

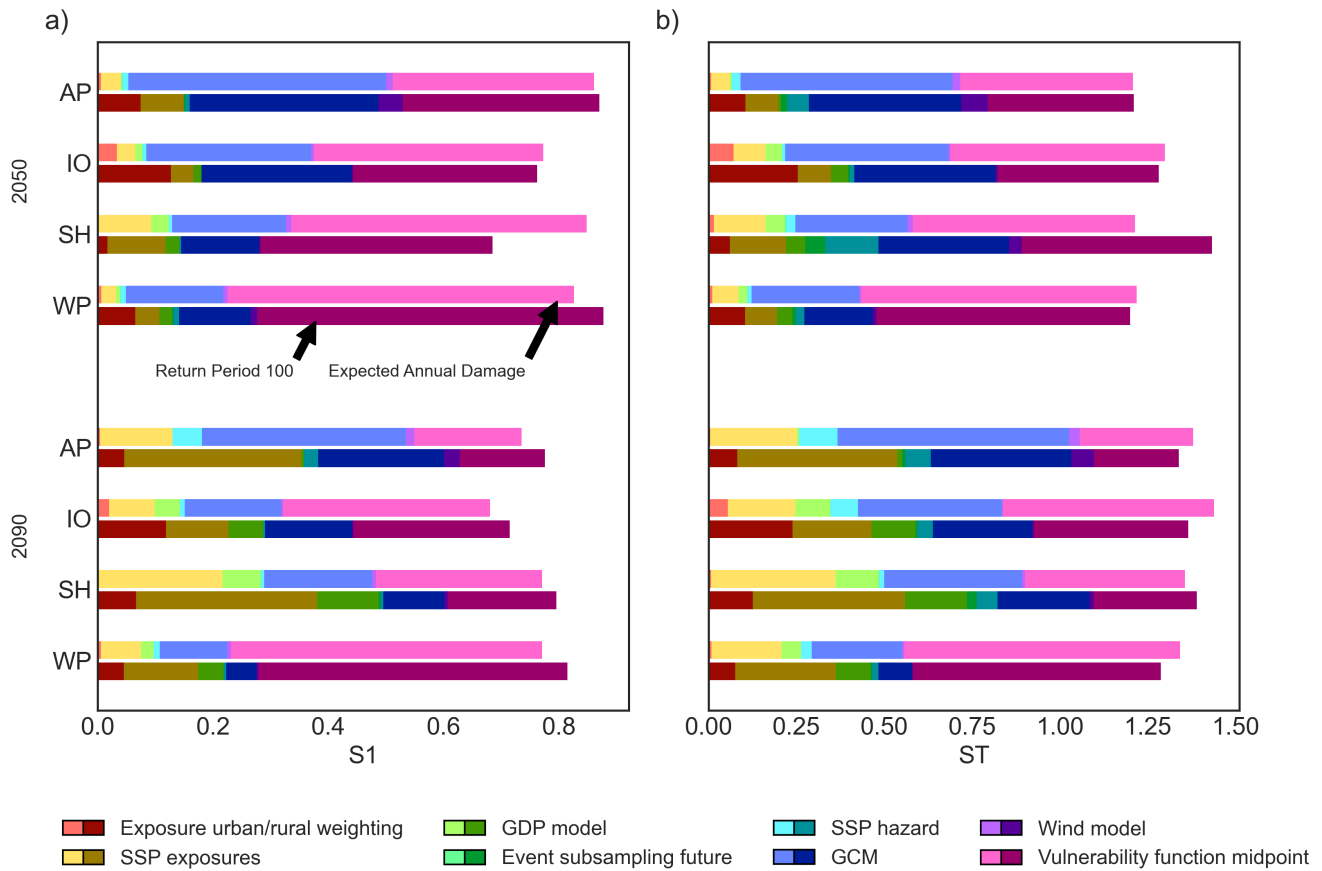
Supplementary Information for article "Uncertainties and sensitivities in the quantification of future tropical cyclone risk"

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Supplementary Figure 1. First- (S1) and total-order (ST) sensitivity indices. First- (a) and total-order (b) sensitivity indices for absolute (calculated in USD) future (2050, 2090) TC risk expressed as expected annual damage (EAD; upper bar) and 100-yr event values (rp100; lower bar) over the four study regions (cf. Fig 1 a) North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP) and all input factors (see Methods and Table 1 therein). Results are grouped by input factors (different colors); *Vulnerability function midpoint* describes the impact function; *Wind model*; *GCM*, *SSP hazard*, *Event subsampling base*, *Event subsampling future* pertain to the hazard component; *GDP model*; *SSP exposure*, *Exposure urban/rural weighting* relate to the exposure.

