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Tropical cyclone risk for global ecosystems in a changing climate

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Coastal ecosystems provide a range of services including erosion prevention, clean water provision and carbon sequestration. With climate change, the rapid change in frequency and intensity of tropical cyclones may alter the composition of the ecosystems themselves potentially degrading the services they provide. Here we classify global ecoregions into dependent, resilient and vulnerable and show that a combined 9.4% of the surface of all terrestrial ecosystems is susceptible to transformation due to cyclone pattern changes between 1980–2017 and 2015–2050 under climate scenario SSP5-8.5 using the STORM model. Even for the most resilient ecosystems already experiencing winds >60 m s^{-1} regularly, the average interval between two storms is projected to decrease from 19 to 12 years which is potentially close to their recovery time. Our study advocates for a shift in the consideration of the tropical cyclone impact from immediate damage to effects on long-term natural recovery cycles.

Species composing ecosystems have co-evolved with the geoclimatic conditions at their location. Hence, they are not only adapted to the average climatic conditions, such as the temperature or precipitation regimes, but also to extreme events such as floods, wildfires or tropical cyclones. Climate change is rapidly modifying the climatic conditions and this has been shown to lead to a shift in suitable conditions for a large number of species among insects, vertebrates and plants[1]. Shifting abiotic conditions may alter the compositions of larger ecosystems and lead to profound modifications of their functioning. Complementing shifts in means, climate change is rapidly modifying the regional and temporal patterns of extreme events[2], which might further impact global ecosystems. A change in frequency and intensity of extreme weather events might even cause more rapid and durable shifts in ecosystems than the gradual increase of the means of climate values[3–6].

Climate change is expected to modify the intensity and frequency of tropical cyclones and their geographical impacts in non-trivial patterns[7–9]. Tropical cyclones are intense low-pressure systems that form over warm ocean waters which can produce strong winds, heavy rainfall and storm surges. Together with the possible ensuing flooding and landslides, they can cause wide-scale disturbances for the ecosystem in the path of the storm and beyond[10,11]. Tropical cyclones may affect all dimensions, including the biogeochemistry, hydrography, mobile biota, sedentary biota or microbiota of ecosystems[5,12]. As the climate warms, the surface waters of the oceans become warmer, providing more fuel for tropical storms to grow in strength[13]. Further, the amount of moisture in the atmosphere is expected to increase, which can lead to more intense rainfall during tropical storms, and the rising sea level will expose new areas to storm surges[14]. Overall, the frequency of high-intensity storms is expected to increase, while low-intensity storms are expected to decrease[8]. Large regional deviations are however expected, such as an overall frequency increase in the northeast Pacific[8]. Beyond the changes in cyclone severity, changes in regional patterns are likely to expose areas that have not historically experienced these types of storms[8,15,16], yielding unprecedented consequences for not only human societies[9,17] but also natural ecosystems[12,18,19].

Tropical cyclones have been shown to impact ecosystems through various processes, such as wind throw, causing defoliation and canopy damage, which can lead to reduced photosynthesis, growth and productivity of trees, as well as increased susceptibility to pest and disease

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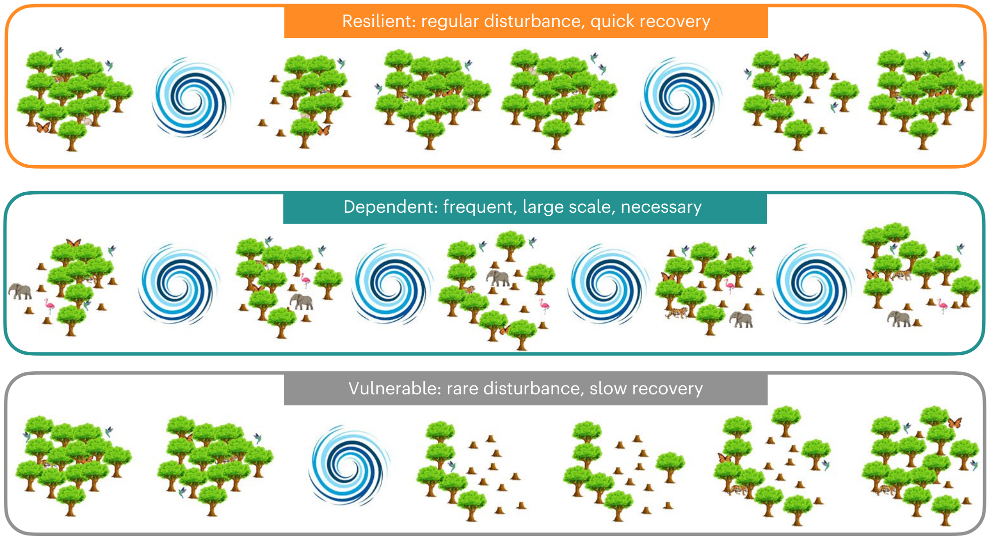

	Area affected	Recovery time (years)	At-risk threshold
Resilient	20–80%	1–20	+20%
Dependent	>80%	1–20	±5%
Vulnerable	<20%	>20	+10%

Fig. 1 | Vulnerability of ecosystems to extreme weather events. The vulnerability is derived from the historical occurrence patterns taking a long-term systemic perspective. Ecosystems are resilient if historically high levels of disturbance primed them to be able to recover quickly from frequent tropical storms, dependent if the disturbance regime is such that it is an integral force in structuring the ecosystem or vulnerable if they have been rarely exposed to tropical cyclones and thus are likely to have difficulty recovering from increased disturbances. Moreover, if the occurrence patterns change substantially in a short period, for instance due to climate change, the ecosystems are at risk. Here we parametrize the vulnerability and the climate change risk indicators as shown in the table at the bottom. Resilient ecosystems have a minimum average return period of 20 years over 20–80% of their area and an increase of 20% of the return period over that area results in climate risk. Dependent ecosystems have a minimum average return period of 20 years over 80–100% of their area and an increase or decrease by 5% of the return period over that area results in climate risk. Ecosystems are vulnerable otherwise and an increase by 10% of the return period over at least 20% of the area results in climate risk. Furthermore, ecosystems with return periods longer than 250 years are always vulnerable and newly at risk if the frequency crosses this threshold. Credit: icons, Freepik.com.

outbreaks[18,20]. Heavy rain can cause landslides, soil erosion and nutrient loss[21] potentially causing decreased growth and productivity of vegetation, but also direct vegetation mortality[22], especially when already disturbed by anthropogenic land use[23]. Storms can add large amounts of saltwater to coastal freshwater and terrestrial ecosystems disrupting habitats[24]. Together, disturbances from tropical storms can alter the structure and composition of ecosystems, change the habitat quality for animal species and lead to mortality or displacement of biota[25,26], causing local loss of biodiversity[27,28]. For instance, extreme weather events account for 11% of global mangrove forest loss between 2000 and 2020[29]. Previous methods, such as remote sensing and field studies have sought to quantify the immediate impact of tropical storms on forests[30], but not how they may modify ecosystems over longer periods. Several studies on the effect of storms on ecosystems have been conducted, most focused on explicit relation for specific species[31], part of the vegetation[19,32] or for regional ecosystems[12]. Estimating the potential effect of tropical cyclones on global ecosystems with a long-term perspective is limited by methodological challenges[19,33–37] and the absence of systematic measurements of ecological response across ecosystems[38].

Ecosystems adapt to abiotic conditions over a timescale from decades to centuries and most ecosystems are expected to be in equilibrium with pre-anthropocene climate[39]. The statistical historical exposure of ecosystems to tropical storms can be quantified using modelled wind fields, which offer an indirect measure of how much they can accommodate disturbance (Fig. 1). Depending on the historical frequency of tropical cyclones and the potential adaptation of ecosystems to these disturbances, ecosystems can be classified as resilient if historically high levels of disturbance primed them to be able to recover quickly from frequent and intense tropical storms. In contrast, ecosystems rarely exposed to tropical cyclones in the past are likely to have difficulty recovering from increased disturbances and can be classified as vulnerable. For some ecosystems, the disturbance regime is such that it is an integral force in structuring the ecosystem that is then dependent on this force[40,41]. While tropical cyclones may appear as purely destructive extreme events, they generate regular disturbances that naturally structure the dynamics of ecosystems[42]. The impacts of tropical cyclones are immediately followed by recovery and therefore those ecosystems are in a state of dynamic equilibrium[12,18,19,33,43]. Furthermore, tropical cyclones may support the regulation of certain ecological processes such as water provision, soil enrichment with nutrients, restoration of ecological niches, support seed dispersion or temporarily mix the salinity and phytoplankton content in estuaries[44]. Thus, tropical cyclones can also play a functional role, shaping specific ecosystems[33,45,46] and being a necessary perturbation to maintain their functionality, thereby supporting biodiversity following the intermediate disturbance hypothesis[47–51].

Coastal ecosystems are known to provide a large number of essential services to human societies such as nutrient cycling, erosion control, hatchery for fishes and crustaceans, water purification, cultural importance, tourism, carbon sequestration and circularly, protection from cyclones[52–54]. Thus, it is timely to assess the risk of tropical cyclones under climate change to ecosystems[55] and integrate this knowledge into the socioeconomic risk assessment methodologies established in the context of the Intergovernmental Panel on Climate Change (IPCC)[2] and Sendai disaster risk reduction[56] frameworks. We propose here using the open-source CLIMADA risk modelling platform[57] to investigate the vulnerability of global coastal ecosystems to tropical cyclones at a global scale, inspired also by the panarchy principles[58]. More precisely, using the STORM model

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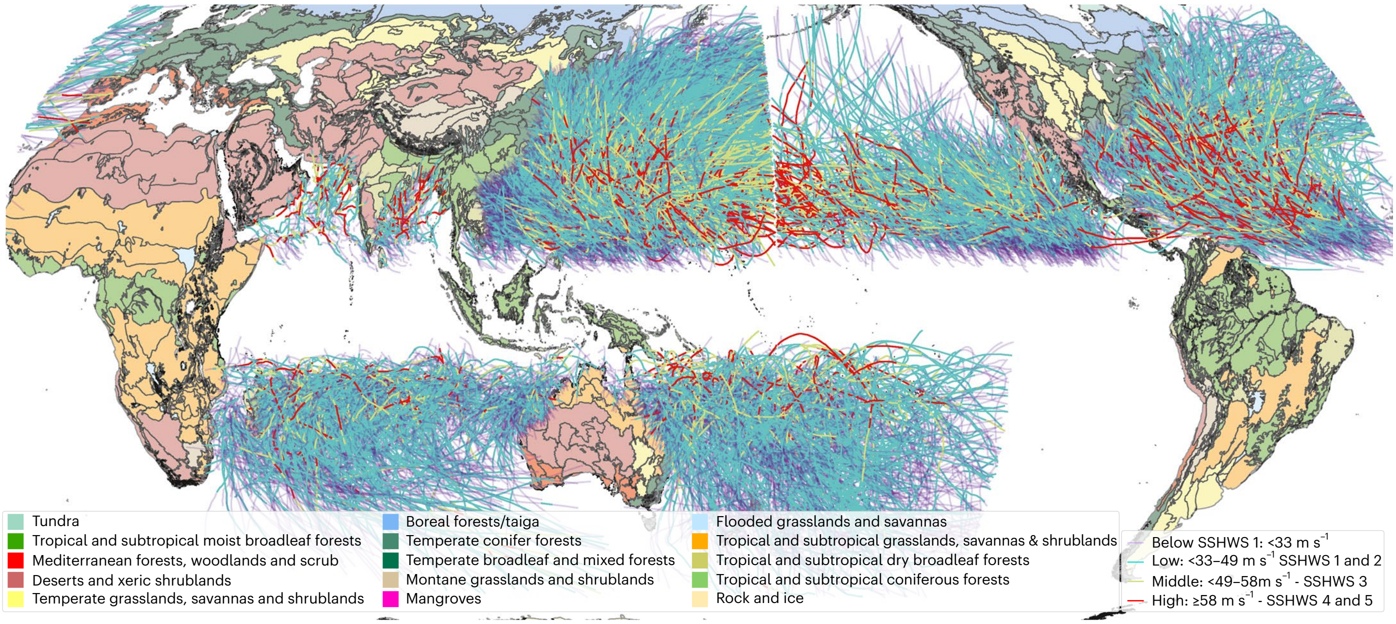

Fig. 2 | Illustrative subset of randomly sampled simulated probabilistic tropical cyclones tracks with ecoregions. The tracks are from the baseline STORM dataset[59], which is based on the historical track records from 1980 to 2017, and these are used to determine the vulnerability of ecosystems (ecoregions are shown as polygons divided into 15 biomes indicated by colours). The sustained 1 min wind speed intensities are divided into low, middle and high intensities based on the Saffir–Simpson scale (SSHWS) (here shown for the centre of each cyclone track). Note that the sharp boundaries of certain tracks at the antimeridian are an artefact of the STORM dataset.

datasets STORM-B and STORM-C[15,59] we will study the spatial frequency distributions of the storms under current climatic conditions (1980–2017) to then derive where climate change under the shared socio-economic pathway SSP5-8.5 in 2015–2050 might put ecosystems at risk of modification.

