Supplementary information

Shifting patterns of mild weather in response to projected radiative forcing

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Below we provide additional figures and analyses to support and extend the results of the main text. The following sections include an analysis of HiFLOR model bias and its impact on the presented results and an analysis of the robustness of the presented results to the chosen criteria.

1 Quantification and impact of model bias

Two reanalysis products have been used to compare the model simulated pattern of the mild weather occurrence against. Both MERRA-2 (Koster et al. 2015) and NCEP-DOE II (Kanamitsu et al. 2002) cover the period 1980-2015 which will be used here. MERRA-2 is a second generation product available at a 0.5° x 0.5° grid, NCEP-DOE is a first generation product available at a 2.5° x 2.5° grid. Only figures concerning MERRA-2 are shown because it is a second generation product and because it is available at higher resolution. NCEP-DOE II is used to estimate the uncertainty present in reanalysis data.

Suppl. Fig. 3a shows the bias of the annual number of mild days in the model (as shown in Fig. 1a of the main text) compared to the MERRA-2 reanalysis product. There is a high pattern correlation between the two fields (0.89), but substantial biases exist. There are large positive biases in large parts of the tropics, negative biases are found in mountainous regions (where HiFLOR has better resolved elevations because of increased horizontal resolution) and in the Northern Hemisphere mid-latitudes.

This pattern of biases can be linked to biases in modeled daily maximum temperatures. In the mid-latitudes maximum temperatures remain below 18°C too frequently, resulting in an overestimation of the limitations set by the T_{max} > 18°C criterion (too few mild days, Suppl. Fig. 3b). Closer to the equator maximum temperatures remain below 30°C too frequently, resulting in an underestimation of the limitations set by the T_{max} < 30°C criterion (too many mild days, Suppl. Fig. 3c). The root mean square errors (RMSEs) are 24 and 48 d/yr. The difference between MERRA-2 and NCEP-DOE is of comparable size, 22 and 49 d/yr respectively.

The bias from the precipitation criterion is mostly an underestimation of the limitations set by P < 1 mm (too many mild days, Suppl. Fig. 3d, RMSE 27 d/yr). As noted in the main text, this is likely related to the drizzle problem that exists in many models and reanalysis products: both generally overestimate the frequency of low intensity precipitation (Dai 2006; Schmidli et al. 2006). For very low criterion values (e.g. 0.2 mm) these differences impact the future projections of mild weather. At a criterion value of 1 mm or higher this impact is much smaller, as will be shown below.

Finally, biases exist for the dewpoint temperature criterion too (Suppl. Fig. 3e). These are probably somewhat related to biases in the temperature field, though small differences in humidity may cause larger difference in dewpoint temperature. Despite relatively large biases and RMSEs in all fields, the high pattern correlations indicate that the global pattern of mild weather from the individual criteria is modeled well.

By means of a linearized climate change experiment, we analyze the potential impact of model biases on the presented results. Monthly mean climate change values of daily maximum temperature, total precipitation and mean dewpoint temperatures were added to the daily MERRA-2 data. For these combined data the number of mild weather was computed, to provide an estimate of climate change based on the MERRA-2 mean climatology.

Despite the model biases, the presented pattern of change in the occurrence of mild weather is similar in the GFDL-HiFLOR model (Fig. 3a of the main text) and in a linearized climate change experiment (Suppl. Fig. 7a). The patterns of change caused by change in the individual criteria are also very similar between the model and the linearized experiment (Suppl. Fig. 5 and Suppl. Fig. 7b-e). The largest differences are found for the precipitation criterion, which shows larger changes in the Northern Hemisphere mid-latitudes. This indicates that the MERRA-2 data was closer to the 1 mm precipitation cut-off value. However, this difference does not significantly impact the change in the occurrence of mild weather when taking into account the three criteria. Also, seasonal changes of mild weather are similar in the HiFLOR model (Fig. 3 of the main text) and in the linearized climate change experiment (Suppl. Fig. 11).

2 Sensitivity to chosen criteria

The three criteria as presented in the main text were chosen to select days that are neither too hot, too cool, too humid nor rainy: T_{max}[18-30°C], D[<20°C] and P[<1mm]. Given these variables and cut-off values a global mean value of 74 d/yr per km^2 or 89 d/yr per person is found (Fig. 1a of the main text). Suppl. Fig. 12 shows the sensitivity of these global mean values to the choice of the value for the individual criteria. Sensitivities are computed by changing criteria values one at a time. The total number of mild days is most sensitive to the values of the temperature criterion. This is in agreement with Suppl. Fig. 2, which shows that this criterion is the largest limitation of mild weather globally. Changes in the temperature cut-off values can therefore have a larger impact. Changes in the values of the precipitation or dewpoint criteria do not have a significant impact on the number of mild days. Note that P[=0mm] is an exception, and results in a strong reduction of the number of days with mild weather, probably caused by the drizzle problem (Dai 2006; Schmidli et al. 2006).

In Suppl. Fig. 13 a similar analysis to investigate the sensitivity of the global mean projected change in the annual number of mild days is shown. Given the standard values for the criteria (Fig. 2a of the main text) this change was -10 d/yr per km^2 or -11 d/yr per person. The global mean values are most sensitive to the T_{max}[>18°C] criterion, though this is a weak dependence. A decrease in the global mean number of mild days is found independent of the cut-off value investigated here.

These results indicate that, though the chosen values of the criteria are somewhat arbitrary, the presented projection of a global decrease of mild weather is robust to the chosen values of the criteria.