Supplementary Table 1. Statistical summary metrics of expected annual damage (EAD) change values by 2050 and 2090 in the four regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP), reported for climate change (CC), socio-economic development (SOC), the product of CC and SOC calculated from the sum of their log values (sum) and total TC risk change (total).

AP	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	3.5	4.7	-0.2	0.3	0.8	5.5	23.7
	CC	2090	6.0	9.8	-0.4	0.1	1.3	7.5	57.4
	SOC	2050	0.9	0.3	0.3	0.6	0.8	1.1	1.8
	SOC	2090	2.3	1.3	0.2	1.4	2.0	2.5	5.6
	sum	2050	4.3	4.7	0.3	1.2	1.8	6.5	24.8
	sum	2090	8.3	10.0	0.1	2.1	3.6	10.0	59.7
	total	2050	7.1	8.6	0.2	1.4	2.4	11.1	52.9
	total	2090	20.5	33.6	0.0	2.3	5.4	23.7	321.6

IO	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	2.8	3.7	-0.4	0.1	0.7	4.3	19.5
	CC	2090	4.9	5.4	-0.1	0.7	1.8	8.1	31.0
	SOC	2050	2.6	1.1	0.5	1.9	2.5	3.1	5.7
	SOC	2090	6.7	3.7	0.7	4.2	6.1	8.8	17.6
	sum	2050	5.4	4.0	0.3	2.5	4.2	7.0	24.2
	sum	2090	11.6	6.9	1.1	6.3	10.1	15.3	46.3
	total	2050	13.0	15.5	0.1	2.6	5.3	18.6	121.5
	total	2090	44.8	51.6	1.0	10.0	21.7	64.9	466.6

SH	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	0.9	1.2	-0.6	0.0	0.3	1.8	13.3
	CC	2090	1.3	1.6	-0.7	0.2	0.6	2.2	12.6
	SOC	2050	2.5	1.2	0.5	1.6	2.2	3.1	9.6
	SOC	2090	8.8	6.7	1.1	4.1	7.1	11.6	57.5
	sum	2050	3.4	1.7	0.6	2.1	3.2	4.4	16.4
	sum	2090	10.1	7.2	1.1	4.9	8.3	13.2	61.0
	total	2050	5.5	4.7	-0.2	2.1	4.0	7.6	70.8
	total	2090	20.8	22.2	0.1	6.9	13.3	25.7	341.2

WP	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	2.0	2.4	-0.2	0.3	0.8	3.3	15.7
	CC	2090	2.8	3.1	-0.2	0.6	1.2	4.4	16.1
	SOC	2050	1.6	0.7	0.2	1.1	1.5	1.9	4.1
	SOC	2090	3.3	2.0	0.1	1.8	2.7	4.3	13.2
	sum	2050	3.6	2.6	0.4	1.7	2.6	4.8	18.3
	sum	2090	6.1	3.9	0.4	3.1	4.9	8.2	20.7
	total	2050	6.5	6.3	0.5	2.2	3.7	9.3	51.2
	total	2090	14.3	13.7	0.1	4.8	9.2	19.1	110.1