Tropical cyclone impact on ecosystems

For modelling the tropical cyclone disturbance, we use the STORM (synthetic tropical cyclone generation model) synthetic probabilistic set of tracks generated statistically using as baseline the historical records from 1980 to 2017[59]. Furthermore, we use the ecoregions introduced by ref. 60 as the definition of global ecosystems (or bio-regions) for which tropical cyclone disturbance is assessed. As shown in Fig. 2, tropical cyclones are regionally confined phenomena. Hence, ecosystems described on the level of regionally defined ecoregions (indicated by polygon shapes), which combine both biological composition and geographic information, are well suited to study the relation with tropical cyclones. In contrast, ecosystems defined on the level of biomes (indicated in colours in Fig. 2) would have too large geographical extents across continents. For instance, the biome tropical and subtropical moist broadleaf forests can be found in the Amazon and Congo basins, which are storm-free, as well as in the Yucatan Peninsula in Mexico and the Philippines, which experience some of the highest tropical cyclone activity worldwide. For each cyclone track, we derive a corresponding wind field using the parametric Holland 2008 model as implemented in CLIMADA[61,62], which is then used as a measure of their severity.

Since it is expected that the impact at different intensities differs vastly, we separate wind speeds into three categories: low (L), middle (M) and high (H) intensity storms (Fig. 2; Methods). For each grid point on land and each storm category, we derive the expected annual frequency as shown in Extended Data Fig. 1. We find that 12.3% of the area of all terrestrial coastal ecosystems experience a tropical cyclone of at least low intensity with a frequency of 1 in 250 years over their territory on average. This is the basis for determining the vulnerability of ecosystems to tropical cyclones.

Impact categories

We classify ecoregions as being vulnerable, resilient or dependent[63] with regards to tropical cyclones for each of the three intensity categories (L, M and H) (Fig. 1), inspired also by the panarchy principles[58] and ecosystems dynamics model assumptions[33]. A vulnerable ecosystem has rarely been exposed to the disturbance, and the damages of tropical cyclones are high since it has probably not evolved resilience and recovery mechanisms (at most 20% of the area is affected with a probability of 1 in 20 years). In contrast, a resilient ecosystem has been exposed to tropical cyclone disturbance historically frequently (>1 in 20 years) on a large portion of its area (>20%) and thus has evolved to cope with the destructive effects and recovers on timescales faster than the historical disturbance frequency. We classify ecosystems as dependent when the disturbance is naturally present at high frequency (>1 in 20 years) over most of its geographical extent (>80%) and thus its natural ecological dynamics may depend on these regular disturbances[64]. We thus implicitly assume that inland areas are relevant for the recovery of the coastal areas if they belong to the same ecological system of interlinked species[27,65,66]. On the basis of these definitions and using the tropical cyclone frequency maps (Extended Data Fig. 1), we determine the vulnerability of all ecoregions as shown in Fig. 3. The exact parametrization is summarized in Fig. 1 and described in the section 'Vulnerability of ecosystems'. While there are clear distinctions in the frequency, intensity and area of exposure to tropical cyclones among ecoregions (Extended Data Fig. 2a,b), the distributions are continuous and the response of ecoregions close to the threshold is less certain. To account for this uncertainty, we run a global uncertainty and sensitivity analysis[67–69] (Supplementary Information) considering variation in the position of all thresholds for classifying ecoregions into dependent, vulnerable and resilient (Supplementary Table 1). We find that the selection of the thresholds does result in shifting resilience and dependence for certain ecoregions (Extended Data Figs. 3a and 4a), but is not the dominant factor for the uncertainty in the risk under climate change (Extended Data Fig. 4b).

Using this classification (summarized in Fig. 1), we find that resilient ecoregions cover an area of 2.5 million km^2, the dependent

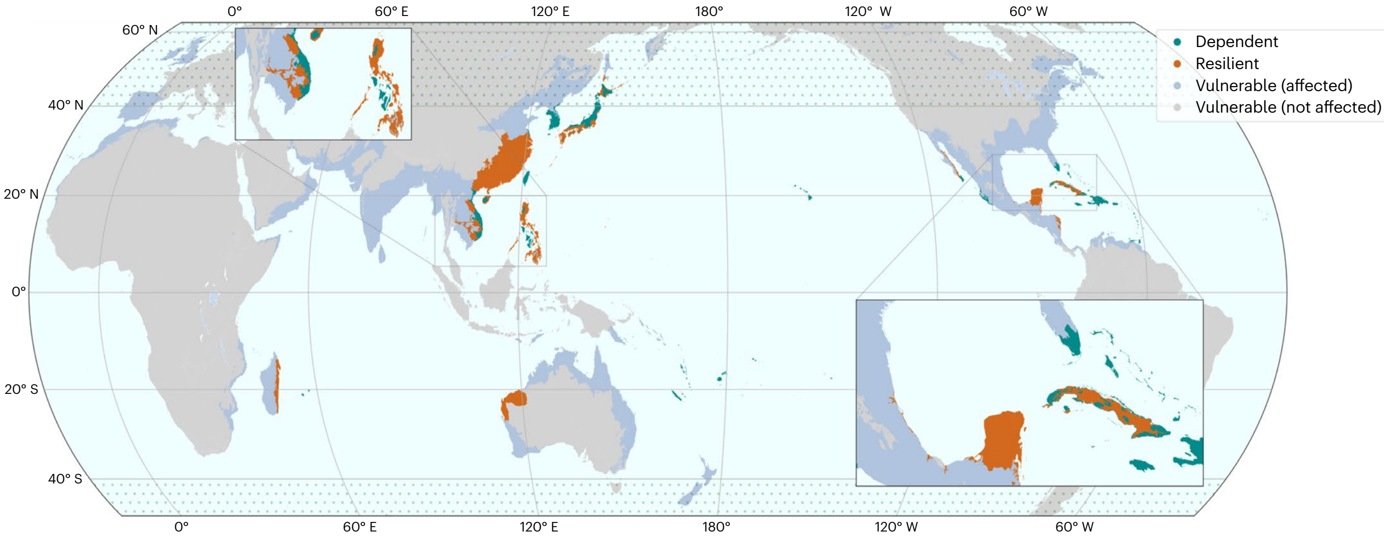

Fig. 3 | Vulnerability of ecosystems to current climate tropical cyclones (STORM 1980–2017). The ecosystems are resilient, dependent or vulnerable (affected or not affected) as defined in the section 'Vulnerability of ecosystems'. An ecosystem is labelled as resilient if it is resilient to at least one storm intensity and dependent if it is dependent on at least one storm intensity but not resilient (Fig. 1 gives detailed parametrization values). The vulnerable regions are either those that rarely experience cyclones (light blue) or those that are currently not affected by cyclones (light grey) because they are too far from the coast or tropical cyclone active regions. A map for each storm intensity is available in Extended Data Fig. 5. The dotted hatching beyond the 40° N or S latitudes indicates the extratropical transition where the cyclone model has low confidence[15]. Note that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference, two regions with frequent cyclones are enhanced in the insets. Supplementary Table 2 gives more details.

ecoregions cover 0.8 million km^2 and the vulnerable ones affected by cyclones cover 16.5 million km^2. Together, the resilient and dependent ecosystems represent 2.3% of the surface of all terrestrial ecosystems and 17% of those affected by storms at least once in 250 years. Of the considered 844 ecoregions worldwide—of which 290 are affected by tropical cyclones—200 are affected and vulnerable. Moreover, 26 ecoregions were classified as resilient and 64 as dependent. We remark that all ecoregions resilient or dependent on a higher-intensity storm, turn out to be dependent on the corresponding lower-intensity storms (that is, are affected more often than 1 in 20 years over 80% of their area). Most of the resilient and dependent ecoregions are concentrated in the larger East Asian regions, the Caribbeans and the Central American peninsula, the Pacific islands and Madagascar as shown in Fig. 3. Among those, we found that only five (Ogasawara subtropical moist forests, Luzon montane rain forests, Luzon rain forests, Mariana's tropical dry forests and Nansei Islands subtropical evergreen forests) are fully adapted to high (H) intensity storms (winds >58 m s^{-1}). For the resilient ecosystems, the average return period of tropical cyclones is 13 (L), 18 (M) and 19 (H) years, for dependent ecosystems 9 (L), 11 (M) and 17 (H) years and for vulnerable (and affected) ecosystems 87 (L), 102 (M) and 117 (H) years. These return periods can be interpreted as average upper ends to the recovery time of the ecosystems. A detailed list of all vulnerabilities, including the average return period, is given in Supplementary Table 2, and the vulnerabilities per category are shown in Extended Data Fig. 5.

Projected effects of climate change

We compare the regime of tropical cyclones between the STORM-B baseline 1980–2017 and the STORM-C future period 2015–2050 under the high-emission scenario SSP5-8.5. While there remain large uncertainties, SSP5-8.5 probably represents a higher bound on climate change for the near future and may be seen as a probable scenario given the ongoing emission trajectories (compare ref. 70). For the future climate, we consider all four global climate models (GCMs) from the STORM-C dataset[15]. We always report results corresponding to the median return period at each grid point and show the results for the individual GCMs in the Extended Data Fig. 7. For each ecoregion, we compare the change in the tropical cyclone frequency for each intensity category separately. We then compare the present status of ecoregions classified as dependent, vulnerable or resilient and identify ecoregions that will suffer a substantial increase in the frequency of tropical cyclones (over at least 20% of their area, increase above 10% (20%) for vulnerable (resilient) ecoregions) or a substantial decrease (at least 5% over 80% of the area for dependent ecoregions). The thresholds are summarized in Fig. 1. With this approach, we assume that a change in frequency can lead to a change in ecosystem composition as the dynamical processes required for recovery are no longer synchronized with the disturbance regime[5,20,27,42,58]. If the average frequency of tropical cyclones in a given region increases substantially, the system would in turn be disturbed in a way that does not allow a return to the initial state as illustrated in Fig. 4. For dependent regions, a substantial decrease changes the composition of the ecosystem as the vital disturbance is reduced.

