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Hazard Intensity Threshold for Exposure Modeling of Systems of Interest to Climate Change

Matthieu Dutel

Laboratoire Génie Industriel, CentraleSupélec, Université Paris-Saclay, Gif-sur-Yvette, France.
Resallience by Sixense Engineering, Nanterre, France. E-mail: matthieu.dutel@centralesupelec.fr

Didier Soto

Resallience by Sixense Engineering, Nanterre, France. E-mail: didier.soto@resallience.com

Adam Abdin

Laboratoire Génie Industriel, CentraleSupélec, Université Paris-Saclay, Gif-sur-Yvette, France.
E-mail: adam.abdin@centralesupelec.fr

Anne Barros

Chair on Risk and Resillience of Complex Systems, Laboratoire Génie Industriel, CentraleSupélec, Université Paris-Saclay, Gif-sur-Yvette, France. E-mail: anne.barros@centralesupelec.fr

The goal of adapting physical assets to climate change is to anticipate and prevent damage to these assets to maintain high levels of system performance. Exposure modeling plays a key role in this adaptation process. While climate data is available, its spatial resolution varies depending on the location of the assets. Information on physical assets also exists, but detailed damage data for a given hazard intensity is often private, particularly regarding specific assets. This lack of information hinders the creation of precise vulnerability curves and accurate hazard intensity thresholds for each asset type and subsystem. Due to these data limitations, using indicators produced by climate services is common practice. However, the relevance of these indicators for the specific system under study is not always certain. This paper presents our approach to selecting a hazard intensity threshold relevant to exposure modeling of physical assets to climate change. Our method is based on Boolean Exposure Modeling (BEM), which requires a clear definition of the hazard event (H). This approach ensures a focused response to the question: "Is the system of interest exposed to H or not?". The methodology is applied to a case study involving administrative divisions of French territory, which contain physical assets. More specifically, the hazard intensity threshold is determined based on the Eurocode EN 1991-1-5. The result is presented as a BEM output map covering 30-year periods, using climate model data as input. This outcome enhances the exposure modeling toolbox for adapting physical assets to climate change by providing a quantitative exposure model tailored to both the assets and climate change.

Keywords: Modeling, exposure, physical assets, climate change, hazards, territory.

1. Introduction

Adapting physical assets to climate change involves modeling the risk of physical damage to these assets. Exposure and vulnerability models are underlying models for estimating physical damage. In this paper, we focus on Exposure Modeling to refine spatial exposure information for adapting physical assets to climate change. We can identify two different trends in Exposure Modeling literature: (i) Mühlhofer et al. (2023) define exposure as “the geo-referenced assets or population data that are located in the area of interest”, a perspective also reflected in Eberenz et al. (2020); (ii) Van Westen et Greiving (2017) define exposure as the “spatial overlay of hazard footprints and elements-at-risk locations”, a viewpoint also adopted in Koks et al. (2019). The first definition defines exposure as an amount of geo-referenced assets, population, or value at risk in an area of interest. Rephrasing it:

an amount of system of interest in a specific area. This first exposure definition does not link the system of interest with the hazard occurrence. In contrast, the second definition states that exposure is the overlay of the system of interest and the hazard for a given location. In this paper, we choose to follow the path of the second exposure definition because it highlights the interaction between the system of interest and the hazard, and it enables precise quantification. This definition aligns with the objective of refining and quantifying spatial exposure information using the Boolean Exposure Model.

Hazard differentiates itself from classical climate data by the exceedance of what we call Hazard Intensity Threshold (HIT) that characterizes the potential start -or the entry into an out-of-design zone- of damage on a system of interest. Common practice is to use climate indicators (for the Hazard) based on: quantiles (e.g. 95th centiles of daily maximal temperature); and fixed intensity (number of days above 35°C) values. In both cases, there is no clear relationship between climate data and the system of interest. That is why this paper proposes an exposure model based on a HIT that links the climate data and the system of interest. In this paper, the physical assets are the ones considered in *NF EN 1991-1-5/NA* (2008): "buildings, bridges, and other structures".

