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Mitigation Benefits and Drivers of Compound Hot–Dry Events under the SSP2-com Scenario

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Climate Dynamics

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Abstract

Compound hot–dry events (CHDEs) pose increasing risks to ecosystems and socioeconomic systems, yet their responses to policy-informed mitigation pathways remain poorly understood. The SSP2-com scenario incorporates updated Nationally Determined Contributions and carbon-neutrality pledges, providing an opportunity to assess how mitigation alters future CHDE risk relative to CMIP6 SSP2-4.5 scenario. Here, we compare projected CHDE frequency and cumulative intensity under the two scenarios and investigate the drivers and physical processes underlying their differences. Under SSP2-com, global land-mean CHDE frequency reaches about twice its historical level by mid-century, while cumulative intensity increases by 33.9%; thereafter, both metrics stabilize, increasing by only 1% and 4%, respectively, from mid- to late century. Differences from SSP2-4.5 remain small and regionally mixed at mid-century but become widespread by late century, when the global land-area-weighted median differences in frequency and cumulative intensity reach -2.9 days yr^{-1} and -5.5% , respectively. The CHDE–temperature relationship also differs between the two pathways, indicating that their late-century divergence cannot be explained by warming magnitude alone. Likelihood Multiplication Factor decomposition shows that mean temperature dominates the overall increase in CHDE risk, whereas precipitation variability and heat–drought dependence increasingly distinguish the two scenarios. These results highlight that future CHDE risk depends on both warming magnitude and the mitigation pathway.

Keywords: Compound hot–dry events; SSP2-com scenario; climate mitigation; heat–drought dependence

1. Introduction

Climate warming is reshaping not only individual extremes but also their interactions, increasing the risk of compound climate extremes (Zscheischler et al. 2018, 2020). When multiple hazard drivers occur simultaneously or sequentially, their interactions can amplify the resulting impacts, which often exceed those associated with individual hazards occurring in isolation (Leonard et al. 2014; Zscheischler and Seneviratne 2017; Ridder et al. 2020). Among these events, compound hot–dry events (CHDEs), characterized by the concurrent occurrence of high temperatures and water deficits (Hao et al. 2022), are of particular concern because heat and dryness can reinforce each other and substantially intensify climate-related impacts. CHDEs have been shown to increase vegetation stress (Zhang et al. 2024; Liu et al. 2025), reduce agricultural productivity (Chen et al. 2019; Lian et al. 2025), enhance wildfire risk (Sutanto et al. 2020; Fan et al. 2023), and weaken terrestrial carbon uptake (Song et al. 2024). Understanding how CHDEs will change under future warming is therefore critical for assessing climate risk, particularly because their impacts can be substantially greater than those of heatwaves or droughts occurring independently.

Future CHDE risk is strongly scenario dependent. As warming increases, CMIP5 and CMIP6 ensembles consistently project more frequent, persistent, and intense CHDEs (Wu et al. 2021; Meng et al. 2022; Jha et al. 2023; Tripathy et al. 2023). Lower warming constrains, but does not eliminate, this intensification. SSP2-4.5 scenario (hereafter referred to as SSP2-4.5) produces smaller increases in CHDE frequency, duration, and severity than SSP5-8.5 scenario, while limiting warming to 1.5°C rather than 2°C markedly reduces CHDE risk across many land regions (Pan et al. 2023; Tripathy et al. 2023). Yet elevated risks persist in regions such as the Mediterranean, southern Africa, and the Tibetan Plateau even under lower-forcing scenarios (De Luca and Donat 2023; Hosseinzadehtalaei et al. 2024). Meanwhile, evolving mitigation commitments have motivated emission pathways beyond the original CMIP6 scenario

framework (Venmans and Carr 2024; Scafetta 2024; Hausfather 2025; Su et al. 2026). Many previous CHDE projections have focused on standard CMIP6 pathways, including SSP2-4.5 and SSP5-8.5 scenario (De Luca and Donat 2023; Yao et al. 2024). Developed before many subsequent updates to Nationally Determined Contributions (NDCs) and carbon-neutrality pledges, these pathways do not explicitly incorporate these later commitments (O'Neill et al. 2016; Tebaldi et al. 2021; Zhong et al. 2025). This motivates the need to assess CHDE risk under pathways that incorporate more recent mitigation commitments.

Against this background, the recently developed SSP2-com scenario (hereafter referred to as SSP2-com) provides a pathway for assessing climate risks under updated mitigation commitments. Built on SSP2, it incorporates updated Nationally Determined Contributions (NDCs), carbon-neutrality pledges from major economies, and recent emission inventories, targeting a near-2 °C warming pathway by the end of the twenty-first century (Zhong et al. 2025). Available SSP2-com simulations show a consistent large-scale response: global warming continues through mid-century but slows markedly thereafter, with late-century warming stabilizing around 2 °C (Lu et al. 2025; Lei et al. 2026). However, whether this mitigation pathway translates into lower CHDE risk remains unclear.

SSP2-4.5 provides a natural reference for evaluating this question. SSP2-4.5 is an intermediate CMIP6 pathway from the “middle-of-the-road” SSP2 socioeconomic family (O'Neill et al. 2016; Fricko et al. 2017), with a nominal radiative forcing of 4.5 W m⁻² by 2100 (Meinshausen et al. 2020). Recent assessments suggest that emissions trajectories substantially above those implied by current policies or below those consistent with current pledges are less likely, while current-policy estimates generally lie close to or slightly below SSP2-4.5 (Venmans and Carr 2024; Hausfather 2025). Because SSP2-com and SSP2-4.5 share the same SSP2 socioeconomic background, their comparison provides a consistent basis for examining the climate implications of

their diverging mitigation trajectories. The two pathways remain broadly similar in warming until around mid-century but diverge thereafter, with substantially lower late-century warming under SSP2-com (Zhong et al. 2025). This temporal divergence provides a clear framework for assessing when and where stronger mitigation begins to reduce CHDE risk.

Here, we use simulations from multiple Earth system models to investigate twenty-first-century changes in CHDEs under SSP2-com and compare them with those under SSP2-4.5. We address three questions: (1) How do the frequency and cumulative intensity of CHDEs evolve under SSP2-com? (2) When, where, and by how much does SSP2-com reduce CHDE risk relative to SSP2-4.5? (3) What climatic factors and physical processes govern the magnitude and regional pattern of these mitigation benefits? The remainder of the paper is organized as follows. Section 2 describes the data and methods. Section 3 presents the main results. Section 4 presents the discussion and conclusions.

2. Data and Methods

2.1 Model simulations and data

We use simulations from multiple Earth system models (ESMs) to assess twenty-first-century changes in CHDEs under SSP2-com and compare them with SSP2-4.5 (O'Neill et al. 2016; Zhong et al. 2025). The comparison quantifies when and by how much the SSP2-com pathway reduces future CHDE risk. Changes under both scenarios are evaluated relative to the 1980–2009 climatology from the corresponding CMIP6 historical simulations (Eyring et al. 2016).

SSP2-com follows the SSP2 socioeconomic pathway and incorporates updated emissions inventories and mitigation commitments into its emissions trajectory. Emissions follow existing commitments through 2030 and subsequently decline toward

global net-zero CO₂ emissions around 2070 (Zhang et al. 2025). Atmospheric CO₂ concentrations therefore peak around mid-century and decline thereafter, producing a progressively lower radiative forcing than SSP2-4.5 during the second half of the century (Zhang et al. 2025; Zhong et al. 2025; Lu et al. 2025; Lei et al. 2026).

Daily SSP2-com simulations are available from four Earth system models: BCC-ESM1 (Lu et al. 2025), CESM2 (Lei et al. 2026), FGOALS-f3-L, and NESM3, with 1, 3, 3, and 5 ensemble members, respectively. For models with multiple members, we first calculate the ensemble mean and then construct an equally weighted multi-model mean (MMM), giving each model the same weight. Given the small model ensemble, we assess robustness using inter-model agreement rather than conventional significance testing. A projected change is considered robust where all four models agree on its sign. We further test the sensitivity to the equal-model-weighting assumption by treating all ensemble members as independent realizations and comparing the resulting member-weighted estimates with the MMM.

