Why climate models underestimate the exacerbated warming in Western Europe

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Abstract

Much of Western Europe has experienced mean summer temperature increases about three times higher than the globe since 1980. Particularly the regional (RCMs), but also global climate models (GCMs) underestimate this strong observed warming of $\approx 2.3 \, ^\circ C$, which is largely thermodynamic but also fuelled by dynamics. RCM- and GCM-simulated atmospheric circulation effects on temperature trends are generally weaker, partly explaining the warming underestimation yet not indicating a model deficiency. Most RCM simulations from the Coordinated Regional Downscaling Experiment (CORDEX), however, omit time-evolving aerosols, and hence fail to capture increasing net radiation due to aerosol reductions. This introduces a bias to the CORDEX RCM multimodel ensemble that is partly masked by overestimated background warming in the driving GCMs. Accounting for the latter, the thermodynamic warming — 1.6 °C for 1980–2022 — is underestimated by nearly 40% (0.6 °C) in simulations with constant aerosols. This mismatch is even stronger for heatwaves than summer means, and manifests increasingly clearly in climate projections throughout the ongoing century. Our results imply that the future warming in Europe is likely to be higher than earlier assumed, as only part of the discrepancy between most RCM simulations and observations can be attributed to internal climate variability.

Introduction

There is a growing demand from society for reliable long-term climate projections, from global to regional and local scales, and ongoing and future developments ultimately influence the resilience of society to rising climate hazards$^{1,2}$. The spatial resolution of global climate models (GCMs) and representation of physical processes and interactions has considerably improved since the 1950s, and the latest IPCC report (AR6) builds on a new set of climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6; ref. 3). Nevertheless, many small-scale features and phenomena such as, e.g., highly variable topography or organized convection, remain unresolved in most GCM simulations$^4$. Dynamical downscaling, that is, running a regional climate model (RCM) for a limited domain with coarser GCM data at the boundaries, has been established as an important modeling branch as it entails more realistic regional climate representations$^5$, although the benefits depend on the variable and domain of interest$^6$. Even though RCMs can be run at convection-permitting km-scale resolution, this is typically only performed for short periods (e.g., ref. 7) or individual countries (e.g., ref. 8) due to the immense computational demands. As such, RCM simulations that serve as the foundation of climate services in different countries (e.g., for Belgium$^9$, the UK$^{10}$, Switzerland$^{11}$, or Germany$^{12}$) generally have a ~10km or coarser resolution. While RCMS were not widely used for the IPCC AR5 (ref. 13) as coordinated intercomparison studies were still emerging, in the IPCC AR6, RCMs from the Coordinated Regional Downscaling Experiment (CORDEX; refs. 14–16) provide the basis for sub-continental climate information (e.g., Chapters 11, 12 and Atlas).

Europe has warmed faster than any other World Meteorological Organization (WMO) region since the 1980s, with annual mean temperatures increasing twice as much as the global average$^{17}$. This is even
more pronounced for Western Europe where temperatures increase nearly three times faster than globally (~2.3 °C compared to ~0.8 °C according to reanalysis, as shown later). However, as shown in Section 2, most simulations part of CORDEX strongly underestimate the warming in Europe, especially during summer\textsuperscript{18,19}. Several CMIP6 GCM simulations also underestimate the warming in Europe compared to observations, although the warming discrepancy is less pronounced. Considering that climate services strongly rely on climate models, it is paramount to understand the causes of this inconsistency. If the models do not adequately represent the processes underlying the observed regional warming, this likely also affects climate projections. Hence it is helpful to partition the signal in contributions from different physical drivers of rising temperatures: Regional warming is the consequence of (i) the “background” global warming, (ii) large-scale circulation changes, often conceptualized as “dynamics”, and (iii),
regional changes in the surface energy budget and partitioning, including snow/ice–albedo–temperature
and soil moisture/vegetation–temperature feedbacks (“thermodynamics”). Human-induced enhanced
greenhouse gas (GHG) concentrations strengthen the downwelling longwave radiation and thereby
increase the surface net radiation, both initiating global warming and inducing a “local” thermodynamic
forcing for a region of interest. In the case of Europe, the surface energy budget is dominated by an
additional anthropogenic forcing: decreasing aerosol emissions have considerably boosted the incoming
surface shortwave radiation since about 1980 (e.g., refs. 20,21). These human-induced radiation changes
have exacerbated the warming in mainland Europe since the 1980s, with shortwave forcing arising from
direct aerosol effects being the primary driver of the surface energy budget\textsuperscript{20}, although a reduction in
clouds could also have played a role\textsuperscript{22}. The CORDEX multimodel mean has, however, been found to
underestimate the observed increase in downward shortwave radiation, since most RCMs do not consider
time-evolving aerosols\textsuperscript{23,24}. Based on climate projections with further declining aerosol emissions in the
future, neglecting long-term changes in aerosol concentrations causes an underestimation of the mean
summer warming at the end of the current century by 1.5 to 2 °C for most of Europe\textsuperscript{25}. Therefore,
different aerosol representations in CORDEX simulations might also contribute to the 1980–2022
warming discrepancy with respect to observations, which we aim to analyze in this study.