Climate change is not spatially uniform. Intensities that the systems of interest will encounter in the future may differ from the ones encountered in the past. The hazards and, thus, the exposure of the system of interest may change. Based on precise HIT, we propose a model to quantify this change based on what we call Boolean Exposure Model (BEM).

To answer these challenges, the main contribution of this paper is the modeling framework to obtain BEM based on the Boolean Hazard Model with Probability (BHMP) and the Boolean System Model (BSM), with a HIT based on climate data and system of interest data. This modeling framework clearly states the interaction between the system of interest and the hazard in the exposure modeling. We apply the BEM to administrative units of metropolitan France with HIT based on Eurocode.

2. Methodology & Models

2.1. *Hazard Model Methodology*

Numerous definitions of hazards exist in the literature. In this paper, we adopt a simplified model for hazard analysis, which we introduce as a Boolean Hazard Model with Probability. This model is described as "Boolean" because its outputs are binary, indicating either True or False. It is categorized as a hazard model because it incorporates a defined threshold—termed a Hazard Intensity Threshold—to determine the presence of a hazard for a specified system of interest. The HIT is tailored to the characteristics of the system under consideration. Further elaboration and application of this model are presented in the Use Case section of the paper. Let H be the Hazard Model, let $BHMP$ be the chosen Hazard Model, let i be the intensity of climate variable coming from the climate data, let i_{Th} be the intensity threshold, let $P_{i_{Th}}$ be a fixed probability threshold used as a criterion for assessing if there is occurrence of hazard.

$$H(i) = BHMP_{i_{Th},P_{i_{Th}}}(i) = \begin{cases} 1, if\ P(i \geq i_{Th}) \geq P_{i_{Th}} \\ \quad 0, otherwise \end{cases} \quad (1)$$

The mathematical definition above is a general definition of the BHMP at one point, not considering the location. But to make it more practical for the use case, let's introduce x the longitude, y the latitude, let $i(x, y)$ be intensity of the climate variable at location (x, y), let $i_{Th}(x, y)$ be the intensity threshold at location (x, y). We have:

$$H(i, x, y) = BHMP_{i_{Th}(x,y),P_{i_{Th}}}(i, x, y) = \begin{cases} 1,\ P(i(x, y) \geq i_{Th}(x, y)) \geq P_{i_{Th}} \\ 0,\ otherwise \end{cases} \quad (2)$$

For clarity, i , the intensity of climate variable is obtained from Global Climate Model data. Then, downscaling is done thanks to a dynamic and/or statistical technique. It is then preferable to choose data that is bias-corrected. The intensity data derived from climate datasets serves as an input to our methodology. The BHMP framework is designed to be adaptable to various types of intensity data. Throughout the remainder of the modeling process, we refer to the Boolean output generated by this model as the "BHMP output".

2.2. *System of Interest Model Methodology*

The System of Interest can be a territory, a territory ensemble (e.g. an ensemble of administrative units), a building or a building network, an infrastructure or an infrastructure network, a critical infrastructure or a critical infrastructure network. The system owner or entities that are in charge of collecting data about the system are producing data about the system of interest thanks to their sensors, field visits, and aggregation of datasets. System of interest open-source datasets are input to our model. We apply a Model of the System of Interest for the Exposure Model. We choose relevant information about the system of interest. This information can include, for example, longitude, latitude, and the presence of the system of interest. Let d_s be the data about the system of interest, let BSM be the Boolean System Model, let x be the longitude and y the latitude.

$$S(d_s, x, y) = BSM(d_s, x, y) = \begin{cases} 1, & if\ presence\ of\ a\ system\ of\ interest\ at\ (x, y) \\ 0, & otherwise \end{cases} \quad (3)$$

In the rest of this paper, we consider the output of this model as BSM output. BSM output clarifies the information we need as input for the exposure model.