We find that 194 ecoregions see a substantial increase in frequency, 5 are confronted with a substantial decrease in frequency and 13 are newly affected. While the substantial decrease in frequency is confined to the Caribbeans and the larger Antilles, the increase is found all over the world (Fig. 5): in Oceania, Madagascar and the East African coast, southeast and northwest North America, the Caribbeans, northern South America, the Pacific islands, East Asia, Australia and the Philippines. Interesting regional pattern also arise, such as in the Caribbeans where parts are at risk from a decrease in low-intensity storms, while other parts are at risk from an increase in high-intensity storms (Extended Data Fig. 6). Overall, the combined surface of all ecosystems at risk from tropical cyclones in a changing climate amounts to 9.4% of the combined area of all land ecosystems worldwide. Of these, the newly affected ones contribute 0.9% of the total area. A detailed list of all values for all ecoregions is given in Supplementary Table 3.

On average, ecoregions at risk from tropical cyclones in a changing climate are subject to a 55%, 99% and 149% increase in frequency for the low-, middle- and high-intensity storms, respectively. This results

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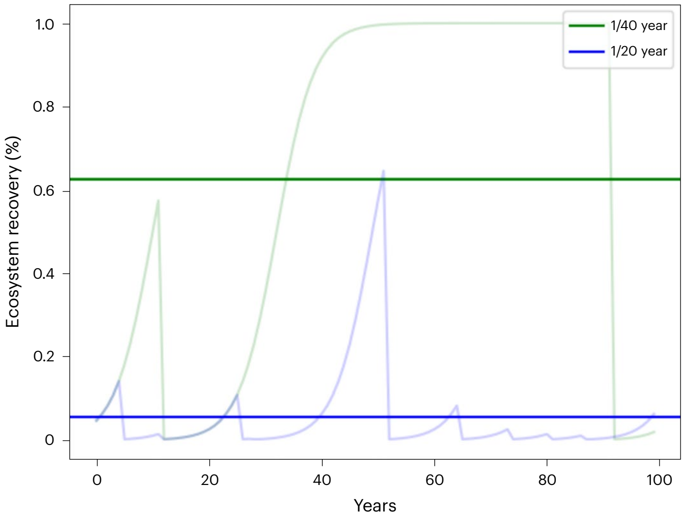

Fig. 4 | Illustration of the effect of a doubling of frequency on an ecosystem equilibrium state. At a larger frequency, the system cannot recover and is eventually pushed into a new state. A simple sigmoidal recovery is assumed for illustrative purposes.

for instance in a reduction of the average time for recovery of resilient systems to high-intensity storms from 19 to 12 years (Table 1). Regarding their geographic distribution, for the high-intensity storms, only ecoregions around China, Japan, Korea and the Philippines are projected to be at risk from a substantial frequency increase. Newly affected and at-risk regions are found in Madagascar, some Pacific islands and in the regions of China, Japan and Korea. For middle-intensity storms, the same regions are potentially affected. Furthermore, regions in Oceania are newly affected, while the Pacific islands and the Antilles are at risk from an increase in frequency. For low-intensity storms, large areas are newly affected or subject to a substantial increase in frequency. Moreover, few dependent ecoregions in the Caribbeans are confronted with a substantial decrease in frequency, which is consistent with findings in ref. 15. Detailed maps for low-, middle- and high-intensity storms are shown in Extended Data Fig. 6. Overall maps for all four GCMs are shown in Extended Data Fig. 7.

The identification of at-risk ecoregions depends nonlinearly on the combination of chosen parameters (Fig. 1) for the classification into resilient, dependent and vulnerable, as well as on the risk threshold levels and the GCMs. Thus, to test the model we performed a full global uncertainty and sensitivity analysis varying all input parameters in reasonable ranges as described in the Supplementary Information and shown in Extended Data Figs. 3b, 4b and 8. We find that the number of regions at risk varies more for low-intensity storms than for high-intensity storms. In the most optimistic choice of input parameters, we still identify 29, 55 and 134 ecoregions at risk from low-, middle- and high-intensity storms, respectively. The number of ecoregions at risk is most sensitive to the choice of risk threshold and the choice of GCM. Out of the four GCMs, three (CMCC-CM2-VHR4, CNRM-CM6-1-HR and HadGEM3-GC31-HM) generally agree on the geographical distribution (Extended Data Fig. 8). The model EC-Earth3P-HR instead shows a large number of ecoregions facing a substantial decrease in frequency, as well as an increase in the Indian Ocean[15]. The number of newly affected ecoregions by low-, middle- and high-intensity storms in optimistic case are 9, 10 and 9, respectively, and these values are most sensitive to the affected area and the affected frequency thresholds.

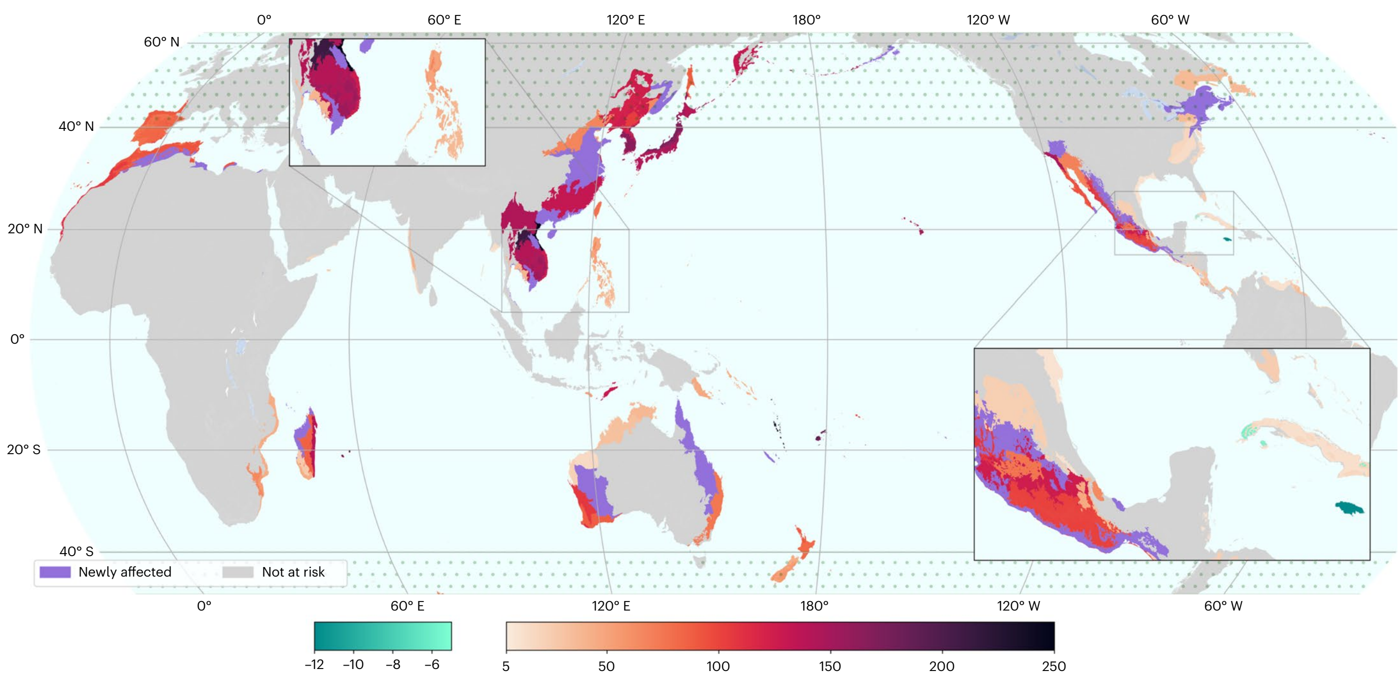

Fig. 5 | Map of the change in tropical cyclone frequency for all ecosystems at risk in the future time 2015–2050 under SSP5-8.5. The at-risk threshold depends on the vulnerability of ecoregions as defined by the tropical cyclone activity in 1980–2017 (Fig. 1 and Extended Data Figs. 1 and 5). Those ecoregions for which the frequency increases from below 1 in 250 years to above this threshold are labelled as newly affected (light purple). Resilient and vulnerable ecoregions may be at risk of an increase only, while dependent ecoregions might also be at risk of a substantial decrease. Regions that are not at risk are shown in grey. The dotted hatching beyond the 40° N or S latitudes indicates the extratropical transition where the cyclone model has low confidence[15]. We remark that the risk for regions in northwest Africa are probably overestimated in geographical extent. Note also that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference, two regions with frequent cyclones are enhanced in the insets. Supplementary Table 3 provides more details.

Table 1 | Recovery time in years

Storm intensity	Period	Resilient (yr)	Dependent (yr)	Vulnerable (yr)
Low	1980–2017	13	9	87
	2015–2050	**12**	**7**	**79**
Medium	1980–2017	18	11	102
	2015–2050	**13**	**9**	**91**
High	1980–2017	19	17	117
	2015–2050	**12**	**9**	**110**

The recovery times are shown at 20% of the area threshold for each ecoregion per storm category averaged over all ecoregions. The values for the historical baseline 1980–2017 are shown in plain text. The values for the median over all GCMs for the future period 2015–2050 under climate projections SSP5-8.5 are shown in bold. In all cases, the available recovery time decreases; that is, storms are more frequent on average.

Discussion

Contrasting with many local assessments[23,28] associated with specific events[27], here we derived potential vulnerability relationships between the large-scale natural hazards of tropical cyclones and ecosystems at a global scale. We used our approach inspired by the panarchy principles[58,71] and based on the frequency patterns of the storms to characterize ecosystem vulnerability under present climate conditions. We identified ecosystems susceptible to being exposed to transformative pressure from tropical cyclone pattern changes due to a warming climate as early as 2050. Beyond the extensively studied socioeconomic realm[2,72–76] our study provides an assessment of the impact of extreme weather events associated with ecosystems, complementing studies on drought[19,55,77], wildfire[78,79] and marine heatwaves[80,81]. We found that climate change is likely to considerably affect a large number of coastal ecosystems through tropical cyclone pattern changes. Most ecosystems currently exposed to tropical cyclones will be confronted with an increase in their frequency and intensity thus narrowing the maximum boundary for their recovery likely to result in ecosystem degradation and biodiversity losses[82]. This might affect their capabilities to provide essential services and thus reshape considerations for the viability of coastal ecosystem-based adaptation measures to climate change[52,83,84]. While previous studies have done local or ecosystem-specific assessments or projections[12,18,32], our study offers a global assessment of ecosystem disturbances risk by tropical cyclones under climate change.

The change in geographical distribution of cyclones may result in several ecosystems being exposed, which have not suffered disturbances historically. Ecosystems with increased impact occur further away from the tropics with an increase in storms undergoing extratropical transitions[85–88]. Forests and other coastal ecosystems at higher latitudes are not resistant to tropical cyclones since, in contrast to low latitude areas, no selection forces made them able to withstand those perturbations[12]. Among the potentially newly affected ecoregions, some are located far outside the tropics, where recent tropical storms have already strongly impacted ecosystems[45]. For those regions historically hit by storms, the general projected increase in storm frequency and intensity might cause particularly important changes to ecosystems as illustrated by the recent events Ana in Mozambique in 2022[89] or Amphan in Bangladesh in 2020[90,91]. A few ecosystems might in contrast have to deal with a substantial decrease in frequency, which also could lead to a change in composition due to the disappearance of a functional disturbance. This might change the natural dynamics of ecosystems and may influence their associated biodiversity[82].

