Answer to Referee Comment #3

Thank you for your review and your suggestions that will improve the readability of the paper. Please find below a point-by-point answer to the comments you raised. Moreover, as suggested by Referee #2 and yourself, the structure of the paper will be rearranged. The suggested structure is presented p7 of this document.

Major revision points:

1) I suggest revising the structure of the manuscript. The current version sometimes jumps from one topic to another and sometimes back again (e.g., paragraph 65-87); some statements refer only to individual hazards (e.g., flooding), while the next sentence is a general statement.

My suggestion is the following structure: (i) Loss / risk model development from a historic perspective, including a detailed discussion of the three components (hazard, exposure, vulnerability); (ii) Uncertainty inherent in each of the components (e.g., uncertainty in hazard modeling due to a lack of appropriate observations and/over observation data over longer time periods is not mentioned); (iii) Possibilities/measures to reduce uncertainty, including past and future developments (e.g., numerical model simulations used in CAT models today); (iv) Perspectives: Challenges, further needs, and expected developments to address these needs (e e.g., role of crowd-sourced data).

Thank you for suggesting this structure for the paper. This will indeed bring more clarity and strengthen the link between the different topics.

I would propose the following modifications:

(i) Loss / risk model development from a historic perspective, including a detailed discussion of the three components (hazard, exposure, vulnerability);
- Include also details on how the transmission and the intersection of information from one component to the other is performed and is crucial in how uncertainty is propagated along the modelling chain
- Include details related to (re)insurance market

(ii) Uncertainty inherent in each of the components (e.g., uncertainty in hazard modeling due to a lack of appropriate observations and/over observation data over longer time periods is not mentioned);
- I would suggest addressing uncertainty at large, not focusing only on uncertainties inherent to the modelling. Uncertainties could be discussed along 3 axes:
  - Uncertainty driven by data quality and availability by component (exposure, hazard and vulnerability), some are inherent, some can be improved
  - Uncertainty caused by modelling assumptions and approaches
  - Uncertainty driven by the implementation in the loss modelling framework

(iii) Possibilities/measures to reduce uncertainty, including past and future developments (e.g., numerical model simulations used in CAT models today);
- I would suggest splitting this section into the (ii) and the (iv) sections as the past developments would be examples of observed and resolved uncertainties; and the future developments will be addressed as expected developments to meet identified limitations in current modelling.

(iv) Perspectives: Challenges, further needs, and expected developments to address these needs (e e.g., role of crowd-sourced data).
- Ok

2) Be more specific and give more details throughout the manuscript (see also minor points).

Agreed.

3) Loss/risk models are not appropriately described. In the hazard module, I miss the description of the (historic) event set, relevant parameters of the footprints/tracks (e.g., magnitude, width, length, orientation), and – based on this – stochastic modeling (indicated in Figure 1, but not mentioned in the text).

A description on the three components, as well as how the interconnexion is performed, will be added.

4) Refer to Solvency II and the need to assess probable maximum losses for 200-year return periods (PML200), as well as the need for a basic understanding of the models applied by the insurance companies.

Agreed, I will include this in the introduction, or the first section defined in comment 1. While Solvency 2 accelerated the use of natural hazard models within the insurance industry to evaluate the risk (i.e. focus on extreme losses at portfolio level), the challenge for the insurance industry is now to connect these models to their pricing tools, for which average loss at a building level is used.

5) Even though the insurance perspective is explicitly mentioned in the title, I miss a thorough discussion in the manuscript (see also point 1). Which perils are well represented by the models (and where), which are not? What are difficulties and challenges? What are new perspectives that might emerge in the future (e.g., role of machine learning / Big Data)? Some of these points are formulated as questions, but without providing answers or at least some hints (e.g., L109-111; L140-143).

Could you please precise the question "Which perils are well represented by the models (and where), which are not?"?

Do you mean how well are the perils represented in terms of hazard and frequency in the hazard component? or do you mean how well the perils are represented in terms of losses?

6) In the context of global change, the manuscript only mentions climate change (very briefly) and increased population/wealth. However, global change has several other implications, such as the energy transition with an increased share of renewables with other vulnerabilities (e.g., solar panels are very susceptible to hail), increased reliance on critical infrastructure, or societal changes. All these issues have the potential to significantly change vulnerability and risk.