To quantify the mitigation benefits of SSP2-com, we compare it with SSP2-4.5 using matched ensemble members. Of the four SSP2-com models, only CESM2 and NESM3 provide corresponding SSP2-4.5 simulations, so the comparison is restricted to these two models. Matching historical and scenario members minimizes differences associated with ensemble sampling. We assess the representativeness of this two-model sample against an independent ensemble of 18 CMIP6 models under SSP2-4.5. CESM2 and NESM3 are compared with the broader ensemble distribution of projected CHDE changes to evaluate whether they reproduce the overall CMIP6 response. The models are listed in Table 1.

Table 1. CMIP6 models used for the historical and SSP2-4.5 simulations.

Model	Institute/Country
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ACCESS-CM2	CSIRO-BOM/Australia
ACCESS-ESM1-5	CSIRO/Australia
BCC-CSM2-MR	BCC-CMA/China
CanESM5	CCCMA/Canada
CESM2	NCAR/USA
CMCC-ESM2	CMCC/Italy
CNRM-CM6-1	CNRM-CERFACS/France
EC-Earth3	EC-Earth-Consortium/EU
FGOALS-g3	LASG-IAP/China
GFDL-ESM4	GFDL-NOAA/USA
INM-CM5-0	INM/Russia
IPSL-CM6A-LR	IPSL/France
MIROC6	MIROC/Japan
MPI-ESM1-2-LR	MPI-M/Germany
NESM3	NUIST/China
NorESM2-LM	NCC/Norway
TaiESM1	AS-RCEC/Taiwan, China
UKESM1-0-LL	MOHC/UK

155

156 We analyze daily near-surface air temperature (tas), precipitation (pr), total cloud
157 cover (clt), surface downward shortwave radiation (rsds), latent heat flux (hfls), and
158 sensible heat flux (hfss). All models contribute to the analysis of projected CHDE
159 changes, while land–atmosphere feedback is examined primarily using NESM3, which
160 provides all required surface radiative and turbulent variables. Future changes are
161 expressed relative to the baseline period. All outputs are bilinearly regirded to a
162 common $1^\circ \times 1^\circ$ latitude–longitude grid before inter-model comparison.

2.2 Definition of CHDEs

CHDEs are defined as the concurrent occurrence of hot and dry extremes on a daily timescale. At each grid cell, the warm season is defined as the three consecutive months with the highest climatological mean temperature. Hot extremes are identified using a calendar-day percentile approach. For each calendar day, temperatures within a 7-day moving window (± 3 days) are pooled across all years of the baseline period to construct the reference distribution. Daily temperature is then expressed as its percentile rank within the corresponding distribution, accounting for the local seasonal cycle. Dry extremes are identified from 30-day accumulated precipitation using the same percentile framework. Accumulated precipitation is multiplied by -1 so that larger values represent drier conditions, and its percentile rank is calculated relative to the corresponding calendar-day distribution over the baseline period. Hot and dry extremes are defined when their respective percentile ranks exceed the 75th percentile. A CHDE occurs when both thresholds are exceeded simultaneously for at least three consecutive days.

We characterize CHDEs using two metrics. Frequency is the annual number of CHDE days (days yr^{-1}), whereas cumulative intensity is the annual sum of daily CHDE intensity. Daily intensity is defined as the product of standardized temperature and standardized dryness, with dryness represented by sign-reversed 30-day accumulated precipitation. Cumulative intensity therefore captures both event persistence and the magnitude of the concurrent hot and dry anomalies.

2.3 Attribution framework for changes in joint probability

To quantify the drivers of projected CHDE changes, we apply the joint-probability decomposition framework of Li et al. (2024). Temperature and drought are expressed as right-tail extremes, with drought represented by sign-reversed 30-day accumulated

precipitation, and their joint distribution is described using a Gaussian copula. Changes in CHDE probability are then decomposed into contributions from the mean and variability of each marginal distribution and from changes in heat–drought dependence. The decomposition therefore separates five components: heat mean, drought mean, heat variability, drought variability, and heat–drought dependence.

Let X denote daily mean temperature and Y sign-reversed 30-day accumulated precipitation. The historical CHDE probability is defined as the joint exceedance probability of their respective thresholds:

$$P_{his} = P_{his}(u > u_{his}, v > v_{his}) = 1 - u_{his} - v_{his} + C_{his}(u_{his}, v_{his}) \quad (1)$$

where P_{his} denotes the historical CHDE probability, C_{his} the copula describing historical heat–drought dependence, u_{his} and v_{his} the thresholds for hot and dry extremes, respectively. The future CHDE probability, P_{fut} , is defined analogously using the corresponding future marginal distributions and dependence structure.

To quantify the relative change in CHDE likelihood, we use the likelihood multiplication factor (LMF), defined as the ratio of future to historical CHDE probability:

$$LMF = \frac{P_{fut}}{P_{his}} \quad (2)$$

An LMF greater than 1 indicates an increase in CHDE likelihood relative to the historical climate, whereas an LMF below 1 indicates a decrease.

To attribute changes in CHDE likelihood to changes in the marginal distributions and their dependence, we use a sequential replacement approach. Historical temperature and drought variability are first replaced with their future values while holding the means and dependence fixed. The mean states are then updated, followed by the heat–drought dependence with the marginal distributions held fixed. This yields five contributions: heat mean, drought mean, heat variability, drought variability, and

214 heat–drought dependence. In logarithmic space,

$$\begin{aligned} 215 \quad \log(LMF) &\approx \log(LMF_{pr-m}) + \log(LMF_{tas-m}) + \log(LMF_{pr-v}) \\ 216 \quad &+ \log(LMF_{tas-v}) + \log(LMF_{dep}) \end{aligned}$$

217 Here, LMF_{tas-m} and LMF_{pr-m} represent the contributions from changes in
218 temperature and drought mean states, LMF_{tas-v} and LMF_{pr-v} those from changes in
219 variability, and LMF_{dep} the contribution from changes in heat–drought dependence.

220 By calculating these individual components, the relative importance of different
221 factors in driving changes in CHDE risk can be quantitatively assessed, thereby
222 providing insights into the dominant mechanisms governing CHDE changes under
223 realistic mitigation pathways.

224

225 **2.4 Spatial aggregation analysis**

226 Following Fischer and Knutti (2014), we characterize the large-scale CHDE
227 response using area-weighted spatial aggregation. Grid-cell changes in CHDE
228 frequency and cumulative intensity are aggregated over global land and selected
229 hotspot regions. Spatial heterogeneity is further described using area-weighted
230 probability density functions estimated with Gaussian kernel density estimation, with
231 bandwidth selected using Silverman’s rule. The PDFs represent the fraction of land area
232 experiencing a given magnitude of change. Multi-model means are derived from the
233 four ESMs, with inter-model spread represented by the 25th–75th percentile range.
234 Area-weighted medians and the fraction of land area showing increases provide
235 additional measures of the overall response.

236

3. Results

3.1 Late-century emergence of CHDE mitigation benefits under SSP2-com

Under SSP2-com, CHDE risk increases strongly through mid-century before diverging markedly across regions later in the century (Fig. 1). At mid-century, CHDE frequency and cumulative intensity increase across most global land areas and exhibit broadly consistent spatial patterns, with the largest changes in the tropics, Central Asia, and the Mediterranean. Northern South America and northern Africa show particularly large increases, with frequency reaching nearly five times the historical level and cumulative intensity increasing by more than 150%. Central Asia shows similarly pronounced changes, with frequency reaching 2–4 times the historical level and cumulative intensity increasing by more than 120% (Fig. 1a, c). Later in the century, further CHDE intensification weakens across many land areas and becomes increasingly region dependent. Relative to 2040–2060, CHDE frequency declines to 0.75–1.0 times the mid-century level over Central North America and Central Asia (Fig. 1b), while cumulative intensity decreases by approximately 30–50% in these regions (Fig. 1d). In contrast, both metrics continue to increase over the Tibetan Plateau (Fig. 1b, d). These projected changes are robust across models and ensemble treatments. Individual models and their ensemble members reproduce similar spatial patterns (Fig. S1–S8). These results indicate that the mitigation signal under SSP2-com emerges mainly after mid-century, suppressing or reversing further CHDE intensification across many regions while remaining strongly region dependent.

