Cyclone generation Algorithm including a THERmodynamic module for Integrated National damage Assessment (CATHERINA 1.0) compatible with CMIP climate data

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Answer to the review of the revised version

Topical editor comment: Please check the reviewer comments. Particularly, I want to ask you to make clear and well organized manuscript structures for better readability.

We thank the topical editor for the valuable comments. In the new version, we revised the structure of the paper to improve readability and in particular to better distinguish the modeling of (1) hazard intensity, (2) asset exposure, (3) damage modeling and (4) applications and results.

Referee 1

We thank the reviewer for the careful reading of our manuscript and for the insightful comments, which as we hope allowed us to improve the paper.

Q1. The modelers have gone to great effort to reproduce the historic climatology of global tropical cyclones over the last 40 years. The aggregate difference between their simulations of the last 40 years and the historic cyclones is small. There is no similar way to test whether the model captures the future behavior of cyclones in new climate conditions. What you can see is that the future cyclone results are uncertain. There is no clear statistical difference between cyclone characteristics under RCP2.6, RCP4.5, and RCP8.5 by the end of the century. But this may be because the true difference is small not necessarily because the model is flawed

It may have not been clear enough in the last version, but each of the seven climate models considered in this paper does predict significantly stronger winds in higher concentration pathways. To make this appear clearly, in the new version results are now grouped by model instead of by RCP (see Figure 23). Table 1 below shows the average maximum wind speed for each concentration pathway and for each model as well as the average over all models. We see that there is a increase of 5 m/s in terms of maximum wind speed between RCP26 and RCP45 and an increase of 8 m/s between RCP26 and RCP85, which is quite substantial.

Table 1: Mean of the maximum wind speed of synthetic cyclones in representative representation pathways

	RCP26	RCP45	RCP85
ACCESS1-0 (BoM-CSIRO, Australia)		66.42	70.21
bcc-csm1-1-m (BCC, China)	65.65	71.00	71.91
CanESM2 (CCCMA, Canada)	59.22		66.70
GISS-E2-H (NASA, USA)		71.79	75.02
inmcm4 (INM, Russia)		61.42	64.70
IPSL-CM5A-MR (IPSL, France)	60.70	63.89	69.61
NorESM1-ME (NCC, Norway)	57.40	59.02	63.32
Mean	60.74	65.59	68.78

Q2. The modeling of the damage from the cyclones does not seem nearly as careful as the modeling of the cyclones themselves. The paper makes an internally inconsistent assumption that emissions are independent of economic outcomes. However, that is not possible- just as it is not possible for solar radiation to increase without warming ocean temperatures. Without the 3% per year growth of GDP in SSP5, one cannot generate enough emissions to see RCP8.5.

We agree that, at a global level, some RCP-SSP couples cannot be obtained under the assumptions used in state-of-the-art integrated assessment models. In the new version, when illustrating our results at the global level we kept only the most meaningful SSP-RCP couples (see e.g. Figure 24). According to Rogelj et al. (2018) the SSP3 does not allow RCP26, and the RCP85 is reached only in the growth conditions of the SSP5 (cf Table 1) . Note however that SSP2 can by definition be obtained by combination of other SSP at regional level, and cyclone damage depends on regional population and GDP growth, so that it makes sense to consider the couples independently for regional analysis.

Q3. Damage function The paper assumes that the aggregate damage from a cyclone increases with the cube of wind speed. But empirical research has shown that aggregate damage increases faster than the cube (Nordhaus 2010). Further, aggregate damage is more accurately predicted by minimum pressure than maximum wind speed (Mendelsohn et al. 2012).