I totally agree and will adapt the paper accordingly. I will also add details on the importance of prevention / protection measures in the reduction of the impact of natural hazards.

7) Section 5 is a summary rather than conclusions.

In the light of the suggested new structure, this section is no longer needed.

Minor revision points:

1. L4: the models assess both the risk of experienced events and not yet experienced

Is it an affirmation or a suggestion to rephrase? What do you mean by models assess the risk of experienced events?

2. L10: "protect clients' property and activities"; it's rather risk transfer than protection

Insurance protection goes beyond the financial aspect of the risk transfer (i.e. the payment of a premium by the policy holder against the payment of future claims by the insurance company); it also includes prevention actions such as increasing risk awareness and proposing adapted protective solutions. I suggest to develop this point in the paper by giving two examples:

1) For the commercial business (corporates' policy holders): technical risk experts perform on-site visits to evaluate buildings' conditions and identify potential vulnerabilities to natural hazards. The objective is to assess how natural hazards could generate damage either to the building itself (e.g. storage warehouse, data center, shopping centers) or to its contents (e.g. machineries, production chain, products' stock…), and if such damages could cause business interruption (e.g. employees / clients cannot access the building for 10 days leading to a loss of turnover or profits). Following such assessment, prevention measures are then suggested or imposed to reduce the risk (e.g. elevate goods or machinery in the case of a flood event or reinforce some key components of the building to reduce the impact of ground shaking).
2) For the retail business (individual policy holders) : in this case, as protection actions cannot be tackled individually because of the mass of clients, they are taken globally. For example, after the Great Fire of London in 1666 that destroyed most of the buildings of the City -made of wood at that time-, insurance premium rates were lowered for building made of brick in order to encourage the use of bricks instead of wood and therefore reduce the fire risk in London.

3. L16-19: maybe instead of formulations such as "unknowns unknowns", you may refer to their statistics? Further, is would be very helpful to learn more about how "unknowns unknowns" are considered by the insurance industry

When statistical metrics can be assessed to measure uncertainty, it means that it is possible to delineate the extent of what we know, but not necessarily to capture what we still don't know. Implementing statistical measure of uncertainty would be already a significant step for natural hazard modelling and (re)insurers.

Unknown unknowns are usually dealt through the definition and quantification of scenarios combining several simultaneous and adverse situations. The objective is then to test the robustness and limitation of the risk management solutions put in place.

4. L19-20: see comment 1 above

Answered in comment 1.

5. L30: explain "actuarial methods"; specify "extreme losses" (e.g., PML200, cf. major revisions point 4)

Agreed and included in the revision of the paper. In the context of natural hazard, actuarial methods refer to statistical functions used with the objective to estimate the value at risk of a given portfolio. Losses are assessed as extreme when their probability of occurrence is higher than the quantile 99.5.

6. L34: "…whose impact was unexpected…": In what sense and why?

According to McChristian (2012), before the occurrence of Hurricane Andrew, the loss assessment for an event of this strength was $4 to $5 bn, which is 3 times lower than the actual loss of Hurricane Andrew at $15 bn. Insurers underestimated their exposure at risk as well as its vulnerability to such an event. The author also indicates that recent loss history was adjusted to reflect current macro-economic trends and did not capture the increasing population over coastal areas. Historical loss data were too coarse to capture the separated impact on losses driven by storm surge versus wind, nor the impact driven by growing exposure or a change in building codes. Consequently, statistical models used to extrapolate the historical losses record to assess more extreme losses could not take these effects into account either.

7. L42 briefly explain why each peril and region is usually modelled separately (you may refer here already to the global loss models suggested in the conclusions)

To be included.

8. L45-47: I'm not sure what you mean by "format". If this refers to the data format only, then I would say that this problem is much easier solvable compared to the uncertainty inherent in each of the four model components (cf. major revision point 1).

The implementation of research within components of the loss modelling framework is a key aspect of natural hazard modelling and one of the challenges faced today by the community. Data format is just the tip of the iceberg and refers to the way data is gathered and organized in each component of the loss modelling framework with the objectives of optimizing the run time (i.e. results are expected to be available after a few hours of run time) while dealing with IT constraints (i.e. memory limit, CPU/GPU…).