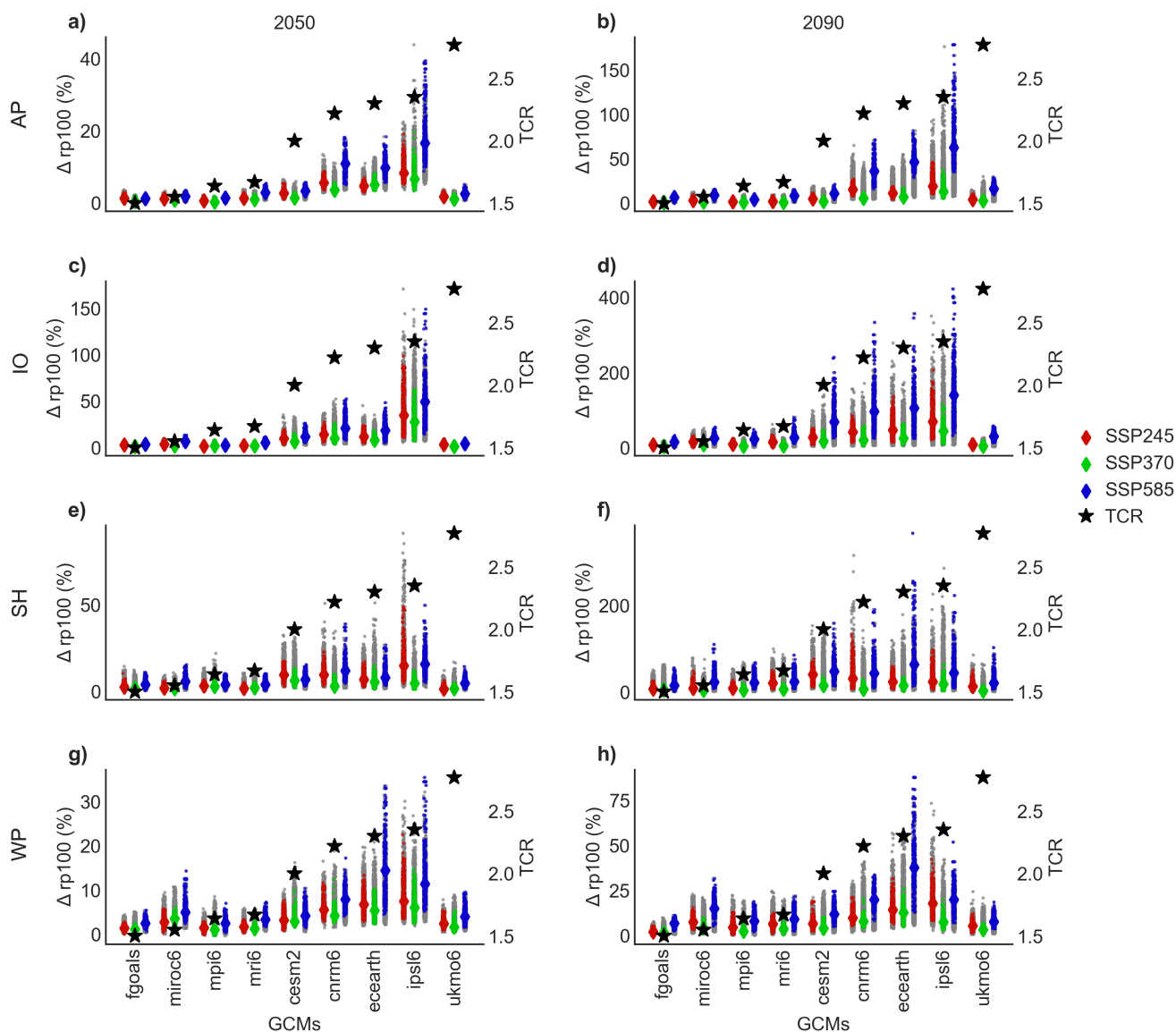
Supplementary Table 2. Statistical summary metrics of 100-yr event change values by 2050 and 2090 in the four regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP), reported for climate change (CC), socio-economic development (SOC), the product of CC and SOC calculated from the sum of their log values (sum) and total TC risk change (total).

AP	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	1.7	2.1	-0.4	0.3	0.7	2.8	18.8
	CC	2090	2.6	3.5	-0.5	0.3	1.0	4.2	33.2
	SOC	2050	0.8	0.3	0.2	0.6	0.7	0.9	2.3
	SOC	2090	2.1	1.4	0.1	1.3	1.6	2.3	8.2
	sum	2050	2.4	2.2	-0.1	1.0	1.5	3.5	20.1
	sum	2090	4.7	3.9	-0.2	1.9	3.2	6.2	37.5
	total	2050	3.6	3.8	-0.1	1.1	1.9	5.4	43.9
	total	2090	9.7	12.7	-0.4	2.2	4.8	12.4	178.6