Our paper uses state of the art damage functions of Eberenz et al. (2021), which are calibrated to optimally represent the fraction of value destroyed by a cyclone with a given wind speed. The damage functions are of the form

$$f(V, v_h^j) = \frac{(\max(V - v_0, 0))^3}{(v_h^j - v_0)^3 + (\max(V - v_0, 0))^3},$$

Figure 1: Rogelj et al. (2018) SSP-RCP matrix

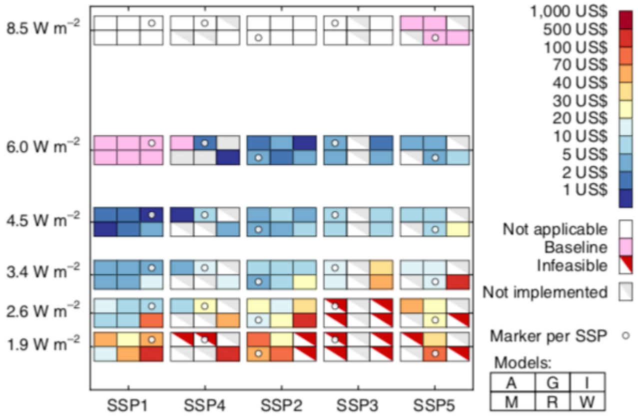

Fig. 5 | Variation of carbon prices over SSP and radiative forcing target space. Values are shown as average global average carbon prices over the 2020–2100 period discounted to 2010 with a 5% discount rate. Mitigation challenges are assumed to increase from left to right across the SSPs (that is, SSP1, SSP4, SSP2, SSP3, SSP5). Each box represents one model–SSP–radiative forcing target combination. A, AIM/CGE; G, GCAM4; I, IMAGE; M, MESSAGE-GLOBIOM; R, REMIND-MAgPIE; W, WITCH-GLOBIOM. All scenarios with a carbon price greater than 0 (that is, all but the baselines) have been designed to reach one of the radiative forcing targets on the vertical axis. Models for which no baseline data are indicated have baselines that result in an end-of-century radiative forcing between 6.0 and 8.5 W m^{-2}.

where v_0 and v_h^j are parameters to be calibrated. For wind speeds just above the threshold v_0, the local damage indeed increases as a third power of the *excess wind speed over threshold*, which is much steeper than the third power of the wind speed. On the other hand, for very strong winds the damage function converges to unity, meaning that all wealth may potentially be wiped out. However, the presence of the cubic excess-over-threshold function does not mean that the total damage will be proportional to the third power of the maximum wind speed over threshold - stronger cyclones will also spend more time over land, increasing the exposed value. Thus, the third power in our damage function cannot be compared with the ninth power in (Nordhaus, 2010). Besides, the very high damage exponent estimated in that paper clearly cannot be used in projections, since even a moderate increase of the wind speed will quickly lead to the entire world GDP being wiped out. Finally, the estimates of (Nordhaus, 2010) may be statistically biased because of missing variables such as local GDP density (as acknowledged by the author himself).

Furthermore, some authors do indeed recommend to use the central pressure as a proxy for damages, however the vast majority of the papers on storm damage estimation use the maximum wind speed (Cusack, 2013; Donat et al., 2011; Elsner et al., 2011; Etienne & Beniston, 2012; Feuerstein et al., 2011; Koks et al., 2020; Leckebusch et al., 2007; Pinto et al., 2007; Schwierz et al., 2010), and state of the art damage functions available in the literature are based on this parameter. Since there is a strong relationship between central pressure and wind speed, using central pressure would not make a significant difference and would require calibrating the damage function for each region from scratch instead of using the results of Eberenz et al., 2021. We therefore choose to build upon the existing literature in the context of this illustration, and use the maximum wind speed as a proxy for damages.

Q4. It is not totally clear, but it appears that the authors have assumed damage will increase proportionally with GDP and population over time. The paper makes no mention of adaptation to tropical cyclones. However, it is quite clear that all countries but the USA have adapted to tropical cyclones (Bakkensen and Mendelsohn 2019). Damage has increased only slightly with GDP and population density in almost every country. Only in the USA have damages increased proportionally with GDP. Even in the USA, is it reasonable to assume that this will continue to 2100?