There is therefore a gap between the quality and the sophistication of modelling produced by research and the derivative data compiled to meet the requirements of the loss modelling framework. As an example, the severity of natural events is captured in the hazard component through the use of hazard footprints, defined as the maximum hazard value (e.g. windspeed, flood depth, peak ground acceleration…) at each grid cell of the considered area over the duration of the event. The information relative to the event duration and to the evolution of the hazard value over time are lost, while they are parameters that impact the assessment of buildings' damage.

As part of the restructuring of the paper (as presented in the supplement document), more details on why the transmission and the intersection of information from one component to the other is crucial.

9. L48-52: Is a storm like Hurricane Andrew accounted for in today's risk models, so has it turned from an "unknown unknown" to a "known known"?

The modelling approach by component developed in the aftermath of Hurricane Andrew remedied to the limitation of models at the time that did not consider the non-linear impact of growing exposure in exposed areas. I would say

that, nowadays, models can reproduce quite precisely the impacts generated by Hurricane Andrew at that time. However, since the occurrence of Andrew, there have been evolutions of the local environment that are not captured by models today. For example:

- soil erosion or the sinking of coastal cities such as Miami may increase the impact of hurricanes
- the reinforcement of mangroves along the coastline may decrease the impact of hurricanes

Hurricane Andrew impacts in 1992 are known knowns as we have data and models that can reproduce it. This does not mean that Hurricane Andrew-like event in 2022 are known knowns.

10. L56-58: Mention that both monitoring of extremes as well as numerical modeling has substantially improved over the last decades leading to a better hazard estimation.

Agreed.

11. L60: "..notably the location at high granularity and the physical properties of building." Be more specific, give details; what granularity is required for what (exposure vs. hazard) depending on the different perils?

This point will be integrated in the changes suggested in major comment 1 and the description of the 4 components.

12. L66: "building damage" and "hazard magnitude" are two different topics; I wouldn't include both in one sentence.

Hazard magnitude might be a shortcut. What I mean is that to improve the loss modelling, in particular the vulnerability component, we need to collect the information on:

(i) how severe was the event at the location of the building (i.e. values of the relevant hazards' variables leading to building's damage)
(ii) how damaged is the building (including also all relevant information on the building itself)
(iii) what were the associated repairing costs

13. L68-69: "It is less the case for other perils"; I cannot follow this statement, considering the devastation by, for example, tornadoes or hurricanes. "population is evacuated" is too general; evacuation is a measure in case of hurricanes, but usually not in case of windstorms, floods, or large hail.

Agreed, I will rephrase and clarify.

14. L71 "Damage information…" Move this sentence to the beginning of this paragraph.

Agreed and modified.

15. L80-81: this sentence is unclear (but becomes a bit clearer when reading the next sentence); I suggest to reformulate and to explicitly mention serial clustering at the beginning.

Agreed, it could be rephrased as follows:

As the occurrence of natural events brings new information and data, it is integrated into the loss modelling framework to improve the assessment of loss. For example, the modelling of serial clustering of European windstorms has greatly improved following the occurrence of Lothar and Martin in 1999.

16. L84: you may also cite Vitolo et al. (2009, MZ, DOI 10.1127/0941-2948/2009/0393), the first paper on that topic

Agreed.

17. L88: Expand the discussion about uncertainty as this is highly relevant (cf. major point 1)

This point will be integrated in the changes suggested in major comment 1.

18. L96 and elsewhere: the expression "loss simulation engine" is strange. You mean a model? And why loss and not risk (if probability is considered in the hazard module)?

Agreed. I would rather use the expression "loss simulation process" to designate the process that performs the loss assessment. For each building of the insurance portfolio and for each event of the hazard component:

1. building's location available in the exposure component is intersected with the event footprint to obtain the hazard intensity value at the location of the building.
2. based on the hazard intensity value and the physical properties of the building, the corresponding damage ratio is derived using the vulnerability curve associated to the characteristics of the building.
3. the damage ratio is applied to the sum insured of the building, as given in the financial module, which results into a loss amount. Financial conditions are applied to the loss amount to get the ultimate loss borne by the insurance company.