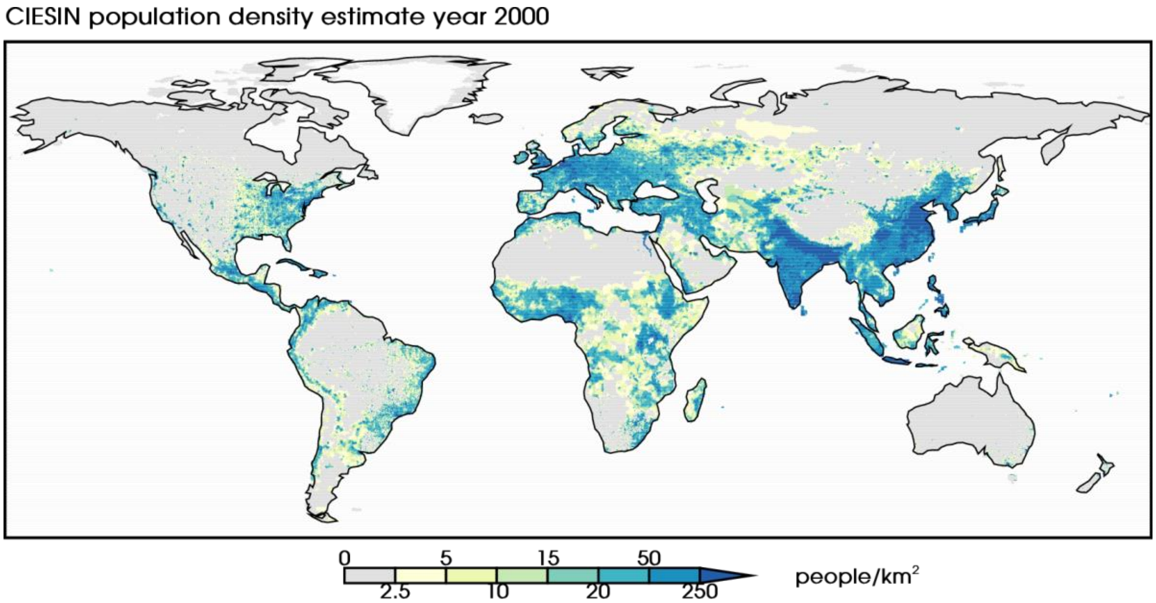
References

Koster, R.D., et al. (2015): Technical Report Series on Global Modeling and Data Assimilation, Volume 43. *MERRA-2; Initial Evaluation of the Climate*.

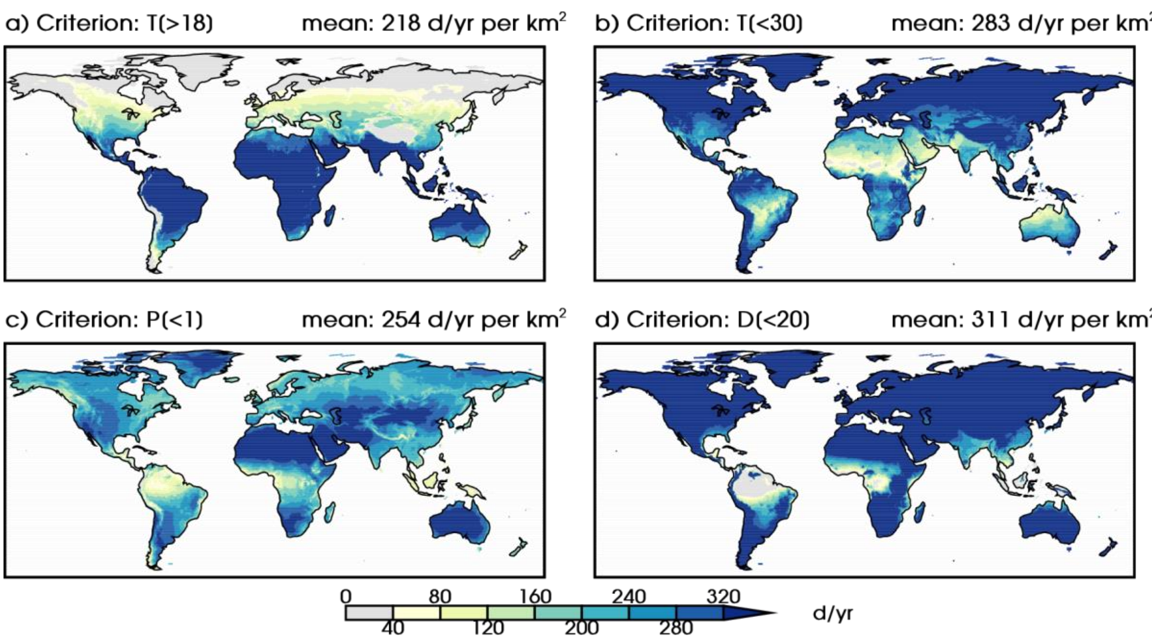
Kanamitsu, M., Ebisuzaki, W., Woollen, J. and Shi-Keng, Y. (2002): NCEP-DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society*, **83**, 1631-1643.

Dai, A. (2006): Precipitation characteristics in eighteen coupled climate models. *Journal of Climate*, **19**, 4605-4630.