Indeed, the present framework does not capture future adaptation. We mention that it can be introduced through the local parameter v_h^j of the damage function, and past adaptation is already included in the model through the calibration of this v_h^j. We can see through the shape of damage functions that the USA still suffer significant damage when the wind increases while other countries are more resilient (e.g., Philippines, China, Japan, South Korea, Hong-Kong and Taiwan). To better account for future adaptation and disentangle the impact of different risk components, we now introduce parameters α_1 and α_2 into the model for future exposed value:

$$\Phi(x,y,j,k,t) \quad = \quad \underbrace{(F^{cap}_{\mathrm{GDP}}(j,k,t))^{\alpha_1}}_{\text{Global macro factor}} \cdot \underbrace{(F_{pop}(x,y,k,t))^{\alpha_2} \cdot \mathcal{L}_P(x,y)}_{\text{Local factor}} . \tag{1}$$

The choice $\alpha_1 = \alpha_2 = 1$ assumes linear increase of exposure both with respect to GDP per capita and with respect to local exposed population. Using $\alpha_1 = 1/3$, which is close to the value estimated in (Bakkensen and Mendelsohn, 2019), allows to account for possible future adaptation . The configurations $\alpha_1 = 1, \alpha_2 = 0$ and $\alpha_1 = 0, \alpha_2 = 1$ allow to decompose the risk contribution between GDP and exposed population. Finally, the choice $\alpha_1 = 0, \alpha_2 = 0$ uses the current exposure value with no socioeconomic growth factor.

Figure 2 and Table 2, which are also included in the new version of the paper, present the damage statistics for different combinations of α_1 and α_2. Assuming no future adaptation ($\alpha_1 = \alpha_2 = 1$), and using the historical simulations with ERA5 data as baseline, over the period 2070-2100, we find that the RCP 2.6 scenario, which is in line with the Paris Agreement and keeps global warming below 2°C by 2100, involves a growth of expected global annual financial losses from tropical cyclones by a factor of 4.2 on average. Ignoring socioeconomic and population growth factors ($\alpha_1 = 0$ and $\alpha_2 = 0$) our model suggest that the expected financial loss would grow by a factor of 1.6 due to increasing cyclone intensity. Taking into account adaptation, i.e. limiting the growth of damage with respect to GDP per capita ($\alpha_1 = 1/3$ and $\alpha_2 = 1$), the expected damage would grow by a factor 2.6. In the case of SSP2-RCP 4.5 (between 1.7 and 3.2°C warming by 2100) and SSP5-RCP 8.5 (between 3.2 and 5.4°C warming by 2100), the average expected damage will be multiplied by 5.4 and 14.2 respectively without adaptation. In the RCP8.5 the expected damage will still grow by a factor 2.8 ignoring the change in GDP per capita and population ($\alpha_1 = 0$ and $\alpha_2 = 0$).

Thus, even if the amount of wealth exposed to tropical cyclones in the future is the same as today, our model still projects that the expected annual damage will grow by a factor 1.6 in RCP2.6 and by a factor 2.8 in RCP8.5 due to increasing cyclone intensity.

Q5. The link between simulated tracks and expected future damage is not clear in the paper. The damage depends on the strength of the cyclone, whether it strikes at low or high tide, and whether it hits a major metropolitan area or not. Are there enough simulated cyclones to get the proportion of these different outcomes correct for each country?

If our understanding is correct, the question is whether the number of simulated cyclone trajectories is sufficient to reliably estimate expected future damage. First of all, the main objective of this submission to GMD is not to provide precise estimates of cyclone damage, but to present a new model for cyclone damage estimation. The illustrations in the paper were obtained by simulating 300 representative years for each of the 7 climate models. Since simulations from each model were done independently this gives us 2100 statistically independent samples for yearly cyclone damage. Using our code which is publicly available, anyone can simulate many more trajectories, this is just a question of time and computing power.

This being said, we are confident that at the global level and for large countries, which are hit by cyclones several times every year, the number of simulations is sufficient. We provide the standard errors in table 2 at the global level and it is clear that they are quite small compared to the average damage estimate with relative errors well below 10%. At country level (Table 3), the relative standard errors are higher (up to 20%) and we acknowledge that further launches would improve the results, especially for small countries.

More generally, our estimates are subject to three types of uncertainty: internal climate variability, climate model uncertainty and socio-economic uncertainty related to future exposure growth, adaptation measures and concentration pathways. The first two types of uncertainty are quantified by the standard errors in Table 2, while the last one may be evaluated by performing simulations under different assumptions on adaptation, SSP narratives and representative concentration pathways as illustrated in Figure 2.

