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Economic impacts and risks of climate change under failure and success of the Paris Agreement

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The Nationally Determined Contributions (NDCs) represent the world's first effort toward the Paris Agreement goal of keeping global temperature increase well below 2 °C and pursuing 1.5 °C. Little is known about how much the proposed mitigation efforts can reduce the risks and economic damages from unabated climate change and about the consequences if key emitters drop the Paris Agreement. Here, we use CLIMRISK, an integrated assessment model designed to support climate policy at the global, national, and subnational scales where mitigation and adaptation policy decisions are made. We characterize the consequences of unabated climate change and the benefits of current climate policy proposals by means of probabilistic estimates of the economic damages of climate change and uni- and multivariate dynamic climate risk indices at a detailed spatial resolution. The results presented reveal that the economic costs and risks are highly unequally distributed between and within countries and larger than previously estimated when warming in urban areas and temporal persistence of impacts are accounted for. Costs and risks can be significantly limited by strict implementation of NDCs, but increase noticeably under noncompliance by large emitters, like the United States.

Keywords: climate change; economic impacts; integrated assessment model; risk

Introduction

The potential benefits of active international climate policy are usually evaluated for idealized long-term mitigation goals under the assumption of full compliance from participating countries.[1–3] However, achieving these goals depends on shorter-term targets that are periodically revised and on the possible partial compliance or withdrawal from key participants.[4] In a context of active climate policy, scenarios representing strict and partial compliance of emissions reduction commitments become increasingly relevant.[5] Moreover, impacts and risks of climate change are typically nonlinear on warming and deviations in emissions produce more than proportional changes in projected losses and risks.[6–9] Under the current high-warming trajectory, relatively small deviations in emissions may have considerable effects on risk reduction and avoided damages. Accounting for the nonlinear effects of climate change on human and natural systems can provide strong incentives for supporting climate policy and abiding by climate accords: even limited international mitigation efforts can produce important benefits, while partial compliance, delayed action, or withdrawal from some participants can have considerable negative effects on avoided damages and risk reduction that would otherwise been achieved.

The Paris Agreement, which is the current landmark for climate policy, aims to limit global warming well below 2 °C and pursuing 1.5 °C through

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time-evolving intended mitigation commitments that party countries update every 5 years.[10] It is uncertain whether this climate goal can be met due to the voluntary character and insufficient commitments to reduce greenhouse gas emissions,[11–13] and in recent years, there were political debates in some large emitters to withdraw from the Paris Agreement.[4,14] The Biden administration has significantly increased the U.S. ambitions on emissions reductions; however, it is still debated if current global efforts will be enough and the upcoming COP26 will be crucial as it is where governments are expected to formalize their commitments.[15] Emission and energy efficiency indicators to track the progress of NDCs have been proposed to inform parties about the need to modify their pledges to attain their long-term goal.[12] Insights about the risks and economic damages from climate change that can be avoided by the current climate policy proposals and of possible deviations from them may be a more compelling indicator. Such insights are best presented at a level that policymakers can relate to, like the country level or smaller spatial units which policymakers commonly represent, instead of the large aggregate regions that are currently used in assessments of the economic impacts of climate change.[16] Moreover, an analysis of the residual damages and risks from mitigation policy is useful for highlighting those that are unavoidable under that particular effort. Such information can help guiding the ongoing discussions at the UN level about adaptation and financial assistance for developing counties, like the Warsaw International Mechanism for Loss and Damage (L&D) endorsed in the Paris Agreement.[17] To give insights for these policy debates, our study aims to assess the economic impacts and risks of climate change at the different spatial scales where policymakers decide about adaptation strategies and contributions to international mitigation efforts. At the subnational level, this information can also be used to identify risk hotspots, to prioritize regional actions, and to trigger complementary research at the local scales to develop specific adaptation strategies.

The economic costs of climate change and the benefits of reducing greenhouse gas emissions are typically estimated by integrated assessment models (IAMs) of climate and the economy.[18,19] IAMs have advised climate policy, like on the social cost of carbon that was adopted by the United States[20] and other governments,[21] or by showing the economic rationale for cuts in greenhouse gas emissions, like the Stern Review that had an influence on the policy debate.[22] IAMs have also been applied to investigate the importance of full compliance of different mitigation efforts included in international agreements, as well as the effects of delaying mitigation actions[16,23] and to evaluate if stringent international mitigation efforts are economically optimal.[24,25] An advantage of IAMs is their flexibility in estimating the aggregate economic impacts of climate change at a global scale under a large variety of climate and socioeconomic scenarios, but in doing so, they necessarily rely on reduced functional forms of complex interactions between climate and socioeconomic systems. These models have received various criticisms,[26] including their aggregated spatial resolution,[27] the incomplete representation of climate change risks,[28–30] and an incomplete account for nonmarket impacts, like on ecosystems.[31] Recent contributions to the IAMs literature that have focused on these limitations include the adoption of agent-based methods,[32,33] improving the representation of ecological damages,[34] and the assessment of climate catastrophes.[35,36] Here, we use CLIMRISK, a spatially explicit policy evaluation IAM[37–39] for the assessment of the risks and economic damages of climate change. CLIMRISK produces a variety of climate, socioeconomic and damage projections, and user defined uni- and multivariate, dynamic risk measures to provide decision making a broader picture about the potential consequences of climate change than current climate-economy IAMs. CLIMRISK addresses some of the limitations of IAMs mentioned in the literature as it provides a multidimensional and more complete representation of risks; a multiscale projection of hazards (climate), exposure (population and gross domestic product (GDP)), and damages that ranges from the grid cell, to regional and global; and a set of damage functions that encompass conservative and high-damage estimates. Another main improvement in this model is its capacity to account for the synergistic effects of global and urban warming, which can only be approximated with a spatially explicit model. In this paper, CLIMRISK is applied to provide new costs and risk estimates for different policy scenarios that range from partial to full compliance of NDC and up to the achievement of the Paris Agreement goal

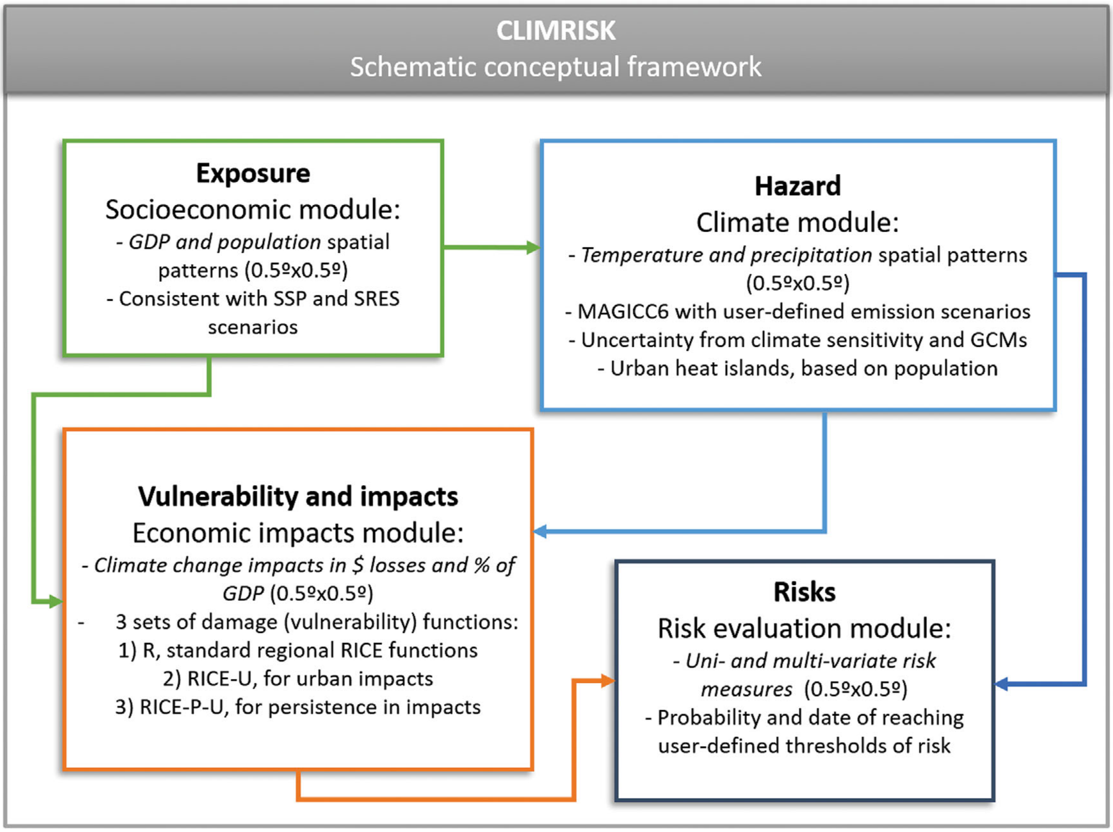

Figure 1. Schematic conceptual framework of CLIMRISK.

of limiting global warming below 2 °C and pursuing 1.5 °C.

