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LETTER

Shifting patterns of mild weather in response to projected radiative forcing

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Abstract Climate change has been shown to impact the mean climate state and climate extremes. Though climate extremes have the potential to disrupt society, extreme conditions are rare by definition. In contrast, mild weather occurs frequently and many human activities are built around it. We provide a global analysis of mild weather based on simple criteria and explore changes in response to radiative forcing. We find a slight global mean decrease in the annual number of mild days projected both in the near future (−4 days per year, 2016–2035) and at the end of this century (−10 days per year, 2081–2100). Projected seasonal and regional redistributions of mild days are substantially greater. These changes are larger than the interannual variability of mild weather caused by El Niño–Southern Oscillation. Finally, we show an observed global decrease in the recent past, and that observed regional changes in mild weather resemble projections.

1 Introduction

A large body of climate research is devoted to the changing character of the mean climate state (e.g., global mean temperature, sea level, sea ice extent, IPCC 2013) or climate extremes (e.g., heat waves, storms, heavy precipitation, droughts, IPCC 2012). Though these aspects are of large societal importance, the focus on the climatic mean state or climate extremes neglects the study of meteorological conditions that occur more regularly and are of societal significance in a different way.

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The aim of this study is to investigate mild weather. Mild weather is weather that is neither too hot, too cold, too humid nor rainy–weather that could also be described as being "pleasant". Mild weather occurs frequently in most parts of the world. It does not disrupt society the way climate extremes do, instead many human outdoor activities are enhanced by or depend on mild weather. Examples of such activities include picnics, football games, dog walks, bike rides, and outdoor events such as music festivals or weddings. Furthermore, the absence of mild weather during construction work, infrastructure projects, road works, landscaping projects, air travel, and rail or road transportation may cause delays with significant negative economic consequences. This relationship with recreational and industrial human activity makes mild weather a relevant meteorological condition for society.

We present a global study of the daily occurrence of mild weather based on simple and relatable criteria. The spatial and temporal distribution is discussed, and projections of change in response to projected radiative forcing in the near and far future are made. A high-resolution global climate model, HiFLOR (Murakami et al. 2015), is used to allow for the investigation of local features and changes.

The human interaction with weather is complex and depends on place, culture, person, and situation; different people have different preferences, and these preferences depend on context and experience (Knez et al. 2009). The meteorological definition of mild weather is therefore non-trivial and may vary for different activities or personal preferences. Here, we use a global definition of mild weather, based on simple meteorological criteria that should be relatively easy to relate to:

- Daily maximum air temperature between 18 and 30 °C.
- Daily total precipitation not exceeding 1 mm.
- Daily mean dewpoint temperature not exceeding 20 °C.

Temperatures are taken at 2 m reference height. These simple criteria may be refined for specific activities or regions in future studies. Lowering the precipitation criterion increases the uncertainty of the presented results due to disagreements between the model and reanalysis products. Very low precipitation intensities are notoriously difficult to model, leading to biases in both model data and reanalysis output (Dai 2006; Schmidli et al. 2006). Dewpoint temperature was chosen rather than the more familiar relative humidity because it is a better indicator of human comfort (Lawrence 2005). In the supplementary information, we show that our results are robust to reasonable changes to these criteria and provide an assessment of model bias and its impact on the results. The selection of mild weather has purposely been based on the daily occurrence of mild weather rather than the mildness of the mean climate. This is an important distinction as the value of the annual mean climate masks daily and seasonal variability in weather and climate, the variation that people relate to (Weber 2010).

2 Methods

The analysis has been based on model experiments performed with the NOAA GFDL HiFLOR global coupled model. HiFLOR is built from a high-resolution atmospheric/land model (0.25° × 0.25°) coupled to a low-resolution oceanic/sea ice model (1° × 1°, Murakami et al. 2015). The high atmospheric resolution allows for the better resolvement of coastlines and finer-scale mountains (e.g., Californian Sierra, European Alps) that are absent at resolution lower than 30 km (Kapnick and Delworth 2013; Van der Wiel et al. 2016).

