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The Benefits of Reduced Anthropogenic Climate changE (BRACE): a synthesis

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Abstract Understanding how impacts may differ across alternative levels of future climate change is necessary to inform mitigation and adaptation measures. The Benefits of Reduced Anthropogenic Climate changE (BRACE) project assesses the differences in impacts between two specific climate futures: a higher emissions future with global average temperature increasing about 3.7 °C above pre-industrial levels toward the end of the century and a moderate emissions future with global average warming of about 2.5 °C. BRACE studies in this special issue quantify avoided impacts on physical, managed, and societal systems in terms of extreme events, health, agriculture, and tropical cyclones. Here we describe the conceptual framework and design of BRACE and synthesize its results. Methodologically, the project combines climate modeling, statistical analysis, and impact assessment and draws heavily on large ensembles using the Community Earth System Model. It addresses

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uncertainty in future societal change by employing two pathways for future socioeconomic development. Results show that the benefits of reduced climate change within this framework vary substantially across types of impacts. In many cases, especially related to extreme heat events, there are substantial benefits to mitigation. The benefits for some heat extremes are statistically significant in some regions as early as the 2020s and are widespread by mid-century. Benefits are more modest for agriculture and exposure to some health risks. Benefits are negative for agriculture when CO_2 fertilization is incorporated. For several societal impacts, the effect on outcomes of alternative future societal development pathways is substantially larger than the effect of the two climate scenarios.

1 Introduction and study design

Understanding and quantifying the difference in climate-related risks between alternative levels of future climate change are critical to informing climate change policies. In broad terms, decisions about responding to climate change attempt to balance risks associated with climate change impacts with the costs of mitigating and adapting to climate change. While there is a well-developed literature quantifying mitigation costs and other aspects of emissions reduction pathways, there are fewer quantitative comparisons of impacts across climate scenarios and they are less systematic or comprehensive in terms of regional and sectoral coverage. As a consequence, it is challenging to draw conclusions about differences in impacts between different climate futures.

Recently some studies have carried out more systematic analyses that could improve such assessments. The Climate Impact Risk Assessment (CIRA) (EPA 2015) investigated impacts in the USA across six broad sectors (water resources, electricity, infrastructure, health, agriculture and forestry, and ecosystems) for climate scenarios ranging between 3.2 and 8.6 W/m^2 of radiative forcing by 2100, with central estimates of warming spanning about 2 °C to more than 5.6 °C above pre-industrial. Similarly, the American Climate Prospectus (Houser et al. 2015) evaluated impacts to US coastal property and infrastructure, agricultural production, energy demand, labor productivity, and public health for scenarios ranging between 2.6 and 8.5 W/m^2 by 2100, accounting for uncertainty in the climate response to this forcing. Both studies concluded that there would be substantial benefits (in monetized terms) to the USA of reduced climate change, with large variations across regions. Other projects, such as AVOID (Warren et al. 2013), were global in scope, quantifying reductions in both physical and economic impacts for a range of mitigation scenarios.

In this paper, we synthesize the results of the Benefits of Reduced Anthropogenic Climate changE (BRACE) project, which aims to improve our understanding of how climate change risks vary across levels of climate change with a specific emphasis on the role of internal variability in limiting statistically significant differences. The 20 papers in this special issue examine various aspects of risk across two different climate change scenarios for the twenty-first century defined by Representative Concentration Pathways (RCPs): RCP8.5, a relatively high-forcing pathway reaching 8.5 W/m^2 by 2100 that assumes no emissions mitigation, and RCP4.5, a moderate forcing pathway that assumes mitigation is undertaken to limit radiative forcing to 4.5 W/m^2. Most BRACE studies employ a 30-member initial condition ensemble of RCP8.5 (Kay et al. 2015) produced with the Community Earth System Model (CESM) version 1.1, referred to as the CESM Large Ensemble (CESM-LE), and a new 15-member CESM "medium" ensemble of RCP4.5 developed for the BRACE study (CESM-ME) (*Sanderson et al.* 2015). Many of the BRACE studies report results for the 2060–2080 period, during which time global mean temperature averages about +3.7 °C relative to pre-industrial in RCP8.5 and +2.5 °C in RCP4.5 (4.9 and 3.4 °C over land, respectively).

The choice to base the climate projections in BRACE largely on single-model initial condition ensembles has pros and cons. It sacrifices a representation of structural uncertainty in the climate model, and any conclusions must therefore be tempered by the caveat that they can only be sure to hold for CESM. However, at continental scales, CESM variability is comparable to the multi-model uncertainty for seasonal temperature and precipitation across models participating in the Coupled Model Intercomparison Project phase 5 (CMIP5), so that CESM likely represents a realistic estimate of the full range of outcomes at this scale (*Sanderson et al.* 2015). Also, the approach provides a more precise representation of extreme events than would a single-model run, since multiple ensemble members allow for a better estimation of the statistics of these (by definition) rare events (*Tebaldi and Wehner* 2016). In addition, the role of natural variability can be more clearly differentiated from the forced response of the climate system, and isolated from structural uncertainty present in multi-model ensembles such as CMIP5.