To further clarify the specific evolution characteristics of CHDES changes with emissions, we examine the timeseries of CHDE frequency and cumulative intensity. Global land-mean CHDE frequency and cumulative intensity increase steadily until around 2060, after which both metrics stabilize and decline slightly (Fig. 1e–f). The equally weighted multi-model mean closely agrees with the estimate obtained across all ensemble members, indicating that this temporal evolution is insensitive to the

ensemble-weighting approach (Fig. 1e–f). The delayed reversal shows that the mitigation signal in CHDE risk emerges only gradually after mid-century.

Northern South America (NSA), the Mediterranean (MED), and the Tibetan Plateau (TIB) are selected for regional analysis because they show high CHDE risk under SSP2-4.5 but contrasting responses under SSP2-com (De Luca and Donat 2023; Tabari and Willems 2023). Their contrasting behavior provides a useful test of the regional heterogeneity of mitigation benefits. Regional boundaries follow the IPCC AR6 classification (Iturbide et al. 2020).

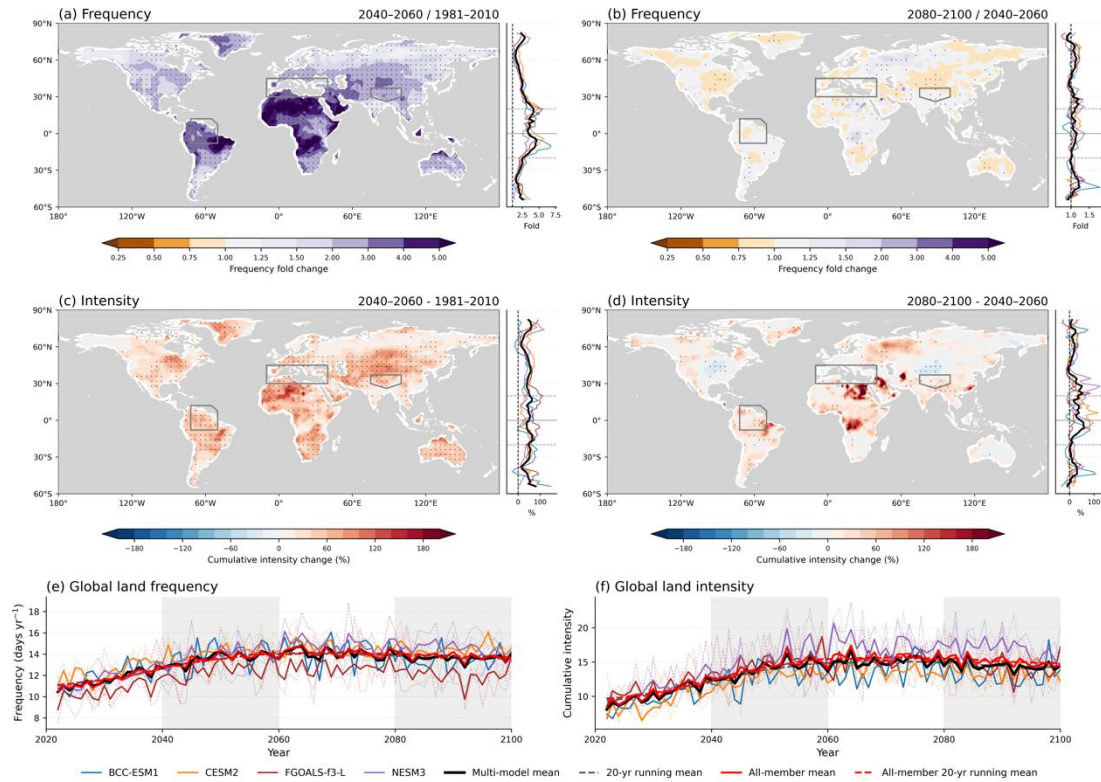


Fig.1 Projected changes in the frequency and cumulative intensity of CHDEs under the SSP2-com. (a) Ratio of CHDE frequency in 2040–2060 to that in the historical period (1980–2009). (b) Ratio of CHDE frequency in 2080–2100 to that in 2040–2060. (c) Percentage change in cumulative intensity during 2040–2060 relative to the historical period. (d) Percentage changes in cumulative intensity during 2080–2100 relative to 2040–2060. Dashed boxes mark the three focus regions

(NSA, MED and TIB), defined following the IPCC AR6 regional classification. Line plots to the right of a–d show the corresponding zonal-mean changes. (e) and (f) Temporal evolution of global land-mean CHDE frequency and cumulative intensity, respectively. Colored solid lines show the ensemble mean for each model, with blue, orange, brown and purple denoting BCC-ESM1, CESM, FGOALS-f3-L and NESM3, respectively; thin colored dashed lines show individual ensemble members. The black solid line denotes the multi-model ensemble mean (MME), calculated by equally weighting each model, and the red solid line denotes the mean across all ensemble members. Corresponding dashed lines show 20-year running means. Grey shading marks the mid-century (2040–2060) and late-century (2080–2100) periods analyzed in this study.

Spatial aggregation reveals a widespread shift toward higher CHDE risk by mid-century, followed by increasingly divergent regional trajectories later in the century (Fig. 2). Relative to the historical period, the area-weighted distributions of both CHDE frequency and cumulative intensity shift markedly toward higher values across global land and all three selected regions during 2040–2060. Globally, CHDE frequency reaches twice its historical level and cumulative intensity increases by 33.9%, with increases affecting 91.2% and 74.4% of global land area, respectively (Fig. 2a-b). Regional increases are even larger in frequency, reaching 2.20, 3.18, and 2.88 times the historical level over the TIB, NSA, and MED, respectively (Fig. 2c, e, g), while cumulative intensity increases by 32.9%, 35.6%, and 47.5% (Fig. 2d, f, h). The MED combines a large regional-mean increase with a particularly widespread spatial response, with frequency and cumulative intensity increasing over 95.9% and 88.4% of the region, respectively (Fig. 2g-h). By late century, the widespread mid-century increase gives way to near-stabilization globally but marked regional divergence. Relative to 2040–2060, global land-mean CHDE frequency and cumulative intensity increase by only 1% and 4%, respectively. The MED shows a partial reversal, with more than half of the region experiencing decreases in both metrics and regional-mean

frequency and cumulative intensity declining by 4.0% and 0.6%, respectively (Fig. 2g-h). In contrast, cumulative intensity continues to rise over the TIB and NSA by 9.2% and 20.3%, respectively, despite little further increase in frequency (Fig. 2c-f). These results reveal a broad spatial expansion of CHDE risk by mid-century, followed by increasingly heterogeneous regional responses toward the end of the century.