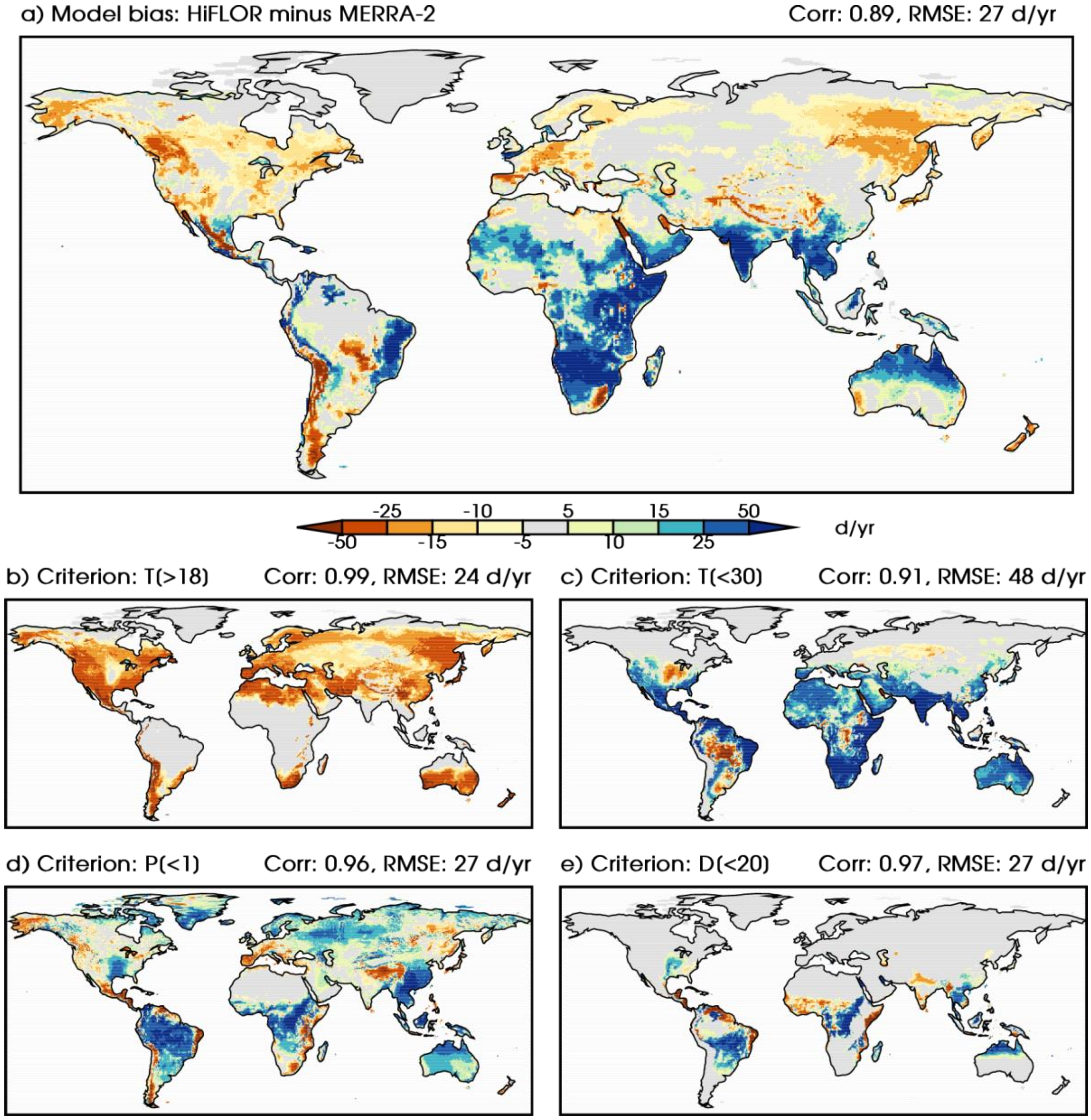
Schmidli, J., Frei, C. and Vidale, P.L. (2006): Downscaling from GCM precipitation: a benchmark for dynamical and statistical downscaling methods. *International Journal of Climatology*, **26**, 679-689.



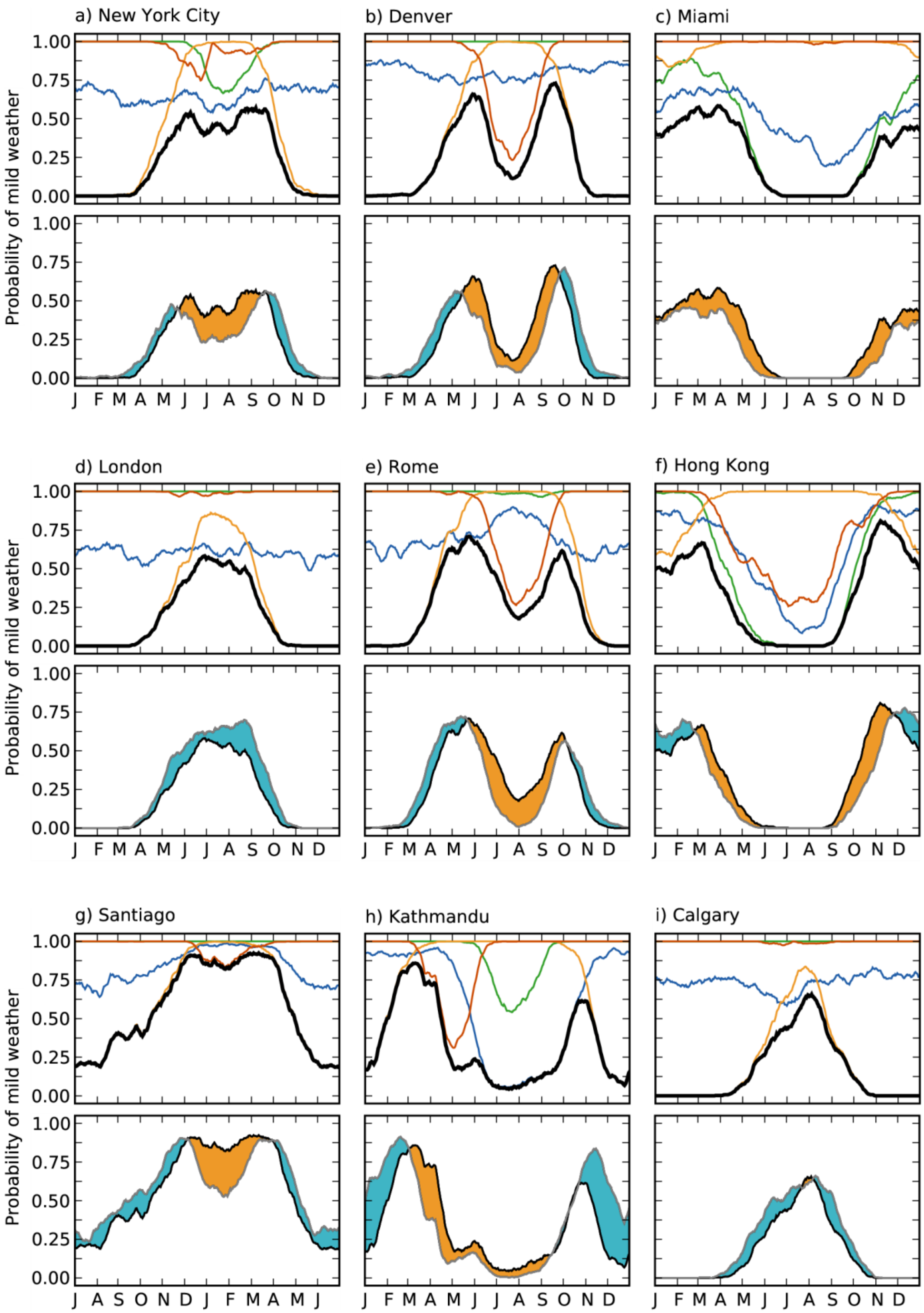
Supplementary Figure 1 | Global distribution of population density for the year 2000. Estimate from CIESIN GPWv4. Note the irregular color scale.