Given the dependence of risk (and impacts) on both biophysical and socioeconomic factors, we compare impacts not only between two different climate outcomes but also between two alternative societal development pathways defined by Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017). We selected SSP3 ("Regional Rivalry") and SSP5 ("Fossil-fueled Development") in order to span a range of uncertainty in societal determinants of climate change impacts: SSP3 has relatively high societal vulnerability to impacts, while in SSP5, vulnerability is relatively low. Both SSPs are consistent with the two RCPs compared.[1] The choice of RCPs and SSPs, and the production of CESM ensembles, is discussed further in the electronic supplemental material (SM).

The BRACE papers cover topics including extreme heat and precipitation, health, agriculture, and tropical cyclones, and in most cases are global in scope (although a few focus on the USA). They include impacts on the physical climate system and managed systems such as crops and urban areas, as well as on society. They also include methodological contributions related to pattern scaling, a form of computationally efficient climate model emulation that can make the assessment of avoided impacts much easier to carry out.

Here we describe the study design (Sect. 2) and methodological approaches and types of models used across studies (Sect. 2), and we synthesize results in Sect. 3. Conclusions, limitations, and future research directions are discussed in Sect. 4. To clarify the content of the study, references to papers in the special issue are given in italics.

2 Methodological approaches

In order to project a range of impact outcomes, BRACE required models and analyses of climate, managed, and human systems, as well as integrated approaches (Fig. S1, SM).

2.1 Physical modeling

Direct analysis of CESM-LE and CESM-ME output included examination of differences in temperature extremes at the daily (*Tebaldi and Wehner* 2016), monthly (*Sanderson et al.*

[1] While SSP3 is typically considered to produce insufficient forcing to be consistent with RCP8.5, we design and use a variant with somewhat higher GDP growth (and therefore emissions) such that forcing reaches approximately 8.5 W/m^2 by the end of the century (*Ren et al.* 2016).

2015), and seasonal (*Lehner et al.* 2016) scales, as well as for multi-day measures of heat waves (*Oleson et al.* 2015; *Xu et al.* 2015), for which a bias-corrected version of the CESM temperature output was used. Differences in daily precipitation extremes were also examined (*Fix et al.* 2016), and the CESM output was used to develop emulators of CESM projections of both precipitation and temperature extremes (*Alexeeff et al.* 2016; *Fix et al.* 2016). Although these emulators were not used directly in other BRACE studies, emulation can improve impact assessment in general by generating climate change projections at low computational cost for scenarios that have not been simulated with ESMs. The emulation of temperature successfully predicted the spatial pattern of CESM seasonal means, including interannual variability, as a function of global average temperature change (*Alexeeff et al.* 2016), while the emulation of precipitation successfully predicted the distribution of annual maxima of daily precipitation over the USA (*Fix et al.* 2016).

In addition to the CESM-LE and CESM-ME, a 15-member ensemble of a variant of RCP8.5 was produced in which aerosol emissions and their precursors were held fixed at current (2005) levels in order to investigate the sensitivity of temperature extremes (*Xu et al.* 2015) and terrestrial aridity (*Lin et al.* 2015) to atmospheric aerosol concentrations. Results showed that temperature extremes indeed depended on the mix of aerosol and greenhouse gas forcing assumed in a scenario, while aridity (in contrast to precipitation) was less sensitive to such differences.

Further, high horizontal resolution (~25 km) time slice experiments with the Community Atmosphere Model 5 (CAM5), forced with sea-surface temperatures from CESM, were carried out to investigate the future frequency and intensity of tropical cyclones (*Bacmeister et al.* 2016). As an alternative to high-resolution time slice simulations to simulate tropical cyclone activity, an index was developed that allowed prediction of the damage potential of cyclones based on large-scale variables derivable from the coarser resolution CESM output (*Done et al.* 2015).

The use of different types of CESM simulations across BRACE studies is summarized in Table S1 (SM).

2.2 Modeling managed systems

Impacts on managed systems were investigated with both process-based and statistical models. The Community Land Model (CLM), the land surface component of CESM, represents both urban land cover and multiple crop types. Results from CLM were used to analyze future heat wave intensity, frequency, and duration separately for urban and rural areas, accounting for the urban heat island effect (*Oleson et al.* 2015), and to project future impacts of climate and CO_2 on crop yield (*Levis et al.* 2016). Yield consequences were also investigated using a statistical crop yield model estimated on historical data and driven by CESM-LE and CESM-ME output for future years (*Tebaldi and Lobell* 2015).

2.3 Societal impacts

A set of analyses integrated modeling of climate, managed, and human systems to various degrees to project societal impacts. Several studies addressed health impacts. The potential exposure of future population to the primary mosquito that transmits the dengue, Zika, chikungunya, and yellow fever viruses was investigated by combining global spatial projections of population (Jones and O’Neill 2016) with a projection of area suitable for mosquito habitat driven by CESM output (*Monaghan et al.* 2015). A similar approach was taken to project future global population exposure to urban and rural heat waves as modeled in CESM (*Jones et al.* submitted; *Xu et al.* 2015). Two studies went beyond exposure to project heat-related mortality risk based on epidemiological models fitted to historical data. One focused on high-mortality events for cities across the USA (*Anderson et al.* 2016a, 2016b), drawing on CESM output and spatial population projections, while the other examined all heat-related mortality for a single city (*Marsha et al.* 2016). In that case, CESM temperature fields were statistically downscaled to higher resolution using outputs from a city-level urban energy balance model to project spatial patterns of extreme heat across the city of Houston. These projections were combined with assumptions about future demographic and economic changes to project mortality.