Materials and methods

CLIMRISK: a model for the assessment of impacts and risks of climate change

CLIMRISK is an IAM for the evaluation of the economic impacts and risks of climate change. It is designed to support decision making by providing a broader picture than current climate–economy IAMs about the potential consequences of climate change under different reference and policy greenhouse gases emission scenarios (see Supplementary Information File S1, online only). Projecting what the consequences of climate change could be during this century is a complex, multidimensional task of which the economic costs are only one dimension. If taken in isolation, these cost estimates can provide a potentially biased and incomplete assessment of the challenges from climate change. This is why CLIMRISK integrates a variety of climate, socioeconomic, and damage projections to produce uni- and multivariate, dynamic risk measures. CLIMRISK generates tailor-made output about different dimensions of the potential consequences of climate change and the benefits of active climate policy. CLIMRISK is a spatially explicit, policy evaluation model,[37–39] in which the risks and economic damages of different reference and policy scenarios can be assessed and compared based on a variety of metrics.

Figure 1 shows the conceptual framework of CLIMRISK, and a simplified schematic diagram of the model's structure is offered in Figure S1B (online only). The model is composed of four interlinked modules: (module 1) socioeconomic scenarios that determine the *exposure* to climate change, (module 2) probabilistic climate projections of the climate *hazard*, (module 3) estimate the economic impacts based on regional and urban damage functions that represent *vulnerability*, and (module 4) uni- and multivariate *risk* measures (the modules are briefly described below, and Section S1 of the Supplementary Information (online only) provides a complete description of the model structure and the modeling choices for each of the four modules).

Exposure: socioeconomic scenarios. Scenarios of GDP in CLIMRISK determine the economic exposure to climate change (see Fig. S1B, online only), which is an important input in the climate impacts calculation (module 3). Consistent with GDP scenarios, population scenarios produced in CLIMRISK provide a proxy for identifying urban areas and are used for estimating the urban heat island (UHI) warming (module 2) and for calculating urban damages (module 3).

GDP and population scenarios have an annual frequency and three different spatial resolutions: global, 13 regions, and spatially explicit in a 0.5° × 0.5° global grid. The projections are exactly consistent at all spatial scales. For producing spatially explicit information, CLIMRISK combines the Shared Socio-Economic Pathways (SSP) and Special Report on Emissions Scenarios (SRES) projections that are available from the SSP Public Database Version 1.1 (https://tntcat.iiasa.ac.at/SspDb)[40] and the GGI Scenario Database Version 2.0.1 (http://www.iiasa.ac.at/Research/GGI/DB/).[41,42] These databases that are commonly used in climate impact studies gather a variety of scenarios about GDP and population, among other variables, that have been produced by different modeling groups. A detailed exposition of how the socioeconomic scenarios in CLIMRISK are produced is given in Section S1.2.1 of the Supplementary Information (online only). To account for the uncertainty represented by the different development narratives and their quantification, CLIMRISK includes all the SSP narratives (SSP1, SSP2, SSP3, SSP4, and SSP5; see Table S22, online only) and, for the case of GDP, the uncertainty in quantification is also considered by including three different modeling groups (OECD Env-Growth, IIASA, and PIK).[43–45]

Hazard: global and regional probabilistic climate change scenarios and the UHI. LIMRISK uses a stochastic version of the MAGICC6 software[46] to produce probabilistic climate change scenarios of temperature and precipitation, that enter the estimation of climate impacts (module 3) and risk measures (module 4). A detailed exposition of how climate scenarios are constructed is provided in Section S1.2.2 of the Supplementary Information (online only). MAGICC is a reduced complexity climate model which has been used widely by the climate change community for projecting future changes in climate and as input for impact, vulnerability, and adaptation studies.[46–49] CLIMRISK uses a triangular probability distribution for the climate sensitivity parameter in MAGICC6 based on the high, low, and medium climate sensitivity values reported by the IPCC and commonly used in the literature[50] (see section S1.2.2 of the Supplementary Information, online only). The output from MAGICC6 used in CLIMRISK is global annual temperature projections. For the results in this paper, ensembles of 500 realizations of global annual temperature change covering this century and for each of the emissions scenarios were calculated. Section S1.2.2 of the Supplementary Information (online only) shows how closely this stochastic version of MAGICC6 is able to reproduce the best estimates and ranges of increases in global temperature reported in the latest IPCC's report.[50]

The global temperature projections produced by MAGICC6 described above are used to create probabilistic regional annual temperature and precipitation scenarios in CLIMRISK by means of the pattern scaling technique (see S1.2.2 of the Supplementary Information, online only). The adequacy of this technique to approximate the spatial patterns of general circulation models (GCMs) has been favorably evaluated for variables, such as temperature and precipitation for different generations of climate models.[51–53] CLIMRISK combines the global temperature scenarios with the regional temperature and precipitation patterns from 41 GCMs included in the Coupled Model Intercomparison Project 5 (CMIP5).[53,54] The spatial patterns of the GCMs in Table S18 (online only) are randomly selected using a uniform distribution[55,56] and are scaled by the realizations of global temperature obtained using the stochastic version of MAGICC6. Probabilistic regional climate change scenarios in CLIMRISK have a spatial resolution of 0.5° × 0.5°.

CLIMRISK also simulates the effects of the UHI which can imply significant increases in local temperature additional to those from global climate change and the resulting joint impacts are larger than the sum of the parts[8] (see S1.2.2 of the Supplementary Information, online only). Replacing natural land by materials that have higher heat capacities and thermal conductivity, such as concrete and asphalt, alters the energy balance at the local scale. These changes modify the local climate and lead to higher temperatures. The increases in urban temperature are approximated here using empirical relationships proposed in a variety of studies.[57–59] These empirical relationships have previously been applied in an IAM for estimating economic impacts of climate change in cities.[8] Future warming at the city level at a particular point in time is then determined as the sum of the change in annual mean temperature from global warming and the UHI effect. Section S1.2.2 of the Supplementary Information (online only) provides details and a discussion about UHI modeling, as well as a comparison of results with more complex approaches.