Three experiments were performed to identify the effects of radiative forcing. For each of the experiments the model was integrated for 50 years and modeled sea surface temperatures (SST) were restored to a prescribed repeating climatology (SST_T):

$$dSST \Big/ dt = \varphi + 1 \Big/ \tau \ (SST_T - SST),$$

in which φ is the model computed tendency, τ is the restoring time scale (5 days) and t is time. Note that within these experiments, all variability is the result of atmospheric internal variability alone. The prescribed SST climatology for the control experiment was based on the Met Office Hadley Centre Sea Ice and SST dataset (HadISST1.1, Rayner et al. 2003) over the years 1986–2005. The two climate change experiments used the same climatological SSTs plus SST anomalies from the CMIP5 multi-model climate change experiment archive. These anomalies were based on RCP4.5 pathway (Van Vuuren et al. 2011). A near-term experiment (mean SST anomaly over years 2016–2035) and a long-term experiment (similar for years 2081–2100) were performed. Seventeen CMIP5 models contributed to the SST climate change anomalies[1].

A fourth experiment with interannually varying prescribed SSTs was performed to analyze El Niño-Southern Oscillation (ENSO) forced variability. In this historical experiment, SSTs were restored to the time varying 1971–2015 HadISST1.1 field. Six ensemble members were created to decrease the effects of atmospheric internal variability.

To test the robustness of the model results, the projected changes of mild weather occurrence from HiFLOR was compared to the change in the original CMIP5 data[2]. Note that the CMIP5 experiments are slightly different from the experiments with HiFLOR. SSTs in the CMIP5 experiments are not restored to a repeating climatology but are integrated in transient mode. To quantify biases in the distribution of mild weather in HiFLOR, model data were compared to the MERRA-2 reanalysis from 1980–2015 (Koster et al. 2015). Furthermore, a linearized climate change experiment was conducted using MERRA-2 daily data and monthly climate change estimates for daily maximum temperature, precipitation, and dewpoint from HiFLOR.

Human population-weighting was done based on data from CIESIN (2015) for the year 2000 (Suppl. Fig. 1). The year 2000 was chosen because it corresponds to the years of the control experiment. For simplicity and because of uncertainties in projections of human population change, all human population-based calculations are relative to the global population of 2000. Therefore, changes in the number of days with mild weather due to radiative forcing are given for a constant human population distribution (referred to as days per year per person).

Finally, the multivariate ENSO index (Wolter and Timlin 2011) is used, this is an ENSO index based on six observed atmospheric and oceanic variables (sea-level pressure, zonal and meridional surface wind, sea surface temperature, surface air temperature, and total cloud fraction). Because ENSO is a coupled atmosphere-ocean phenomenon, this index is preferable

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[1] Models included: ACCESS1-0, ACCESS1-3, CanESM2, CCSM4, CMCC-CM, CSIRO-Mk3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, NorESM1-M

[2] Models included: BNU-ESM, CNRM-CM5, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M

over an index purely based on sea surface temperatures. MEI data was downloaded from the NOAA ESRL website[3].

3 Results

3.1 Present day global distribution of mild weather

The global distribution of days with mild weather in the control experiment is shown in Fig. 1a. Globally, an annual average number of 74 days with mild weather is found; this translates to 20% of all days in a year or, accounting for population density, 89 days per year per person. Generally, mild weather in tropical regions is limited by rain or humidity, in the subtropics by heat, and in polar regions by cold (Suppl. Fig. 2). Temperate regions have the highest number of mild days, though sharp regional differences exist. For example, mountainous regions are too cold, and in some cases, too wet, resulting in a limited number of mild days. Arid regions (Peel et al. 2007), such as the Sahara, southern Africa, and Australia, are limited by heat only and stand out as areas with frequent mild weather. The modeled distribution of mild weather has substantial biases compared to the distribution from the MERRA-2 reanalysis product (Suppl. Fig. 3), most notably an overestimation of the number of mild days in very warm regions and an underestimation in the mid-latitudes and mountainous areas. A detailed discussion of model bias, uncertainty in reanalysis products, and a quantification of the impacts on the presented results is given in the Supplementary Information.