The loss simulation process produces Exceedance Probability curves characterizing the risk, i.e. the probability to exceed an amount of loss.

19. L98: explain "epistemic uncertainty"

Epistemic uncertainty is the uncertainty due to lack of information or knowledge of the hazard, in particular because historical observations are not sufficient to capture the complexity of the hazard.

20. 1 st paragraph of Section 4m & Introduction: in the last sentence of the introduction, it was written that the paper focuses on the impact of natural hazards to property exposure. Section 4, however, describes supply chains and related interlinks. Of course, that topic is highly relevant for the general impact of natural hazards, but not for property exposure/loss.

Indeed, while Business Interruption (BI) following natural events is included in insurance contracts, Non-Direct Business Interruption (NDBI) is usually excluded. The point here is that by investigating this type of exposure and the risk associated to it, it might become possible to include it.

21. L127: "shortages of cameras and smartphones". Even more important were shortages in HDs (hard discs) and chips reducing the overall computation power (cameras and smartphones at that time were mainly gadgets not generating real added value).

Thank you for that comment, I will mention that as well.

22. Check the references for consistency (e.g., some journals or manuscript titles are in bolt letters, other not)

Agreed and modified.

Edits:

1. Check the appropriate use of \citep and \citet throughout the paper

Agreed and corrected.

2. L2: "undertaken" is not appropriate here

Corrected

3. L41: "…here before cited…" needs rewording

It has been reworded

4. L42: "peril x region" is unclear

Replaced by "each scope, defined by one peril and one region,"

5. L63: "all being critical…" losses

Corrected

6. L74: "…to collect…"

Corrected

7. L83: "winter windstorms"; "Serial clustering" (note that there are different kinds of clustering, thus serial is important to include)

Corrected

8. L85 process > probability

Corrected

9. L86 exhibited in > shown by

Corrected

10. L87: what do you mean by "dimensioning"?

Sizing

11. L88: could > should

Corrected

12. L115: "is intersected with hazard" > is interlinked with the hazard

Corrected

13. L121/L124: "have become more interconnected" is mentioned twice here; further, mention the interrelation and dependencies of supply chains

Agreed.

14. L133: clients > companies; siloed > ?

To be rephrased.

15. L137: to which case study do you refer here?

Rephrased "Another way to tackle unknown unknowns is to develop forward-looking views of the risk, as it is done in studies quantifying the impact of climate change on insurers' business."

16. L138: "exercise" is not an appropriate expression

Replaced by "analysis"

Suggested structure following RC2 and RC3 comments:

(i) Loss / risk model development from a historic perspective
- Example of Hurricane Andrew
- Detailed discussion on
    - the three components (hazard, exposure, vulnerability)
    - the loss simulation process (i.e. how the transmission and the intersection of information from one component to the other is performed)
- Details related to the (re)insurance market and its evolution regarding natural hazard risk modelling

(ii) Uncertainty in each of the components (current state) and its quantification / how we improve and measure what we know
- Uncertainty driven by data quality and availability by component (exposure, hazard and vulnerability), some are inherent, some can be improved (e.g., uncertainty in hazard modelling due to a lack of appropriate observations and/over observation data over longer time periods is not mentioned). Include examples such as:
    - Improvement of exposure data to get precise information on buildings' coordinates and physical characteristics
    - The access to various type of hazard measurements, the availability of reanalysis datasets for atmospheric hazards
- Uncertainty caused by modelling assumptions and approaches. Include examples such as:
    - Improvement of the modelling of serial clustering of European Windstorms
    - The impact of parameters setting in hydrologic tools (Kaczmarska et al. 2018)
- Uncertainty caused by the implementation in the loss modelling framework

(iii) Perspectives: Challenges, further needs, and expected developments to address these needs
- Need for systematic analysis and quantification of uncertainties, component by component and on the overall loss simulation process
- Identified challenges (e.g. how to model interrelated hazards and their impacts, how to model the impact of natural hazards on supply chain, the role of machine learning…)
- Management of unknown unknowns in natural hazard modelling