2.3. *Hazard Intensity Threshold Methodology*

Our objective is to determine a HIT that is associated with both climate data and the system of interest. Importantly, the HIT is not solely based on climate data records but is obtained from a combination of climate data and physical asset characteristics. The feasibility of a database containing predefined HIT values was investigated through a literature review and expert interviews (see Section 3.2 for further details). National standards, including those linked to Eurocode, were utilized to select a Hazard Intensity Threshold that is specifically tailored to both the physical assets of the administrative unit and the corresponding climate data.

2.4. *Boolean Exposure Model Methodology*

The inputs of the Exposure Model are the outputs of the System of Interest Model and the outputs of the Hazard Model. The Exposure is the spatial overlay between the Hazard and the System of Interest. The Exposure is then:

$$E(H, S) = H \cap S \quad (4)$$

Where; E is the Exposure Model output spatial distribution; H is the Hazard Model output spatial distribution; S is the System of interest output spatial distribution; $E(H, S)$ is the Exposure of System of interest to Hazard. In this paper, we propose a Boolean Exposure Model to answer only one question is the System of Interest Exposed to H or not? If we take the Boolean Exposure Model at one point, for a given longitude, for a given latitude we have:

$$BEM(i, d_s, x, y) = BHMP_{i_{Th}(x,y), P_{i_{Th}}}(i, x, y) \times BSM(d_s, x, y) \quad (5)$$

Where BEM is the Boolean Exposure Model. Another way to express the same model is: if we take BEM, BHMP, BSM as geographical maps, containing all the locations (i.e. all the longitudes and latitudes) we have:

$$BEM = BHMP \cap BSM \quad (6)$$

BEM can help answer very precise questions in the field of exposure modeling by quantifying the number of systems of interest exposed. This model can theoretically be applied to different levels of the system of interest. If this model is applied to a case study, it provides Boolean data about the exposure of a system of interest facing a hazard related to climate change. Furthermore, the model definition is general. It is defined and designed for climate hazards and for physical systems but there are no constraints to apply this model in other domains. We propose to show a use case in the next section in the context of physical systems facing hazards related to climate change. We try, with this use case to show the relevance of the Boolean Exposure Model explained above, in a very practical use case.

3. Case Study

3.1. *Climate data case study input*

This study focuses on a single climate hazard: extreme temperatures in the French Metropolitan area. The system of interest comprises the administrative units within this region. For the analysis, we utilize existing climate datasets. Specifically, the input climate data used to study extreme temperatures consists of projected daily maximum temperatures near the surface, corrected for bias. We use the climate service DRIAS-2020 which is described in the work of Soubeyroux et al. (2020). All the data coming from DRIAS 2020 for the Global Circulation Model are based on CMIP5. The Regional Climate Models in DRIAS 2020 are based on Euro Cordex. The Representative Concentration Pathways (RCP) available in Euro Cordex are: RCP2.6, RCP4.5 and RCP8.5. RCP2.6 corresponds to a radiative forcing of +2.6W/m², while RCP8.5 corresponds to a radiative forcing of +8.5W/m². From this platform, we choose to use only one climate model framework. The climate modeling pipeline which provides the climate data inputs is: (i) The Global Circulation Model (GCM): CNRM-CM5 r1 from the French National Centre for Meteorological Research (CNRM) with a resolution of 1.4° i.e approximately 150 km. (ii) The Regional Climate Model (RCM): ALADIN6.3 v2 from CNRM with a resolution of 0.11° i.e approximately 12 km. (iii) Bias Correction and Spatial Disaggregation (BCSD): ADAMONT France from METEO-FRANCE with a resolution of 8km. The output of the climate model pipeline we are interested in is `TasMaxAdjust`. `TasMaxAdjust`, the daily maximum temperature near the surface corrected for bias is available on the 8 km SAFRAN grid. It is how we obtain the intensity, i associated with (x, y) in the context of our case study. This i is an input for the hazard model, BHMP. It is thus, also an input for the exposure model, BEM.

