Indicators of 21st century socioclimatic exposure

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Policies that attempt to curb greenhouse gas emissions, allocate emissions rights, or distribute compensation to those most damaged by climate change must explicitly incorporate the international heterogeneity of the climate change threat. To capture the distinct susceptibilities associated with lack of infrastructure, potential property loss, and gross human exposure, we develop an integration of climate change projections and poverty, wealth, and population metrics. Our analysis shows that most nations of the world are threatened by the interaction of regional climatic changes with one or more relevant socioeconomic factors. Nations that have the highest levels of poverty, wealth, and population face greater relative exposure in those dimensions. However, for each of those socioeconomic indicators, spatial heterogeneity in projected climate change determines the overall international pattern of socioclimatic exposure. Our synthesis provides a critical missing piece to the climate change debate and should facilitate the formulation of climate policies that account for international variations in the threat of climate change across a range of socioeconomic dimensions.

climate change | CMIP3 | GCM | global warming | greenhouse gas

It is now firmly established that human activities are the fundamental cause of recent global- and continental-scale warming (1). Policies that attempt to curb greenhouse gas (GHG) emissions, allocate GHG emissions rights, or distribute compensation to those most damaged by climate change must explicitly incorporate the international heterogeneity of the climate change threat, including potential variations in physical climate change, human suffering, and loss of wealth. However, how these climate change susceptibilities vary and interact across nations is not yet known, nor is the net threat associated with the collective effects of multiple stressors.

Although 169 nations have ratified the Kyoto Protocol to reduce GHG emissions, the world's largest emitter, the United States, has rejected the treaty, and the world's two most populous nations, China and India, remain under no emissions constraints. Gaining wider international participation in future climate treaties remains a vexing challenge for international climate policy. Climate change presents a classic collective action problem because nations who choose to reduce their emissions are able neither to directly capture the benefits of those reductions nor to limit benefits to their own citizens. As a result, international treaties are open to serious temptations for "free riding" by some nations on the emissions reductions of others, leading to a call for binding emissions limits over time for all nations (2). However, agreement on such binding limits may well require a greater understanding of how the costs and benefits of climate change are likely to vary between nations.

Variations in national climate change exposure are thus central to ongoing negotiations regarding GHG emissions reductions. Because we know that climate change will not occur homogenously over the globe (e.g., refs. 1 and 3), or even within a single region (e.g., refs. 4 and 5), we cannot simply use socioeconomic variables as indicators of susceptibility. Rather, we must analyze the interaction of those socioeconomic variables with the expected heterogeneity of physical climate change. However, it is unreasonable to think that there is any single index of climate change susceptibility that will be appropriate for every question or issue. Thus, we offer several indices, each indicating its own type of exposure, with its own distinctive ethical and practical implications.

Although we recognize that some climatic changes will bring certain benefits to specific regions (e.g., ref. 6), our emphasis here is on the relative challenges that climate change could present to each nation over the next several decades. We thereby aggregate three climatic factors (temperature, precipitation, and sea level) with three socioeconomic factors (poverty, wealth, and population). The poorest of the world's citizens are especially vulnerable to environmental stress, both because they often live in the most vulnerable locations with the least developed infrastructure and because they possess the fewest resources to cope with even modest negative perturbations (6). At the same time, areas of greater wealth are more exposed to climate change in the opposite respect, in that they have more property infrastructure to lose, as evidenced by the immense cost of natural disasters that occur in relatively wealthy areas. Finally, independent of poverty or wealth, population itself creates a third type of climate-related exposure because climatic changes in populated areas pose greater total human threats than the equivalent changes in unpopulated areas.