The major strengths of our approach are the global applicability, the exclusive use of available open-data sources, the possibility to extrapolate the results to future climates, the computational simplicity, the parametric flexibility, the purely statistical basis of the approach, the potential for direct generalization to other climate hazards and the seamless integration into the established IPCC risk[2,92] framework. While we concentrated on the characterization of vulnerabilities and risk under future climates, the approach also provides estimates of upper bounds to recovery times from the average return periods of the storms (Supplementary Table 2). These can potentially inform dynamical ecosystem models[37] or help ecosystem management practitioners anticipate potential regime changes. Furthermore, since the proposed framework is seamlessly integrated into the open-source risk modelling platform CLIMADA[93], it is easily applicable to any natural hazard, such as floods, earthquakes, extreme heat or wildfires. For several of these hazards, open data are readily available from the ISIMIP[94] or the CLIMADA data APIs[93]. However, some hazards assessment might be more difficult since the intensity and frequency might depend on the ecosystem itself—think for instance of wildfires whose ignition probability depends on the available biomass fuel.

Our study represents one step towards a systemic, global and long-term understanding of the vulnerability of ecosystems to tropical cyclones. It has some limitations that open perspectives for more detailed quantification in the future. The proposed statistical approach based on the hazard distribution alone does not contain any ecological function understanding as this is not yet feasible at the global scale[95]. Our approach hinges on the assumption that ecosystems have co-evolved with the extreme disturbances at their location. However, given the major anthropogenic pressure on all planetary ecosystems in the last centuries[96,97], it is only a partially valid assumption. Furthermore, the fact that tropical cyclone activity has fluctuated over time inherently requires making an arbitrary choice on the relevant timescales. In addition, several semi-informed, partially normative, parametrizations choices had to be made, including the definition of the storm intensity categories, the choice of spatial extent for the vulnerability definitions, the choice of recovery time maxima for the resilient and dependent ecosystems, as well as the thresholds for the substantial changes in a changing climate. While our sensitivity analysis suggests that this does not impact the major conclusion of our study, we also acknowledge that results may strongly vary for individual ecoregions. Empirical studies would be required to better characterize these key parameters. Furthermore, we only considered the changes in the annual frequency distributions, but not the potential effects on ecosystems from a change in the seasonality of tropical cyclones[98], nor do we account for the clustering in time properties, which may follow multiyear patterns in several regions[99]. We also did not explicitly consider the resulting storm surges, heavy precipitations, landslides or floods which would be needed for a full mechanistic understanding of the impacts of tropical cyclones on coastal ecosystems. We further did not consider similar strong wind hazards such as winter storms, gales or derechos that might co-affect certain ecosystems. Our study is also bound by the limitations of the data models used, namely the STORM and Holland models for representing current and future tropical cyclone wind-field distributions[9,15,100] and the ecoregions model for describing coherent ecosystems.

Neither the STORM track model nor the Holland wind model represent well the extratropical transition of storms. In general, the Holland model overestimates the wind intensities and the STORM model both the intensity and frequency of tracks for extratropical cyclones[59,61]. The last leads to particularly large uncertainty for the regions Canada, Europe and northwest Africa. For mixed regions where typically both tropical and extratropical cyclones may occur, such as New Zealand, Korea or Japan, the frequencies for middle- and high-intensity storms are probably overestimated. This could be addressed by using a statistical–dynamical tropical cyclone model that might better capture the poleward migration of cyclones and their extratropical transition[101,102]. Moreover, one of the STORM model basin boundaries is located right over Australia[59] interrupting cyclone propagation from the South Pacific into the South Indian Ocean resulting in an underestimation of the cyclone frequency over the central region in northern Australia. Similarly, cyclones do not propagate from the Atlantic into the eastern Pacific basin, potentially affecting impact estimations over Central America[15]. While both effects might considerably affect the frequency distribution, our final results may still be mostly robust as we bin the intensities into three broad categories and consider only relative changes. For the future climate, we also recall that the choice of GCM is the largest sensitivity for the number of ecoregions at risk, which highlights the remaining large uncertainty on tropical cyclone downscaling in climate models[8,103] and how these lead to differentiated impacts[100]. The effect of different climate scenarios was not explicitly explored, partly due to data availability and partly because larger deviations in average climate conditions mostly appear towards the end of the century; see for example, Table SPM.1 in the 2021 IPCC report[104]. Hence, the differences arising from climate scenarios are probably smaller than those from the GCMs for the period 2015–2050. We also note that the reference study by ref. 8 obtains compatible changes in basin-wide intensity and frequency distributions to the STORM-C dataset[59] used here for a +2 °C global mean surface temperature warming relative to 1986–2005. This warming level, and thus the risk estimates derived here, is within the very likely range for SSP2-4.5, SSP3-7.0 and SSP5-8.5 in 2041–2060 and outside for SSP1-2.6 and SSP1-1.9 (ref. 104).

The ecoregions by ref. 60 have simplified boundaries at the coast, which for small island ecoregions, for example, Cook Islands tropical moist forests, Ogasawara subtropical moist forests, Tuamotu tropical moist forests, Nansei Islands subtropical evergreen forests, and very fragmented coastal areas, for example, Mississippi lowland forests, Palawan rain forests, Mindanao-Eastern Visayas rain forests, results in coarse results. Furthermore, certain coastal ecoregions extend very far inland, such as for example Aravalli west thorn scrub forests, Baluchistan xeric woodlands, Jian Nan subtropical evergreen forests, Manchurian mixed forests, Great Sandy-Tanami desert, southeast United States conifer savannas, Mississippi lowland forests, Mediterranean woodlands and forests. It is then unclear whether the inland areas are relevant for the recovery of the coastal areas from the impact of tropical cyclones, as is implied by our resilient area threshold. Ecoregions are further defined disregarding any human influence. Large areas have been transformed from natural ecosystems to urban or agricultural land and many remaining ecosystems are strongly fragmented, which may limit their ability to recover from the aftermath of natural disasters[65]. Finally, the ecoregions are considered static, even though changing climate conditions, such as average temperatures or precipitation, already are leading to the migration of species and change in the composition of ecosystems at scale[66,105,106]. All these aspects are likely to disturb the species interlinked networks of the ecosystems which are key for recovery and might lead to an underestimation of the risk of tropical cyclones in the future climate.

In conclusion, our study shows how changes in tropical cyclone patterns under a changing climate can impact a large number of coastal ecosystems by 2050. The identified potential strong impact of tropical cyclone pattern changes alone indicates the need for the more explicit inclusion of the effect of extreme weather hazards on global ecosystems in earth-system and climate-envelop models to improve our understanding of climate projections[1,66,95,107,108]. In the context of ecosystem management to mitigate and adapt to climate change, our findings show that we need to not only consider immediate damages from a tropical cyclone event but also think about multiyear shifts in ecosystem trajectories in a changing climate. In light of our analyses, policy and management approaches need to be re-assessed to consider the consequences of storms for ecosystems at a global scale. Our study does not directly allow us to conclude whether the increased risk to ecosystems translates into a decrease or an increase in ecosystem service provisions; yet, based on ecosystem disturbance studies, a strongly perturbed ecosystem is expected to be less capable of sustaining biodiversity, carbon storage or providing flood protection[109]. Considering the further pressure on coastal ecosystems from both average climate variables changes[1] and anthropogenic activities[96], it is worrying to add yet another potential threat to the list in the form of tropical cyclones.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02194-w.

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Methods

First, we describe the tropical cyclones and ecoregions data in general, then describe how vulnerabilities are defined, how climate change is accounted for, and finally how uncertainties and sensitivities were computed.

Tropical cyclones

Tropical cyclone frequencies at different intensities are directly extracted from a probabilistic set of wind fields of maximum 1 min sustained winds at 10 m above the ground. The two-dimensional wind fields are computed using the parametric Holland 2008 model[61] from tropical cyclone tracks (time series of the position, pressure and maximum wind speed of the centre of the cyclones) as implemented in the risk modelling platform CLIMADA[57]. The probabilistic set of tracks from the statistical model STORM[59] are used (Fig. 2). As the current climate baseline we consider the STORM-B set which contains 10,000 years of simulated tropical cyclone tracks[59] based on the observational data from the IBTrACS[110] database from 1980 to 2017 (for a total of 144,000 tracks worldwide). For climate conditions we consider the STORM-C set which contains 10,000 years of simulated tropical cyclones representative of the period 2015–2050 under the emission scenario SSP5-8.5 and for four GCM (CMCC-CM2-VHR4, CNRM-CM6-1-HR, EC-Earth3P-HR and HadGEM3-GC31-HM)[15]. In both cases, each storm in the 10,000 year set is assigned an annual occurrence probability of 1 in 10,000. We note that in CLIMADA[111] the STORM track winds are converted from 10 min maxima to 1 min maxima by applying the inverse multiplying factor 1/0.88 (ref. 59).

Since the maximum sustained wind speed from historical tropical cyclones ranges from 20 to 95 m s^{-1}, the ensuing direct damages can vary a lot. Assuming that the ecological response is strongly dependent on the magnitude of the direct damages (for example, branch breaking versus tree up-rooting), we divide the tropical cyclone wind intensities into three qualitative categories, L, M and H, based on the SSHWS scale (see also the discussion in Supplementary Information):

- Low: 33–49 m s^{-1}—SSHWS 1 and 2
- Middle: 49–58 m s^{-1}—SSHWS 3
- High: ≥58 m s^{-1}—SSHWS 4 and 5

These correspond to the percentiles 72, 93 and 98 of the used baseline STORM dataset wind speeds for the current climate (Extended Data Fig. 9). For each intensity category $c \in$ [Low, Middle, High], at each grid location x (global resolution of 150 arcsec on land), we obtain the empirical average annual frequency f_x^c by direct summation of all occurred events N_x^c of category c divided by the total number of years $Y = 10{,}000$,

$$f_x^c = \frac{N_x^c}{Y}. \tag{1}$$

This method of estimating the annual occurrence frequency can be compared to the 'empirical method' used in ref. 112 to estimate return periods of tropical cyclones in the STORM dataset for different intensities. The latter are shown to be very close to the return periods extracted from the historical records from IBTrACS. Thus, we expect that equation (1) also represents historical storm frequencies which are appropriate for understanding co-evolution of ecosystems with the disturbance.

We estimate the average annual frequency for each intensity category for the present climate using the wind fields computed from the STORM-B tracks (Extended Data Fig. 1) and for the four GCMs from the STORM-C tracks (Extended Data Fig. 10). For the vulnerability and climate risk assessment, we consider only values above the affected frequency threshold (1 in 250 years). We assume that ecosystems and, in particular, other environmental factors such as temperature, humidity or precipitation, as well as human factors, such as urbanization, change on timescales much faster than would be required to be in dynamical equilibrium with events that occur with less than 1/250 = 0.4% annual probability.

Ecoregions

For the description of the ecosystems, we directly use the 847 ecoregions defined as multipolygons by ref. 60. Of these, three (Malpelo Island xeric scrub, St. Peter and St. Paul Rocks and Trindade-Martin Vaz Islands tropical forests) are removed from our dataset as they are <10 km^2 which is too small compared to the tropical cyclone resolution of 4 km^2.

Vulnerability of ecosystems

It is assumed that an ecosystem must be in a stable dynamical equilibrium with the external perturbations acting on it. To describe the vulnerability of ecosystems to tropical cyclones, we thus use a purely statistical approach based on the description of the temporal patterns of the tropical cyclone. This approach is inspired by the well-established framework for extreme weather risk analysis[2,57].