3.2. *Hazard Intensity Threshold Data*

The Eurocode 1(*EN 1991-1-5*, 2003) is about the actions on structures. *NF EN 1991-1-5 (2004)* is the French standard based on the Eurocode EN 1991-1-5. *NF EN 1991-1-5/NA* (2008) is the French national appendix containing Clause 6.1.3.2. (1). NF EN 1991-1-5 gives "principles and rules for the calculation of temperature actions and their effects on buildings, bridges and other structures, including their structural components". This standard concerns the physical assets and the thermal actions on them. Our focus in this study is Clause 6.1.3.2. (1) of National Annexes to national standard NF EN 1991-1-5 based on the Eurocode EN 1991-1-5. Even more precisely, we only focus on the specified values taken for $\mathrm{T_{max}}$ in Clause 6.1.3.2. (1) of NF EN 1991-1-5/NA. $\mathrm{T_{max}}$ is the "value of the maximum air temperature under shelter, with an annual probability of being exceeded of 0.02 (equivalent to a mean return period of 50 years), based on the maximum hourly values recorded". For each French department, a $\mathrm{T_{max}}$ is associated. The unique values of $\mathrm{T_{max}}$ are $\mathrm{T_{max}} = 35°C$ or $\mathrm{T_{max}} = 40°C$ depending on the French department recorded values. This allows to set $i_{x,y,Th} = \mathrm{T_{max}}$ in the use case. $P_{i_{x,y,Th}} = 0.02$ as fixed in the French standard based on the Eurocode.

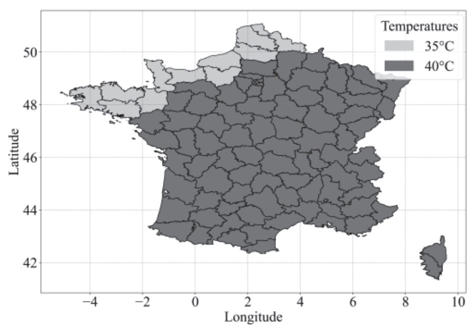

Fig.1. Maximum air temperature under shelter, by French department from Clause 6.1.3.2 (1) of NF EN 1991-1-5/NA.

Fig.1. can be considered as a baseline of an exposure map. This map represents the maximum air temperature under shelter taken in the NF EN 1991-1-5/NA for each French department. The NF EN 1991-1-5/NA has an application domain for the following physical assets: "buildings, bridges, and other structures". The work of Markova et al. (2024) sets the context for the evolution of the Eurocode EN 1991-1-5, considering climate change. The work

of Rianna et al. (2023) investigates the updates of thermal loads in the National Annexes of the Eurocode with a case study for Italy. Compared to these two works, our focus is on the Boolean exposure of administrative units containing physical assets to extreme temperatures in changing climate. Instead of updating NF EN 1991-1-5/NA, we use it as a HIT.

3.3. *System of Interest case study input*

In this case study, the systems of interest are administrative units. These administrative units contain infrastructures covered by *NF EN 1991-1-5*, such as buildings, bridges, and other structures. Here, we assess exposure at the administrative level rather than analyzing individual infrastructures directly.

French National Institute for Geographic and Forestry Information (IGN) is providing information on the different hierarchical administrative units in France thanks to ADMIN-EXPRESS (June 2024 edition)(*Admin Express | Géoservices*, 2024.).

For each $(longitude, latitude)$ of French territory administrative units of different hierarchical levels are assigned: (i) French *Communes*, (ii) French *Départments*, (iii) French *Régions*. We are taking the French administrative units as system of interest containing physical assets. d_s is the data about the system of interest i.e data about the French Administrative units from IGN. We have d_s for each (x, y). If on the (x, y) i.e on the $(longitude, latitude)$ there is presence of the wanted administrative unit, $BSM(d_s, x, y) = 1$, ,$BSM(d_s, x, y) = 0$, otherwise.