An integrated assessment of agricultural impacts was carried out (*Ren et al.* 2016), using a global economic model, the integrated Population Economy Technology Science (iPETS) model, to evaluate the economic consequences of crop yield changes as modeled in CLM (*Levis et al.* 2016) for alternative climate and socioeconomic scenarios. Another study projected the economic impacts of future tropical cyclone activity on coastal areas (*Gettelman et al.* 2017) by combining a global spatial model of cyclone damage with projected tropical cyclones from *Bacmeister et al.* (2016).

3 Results

We first provide an overview of the BRACE results by sector or topic, focusing our discussion on those topics for which multiple results exist and comparison can provide some insight, before moving on to the spatial distribution of avoided impacts, their timing, and the influence of societal conditions.

3.1 Impacts by sector

Figure 1 illustrates selected impacts in RCP8.5 and RCP4.5, as well as the differences between them, for outcomes for extreme events, health, agriculture, and tropical cyclones. A complete summary of impacts is contained in Table S2. In this discussion, outcomes are for approximately the 2061–2080 period, and “recent” refers approximately to 1986–2005; variations from these definitions for particular impacts are indicated in Table S2. Most impacts are global, but a few focus on the USA or on subnational US locations.

3.1.1 Extreme events

Most analyses of extreme events focus on extreme heat and generally find that mitigation leads to substantial reductions in outcomes—of half or more—according to a variety of metrics and for a range of temporal scales. For example, at the daily scale, mitigation substantially reduces the frequency of exceptionally hot days (or three consecutive such days) in a given year (*Tebaldi and Wehner* 2016). The likelihood of these currently rare events (defined as having just a 5% chance of occurring in a given year today) would increase by a factor of 6 to 20 in RCP8.5, but only by a factor of 2 to 4 in RCP4.5 (Fig. 1a). Magnitudes of exceptionally hot days are also reduced through mitigation. In RCP8.5, the magnitude of the hottest day in a given grid cell increases on average by 4 °C or more over fully two thirds of the land surface (Table S2; Fig. S2); mitigation to RCP4.5 reduces this area to less than 10% of the surface.