Vulnerability and impacts: damage functions. CLIMRISK's spatially explicit resolution (0.5° × 0.5°) allows the use of more specific damage functions that represent more adequately the differences in vulnerability at subnational scales. This spatial resolution is much more detailed than existing IAMs, which typically estimate the economic impact of climate change at a global scale or divide the world in several large regions.[18] This contributes to a better quantification of the expected impacts of climate change at the grid, regional, and global scales. Urban areas have been shown to be of particular importance for assessing the costs and risks of climate change due to factors, such as high exposure and local warming. Cities account for about 80% of global GDP, 50% of global population, and are expected to contribute to a substantial share of the total economic damages at all geographical scales.[8,60,61] This warrants special efforts for improving the representation of urban areas in IAMs to advance the assessment of the aggregate economic impacts of climate change. The omission of the interactions between local and global climate change can bias downward the estimates of the economic impacts of climate change at the national, regional, and global levels.[8] Similarly, due to the nonlinearity of climate impacts, omitting such interactions can lead to underestimating the benefits of global mitigation efforts. Its explicit spatial resolution and modeling of UHI effects makes CLIMRISK the first IAM that allows to account for the synergistic effects of local and global warming and to integrate this in its damage and risk projections. CLIMRISK explicitly addresses urban areas in all of its modules, including the incorporation of a damage function specifically developed and calibrated for urban areas.[8]

The default set of damage functions in CLIMRISK accounts for differences in vulnerability between regions as well as between urban and nonurban areas. This is achieved by including a specific damage function for urban areas and region-specific damage functions for areas not predominantly urban. CLIMRISK uses the RICE model[16,62] regional damage functions, an urban damage function,[8] and a modification of both types of damage functions that considers persistence and impact dynamics, and that approximates indirect impacts[63] (see Supplementary Information S1.3, online only). These modifications allow to account for omissions that have important effects on the assessments of the economic costs of climate change.[8,63] Four sets of regional damage functions are considered in CLIMRISK: those of the original RICE model (RICE); those of the RICE model that integrate the persistence of climate shocks (RICE-P); those that include the effects of UHI (RICE-U) and; those that include both the effects of UHI and the persistence of climate shocks (RICE-P-U) and that are consistent with highly nonlinear functions in the literature.[64] The impacts calculated with the original RICE functions are smaller compared with our RICE-U and RICE-P-U functions due to the omission of the relevant factors described above (see Supplementary Information S1.3, online only; a detailed comparison with standard damage functions is available at Refs. 8 and 64). These sets of damage functions encompass conservative and high-damage estimates that are available in the literature[63] and allow to represent the uncertainty in climate-induced damages without requiring a higher computational cost associated with the use of stochastic damage functions.[65] In this paper, CLIMRISK results are reported for 13 world regions (Table S17, online only), while results in maps are shown at the model's native 0.5° × 0.5° resolution.

Risk: uni- and multivariate measures. CLIMRISK is the first economic integrated assessment model to include climate–economy risk measures to complement the projection of the economic impacts of climate change. The risk evaluation module is designed to estimate a variety of user-defined, spatially explicit climate and economic risk measures as well as multivariate risk indices that are helpful to identify risk hotspots where the user's defined risks converge. These tailor-made risk measures, along with the economic damage estimates, aim to help adaptation decision-making processes and critical path planning for climate change mitigation policy. The relevance of expanding IAMs to consider more dimensions of the consequences of climate change than only monetary estimates has been suggested in the literature.[29,66,67]

The climate risk measures in this version of CLIMRISK include the marginal and joint probabilities for reaching thresholds in annual temperature and precipitation change, and the estimates of the date for reaching these thresholds. A detailed exposition of these risk measures and how they are computed is provided in Section S1.4 of the Supplementary Information (online only). For the estimates presented in this paper, the date at which a climate threshold is declared to be reached requires that at least 50% of the simulations are at or over the threshold.

The economic risk measures in the present version of CLIMRISK include the date for reaching a given percent loss in GDP or for experiencing economic losses of a certain magnitude. These risk measures are computed for all four sets of damage functions in CLIMRISK (see Supplementary Information S1.3, online only). The climate and economic risk measures are combined to produce multivariate risk indices, which indicate the number risk thresholds that have been reached at a given year and for each grid cell. CLIMRISK shows in which areas the user-defined risks converge and when different risk levels would be attained. CLIMRISK also produces dynamic estimates of these risk indices that show the evolution of risks over time (see animated gifs in Figs. S26–S33, online only). Finally, it is important to note that the aim of this module of CLIMRISK is to identify risk hotspots and to ideally trigger additional local and sector-specific research which cannot be replaced by global IAM projections.

For the main results in this paper, we selected an increase of 2.5 °C or more in annual temperatures with respect to 1990 (a sensitivity analysis is included for 1.5 and 3.5 °C), reductions of at least 10% in annual precipitation with respect to 1990, economic impacts that represent at least a 5% decrease in GDP per year, and absolute economic losses of 1 billion dollars or more per year. Even though these thresholds are subjective, they can be linked to significant impacts in a variety of systems: Table S19 (online only) shows a summary of the impacts on ecosystems predicted for a range of increases in regional temperatures up to 3.7 °C and suggests severe impacts on a wide range of regions across the world[68,69] (see Supplementary Information S2, online only); the threshold of at least a 10% reduction in annual precipitation highlights regions that are likely to experience reductions in precipitation and droughts which have been associated with larger risks of human conflict[70–72] and migration;[73–75] exceeding the joint threshold of the changes in temperature and precipitation described above, suggests regions where negative impacts on biomass production are expected to occur as well as where wildfires are expected to increase;[76–82] losses of at least 5% in GDP per year constitute considerable deviations from expected growth and entail important socioeconomic challenges; the threshold of losses exceeding 1 billion dollars is used in the literature to define weather/climate events with important socioeconomic implications.[83–85]

Socioeconomic and emissions scenarios. This section briefly describes the selection of socioeconomic and emissions scenarios used for the main results and sensitivity analyses presented in this paper. The combination of the SSP5 and RCP8.5 scenarios used for our main results provides a consistent baseline to evaluate the consequences and risks of an increase of 8.5W/m^2 in the radiative forcing at the end of this century (as defined in RCP8.5). This combination serves as reference for exploring and comparing the benefits from different international mitigation efforts.[3,86] Even stringent mitigation scenarios, such as the RCP3PD, have been found costly, but feasible under the SSP5–RCP8.5 baseline by a majority of integrated assessment models.[3] The SSP5 depicts a global development based on fossil fuels with rapid technological progress, economic growth, and energy intensive lifestyles that lead to radiative forcing levels higher than any other SSP pathway (>8 W/m^2 in 2100).[87] Sensitivity analyses are included for the stringent climate policy RCP3PD scenario, which can be attained by different SSP storylines. We provide results for the SSP1 and SSP2,[40] as well as for the SSP3, for which attaining this mitigation level is less likely but possible.[88]

The OECD Env-Growth socioeconomic scenarios were selected as the main baseline case because they tend to represent a central estimate. Some results that use the two other modeling groups (IIASA and PIK) are also included in the Supplementary Information (online only) as part of our sensitivity analysis.

The RCP8.5 and RCP3PD emissions scenarios used in this paper are those included in the MAGICC6 software[46] (see Supplementary Information S1.2.2, online only) used for generating climate projections in module 2. The RCP8.5 is not a business-as-usual scenario, but a high-emissions, no mitigation pathway. The RCP3PD is selected as an emissions trajectory that is consistent with the Paris Agreement goal of limiting global warming well below 2 °C by 2100. Note, however, that there are many trajectories that could lead to similar levels of warming. For the Nationally Determined Contributions (NDC)-type scenarios, the reductions per region were obtained using the C-ROADS software (https://www.climateinteractive.org/tools/c-roads/) for the main greenhouse gases (CO_2, CH_4, and N_2O), and these reductions were applied to the RCP8.5 scenario included in MAGICC6 (Figs. S33 and S34, online only). These emissions reductions reflect the contributions expressed by the different countries in their NDC and the relative level of effort is maintained until 2100 (see http://climateactiontracker.org/). The NDC scenarios in CLIMRISK include the cases of: (1) strict compliance; (2) the United States cancelling its participation in the agreement; and (3) China dropping out of the NDCs. Note that in both cases, the scenarios assume that the countries do not participate in NDC agreement at any point in time, and that their noncompliance does not affect NDCs from other countries. The main objective of these scenarios is to estimate *ceteris paribus* what the direct consequences of such countries not participating in the NDCs effort. These scenarios do not consider how other countries would respond to the United States or China dropping out of the NDC agreement. Figure S33 (online only) shows the greenhouse gas emissions of CO_2, CH_4, and N_2O for each of the scenarios used in our calculations and Figure S34 (online only) depicts the corresponding annual mean global temperature projections.