3.4. *Operations performed in the case study*

The operations to obtain the BEM outputs are performed in 9 steps (see Table 1).

Table 1. Overview of the 9 steps to implement the case study

Step	Operation performed
1	Obtain daily maximum temperatures
2	Obtain yearly maximum temperatures
3	Split maximum temperature data into 30-years periods
4	Apply HIT
5	Compute empirical probability
6	Apply BHMP
7	Apply BSM
8	Preparation of HIT data for BEM application
9	Obtain BEM output

Step 1, Climate data as inputs. The climate data we take as input is: daily TasMaxAdjust from 1951 to 2005 for the historical period; daily TasMaxAdjust projections from 2006 to 2100 with scenarios {RCP2.6, RCP4.5, RCP8.5} for the projected period.

Step 2, Obtaining the $\mathrm{Txx}_{\mathrm{annual}}$. For each year, $(longitude, latitude)$, we compute $Txx_{annual}(x, y) = \max_{year} TasMaxAdjust(x, y)$.

Step 3, Splitting climate data in 30 years intervals. For each climate projected and historical datasets, we split them in 30 years datasets with a stride of 24 years.

Step 4, Thresholds 35°C and 40°C on all years and all locations. We apply a Boolean Hazard Model (BHM), based on HIT. In this use case, since there are two thresholds depending on the given $(longitude, latitude)$ we first apply the two thresholds on all data, for 35°C and 40°C. We obtain two columns where for each $(longitude, latitude, year)$ we see if there is an exceedance of the threshold or not. Very practically, we obtain: $BHM(T_{xx}(x, y, year)) > 35°C)$ and $BHM(T_{xx}(x, y, year)) > 40°C)$. Here, we use a BHM, since we do not use any probability at this step.

Step 5, Empirical Probability of event $\mathrm{Txx} > \mathrm{i}_{\mathrm{Th}}$. For each location, for each period we compute an empirical probability.

$$P(Txx > 35°C) = \frac{Number\ of\ years\ event\ Txx{>}35°C\ occurs}{Total\ number\ of\ years\ of\ the\ dataset} \tag{7}$$

and

$$P(Txx > 40°C) = \frac{Number\ of\ years\ event\ Txx{>}40°C\ occurs}{Total\ number\ of\ years} \tag{8}$$

For each location, each period of 30 years, each reference period, each scenario, each HIT, for projections of long-term climate data, we obtain an empirical probability.

Step 6, Thanks to step 5, we have $P(Txx > 35°C)$, $P(Txx > 40°C)$. The probability threshold we take in this study is $P_{i_{Th}} = 0.02$ according to the Eurocode. On all locations, we apply BHMP as described in Eq. (2). We then obtain the BHMP outputs H_{35}:

$$H_{35}(i = T_{xx}, x, y) = BHMP_{i_{Th}=35°C, P_{i_{Th}}=0.02}(i, x, y) = \begin{cases} 1, & P(i(x,y) \geq 35°C) \geq 0.02 \\ 0, & otherwise \end{cases} \quad (9)$$

and H_{40}:

$$H_{40}(i = T_{xx}, x, y) = BHMP_{i_{Th}=40°C, P_{i_{Th}}=0.02}(i, x, y) = \begin{cases} 1, & P(i(x,y) \geq 40°C) \geq 0.02 \\ 0, & otherwise \end{cases} \quad (10)$$

on all locations. We differentiate the i_{Th} by location in step 9.

Step 7, Preparation of the System of Interest data. Some simple operations are implemented: change of the Coordinate Reference System, choice of a subset of columns.

Step 8, Preparation of HIT data. We took data from the French department administrative units (from ADMIN EXPRESS), we took data from the national appendix of the Eurocode associating with each French department a T_{max} threshold. We then have a dataset with the department code, the geolocation, and the associated temperature, HIT.