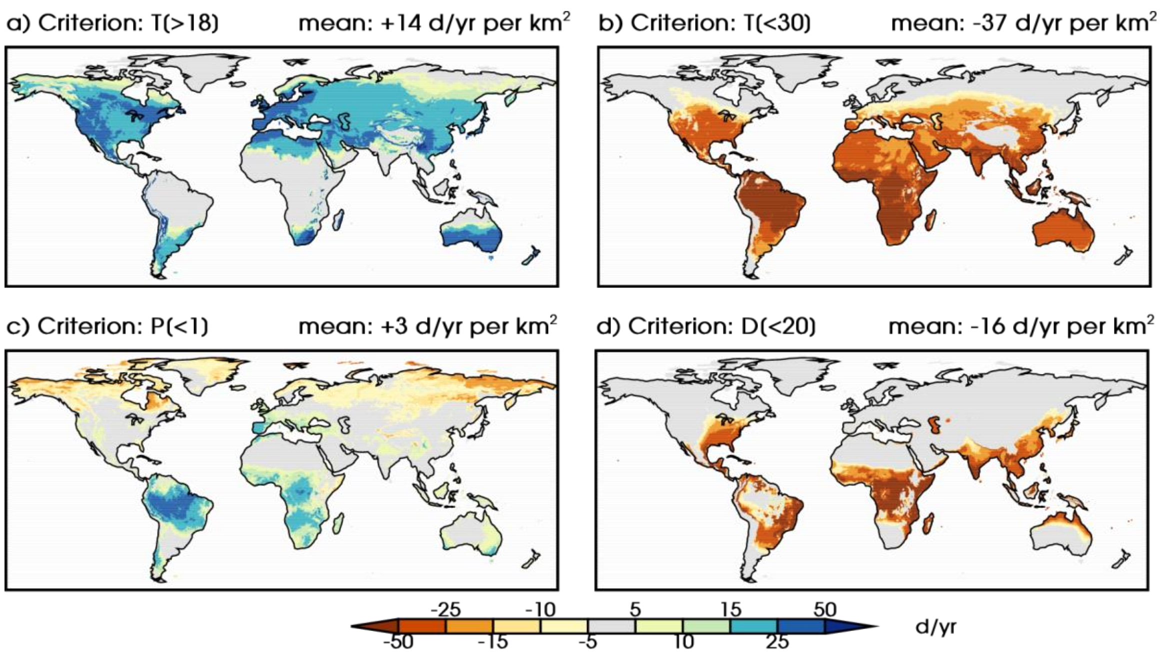
Supplementary Figure 2 | Annual number of days with mild weather based on a single criterion. **a**, Daily maximum 2 m air temperature above 18°C. **b**, Daily maximum 2 m air temperature below 30°C. **c**, Daily total precipitation not exceeding 1 mm. **d**, Daily mean 2 m dewpoint temperature not exceeding 20°C. Note that by definition the T[18-30] criterion is the linear combination of T[>18] and T[<30] and results in 136 d/yr per km^2.



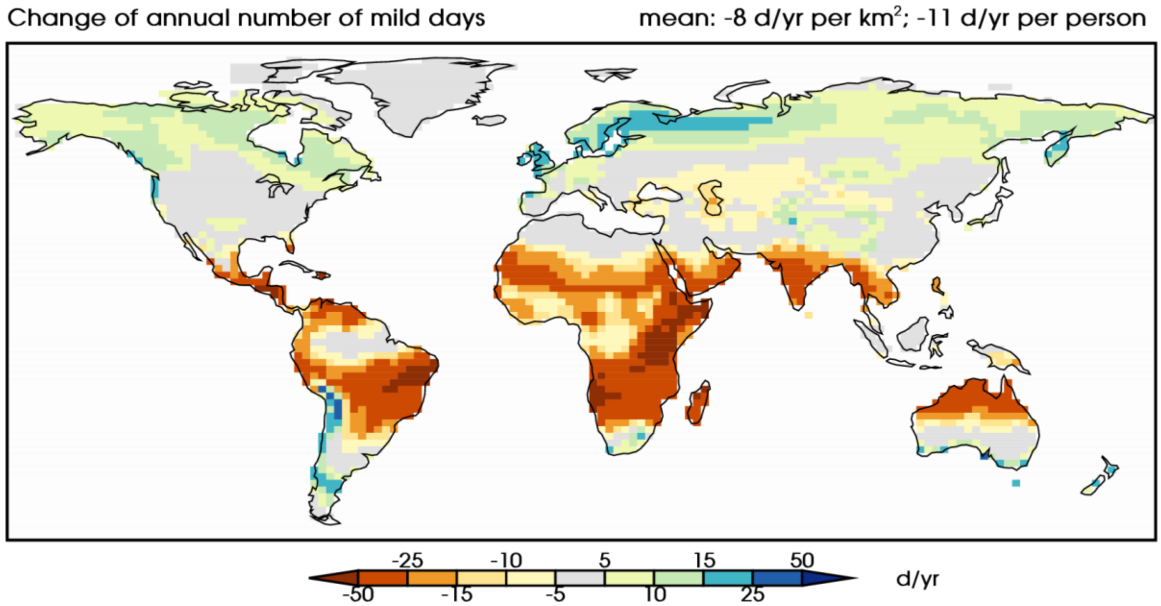
Supplementary Figure 3 | Model bias for the annual number of days with mild weather. Difference between the control experiment (Fig. 1a of the main text) and the MERRA-2 re-analysis (1980-2015). **a**, Global distribution based on all criteria. **b-e**, Global distribution based on individual criterions: **b**, Daily maximum 2 m air temperature above 18°C. **c**, Daily maximum 2 m air temperature below 30°C. **d**, Daily total precipitation not exceeding 1 mm. **e**, Daily mean 2 m dewpoint temperature not exceeding 20°C.