Both the background warming and local thermodynamic forcing arise primarily in response to
anthropogenic emissions, with globally increasing GHG and decreasing aerosol concentrations over
Europe (and other regions). Regional warming can also occur naturally, however, as the atmosphere
displays abundant internal variability at all timescales, generated both within the atmosphere and
through interactions with slower components of the climate system such as the ocean. The North Atlantic
Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO), e.g., are known to modulate the climate
across much of the northern extratropics\textsuperscript{26–28}, and have contributed to rising air temperatures in the
Northern Hemisphere, especially in the late 1990s and early 2000s (ref. 29). Recently, circulation changes
have been linked to accelerated heatwave trends in Western Europe, but it remains unclear whether these
dynamical changes are the result of natural climate variability or constitute a response to the human-
induced climate warming\textsuperscript{30}. Thus far, externally forced changes in the atmospheric circulation have
generally been considered “fairly small” compared to unforced internal variability\textsuperscript{31,32}. Either way, if the
simulated dynamical changes are not in line with observations, this could cause a warming discrepancy. In fact, a study has suggested that a weaker dynamical contribution in CMIP6 simulations compared to observation-derived data could be the main cause of an underestimation in the simulated rise in heat extremes\(^{33}\). This could imply that the warming mismatch is at least partly caused by long-term changes or inter-decadal variability in atmospheric dynamics not captured by climate model simulations, although the impact on summer mean temperatures has not yet been quantified.

Focussing on Western Europe, we estimate here the thermodynamic and dynamic contributions to the 1980–2022 summer warming using both observation-derived and climate model data, and identify the causes for the climate model underestimation of mean warming over this highly populated region. We find two main factors that cause lower than observed regional temperature increases: For both sets of multi-model experiments, a weaker modeled dynamical contribution than in observation-derived data leads to an underestimation of about 0.6 °C (CMIP6 GCMs) and 0.8 °C (CORDEX RCMs) of the observed trend. While this is partially compensated by excessive background warming in both ensembles (> 0.3 °C), the CORDEX RCMs further display a lack of regional thermodynamic warming. This warming mismatch of ~0.5 °C is primarily inflicted by omitted changes in aerosol forcing in a majority of the participating models, and accounts for half of the CORDEX ensemble-mean trend underestimation. The identified regional thermodynamic bias in RCM simulations is of high relevance for country-level climate services, which tend to rely on these simulations in Europe due to their higher resolution.

**Results & discussion**

**Comparing simulated and observation-derived warming in Europe**

Since 1980, much of Europe has warmed by more than 2 °C during summertime (June–August), with some areas even exceeding a warming of 3 °C in ERA5 (Fig. 1a), resulting in an almost three times larger regional warming compared to the observed global warming over that time frame (0.8 °C). Based on a state-of-the-art 49-member RCM simulation ensemble from the CORDEX experiment, however, the modeled warming signal is far weaker (blue colors in Fig. 1b). Averaged over the land areas of western West-Central Europe (WWCE; delineated in Figs. 1a–b) and gauged with linear trends, this amounts to 1.0 °C less warming than observed (ERA5, 2.3 °C). We focus our analysis on the WWCE region and provide area-averaged summer temperatures; all timeseries are smoothed and expressed as changes with respect to 1980 (see Methods for details). We note that this entails no assumption of linearity, and hence the resulting long-term temperature changes visualized in Fig. 1c are generally similar – but not identical – to linear trends. Only a few CORDEX simulations feature a warming of more than 2 °C since 1980 (purple range in Fig. 1c), and even the simulation with the strongest temperature increase (thin purple line) does not clearly exceed the reanalysis-warming. This suggests that there is a systematic bias in either (a) the prescribed forcing, (b) the regional model response to this forcing, or (c), a strong misrepresentation of the variability. The CMIP6 multi-model ensemble (green shading in Fig. 1d) also features weaker than
observed trends in most simulations, yet the upper warming range is considerably higher compared to CORDEX, and the overall distribution actually includes the ERA5 data, thus not necessarily implying a demonstrated discrepancy. The CORDEX simulations also feature less warming in winter and spring than observation-derived datasets, whereas linear trends in simulated and observed fall temperature are fairly consistent (Fig. 1e). Our analysis focuses on summertime temperatures, however, because compared to other seasons, (i) summer has warmed the fastest since 1980 according to both ERA5 and E-OBS (Fig. 1e), and (ii), elevated summer baseline temperatures fuel more intense and frequent heatwaves that exert greater impacts on society and ecosystems (e.g., refs 34–36).

Revisiting the drivers of regional warming, we first examine whether insufficient background warming contributes to the summer warming discrepancy in WWCE. The background warming is indicated by linear trends in global annual mean 2m-temperatures from the corresponding driving GCM of each CORDEX simulation, and visualized together with WWCE summer warming since 1980 (purple dots in Fig. 2a). Within the CORDEX ensemble used here, forced by 8 individual GCMs, most models clearly exceed ERA5’s 1980–2022 global mean temperature increase of 0.8 °C. A majority of CMIP6 simulations also overestimate the global mean temperature change compared to ERA5, but the displayed range of background warming is substantially larger than for the CORDEX ensemble. Still, most regional temperature changes of ~1 °C or less are found in CORDEX simulations, and nearly all of these also remain below the 1:1 line, i.e. they feature less WWCE summer warming than for the entire globe throughout 1980–2022. At the other end of the simulated regional warming spectrum by the CORDEX ensemble, a handful of models manage to reproduce ERA5-like WWCE warming, but at a staggering background warming of ~1.6 °C, i.e. double the observed warming. Similarly, CMIP6 models associated with strong WWCE warming generally feature stronger than observed global mean temperature changes. These simulations agree with the observed WWCE summer warming for the wrong reason, since climate models should accurately capture the regional response to global warming (rather than to underestimate this response but simultaneously overestimate the warming at global scale).

