Answers to Referee 1: Technical details

January 2022

Q1 - Cyclone description accuracy It is not clear that this tropical cyclone model leads to accurate forecasts of storms. Changes in wind patterns can have no effect in this model. Is the cyclone model in this paper as accurate as the models developed by Emanuel? Or is this model a step backwards?

The model is based on the theory of Emanuel (1988), which proposes to express the maximum potential intensity (i.e. the minimum central pressure achievable given local climate conditions) as:

$$\text{MPI} = P_{env} \cdot \exp(-X) \tag{1}$$

To demonstrate the importance of introducing the additional variables in the definition of X, we reiterate the principle of the demonstration. Let $x = \exp(-X)$ define the depression ratio: $x = \frac{P_c}{P_{env}}$. The central pressure equation was shown in Emanuel (1988) to be expressed in the form:

$$\ln(x) = A\left[\frac{1}{x} - B\right]$$

Noting $\mathcal{E} = \dfrac{\text{SST} - T_{tropo}}{\text{SST}}$ the thermodynamic efficiency, Emanuel (1988, p. 1145) writes:

$$A = \frac{\mathcal{E}}{1-\mathcal{E}} \frac{L_v}{R_v T_{\text{tropo}}} \frac{e_s}{P_{env}} \times \tag{2}$$

$$\left[1 - \underbrace{\frac{g\bar{z_0}^{\star}}{\mathcal{E}L_v}}_{(a)} - \underbrace{\frac{1}{8}\frac{f^2\bar{r_1^2}^{\star}}{\mathcal{E}L_v}}_{(b)} + \underbrace{\frac{C_l T_{\text{tropo}}}{\mathcal{E}L_v}\left(\mathcal{E} + (1-\mathcal{E})\ln(1-\mathcal{E})\right)}_{(c)} \right] \tag{3}$$

where L_v is the latent heat of vaporization, R_v the gas constant of water vapor, C_l is the heat capacity of liquid water where (a) (b) and (c) are functions of the thermodynamic efficiency (so SST and tropopause temperature) and:

$$B = \text{RH}\left[1 + \frac{e_s}{P_{env}} \frac{\ln(\text{RH})}{A}\right] + \frac{1}{4} \underbrace{\frac{f^2 r_{env}^2 \left(1 + \text{RH}\frac{e_s}{P_{env}}\right)}{R_d T_{\text{tropo}}(1-\mathcal{E})A}}_{(d)} \tag{4}$$

where r_{env} denotes the outer radius (fixed at 500 km in CATHERINA), and (d) is a function of all the raw variables required in our model. This theoretical expression can be – and has been – simplified. For instance, in the expression of A, the term (a) refers to the potential energy used to lift-up water substance, this factor is inversely proportional to the thermodynamic efficiency $\mathcal{E}$. The second factor (b) represents the energy require for radial translation of water substance (this term is neglected in Emanuel (1988, p. 1146)). The last factor (c) is the contribution of water substance to heat capacity.

Following this formulation of (1) and integrating additional simplifications proposed in subsequent papers Emanuel (1991), we finally use the framework summarized in Holland (1997) to define locally the MPI in such a way that it provides a statistically significant instrumental variable in the description of tropical cyclone intensification, which is the aim of the algorithm.

Q3 - Damage function calibration The model depends a great deal on the damage function. But it is not clear how this damage function was estimated.

The optimization is performed by Eberenz et al. (2021) to define the regional damage functions. Eberenz et al. (2021) first define the event damage ratio (EDR) as a fraction error between normalized reported (NRD) and simulations (SED) for each cyclone ($\text{EDR}(i) = \frac{\text{SED}(i, v_h(j))}{\text{NRD}(i)}$) and the total damage ratio (TDR) is defined in each region summing over events: ($\text{TDR}(j) = \frac{\sum_i \text{SED}(i, v_h(j))}{\sum_i \text{NRD}(i)}$) For each event, there is a value for v_h allowing to optimally calibrate the explicit damage function described in Emanuel (2011).

Eberenz et al. (2021) propose two complementary optimization methodologies to find the value of $v_h^\star$ maximizing the prediction of the regional damages Eberenz et al. (2021):

(*i*) Root mean square fraction (RMSF), minimizing the spread of the event damage ratios (EDR) – defined as the ratio of simulated damage vs. reported damage:

$$v_h{}^\star_{\text{RMSF}}(j) = \text{argmin}_j \exp\left(\sqrt{\frac{1}{N}\sum\left(\ln(\text{EDR(i)})\right)^2}\right) \tag{5}$$

(*ii*) Total damage ratio (TDR), finding the value of $v_h^\star$, such as the ratio of total simulated damage – obtained summing over event damage – and total reported damage tends to 1:

$$v_h{}^\star_{\text{TDR}}(j) = \text{argmin}_j \left|\text{TDR}(j) - 1\right| \tag{6}$$

and the optimal parameters are provided in the paper. We chose not to include the formulation of these optimization problems in the prior manuscript because we did not compute the optimal values and used those proposed by Eberenz et al. (2021). However, we will clarify the calibration in the revised version.

Q5/6 - Spatial distribution/National asset dynamics The model appears to assume the spatial distribution of assets are fixed within a country.The paper does allow national assets to change over time, but they do not describe how this is done.

To estimate future exposures along the cyclone track in each scenario, we use the downscaled estimation for the exposed wealth (Eberenz et al., 2020) and the coefficients representing the change between the current state and the future scenario in the framework of the shared-socioecomic pathwways (Jones & O'Neill, 2020; O'Neill et al., 2017; O'Neill et al., 2014).