Results

We first adapt the regional climate change index (RCCI) of Giorgi (3) to calculate an aggregate national climate change index, or NCCI. (See *Methods*; note that we subdivide a few very large nations that show high spatial variability of population and climate change.) The NCCI constitutes the basic climate information that we use to estimate the relative socioclimatic exposure of each nation (Fig. 1*a*). We note that this index measures the relative climate response to global warming across different nations and not the absolute response. Based on the relative magnitude of the RCCI, Giorgi (3) identified a number of regional climate change hotspots, including the Mediterranean, southern Africa, central America, central Asia, and the high latitudes of Eurasia and North America. Although not based on exactly the same definition as the RCCI, our NCCI identifies similar regions of high sensitivity to global warming. Furthermore, in terms of physical climate change alone, China, India, and the United States face moderate threats relative to the range of projected change across all nations.

We create a more complicated measure of climate change exposure by accounting for the relative size of the population affected in each nation (see *Methods*). This climate change population index produces China and Bangladesh as the most threatened nations on a gross population basis, followed by a suite of countries that includes India, Russia, Brazil, and the United States (Fig. 1*b*).

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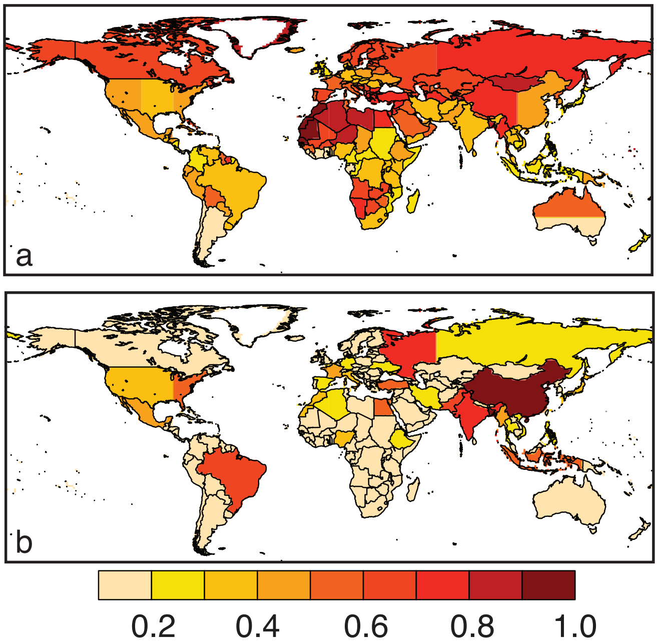

Fig. 1. Exposure of population to 21st century climate change. (*a*) National climate change index. (*b*) Climate change population index. The national climate change index is adapted from ref. 3 and aggregates projected future changes in seasonal temperature and precipitation with the percentage of population living within the low-elevation coastal zone (21). The climate change population index aggregates the national climate change index with the total population of each nation.

Compared with the NCCI, population scaling intensifies the relative exposure of China, India, and Brazil, and reduces the relative exposure of Canada, the Scandinavian nations, and most of Africa.

We use two climate–poverty metrics, one based on the percentage of the population in poverty and one based on the gross impoverished population (see *Methods*). The percentage-based climate poverty density index reveals nations in Africa and south Asia as the most threatened (along with Syria) (Fig. 2*a*). Mauritania exemplifies the role of climate in shaping climate–poverty exposure, with a per capita poverty rate (63.1%) that is much lower than many in sub-Saharan Africa and south Asia (7) but a large NCCI that creates one of the highest per capita climate–poverty exposures on the globe. When population scaling is applied, the relative poverty exposure of most African nations is dramatically reduced (Fig. 2*b*). Instead, south and east Asia, including India and China, emerge as the primary locus of climate–poverty susceptibility as measured by the gross population-based climate poverty intensity index. India shows an interesting interaction of the three variables: a relatively modest NCCI (Fig. 1*a*) that moderates its high per capita poverty rate (79.9%) but an extremely large impoverished population that makes it a hotspot of gross climate–poverty susceptibility.