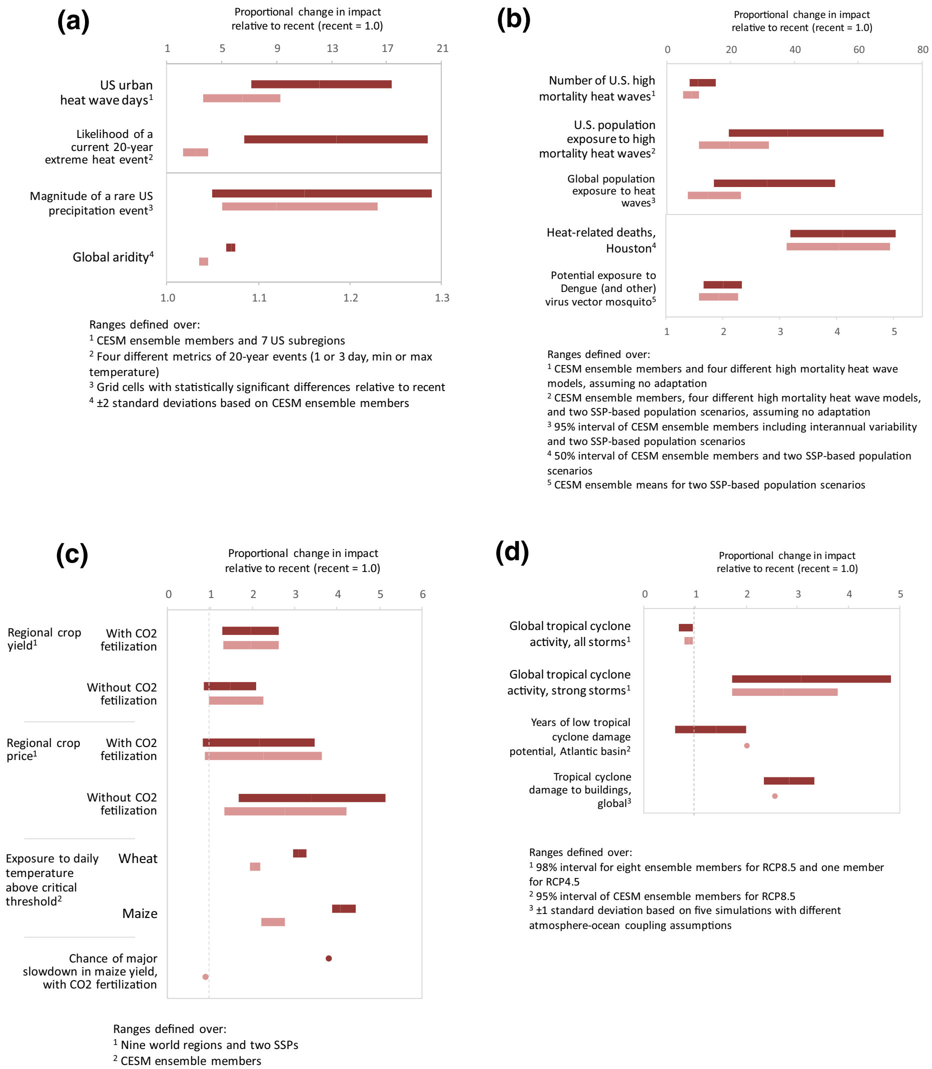

Fig. 1 Differences between RCP8.5 and RCP4.5 for impacts related to **a** extreme events, **b** health, **c** agriculture, and **d** tropical cyclones (see Fig. S2 for additional results related to extreme events and agriculture). *Bars* show uncertainty ranges for impacts in RCP8.5 (*red*) and RCP4.5 (*pink*) for the late twenty-first century relative to a recent period (2061–2080 relative to 1986–2005 unless otherwise indicated). Outcomes are expressed as the ratio of impacts relative to recent (where recent = 1.0). For societal impacts, total impacts are shown, i.e., the impact due to both climate and societal change. Ranges are defined differently for each impact (see Table S2 and notes to each panel); they are comparable between RCPs for a given impact but not across impacts. Note that **a** and **b** employ two different *x*-axis scales; the area *above*/*below* the *horizontal dividing line* corresponds to the axis at the *top*/*bottom* of the figure

A number of different multiple-day heat metrics are used in health impacts research, and *Oleson et al.* (2015) focus on one that is employed by *Anderson et al.* (2016a, 2016b) to predict mortality in the USA: heat wave days defined for each grid cell as two or more consecutive days with daily mean temperature above the 98th percentile of current climatology. US heat wave days increase substantially in both scenarios, but RCP4.5 cuts the average number of days per year about in half (Fig. 1a), with the largest reductions occurring in the southeast and south central regions.

At the seasonal scale, viewing extreme heat from the perspective of record-setting temperatures, mitigation cuts the risk of experiencing a summer warmer than the local historical record (set during 1920–2014) in half, from 80% (averaged across the globe) in RCP8.5 to 41% in RCP4.5 (*Lehner et al.* 2016) (Fig. S1).

Mitigation also lessens the increase in the magnitude of US precipitation extremes, although by a much more modest amount. Measured as the daily precipitation level that has a 1% chance of occurring in a given year, extreme precipitation increases in RCP8.5 by a mean of 15%, and up to nearly 30% in some locations, while mitigation to RCP4.5 would reduce the increase to a mean of 12%, with a local maximum of 23% (*Fix et al.* 2016) (Fig. 1a). Globally, total precipitation is expected to increase with future warming, but at the same time, drying of the land surface will occur, due to an increase in potential evapotranspiration that is expected to be larger than the precipitation increase (*Lin et al.* 2015) (Fig. 1a).

3.1.2 Health

Results for health impact studies also indicate the potential for mitigation to provide substantial benefits, but suggest that conclusions are sensitive to the measure of impact and to socioeconomic conditions, including adaptation measures.

For example, *Anderson et al.* (2016a, 2016b) find that "high-mortality heat waves"—those that temporarily increase mortality rates by 20% or more—are likely to increase substantially in the USA in both RCPs, but much less so in the mitigation scenario. These types of events constitute <1% of all heat waves in the USA but are especially important due to their large impacts on mortality. Projected numbers of such events increase greatly from a recent average of just 5–6 over the course of a 20-year period, in any of 82 different urban communities in the USA, to a range of 40–85 in RCP8.5 (*Anderson et al.* 2016b) (Fig. 1b). That frequency is cut by up to a third in RCP4.5 (Table S2). When accounting for projected changes in population in these communities according to two different SSP-based population projections, population exposure to these events is reduced by nearly half in the mitigation scenario (Fig. 1b).

This reduction by half in population exposure to extreme heat extended globally as well. *Jones et al.* (submitted) found that exposure to future heat wave days (but not necessarily to high-mortality events) increased to nearly 800 billion person-days per year in RCP8.5 (relative to just 15 billion today), but was limited to not more than 350 billion person-days per year in RCP4.5 (Fig. 1b).

Other studies suggest that impact results may be sensitive to the metric used and to socioeconomic conditions. *Marsha et al.* (2016) project all heat-related mortality for the city of Houston, finding that climate change increases that mortality by about 2% in RCP8.5. While mitigation to RCP4.5 reduces the climate impact by about half, it is a relatively small change in absolute terms. This study differs from (*Anderson et al.* 2016b) in several ways, not least because the mortality metric for Houston is all heat-related mortality, rather than mortality due only to the <1% of heat waves with especially high mortality risks. A caveat to both sets of results is that they assume no adaptation, which would reduce risk exposure.

A study of population exposure to the mosquito *Aedes aegypti*, which transmits dengue, Zika, chikungunya, and yellow fever viruses, also found not only a benefit to mitigation but a strong influence of societal change (*Monaghan et al.* 2015). Climate change and population growth lead to an approximate doubling of potential human exposure to

A. aegypti for both RCP4.5 and RCP8.5 by 2061–2080 relative to the nearly 4 billion people exposed currently (Fig. 1b). While the climate effect on overall human exposure is similar for RCP4.5 and RCP8.5, more than 2 billion people would be exposed to *increased suitability* for *A. aegypti* in the future under RCP8.5, a number that would be reduced by one third under RCP4.5 (Table S2; Fig. 2a). Areas with enhanced suitability (i.e., having longer seasons and/or higher abundances of the mosquito) are historically where virus transmission risk is highest.