IO	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	2.0	3.3	-0.6	0.0	0.5	2.7	25.3
	CC	2090	3.1	3.7	-0.3	0.5	1.5	4.4	24.5
	SOC	2050	2.6	1.1	0.3	1.8	2.5	3.2	6.5
	SOC	2090	6.7	3.7	0.5	4.1	6.0	8.8	21.2
	sum	2050	4.6	3.6	0.1	2.4	3.6	5.5	29.5
	sum	2090	9.8	5.5	0.8	5.6	8.7	12.6	42.1
	total	2050	10.3	14.1	0.0	2.5	4.7	12.4	170.9
	total	2090	31.1	36.2	0.6	9.0	17.2	39.6	422.4

SH	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	0.9	1.4	-0.7	0.0	0.4	1.3	20.4
	CC	2090	1.3	1.5	-0.6	0.2	0.7	1.9	10.5
	SOC	2050	2.9	1.7	0.3	1.8	2.5	3.7	10.9
	SOC	2090	11.7	10.4	0.7	4.4	8.1	15.4	67.9
	sum	2050	3.8	2.2	0.3	2.2	3.3	4.8	25.1
	sum	2090	13.0	10.8	0.4	5.3	9.5	17.1	72.0
	total	2050	5.9	5.7	-0.3	2.4	4.1	7.4	91.5
	total	2090	22.1	23.3	0.3	7.4	14.4	28.3	367.6

WP	delta	year	mean	std	min	25%	50%	75%	max
	CC	2050	1.2	1.4	-0.6	0.2	0.7	1.7	11.8
	CC	2090	1.5	1.8	-0.5	0.4	0.9	2.2	18.8
	SOC	2050	1.7	0.8	-0.1	1.2	1.6	2.1	4.6
	SOC	2090	3.9	2.7	-0.1	2.0	3.2	4.9	18.0
	sum	2050	2.9	1.7	-0.3	1.6	2.5	3.7	13.7
	sum	2090	5.4	3.4	-0.2	2.8	4.6	7.1	26.2
	total	2050	4.5	3.7	-0.4	1.9	3.4	5.9	35.5
	total	2090	9.1	7.6	-0.2	4.0	7.0	11.7	87.7



Supplementary Figure 2. TC risk change from different global climate models (GCMs) and emission scenarios.

Model simulations of the expected 100-yr event (rp100) change by 2050 (a, c, e, g) and 2090 (b, d, f, h) attributed to the nine GCMs and three emission scenarios underlying the TC hazard sets (see Methods). GCMs are ordered by increasing transient climate response (TCR) values (Supplementary Table 7), which are shown as black stars on a secondary y-axis. Model realization of matching hazard and exposure scenarios are marked in color (SSP245 in red, SSP370 in green, SSP585 in blue) with diamond-shaped markers delineating the median of their distribution. Results are shown over the four study regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP) (cf. Fig. 1 a)).

Supplementary Table 3. TC hazard frequency values for event sets of the nine different GCMs and three emission scenarios in the two future time periods (2050, 2090) and four study regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP). Frequency values above the multimode average (last row) are highlighted in red.