There is large seasonality in the distribution of mild weather in the temperate regions, for selected locations, this is shown in Fig. 1b–g (additional locations are included in Suppl. Fig. 4). Close to the tropics, summers are too humid (i.e., humidity-limited) and mild weather is limited to winter (Fig. 1d, e). The mid-latitudes are cold-limited in winter and mild weather occurs primarily during summer (Fig. 1c, f). Mediterranean climates experience two seasons of mild weather annually: summers are heat-limited (Fig. 1b, g), rain-limited (Fig. 1g), or humidity-limited and winters generally cold-limited (Fig. 1b, g). In these locations, the shoulder seasons are mild with daily probabilities of mild weather as high as 0.75.

3.2 Changes in response to radiative forcing

In response to 21st century radiative forcing (RCP4.5), the global distribution of mild weather is projected to change (Fig. 2a). The tropics and subtropics are projected to have fewer days with mild weather; the extratropics are projected to have slightly more days with mild weather. This results in a global mean decrease of 10 days with mild weather per year (–14%). The global mean value of change is smaller than local changes. Assuming no changes in the distribution of people, it corresponds to 11 mild days per year less per person globally. The projected changes result from increasing temperatures which make the mid-latitudes more frequently mild but the tropics less frequently mild, and from shifts in precipitation: fewer rain days in the tropics and more rain days in polar regions. Dewpoint temperature is projected to limit the number of days with mild weather more frequently and in more locations globally (Suppl. Fig. 5).

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[3] http://www.esrl.noaa.gov/psd/enso/mei/, accessed 16 May 2016