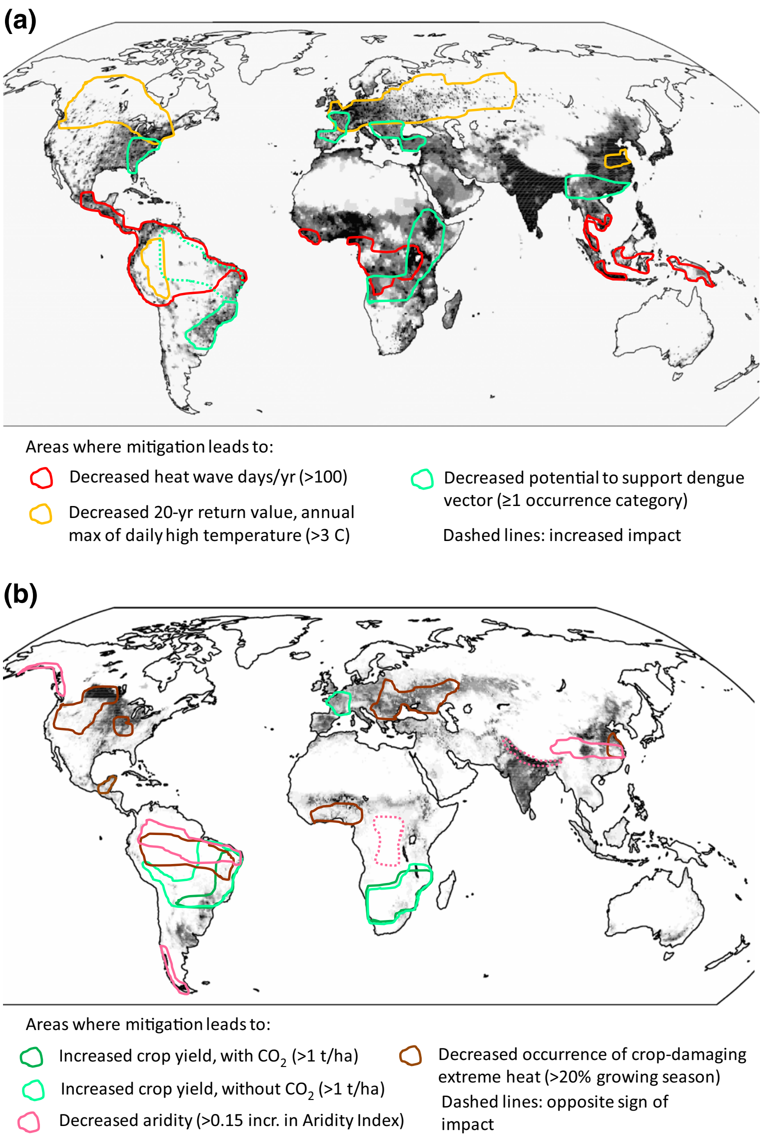

Fig. 2 **a** Spatial distribution of especially large benefits of mitigating from RCP8.5 to RCP4.5 superimposed on the spatial distribution of the projected population in 2070 for SSP5. Results from *Jones et al.* (submitted), *Tebaldi and Wehner* (2016), and *Monaghan et al.* (2015). **b** Same as **a**, but superimposed on the spatial distribution of the projected cropland in 2070 for SSP5, with results from *Ren et al.* (2016), *Levis et al.* (2016), *Tebaldi and Lobell* (2015), and *Lin et al.* (2015). See Fig. S3 (SM) for maps of benefits from individual impacts

3.1.3 Agriculture

Mitigation is generally a modest benefit to agriculture in global average terms, although effects vary substantially by region and crop types. They are also strongly affected by assumptions about CO_2 fertilization, which can change the sign of the result.

For example, process-based crop modeling in CLM finds that CO_2 fertilization increases crop growth so effectively that even in the high climate change scenario (RCP8.5), there is an 11% net increase in potential yield (i.e., yield effects in the absence of any economic adjustments) averaged globally over all crop types (*Levis et al.* 2016; *Ren et al.* 2016) (Table S2). Mitigation to RCP4.5 (which lowers CO_2 concentrations) reduces this potential benefit. However, when these potential yield results are used in an integrated assessment analysis with the iPETS model (*Ren et al.* 2016), mitigating to RCP4.5 only has a small negative impact on global mean outcomes for *actual* yield (including the effects of non-climate drivers and economic adjustments to climate impacts) and prices and little effect on the range of outcomes across regions (Fig. 1c).

In contrast, when CO_2 fertilization is assumed not to operate, impacts of climate change on potential yield (through temperature and precipitation change) are negative (−12% global average over all crop types; Table S2). Mitigation reduces the negative impact on potential yield (to −7% global average), and in the integrated assessment analysis, this increases actual yields somewhat (relative to RCP8.5) and ameliorates regional crop price increases by a quarter to a half (Fig. 1c). These aggregate results depend on a range of factors. For example, the benefits of CO_2 fertilization vary by crop type and are dominated by the C3 crops (including wheat; Table S2). In addition, management assumptions matter: fertilizer and irrigation allow crops to benefit more from CO_2 fertilization, and to suffer less from climate impacts, than they otherwise would (*Levis et al.* 2016).