The local physical exposure at the coordinates (x, y) at time t in a region j in scenario k is defined as follows:

$$\Phi(x,y,j,k,t) = \underbrace{F^{cap}_{\text{GDP}}(j,k,t)}_{\text{Global macro factor}} \cdot \underbrace{F_{pop}(x,y,k,t) \cdot \mathcal{L}_P(x,y)}_{\text{Local factor}}. \tag{7}$$

where $\mathcal{L}_P(x, y)$ is the data from Eberenz et al. (2020) (discussed in question 4). The factor F^{cap}_{GDP} is the projected GDP per capita growth for each region:

$$F^{cap}_{\text{GDP}}(j,k,t) = \frac{\text{GDP}(j,k,t)/\text{GDP}(j,t=2020)}{P(j,k,t)/P(j,t=2020)} \tag{8}$$

where P is the total population of the region retrieved from SSP database (Riahi et al., 2017)[1]. We use the most granular projections of GDP per capita variation curves i.e. the projection for each region. The factor F_{pop} is defined as follows:

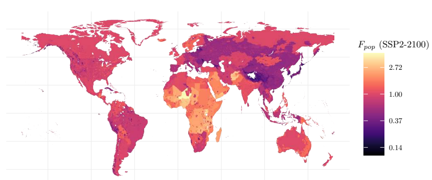
$$F_{pop}(x,y,k,t) = \frac{p(x,y,k,t)}{p(x,y,t=2020)} \tag{9}$$

where $p(x, y, k, t)$ represents the local projections of population Jones and O'Neill (2020).

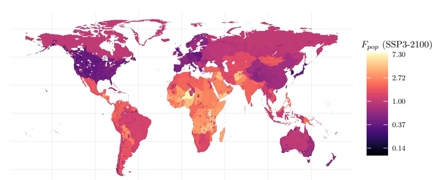
[1] https://tntcat.iiasa.ac.at/SspDb/.

Figure 1: Variation of population exposure in 2100

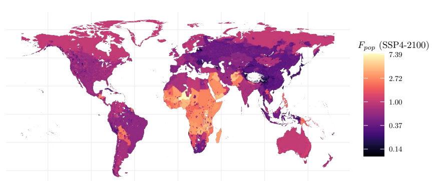
(a) The middle road (SSP2)



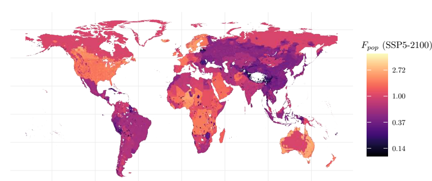
(b) The rocky road (SSP3)



(c) Inequality (SSP4)

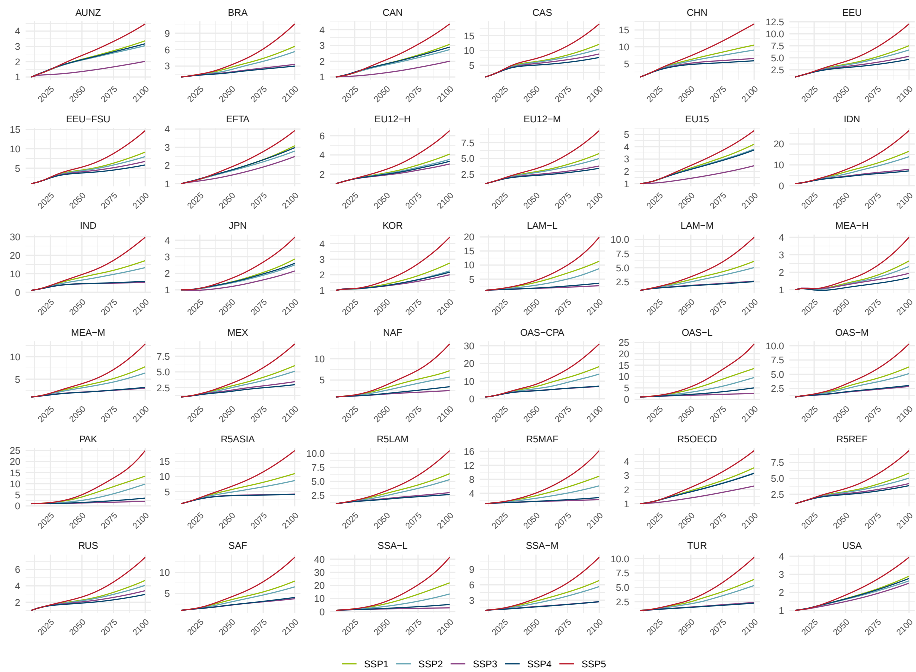


(d) Highway (SSP5)



The scenario-based population grid generation is detailed by Jones and O'Neill (2020) with a last version downscaled at 1km following Gao (2020). This population grid is available every 10 years. We use the closest value in the definition of the exposure.

Figure 2: Regional F_{cap} factor variation in SSPs IIASA database



Source : https://tntcat.iiasa.ac.at/SspDb/.

Q9 - Results: quantiles vs. expected Figure 19 suggests the model predicts a small probability of very large damage but an expected value that is quite small. What explains this large tail to the distribution of damage? Is this simply the probability of a large storm striking a large coastal city? What is the expected value of damage?

Table 1: Simulated expected annual damage (USD Billions)

SSP	RCP	Mean damage USD Bn
Historical	Historical	51,34
SSP2	RCP26	65,36
SSP2	RCP45	89,80
SSP2	RCP85	118,43
SSP3	RCP26	45,74
SSP3	RCP45	63,43
SSP3	RCP85	84,13
SSP4	RCP26	44,24
SSP4	RCP45	60,22
SSP4	RCP85	82,02
SSP5	RCP26	113,09
SSP5	RCP45	155,88
SSP5	RCP85	208,46

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