GCM	emission scenario	AP		IO		SH		WP	
		2050	2100	2050	2100	2050	2100	2050	2100
CESM2	SSP245	13.47	11.99	7.52	7.47	15.97	19.67	19.53	16.88
CESM2	SSP370	12.53	10.64	7.31	8.15	15.82	20.36	20.22	20.99
CESM2	SSP585	12.70	9.71	7.09	10.74	16.15	22.79	18.37	19.22
CNRM6	SSP245	15.16	15.63	5.53	5.85	10.94	11.19	21.61	22.05
CNRM6	SSP370	14.83	15.69	5.40	6.24	11.44	11.76	21.61	23.42
CNRM6	SSP585	15.93	15.96	5.51	6.21	11.53	10.94	22.13	25.32
ECEARTH	SSP245	19.57	19.76	6.17	7.79	13.42	13.53	25.35	24.79
ECEARTH	SSP370	22.65	23.71	5.81	7.84	13.25	12.89	25.25	26.58
ECEARTH	SSP585	21.81	28.38	6.89	9.12	13.85	13.72	26.33	27.64
FGOALS	SSP245	9.32	8.56	2.92	2.99	8.95	8.66	14.76	13.93
FGOALS	SSP370	9.04	7.73	2.80	2.99	8.87	8.61	14.77	13.99
FGOALS	SSP585	8.97	7.81	2.97	3.17	9.06	8.93	14.29	14.60
IPSL6	SSP245	19.42	20.44	7.78	7.89	12.88	11.38	23.29	24.56
IPSL6	SSP370	18.83	20.51	7.49	7.45	12.50	11.38	22.26	26.52
IPSL6	SSP585	20.06	23.76	8.29	8.91	12.01	11.35	25.04	29.61
MIROC6	SSP245	10.74	11.06	3.20	3.73	9.15	9.05	17.54	18.78
MIROC6	SSP370	10.76	11.72	3.09	4.14	8.87	9.79	18.50	18.47
MIROC6	SSP585	11.24	12.42	3.86	4.42	9.68	9.39	18.28	21.37
MPI6	SSP245	9.73	8.78	2.86	3.54	9.68	9.32	17.62	17.50
MPI6	SSP370	9.91	7.73	2.29	3.21	9.16	9.31	16.34	14.91
MPI6	SSP585	9.66	8.34	2.69	3.60	9.45	9.08	16.88	16.27
MRI6	SSP245	11.27	9.86	3.07	3.80	8.27	9.12	17.08	15.88
MRI6	SSP370	10.09	7.93	2.72	3.59	8.52	9.13	15.03	14.83
MRI6	SSP585	10.81	9.12	3.62	4.87	8.21	8.98	15.84	15.74
UKMO6	SSP245	11.51	12.42	3.59	3.55	8.91	8.55	17.58	17.72
UKMO6	SSP370	11.58	12.03	3.04	3.84	8.78	8.81	15.93	16.81
UKMO6	SSP585	11.51	12.91	3.52	4.32	8.96	8.71	18.38	16.11
average		13.45	13.50	4.70	5.53	10.90	11.35	19.25	19.80

Supplementary Table 4. TC hazard intensity change values for event sets of the nine different GCMs and three emission scenarios in the two future time periods (2050, 2090) and four study regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP). Intensity values above the multimode average (last row) are highlighted in red. Note, the intensity change is calculated relative to the historical period (1995-2014) and we used the Holland (2008)¹ wind model for the hazard generation.

GCM	emission scenario	AP		IO		SH		WP	
		2050	2100	2050	2100	2050	2100	2050	2100
CESM2	SSP245	4.22	4.53	3.97	5.50	3.90	4.28	5.26	5.26
CESM2	SSP370	4.19	3.77	4.27	6.19	3.51	5.36	4.96	7.49
CESM2	SSP585	4.47	3.93	4.25	8.15	3.36	5.80	4.91	9.58
CNRM6	SSP245	7.11	7.97	3.17	4.00	4.71	4.14	7.06	7.65
CNRM6	SSP370	6.84	8.09	3.31	4.20	4.69	4.32	7.64	8.37
CNRM6	SSP585	7.58	9.18	3.63	4.46	4.62	3.86	6.87	8.76
ECEARTH	SSP245	5.25	6.09	2.82	3.83	4.61	4.15	5.23	6.39
ECEARTH	SSP370	6.45	7.30	2.72	3.82	3.83	4.65	5.04	6.64
ECEARTH	SSP585	6.32	8.74	3.04	4.57	3.78	5.98	5.86	8.71
FGOALS	SSP245	0.16	-0.31	0.66	0.91	0.78	1.02	1.31	1.05
FGOALS	SSP370	-0.07	-0.80	0.44	0.97	1.19	2.07	1.45	1.13
FGOALS	SSP585	0.08	-0.26	0.67	2.47	1.17	1.85	1.10	2.91
IPSL6	SSP245	6.38	7.71	5.18	5.85	5.90	6.11	8.12	9.07
IPSL6	SSP370	6.22	8.17	4.73	5.49	5.72	5.12	7.50	7.44
IPSL6	SSP585	7.31	8.74	5.32	6.79	5.61	5.74	8.03	7.75
MIROC6	SSP245	0.98	1.57	0.55	1.61	-0.66	0.42	0.41	1.57
MIROC6	SSP370	1.23	1.57	0.70	1.63	-0.62	1.34	1.09	2.55
MIROC6	SSP585	1.42	2.92	1.17	2.49	0.01	0.78	2.45	3.63
MPI6	SSP245	0.27	0.04	-0.70	0.14	-0.58	-0.80	1.30	0.83
MPI6	SSP370	0.70	-0.04	-0.52	-0.12	-0.49	-0.78	0.76	1.28
MPI6	SSP585	0.41	0.56	-0.16	0.39	-0.79	-0.36	0.61	2.25
MRI6	SSP245	1.69	1.69	0.28	1.68	-0.03	0.86	0.43	0.35
MRI6	SSP370	0.88	1.97	0.64	1.51	0.10	0.43	-0.51	0.36
MRI6	SSP585	1.96	2.75	1.23	2.17	-0.10	2.00	0.42	2.61
UKMO6	SSP245	1.48	2.10	0.60	1.28	-0.08	0.17	1.17	0.94
UKMO6	SSP370	1.94	3.17	0.43	1.17	0.13	1.19	0.10	1.47
UKMO6	SSP585	1.93	4.16	0.58	1.97	-0.17	1.06	1.23	1.76
average		3.24	3.90	1.96	3.08	2.00	2.62	3.33	4.36