Results

Projected economic impacts and risks of climate change under reference and policy scenarios

Table 1 shows the discounted climate change impacts as absolute losses and expressed as a percentage of current GDP under the RCP8.5 and SSP5 scenarios for selected regions. For all present value calculations in this paper, a 4% discount rate was chosen. Under the conservative damage functions, the present value of the median impacts over this century is between 77% and 102% of current GDP for some regions (United States, EU, Japan, Russia, and Eurasia), while it exceeds 200% of current GDP for others (Africa, China, India, the Middle East, and some parts of Asia). The central estimate for the world is 204% of current global GDP. Note that accounting for the interaction of local and global climate change in urban areas results in economic impacts that are about twice as high for most regions compared with estimates that ignore the UHI (Tables S2 and S8, online only). The high-impact damage functions result in median impacts that are between almost a factor of 2 (EU) and about a factor of 6 higher (Africa), while for the world it is about 4. Also, the 95% confidence intervals provided by CLIMRISK depict that uncontrolled climate change entails very high levels of risk for many regions. Figure 2 shows the median economic impacts in billions of US$ per grid cell for the years 2050 and 2100 (Figs. S8 and S9, online only). The spatially explicit resolution shows impact to be highly unevenly distributed between and within countries and concentrated in urban areas. For some grid cells, impacts exceed US$5 billion and particularly high losses occur in large parts of Asia and Africa (notably with RICE-P-U). Sensitivity analyses show that the findings about urban damages are robust to uncertainty in estimating the UHI effect (Tables S9 and S10, online only).

The economic benefits of full and partial compliance of climate policy scenarios are presented in Table 2 (and Tables S11–S13, online only). The RCP3PD scenario, which is consistent with the goals of the Paris Agreement, brings substantial benefits. Compared with RCP8.5 (Table 1), the RCP3PD limits climate change costs by about half

Table 1. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP and in billions US$2005 under the RCP8.5 and SSP5 scenarios for selected regions and a set of conservative (RICE-U) and high-impact (RICE-P-U) damage functions

Region	RICE-U	RICE-P-U
USA	90% $11,844 (52%, 133%) [$6819, $17,476]	208% $27,388 (120%, 307%) [$15,803, $40,339]
EU	102% $15,164 (60%, 148%) [$8921, $22,131]	193% $28,776 (114%, 281%) [$16,954, $41,944]
JAPAN	77% $2986 (47%, 109%) [$1833, $4248]	178% $6946 (110%, 253%) [$4273, $9865]
RUSSIA	89% $1800 (52%, 131%) [$1041, $2640]	373% $7519 (217%, 545%) [$4369, $10,991]
EURASIA	80% $1164 (43%, 121%) [$633, $1765]	238% $3476 (130%, 360%) [$1894, $5260]
CHINA	218% $20,594 (129%, 314%) [$12,190, $29,666]	923% $87,193 (548%, 1326%) [$51,763, $125,289]
INDIA	708% $25,862 (429%, 1009%) [$15,653, $36,868]	2920% $106,653 (1774%, 4147%) [$64,813, $151,506]
MEAST	279% $7202 (169%, 397%) [$4358, $10,276]	1151% $29,764 (700%, 1636%) [$18,091, $42,305]
AFRICA	830% $22,857 (482%, 1219%) [$13,272, $33,560]	5275% $145,215 (3091%, 7556%) [$85,079, $208,015]
LAM	141% $6241 (87%, 201%) [$3847, $8870]	369% $16,318 (228%, 523%) [$10,085, $23,140]
OHI	124% $4252 (71%, 183%) [$2444, $6281]	287% $9831 (165%, 423%) [$5663, $14,496]
OASIA	399% $14,634 (235%, 582%) [$8601, $21,330]	1637% $59,994 (967%, 2376%) [$35,437, $87,076]
MX	137% $1933 (85%, 194%) [$1202, $2730]	358% $5052 (224%, 505%) [$3150, $7119]
WORLD	204% $136,533 (121%, 296%) [$80,814, $197,841]	799% $534,125 (475%, 1148%) [$317,374, $767,345]

NOTE: Figures in brackets are in billions US$2005; 95% confidence intervals based on uncertainty in global warming projections are shown in parentheses for the percentage of a region's current GDP and in brackets for billions US$2005. Figures are rounded to the nearest integer. Illustrative reading of this table: the entry in the first row, second column of this table shows that, using the conservative RICE-U damage function, the present value of the climate change losses accumulated over this century for the United States is equivalent to about 90% of the country's GDP in 2010, with a 95% confidence interval that ranges from (in parentheses) 52% to 133%. These figures are equivalent to $11,844 billion dollars with (in brackets) $6819–$17,476 billion dollars as the lower and upper bounds of the 95% confidence interval. Calculations are based on a 4% discount rate.

or more (Africa) for most regions. These results imply that even if the Paris objective is met, sizeable residual economic impacts need still be addressed by adaptation or L&D. The ambition of the current NDCs is insufficient for reaping benefits like those of the RCP3PD, but it allows for large reductions in impacts and risks in all regions. For instance, for the United States, median benefits of RCP3PD are between 52% (RICE-U) and 119% (RICE-P-U) of current GDP, while these estimates drop to 21% (RICE-U) and 48% (RICE-P-U) under the NDC scenario. For Africa, median benefits can reach up to 3317% of current GDP (RICE-P-U) under RCP3PD and decline to 1301% with the current NDCs. For the world, the median benefits of the RCP3PD represent between 117% and 456% of current GDP, while for the NDC scenario, these estimates are 46–179%. If large emitters, like the United States (NDCnoUSA) or China (NDCnoCHINA), withdraw from the Paris Agreement, then the mitigation benefits from the NDCs become noticeably smaller. From the viewpoint of countries participating in the NDCs, their mitigation efforts become less efficient. Alternatively, the

Table 2. **Median total discounted economic benefits of climate change mitigation policy over this century expressed as a percentage of a region's current GDP and in billions US$2005 under the RCP3PD, INDC with full compliance and without compliance of the United States (INDCnoUSA) and China (INDCnoCHINA) scenarios for selected regions and a conservative (RICE-U) and high-impact (RICE-P-U) damage function**