As with poverty, we evaluate climate–wealth exposure using both per capita and total population indicators. The per capita climate wealth density index reveals Canada and the Scandinavian nations as the most threatened (Fig. 2*c*). Because of their high NCCI, Mediterranean nations such as Greece, Italy, France, and Spain show relatively high per capita climate–wealth exposure despite having lower per capita incomes than most of their western European neighbors (8). When total population is considered, the United States and France emerge with the highest climate wealth intensity index, followed by Japan, China, and a number of European nations. Likewise, Canada and the Scandinavian nations move to the bottom of the relative scale when total population is included. Reflecting its growing economic inequality and large population, China emerges as a hotspot of both wealth and poverty exposure when weighted by population. By contrast, Russia shows less exposure when considering either poverty or wealth than when considering physical climate change alone.

We synthesize the information from the individual metrics by summing the contribution of the different climate-related stressors (see *Methods*). This summary reveals that most nations face substantial socioclimatic exposure from the interaction of climate change with some combination of population, poverty, and wealth (Fig. 3). Additionally, all three of the major unconstrained emitters of GHGs—the United States, India, and China—face considerable vulnerabilities over the next 100 years, even on a per capita basis [supporting information (SI) Fig. 4]. Furthermore, there is no region of the world that escapes significant exposure to one form of climate change threat or another.

Discussion

We note some caveats in our formulation. Foremost, the world's future socioeconomic pathway will be critical in determining the relative exposure of different nations. For instance, although the physical climate change associated with a given future level of GHG concentrations will be insensitive to the socioeconomic conditions that create those GHG concentrations, the impact of that future climate change will not be similarly insensitive (e.g., ref. 9). Furthermore, future GHG concentrations—and hence future climate change—will be affected significantly by socioeconomic factors (10). Thus, the realized socioeconomic pathway will likely influence socioclimatic exposure both directly (by affecting socioeconomic indicators) and indirectly (by affecting physical climate forcing).

Although we integrate projected 21st century climatic changes with present socioeconomic indicators, these indicators are certain to change in the future, as is the relative distribution of these indicators across nations. For example, our NCCI is calculated by using the *Special Report on Emission Scenarios* (SRES) (10) A1B scenario. This scenario assumes substantial convergence of income between what are now poor and wealthy nations. Should this A1B scenario come to pass, the poverty exposure that we have calculated would likely be reduced for some nations. Likewise, the A1B scenario also assumes a different international population distribution than today, which would change the relative distribution of population-based socioclimatic exposure.

Furthermore, the future international distribution of socioeconomic indicators is sensitive to the future socioeconomic pathway (9). For example, differential population and economic growth causes substantial variation in the risk of hunger across the SRES socioeconomic scenarios (11). In particular, higher levels of global inequality are expected to increase the risk of hunger for poorer nations (11), whereas economic convergence is expected to reduce that risk substantially over the course of the 21st century (12). The case is similar for sea level rise, with economic development leading to a decrease in the global population exposed to coastal flooding in the convergent scenarios but an increase in the heterogeneous A2 scenario (13). Because of these sensitivities to socioeconomic pathway, it is critical that further analyses of socioclimatic exposure quantify and incorporate potential future changes in socioeconomic indicators.

Our treatment of climate change is also somewhat simplistic because it is focused on the relative magnitude of change rather than on the climate thresholds that are critical for different natural and human systems. For instance, the seasonal drying experienced by Brazil in our index (1) could have substantial impacts on the Amazon rainforest (e.g., refs. 14 and 15), even though Brazil does not appear as a prominent climate change hotspot in our NCCI. Similarly, additional climate indicators—such as interannual variability and extreme events—would also contribute to the threat of climate change. For example, systems that are highly sensitive to daily-scale extremes can show little or no response to changes in seasonal mean quantities but substantial response to the associated