Q6. The authors never explain how CATHERINA1.0 can possibly lead to an estimate of the risk to sovereign debt or other major macroeconomic outcomes.

We added a section to illustrate how the additional damage could be integrated in a simplified credit model (section 5.3).

Q7. Most of the future results in the paper do not come from a change in the cyclones themselves but rather in the damage each cyclone causes. This is entirely because the authors are assuming there will be a lot more in harm's way in the future. It is possible but not at all likely that the world will be this foolish.

We agree that socioeconomic factors strongly impact the future damage in accordance with the academic literature (Noy, 2016; Pielke Jr et al., 2008; Weinkle et al., 2018; Weinkle et al., 2012; Ye et al., 2020). However, we are confident that the evolution of future cyclone's intensity also plays a role. To illustrate this, we computed a damage projection assuming no GDP growth (with $\alpha = 0$). We can see in Table 2 that without GDP per capita or population factor the simulated damage increase by 1.6 in the SSP2-RCP26, by 2 in the SSP2-RCP45 and by 2.8 in SSP5-RCP85.

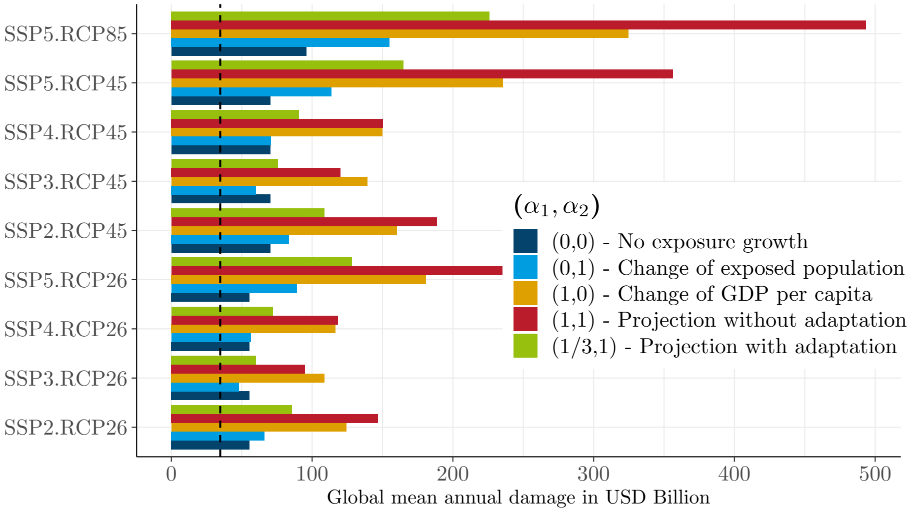

Figure 2: Expected value of global annual damage (in USD billions) in different SSP-RCP and exposure projection hypothesis configurations. The vertical dotted line corrsponds to historical simulations with ERA5 data.

Table 2: Simulation statistics (in USD billion)