Region	Policy	RICE-U	RICE-P-U
USA	RCP3PD	52% (28%, 78%) $6815 [$3717, $10,239]	119% (65%, 178%) $15,601 [$8527, $23,391]
	INDC	21% (13%, 33%) $2731 [$1691, $4393]	48% (30%, 76%) $6247 [$3881, $10,032]
	INDCnoUSA	16% (10%, 25%) $2065 [$1253, $3313]	36% (22%, 57%) $4717 [$2872, $7556]
	INDCnoCHINA	14% (10%, 23%) $1814 [$1302, $2987]	32% (23%, 52%) $4149 [$2990, $6820]
EU	RCP3PD	57% (32%, 86%) $8549 [$4708, $12,779]	108% (60%, 161%) $16,110 [$8885, $24,051]
	INDC	23% (14%, 37%) $3410 [$2126, $5461]	43% (27%, 69%) $6423 [$4014, $10,275]
	INDCnoUSA	17% (11%, 28%) $2580 [$1577, $4121]	33% (20%, 52%) $4855 [$2974, $7747]
	INDCnoCHINA	15% (11%, 25%) $2263 [$1634, $3710]	29% (21%, 47%) $4262 [$3087, $6981]
JAPAN	RCP3PD	38% (21%, 56%) $1475 [$823, $2183]	87% (49%, 129%) $3395 [$1898, $5014]
	INDC	15% (10%, 24%) $585 [$374, $932]	34% (22%, 55%) $1344 [$862, $2140]
	INDCnoUSA	11% (7%, 18%) $437 [$274, $696]	26% (16%, 41%) $1004 [$630, $1597]
	INDCnoCHINA	10% (7%, 16%) $388 [$290, $634]	23% (17%, 37%) $891 [$670, $1455]
RUSSIA	RCP3PD	49% (27%, 73%) $984 [$542, $1465]	200% (111%, 296%) $4028 [$2227, $5972]
	INDC	19% (12%, 31%) $393 [$247, $628]	80% (50%, 127%) $1603 [$1017, $2556]
	INDCnoUSA	15% (9%, 23%) $294 [$181, $468]	59% (37%, 94%) $1196 [$743, $1901]
	INDCnoCHINA	13% (10%, 21%) $261 [$192, $427]	53% (39%, 86%) $1065 [$789, $1738]
EURASIA	RCP3PD	48% (25%, 72%) $697 [$371, $1057]	141% (75%, 213%) $2058 [$1100, $3111]
	INDC	19% (12%, 31%) $282 [$172, $457]	57% (35%, 92%) $832 [$510, $1345]
	INDCnoUSA	15% (9%, 23%) $212 [$127, $343]	43% (26%, 69%) $624 [$376, $1007]
	INDCnoCHINA	13% (9%, 21%) $188 [$133, $311]	38% (27%, 63%) $554 [$395, $916]
CHINA	RCP3PD	110% (63%, 161%) $10,433 [$5930, $15,199]	460% (263%, 668%) $43,491 [$24,807, $63,143]
	INDC	43% (28%, 68%) $4099 [$2686, $6454]	181% (119%, 284%) $17,061 [$11,245, $26,791]
	INDCnoUSA	32% (21%, 50%) $3029 [$1943, $4760]	133% (86%, 209%) $12,572 [$8110, $19,703]
	INDCnoCHINA	29% (22%, 46%) $2720 [$2093, $4389]	120% (93%, 193%) $11,317 [$8772, $18,217]

Continued

Table 2. ***Continued***

Region	Policy	RICE-U	RICE-P-U
INDIA	RCP3PD	409% (241%, 589%) $14,948 [$8792, $21,516]	1655% (978%, 2372%) $60,461 [$35,716, $86,662]
	INDC	158% (104%, 244%) $5775 [$3793, $8930]	639% (422%, 984%) $23,333 [$15,430, $35,944]
	INDCnoUSA	120% (77%, 185%) $4372 [$2815, $6743]	482% (313%, 741%) $17,618 [$11,420, $27,067]
	INDCnoCHINA	104% (79%, 165%) $3813 [$2881, $6037]	422% (321%, 665%) $15,401 [$11,737, $24,290]
MEAST	RCP3PD	153% (89%, 222%) $3965 [$2299, $5751]	620% (361%, 895%) $16,021 [$9334, $23,133]
	INDC	60% (39%, 93%) $1543 [$1008, $2408]	241% (158%, 374%) $6226 [$4098, $9680]
	INDCnoUSA	45% (29%, 70%) $1163 [$744, $1811]	181% (117%, 281%) $4677 [$3014, $7255]
	INDCnoCHINA	39% (30%, 63%) $1021 [$771, $1631]	159% (122%, 254%) $4116 [$3142, $6555]
AFRICA	RCP3PD	542% (308%, 801%) $14,928 [$8475, $22,041]	3317% (1900%, 4728%) $91,313 [$52,303, $130,148]
	INDC	213% (134%, 336%) $5869 [$3682, $9249]	1301% (827%, 1906%) $35,805 [$22,769, $52,465]
	INDCnoUSA	164% (101%, 257%) $4504 [$2776, $7078]	993% (620%, 1421%) $27,344 [$17,079, $39,121]
	INDCnoCHINA	141% (101%, 227%) $3883 [$2777, $6260]	860% (625%, 1251%) $23,669 [$17,215, $34,436]
LAM	RCP3PD	73% (41%, 108%) $3248 [$1827, $4790]	190% (107%, 279%) $8393 [$4733, $12,351]
	INDC	29% (19%, 46%) $1284 [$819, $2033]	75% (48%, 118%) $3314 [$2121, $5239]
	INDCnoUSA	22% (14%, 35%) $967 [$604, $1528]	56% (35%, 89%) $2492 [$1562, $3931]
	INDCnoCHINA	19% (14%, 31%) $851 [$630, $1380]	50% (37%, 80%) $2196 [$1633, $3556]
OHI	RCP3PD	73% (40%, 109%) $2499 [$1367, $3749]	167% (91%, 250%) $5722 [$3137, $8568]
	INDC	29% (18%, 46%) $1000 [$619, $1605]	67% (41%, 107%) $2289 [$1421, $3667]
	INDCnoUSA	22% (13%, 35%) $758 [$460, $1213]	50% (31%, 81%) $1731 [$1054, $2767]
	INDCnoCHINA	19% (14%, 32%) $664 [$475, $1091]	44% (32%, 73%) $1519 [$1092, $2492]
OASIA	RCP3PD	241% (136%, 356%) $8827 [$4974, $13,043]	968% (548%, 1423%) $35,453 [$20,074, $52,144]
	INDC	95% (60%, 150%) $3487 [$2197, $5509]	382% (242%, 600%) $13,983 [$8873, $21,997]
	INDCnoUSA	72% (45%, 114%) $2653 [$1640, $4180]	290% (180%, 454%) $10,609 [$6606, $16,638]
	INDCnoCHINA	63% (46%, 102%) $2309 [$1671, $3734]	253% (184%, 407%) $9257 [$6759, $14,899]
MX	RCP3PD	70% (40%, 103%) $986 [$560, $1446]	181% (103%, 264%) $2545 [$1448, $3726]

Continued

Table 2. ***Continued***

Region	Policy	RICE-U	RICE-P-U
	INDC	28% (18%, 43%) $388 [$250, $612]	71% (46%, 112%) $1000 [$646, $1576]
	INDCnoUSA	21% (13%, 33%) $292 [$184, $459]	53% (34%, 84%) $751 [$475, $1181]
	INDCnoCHINA	18% (14%, 29%) $257 [$192, $415]	47% (35%, 76%) $663 [$498, $1069]
WORLD	RCP3PD	117% (66%, 172%) $78,354 [$44,385, $115,258]	456% (261%, 661%) $304,591 [$174,189, $441,414]
	INDC	46% (29%, 73%) $30,846 [$19,664, $48,671]	179% (115%, 275%) $119,460 [$76,886, $183,707]
	INDCnoUSA	35% (22%, 55%) $23,326 [$14,578, $36,713]	135% (85%, 206%) $90,190 [$56,915, $137,471]
	INDCnoCHINA	31% (22%, 49%) $20,432 [$15,041, $33,006]	118% (88%, 185%) $79,059 [$58,779, $123,424]

NOTE: Figures in the upper part of each entry are expressed as a percentage of the region's current GDP, while figures in the lower part of each entry are in billions of US$2005; 95% confidence intervals based on uncertainty in global warming projections are shown in parentheses for the percentage of a region's current GDP and in brackets for billions US$2005. Figures are rounded to the nearest integer. Illustrative reading of this table: the entry in the first row, third column of this table shows that, using the conservative RICE-U damage function, the present value of the benefits for the United States of implementing the RCP3PD in comparison with the RCP8.5 is equivalent to about 52% of the country's GDP in 2010, with a 95% confidence interval that ranges from (in parentheses) 28% to 78%. These figures are equivalent to $6815 billion dollars with (in brackets) $3717–$10,239 billion dollars as the lower and upper bounds of the 95% confidence interval. GDP scenario: SSP5 OECD Env-Growth. Reference emissions scenario: RCP8.5. Calculations are based on a 4% discount rate.

withdrawal of these countries can be expressed as climate change impacts on specific regions (Tables S14–S16, online only). For instance, the costs of the United States dropping out are between 5% (RICE-U) and 12% (RICE-P-U) of current GDP for the United States itself and range up to between 50% (RICE-U) and 307% (RICE-P-U) of current GDP for Africa. These costs are higher if China withdraws reaching between 15% (RICE-U) and 61% (RICE-P-U) of its own GDP.