Unraveling dynamic and regional thermodynamic warming contributions

Therefore, we continue our analysis for a subset of simulations with the most accurate background global warming compared to ERA5 (indicated by black marker edges in Fig. 2a). We find that differences in WWCE warming between simulations and the reanalysis product emerge more clearly (Fig. 2b), particularly for the CORDEX model subset. Inspecting the temporal evolution of surface net radiation for the same simulation subsets and domain (Fig. 2c), ERA5 points to a strong increase, whereas most — but not all — CORDEX simulations indicate only weak changes. This implies that most of the CORDEX ensemble members suffer from a bias in the regional thermodynamically induced trend. We examine this more closely further below, but already note that this is caused by different aerosol representations in the RCMs within CORDEX (e.g., refs. 23,24). In contrast, the CMIP6 subset used here shows no clear forcing bias. Nonetheless, the strong-observation-derived temperature rise is still not captured (cf. model median
vs. ERA5 in Fig. 2c). This suggests that the sole remaining regional warming driver — atmospheric dynamics — contributes to deviating temperature trends.

In a next step, we thus disentangle the 1980–2022 summer warming in WWCE into a dynamic and a thermodynamic component using dynamical adjustment for ERA5 and climate model simulations (see Methods). With this approach, we first estimate the impact of large-scale circulation changes over Europe — represented with 500-hPa geopotential height fields — on mean WWCE summer temperatures, i.e. the dynamical contribution to the total regional warming (schematically represented in Fig. 3a). The thermodynamic contribution is then obtained as the residual, and corresponds to the combined effects of the background global warming and the regional thermodynamic forcing (i.e., mostly increasing net radiation). Since WWCE only represents 0.19% of the global area, we consider the global-scale mean temperature rise as a background effect that contributes to — yet is effectively independent from — the regional warming itself. Fig. 3b visualizes total summer warming over 1980–2022 for model simulations, again for subsets of the CORDEX and CMIP6 ensembles constrained by background warming, and ERA5. For the latter, circulation changes act to increase the regional temperature change by 0.74 °C, which is nearly one third of the total warming (Fig. 3c). Most CMIP6 simulations feature positive, but generally far weaker dynamic contributions, leading to an underestimation of the temperature increase. These findings are consistent with a recent study that suggests dynamics as the main “culprit” for discrepancies between observed and simulated trends in heat extremes33. Given that the dynamic contribution to summer warming in WWCE is a manifestation of unforced internal variability, dynamically inflicted differences between ensemble mean and observed temperature trends do not imply systematic model biases.

Still, as a clear majority of the CORDEX simulations features slightly negative dynamical contributions to the summer warming, this causes an even stronger underestimation of the temperature trend. The difference in dynamical contributions between these model ensemble subsets should be interpreted with caution; the 15 RCM simulations used here are driven by 2 GCM simulations that largely prescribe the large-scale atmospheric flow within the respective RCM domain boundaries37, such that there are effectively only 2 independent circulation realizations. The 15 GCM simulations that form the CMIP6 subset, on the other hand, all feature a freely evolving global atmosphere, which explains why the portrayed range is wider than for the CORDEX RCMs. This also holds for the entire (unconstrained) model ensembles (SFig. 1), and although the overall difference between simulated dynamical warming is smaller than for the subsets shown in Fig. 3c, the CORDEX models still largely feature negative (ensemble mean -0.05 °C) and hence even weaker contributions than the CMIP6 ensemble (+0.16 °C on average). This does not explain the entire discrepancy with respect to the observed warming, however, since the CMIP6 and CORDEX subsets also underestimate the thermodynamic warming (Fig. 3d) by -0.17 and -0.38 °C on average.

The strong thermodynamic bias apparent for the CORDEX models, being driven by simulations with nearly identical background warming as across the CMIP6 subset (markers with black dots in Fig. 2a), must have a regional origin. More available surface net radiation boosts the surface turbulent heat fluxes,
which is known to (i) directly impact air temperatures through surface sensible heating, and (ii), further enhance the net radiation through surface latent heating by the associated moistening of the atmosphere and resulting water-vapor feedback\(^\text{20}\). We thus relate the regional thermodynamic warming, obtained by removing the background warming from the total thermodynamic warming (shown in Fig. 3d), to changes in the surface net radiation in WWCE. A relatively linear relationship emerges (markers and fitted green line in Fig. 4a), with a temperature sensitivity of about 0.5 °C for a 10 W/m\(^2\) net radiation change, which is also the case when fitting the total thermodynamic warming to regional net radiation changes (SFig. 2). Following the aerosol representation classification of ref. 24, the CORDEX models with constant aerosols feature weak, mostly positive surface net radiation trends (red markers in Fig. 4a). The remaining CORDEX simulations with time-evolving aerosols, on the other hand, exhibit net radiation increases broadly consistent with ERA5 (blue markers in Fig. 4a). A budget analysis performed for ERA5 and all available simulations — regardless of background warming — reveals that changes in WWCE surface net radiation are predominantly fuelled by enhanced downward shortwave radiation, and to a lesser extent downward longwave radiation (Fig. 4b), as previously reported\(^\text{20}\). This does, of course, not hold for the CORDEX simulations that (by design) neglect long-term decreases in aerosol concentrations over Europe since the 1980s, resulting in a comparatively miniscule shortwave forcing as reported previously (e.g., ref. 23).