SSP	RCP	(α_1, α_2)	Mean	Standard Error	50^{th} perc.	66^{th} perc.	95^{th} perc.
Hist.	ERA-5		34.72	5.14	6.81	15.72	155.94
	IBTrACS		47.59	N.R.	25.72	42.94	160.88
	Rep. EM-DAT		21.1	N.R.	9.19	13.90	62.79
SSP2	RCP26	(1,1)	146.82	11.54	40.06	83.81	583.74
		(1/3,1)	85.74	7.14	21.14	45.38	362.46
		(0,1)	66.14	5.63	15.31	32.64	286.85
		(1,0)	124.31	8.82	39.61	78.72	492.96
		(0,0)	55.51	4.29	15.47	31.35	225.87
	RCP45	(1,1)	188.47	9.75	58.41	121.04	779.64
		(1/3,1)	108.87	5.94	30.81	63.41	483.78
		(0,1)	83.54	4.66	22.56	48.69	376.56
		(1,0)	160.12	7.64	57.59	112.31	637.80
		(0,0)	70.28	3.64	22.43	45.00	300.45
SSP3	RCP45	(1,1)	120.10	6.18	40.61	76.71	478.18
		(1/3,1)	75.60	3.95	25.26	46.68	315.38
		(0,1)	60.18	3.18	19.61	36.83	255.95
		(1,0)	139.20	7.10	46.09	93.13	580.09
		(0,0)	70.28	3.64	22.43	45.00	300.45
SSP4	RCP26	(1,1)	118.24	10.09	27.27	58.87	501.24
		(1/3,1)	72.07	6.18	16.29	35.57	313.51
		(0,1)	56.35	4.85	12.74	27.92	245.90
		(1,0)	116.63	8.96	32.90	67.65	483.69
		(0,0)	55.51	4.29	15.47	31.35	225.87
	RCP45	(1,1)	150.33	8.38	40.57	85.66	664.69
		(1/3,1)	90.75	5.10	24.13	52.11	413.71
		(0,1)	70.62	3.99	18.58	40.51	325.38
		(1,0)	149.90	7.68	47.48	98.81	622.79
		(0,0)	70.28	3.64	22.43	45.00	300.45
SSP5⋆	RCP45	(1,1)	356.26	18.92	104.58	219.89	1 478.45
		(1/3,1)	164.69	9.22	41.80	91.28	730.27
		(0,1)	113.56	6.48	27.15	60.71	530.05
		(1,0)	235.48	10.80	88.32	176.36	910.28
		(0,0)	70.28	3.64	22.43	45.00	300.45
	RCP85	(1,1)	493.56	27.04	140.69	281.66	2 290.21
		(1/3,1)	226.00	12.67	57.58	122.55	1 072.03
		(0,1)	155.05	8.76	36.95	81.72	737.30
		(1,0)	324.71	15.23	127.63	226.70	1 366.12
		(0,0)	95.89	4.81	30.70	59.48	445.36

Note: ⋆ The couple SSP5-RCP26 exists in the integrated assessment modeling literature (Rogelj et al., 2018) but is not displayed because the SSP5 is more likely tied to high concentration scenarios.

Table 3: Country statistics ($\alpha_1 = 1$, $\alpha_2 = 1$)