The NDC mitigation effort can significantly limit climate change risks according to a variety of measures. First, two economic risk measures are explored: (1) a decrease of at least 5% in GDP per year, which constitutes a considerable deviation from expected growth and entails important socioeconomic challenges; and (2) the threshold of losses exceeding 1 billion dollars that denote weather/climate events with important socioeconomic implications.[83–85] Figure S10A (online only) depicts the dates when median economic losses per year exceed 5% of the GDP using the conservative damage function (Fig. S10C, online only, shows RICE-P-U results). The threshold is exceeded by the mid-century for some parts of Asia and Africa and some large urban areas around the world. Large parts of Asia and almost the entire African continent are projected to experience annual losses larger than 5% of their GDP in the second half of this century. The dates for reaching this threshold are delayed about 20 years by the NDC in most of the world, except for some small parts of Africa, the Middle East, and South Asia (Fig. S10B and S10D, online only). The threshold of economic losses larger than US$1 billion is exceeded in many large urban areas within the next two decades, while the surrounding areas reach it during the second half of the century (Fig. S11A and S11C for RICE-P-U, online only). This risk measure is barely affected by a strict implementation of the NDC scenario (Fig. S11B and S11D, online only). Pushing forward in time any of the economic risk thresholds in large urban areas would require the implementation of local strategies to reduce the UHI effect in addition to international mitigation efforts.[8]

The economic costs of climate change are only one dimension of the risks this phenomenon poses. Therefore, if taken in isolation, these estimates can provide a poor, and incomplete, assessment of climate change consequences. The impacts of

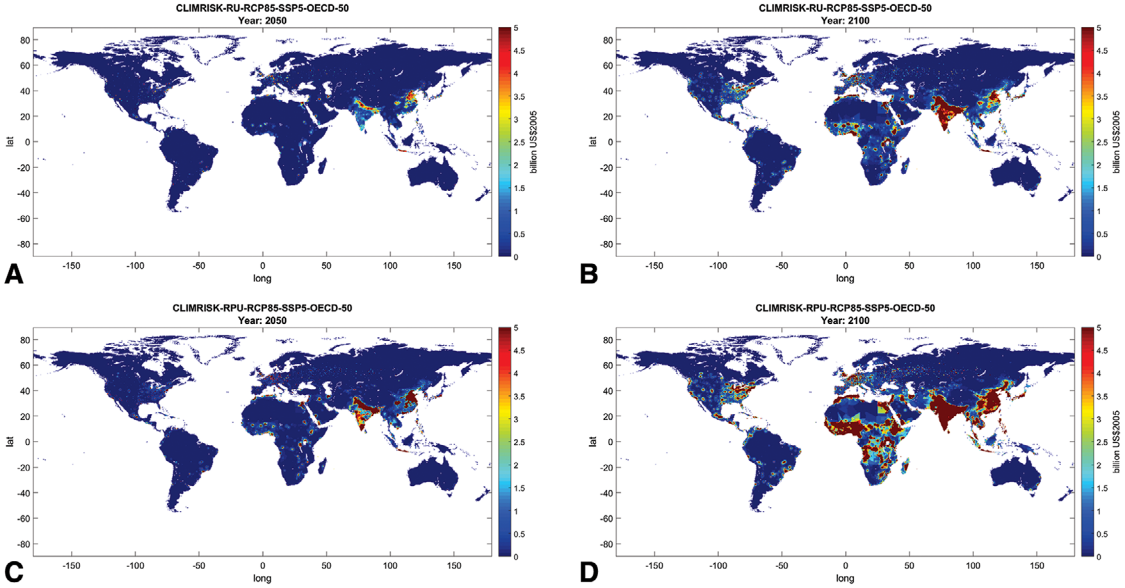

Figure 2. (A–D) Spatially explicit economic impacts of climate change under the RCP8.5 and SSP5 scenarios. Median economic impacts of climate change expressed in US$ per grid cell in year 2050 (panel A for RICE-U and panel C for RICE-P-U) and 2100 (panel B for RICE-U and panel D for RICE-P-U). Figure S10 (online only) shows damages as a fraction of GDP.

climate change on ecosystems are particularly difficult to quantify in economic terms and are poorly represented in damage functions of current climate–economy IAMs.[31,29,89] Monetary values alone cannot provide an adequate representation of risk. Table S19 (online only) contains a summary of the expected impacts on ecosystems for increases in regional temperature for up to 3.7 °C that have been reported in the literature.[68] Figure 3 presents the dates for exceeding warming thresholds of 1.5, 2.5, and 3.5 °C for each grid cell estimated using CLIMRISK (Figs. S12 and S13, online only). Under the RCP8.5 scenario, the threshold of 1.5 °C (Fig. 3E) would be reached in 2030 for most of the land, including Africa, the Amazon, and central Australia. For latitudes above 60° north, this could happen during the 2020s. For most of the oceans, this warming level would occur before 2060. Some of the associated impacts on ecosystems (Table S19, online only) in the regions where this threshold is exceeded are that 9–31% of species would be committed to extinction and the bleaching of all coral reefs. Full compliance of NDC commitments would delay reaching this threshold about a decade in most of western Europe, southern part of North America, the Amazon, Australia, and the central part of Africa (Fig. 3F). Under the RCP8.5, a 2.5 °C warming would be reached in most continental land during the 2050s and about a decade earlier in large parts of Canada and Russia (Fig. 3C; and Fig. S12, online only). A strict implementation of the NDC scenario (Fig. 3D; and Fig. S13, online only) would provide a 10-year delay for reaching impacts, such as 21–52% of species committed to extinction, extinction of remaining coral reef ecosystems, commitment to extinction in Africa of 24–59% of mammals, 28–40% of birds, 13–70% of butterflies, 18–80% of other invertebrates, and 21–45% of reptiles. As shown by Figure 3A and 3B, mitigation actions are most effective for delaying or avoiding the occurrence of the worst outcomes. Exceeding warming larger than 3.5 °C would occur 20 years later under full compliance of the NDC scenario in comparison with the RCP8.5. This international effort would push reaching this threshold for most of the land grid cells to the last two decades of this century or into the next one. The impacts associated with an increase between 2.5 and 3.5 °C include the eventual loss of 9–62% of the mammalian species from Great Basin montane areas in the United States, 24% loss of freshwater fish habitat in North America, the risk of extinction of alpine species in Europe, 38–67% of frogs, 48–80% of mammals, 43–64% of reptiles, and 49–72% of birds committed