Supplementary Table 5. TC hazard intensity change values for event sets of the nine different GCMs and three emission scenarios in the two future time periods (2050, 2090) and four study regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP). Intensity values above the multimode average (last row) are highlighted in red. Note, the intensity change is calculated relative to the historical period (1995-2014) and we used the Emanuel and Rotunno (2011)² wind model for the hazard generation.

GCM	emission scenario	AP		IO		SH		WP	
		2050	2100	2050	2100	2050	2100	2050	2100
CESM2	SSP245	5.09	5.72	4.47	6.39	4.75	5.58	5.82	5.85
CESM2	SSP370	5.13	5.22	4.97	7.94	4.23	7.18	5.69	9.44
CESM2	SSP585	5.51	6.04	5.02	10.35	4.36	8.10	5.53	11.79
CNRM6	SSP245	8.61	9.91	4.17	5.06	6.31	5.81	8.86	9.56
CNRM6	SSP370	8.33	10.19	4.37	5.53	6.25	6.24	9.46	10.45
CNRM6	SSP585	9.31	11.61	4.64	5.96	6.38	5.84	8.59	11.15
ECEARTH	SSP245	6.12	7.09	3.13	4.29	5.29	4.92	6.12	7.29
ECEARTH	SSP370	7.23	8.63	3.05	4.60	4.52	5.87	5.88	8.41
ECEARTH	SSP585	7.37	10.73	3.34	5.83	4.51	7.75	6.90	11.17
FGOALS	SSP245	0.79	0.31	1.07	1.31	1.04	1.31	1.78	1.40
FGOALS	SSP370	0.70	0.28	0.76	1.49	1.44	2.49	1.90	1.59
FGOALS	SSP585	0.84	1.10	1.04	3.27	1.42	2.36	1.42	3.63
IPSL6	SSP245	7.37	9.19	5.89	6.81	7.18	7.49	9.64	10.70
IPSL6	SSP370	7.36	9.85	5.56	6.56	7.07	6.54	9.03	9.08
IPSL6	SSP585	8.61	11.09	6.24	8.43	6.89	7.28	9.78	9.71
MIROC6	SSP245	1.24	2.04	0.53	1.59	-0.69	0.58	0.53	2.05
MIROC6	SSP370	1.64	2.26	0.74	1.74	-0.61	1.81	1.33	3.17
MIROC6	SSP585	1.74	3.78	1.19	2.86	0.10	1.20	2.91	4.61
MPI6	SSP245	0.47	0.26	-0.62	0.26	-0.46	-0.70	1.60	1.06
MPI6	SSP370	0.92	0.31	-0.38	0.46	-0.38	-0.29	1.02	2.24
MPI6	SSP585	0.65	1.24	-0.15	1.28	-0.67	0.45	0.85	3.50
MRI6	SSP245	1.92	1.85	0.28	1.81	0.00	1.16	0.70	0.73
MRI6	SSP370	1.17	2.47	0.60	1.80	0.23	1.09	-0.29	1.27
MRI6	SSP585	2.26	3.72	1.29	2.99	0.12	3.31	0.71	4.02
UKMO6	SSP245	2.22	2.86	0.72	1.56	0.04	0.52	1.37	1.59
UKMO6	SSP370	2.67	4.66	0.54	1.87	0.24	2.24	0.26	2.87
UKMO6	SSP585	2.72	5.98	0.76	3.22	0.02	2.64	1.69	3.50
average		4.00	5.13	2.34	3.90	2.58	3.66	4.04	5.62