Using the tropical cyclone average annual frequency at each grid point for each intensity category, f_x^c, we first compute the percentile $p^{E,c}$ distribution over all points within the multipolygon defining each separate ecoregion E. We then classify the ecoregions into resilient, dependent and vulnerable (affected or not affected), according to the following parametrization (Fig. 1): a regular disturbance is assumed if it happens with a frequency of a least $f = 1/20$ years; that is, allows for a recovery time of at most 20 years. A resilient ecoregion is regularly disturbed on at least $X_r = 20\%$ of its total area and a dependent one on at least $X_d = 80\%$. All other ecoregions are vulnerable because they are either not affected or affected but rarely with a frequency of at least $f^a = 1/250$ years (at most 1/20 years) over $X_r = 20\%$ of their total area. In terms of percentiles, it means that, if the 80th percentile exceeds the regular disturbance $p_{80}^{E,c} > f$ threshold, then the ecoregion E is resilient to intensity category c. If the 20th percentile exceeds the regular frequency $p_{20}^{E,c} > f$, the ecoregion E is dependent on intensity category c. If the 80th percentile is below the regular disturbance but above the affected thresholds $f < p_{80}{}^{E,c} < f^a$, the ecoregion E is vulnerable and affected by intensity category c. If an ecoregion is either not experiencing any tropical cyclones or the 80th percentile is below the affected threshold, it is considered vulnerable.

Climate change

For the climate change assessment, we start from the average annual frequency $\tilde{f}_x^{c,g}$ for each intensity category c at each grid point x for each of the four GCMs g. For each ecoregion, we first compute the percentile distribution $\tilde{p}_g^{E,c}$ of the average tropical cyclone frequency per category per GCM and then take the median $\tilde{p}^{E,c}$ (the per GCM values are used in the Extended Data Figs. 3b, 4b, 7 and 8 and Supplementary Information). To determine whether an ecosystem is at risk, we compare these percentiles $\tilde{p}^{E,c}$ with the percentiles $p^{E,c}$ for the historical climate depending on their vulnerability. For vulnerable and resilient systems, we compare p_{80} and $\tilde{p}_{80}$, while for dependent systems it is p_{20} and $\tilde{p}_{20}$. We then compute the relative ratio $r_q^{E,c} = (p_q^{E,c} - \tilde{p}_q^{E,c})/p_q^{E,c}$ to obtain the relative change in tropical cyclone frequency. Ecoregions are then classified as at risk if the ratio crosses the threshold $T = 10\%$ for vulnerable affected systems $r_{80} > T$, double the threshold $r_{80}^{E,c} > 2T$ for resilient ecoregions, half the threshold $r_{20}^{E,c} > T/2; r_{20}^{E,c} < -T/2$ for dependent ecoregions. We thus assume that resilient systems can cope with twice the increase in frequency of vulnerable ones and we assume that dependent systems are probably fine-tuned to the perturbation of the cyclones and thus are twice as sensitive to changes in frequency. Vulnerable, but historically not affected, ecoregions are considered newly affected if $\tilde{p}_{80}^{E,c} > f^a$.

Uncertainty and sensitivity analysis

The overall values for the area, recovery time and frequency change, summarized in Fig. 1, are a clear modelling choice that will impact the classification of ecosystems at risk. We thus performed a global uncertainty and sensitivity analysis (Supplementary Information and Extended Data Figs. 3, 4 and 8) by sampling the values in plausible ranges using the Sobol sequence[113,67–69]. The chosen ranges are: at-risk threshold T = [5%, 30%], area for resilience X_r = [70%, 90%], area for dependence X_d = [10%, 30%], the maximum recovery time f = [1/10, 1/50], the affected frequency f^a = [1/200, 1/300] and the four GCMs plus the median. We then computed the first-order Sobol indices to assess the sensitivity using the SALib library[114].

Data availability

The STORM tracks for present and future climate can be downloaded from refs. 15,59. The wind fields can be directly computed with CLIMADA[111], which is an open-source Python package directly conda and pip installable. The ecoregions can be retrieved from ref. 60. The main data outputs are provided as Supplementary Tables 2 and 3.

Code availability

Code to reproduce the results of this paper is available via Zenodo at https://doi.org/10.5281/zenodo.12801008 (ref. 115). For this study, the Python (3.8+) version of CLIMADA (3.2+) can be used[111]. The source code is openly and freely available under the terms of the GNU General Public License v.3. The sensitivity analysis was performed with the open-source Python package SALib v.1.4.5 (ref. 114).

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Author contributions

C.M.K. conceived and designed the study, analysed the results and wrote the manuscript. L.P. contributed to the writing, interpretation of the results and general framing of the study. L.V. contributed an early study. D.N.B. provided input on the overall framework. All authors reviewed and edited the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-024-02194-w.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-024-02194-w.

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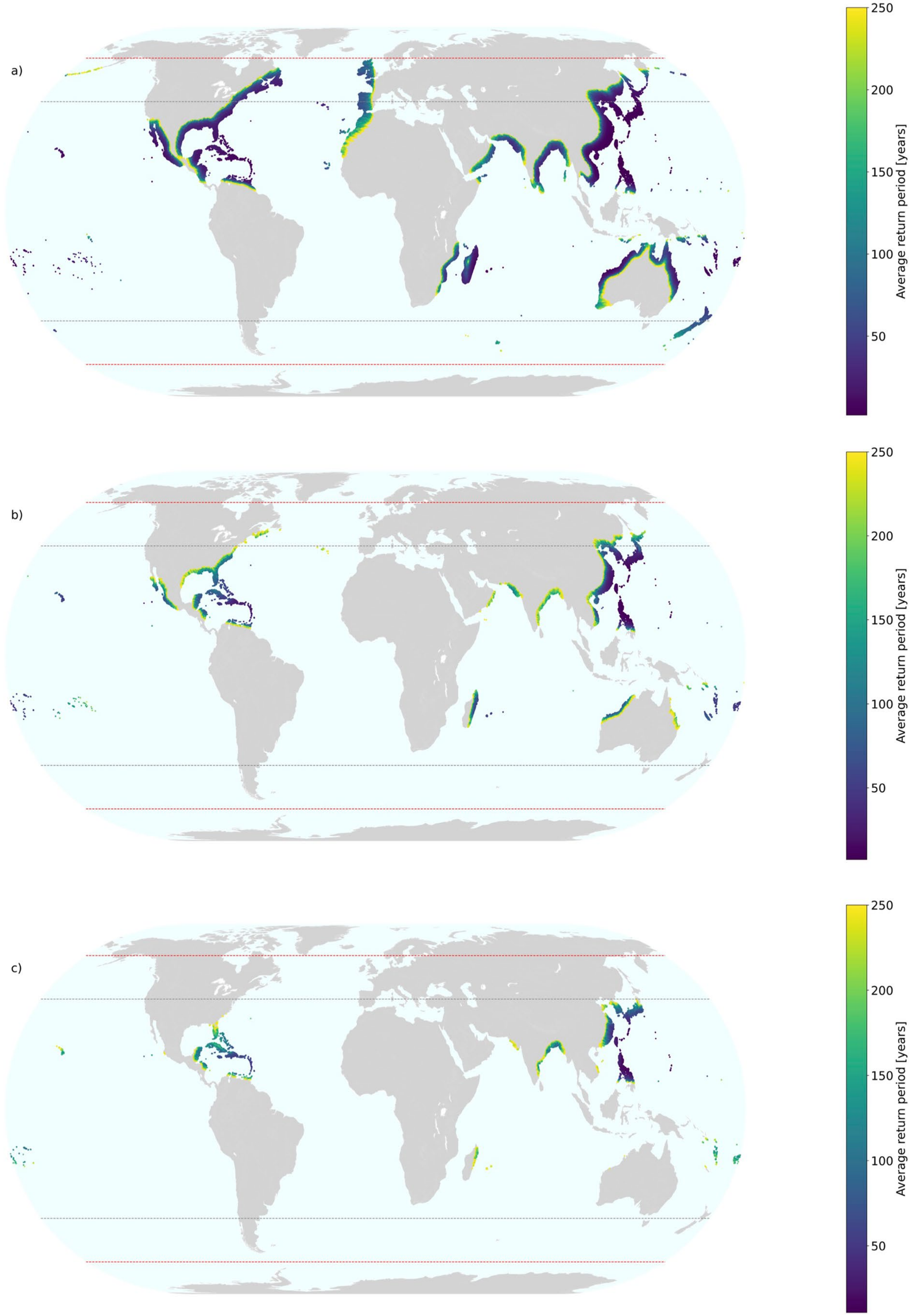

Extended Data Fig. 1 | See next page for caption.

Extended Data Fig. 1 | Average return periods of tropical cyclones in the current climate. Average return period for tropical cyclones in the baseline climate 1980 – 2017 of the STORM model. Only return periods below 250 years are shown for the tropical cyclone categories **a**) L (low) SSHWS 1-2, **b**) M (middle) SSHWS 3, and **c**) H (high) SSHWS 4-5 intensity. Note that the regions far from the tropics are not hit by tropical cyclones, but by the extra-tropical storms remnants of storms that originated in the tropics. The horizontal grey (red) lines represent the 40 (60) degrees N/S latitudes that roughly indicate the extra-tropical transition (and the polar circle) beyond which the tropical cyclone intensities are likely overestimated (cyclones are absent).

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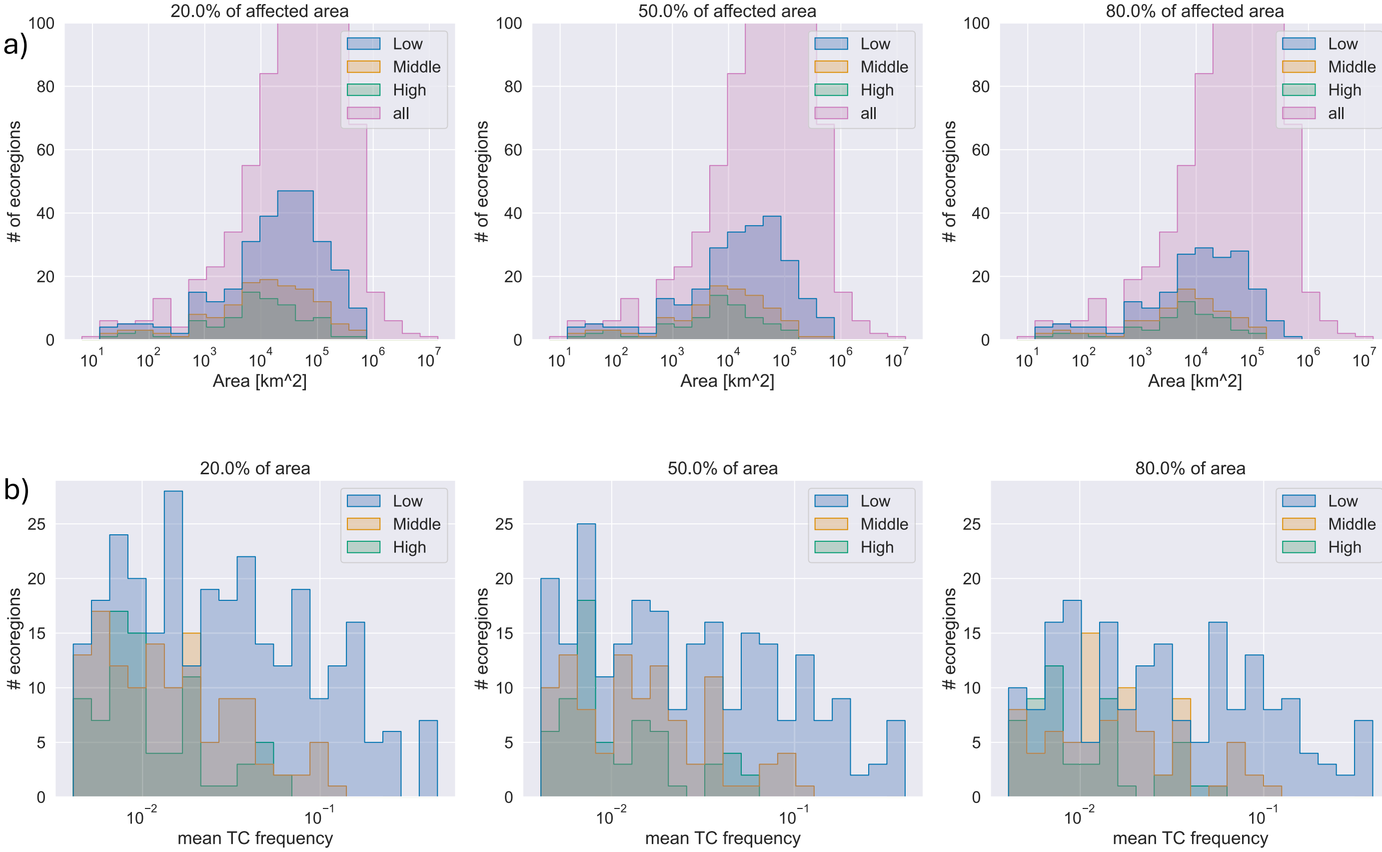