a) New York City
b) Denver
c) Miami
d) London
e) Rome
f) Hong Kong
g) Santiago
h) Kathmandu
i) Calgary
Probability of mild weather
0.00
0.25
0.50
0.75
1.00
J F M A M J J A S O N D
J A S O N D J F M A M J

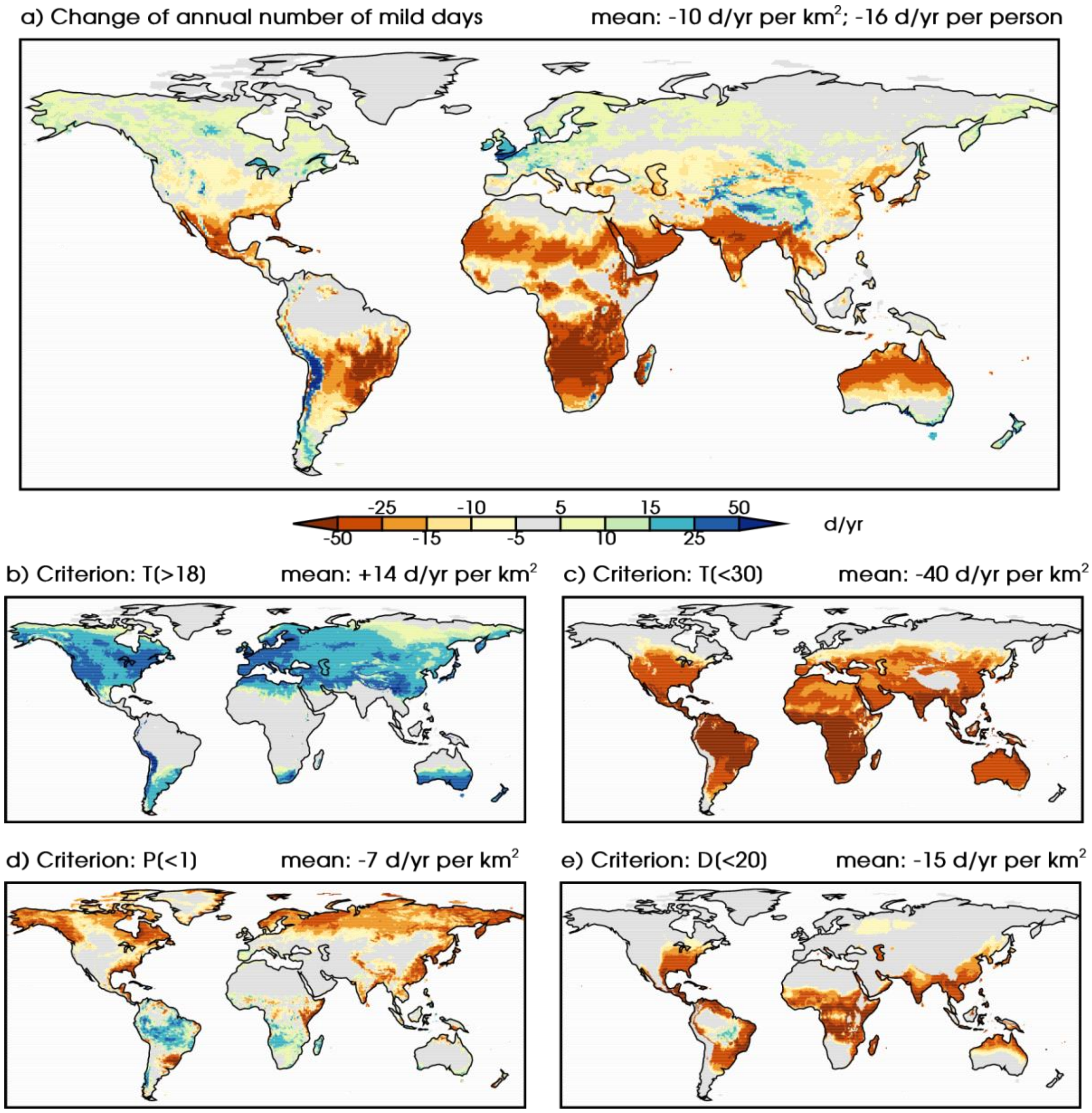
Supplementary Figure 4 | Annual cycle of the probability of a day being mild for additional locations. **top**, Annual cycle of the probability of a day being mild for different locations (black line), and annual cycle of days that satisfy individual criteria for temperature (orange and red lines), precipitation (blue line) and dewpoint temperature (green line). Same as Figs. 1b-g of the main text. **bottom**, 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). Orange color shading indicates positive changes, blue color shading indicates negative changes. Same as Figs. 2b-g of the main text. Time series have been smoothed by a 15-day running mean.



