. 1: Information on non-exposed buildings and buildings exposed to river flooding, torrential flooding and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposed buildings is given.
> Tab. 2. Information on non-exposed principal residents and principal residents exposed to river flooding, torrential flooding, and snow avalanches, aggregated on the level of Federal States in Austria. Additionally, information on multi-exposure is given.

- Page 2433, L8 onwards: the authors need to broaden the explanation of risk trends beyond exposure, here and throughout the paper. The losses in Figure 1 are of course resulting from the combination of hazard, exposure and vulnerability. The trend in exposed buildings will therefore never be the same as the trend in losses. How would changes in hazard (e.g. rainfall) over these years played a role and interacted with the increasing exposure? Any chance of adding some analytics (or suggesting how this can be done) in order to test the influence of exposure increase on losses?

In this work we analysed the spatial and temporal dynamics of exposure, neglecting any signal from climate change, natural hazard dynamics, and vulnerability (please see revised introduction section). This allows us to explicitly focus on changes in the building stock and to assess the influence of this data on the overall dynamics of natural hazard risk (please see revised conclusion section). In other words, we only compute Δ exposure in order to figure out the impact of this variable on the overall risk (just discussed in the conclusion since this is not the intention of this paper).

- The discussion and conclusion sections offer room for improvement in several aspects:
o The discussion section needs to gain a significant chunk of discussion surrounding the limitations of the data and methods used in this study. Limitations will include for example the detail and quality of hazard data used in this study (which as said, needs more explanation in the Methods section too); the negligence of building type affecting the actual exposure (mainly high rise apartment buildings vs low rise houses); the building construction year data (e.g. what happens with buildings that are destructed and rebuild during the time of analysis?); etc.

Thanks for your suggestions. We will re-write the discussion section in order to be clearer and to better link the introduction section with the identified gaps to the results. Nevertheless, the mentioned difference between building types (high rise vs. low rise apartments) is from our point of view related to the issue of different structural and physical vulnerability, which was excluded in this paper. A discussion on these issues can be found in our works related to vulnerability {e.g., \Totschnig, 2013 #4095; Totschnig, 2011 #3287}. Additional information on the hazard data will be provided in Section 2.1 (please see our remarks above and the revised section 2.1); and additional information on the building construction year data will be included in Section 2.2 (Methods).

> Since the implementation of the Federal Law related to the Building Register (Republik Österreich, 2009), municipalities in Austria are responsible for the collection and digital processing of specified information related to the entire building stock. This information is centrally stored in a database and contains information on the location and size of each building, as well as on the building category and the construction period (1919-2000) and year of construction (since 2001), respectively (Statistik Austria, 2012). The latter information is related to the existing building stock. However, even though a building will be destroyed, the information and property attributes will be stored in the database in order to provide a full overview on the construction history. Additional information related to the

individual floors, such as their height and net area, main purpose and configuration, is included for each property. (…)

o The conclusion section brings too many new facts, data and references. Many things never mentioned before in the paper (such as average annual fatalities because of the different hazards) are now mentioned here for the first time, which is in my view not the way a concluding section should be (which is, a conclusion of the findings based on facts in the results and discussion sections)

o I suggest the following to solve these issues (but feel free to solve them in another way):

▪ Change 'Results' into 'Results and Discussion', where you integrate a selection of the results-related discussion points from the current 'Discussion' section

▪ Add a new section 'Implications and limitations' (or similar), containing a selection of points from the current Discussion and Conclusions section

▪ Shorten the Conclusions section to contain only concluding remarks.

We will revise the results, discussion and conclusion sections in order to be more concise. Moreover, we will add some information on implications and limitations.

- Figure 3: I like these maps very much, from a visual perspective. However a few things are unclear in the current form:

o What is the difference between left and right figures? I assume one is number of buildings and the other economic value? This needs to be clarified.

o Just a suggestion: given that the differences between both indicators are so small (i.e. the difference between the left and right set of maps), for me it would be more interesting to see a set of figures showing the absolute number of buildings (or economic value) exposed to the hazards. E.g. have maps with the number of buildings exposed (absolute) on the left, and maps with the number of buildings exposed (deviation from the mean) on the right.

Thank you for sharing these thoughts. Together with the previous comments on exposed citizens we decided to exchange the set of maps right column) and to include information on exposed citizens. The additional data will then also be included in the results section.

- Figure 4 needs better caption and information in the figure. Right now it is unclear what the different panels are.

o E.g. what does panel e) indicate, and why does the exposure to flooding decrease here? Does this indicate that buildings are removed from the database, or got destructed?

o Also, the base year needs to be mentioned. At this point it is not clear what the factor change refers to.

o Why do the trends in panels c and e follow a step-wise pattern and the other figures a continuous flow? What exactly do they show differently, that would cause such different patterns? This is currently unclear to me, also after re-reading the text.

We will include some comments on these questions in the results section since obviously we did not manage to be precise enough.
Apart from the layout of Figure 4, which will be revised, we will also change the order of charts. Fig. (a) and (b) show the temporal development in terms of cumulative data, therefore the graphs are increasing (the number of buildings is increasing). Fig. 4 c will be converted in a new Figure 5 and separately discussed (also in the results section), we will also include the data on exposed citizens. Fig. (c) and (e) are based on averaged construction activities (the construction periods available in the dataset), and therefore the graphs are stepwise. We will also extend the Figure caption:

> Figure 4. Temporal development of building stock in Austria. In Fig. 4 (a), the cumulative absolute increase in the number of buildings is shown for non-exposed buildings and buildings exposed to snow avalanches, torrential as well as river flooding. In Fig. 4 (b), the relative increase of the building stock is shown for the total number of buildings and buildings exposed to snow avalanches, torrential as well as river flooding, 1919 = 1. In Fig. 4 (c) the average annual number of newly constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding. In Fig. 4 (d) [in the current version = 4 (e)] the annual number of newly-constructed exposed buildings versus the total number of newly-constructed buildings is shown for buildings exposed to snow avalanches, torrential as well as river flooding.

Minor comment: I suggest to change 'amount' of people/buildings/citizens/hotels to 'number on each occurrence (i.e. use amount for mass nouns and number for count nouns).

Thank you for this hint, we will change the wording accordingly.

References

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