	SSP	Config	Mean	Std. error	per50	per66	per75	per95
AUS	SSP2	RCP26	13.19	2.46	0.01	0.24	1.26	41.36
		RCP45	22.88	3.10	0.07	0.88	3.35	99.62
		RCP85	24.57	3.51	0.06	0.95	3.59	85.48
	SSP3	RCP26	6.37	1.21	0.01	0.11	0.59	19.47
		RCP45	10.85	1.47	0.04	0.40	1.46	46.30
		RCP85	11.55	1.68	0.03	0.44	1.55	36.53
	SSP4	RCP26	11.79	2.21	0.01	0.21	1.12	36.01
		RCP45	20.27	2.74	0.06	0.77	2.83	87.33
		RCP85	21.71	3.12	0.05	0.85	3.11	73.63
	SSP5	RCP26	25.14	4.66	0.02	0.49	2.62	79.28
		RCP45	44.76	6.17	0.15	1.83	7.12	202.33
		RCP85	48.46	6.82	0.13	2.04	7.42	170.75
CHN	SSP2	RCP26	8.67	0.73	1.42	3.19	5.70	46.16
		RCP45	10.12	0.56	2.32	6.08	10.25	46.55
		RCP85	13.14	0.79	3.06	7.52	12.48	64.57
	SSP3	RCP26	7.31	0.60	1.27	2.87	4.71	39.87
		RCP45	8.68	0.48	2.10	5.40	9.06	39.45
		RCP85	11.26	0.67	2.82	6.77	11.17	53.47
	SSP4	RCP26	5.15	0.44	0.81	1.84	3.17	26.53
		RCP45	5.84	0.33	1.29	3.43	5.71	27.61
		RCP85	7.56	0.46	1.67	4.35	7.05	38.88
	SSP5	RCP26	13.48	1.16	2.07	4.84	8.52	73.92
		RCP45	15.75	0.89	3.46	9.17	15.86	72.24
		RCP85	20.51	1.26	4.63	11.28	19.06	100.22
IND	SSP2	RCP26	12.56	1.47	2.10	5.36	8.87	41.73
		RCP45	16.31	1.73	2.75	7.35	11.00	64.34
		RCP85	18.58	2.03	3.14	7.53	12.80	73.64
	SSP3	RCP26	7.53	0.77	1.45	3.71	6.16	29.12
		RCP45	9.79	0.91	1.91	4.71	7.39	40.15
		RCP85	11.08	1.04	2.19	5.14	8.17	44.18
	SSP4	RCP26	5.61	0.70	0.90	2.34	3.76	17.98
		RCP45	7.23	0.80	1.12	2.89	4.68	29.59
		RCP85	8.11	0.90	1.26	3.00	5.12	29.94
	SSP5	RCP26	19.49	2.46	2.88	7.59	12.62	65.87
		RCP45	25.36	2.91	3.85	10.26	15.58	97.04
		RCP85	29.03	3.45	4.45	10.61	18.55	105.09
JPN	SSP2	RCP26	2.40	0.22	0.28	0.87	1.48	12.27
		RCP45	2.87	0.23	0.33	1.03	2.01	14.08
		RCP85	3.78	0.34	0.54	1.44	2.80	18.06
	SSP3	RCP26	1.38	0.12	0.19	0.57	0.91	7.08
		RCP45	1.63	0.13	0.23	0.66	1.22	7.77
		RCP85	2.16	0.18	0.37	0.96	1.70	10.13
	SSP4	RCP26	2.10	0.19	0.24	0.76	1.29	10.54
		RCP45	2.50	0.21	0.29	0.90	1.70	12.36
		RCP85	3.28	0.29	0.47	1.24	2.37	15.52
	SSP5	RCP26	4.57	0.43	0.51	1.63	2.85	21.28
		RCP45	5.55	0.44	0.64	1.99	4.02	27.04
		RCP85	7.32	0.68	1.02	2.87	5.49	33.72
KOR	SSP2	RCP26	0.85	0.15	0.05	0.24	0.43	3.42
		RCP45	1.23	0.22	0.07	0.24	0.49	5.03
		RCP85	1.33	0.20	0.09	0.31	0.66	5.82
	SSP3	RCP26	0.55	0.10	0.03	0.15	0.28	2.20
		RCP45	0.79	0.14	0.04	0.15	0.29	3.15
		RCP85	0.83	0.12	0.06	0.20	0.40	3.72
	SSP4	RCP26	0.72	0.13	0.04	0.20	0.37	2.86
		RCP45	1.03	0.18	0.05	0.19	0.39	4.19
		RCP85	1.09	0.16	0.07	0.25	0.54	4.87
	SSP5	RCP26	1.88	0.33	0.13	0.53	0.98	8.56
		RCP45	2.75	0.48	0.16	0.54	1.13	11.09
		RCP85	3.05	0.47	0.20	0.71	1.54	12.48
MEX	SSP2	RCP26	9.18	0.91	0.52	2.41	5.26	50.38
		RCP45	12.11	0.92	1.19	4.30	8.29	71.05
		RCP85	15.54	1.15	2.06	6.47	11.93	80.18
	SSP3	RCP26	9.63	0.96	0.56	2.68	5.68	53.54
		RCP45	12.94	0.98	1.32	4.74	9.07	72.48
		RCP85	16.65	1.23	2.25	7.10	12.32	87.09
	SSP4	RCP26	4.76	0.48	0.27	1.23	2.67	28.14
		RCP45	6.11	0.46	0.62	2.04	4.29	34.82
		RCP85	7.72	0.59	1.00	3.07	5.77	38.43
	SSP5	RCP26	10.91	1.09	0.56	2.66	5.86	61.01
		RCP45	14.08	1.09	1.30	4.69	9.41	81.86
		RCP85	18.09	1.36	2.24	7.07	13.52	93.66
USA	SSP2	RCP26	131.80	13.76	17.99	51.49	88.19	588.12
		RCP45	150.20	10.45	26.06	64.81	120.59	747.43
		RCP85	210.89	14.22	39.68	93.71	176.39	1 078.51
	SSP3	RCP26	82.27	8.83	10.46	31.31	52.37	372.94
		RCP45	92.22	6.61	14.40	39.85	72.11	455.65
		RCP85	127.71	8.73	22.04	53.80	101.54	661.06
	SSP4	RCP26	115.13	12.16	15.28	44.81	76.52	512.94
		RCP45	130.25	9.18	21.91	56.20	103.88	649.04
		RCP85	181.86	12.32	32.58	79.12	148.01	944.76
	SSP5	RCP26	258.84	26.45	38.70	102.77	183.70	1 085.39
		RCP45	301.50	20.48	51.24	133.52	249.84	1 450.39
		RCP85	430.81	29.13	81.24	197.55	386.07	2 107.37