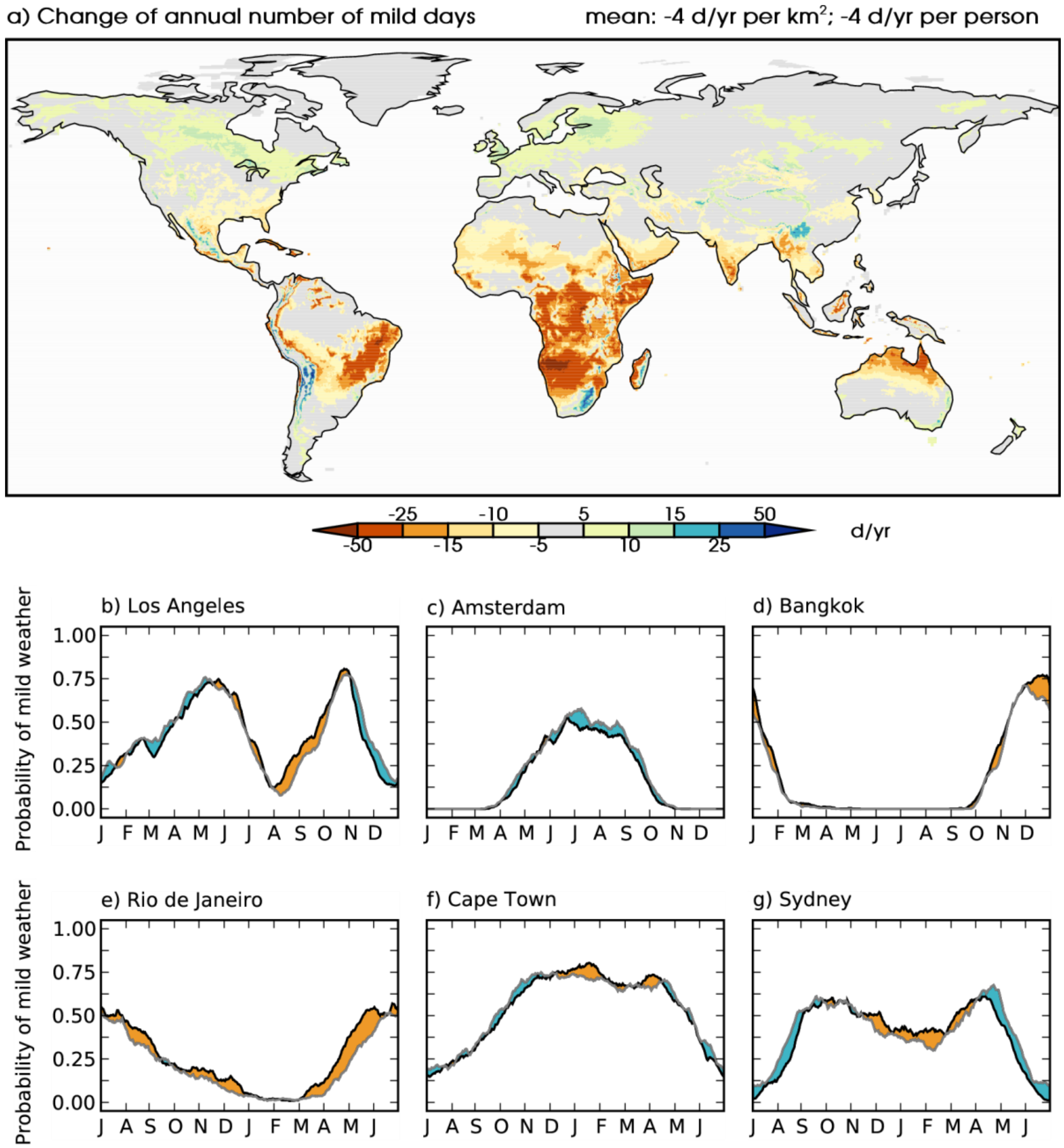
Supplementary Figure 5 | Change in the annual number of days with mild weather in years 2081-2100 based on a single criterion. **a**, Daily maximum 2 m air temperature above 18°C. **b**, Daily maximum 2 m air temperature below 30°C. **c**, Daily total precipitation not exceeding 1 mm. **d**, Daily mean 2 m dewpoint temperature not exceeding 20°C.



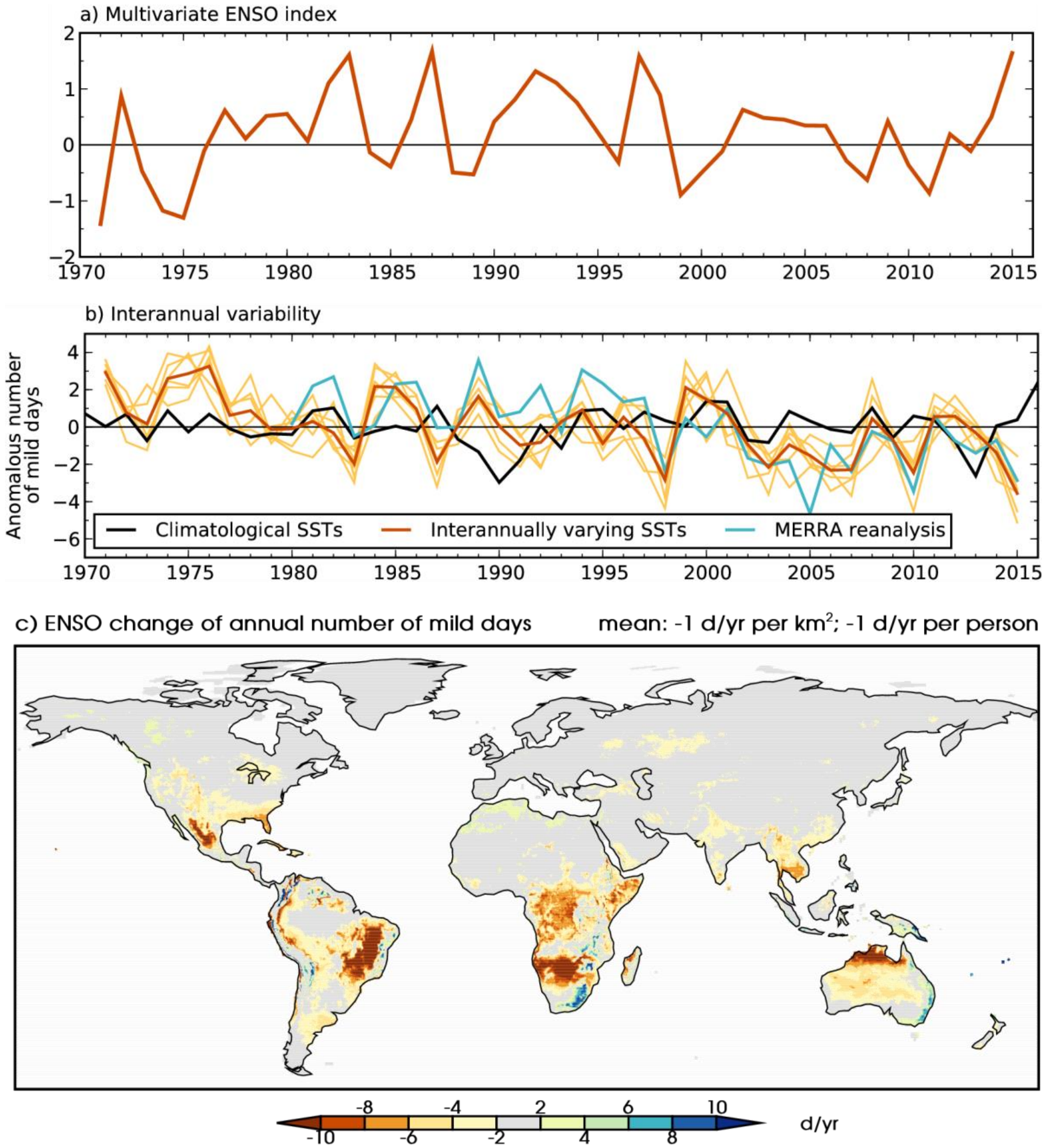
Supplementary Figure 6 | Change in the annual number of days with mild weather in years 2081-2100. As Fig. 2a of the main text but here for an ensemble of CMIP5 models, regridded to a common 2°x2° grid.