An empirical model of climate effects on yield lends support to these analyses (*Tebaldi and Lobell* 2015). While it projects somewhat more negative impacts of climate than does CLM, and less positive impacts of CO_2 fertilization (based on a pre-existing CO_2-yield relationship), relative effects across crops and across RCPs are similar (Fig. S2). This analysis also estimated the chances of experiencing a particularly bad decade for yields, defined as a negative climate effect on yield of 5% or more over the course of 10 years. For maize (a C4 crop), mitigation reduced the risk of a bad decade from 35% in RCP8.5 to just 8% in RCP4.5 (assuming CO_2 fertilization, although results did not differ substantially without it). For wheat, a C3 crop that is more sensitive to CO_2 fertilization assumptions, results were similar without fertilization, but risks were very low in both RCPs when fertilization was included (Fig. 1c).

Like most crop models, neither CLM nor the empirical model accounts for the effect of temperature or precipitation extremes on yields. If yield is sensitive to extreme heat, there is the potential for a substantial climate effect: in RCP8.5, the areas currently supporting wheat and maize production would be subject to daily maximum temperatures that exceed a critical threshold for their growth for 20–25% of the growing season (vs less than 1% of the season today). Mitigating to RCP4.5 reduces that exposure by about a third (*Tebaldi and Lobell* 2015) (Fig. 1c).

3.1.4 Tropical cyclones

The consequences of mitigation for tropical cyclone activity and its impacts are difficult to determine robustly, given the high variability in cyclone frequency and magnitude and the computational expense of simulations with a resolution high enough to resolve these events. For example, results show that the projected frequency of all tropical cyclones declines as the planet warms (*Bacmeister et al.* 2016) (Fig. 1d), and therefore, it is reasonable to expect mitigation to RCP4.5 to lead to more tropical cyclones (on average) than there would be in RCP8.5, but variability precludes a robust conclusion about this relationship. In contrast, the frequency of the strongest storms (categories 4 and 5) is projected to increase substantially with warming, particularly in the Northwest Pacific region, but here again it is not possible to statistically distinguish results under the two RCPs from each other.

One approach to investigating the potential economic damages from tropical cyclones is to derive an index of potential damage based on broader-scale physical characteristics of the climate that are available in lower resolution simulations. Using this approach, *Done et al.* (2015) project declining damage potential for the North Atlantic basin in both RCP8.5 and RCP4.5 (with the two outcomes not distinguishable from each other). This outlook is consistent with Bacmeister et al.'s high-resolution simulations, which find a decline in overall cyclone activity for the North Atlantic basin and no significant change in the most intense storms.

Another approach is to combine the high-resolution tropical cyclone simulations with a model of their economic damages to physical assets (buildings). In this case, economic damages increase significantly in the climate change scenarios (*Gettelman et al.* 2017), driven not only by the increase in the more intense storms (and despite the reduction in the total number of storms) but also by increases in asset value as societal development occurs (although possible adaptation is not included). No significant difference in damage between RCPs is detectable due to the large uncertainty in outcomes.

3.2 Spatial distribution of benefits of mitigation across sectors

Impacts occur unevenly across space, and therefore, the benefits of mitigation are also likely to be unevenly distributed. We mapped the difference in a number of biophysical impacts between RCP4.5 and RCP8.5 for a range of spatially explicit outcomes (see SM, Fig. S3) and then identified geographic areas where those differences were especially large. These hotspots of the benefits of mitigation are merged into two maps in Fig. 2. In the first, we group those outcomes most relevant to impacts on people, and overlay them on a map of projected population distribution, while in the second, we include outcomes most relevant to impacts on agriculture and overlay them on a map of projected crop distribution.

While the benefits across types of outcomes do not cluster strongly—with hotspots occurring on all inhabited continents except Australia—some patterns emerge. Low-latitude regions see a number of substantial gains from mitigation, particularly in the Amazon region. Decreases in heat wave days per year are substantial here, a consequence of the low variability in daily temperature, which implies that a shift in the distribution of daily temperatures can have a large effect on the number of days exceeding a temperature threshold. The Amazon and nearby regions also see a substantial decrease in the magnitude of extremely hot days, in aridity, and in the frequency of crop-damaging extreme heat, as well as an increase in crop yields. Substantial reductions in the potential exposure to the virus-transmitting mosquito also occur at low latitudes in South America and Africa. Many of the low-latitude regions in which impact benefits occur correspond to areas of high population density (an exception is the Amazon region), less so with areas of high current crop-growth density.

Mid- to high-latitude regions of North America, Europe, and China also see a number of benefits from mitigation. Substantial decreases in the magnitude of extremely hot days occur here, measured as decreases in the 20-year return value for daily maximum temperature, a consequence of the larger shifts in the distribution of daily temperatures projected at higher (as compared to lower) latitudes. Potentially crop-damaging heat extremes are substantially reduced in frequency, which could be particularly important given that this occurs over areas with high current crop production. There is also some concentration of reduction in potential exposure to the mosquito vector over populated areas.