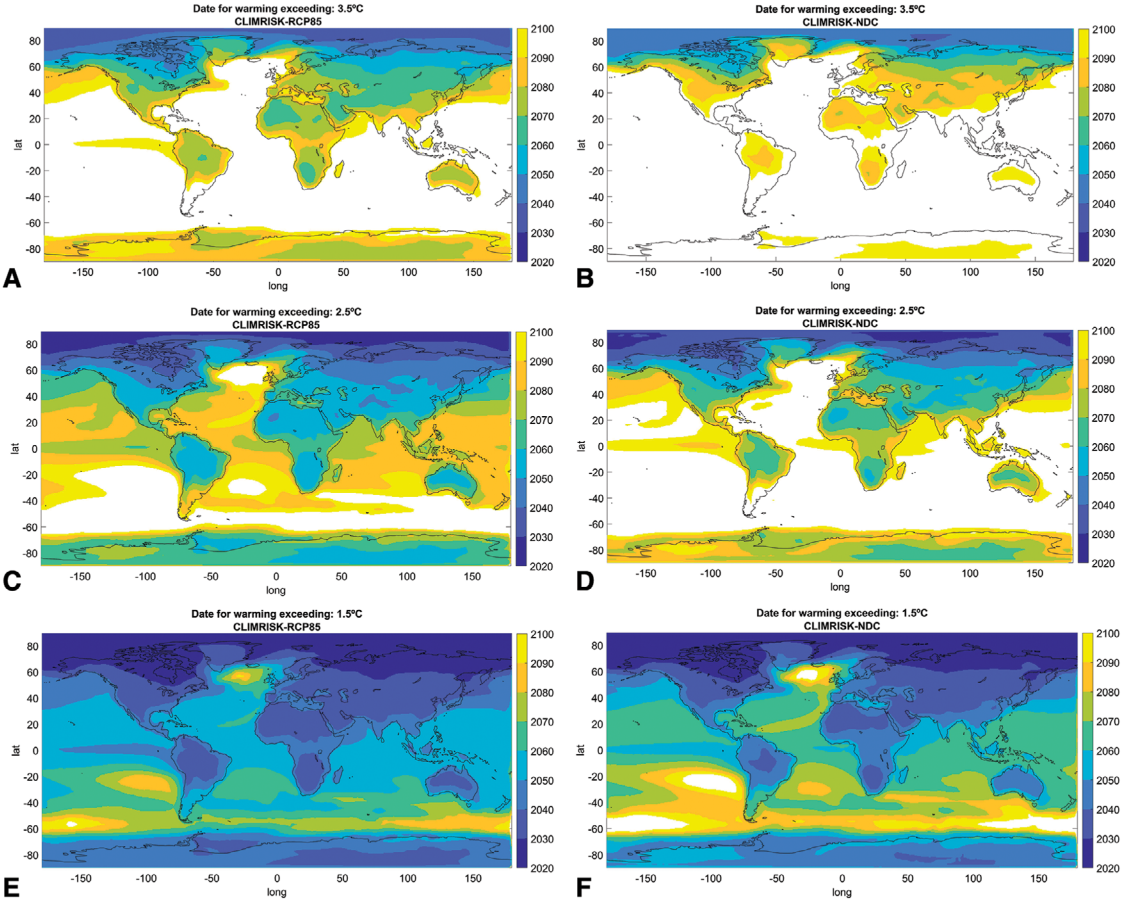

Figure 3. (A–F) Dates for exceeding levels of warming of 3.5, 2.5, and 1.5 °C in annual temperature. Panels A, C, and E show the estimated dates for exceeding levels of warming per grid cell of 3.5, 2.5, and 1.5 °C (w.r.t. 1990), respectively, under the RCP8.5 scenario. Panels B, D, and F show the estimated dates for exceeding levels of warming per grid cell of 3.5, 2.5, and 1.5 °C (w.r.t. 1990), respectively, under the NDC scenario.

to extinction in Queensland, Australia. For slightly higher regional temperatures (3.7 °C), 4–38% of birds could be extinct in Europe. Risk thresholds are nonlinear and relatively small deviations from a given trajectory can cause considerable effects. This is illustrated by Figures S14 and S15 (online only), which show that the withdrawal from the United States or China would make some areas exceed these thresholds sooner.

Reductions in precipitation and droughts have been associated with increasing risks of human conflict[70–72] and migration.[73–75] Mapping the dates for exceeding a 10% decrease in annual precipitation reveals two clear latitudinal patterns of the regions that would experience drier climate conditions in this century (Figs. S16 and S17, online only). The first occurs in the northern hemisphere between latitudes 5° and 40°. It includes the Mediterranean region, the Caribbean, the northwest and southeast of Mexico, and parts of Central America. The second pattern occurs in the southern hemisphere and covers the west coast of Australia, South Africa, and Chile. For large parts of these regions, it is projected that this threshold is exceeded in the next two to three decades. The NDCs produce less notorious risk for this precipitation threshold (Figs. S16 and S18, online only). Warmer and drier climates have been identified to have negative effects on forests and shrubland biomass production, and plant composition,[76,78–80] as well as to increase wildfire hazard and declining ecosystem services.[77,81,82] To explore these risks, an

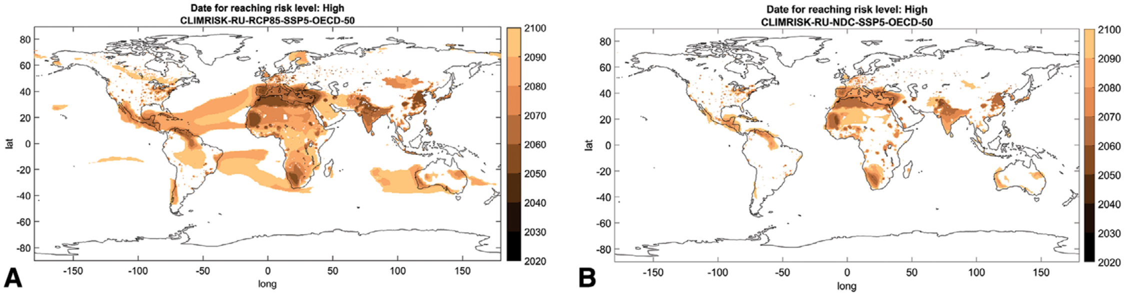

Figure 4. Dates for exceeding the thresholds in the multivariate risk index. Panels (A) and (B) show the estimated dates for reaching a high score in the multivariate risk score, under the RCP8.5 and NDC scenarios, combined with SSP5.

index for jointly exceeding warming thresholds of 1.5 and 2.5 °C and precipitation decrease of at least 10% was produced. Results show that the Mediterranean, parts of southern Africa, northwest and southern Mexico, Central America, and Australia are prone to experience significantly warmer and drier climates during the next two to three decades (Figs. S19–S21, online only). The NDCs can push reaching the joint threshold of 2.5 °C and at least a 10% decrease in precipitation forward in time from about one decade in the Mediterranean, and about two decades in Mexico, Central America, and Australia (Figs. S19 and S22, online only).

The use of multivariate climate–economy indexes can define hotspots of climate change risks. CLIMRISK's multivariate risk indices provide a score for each grid cell of medium, high, or very high, depending on the count of exceeded physical and economic thresholds per grid cell: 2.5 °C and −10% in annual temperature and precipitation, respectively, and 5% of GDP and 1 billion dollars per year (see Supplementary Information S1.4, online only). The high-risk score is reached during the 2050s in the northwest of Africa, South Africa, Spain, parts of the Middle East, India, and China, and in some of the largest urban areas. One or two decades later, this score is attained in southern Europe, Mexico, the east coast of the United States and parts of Central and South America, Australia, and most large urban areas around the world (Fig. 4; and Fig. S23, online only, for RICE-P-U). Figures S24 and S25 (online only) show the dates for reaching moderate and very high scores, and the evolution of the multivariate risk index (Fig. S26, online only). The NDCs are effective to reduce the highest scores of risk for most regions (Fig. 4; and Figs. S27 and S31, online only), but moderate risk can hardly be reduced (Fig. S24, online only), unless the Paris Agreement goal is met (Figs. S28, S29, and S32, online only). This underlines the limits of risk reduction that mitigation efforts alone can accomplish, and the need to identify hotspots where adaptation is urgent.

Discussion and conclusions

CLIMRISK is an economic IAM that offers tailor-made output to characterize different dimensions of the potential consequences of climate change and the benefits of active climate policy. Our results shown that the consequences of unabated climate change can be substantially higher than previously estimated when additional warming in urban areas and temporal persistence of impacts are accounted for. A substantial proportion of the economic damages and risks projected for the next few decades are unavoidable by mitigation due to the dynamics of the climate and social systems. While meeting the Paris Agreement goal would permanently limit the costs and risk of climate change, full compliance of NDCs can successfully delay some of the worst outcomes by about one to three decades. Withdrawal from the NDCs by large emitters, like the United States or China, would impose considerable costs for all countries, including those that withdraw. Our results show that, under the current high-emissions, high-warming path the world is following, even relatively small deviations from this trajectory can produce large changes in the projected total costs and risks of climate change. This is much more pronounced when the synergistic effects of global and local warming in cities are accounted for. These effects can only be captured in a spatially explicit

IAM, such as CLIMRISK, which models urban warming and impacts. Moreover, the estimates presented here show that the downward bias in total economic cost estimates produced when the effects of UHI are ignored[8] is more severe under low global warming scenarios such as those consistent with the Paris Agreement. A direct consequence is that sizeable residual economic impacts would remain even under stringent mitigation scenarios and larger risk reduction and adaptation efforts would be required than previously suggested by IAM estimates. Such efforts would be particularly important in cities.