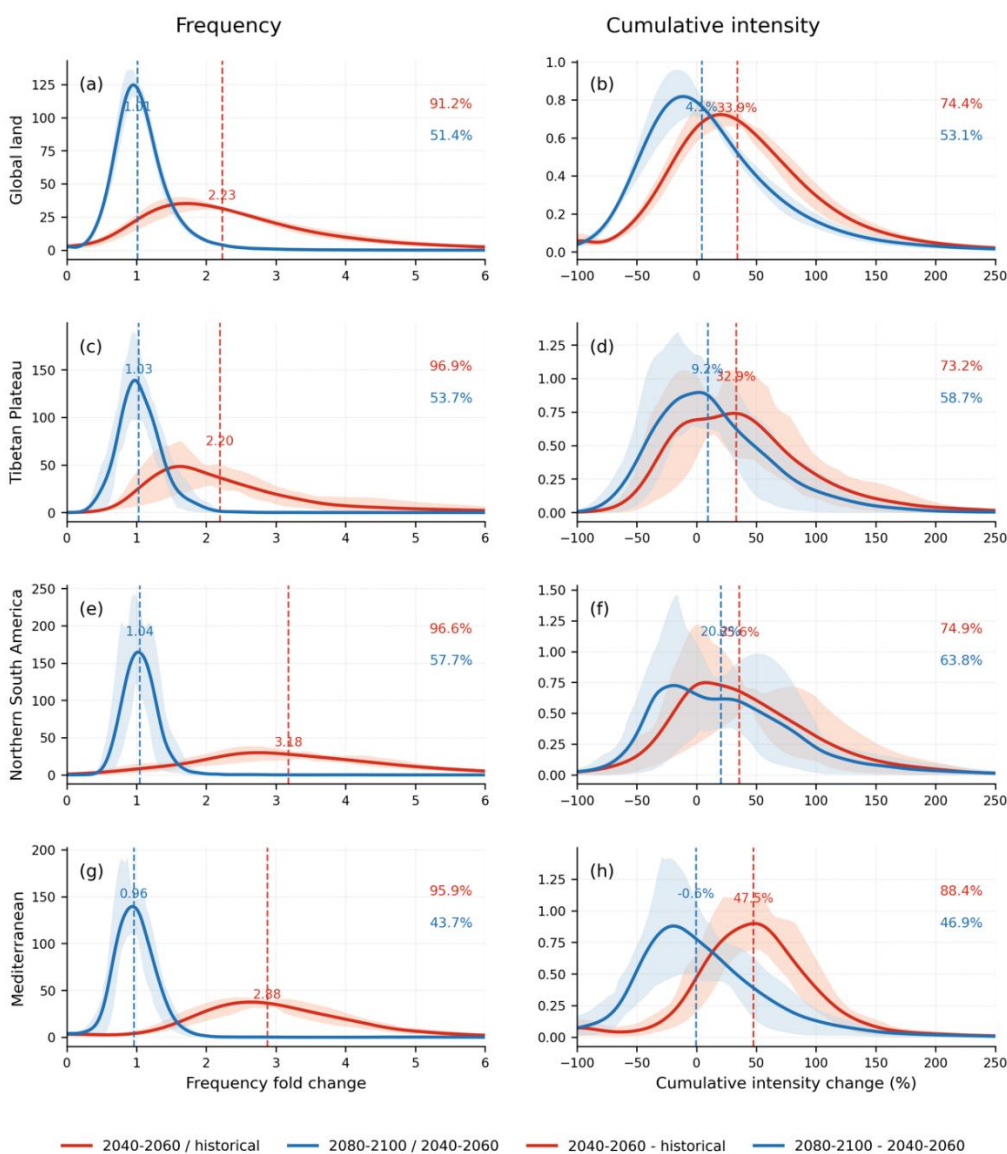


Fig. 2 Spatially aggregated probability density functions (PDFs) of projected changes in CHDE frequency and cumulative intensity under SSP2-com. (a), (c), (e), and (g) Area-weighted PDFs of changes in CHDE frequency, expressed as ratios relative to the corresponding reference

period. (b), (d), (f), and (h), Corresponding PDFs of changes in cumulative intensity (%). Results are shown for global land, TIB, NSA and MED, respectively. Red curves denote changes in 2040–2060 relative to the historical period (1980–2009), whereas blue curves denote changes in 2080–2100 relative to 2040–2060. Solid lines show the multi-model ensemble mean, and shading indicates the inter-model spread defined by the 25th–75th percentile range. Vertical dashed lines mark the area-weighted median changes, with values labelled. Percentages in each panel indicate the fraction of land area with increased CHDE frequency (ratio > 1) or cumulative intensity (change > 0).

3.2 Mitigation benefits and pathway dependence of CHDEs

To determine when and where SSP2-com mitigates CHDE risk relative to CMIP6 SSP2-4.5, we compare the spatial differences in CHDE frequency and cumulative intensity between the two scenarios (Fig. 3a-d). By mid-century, we find only weak and regionally mixed mitigation signals. SSP2-com results in fewer CHDE days across much of the Northern Hemisphere mid-latitudes, but more CHDEs over eastern Australia, India, and parts of tropical Africa and South America (Fig. 3a). We also find slightly higher cumulative intensity under SSP2-com across much of the tropics and Southern Hemisphere (Fig. 3c). Till late century, the response becomes much more spatially coherent: SSP2-com yields fewer CHDEs and lower cumulative intensity across most global land areas (Fig. 3b, d). The reduction in frequency exceeds 15 days yr^{-1} over the Mediterranean and reaches approximately 10–13 days yr^{-1} over Central Asia (Fig. 3b). Regional averages over NSA, TIB, and MED show the same transition from mixed responses at mid-century to consistent reductions by late century (Fig. 3g-h). These spatial patterns show that the mitigation benefits of SSP2-com are limited at mid-century but become widespread by the late twenty-first century.

We next aggregate the scenario differences over global land to quantify the overall strength of this mitigation signal (Fig. 3e, f). At mid-century, the distribution of frequency differences remains centered near zero, with an area-weighted median of

343 $-0.3 \text{ days yr}^{-1}$, while the median difference in cumulative intensity is $+1.4\%$. These
344 values confirm that SSP2-com provides little global-scale mitigation during this period.
345 By late century, both distributions shift clearly toward negative values, with median
346 differences of $-2.9 \text{ days yr}^{-1}$ in frequency and -5.5% in cumulative intensity. Although
347 the broad distributions indicate substantial regional heterogeneity, the overall negative
348 shift demonstrates a widespread reduction in CHDE risk under SSP2-com. The
349 aggregated results therefore confirm the spatial patterns: the mitigation signal remains
350 weak at mid-century but becomes substantial and globally coherent by late century.

351 Because only two models provide simulations for both SSP2-com and SSP2-4.5,
352 we further examine whether the SSP2-4.5 reference projection is strongly model
353 dependent using a broader multi-model ensemble (Fig. S9). All available models
354 project increasing CHDE frequency and cumulative intensity over time, indicating a
355 consistent CHDE response under SSP2-4.5 across models. This agreement supports the
356 robustness of the SSP2-4.5 reference projection, although uncertainty remains in the
357 magnitude of the SSP2-com–SSP2-4.5 differences.

358

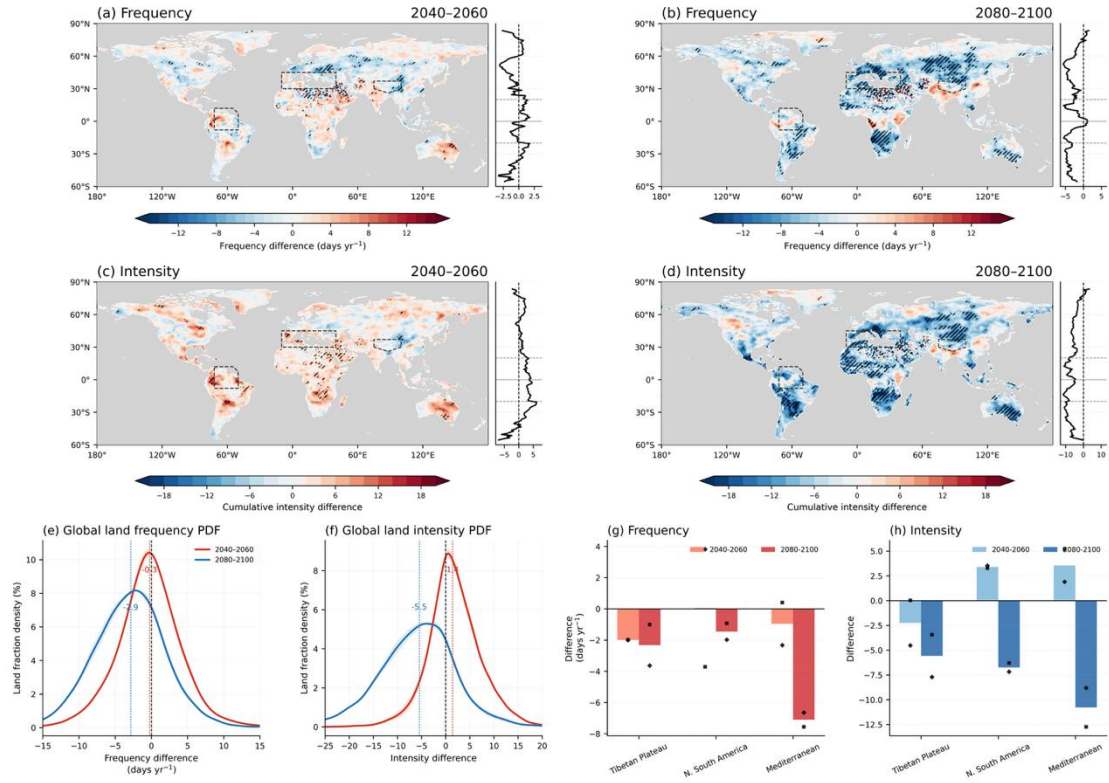


Fig. 3 Differences in CHDE frequency and cumulative intensity between the SSP2-com and SSP2-4.5. (a), (b), Multi-model ensemble mean differences in CHDE frequency (days yr^{-1}) during the mid- (2040–2060) and late twenty-first century (2080–2100), respectively. (c) and (d), Corresponding differences in cumulative intensity. Positive values indicate higher CHDE risk under SSP2-com, whereas negative values indicate lower risk than under SSP2-4.5. Stippling marks regions where all models agree on the sign of the difference, and black hatching denotes regions where the differences pass the statistical significance test. Dashed boxes mark the regions analysed in this study. Line plots to the right of a–d show the corresponding zonal-mean differences over land. (e) and (f), Area-weighted probability density functions (PDFs) of differences in CHDE frequency and cumulative intensity over global land, respectively. Solid lines show the multi-model ensemble mean, and vertical dotted lines mark the area-weighted median differences. Red and blue curves denote the mid-century and late-century periods, respectively. (g) and (h), Area-weighted regional mean differences in CHDE frequency and cumulative intensity over TIB, NSA and MED. Bars show the multi-model ensemble mean, and symbols denote individual model results.