Extended Data Fig. 2 | Statistics of ecoregions affected by tropical cyclones. Shown are the **a**) area of ecoregions and **b**) mean tropical cyclone frequency for Low, Middle, and High intensity winds. From left to right, we vary the percentage of the ecoregion's area that must be affected at least 1/250 years for the whole ecoregion to be counted as affected. The 20% (80%) is the threshold for defining resilient (dependent) ecoregions. The 50% represents the median. Ecoregions that are not affected (less than 1/250 years frequency at 20% of the area) are ignored.

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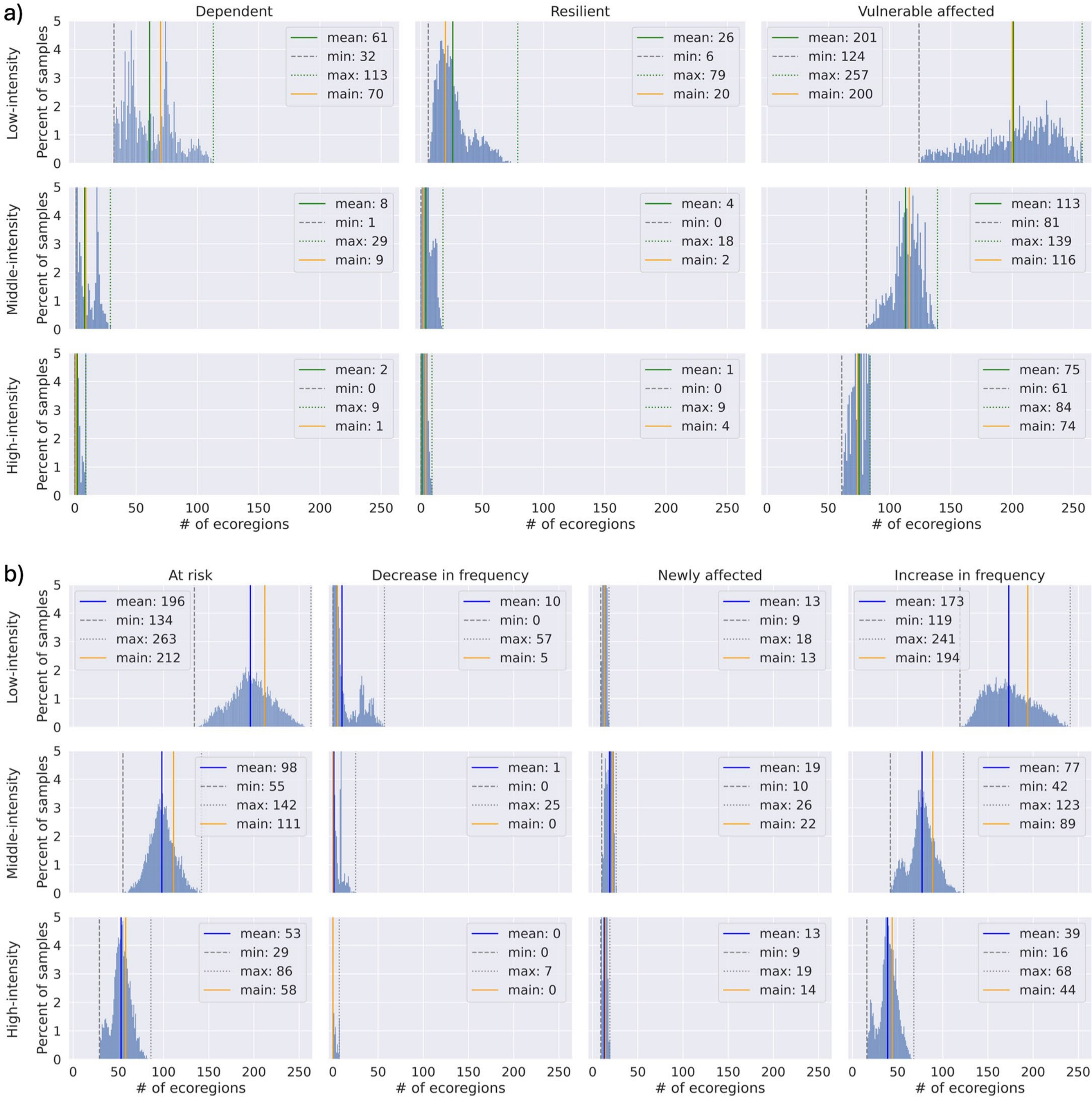

Extended Data Fig. 3 | Uncertainty distributions for the vulnerability and climate risk of ecoregions. Shown are **a**) the uncertainty in the classification of ecosystems into vulnerable, resilient and dependent for tropical cyclones of Low, Middle and High intensity and **b**) the uncertainty in the number of at-risk ecosystems in future climate depending on the climate model and the at-risk threshold.

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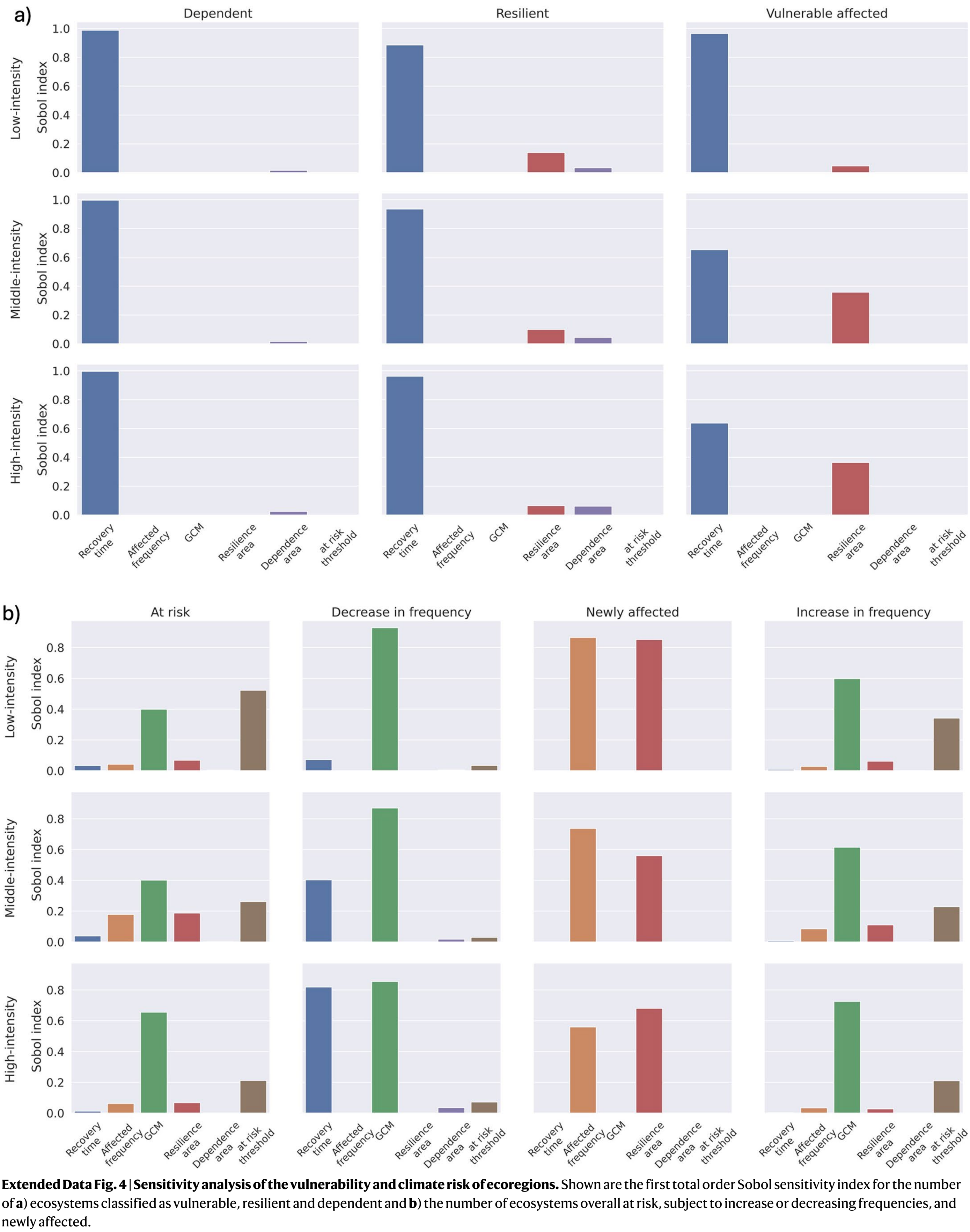

Extended Data Fig. 4 | Sensitivity analysis of the vulnerability and climate risk of ecoregions. Shown are the first total order Sobol sensitivity index for the number of **a**) ecosystems classified as vulnerable, resilient and dependent and **b**) the number of ecosystems overall at risk, subject to increase or decreasing frequencies, and newly affected.