Step 9, Obtaining BEM output**.** We take the output of step 6. We have H_{35} and H_{40} for each (x, y). We take the *commune* administrative units geolocations. We operate the overlay with this specific case study: (i) For each *commune*, we take the centroid of the commune, (ii) As described in section 3.2. the intensity thresholds are not spatially uniform across the entire territory. If the *commune* is in a department with the threshold of $i_{Th} = 35°C$, we take the nearest value of H_{35}. Similarly, if the *commune* is in a department with the threshold of $i_{Th} = 40°C$, we take the nearest value of H_{40}. Let (X_{35}, Y_{35}) be the set of locations where $i_{Th} = 35°C$, and (X_{40}, Y_{40}) the set of locations where $i_{Th} = 40°C$ according to the annex of Eurocode. From Eq.(6) we have: $BEM = BHMP \cap BSM$. Since the HIT is not the same on all the French territory we operate:

$$BEM_{35°C} = BHMP_{i_{Th=35°C}(X_{35},Y_{35}), P_{i_{Th}}=0.02} \cap BSM \quad (11)$$

$$BEM_{40°C} = BHMP_{i_{Th=40°C}(X_{40},Y_{40}), P_{i_{Th}}=0.02} \cap BSM \quad (12)$$

$$BEM = BEM_{35°C} \cup BEM_{40°C} \quad (13)$$

Thus, we obtain a BEM output map covering 30-year periods, using climate data, administrative unit data and precise HIT data as inputs. To clarify, in our case study,

$$H(i, x, y) = BHMP_{i_{Th}(x,y), P_{i_{Th}}}(i, x, y) = BHMP_{i_{Th=35°C}(X_{35},Y_{35}), P_{i_{Th}}=0.02} \cup BHMP_{i_{Th=40°C}(X_{40},Y_{40}), P_{i_{Th}}=0.02}. \quad (14)$$

In the result section, “H” will always refer to this specific formulation.

4. Results

A single climate model framework was utilized, rather than an ensemble, to demonstrate the applicability of the BEM methodology with a specific HIT. The results are not intended for direct application but to validate the methodology. BEM outputs cover 30-year periods using climate model data, administrative units as the system of interest, and a defined HIT.

At the country level, the BEM output indicates that the event "H", as described in section 3.4., occurs at least once at some location (longitude, latitude) within the French territory during all periods and scenarios. This confirms that the fixed HIT is exceeded at least once across all scenarios for the chosen climate model framework. While this outcome could be anticipated, the application of the BEM methodology provides quantitative confirmation rather than relying on assumptions. These results highlight that, across the entire French territory, the event "H" consistently occurs at least once.

Exposure is not spatially uniform information because: (i) climate data is not spatially uniform, (ii) the HIT taken in the use case is not spatially uniform, (iii) the system of interest is not spatially uniform. Having information at country level is then not sufficient for precise adaptation actions at local level. Our result contribution is here: “Is the system of interest exposed to H or not?” can be asked at different levels of administrative units : French ‘Région’, French ‘Département’, French ‘*Commune*’. While other administrative units are interesting, for the sake of brevity, we go straight to the main result which is about French ‘*Communes*’. The main result of our study is the Fig.2. BEM output maps at *‘Commune’* level for the 30-year periods; for historical period and scenarios RCP 2.6, RCP 4.5, RCP 8.5 with one climate model framework and a precise non-spatially uniform HIT.