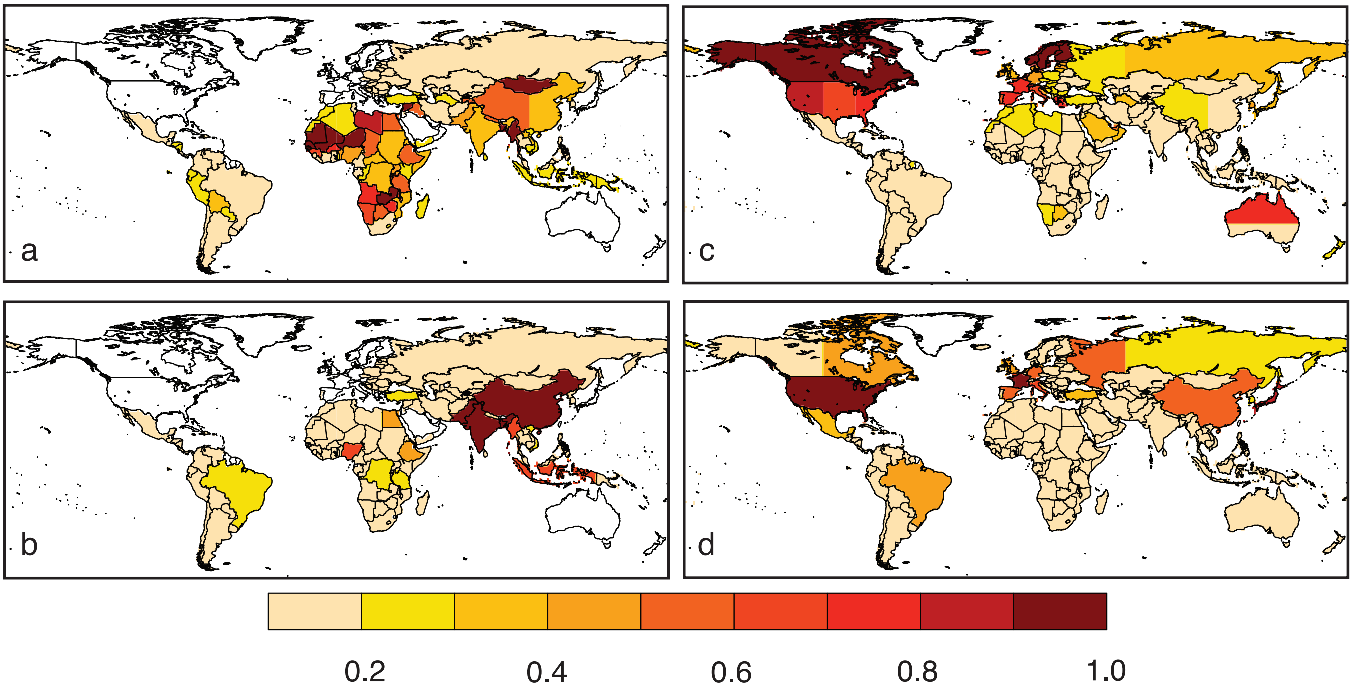

Fig. 2. Exposure of poverty and wealth to 21st century climate change. (*a*) Climate poverty density index. (*b*) Climate poverty intensity index. (*c*) Climate wealth density index. (*d*) Climate wealth intensity index. The climate poverty density index aggregates the national climate change index with the percent of each nation's population living on less than two international dollars per day. The climate poverty intensity index aggregates the national climate change index with the gross impoverished population of each nation. The climate wealth density index aggregates the national climate change index with the per capita gross national income of each nation. The climate wealth intensity index aggregates the national climate change index with the population-weighted gross national income of each nation.

changes in extremes (e.g., ref. 16). Likewise, abrupt transitions—or "surprises"—not considered in our index could provide the greatest environmental shocks (e.g., ref. 17). Furthermore, the uncertainties associated with universal metrics are complicated by the fact that the critical thresholds are not known for many systems.

We also acknowledge that aggregating socioclimatic exposure based on both poverty and wealth may seem counterintuitive at first glance. However, distinct exposures clearly result from poverty and wealth, with lack of resources potentially reducing the ability to cope with environmental stress and abundance of resources increasing the value of potential losses. In fact, it is quite possible for these dual exposures to coexist within a single nation. For instance, China and India have the second and fourth largest economies in the world (8) but have respective poverty rates of 46.7% and 79.9% (below the $2/day threshold) (7). Similarly, consider a stratified nation like Botswana, which has a relatively high poverty rate (50.1%) but a per capita income ($11,510 per capita) that is well above the global median and higher than many nations with considerably lower poverty rates (e.g., Belarus, Bulgaria, Chile, Costa Rica, Macedonia, and Russia).