Supplementary Table 6. Transient climate response (TCR) and equilibrium climate sensitivity (ECS) values for the nine GCMs, including a screen if the models fall into the likely range of projected TCR or ECS. Values are obtained from Hausfather et al. (2022)³ supplementary data. The last column groups GCMs into two clusters of low and medium-high TC risk change according to the results of Section 2.3 in the main text.

Model	TCR	TCR screen (likely)	ECS150	ECS130	ECS screen (likely)	TC risk increase
CESM2	2.00	yes	5.15	6.43	no	med-high
CNRM-CM6-1	2.22	no	4.90	4.76	no	med-high
EC-Earth3	2.30	no	4.26	N/A	no	med-high
FGOALS-g3	1.50	yes	2.87	3.10	yes	low
IPSL-CM6A-LR	2.35	no	4.70	5.18	no	med-high
MIROC6	1.55	yes	2.60	2.59	yes	low
MPI-ESM1-2-HR	1.64	yes	2.98	3.34	yes	low
MRI6-ESM2-0	1.67	yes	3.13	3.42	yes	low
UKESM1-0-LL	2.77	no	5.36	5.49	no	low

Supplementary Table 7. Spearman's rank correlation coefficients (ρ) between the TCR values (Supplementary Table 7) and the calculated TC risk metrics (change in expected annual damage (EAD) and 100-yr event (rp100)) in the future (2050, 2090) in the four study regions North Atlantic/Eastern Pacific (AP), North Indian Ocean (IO), Southern Hemisphere (SH), and North Western Pacific (WP) and for the entire globe (regions combined). Correlation coefficients between TCR and global hazard frequency and intensity are reported as well.

risk metric	year	region	ρ	pval
EAD	2050	AP	0.71	0.0
		IO	0.52	0.0
		SH	0.44	0.0
		WP	0.60	0.0
		global	0.54	0.0
EAD	2090	AP	0.66	0.0
		IO	0.48	0.0
		SH	0.33	0.0
		WP	0.57	0.0
		global	0.48	0.0
rp100	2050	AP	0.65	0.0
		IO	0.48	0.0
		SH	0.34	0.0
		WP	0.50	0.0
		global	0.46	0.0
rp100	2090	AP	0.66	0.0
		IO	0.45	0.0
		SH	0.27	0.0
		WP	0.41	0.0
		global	0.39	0.0
hazard metric	year	region	ρ	pval
frequency	2050	global	0.65	0.00
	2090	global	0.63	0.00
intensity	2050	global	0.59	0.00
	2090	global	0.57	0.00

Supplementary Table 8. List of CMIP6 models used in the downscaling of tropical cyclone event sets.

Institution	Model	Short name	Source
National Center for Atmospheric Research	CESM2	CESM2	Danabasoglu et al. (2020) ⁴
Centre National de Recherches Météorologiques	CNRM-CM6-1	CNRM6	Voltaire et al. (2019) ⁵
EC-Earth consortium	EC-Earth3	ECEARTH	EC-Earth Consortium (2019) ⁶
Institute of Atmospheric Physics, Chinese Academy of Sciences	FGOALS-g3	FGOALS	Li et al. (2019) ⁷
Institut Pierre Simon Laplace	IPSL-CM6A-LR	IPSL6	Hourdin et al. (2016) ⁸
Japan Agency for Marine-Earth Science and Technology	MIROC6	MIROC6	Tatebe et al. (2019) ⁹
Max Planck Institute	MPI-ESM1-2-HR	MPI2	Müller et al. (2018) ¹⁰
Meteorological Research Institute, Tsukuba, Japan	MRI6-ESM2-0	MRI6	Yukimoto et al. (2019) ¹¹
United Kingdom Met Office	UKESM1-0-LL	UKMO6	Sellar et al. (2020) ¹²

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