Impacts and risks have a highly unequal spatial distribution. Especially high impacts occur in poor regions, like African countries as well as in large cities across the world. Moreover, urban areas are shown to be risk hotspots and are projected to face substantial economic losses in the short term. Large cities can play a role in reducing their own, and global, risks as they can partly compensate lacking mitigation policies at the country level,[90] and adopt cost-effective measures to limit urban warming.[8] These results support more stringent policies at the local, national, and global governance levels to reduce anthropogenic climate change and adapt to partly unavoidable impacts.

The results presented in this paper strongly suggest that addressing the limitations of IAMs that have been pointed out in the literature offers important opportunities for advancing the modeling and understanding of climate change costs and risks. Areas of development of particular importance for the IAM community include improving the representation of extreme events and their direct and indirect impacts, providing better representations of low-probability high-impact climate catastrophes, social and natural tipping points, as well as including adaptation and decision processes.

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Supporting information

Additional supporting information may be found in the online version of this article.

Table S1. Increases in global temperatures are calculated with respect to the 1986–2005 period.

Table S2. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S3. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S4. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S5. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S6. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP3PD scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S7. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP3PD scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S8. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP3PD scenario for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S9. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a conservative damage function that does (RICE-U) account for urban impacts originating from combined local and global warming, for the central and 95% lower and upper bounds of the UHI effect estimates: SSP5 OECD.

Table S10. Median total discounted economic costs of climate change over this century expressed as a percentage of a region's current GDP under the RCP8.5 scenario for selected regions and a high-impact damage function that does (RICE-P-U) account for urban impacts originating from combined local and global warming, for the central and 95% lower and upper bounds of the UHI effect estimates.

Table S11. Median total discounted economic benefits of climate change mitigation policy over this century expressed as a percentage of a region's current GDP under the RCP3PD, NDC with full compliance and without compliance of the United States (NDCnoUSA) and China (NDCnoCHINA) scenarios for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S12. Median total discounted economic benefits of climate change mitigation policy over this century expressed as a percentage of a region's current GDP under the RCP3PD, NDC with full compliance and without compliance of the United States (NDCnoUSA) and China (NDCnoCHINA) scenarios for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S13. Median total discounted economic benefits of climate change mitigation policy over this century expressed as a percentage of a region's current GDP under the RCP3PD, NDC with full compliance and without compliance of the United States (NDCnoUSA) and China (NDCnoCHINA) scenarios for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-P-U) account for urban impacts originating from combined local and global warming.

Table S14. Total discounted costs over this century expressed as a percentage of a region's current GDP of key participants (the United States or China) dropping out of the NDC mitigation effort for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-U-P) account for urban impacts originating from combined local and global warming.

Table S15. Total discounted costs over this century expressed as a percentage of a region's current GDP of key participants (the United States or China) dropping out of the NDC mitigation effort for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-U-P) account for urban impacts originating from combined local and global warming.

Table S16. Total discounted costs over this century expressed as a percentage of a region's current GDP of key participants (the United States or China) dropping out of the NDC mitigation effort for selected regions and a conservative damage function that does not (RICE) or does (RICE-U) account for urban impacts originating from combined local and global warming and for a high-impact damage function that does not (RICE-P) or does (RICE-U-P) account for urban impacts originating from combined local and global warming.

Table S17. Relation between world regions and countries included in CLIMRISK.

Table S18. General circulation models' names and institutions included in CLIMRISK.

Table S19. Expected impacts to ecosystems as a function of regional temperature increase.

Table S20. Parameter values for the regional damage functions in CLIMRISK.

Table S21. Persistence parameter values for the regions in CLIMRISK.

Table S22. Brief description of the SSP narratives.

Figure S1. Conceptual framework and simplified model structure of CLIMRISK.

Figure S2. Schematic representation of the socioeconomic and climate modules of CLIMRISK.

Figure S3. Probabilistic simulations of global temperature increase for the historical period and the RCP8.5 scenario.

Figure S4. Schematic representation of the economic impact module of CLIMRISK.

Figure S5. Temperature–damage relationships of damage functions in CLIMRISK and other studies.

Figure S6. Differences in projecting economic losses using global and grid-scale temperature change projections and the proposed scaling factor.

Figure S7. Schematic representation of the risk evaluation module of CLIMRISK.

Figure S8. Animation of the spatially explicit economic impacts of climate change for the RICE-U damage function.

Figure S9. Animation of the spatially explicit economic impacts of climate change for the RICE-P-U damage function.

Figure S10. Dates for exceeding the threshold of economic impacts exceeding 5% of GDP per year using the RICE-P-U damage function.

Figure S11. Dates for exceeding the threshold of economic impacts exceeding 1 billion US$ per year.

Figure S12. Animation of the probability of exceeding 2.5 °C of warming (w.r.t. 1990) per grid cell, during this century under the RCP8.5 scenario.

Figure S13. Animation of the probability of exceeding 2.5 °C of warming (w.r.t. 1990) per grid cell during this century under the NDC scenario.

Figure S14. Dates for exceeding levels of warming of 3.5 °C in annual temperature.

Figure S15. Dates for exceeding levels of warming of 2.5 °C in annual temperature.

Figure S16. Dates for exceeding the threshold of a 10% decline in precipitation (w.r.t. 1990) per grid cell during this century.

Figure S17. Animation of the probability of exceeding a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century under the RCP8.5 scenario.

Figure S18. Animation of the probability of exceeding a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century under the NDC scenario.

Figure S19. Dates for exceeding 2.5 °C of warming and a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century.

Figure S20. Dates for exceeding 1.5 °C of warming and a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century.

Figure S21. Animation of the joint probability of exceeding 2.5 °C of warming and a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century under the RCP8.5 scenario.

Figure S22. Animation of the joint probability of exceeding 2.5 °C of warming and a −10% decrease in precipitation (w.r.t. 1990) per grid cell during this century under the NDC scenario.

Figure S23. Dates for reaching a high score in the multivariate risk index.

Figure S24. Dates for reaching a moderate score in the multivariate risk index.

Figure S25. Dates for reaching a very high score in the multivariate risk index.

Figure S26. Animation of the evolution of the multivariate risk index during this century per grid cell under the RCP8.5 scenario and the RICE-U damage function.

Figure S27. Animation of the evolution of the multivariate risk index during this century per grid cell under the NDC scenario and the RICE-U damage function.

Figure S28. Dates for reaching moderate, high, and very high scores in the multivariate risk index under the RCP3PD scenario.

Figure S29. Animation of the evolution of the multivariate risk index during this century per grid cell under the RCP3PD scenario and the RICE-U damage function.

Figure S30. Animation of the evolution of the multivariate risk index during this century per grid cell under the RCP8.5 scenario and the RICE-P-U damage function.

Figure S31. Animation of the evolution of the multivariate risk index during this century per grid cell under the NDC scenario and the RICE-P-U damage function.

Figure S32. Animation of the evolution of the multivariate risk index during this century per grid cell under the RCP3PD scenario and the RICE-P-U damage function.

Figure S33. Emissions of fossil CO_2, CH_4, and N_2O for the RCP8.5, NDC, NDCnoUSA, NDCnoCHINA, and RCP3PD scenarios.

Figure S34. Global annual temperature change for a reference, three policy scenarios based on the Intended Nationally Determined Contributions and a policy scenario consistent with the objective of the Paris Climate Agreement.

Competing interests

The authors declare no competing interests.

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