375

376 To determine whether the differences in CHDE risk between SSP2-com and SSP2-
377 4.5 arise solely from different warming levels or also depend on the mitigation pathway,
378 we examine the sensitivity of CHDEs to global land mean temperature (Fig. 4). Under
379 SSP2-com, we find a marked change in temperature sensitivity between the warming
380 and stabilization phases (Fig. 4a-b). During 2031–2060, when global land temperature
381 continues to rise, CHDE frequency and cumulative intensity increase at 3.90 days yr⁻¹
382 K⁻¹ and 7.37-unit K⁻¹, respectively. During 2070–2100, however, global land
383 temperature stabilizes and slightly declines ($\Delta T = -0.08^\circ\text{C}$), while the temperature
384 sensitivities of CHDE frequency and cumulative intensity increase to 8.19 days yr⁻¹ K⁻¹
385 and 14.05-unit K⁻¹, approximately twice their mid-century values. Thus, the CHDE–
386 temperature relationship under SSP2-com changes substantially once warming
387 approaches stabilization, indicating that CHDE responses are not controlled by
388 warming magnitude alone.

389 We then compare this behavior with the continuously warming SSP2-4.5 (Fig. 4c-
390 d). Under SSP2-4.5, the sensitivity of CHDE frequency remains nearly unchanged, at
391 3.80 days yr⁻¹ K⁻¹ during 2031–2060 and 3.64 days yr⁻¹ K⁻¹ during 2070–2100,
392 indicating an approximately linear increase in frequency with continued warming. In
393 contrast, the sensitivity of cumulative intensity increases from 6.12 to 11.18 unit K⁻¹,
394 suggesting that continued warming has a stronger effect on CHDE intensity than on
395 frequency. These results show that the response of CHDEs is not determined by
396 warming magnitude alone but also depends on the mitigation pathway, with the
397 strongest divergence emerging as warming stabilizes under SSP2-com. This pathway
398 dependence motivates a further examination of the climatic drivers underlying the
399 contrasting CHDE responses.

400

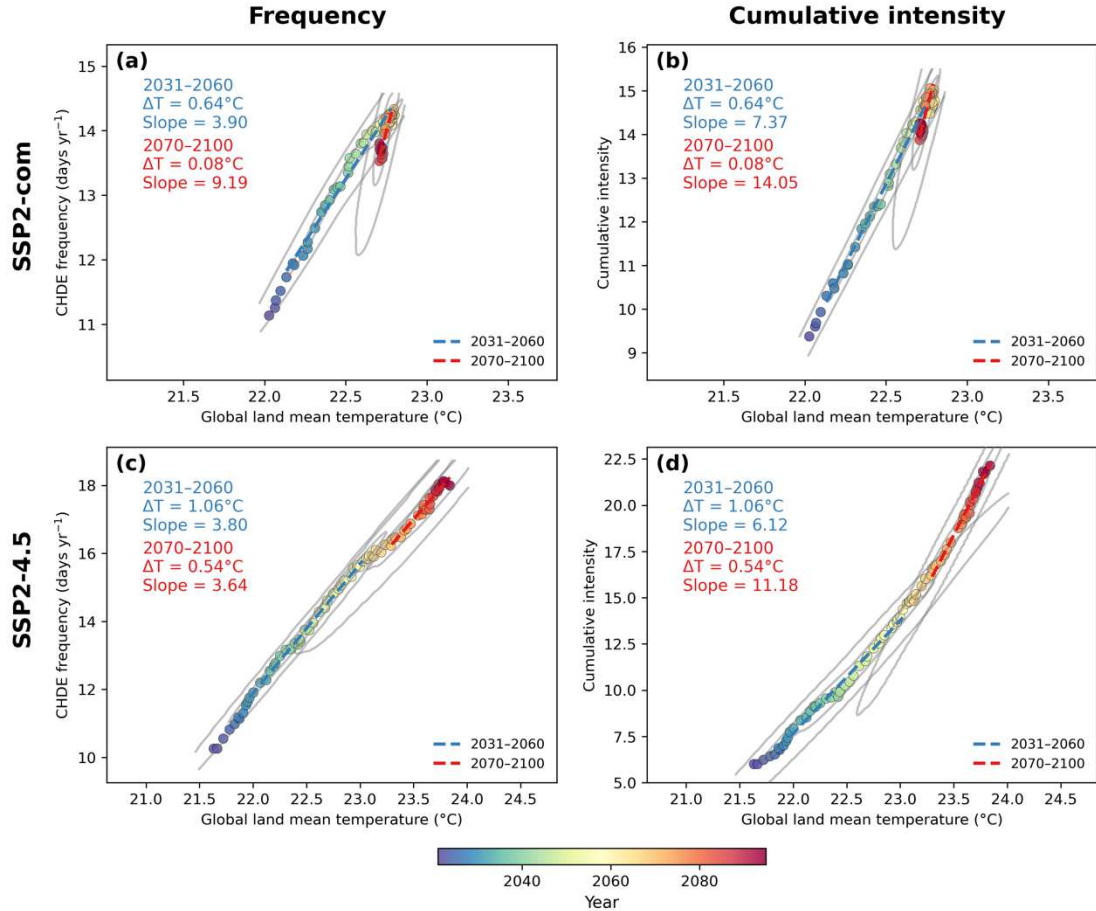


Fig. 4 Response of global land mean CHDE frequency and cumulative intensity to warming under SSP2-com and SSP2-4.5. (a) and (b) , Relationships of global land-mean temperature with CHDE frequency and cumulative intensity under SSP2-com, respectively. (c) and (d), Corresponding relationships under SSP2-4.5. Coloured dots show 11-year running means of annual multi-model ensemble mean (MME) values, with colour indicating year. Grey contours show the joint probability density estimated using nonparametric kernel density estimation. Dashed lines indicate linear regressions for the mid-century (2031–2060; blue) and late-century (2070–2100; red) periods. The corresponding temperature changes (ΔT) and regression slopes are shown in each panel. Columns represent CHDE frequency and cumulative intensity, and rows represent the two scenarios. Differences in regression slopes between the two periods indicate changes in the temperature sensitivity of CHDEs under different mitigation pathways.

3.3 Drivers and physical mechanisms of CHDE changes

To identify the factors responsible for the contrasting CHDE responses under SSP2-com and SSP2-4.5, we decompose changes in the likelihood multiplication factor (LMF) into contributions from temperature mean, 30-day accumulated precipitation mean, temperature variability, precipitation variability, and the heat–drought dependence structure (Fig. 5). Over global land, mean temperature provides the dominant contribution to increasing CHDE risk in both scenarios and periods, accounting for approximately 101%–112% of the total change (Fig. 5a). This dominant warming contribution therefore explains the overall increase in future CHDE risk, but not the divergence between the two mitigation pathways. Precipitation-related changes partly counteract this warming effect. Because precipitation is sign-reversed in the decomposition, increases in mean precipitation contribute negatively to CHDE risk, offsetting approximately 20%–25% of the total increase, whereas changes in precipitation variability contribute positively by about 8%–9%. Changes in the heat–drought dependence structure provide an additional positive contribution of approximately 5%–8%, indicating that stronger dependence between heat and drought further amplifies CHDE risk. The contrast between SSP2-com and SSP2-4.5 becomes most evident by the late twenty-first century. Under SSP2-com, CHDE risk approaches stabilization as global temperature levels off, while the offsetting contribution from precipitation mean increases from about 20% at mid-century to approximately 25% by late century. Meanwhile, precipitation variability decreases slightly (Fig. S10), further limiting the increase in CHDE risk. Under SSP2-4.5, by contrast, CHDE occurrence probability continues to increase substantially, accompanied by stronger contributions from precipitation variability and heat–drought dependence (Fig. 5a). These results indicate that mean temperature sets the first-order increase in CHDE risk under both pathways, whereas differences in precipitation variability and heat–drought dependence increasingly distinguish SSP2-com from SSP2-4.5 as their temperature

trajectories diverge.