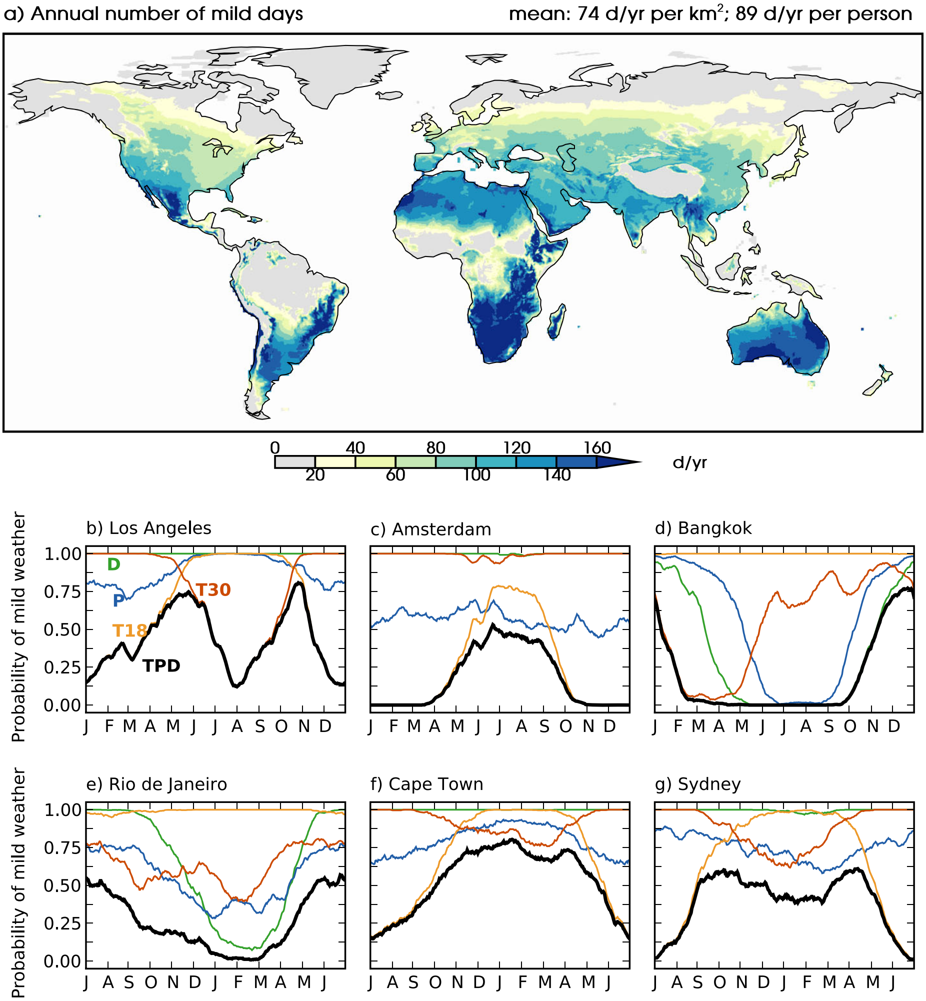

Fig. 1 Annual number of days with mild weather. **a** Global distribution, values in the *top right* indicate a spatial mean over land areas and a human population weighted mean. **b–g** Annual cycle of the probability of a day being mild for different locations (TPD, *black line*) and annual cycle of days that satisfy individual criteria for temperature (T18, *orange line* and T30, *red line*), precipitation (P, *blue line*), and dewpoint temperature (D, *green line*). Time series have been smoothed by a 15-day running mean, all data from HiFLOR

The general pattern of changes from HiFLOR is similar to that found in an ensemble of CMIP5 models (Suppl. Fig. 6, pattern correlation with Fig. 2a of 0.86) and in a linearized climate change experiment using MERRA-2 reanalysis data (Suppl. Fig. 7a, pattern correlation with Fig. 2a of 0.93). However, regional differences exist, most significantly over regions of complex orography that are represented at higher resolution only (see Section 2). An increase in the number of days with mild weather is projected for mountainous areas globally, mostly caused by locally increasing temperatures (Suppl. Fig. 5a).

The projected changes are not distributed equally over the year. The annual mean map of change (Fig. 2a) masks large seasonal shifts (Fig. 3). For example, in northern