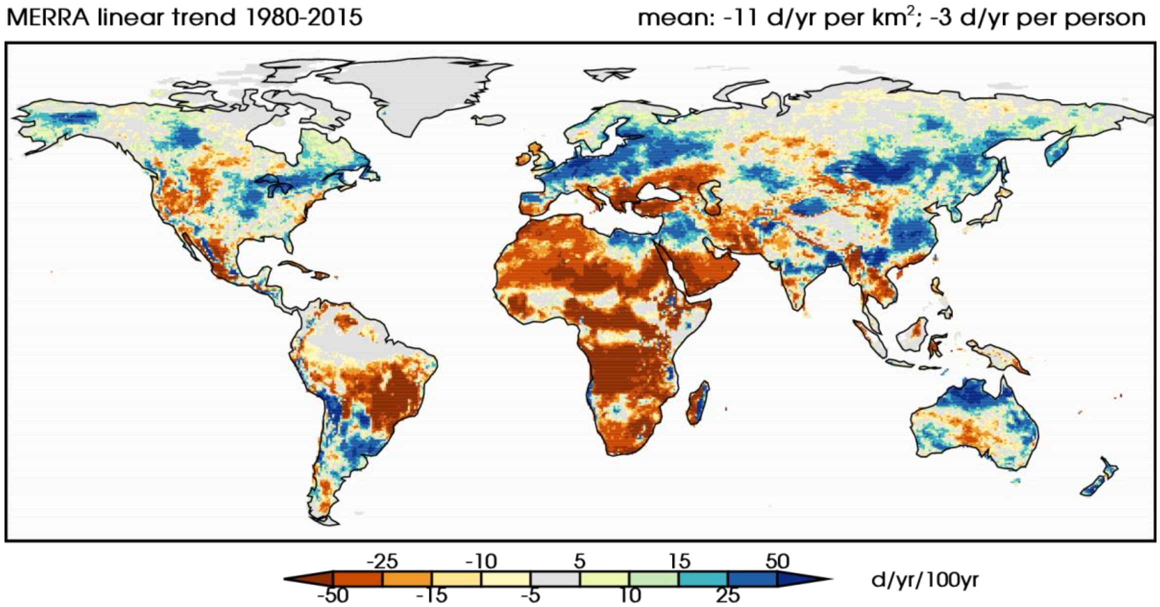
Supplementary Figure 7 | Change in the annual number of days with mild weather in years 2081-2100. As Fig.2a of the main text and Suppl. Fig. 6, but here based on MERRA-2 reanalysis data and modelled changes of temperature, precipitation and dewpoint. **a**, Global distribution based on all criteria. **b-e**, Global distribution based on individual criterions: **b**, Daily maximum 2 m air temperature above 18°C. **c**, Daily maximum 2 m air temperature below 30°C. **d**, Daily total precipitation not exceeding 1 mm. **e**, Daily mean 2 m dewpoint temperature not exceeding 20°C.



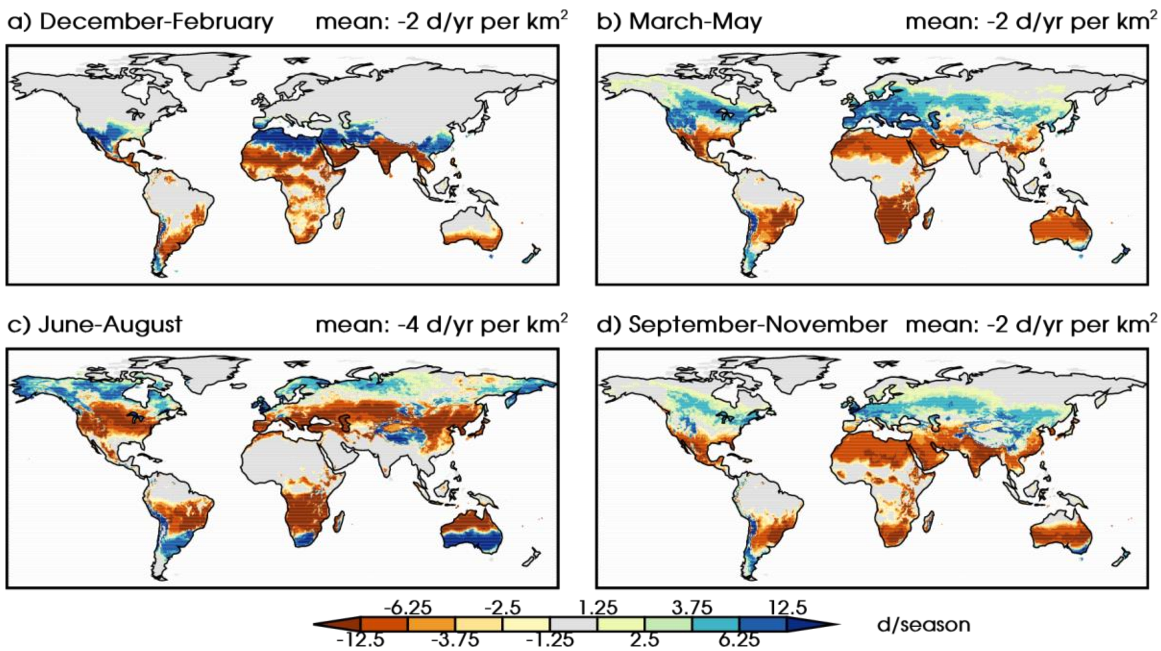
Supplementary Figure 8 | Change in the annual number of days with mild weather in years 2016-2035. Same as Fig. 2 in the main text, but for the near-term projection. **a**, Global distribution. **b-g**, Annual cycle of the probability of a day being mild for different locations for years 1986-2005 (black line) and years 2016-2035 (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.