We further examine whether the drivers of the scenario differences are consistent across the three CHDE hot-spot regions (Fig. 5b–d). Mean temperature remains the dominant driver in all regions. Over MED and NSA, temperature mean contributes approximately 70%–80% of the total CHDE-risk change, while changes in precipitation mean further increase risk, contributing about 20%–40% in MED and 6%–13% in NSA. Over TIB, the contributions from temperature and precipitation means are broadly similar to global land. Changes in heat–drought dependence contribute positively in all three regions, indicating a common amplifying effect of strengthened compound dependence. The factors responsible for the late-century difference between SSP2-com and SSP2-4.5 vary by region. Over MED, the relative contribution structure changes little between the two scenarios, suggesting that the lower CHDE risk under SSP2-com primarily reflects its lower warming level. In contrast, over NSA and TIB, the contribution structure differs markedly between the two pathways: the relative contributions from temperature and precipitation means decrease, whereas those from temperature variability, precipitation variability, and heat–drought dependence become more important. These regional contrasts further demonstrate that the mechanisms underlying CHDE are pathway- and region-dependent.

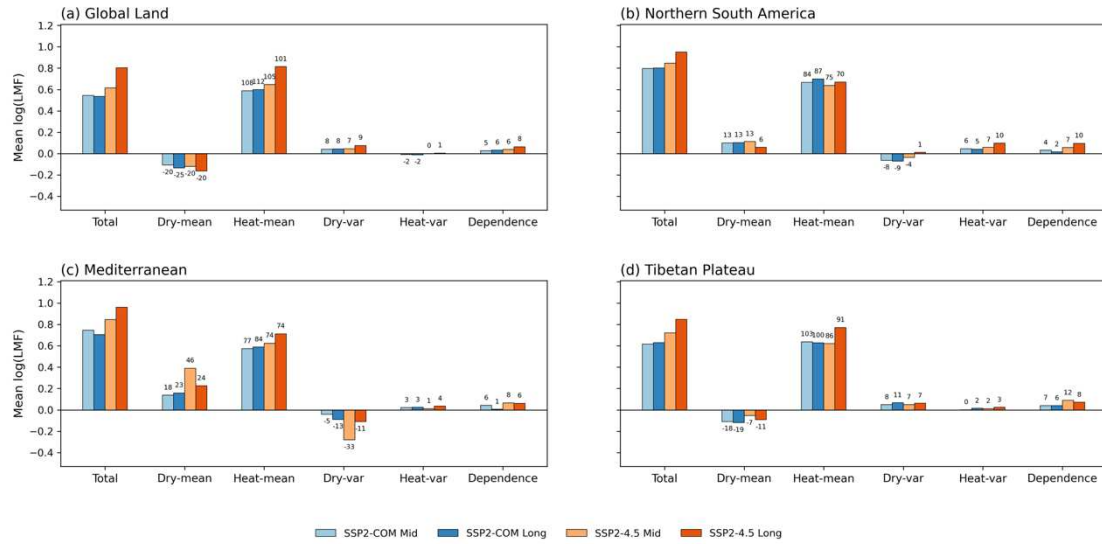


Fig. 5 Decomposition of changes in CHDE risk based on the LMF. (a–d), multi-model ensemble mean contributions to changes in CHDE risk over global land, northern South America (NSA), the Mediterranean (MED) and the Tibetan Plateau (TIB), respectively. Changes in LMF are decomposed into contributions from drought mean (Dry-mean; sign-reversed 30-day accumulated precipitation), temperature mean (Heat-mean), drought variability (Dry-var; sign-reversed 30-day accumulated precipitation), temperature variability (Heat-var) and the temperature–drought dependence structure (Dependence). Results are shown for the mid-century (2040–2060; Mid) and late-century (2080–2100; Long) periods under SSP2-com and SSP2-4.5. Numbers above or below the bars indicate the contribution of each component as a percentage of the total LMF change. Positive contributions enhance CHDE risk, whereas negative contributions offset the increase in CHDE risk.

To further explain the pathway-dependent CHDE responses identified above, we examine whether the differences between SSP2-com and SSP2-4.5 are reflected in surface radiative and turbulent energy fluxes. We compare changes in total cloud cover, surface downward shortwave radiation, latent heat flux, and sensible heat flux in the warm-season mean state and during CHDEs (Fig. 6). Over global land, the warm-season mean state shows reduced cloud cover and enhanced downward shortwave

radiation under both scenarios, accompanied by increases in both latent and sensible heat fluxes. These changes become more pronounced toward the late twenty-first century, when the increase in sensible heat flux strengthens relative to that in latent heat flux. Importantly, this shift toward sensible heating is stronger under SSP2-4.5 than under SSP2-com, consistent with the larger late-century CHDE risk under continued warming.

The surface-energy response to the two pathways, however, differs substantially among the three hot-spot regions (Fig. 6). Over MED, cloud cover decreases markedly and downward shortwave radiation and sensible heat flux increase under both scenarios, indicating a strong shift toward surface heating. The late-century changes are larger under SSP2-4.5 than under SSP2-com, consistent with the stronger CHDE increase under continued warming. Over NSA, latent heat flux initially increases more strongly than sensible heat flux, but this relationship reverses by late century, particularly under SSP2-4.5, as cloud cover decreases and sensible heating becomes more prominent. TIB shows the opposite mean-state energy response to MED and late-century NSA: cloud cover increases, downward shortwave radiation decreases, latent heat flux increases, and sensible heat flux decreases. The differences between SSP2-com and SSP2-4.5 are also smaller over TIB than over MED and NSA. These contrasting regional responses indicate that the energetic pathways associated with the SSP2-com–SSP2-4.5 difference are strongly region dependent.

Despite these regionally contrasting changes in the warm-season mean state, the surface-energy anomalies associated with CHDEs themselves show a more coherent pattern across regions. Relative to the corresponding warm-season background, CHDEs are generally associated with reduced cloud cover, enhanced downward shortwave radiation, suppressed latent heat flux, and enhanced sensible heat flux. The reduction in latent heat flux weakens evaporative cooling, while the accompanying increase in sensible heat flux enhances surface heating. This energy redistribution is consistent

with the well-established soil moisture–temperature feedback: soil moisture depletion suppresses evapotranspiration and latent cooling, allowing a larger fraction of the available surface energy to be converted into sensible heat and thereby amplifying near-surface warming (Fischer et al. 2007; Miralles et al. 2014; Seo and Ha 2022; Fu and Wang 2023). Fischer et al. (2007), for example, showed that soil moisture depletion associated with precipitation deficits reduces latent cooling and substantially amplifies European summer heatwaves, while Miralles et al. (2014) demonstrated that progressive land-surface desiccation can reinforce atmospheric heat accumulation over successive days. More recent studies of CHDEs further show that declining soil moisture suppresses evapotranspiration and strengthens soil moisture–temperature coupling, thereby amplifying compound drought–heatwave conditions (Seo and Ha 2022), while dry soils can substantially enhance sensible heat flux and near-surface temperature through land–atmosphere coupling (Fu et al. 2023). Our results suggest that the same feedback differs in strength between the two mitigation pathways. The turbulent-flux anomalies are generally stronger in the late-century period and under SSP2-4.5 than under SSP2-com, indicating a stronger redistribution of surface energy from evaporative cooling toward sensible heating under continued warming. This stronger event-scale land–atmosphere feedback under SSP2-4.5 provides a physical mechanism consistent with its higher CHDE risk relative to SSP2-com.