The striking discrepancy of shortwave forcing in CORDEX simulations with and without time-evolving aerosols implies that the downward shortwave radiation increase evident for ERA5 and CMIP6 is largely caused by temporally evolving aerosol attenuation. Additional analyses presented in the Suppl. Information confirm that cloud-related shortwave radiation changes are minor (+1 W/m\(^2\)) compared to aerosol effects (+21.3 W/m\(^2\)) for ERA5 (SFig. 3a). This is in line with evidence for decadal variations in observed shortwave radiation since the mid-20th century in West-Central Europe being primarily human-induced\(^\text{21}\) (rather than, e.g., caused by changes in cloudiness). While CMIP6 models tend to have stronger cloud contributions than ERA5, aerosols remain the key driver of increasing shortwave radiation (SFig. 3b). This further substantiates that neglecting time-evolving aerosols causes a lack of regional thermodynamic forcing (and resulting warming response). Before we proceed with our analysis for WWCE, we note here that European aerosol concentrations are largely attributable to domestic emissions, which are highest in eastern and southeastern parts of the continent\(^\text{38}\). Consequently, at the eastern edge of our analysis region, and particularly even further to the east, downward shortwave trends for 1980–2022 are underestimated more severely in simulations with constant aerosol forcing than in any other part of Europe (Fig. 4c). In terms of the impact on temperature trends, our analysis region with an average bias of ~0.6 °C is more affected than southern or northern Europe (Fig. 4d), but even stronger biases emerge to the east with local exceedances of 1 °C, consistent with the pattern in shortwave trend biases (Fig. 4c) and aerosol emissions\(^\text{38}\).

Quantifying the aerosol forcing-induced warming mismatch
Building on the disentangled temperature contributions from the dynamical adjustment we summarize our findings for WWCE in Table 1, always based on averages for the respective models and using ERA5 as a reference to calculate biases. As previously noted, the dynamical contribution is generally much weaker across both the CMIP6 and CORDEX ensembles, causing a mean temperature trend underestimation of 0.58 °C and 0.79 °C, respectively. However, we focus on the thermodynamic warming here, since this is what each model simulation — and, contrary to the dynamic warming, especially the ensemble mean — should capture. For the CMIP6 ensemble, there is a slight positive thermodynamic bias, whereas it is negative for the CORDEX simulations, despite the fact that both model ensembles have a mean background warming excess of about 0.3 °C that counteracts the remaining (or residual) negative thermodynamic bias. We estimate the regional thermodynamic bias using the relationship between thermodynamic warming (i.e., the slope shown in Fig. 4a) for the CORDEX subset, and the respective mean net radiation trend discrepancy with respect to ERA5 for the entire CORDEX ensemble and all subgroups. Similarly, using the slope determined analogously to Fig. 4a for the CMIP6 subset (SFig. 4), we obtain the regional thermodynamic bias for the CMIP6 models based on mean 1980–2022 changes in summer net radiation. Whereas this reveals only slight biases for the CMIP6 models, for the CORDEX models, our estimates of the regional warming bias are clearly negative for the entire ensemble (-0.47 °C), the subset (-0.37 °C) and its subgroup with constant aerosol representations only (-0.61 °C). Only the subgroup with time-evolving aerosols does not suffer from a clear bias (-0.01 °C). The respective residual thermodynamic biases are all within ±0.1 °C, which suggests that it is indeed a general lack of increasing net radiation — in turn due to a majority of the RCMs relying on constant aerosols — that causes most of the thermodynamic warming underestimation. The extent of the bias depends on the composition of the respective ensemble; for our 49-member CORDEX ensemble consisting of 35 RCM simulations with constant aerosols, it amounts to about 0.5 °C on average. Comparing the thermodynamic biases between the two subgroups with constant and evolving aerosols, we find a total (& residual) thermodynamic difference of 0.59 °C, and a regional thermodynamic difference estimated through net radiation changes of 0.60 °C. In other words, neglecting long-term changes in aerosols reduces the total thermodynamic warming by 35%–40%.

Table 1: Summer warming in WWCE between 1980 and 2022 for model simulations and ERA5, disentangled into dynamical and thermodynamic (TD) contributions (see Methods). The total bias with respect to the thermodynamic warming in ERA5 is shown, further disentangled into a background warming (BW) bias and a residual. The latter roughly corresponds to — but is obtained independently from — our estimate of the regional thermodynamic bias, which we estimate by converting simulated net radiation trend differences with respect to ERA5 into warming biases. The total, dynamic and thermodynamic warming are estimated with a linear trend and represent the respective total 1980–2022 changes, and all values are shown in °C.
### Thermodynamic Warming Estimates

<table>
<thead>
<tr>
<th>Model</th>
<th>Total warming</th>
<th>Dynamic warming</th>
<th>TD warming</th>
<th>Total TD bias</th>
<th>Backgr. warming bias</th>
<th>Resid. bias</th>
<th>$R_{\text{net}}$-based TD bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA5</td>
<td>2.33</td>
<td>0.74</td>
<td>1.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORDEX</td>
<td>1.32</td>
<td>-0.05</td>
<td>1.37</td>
<td>-0.22</td>
<td>+0.33</td>
<td>-0.55</td>
<td>-0.47</td>
</tr>
<tr>
<td>CORDEX subset</td>
<td>1.06</td>
<td>-0.16</td>
<td>1.21</td>
<td>-0.38</td>
<td>+0.08</td>
<td>-0.46</td>
<td>-0.37</td>
</tr>
<tr>
<td>CORDEX aerEvo</td>
<td>1.42</td>
<td>-0.16</td>
<td>1.57</td>
<td>-0.02</td>
<td>+0.08</td>
<td>-0.10</td>
<td>-0.01</td>
</tr>
<tr>
<td>CORDEX aerCon</td>
<td>0.81</td>
<td>-0.16</td>
<td>0.98</td>
<td>-0.61</td>
<td>+0.08</td>
<td>-0.69</td>
<td>-0.61</td>
</tr>
<tr>
<td>CMIP6</td>
<td>1.85</td>
<td>0.16</td>
<td>1.69</td>
<td>+0.10</td>
<td>+0.32</td>
<td>-0.22</td>
<td>+0.04</td>
</tr>
<tr>
<td>CMIP6 subset</td>
<td>1.71</td>
<td>0.29</td>
<td>1.42</td>
<td>-0.17</td>
<td>+0.03</td>
<td>-0.20</td>
<td>+0.04</td>
</tr>
</tbody>
</table>