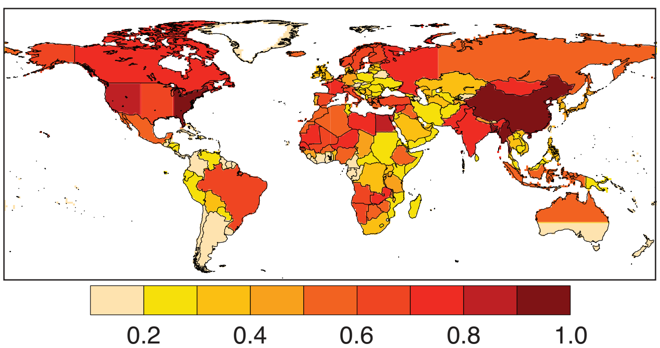

Fig. 3. Summary of 21st century socioclimatic exposure. This summary indicator aggregates the climate change population index (Fig. 1*b*), the climate poverty density index (Fig. 2*a*), and the climate wealth density index (Fig. 2*c*). Alternative summary indicators can be found in SI Fig. 4.

In addition, a number of "post-Kyoto" proposals suggest graduated emissions limits for developing economies as they hit certain GDP per capita thresholds. Our analysis suggests that some level of self-interest could be activated to support these political instruments: As a nation gains wealth and moves into higher percentiles of income, it has more exposure to climate change losses and increased motivation to begin actively participating in an international mitigation strategy. Our view, therefore, is that a complete analysis of relative exposure to climate change requires consideration of both poverty- and wealth-based metrics.

Lastly, it is important to consider that we use relative measures of each climatic and socioeconomic variable. Thus, a nation with a low relative value is not necessarily immune to climate change, nor does it lack any socioeconomic pressures. In addition, actual causal interactions between poverty, wealth, and climate exposure will be far more complicated than presented here. Improved quantification of the socioclimatic exposure faced by each nation will require sophisticated, interdisciplinary investigations of how multiple physical, biological, economic, and social processes interact across a range of spatial and temporal scales. The present study thus serves as an initial foundation for more detailed, sophisticated investigations that consider a range of future socioeconomic scenarios.

Conclusions

The results presented here indicate that nearly every nation of the world faces important socioclimatic exposure in the coming decades. However, all threats are clearly not equal: Being subject to major property losses is not the same, politically or ethically, as being subject to major morbidity or mortality risks. Likewise, per capita indicators may be most important for a nation considering its own climate change exposure, whereas total population indicators may be far more relevant to individuals or groups struggling to craft and evaluate new international climate change mitigation regimes. We have shown that each of these measures varies between nations, and that the picture of relative susceptibility is very different depending on the socioclimatic indicator being assessed.

Because each type of vulnerability is important for different players in the climate change debate, integrating socioclimatic heterogeneities could be critical for crafting successful climate agreements. For instance, arguments over who should pay for climate change mitigation are now expressed both in terms of who is most responsible for the cause and who is most vulnerable to the effects, although those relative vulnerabilities have previously not been quantified. Granted, whether specifying relative national climate change exposure is helpful or harmful to international negotiations remains an important and open question (18, 19). However, to the degree that political actors perceive their own polity as being at significant risk, they are often more motivated to take action (20). Our analysis shows that when the international heterogeneity of potential climate change is aggregated with the international heterogeneity of socioeconomic indicators, nearly every nation of the world faces important socioclimatic exposures.