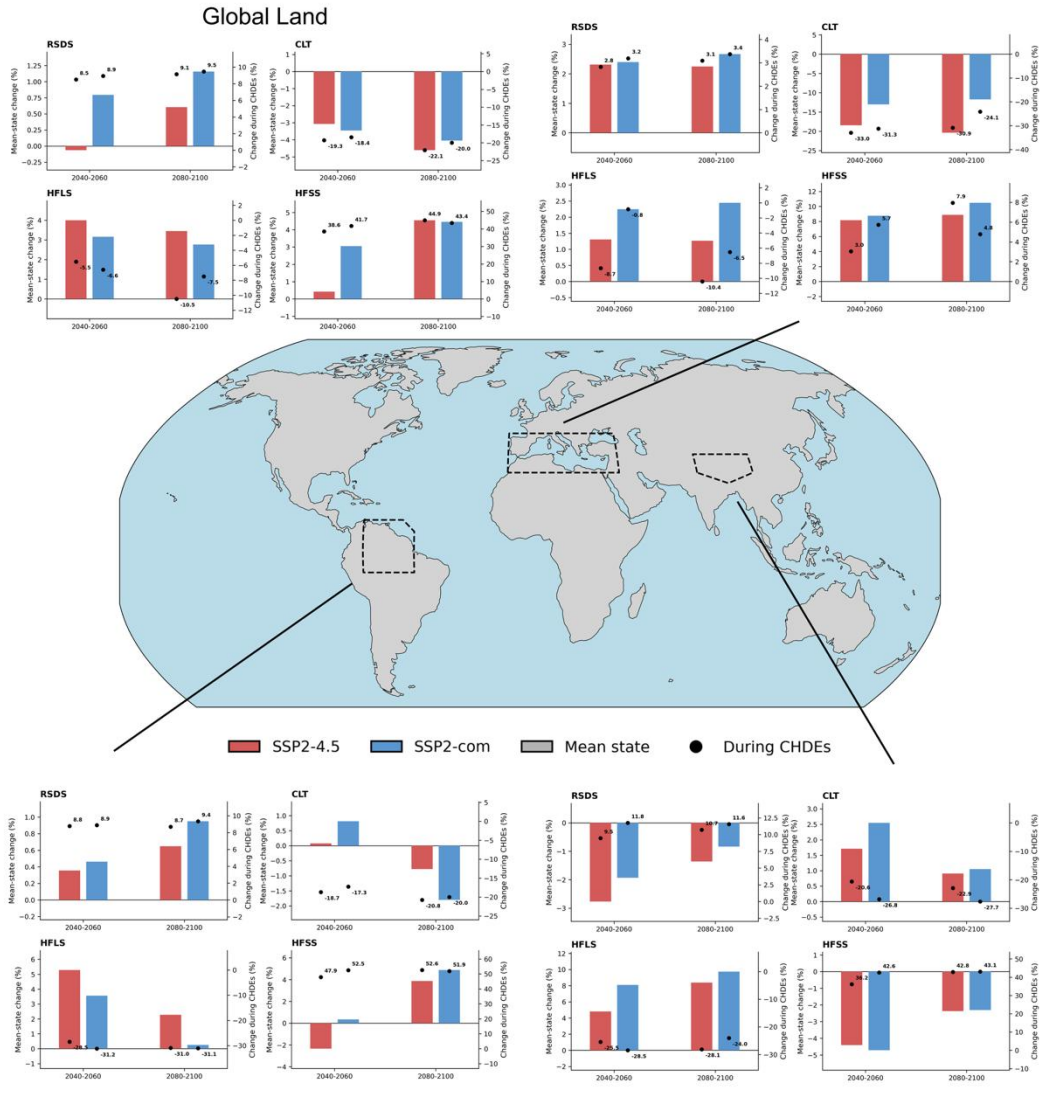


Fig. 6 Changes in surface radiative and turbulent fluxes associated with CHDEs over global land and selected hot-spot regions under SSP2-com and SSP2-4.5. Surface radiative variables include surface downward shortwave radiation (RSDS) and total cloud cover (CLT), and turbulent fluxes include latent heat flux (HFLS) and sensible heat flux (HFSS). Bars show percentage changes in the warm-season mean state (left y axis), and black circles show percentage changes during CHDEs (right y axis). Red and blue denote SSP2-4.5 and SSP2-com, respectively. Changes are shown for 2040–2060 and 2080–2100 relative to the historical warm-season climatology. Positive and negative values indicate increases and decreases relative to the historical climatology, respectively. The map shows the study regions: global land, the Mediterranean (MED), northern South America (NSA) and the Tibetan Plateau (TIB).

537

538 **4. Conclusions and Discussion**

539 CHDEs are projected to intensify under continued global warming, but how their
540 future evolution changes under policy-informed mitigation pathways remains
541 insufficiently understood. In this study, we used the SSP2-com scenario, which
542 incorporates updated mitigation commitments, to assess whether and to what extent
543 strengthened mitigation can reduce future CHDE risk relative to the conventional
544 CMIP6 SSP2-4.5 pathway. Specifically, we compared projected changes in CHDE
545 frequency and cumulative intensity under the two scenarios and further examined
546 whether their differences can be explained by warming magnitude alone or also arise
547 from changes in precipitation characteristics, heat–drought dependence, and land–
548 atmosphere processes. The main conclusions are as follows.:

- 549 1) Under SSP2-com, CHDE risk increases substantially by mid-century but shows
550 little further intensification toward the end of the century. During 2040–2060,
551 global land-mean CHDE frequency reaches approximately twice its historical
552 level, while cumulative intensity increases by 33.9%, with increases occurring
553 over 91.2% and 74.4% of global land area, respectively. Thereafter, the increase
554 weakens markedly: by 2080–2100, CHDE frequency and cumulative intensity
555 are only about 1% and 4% higher than their mid-century levels. This
556 stabilization is strongly region dependent, CHDE frequency and cumulative
557 intensity decrease by 4.0% and 0.6% over the Mediterranean (MED), whereas
558 cumulative intensity continues to increase by 9.2% over the Tibetan Plateau
559 (TIB) and 20.3% over northern South America (NSA). Thus, mitigation
560 substantially constrains the global late-century intensification of CHDEs, but
561 does not eliminate regionally persistent or increasing risks.
- 562 2) The mitigation benefits of SSP2-com relative to SSP2-4.5 become pronounced
563 mainly in the late twenty-first century. At mid-century, the global land-area-

weighted median differences between the two scenarios are small, reaching only -0.3 days yr^{-1} in CHDE frequency and $+1.4\%$ in cumulative intensity. By late century, these differences expand to -2.9 days yr^{-1} and -5.5% , respectively, and the reduction in CHDE risk becomes much more spatially widespread. This temporal evolution is consistent with the fact that the SSP2-com and SSP2-4.5 pathways remain relatively similar before their forcing trajectories diverge more substantially after mid-century. But the divergence in CHDE risk between SSP2-com and SSP2-4.5 cannot be explained by temperature changes alone.

- 3) The contrasting CHDE responses between SSP2-com and SSP2-4.5 arise from combined changes in mean climate, variability, heat–drought dependence, and land–atmosphere feedback. The LMF decomposition shows that mean temperature remains the dominant driver of the overall increase in CHDE risk under both scenarios, whereas the differences between the two pathways are more strongly shaped by the other components. Under SSP2-com, stronger offsetting effects from mean precipitation and weaker precipitation variability limit late-century CHDE increases. In contrast, under SSP2-4.5 stronger precipitation variability and heat–drought dependence further amplify risk. These mechanisms are region dependent: reduced warming dominates over MED, while variability and dependence play larger roles over NSA and TIB. Surface-energy changes provide a physical explanation. During CHDEs, the shift from latent to sensible heating is generally stronger under SSP2-4.5, indicating stronger land–atmosphere feedback and contributing to the higher late-century CHDE risk.

Based on our analysis, the late-century emergence of the mitigation benefit under SSP2-com scenario can be interpreted primarily in the context of the evolving forcing trajectories. Atmospheric CO_2 concentrations under SSP2-com peak around the mid-twenty-first century and decline thereafter (Zhong et al. 2025; Lei et al. 2026; Su et al.