It is difficult to quantify this precisely, since model errors and possibly other factors also play a role (otherwise the residual and regional thermodynamic bias estimates would be identical), but our analysis conclusively demonstrates that the thermodynamic warming underestimation by the CORDEX ensemble is largely attributable to simplistic aerosol representations. To our knowledge, previous analyses either examined the impact of aerosol representation in multi-model CORDEX ensembles on past (and projected) shortwave radiation changes\textsuperscript{23,24}, or investigated the influence on temperature in climate projections\textsuperscript{25,39}. Besides these studies, model experiments with a single RCM suggest that nearly a quarter of the simulated 1980–2012 annual mean warming in Europe is achieved by aerosol changes\textsuperscript{40}. Even though comparing this to our estimate based on several models and a different analysis period is not straightforward, it is plausible that we obtain an even stronger aerosol effect on temperature changes than ref. 40: incoming shortwave radiation in mid-to-high latitudes is most intense and exerts the strongest influence on air temperatures during summertime (e.g., ref. 41). Our results suggest that the summertime warming in WWCE in RCMs without time-evolving aerosols — the majority of models participating in the CORDEX initiative — is largely driven by the background warming, as the regional thermodynamic forcing and resulting warming is widely underestimated.

On the other hand, the RCMs with long-term aerosol changes simulate almost the same thermodynamic warming as obtained from ERA5 (cf. dashed lines in Fig. 5a). While these models reach the observation-derived 1980–2022 temperature change attributable to thermodynamics (yellow line in Fig. 5a) on average in the year 2026 (i.e. 4 years too late), it takes 13 years longer for the simulations based on constant aerosols. As such, and despite being forced with a high-emission scenario, the RCMs with constant aerosol forcing only reach the current observed summer warming by about 2039. Crucially, the mismatch introduced by neglecting long-term aerosol changes relative to simulations that account for it increases throughout the ongoing century, reaching about 1.5 °C (and close to 2 °C) in terms of mean
(median) in 2100 (cf. red and blue boxplots in Fig. 5a). This range is consistent with ref. 25, even though the authors assessed surface rather than air temperature changes, and employed a different CORDEX model ensemble.

Finally, we also explore how the lack of local thermodynamic forcing due to neglecting aerosol trends affects summer temperatures at different timescales, from seasonal to daily (Fig. 5b). Unlike for the multi-model averages, the observation-derived 1980–2022 warming for the 5 hottest consecutive days outpaces both changes at shorter and longer timescales. We would not expect the latter if the warming was entirely driven by thermodynamics, and hence consider this an independent line of evidence that dynamics contributed to the summer warming in WWCE. Moreover, we note that the hottest sub-monthly periods occur most frequently in July and August for WWCE, whereas the observed monthly mean warming is clearly highest in June (SFig. 5), fuelled by strong dynamic contributions. Consequently, discrepancies between ERA5 and CORDEX simulations also increase from 10/15-d periods towards the (90-d) seasonal scale. Comparing the mean warming rates of the two CORDEX subgroups, the hottest 10-d period per year increased by about 2 °C and 1 °C for CORDEX simulations with and without time-evolving aerosols, respectively, and the resulting ~1 °C difference implies an even stronger absolute thermodynamic contribution than for summer mean temperatures at ~0.6 °C. While the relative contribution to the total warming does not vary much as much across timescales, but tends to exceed 40%, it is not obvious why a long-term modulation of shortwave — and ultimately net — radiation trends by aerosols enhances temperatures during the hottest sub-monthly time periods more than across the entire summer. We argue that aerosol representation-inflicted biases should emerge most clearly in cloud-free conditions, which are closely related to the large-scale circulation patterns — typically atmospheric blockings — that enable heatwaves in WWCE (e.g., ref. 42). Moreover, the same analysis performed for 1980–2099 shows that at the end of the century (under a scenario assuming further decreases in aerosol emissions), aerosol-related temperature biases exceed 2 °C for the hottest multi-day periods up to 15 days.

**Conclusion**

In this study, we have shown that regional climate models underestimate the past summer warming in Western Europe mainly for two reasons; (i) the dynamic contribution from circulation changes tends to be far weaker than suggested by the observation-derived ERA5 dataset, and (ii), most CORDEX RCMs do not capture the local thermodynamic forcing by neglecting aerosol-mediated shortwave radiation changes. The circulation changes may well be a symptom of multidecadal natural variability and hence be unforced, thus the dynamically inflicted warming discrepancy is not necessarily problematic. On the contrary, the thermodynamic biases introduced by aerosol changes (or lack thereof) is of concern, not least because the associated warming discrepancies grow even larger in climate projections towards the end of the 21st century. The IPCC has emphasized that our confidence in RCM projections depends on whether the key drivers of climate change are “well-simulated and well-projected” by the models43. Our analysis demonstrates, however, that this does not apply to a majority of the RCMs used here. This could
be problematic if not taken into account by climate services that rely on these models, since complex and regionally diverse aerosol effects on climate should not be omitted when assessing future climate risks. Compared to the RCMs that include long-term aerosol changes, the magnitude increase of heatwaves is underestimated by about 1 °C and 2 °C for 1980–2020 and 1980–2099, respectively. Even seemingly small temperature biases might distort the outcome of extreme event attribution analyses, since the probability of heatwaves tends to decrease strongly for increasing magnitude (e.g., ref. 44). Moreover, given that epidemiological studies suggest an exponential increase in heat-related mortality for the most extreme temperatures, it is crucial to estimate the future intensification of heatwaves due to human-induced climate change as accurately as possible. Only then can climate services provide reliable information to decision makers and stakeholders, and thereby contribute to adequate adaptation measures.