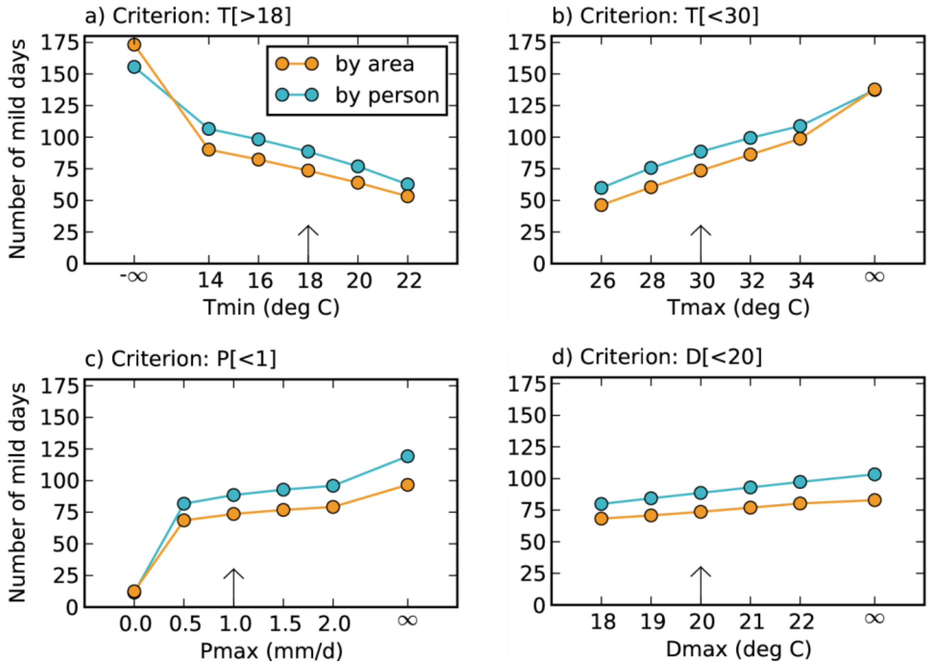
Supplementary Figure 9 | ENSO related changes in the annual number of days with mild weather. **a**, Multivariate ENSO index (MEI) time series. **b**, Global mean number of mild days for the control experiment (black line), individual ensembles in the HiFLOR historical experiment (orange lines), ensemble mean of historical experiment (red line) and MERRA-2 reanalysis (blue line). **c**, Linear regression of annual number of mild days (HiFLOR ensemble mean) on the MEI.



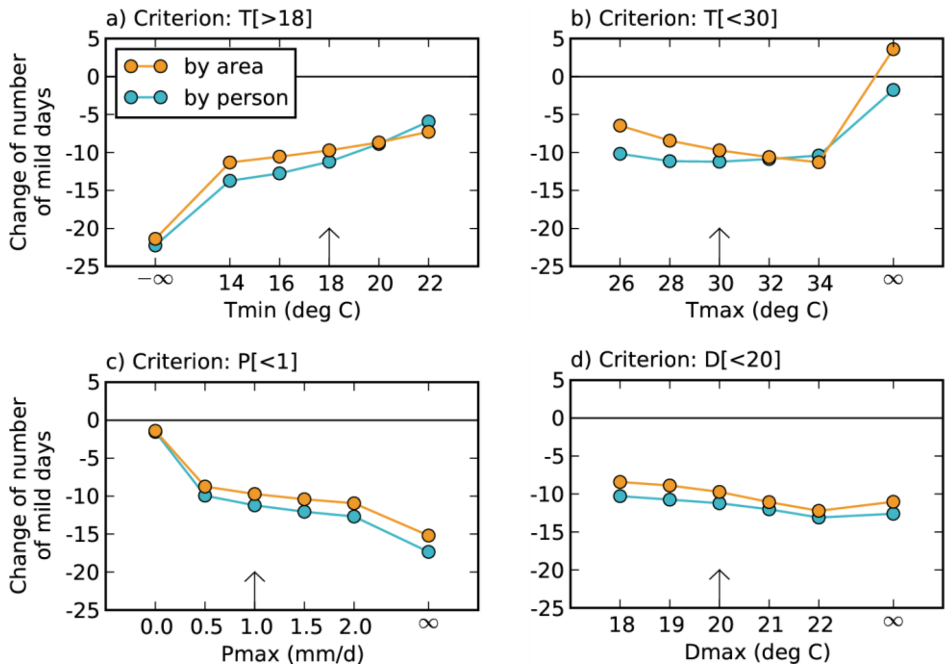
Supplementary Figure 10 | Linear trend of the yearly number of mild days from 1980-2015 in the MERRA-2 reananlysis. Here all values are shown, significant values are shown in Fig. 4b of the main text.



Supplementary Figure 11 | Change in the seasonal number of days with mild weather in years 2081-2100. As Fig. 3 of the main text, but here based on MERRA-2 reanalysis data and modelled changes of temperature, precipitation and dewpoint. **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.



Supplementary Figure 12 | Sensitivity of global mean annual number of days with mild weather to selected criteria. The value of a single criterion is changed, whilst the other criteria remain unchanged. The infinity sign on the x-axes shows the value if the tested criterion is removed completely. Vertical arrows from the x-axes denote the criteria value as set in the main text. **a**, Daily maximum 2 m air temperature above 18°C. **b**, Daily maximum 2 m air temperature below 30°C. **c**, Daily total precipitation not exceeding 1 mm. **d**, Daily mean 2 m dewpoint temperature not exceeding 20°C.



Supplementary Figure 13 | Sensitivity of the change in the global mean annual number of days with mild weather to selected criteria. The value of a single criterion is changed, whilst the other criteria remain unchanged. The infinity sign on the x-axes shows the value if the tested criterion is removed completely. Vertical arrows from the x-axes denote the criteria value as set in the main text. **a**, Daily maximum 2 m air temperature above 18°C. **b**, Daily maximum 2 m air temperature below 30°C. **c**, Daily total precipitation not exceeding 1 mm. **d**, Daily mean 2 m dewpoint temperature not exceeding 20°C.