3.3 Timing of impacts

The point in time at which climate projections for RCP4.5 become statistically significantly different from projections for RCP8.5 depends on a number of factors. Detection generally occurs earlier for projections with a larger number of ensemble members, for outcomes that are more strongly affected by anthropogenic forcing (like temperature, as opposed to precipitation), and for outcomes averaged over larger spatial scales and time periods. In terms of impacts, it is the magnitude of a difference, and not simply the ability to detect a difference *per se*, that matters, but the time of initial detection gives a lower limit on when mitigation benefits related to that specific variable might start to become relevant.

In general, results showed that some measures of extreme heat for some regions differed between RCPs by as early as the 2020s and that by mid-century, differences in a larger number of measures were widespread. For example, exceptionally hot months (defined as a one in 5-year event) are twice as likely in RCP8.5 as they are in RCP4.5 by as early as 2020 in some regions and seasons (e.g., July on the Tibetan plateau, October in Amazonia) and there is widespread elevated risk in RCP8.5 by 2060 (*Sanderson et al.* 2015). Similarly, statistically significant differences between scenarios in the expected distribution of exceptionally hot days (20-year return values) occur in a few locations by the 2020s and over the majority of global land area by mid-century (*Tebaldi and Wehner* 2016). Global, annual mean temperature, as well as linear trends in mean temperature for many regions, also become distinct between scenarios around mid-century (*Sanderson et al.* 2015).

In contrast, there is little distinction between RCPs in the risk of exceptionally dry years across scenarios, with the exception of Amazonia, or in exceptionally wet years, except in a few regions late in the century (*Sanderson et al.* 2015).

3.4 Influence of societal conditions

A number of BRACE studies integrated changes in climate with changes in society, as described by SSPs, and were therefore able to compare the sensitivity of impacts to these two types of change. As shown in Fig. 3, the relative importance of these changes varied by type of impact, but in more than half of cases, societal changes dominated. Results do not imply that in these cases climate change effects are unimportant, but rather that the absolute level of risk for the particular outcome is driven primarily by non-climate factors.

For example, in the case of tropical cyclone damages to buildings (*Gettelman et al.* 2017), the growth in the value of building assets near coastlines according to SSP5 (a rapid economic growth scenario) resulted in an increase in global cyclone damage that was five times as large as the increase due to the change in climate according to RCP8.5 (which increased the number of strong tropical cyclones). Similarly, crop prices were more than three times more sensitive

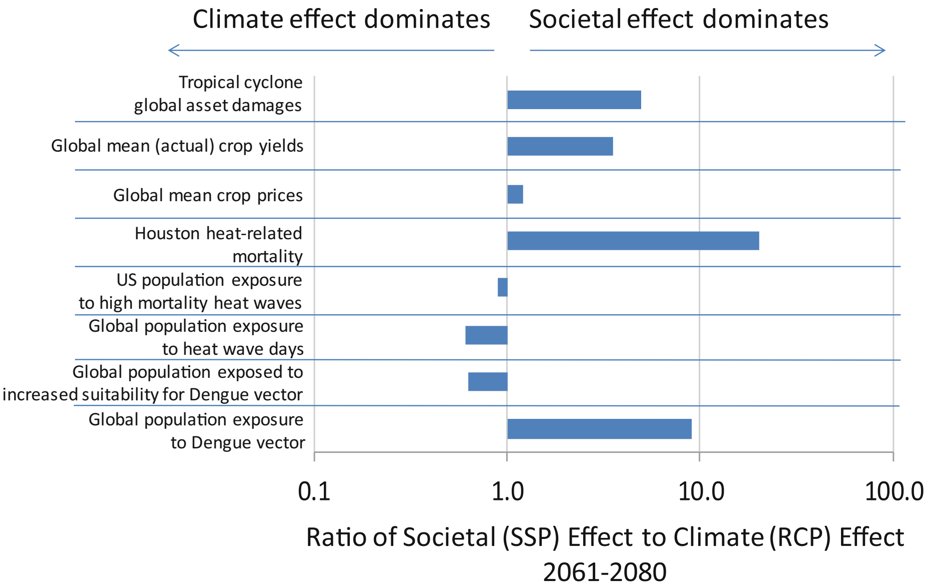

Fig. 3 Ratio of the difference in impact outcomes due to alternative climate change scenarios (RCP4.5 vs RCP8.5) and the difference due to alternative socioeconomic development pathways (SSP3 vs SSP5). Results from *Gettelman et al.* (2017), *Ren et al.* (2016), *Marsha et al.* (2016), *Anderson et al.* (2016b), *Jones et al.* (submitted), and *Monaghan et al.* (2015). Tropical cyclone damage results based on comparison of impacts in SSP-only and climate-only scenarios compared to present

to alternative assumptions about changes in production technologies and demand, as occur in SSPs 3 and 5, than they were to alternative climate outcomes across RCPs 4.5 and 8.5 (*Ren et al.* 2016). Two measures of health impacts were also dominated by societal change. Projected heat-related mortality in Houston (*Marsha et al.* 2016) was 20 times more affected by the difference in demographic and economic conditions between SSPs than by the difference in extreme heat between RCPs. And potential human exposure to the virus-transmitting mosquito (*Monaghan et al.* 2015) was almost ten times more sensitive to SSP population differences than to RCP climate differences when aggregated globally.