Data and methods

Analysis period and domain

Our main analysis is restricted to boreal summer (June–August) in 1980–2022 (or 1980-2099), and we focus on the western half (-10 °W to 15 °W) of West-Central Europe, an IPCC climate reference region, referred to WWCE hereafter. All climate variables are area-weighted when calculating regional means.

Observation-derived data

ERA5

The fifth-generation European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, ERA5, produces hourly records of the atmosphere, land surface and ocean waves by optimally merging numerical model output and observations. We use ERA5 as a reference for climate models and to estimate the dynamic and thermodynamic warming contributions, including 2-meter temperature, radiation and 500-hPa geopotential height data from 1950 to 2022 at a horizontal resolution of 0.25°.

E-OBS

The E-OBS dataset provides a 20-member ensemble of gridded daily meteorological observations across Europe. We employ ensemble mean temperatures from v27.0e on a 0.25° x 0.25° grid, covering the 1950–2022 period. Note that station data used for the interpolation from point observations to the grid are usually not homogenized (except for v19eHOM, but this version does not cover our entire analysis period), and the station density varies in time, which could affect trend analyses.
Model data

We employ regional and global climate model simulations from the EURO-CORDEX\textsuperscript{15,16} and ReKliEs-De\textsuperscript{12} projects at 0.11 degrees (EUR-11) and CMIP6 (ref. 3), respectively, listed in Tables 2–4. For the GCM–RCM model chains of EURO-CORDEX and ReKliEs-De, historical simulations supply data up to 2005, and the remaining years up to 2022 are based on the high-emission representative concentration pathway scenario (RCP8.5). The same applies to the CMIP5 simulations\textsuperscript{50} used to drive the CORDEX simulations, from which we obtain global mean temperatures to estimate the background warming. Similarly, for CMIP6, we concatenate historical and high-emission shared socioeconomic pathway simulations (SSP5-8.5) at the beginning of 2015.

Native model grids are used to calculate regional averages for all simulations with regionmask. To compare grid-cell based trends in model simulations and reanalysis, CORDEX variables are regridded to a regular 0.25° x 0.25° grid. Temperature is regridded bilinearly, all other variables are processed with a conservative regridding algorithm using xESMF.

Table 2: Driving CMIP5 GCMs of the RCMs used for analysis. GCMs with near-ERA5 1980–2022 background warming (see next subsection) are shown in bold font.

<table>
<thead>
<tr>
<th>ID</th>
<th>GCM (CMIP5)</th>
<th>Ensemble member(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CanESM2</td>
<td>r1i1p1</td>
</tr>
<tr>
<td>2</td>
<td>CNRM-CM5</td>
<td>r1i1p1</td>
</tr>
<tr>
<td>3</td>
<td>EC-EARTH</td>
<td>r1i1p1, r12i1p1</td>
</tr>
<tr>
<td>4</td>
<td>IPSL-CM5A-MR</td>
<td>r1i1p1</td>
</tr>
<tr>
<td>5</td>
<td>MIROC5</td>
<td>r1i1p1</td>
</tr>
<tr>
<td>6</td>
<td>HadGEM2-ES</td>
<td>r1i1p1</td>
</tr>
<tr>
<td>7</td>
<td>MPI-ESM-LR</td>
<td>r3i1p1</td>
</tr>
<tr>
<td>8</td>
<td>NorESM1-M</td>
<td>r1i1p1</td>
</tr>
</tbody>
</table>

Table 3: CORDEX GCM–RCM model chains used for analysis, all based on a single GCM ensemble member (usually r1i1p1) as listed in Table 2. EC-EARTH driven RCMs are driven by r1i1p1 except for CCLM4-8-17, HadREM3-GA7-05, REMO2015 and RegCM4-6, for which r12i1p1 was used (also indicated in the GCM column below). The number of available GCM–RCM model chains as well as the RCM aerosol forcing is also provided.
Table 4: CMIP6 simulations used for analysis. GCMs with ensemble members that feature near-ERA5 1980–2022 background warming (see next subsection) are shown in bold font.

<table>
<thead>
<tr>
<th>Institution</th>
<th>GCM</th>
<th>GCM (CMIP5)</th>
<th>n</th>
<th>Aerosol forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLMcom</td>
<td>CCLM4-8-17</td>
<td>(1), (2), (3_r12), (5), (6), (7), (8)</td>
<td>7</td>
<td>constant</td>
</tr>
<tr>
<td>CLMcom-ETH</td>
<td>COSMO-crCLIM-v1-1</td>
<td>(3), (6), (7)</td>
<td>3</td>
<td>constant</td>
</tr>
<tr>
<td>CNRM</td>
<td>ALADIN63</td>
<td>(2), (6), (7), (8)</td>
<td>4</td>
<td>time-evolving</td>
</tr>
<tr>
<td>DMI</td>
<td>HIRHAM5</td>
<td>(2), (3), (4), (6), (7), (8)</td>
<td>6</td>
<td>constant</td>
</tr>
<tr>
<td>GERICS</td>
<td>REMO2015</td>
<td>(1), (2), (3_r12), (4), (5), (6), (7), (8)</td>
<td>8</td>
<td>constant</td>
</tr>
<tr>
<td>ICTP</td>
<td>RegCM4-6</td>
<td>(2), (3_r12), (6), (7), (8)</td>
<td>5</td>
<td>constant</td>
</tr>
<tr>
<td>KNMI</td>
<td>RACMO22E</td>
<td>(2), (3), (4), (6), (7), (8)</td>
<td>6</td>
<td>time-evolving</td>
</tr>
<tr>
<td>MOHC</td>
<td>HadREM3-GA7-05</td>
<td>(2), (3_r12), (7), (8)</td>
<td>4</td>
<td>time-evolving</td>
</tr>
<tr>
<td>MPI-CSC</td>
<td>REMO2009</td>
<td>(7)</td>
<td>1</td>
<td>constant</td>
</tr>
<tr>
<td>SMHI</td>
<td>RCA4</td>
<td>(3), (4), (6), (7), (8)</td>
<td>5</td>
<td>constant</td>
</tr>
</tbody>
</table>