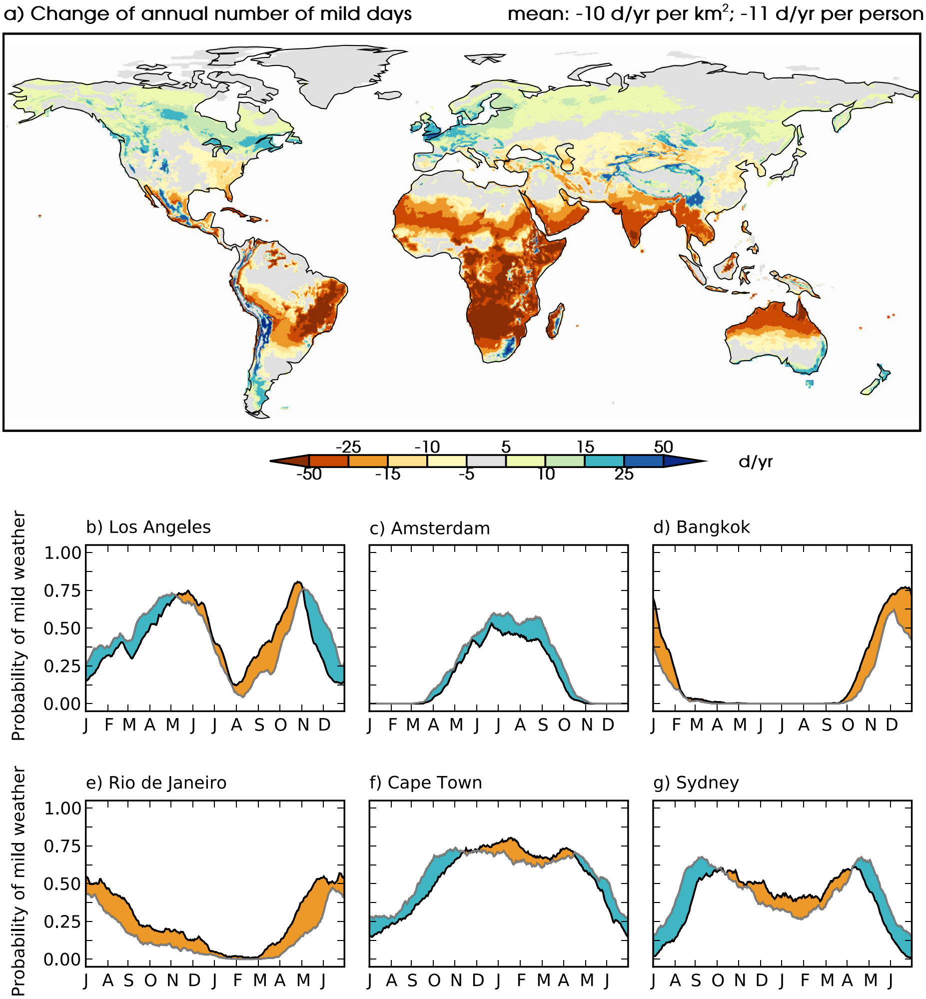

Fig. 2 Change in the annual number of days with mild weather in years 2081–2100. **a** Global distribution. **b–g** Annual cycle of the probability of a day being mild for different locations for years 1986–2005 (*black line*) and years 2081–2100 (*grey line*). *Blue color* shading indicates positive changes, *orange color* shading indicates negative changes. Time series have been smoothed by a 15-day running mean, all data from HiFLOR

Africa and southern Australia, there is an increase of mild weather in local winter (Fig. 3a, c), which is offset in the annual mean by decreasing numbers of mild weather days in the shoulder seasons (Fig. 3b, d). The slight projected decrease of mild days in the Eastern United States arises from a fractionally larger decrease during local summer.

Seasonal shifts are also visible in the figures showing the annual distribution of mild weather for selected locations. Increasing humidity and maximum temperatures further limit the number of days with mild weather in tropical winters (Fig. 2d, e). The mid-latitudes are projected to have slightly more mild summer days because of increased temperatures, though precipitation limits the total increase (Fig. 2c). The locations with two mild shoulder seasons show relatively small changes in the total number of days with