In contrast, by two measures of the impacts of extreme heat events, climate change was at least as important as societal change to outcomes: US exposure to high-mortality heat waves (*Anderson et al.* 2016b) and global exposure to all heat wave days (*Jones et al.* submitted). Climate change also dominated an alternative measure of change in risk due to the virus-transmitting mosquito: exposure to an increase in the suitability of conditions for the mosquito (as opposed to exposure to the mosquito at all).

4 Discussion and conclusions

The BRACE study employed a variety of models and approaches to investigate biophysical and socioeconomic impacts of climate change across two different climate scenarios and two different scenarios of societal change. In many cases, there were substantial benefits to mitigation, including reductions in the likelihood of record summer heat, the land area experiencing more intense or frequent extreme heat events, global heat wave days and population exposure to them, population exposure to high-mortality heat waves in the USA, crop exposure to potentially damaging heat extremes, and reduced risk of a major slowdown in maize yield growth.

In other cases, benefits were modest, not statistically significant, or negative (i.e., mitigation worsened impacts). Potential crop yields can either increase or decrease as a result of mitigation, depending on assumptions about CO_2 fertilization, and in either case, the difference is less than 10% in global average terms. Effects on crop prices were mixed as well, with benefits of mitigation (reduced increases in prices) occurring in the absence of CO_2 fertilization. Potential population exposure to the primary mosquito vector of dengue, Zika, chikungunya, and yellow fever viruses was reduced modestly by mitigation (more so when measured in terms of changes in degree of exposure risk, as opposed to simple presence or absence), as was heat-related mortality in a case study of Houston. Tropical cyclone activity was not statistically distinguishable between RCPs, so no firm conclusion about the benefits of mitigation could be drawn. However, both climate change scenarios produced decreases in overall tropical cyclone activity, but increases in the frequency of the strongest storms and economic damage to building assets, increased globally and in the USA as a result.

Analyses of the timing of effects on heat extremes found that mitigation would produce statistically significant differences across scenarios as early as the 2020s for some metrics and in some regions, and were widespread by mid-century. Geographically, the benefits of mitigation were generally distributed widely but showed some concentration in the Amazon region and at higher latitudes in North America and Europe. Comparisons of the differences in impacts due to mitigation vs the effect of alternative socioeconomic development pathways that differed in the vulnerability of society to climate change showed that in most cases considered, development effects outweighed the effect of climate change.

All of these conclusions must be interpreted in the context of a number of limitations of the BRACE studies and of the project design as a whole. As emphasized in the introduction, a study that relies on a single climate model, even employing relatively large ensembles of simulations as done here with CESM, can only draw conclusions that hold for that model. Even within the context of CESM, not all climate system features are found to be simulated equally well over the historical period, and model skill for future projections therefore may vary across outcomes of interest. We have also focused on just two climate scenarios; conclusions about the benefits of mitigation would differ if a different degree of mitigation, from a different baseline scenario, was chosen. Regarding studies of societal impacts, no study could include all relevant determinants of risks, and in many cases analyses stopped at exposure to a climate hazard without also considering vulnerability to that hazard (which would determine the actual impact experienced). Considering intersectoral dependencies would also likely influence the results, and the treatment of adaptation was generally limited, for example, to a sensitivity study of the health impacts of heat extremes (*Anderson et al.* 2016b) and to autonomous economic adjustments in the agricultural sector (*Ren et al.* 2016). Other studies have shown that adaptation to extreme heat in the USA (as an example) can reduce health impacts by half (Houser et al. 2015).

Nonetheless, the results provide quantitative measures of climate impacts across a consistent set of climate scenarios, socioeconomic development pathways, and set of models. They are also largely consistent with the existing literature, as discussed further in *O'Neill and Gettelman* (In preparation). For example, the impacts of climate change on crop yields that drive our agricultural results are within the range of those found in crop model intercomparison studies (*Ren et al.* 2016), including the fact that climate change (with CO_2 fertilization) can lead to net benefits. In addition, the general finding that changes in societal conditions may outweigh changes in climate as drivers of risk for many sectors is also supported by existing studies.

We hope this work can not only contribute to the current impacts literature but also stimulate and inform future work on avoided impacts. Results suggest that high priorities for societal impact studies include a more complete characterization of vulnerability and treatment of adaptation options. In managed systems, reducing uncertainty in the effect of CO_2 and quantitatively estimating and incorporating the likely negative impacts of extreme events on crop yield appear most important. More generally, uncertainties not accounted for within the BRACE framework would be key components of a more complete estimate of avoided impacts. These include impact model uncertainties (Warszawski et al. 2014), since results rely, for example, on a single crop and urban model (within CLM), one integrated assessment model of economic impacts on agriculture, single health models for US cities and for Houston, and so on. Likewise, it would be useful to test the robustness of conclusions to climate model (and climate sensitivity) uncertainty by carrying out similar analyses with additional models or multi-model ensembles. The types of advances in climate model emulation made within BRACE could contribute to model emulation approaches that could address such uncertainties.

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