Trend estimation

All trends are determined with a linear regression, and total changes are obtained by multiplying the slope (°C / year) with the number of years between 1980 and 2022 (42 years). To additionally estimate and visualize long-term changes without any assumptions of linearity, we also apply a Locally Weighted Scatterplot Smoothing (LOWESS) algorithm using statsmodels with the smoothing width set to 31 years. To facilitate the comparison of temporally evolving climate variables from reanalysis data or observations and model simulations, we represent all data as changes with respect to 1980 after applying the smoothing algorithm. To ensure that observation-derived estimates and model output are treated consistently, we remove any data prior to 1971 (since several CORDEX simulations are only
available from then) and after 2022 before applying the LOWESS filter. The latter, unlike the widely used moving average, provides smoothed data for the entire timeseries. The sole exception to this consists of Fig. 5, for which model data is used up to 2099 to calculate smoothed timeseries and linear trends.

## Model subsets with near-ERA5 background warming

The RCMs that form our 49-member CORDEX ensemble are driven by 8 different CMIP5 GCMs, and consequently have varying degrees of background global warming. The same applies to the GCMs participating in CMIP6. To analyze only simulations with similar global mean temperature increases, we define subsets for both model ensembles; in practice, this is achieved by limiting the 1980–2022 background warming — obtained with linear regression — to 1 °C for all CORDEX simulations. This is fulfilled for 15 out of 49 ensemble members driven by two GCMs (CNRM-CM5 and NorESM1-M), and yields a mean background warming of 0.89 °C. We then select the same number of CMIP6 simulations closest to this value to obtain a subset with comparable background warming (0.84 °C). Compared to the remaining simulations, both subsets feature background warming broadly consistent with each other and ERA5 (0.81 °C). Our results and conclusions are not sensitive to these choices.

**Table 5:** As Table 3, but only listing CORDEX GCM–RCM simulations with near-ERA5 global warming since 1980. The aerosol forcing according to ref. 24 is also indicated.

<table>
<thead>
<tr>
<th>Institution</th>
<th>GCM (CMIP5)</th>
<th>RCM</th>
<th>Aerosol forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLMcom-ETH</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>COSMO-crCLIM-v1-1</td>
<td>constant</td>
</tr>
<tr>
<td>CNRM</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>ALADIN63</td>
<td>time-evolving</td>
</tr>
<tr>
<td>DMI</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>HIRHAM5</td>
<td>constant</td>
</tr>
<tr>
<td>GERICS</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>REMO2015</td>
<td>constant</td>
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<tr>
<td>ICTP</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>RegCM4-6</td>
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<tr>
<td>KNMI</td>
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<td>time-evolving</td>
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<tr>
<td>MOHC</td>
<td>CNRM-CM5, NorESM1-M</td>
<td>HadREM3-GA7-05</td>
<td>time-evolving</td>
</tr>
<tr>
<td>SMHI</td>
<td>NorESM1-M</td>
<td>RCA4</td>
<td>constant</td>
</tr>
</tbody>
</table>

## Disentangling dynamic and thermodynamic contributions to regional warming

We implemented a dynamic adjustment approach\(^{51,52}\) to disentangle the dynamic and thermodynamic contributions to the notable warming trends observed over WWCE. This approach is widely used to attribute a proportion of the variability in the target variable (here, summer mean temperature) to changes in atmospheric circulation, under the assumption that other factors remain constant.
Here, we leverage principles from statistical learning and implement a regularized ridge regression method to establish a physical relationship between the summer mean temperature and the geopotential height at 500 hPa (Z500). Our model is trained on detrended Z500 fields (on a 2.5° x 2.5° grid) and detrended regional mean summer temperatures from a 2070-year pre-industrial control simulation obtained from CESM2. We detrend Z500 by subtracting the daily Z500 average over the circulation domain [30°W – 35°E, 22°N – 72°N] from the daily Z500 at each grid cell and at each time step across the domain. This is done to remove the effect of thermal expansion of the troposphere primarily caused by anthropogenically forced global warming on Z500. Nonetheless, it is important to note that changes in atmospheric circulation are not solely influenced by natural variability. External forcing can also potentially contribute to shaping these circulation patterns, which in turn can have effects on near-surface temperatures.

Note that we train our model on pre-industrial control instead of transient climate simulations to avoid the possibility of the regression model erroneously learning from forced warming signals.

We employ the following equation to isolate the circulation-induced component of summer mean temperatures,

\[ t_n = f(m_{n \times p}) \]

where, \( t_n \) represents summer mean temperature, \( n \) is the number of years, \( m \) is a matrix of detrended Z500 with dimensions \( n \times p \) (\( p \) is the number of grid cells within the circulation domain), and \( f \) denotes a regularized ridge regression model. During the training phase on the control run, a k-fold cross-validation scheme is employed to fine-tune the regression model and prevent overfitting. The temperatures predicted (\( \hat{t} \)) by this model represent the circulation-induced components, while the residuals (\( t - \hat{t} \)) capture the externally forced thermodynamic signal in summer mean temperatures.