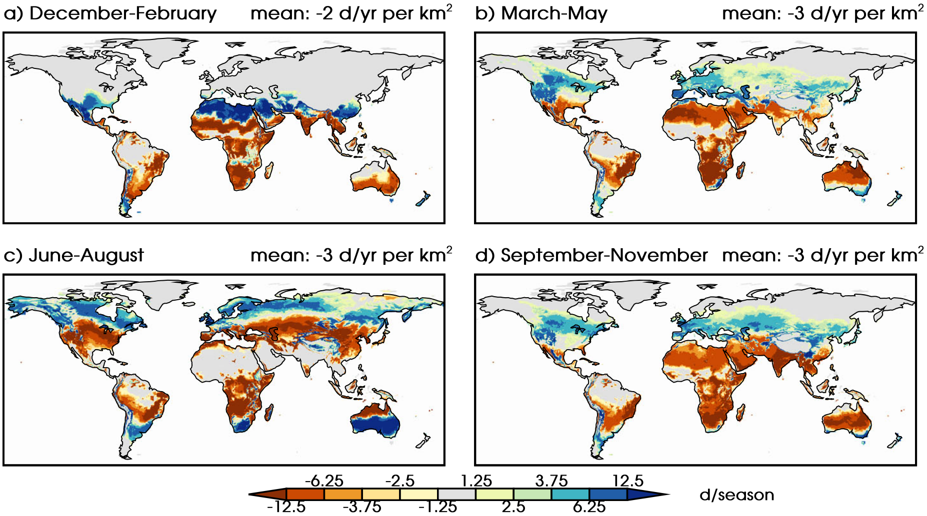

Fig. 3 Change in the seasonal number of days with mild weather in years 2081–2100. **a** December, January, February: Northern Hemisphere winter, Southern Hemisphere summer. **b** March, April, May: shoulder season. **c** June, July, August: Northern Hemisphere summer, Southern Hemisphere winter. **d** September, October, November: shoulder season, all data from HiFLOR

mild weather. However, summers are projected to become less mild because of humidity increases, whereas winters are projected to become more mild because of increasing temperatures (Fig. 2b, f, g).

The above-described changes are for the end of the 21st century based on RCP4.5, but HiFLOR projects that changes should be evident even in the near future (2016–2035) with a similar pattern of change (Suppl. Fig. 8, pattern correlation with Fig. 2a is 0.96). Though the projected changes are stronger at the end of the century, in the next two decades, a global mean decrease of 4 mild days per year is projected (−5%). Shifts in seasonality, similar but of smaller magnitude than to those described for the end of the century, are projected for individual locations in the near future.

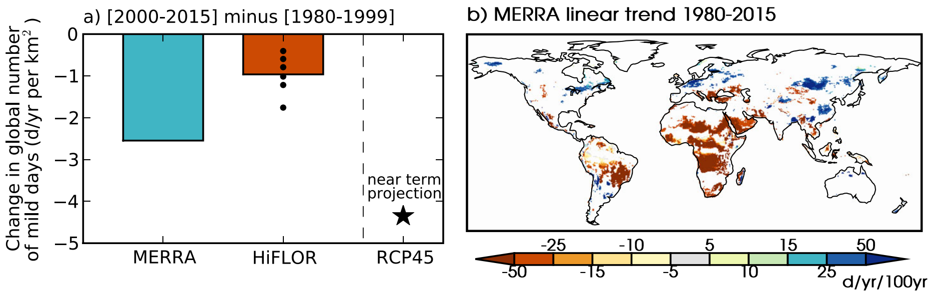

Fig. 4 Changes in the global mean annual number of days with mild weather in the recent past. **a** Change for 2000–2015 minus 1980–1999, MERRA-2 reanalysis (*blue*) and ensemble mean of the GFDL-HiFLOR historical experiment (*red*). *Black dots* show individual modeled ensemble members. For reference, the near-term projection based on RCP4.5 (*black star*, as in Suppl. Fig. 8) is included. **b** Linear trend of the yearly number of mild days from 1980–2015 in the MERRA-2 reanalysis. Only statistically significant trends ($\alpha < 0.05$) are shown, Suppl. Fig. 10 shows all trend values

3.3 Interannual variability

To understand how the magnitude of the projected changes in the occurrence of mild weather measures against year-to-year variability, we investigate the interannual variability of the global number of mild days using the ensemble of historical integrations. Atmosphere-ocean coupled variability forces a slight increase in interannual variability; the standard deviation increases from 0.96 mild days per year in the control experiment to 1.61 mild days per year in the ensemble mean of the historical experiment (Suppl. Fig. 9b). The variability in the historical experiment is closer to that found in the MERRA-2 reanalysis as may be expected (1.96 days per year).

There is a weak relation between mild weather occurrence and ENSO. Using linear regression, we find that moderate El Niño events lead to a global decrease of 1 mild day per year (Suppl. Fig. 9c). The strongest decreases are found in central Mexico, eastern Brazil, northern Australia, Namibia and Botswana; increases are found in eastern Australia and South Africa. These regions see a similar but stronger change in response to RCP4.5 (Fig. 2a). Locally, different criteria may be responsible for the observed relation and individual criteria may have opposing effects. For example, in Australia, temperature increases result in a decreasing number of mild days during El Niño events, but precipitation and humidity decreases result in an increasing numbers of mild days.