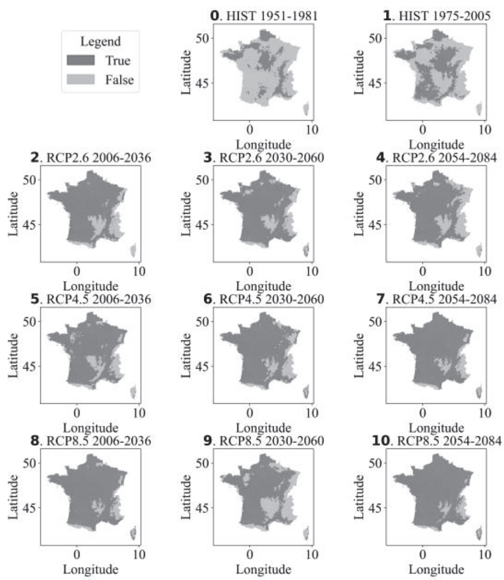

Fig.2. Spatial distribution of Boolean Exposure Model output at French ‘*Commune*’ administrative level. This figure takes only one climate model framework as input CNRM-CM5r1 (GCM); ALADIN6.3v2 (RCM); ADAMONT FRANCE (BCSD) **0**&**1**. BEM output maps for the historical period 1951-2005 with 2 subperiods 1951-1981 and 1975-2005. **2** to **10**. BEM output maps for the projected period 2006-2084; with 3 subperiods 2006-2036, 2030-2060, 2054-2084; with three different RCP: RCP 2.6, RCP 4.5, RCP 8.5.

Answering “Is the system of interest exposed to H or not?” at French “*Commune*’ administrative level, for all the communes is not trivial. We need quantitative result data. The answer depends on each *commune*, each modeling hypothesis taken, each scenario taken, and the period taken. Our main result is presented in Fig. 2. For the given climate model framework in input, for the 34806 *communes* we have studied, we can observe that: (i) There is not a uniform distribution of the exposure; (ii) For historical period 1951-1981, 29% of the French “*Communes*” are exposed, 47% for the 1975-2005 period; (iii) For projections, for all scenarios, for all time periods more than 73% of the *commune* are exposed on the French territory to H. In details, for 2006-2036 period, between 84% (RCP 2.6) and 91% of the *commune* are exposed. For ‘2030-2060’ period, between 73% (RCP 8.5) and 86% (RCP 4.5) of the *commune* are exposed. For ‘2054-2084’ between 76% (RCP 2.6) and 95% (RCP 8.5) of ‘*Communes*’ exposed; (iv) These results highlight the global trend of the increasing number of ‘*Communes*’ exposed to H. (v) The Boolean Exposure Modeling output is available for each 34806 *commune* studied, for each 2 historical periods, for each 3 RCP scenarios over 3 periods i.e. in total there are 382866 Boolean results. These results answer to ‘Is the system of interest exposed to H or not?’ for each scenario, for each period for one climate modeling framework, for each French ‘*Commune*’.

5. Conclusion and discussion

In this work, we have proposed an exposure modeling framework based on Boolean Exposure Modeling. The underlying models are the precise hazard model and the system of interest model. We introduced the importance of the Hazard Intensity Threshold tailored to both system of interest and climate data. We have used this model to study the exposure of administrative units to a hazard based on a HIT linked to National Annexes of Eurocode. Considering modeling hypothesis, results at *commune* level show that the number of ‘*Communes*’ exposed increases for projected periods compared to historical ones. We are proposing Boolean results at the '*Commune*' level in order to improve spatial exposure information. This enables to have localized information for the adaptation of physical assets to climate change, based on relevant HIT. In this study, we acknowledged a lot of limitations: we are not using Extreme Value Theory, nor ensemble of climate model frameworks. Furthermore, other improvement could be the obtention of a finer resolution on climate data thanks to improved downscaling technics or the use of more precise definition of the system of interest. All these works on inputs, would reinforce the BEM's outputs. This could pave the way for future research in physical assets' adaptation to climate change.

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CRediT authorship contribution statement
Matthieu Dutel: Methodology & Models, Software, Results & Figures, Writing – original draft, Writing – review & editing. Didier Soto: Writing – review & editing, Supervision. Adam Abdin: Writing – review & editing, Supervision. Anne Barros: Writing – review & editing, Supervision, Project administration.

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