Finally, we provide the fitted model with summer averages of WWCE temperatures and Z500 fields from ERA5 as well as the CORDEX RCM and CMIP6 GCM simulations to estimate the respective dynamical contributions to the regional warming. This approach of calibrating to a single (typically long pre-industrial control) simulation, and then applying the fitted model to other (transient) simulation ensembles and/or reanalysis data has been extensively tested. We also include 89 members covering the period 1850–2100 from the CESM2 Large Ensemble (CESM2-LE; ref. 54), each branched from the same pre-industrial control run as we employ to train the regression model, but with unique initial conditions. Since this ensemble is based on a single model, we do not consider it in our main analysis, but still display the results in SFig. 1.

Declarations

Author contributions
DLS and JS processed the data, and MH provided the tools to post-process CMIP6 output. DLS and JS conducted the main analysis, and DLS created the figures. DLS, JS, MH, EMF and SIS designed the study. All authors wrote the manuscript. SIS and EMF conceived the study.

Acknowledgments

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References


33. Vautard, R. et al. Heat extremes in Western Europe are increasing faster than simulated due to missed atmospheric circulation trends. *Preprint*, https://hal.science/hal-03937057v2 (2023)  


**Method references**


**Figures**
Summer warming in Europe underestimated by global and regional climate simulations. a Total change in summer mean 2m-temperature (1980–2022) estimated from a linear regression for ERA5, and b, the difference of the median warming obtained for a 49-member CORDEX ensemble and ERA5. In both a.) and b.), the analysis region — the western half of West–Central Europe (WWCE) — is delineated by a black contour. For this domain, c and d depict smoothed regional average summer temperatures over land, comparing ERA5 (black line) to CORDEX and CMIP6 simulations (colored range and lines), respectively. All timeseries are represented by 31-year moving regressions to suppress high-frequency variability, and indicate changes with respect to 1980 (detailed in Methods). e 1980–2022 seasonal and annual mean warming estimated with a linear regression, using model data (purple: CORDEX RCMs, green: CMIP6 GCMs), reanalysis (ERA5, dark gray) and gridded observations (E-OBS, light gray).
Simulations with near-actual background global warming largely underestimate the concurrent WWCE summer temperature increase. **a** Linear trends in WWCE JJA temperature and background global warming for 1980-2022 in ERA5 (black star), CORDEX and CMIP6 simulations (purple and green dots, respectively). CORDEX simulations driven by the two GCMs with global warming rates closest to ERA5 have black edges (n=15). Similarly, the same number of CMIP6 experiments most consistent with the background warming as those highlighted CORDEX simulations (which, on average, is slightly higher than ERA5 at ~0.9 °C) is selected for further analysis, and the corresponding simulations are marked. **b** WWCE summer temperature for ERA5, CORDEX and CMIP6 simulations as in Fig. 1c–d, but restricted to the model subsets highlighted in a. with black dots. **c** As (b), but showing the summer mean surface net radiation for WWCE.
Figure 3

**Disentangling the dynamic and thermodynamic drivers of summertime warming in WWCE.**

**a** Schematic representation of our analysis region, western Central Europe, and the drivers of regional warming, depicting: the (human-induced) global mean temperature increase that provides a ‘background’ warming to the region, the presence of a regional thermodynamic forcing (primarily due to increasing net radiation) and the resulting warming response, and dynamic changes. **b** Total 1980-2022 summer warming for the RCM and GCM subsets from Fig. 2 with near-observed background warming, and ERA5 (black marker). The warming is gauged with linear trends and expressed as temperature change across the whole period, and per decade (secondary vertical axis). **c** Dynamic contribution to the WWCE summer temperature trend. **d** Total thermodynamic contribution to the WWCE summer temperature trend, enabled by both background global warming and regional thermodynamic forcing.
Figure 4

Constant aerosol forcing in CORDEX RCM simulations leads to underestimated net radiation increases, introducing a thermodynamic warming bias. a Changes in net radiation and regional thermodynamic warming in WWCE for the 18 CORDEX simulations driven by the 2 GCMs whose global warming rates are closest to ERA5 (as in Fig. 2c–d). The markers indicate whether the respective RCM includes time-evolving or constant/no aerosols (blue dots and red squares, respectively). b Changes in net radiation and its drivers for reanalysis and model data, again grouping CORDEX simulations according to aerosol representation. c Mean difference in 1980–2022 downward shortwave radiation trends between the two subgroups by aerosol representation from (a), indicating the impact of long-term aerosol emission reductions compared to RCM simulations with temporally constant aerosol forcing. d As (c), but for near-surface temperature trends.
Figure 5

The thermodynamic bias inflicted by constant aerosol forcing increases throughout the ongoing century and emerges even more clearly at the timescale of heatwaves.

a Long-term temperature changes since 1980 for ERA5 and the CORDEX subset, again grouped according to aerosol representation. Additionally, the thermodynamic warming obtained through dynamical adjustment is shown for the 1980-2022 period (dashed lines). The year in which ERA5’s current thermodynamic warming is reached by the respective ensemble means is also indicated. The boxplots for both CORDEX model groups are calculated for the long-term change up to the year 2099. b Linear trends of the hottest n-day periods in each year between 1980–2022 and 1980–2099 in the upper and lower panel for ERA5 and the RCM simulations.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Schumacheretal2023SI.docx