3.4 Changes in the recent past

Finally, we estimate the changes in global mild weather that have occurred over the past decades. Based on the MERRA-2 reanalysis a decrease of 2.5 days per year is found between 1980–1999 and 2000–2015 (Fig. 4a). The historical experiment ensemble mean shows a 1.0 day per year decrease over the same period. This decrease is despite the decadal La Niña-like trend (Meehl et al. 2011), which might have caused an increase of mild weather in the absence of radiative forcing. The near future projected decrease of mild weather (2016–2035) based on RCP4.5 is consistent. The pattern of trends (Fig. 4b) shows statistically significant decreases of mild weather occurrence in Brazil and large parts of Africa and increases in parts of Canada, Europe, and Mongolia. These changes are in agreement with changes due to radiative forcing (Fig. 2a, Suppl. Figs. 6 and 7a). Areas where changes are not statistically significant do not always show this agreement (Suppl. Fig. 10).

4 Discussion

We have presented the first analysis of mild weather occurrence and projected changes with respect to climate change. The analysis is based on simple criteria that may be refined or extended in future work. Such refinements could include additional variables, for example, cloudiness or wind speed, or by defining spatially or seasonally varying criteria. Furthermore, the uncertainty of the projections related to scenario choice could be part of a future assessment. The current analysis is based on RCP4.5, the projected changes are likely to be larger in response to RCP8.5 that prescribes stronger radiative forcing.

In conclusion, the global mean number of mild days in a year is projected to decrease in response to radiative forcing. The largest decreases are found in the tropics and subtropics whereas the mid-latitudes are projected to have a small increase. Furthermore, many locations are projected to experience shifts in the seasonal distribution of mild weather; summers lose mild weather days while winters gain mild weather days. Notably, the projected changes in response to radiative forcing are larger than the interannual variability associated with ENSO and the pattern of observed changes matches model projections. Though the changes are larger at the end of the century, shifts in the global distribution and seasonality of mild weather are already projected for the next decades. Similar to findings of changes in economic damages, countries in the tropics are projected to be negatively impacted by climate change (Benson and Clay 2000; Lemoine and Kapnick 2015).

This is the first global investigation of the annual variation of mild weather and its response to projected radiative forcing. Most studies that investigate climate change impacts investigate changes in the mean state, which the public has difficulty relating to (Weber 2010), or climate extremes, that occur rarely and have a strong negative connotation. In contrast, mild weather is a positive concept and occurs frequently. Given the significance of mild weather for human outdoor activity and the fact that mild weather is highly relatable to the public (mild weather may be considered to be "pleasant weather"), our results provide local, near future, and personally relevant climate change information. The presented information may therefore be used to communicate climate variability and climate change impacts to a broad audience. Given its association with various activities, it should also be explored for having an impact on various industries (e.g., tourism, outdoor events, construction, and transport). We hypothesize that regional changing characteristics of mild weather may be detectable and attributable to climate change at a relatively early stage because of the frequent occurrence of mild weather and the relative size of projected change vs. noted internal variability (Hegerl et al. 2006; Stott et al. 2010).

Given the substantial spatial and temporal redistributions of mild weather in response to radiative forcing and potential impacts on human activity, the authors suggest that the field of climate science extends its focus to include frequently occurring and relatable weather conditions. Furthermore, existing research on the physiological effects of meteorological conditions (including for example physical and mental health studies, leisure studies, and urban planning) may be extended to consider the occurrence of and changes in mild weather. For these reasons, improving our understanding of mild weather should be of high scientific interest.

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Compliance with ethical standards

Author contributions All authors contributed to the design of the study, discussion of the results, and writing of the manuscript. G.A.V. set up the model experiments. K.v.d.W. performed the analyses.

Conflict of interests The authors declare that they have no conflict of interests.

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