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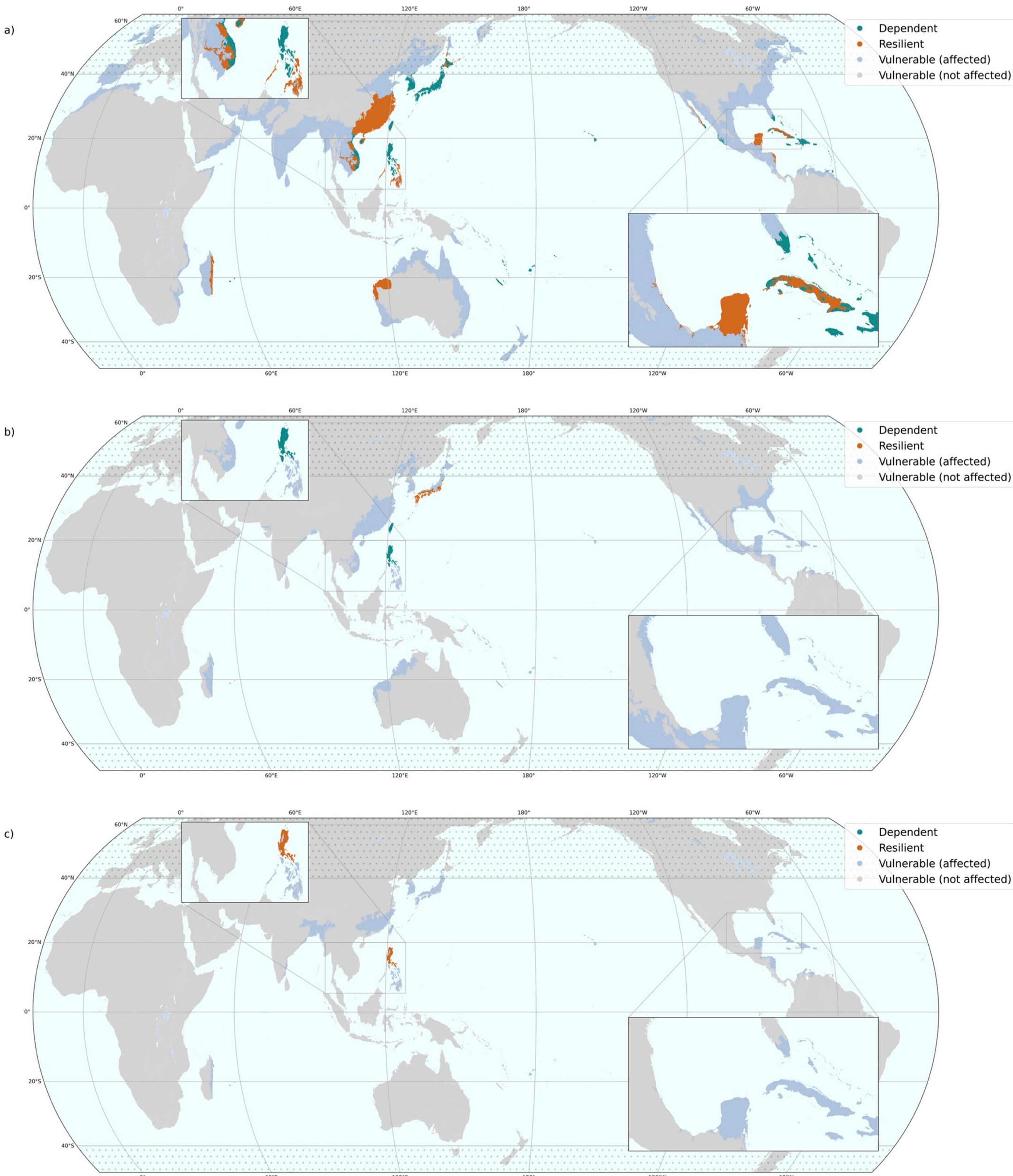

Extended Data Fig. 5 | Map of the vulnerability of ecoregions to tropical cyclones. Vulnerability of ecoregions to tropical cyclones. Results are shown for categories **a**) Low, **b**) Middle, and **c**) High intensity in the baseline climate 1980 - 2017. The ecoregions can be either vulnerable (affected or not affected), resilient or dependent as defined in the main manuscript. The dotted hatching beyond the 40 degrees N/S latitudes indicate the extratropical transition where the cyclone model has low confidence[15]. Note that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference two regions with frequent cyclones are enhanced in the insets.

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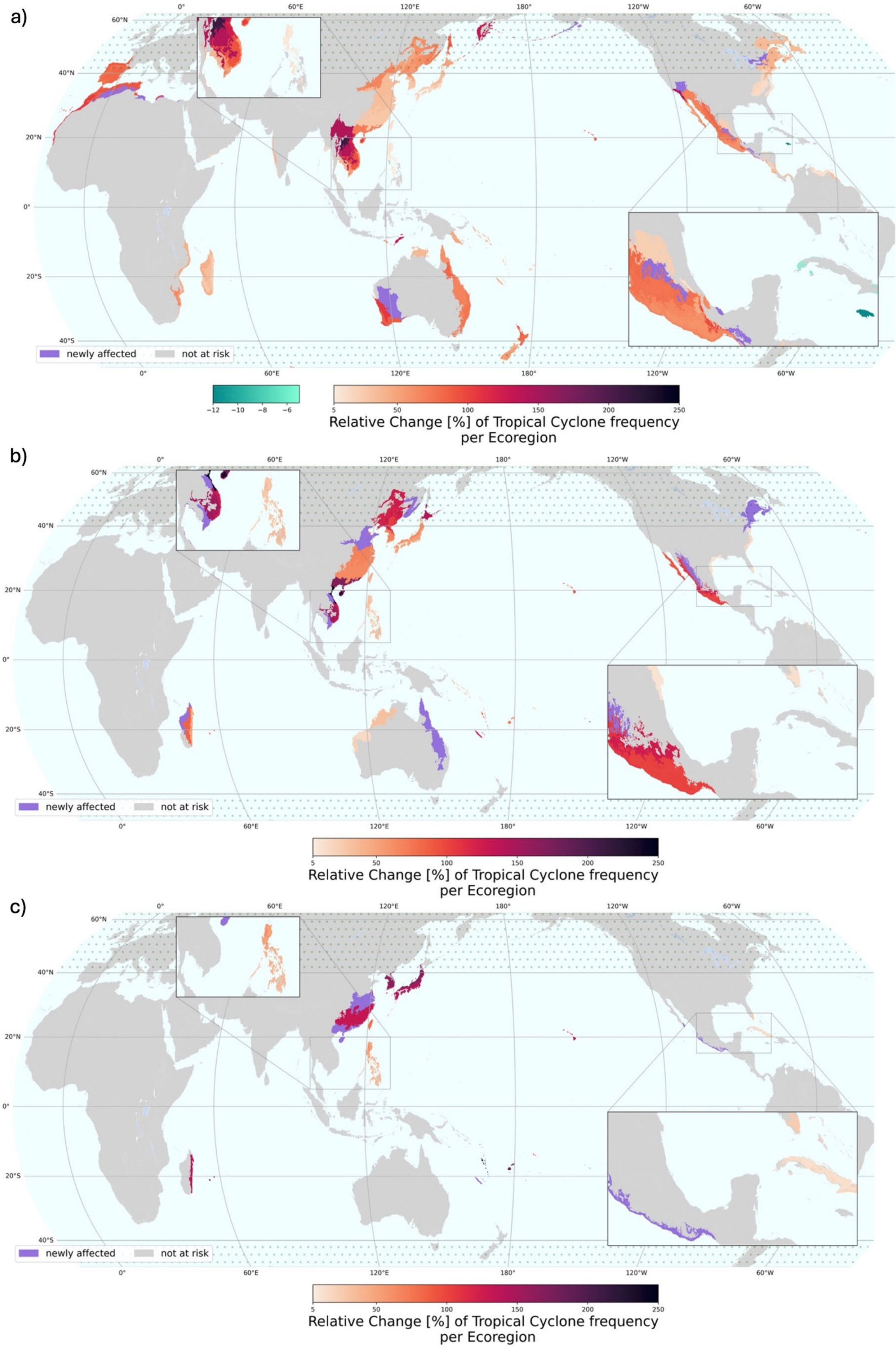

Extended Data Fig. 6 | See next page for caption.

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Extended Data Fig. 6 | Map of the change in tropical cyclone frequency for all ecosystems at risk in 2015-2050 under RCP8.5. Map of the change in tropical cyclone frequency for all ecosystems at risk in 2015-2050 under RCP8.5 compared to their vulnerability as defined by the tropical cyclone activity in 1980-2017. Those ecoregions for which the frequency increases from below 0.004 (return period of 250 years) to above this threshold are labelled as newly affected. From top to bottom, the panels show the results for tropical cyclones of **a**) Low, **b**) Middle, and **c**) High intensity. The dotted hatching beyond the 40 degrees N/S latitudes indicates the extratropical transition where the cyclone model has low confidence[15]. Note that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference two regions with frequent cyclones are enhanced in the insets.

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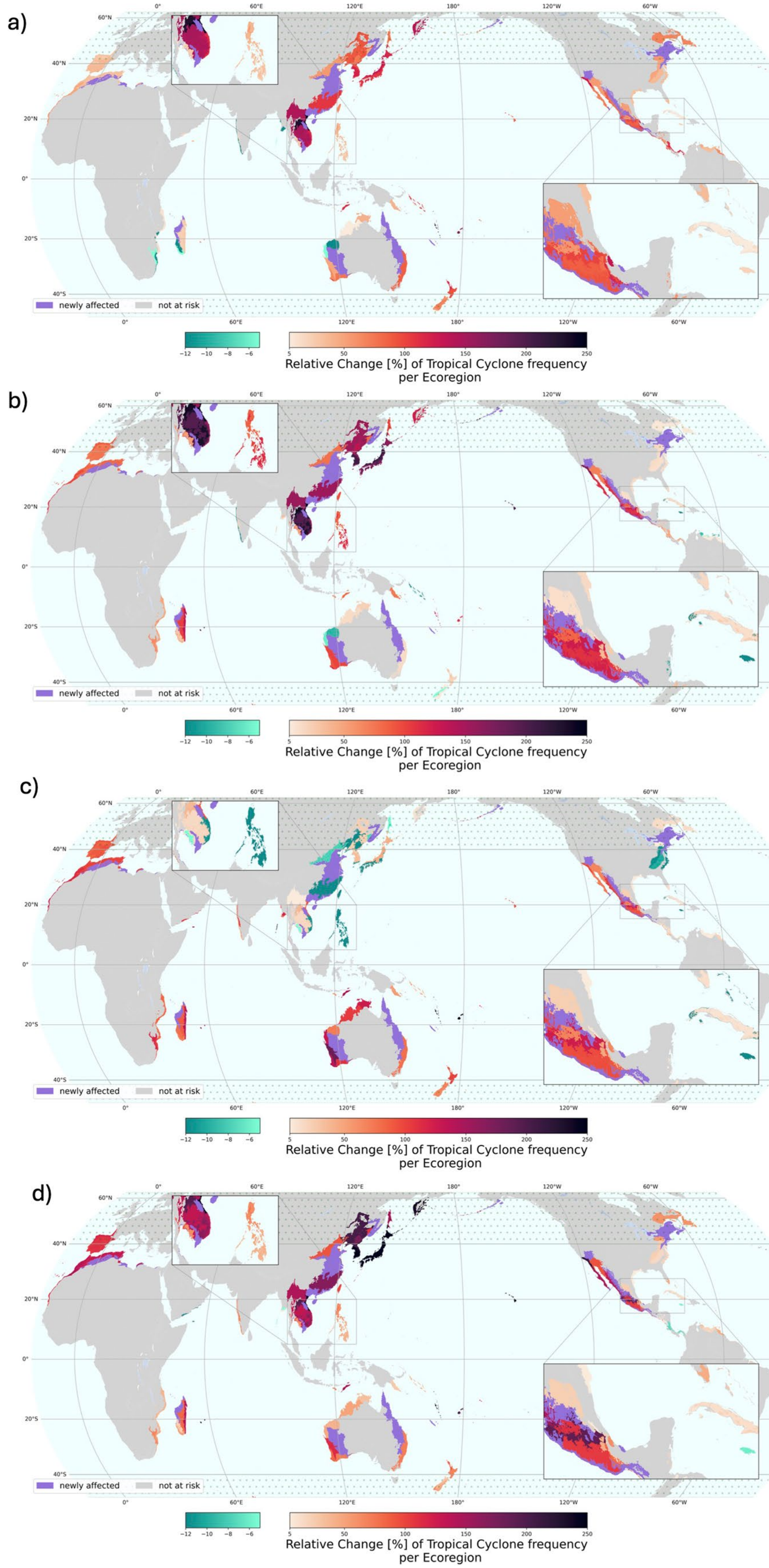

Extended Data Fig. 7 | See next page for caption.