Methods

Climate Change Index. We created a national climate change index (NCCI) (shown in Fig. 1*a*). To do so, we quantified the aggregate change in climate following Giorgi (3). We analyzed the 20c3m and A1B atmosphere–ocean general circulation model (GCM) experiments from the CMIP3 archive (1). Simulations from 22 GCMs are included. We aggregated the prevalence of low-elevation coastal areas from McGranahan *et al.* (21) with mean temperature and precipitation change for the future period of 2071–2100 (relative to the baseline period of 1961–1990), using the seasons of Giorgi (3). We scaled changes in seasonal temperature and precipitation as a function of the mean annual global warming. Seasonal temperature and precipitation have been shown to scale approximately linearly with the magnitude of global warming when analyzing ensemble average change signals from multiple models (22). As a result, our NCCI, which is calculated for the late decades of the 21st century A1B scenario, approximately applies to other future time periods and emissions scenarios.

We weighted seasonal temperature change as in Giorgi (3), with warming of $<$1.1°C/°C global warming (°Cgw) receiving 0 points, 1.1–1.3°C/°Cgw 1 point, 1.3–1.5°C/°Cgw 2 points, and $>$1.5°C/°Cgw 4 points. Positive changes in seasonal precipitation were weighted with $<$1%/°Cgw receiving 0 points, 1–2%/°Cgw 1 point, 2–4%/°Cgw 2 points, and $>$4%/°Cgw 4 points. Because large negative changes in precipitation can have greater impact than large positive changes, we rated large drying more heavily, with greater than −1%/°Cgw receiving 0 points, −1% to −2%/°Cgw 1 point, −2% to −4%/°Cgw 2 points, −4% to −6%/°Cgw 4 points, and less than −6%/°Cgw 8 points. We weighted potential sea level change based on the percentage of each nation's total population living within the low-elevation coastal zone (21), with $<$15% receiving 0 points, 15–30% 1 point, 30–45% 2 points, 45–60% 4 points, and $>$60% 8 points. The weighting of potential sea level rise thus assumes uniform global change in sea level.

Mean seasonal climate changes from the participating GCMs were first gridded to a common 1-degree grid and then averaged over each nation, as defined in ref. 23. Because of their geographic extent, we divided the United States, Canada, Russia, China, and Australia following Giorgi (3). To keep very large outlying values from dominating the relative scale, we next set all values exceeding the 99th percentile value equal to the 99th percentile value. We then divided all values by the 99th percentile value, yielding relative scores between 0 and 1.

Socioclimatic Indicators. Before aggregation, socioeconomic data were gridded to the common 1-degree grid and then scaled as described above, allowing variables of disparate units and orders of magnitude to be aggregated on equivalent relative scales. To quantify total population exposed to climate change, we defined a climate change population index, multiplying the NCCI by the scaled total population of each nation (shown in Fig. 1*b*). We used gridded, spatially explicit population data from ref. 23. To quantify the per capita poverty exposure, we defined a climate poverty density index (shown in Fig. 2*a*), multiplying the NCCI by the scaled percent of each nation's population living on less than two international dollars per day, a metric commonly used to identify the impoverished population (7). To quantify the wealth threatened by climate change, we defined a climate wealth density index (shown in Fig. 2*c*), multiplying the NCCI by the scaled per capita gross national income (purchasing power parity) of each nation (2005) (8). We also defined a population-weighted climate poverty intensity index (climate wealth intensity index) (shown in Fig. 2 *b* and *d*) by multiplying the NCCI by scaled poverty (wealth) by scaled population. In the case of nations for which poverty and income data are not available, we applied the World Bank regional average (7, 8).

As a summary indicator, we summed the scaled climate change population index (Fig. 1*b*), the scaled climate poverty density index (Fig. 2*a*), and the scaled climate wealth density index (Fig. 2*c*) (shown in Fig. 3). We also summarized the climate–poverty and climate–wealth metrics on per capita and total population bases by summing the climate poverty density index and the climate wealth density index (Fig. 2 *a* and *c*), and the climate poverty intensity index and the climate wealth intensity index (Fig. 2 *b* and *d*), respectively (shown in SI Fig. 4). After aggregation, all metrics were finally scaled to yield values relative to the respective 99th percentile value.

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