References

Bakkensen, L. A., & Mendelsohn, R. O. (2019). Global tropical cyclone damages and fatalities under climate change: An updated assessment. *Hurricane risk* (pp. 179–197). Springer.

Cusack, S. (2013). A 101 year record of windstorms in the netherlands. *Climatic Change*, *116*(3), 693–704.

Donat, M. G., Pardowitz, T., Leckebusch, G., Ulbrich, U., & Burghoff, O. (2011). High-resolution refinement of a storm loss model and estimation of return periods of loss-intensive storms over germany. *Natural Hazards and Earth System Sciences*, *11*(10), 2821–2833.

Eberenz, S., Lüthi, S., & Bresch, D. N. (2021). Regional tropical cyclone impact functions for globally consistent risk assessments. *Natural Hazards and Earth System Sciences*, *21*(1), 393–415.

Elsner, J. B., Lewers, S. W., Malmstadt, J. C., & Jagger, T. H. (2011). Estimating contemporary and future wind-damage losses from hurricanes affecting eglin air force base, florida. *Journal of applied meteorology and climatology*, *50*(7), 1514–1526.

Etienne, C., & Beniston, M. (2012). Wind storm loss estimations in the canton of vaud (western switzerland). *Natural Hazards and Earth System Sciences*, *12*(12), 3789–3798.

Feuerstein, B., Groenemeijer, P., Dirksen, E., Hubrig, M., Holzer, A. M., & Dotzek, N. (2011). Towards an improved wind speed scale and damage description adapted for central europe. *Atmospheric Research*, *100*(4), 547–564.

Koks, E. et al. (2020). A high-resolution wind damage model for europe. *Scientific reports*, *10*(1), 1–11.

Leckebusch, G. C., Ulbrich, U., Fröhlich, L., & Pinto, J. G. (2007). Property loss potentials for european midlatitude storms in a changing climate. *Geophysical Research Letters*, *34*(5).

Nordhaus, W. D. (2010). The economics of hurricanes and implications of global warming. *Climate Change Economics*, *1*(01), 1–20.

Noy, I. (2016). The socio-economics of cyclones. *Nature Climate Change*, *6*(4), 343–345.

Pielke Jr, R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., & Musulin, R. (2008). Normalized hurricane damage in the united states: 1900–2005. *Natural Hazards Review*, *9*(1), 29–42.

Pinto, J. G., Fröhlich, E., Leckebusch, G., & Ulbrich, U. (2007). Changing european storm loss potentials under modified climate conditions according to ensemble simulations of the echam5/mpi-om1 gcm. *Natural Hazards and Earth System Sciences*, *7*(1), 165–175.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 c. *Nature Climate Change*, *8*(4), 325–332.

Schwierz, C., Köllner-Heck, P., Zenklusen Mutter, E., Bresch, D. N., Vidale, P.-L., Wild, M., & Schär, C. (2010). Modelling european winter wind storm losses in current and future climate. *Climatic change*, *101*(3), 485–514.

Weinkle, J., Landsea, C., Collins, D., Musulin, R., Crompton, R. P., Klotzbach, P. J., & Pielke, R. (2018). Normalized hurricane damage in the continental united states 1900–2017. *Nature Sustainability*, *1*(12), 808–813.

Weinkle, J., Maue, R., & Pielke Jr, R. (2012). Historical global tropical cyclone landfalls. *Journal of Climate*, *25*(13), 4729–4735.

Ye, M., Wu, J., Liu, W., He, X., & Wang, C. (2020). Dependence of tropical cyclone damage on maximum wind speed and socioeconomic factors. *Environmental Research Letters*, *15*(9), 094061.