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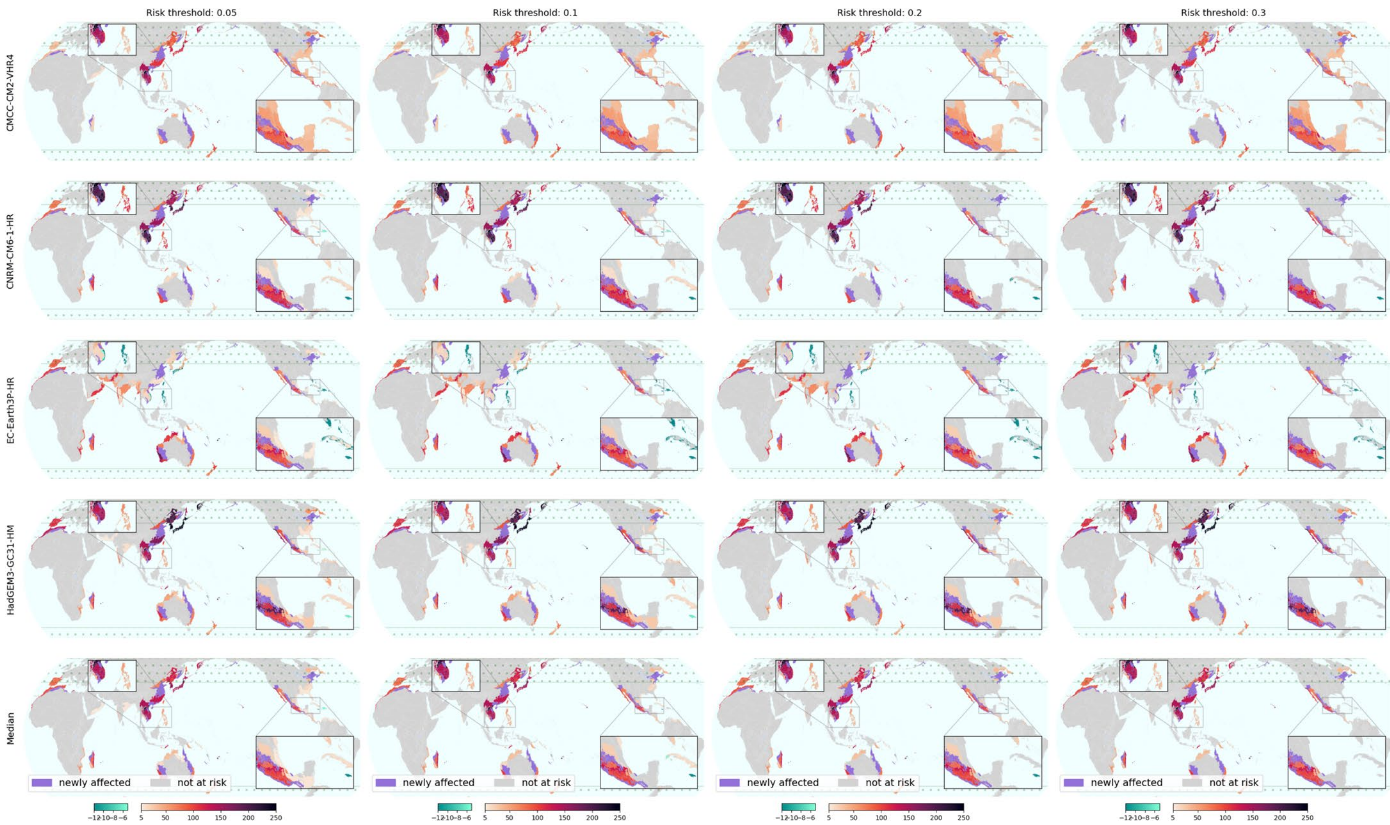
Extended Data Fig. 7 | Map of the change in tropical cyclone frequency for all ecosystems at risk per GCM. Map of the change in tropical cyclone frequency for all ecosystems at risk in the future time 2015-2050 under SSP585. Shown are the frequency changes for GCMs **a**) CMCC-CM2-VHR4, **b**) CNRM-CM6-1- HR, **c**) EC-Earth3P-HR, **d**) HadGEM3-GC31-HM compared to their vulnerability as defined by the tropical cyclone activity in 1980 - 2017. Those ecoregions for which the frequency increases from below 0.004 (return period of 250 years) to above this threshold are labelled as newly affected. The dotted hatching beyond the 40 degrees N/S latitudes indicates the extratropical transition where the cyclone model has low confidence[15]. Note that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference two regions with frequent cyclones are enhanced in the insets.



Extended Data Fig. 8 | Map of at-risk ecosystems for all 4 GCMs and different at-risk thresholds. Map of at-risk ecosystems in future for all the climate model and varying at-risk thresholds. The shown climate models are CMCC-CM2-VHR4, CNRM-CM6-1-HR, EC-Earth3P-HR, HadGEM3-GC31-HM, median from top to bottom and the at-risk threshold are 5%, 10%, 20%, 30% (from left to right). The dotted hatching beyond the 40 degrees N/S latitudes indicates the extratropical transition where the cyclone model has low confidence[15]. Note that several small ecoregions, such as coastal mangroves or small islands, are not easily visible on this map. For visual reference two regions with frequent cyclones are enhanced in the insets.

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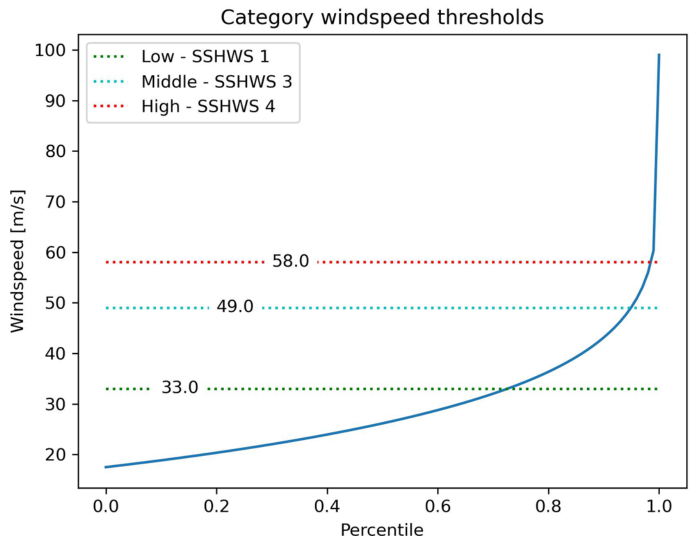

Extended Data Fig. 9 | Intensity categories percentiles. Division of the tropical cyclone 1-minute sustained wind speeds into three categories - Low (L), Middle (M), and High (H) intensity - based on the Saffir-Simpson scale. The 3 categories correspond to the percentiles 72, 93, and 98, respectively, of all storm data points available in the dataset.

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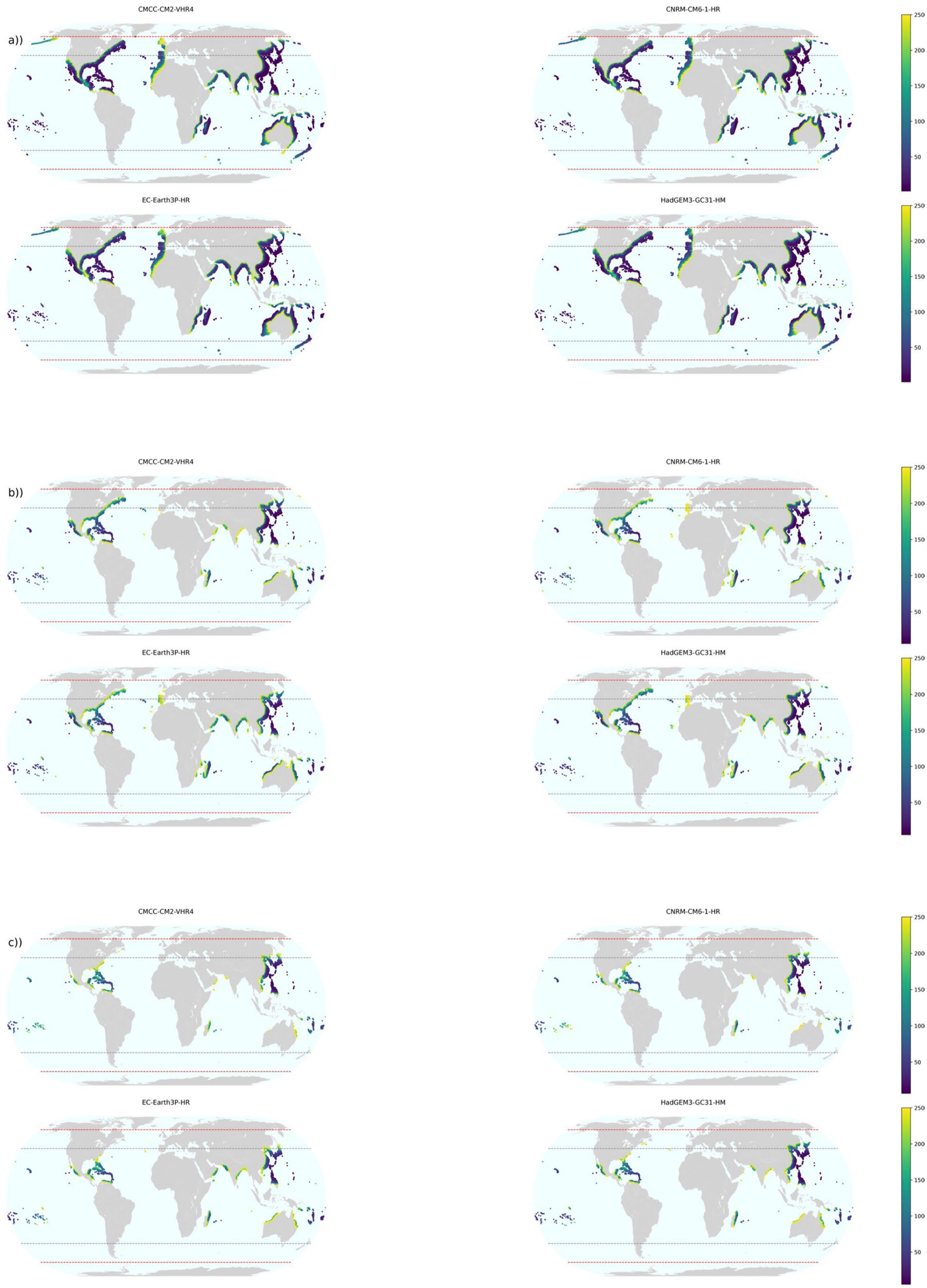

Extended Data Fig. 10 | See next page for caption.

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Extended Data Fig. 10 | Average return periods of tropical cyclones in the future climate. Average return period for tropical cyclones in the future climate 2015 - 2050 of the STORM model for 4 climate models. Only return periods below 250 years are shown for the tropical cyclone categories **a**) L (low), **b**) M (middle), and **c**) H (high) intensity. The models are GCMs CMCC-CM2-VHR4, CNRM-CM6-1-HR, EC-Earth3P-HR, HadGEM3-GC31-HM (top left to bottom right). Note that the regions far from the tropics are not hit by tropical cyclones, but by the extra-tropical storms remnants of storms that originated in the tropics. The horizontal grey (red) lines represent the 40 (60) degrees N/S latitudes that roughly indicate the extra-tropical transition (and the polar circle) beyond which the tropical cyclone intensities are likely overestimated (cyclones are absent).