2026). As a result, the climatic consequences of strengthened mitigation become increasingly apparent only after the SSP2-com pathway diverges substantially from SSP2-4.5. Our results further suggest that CHDE risk may respond differently from global mean temperature because compound extremes integrate not only thermodynamic warming but also changes in hydroclimate variability, heat–drought dependence, and land–atmosphere coupling.

Previous projections based on conventional CMIP6 scenarios have established continued warming as a first-order driver of increasing CHDE risk (De Luca and Donat 2023; Jha et al. 2023; Tripathy et al. 2023). By extending the analysis to the policy-informed SSP2-com pathway, our study shows that mitigation can substantially suppress the late-century escalation of CHDEs. The resulting benefits cannot be inferred from warming magnitude alone. Future CHDE risk therefore depends not only on how much the climate warms, but also on the pathway through which that warming evolves.

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Author contributions

Rongyun Pan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft. Tianjun Zhou: Conceptualization, Supervision, Funding acquisition, Writing – review & editing. Jie Jiang: Writing – review & editing. Kangnian Ren: Writing – review & editing.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The CMIP6 simulations used in this study are publicly available through the Earth System Grid Federation (ESGF) data portal at <https://metagrid.esgf-west.org/search/cmip6/>. The SSP2-com simulations are available through the China Meteorological Administration Climate Model Data Center (CMDC) at <https://cmip.cma.cn/#/cart/items>.

Reference

- Chen W, Zhu D, Huang C, et al (2019) Negative extreme events in gross primary productivity and their drivers in China during the past three decades. *Agric For Meteorol* 275:47–58. <https://doi.org/10.1016/j.agrformet.2019.05.002>
- De Luca P, Donat MG (2023) Projected Changes in Hot, Dry, and Compound Hot-Dry Extremes Over Global Land Regions. *Geophysical Research Letters* 50:e2022GL102493. <https://doi.org/10.1029/2022GL102493>
- Eyring V, Bony S, Meehl GA, et al (2016) Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geosci Model Dev* 9:1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Fan X, Miao C, Zscheischler J, et al (2023) Escalating hot-dry extremes amplify compound fire weather risk. *Earth's Future* 11:e2023EF003976. <https://doi.org/10.1029/2023EF003976>
- Fischer EM, Knutti R (2014) Detection of spatially aggregated changes in temperature and precipitation extremes. *Geophys Res Lett* 41:547–554. <https://doi.org/10.1002/2013GL058499>
- Fischer EM, Seneviratne SI, Lüthi D, Schär C (2007) Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters* 34:. <https://doi.org/10.1029/2006GL029068>
- Fricko O, Havlik P, Rogelj J, et al (2017) The marker quantification of the Shared

645 Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century.
646 Global Environmental Change 42:251–267.
647 <https://doi.org/10.1016/j.gloenvcha.2016.06.004>

648 Fu K, Wang K (2023) Contributions of Local Land–Atmosphere Coupling and
649 Mesoscale Atmospheric Circulation to the 2013 Extreme Flash Drought and
650 Heatwave Compound Event Over Southwest China. *Journal of Geophysical*
651 *Research: Atmospheres* 128:e2023JD039406.
652 <https://doi.org/10.1029/2023JD039406>

653 Hao Z, Hao F, Xia Y, et al (2022) Compound droughts and hot extremes: Characteristics,
654 drivers, changes, and impacts. *Earth-Science Reviews* 235:104241.
655 <https://doi.org/10.1016/j.earscirev.2022.104241>

656 Hausfather Z (2025) An assessment of current policy scenarios over the 21st century
657 and the reduced plausibility of high-emissions pathways. *Dialogues on Climate*
658 *Change* 2:26–32. <https://doi.org/10.1177/29768659241304854>

659 Hosseinzadehtalaei P, Termonia P, Tabari H (2024) Projected changes in compound hot-
660 dry events depend on the dry indicator considered. *Commun Earth Environ*
661 5:220. <https://doi.org/10.1038/s43247-024-01352-4>

662 Iturbide M, Gutiérrez JM, Alves LM, et al (2020) An update of IPCC climate reference
663 regions for subcontinental analysis of climate model data: definition and
664 aggregated datasets. *Earth System Science Data* 12:2959–2970.
665 <https://doi.org/10.5194/essd-12-2959-2020>

666 Jha S, Gudmundsson L, Seneviratne SI (2023) Partitioning the Uncertainties in
667 Compound Hot and Dry Precipitation, Soil Moisture, and Runoff Extremes
668 Projections in CMIP6. *Earth's Future* 11:e2022EF003315.
669 <https://doi.org/10.1029/2022EF003315>

670 Lei Y, Wang Z, Zhong J, et al (2026) Climate mitigation outcomes from China-led
671 emission reductions toward global carbon neutrality. *National Science Review*
672 13:nwaf545. <https://doi.org/10.1093/nsr/nwaf545>

673 Leonard M, Westra S, Phatak A, et al (2014) A compound event framework for
674 understanding extreme impacts. *WIREs Climate Change* 5:113–128.
675 <https://doi.org/10.1002/wcc.252>

676 Li J, Zhang Y, Bevacqua E, et al (2024) Future increase in compound soil drought-heat
677 extremes exacerbated by vegetation greening. *Nat Commun* 15:10875.
678 <https://doi.org/10.1038/s41467-024-55175-0>

679 Lian X, Li Y, Liu J, et al (2025) Northern ecosystem productivity reduced by rossby-
680 wave-driven hot–dry conditions. *Nat Geosci* 18:615–623.

681 <https://doi.org/10.1038/s41561-025-01722-3>

682 Liu Z, Jiao L, Lian X (2025) Impacts of increasing compound hot-dry events on
683 vegetation under the warming-wetting trend in northwest China. *Geography and*
684 *Sustainability* 6:100222. <https://doi.org/10.1016/j.geosus.2024.08.003>

685 Lu Y, Jin L, Zhong J, et al (2025) Earth system responses under a global 2 °C-target
686 scenario aligned with China’s carbon neutrality pledge. *Environ Res Lett*
687 20:104049. <https://doi.org/10.1088/1748-9326/adfbfb>

688 Meinshausen M, Nicholls ZRJ, Lewis J, et al (2020) The shared socio-economic
689 pathway (SSP) greenhouse gas concentrations and their extensions to 2500.
690 *Geoscientific Model Development* 13:3571–3605.
691 <https://doi.org/10.5194/gmd-13-3571-2020>

692 Meng Y, Hao Z, Feng S, et al (2022) Increase in compound dry-warm and wet-warm
693 events under global warming in CMIP6 models. *Global and Planetary Change*
694 210:103773. <https://doi.org/10.1016/j.gloplacha.2022.103773>

695 Miralles DG, Teuling AJ, van Heerwaarden CC, Vilà-Guerau de Arellano J (2014)
696 Mega-heatwave temperatures due to combined soil desiccation and atmospheric
697 heat accumulation. *Nature Geosci* 7:345–349.
698 <https://doi.org/10.1038/ngeo2141>

699 O’Neill BC, Tebaldi C, Van Vuuren DP, et al (2016) The Scenario Model
700 Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 9:3461–
701 3482. <https://doi.org/10.5194/gmd-9-3461-2016>

702 Pan R, Li W, Wang Q, Ailiyaer A (2023) Detectable Anthropogenic Intensification of
703 the Summer Compound Hot and Dry Events Over Global Land Areas. *Earth’s*
704 *Future* 11:e2022EF003254. <https://doi.org/10.1029/2022EF003254>

705 Ridder NN, Pitman AJ, Westra S, et al (2020) Global hotspots for the occurrence of
706 compound events. *Nat Commun* 11:5956. <https://doi.org/10.1038/s41467-020-19639-3>

708 Scafetta N (2024) Impacts and risks of “realistic” global warming projections for the
709 21st century. *Geoscience Frontiers* 15:101774.
710 <https://doi.org/10.1016/j.gsf.2023.101774>

711 Seo Y-W, Ha K-J (2022) Changes in land-atmosphere coupling increase compound
712 drought and heatwaves over northern East Asia. *npj Clim Atmos Sci* 5:100.
713 <https://doi.org/10.1038/s41612-022-00325-8>

714 Song J, Zhou S, Yu B, et al (2024) Serious underestimation of reduced carbon uptake
715 due to vegetation compound droughts. *npj Clim Atmos Sci* 7:23.
716 <https://doi.org/10.1038/s41612-024-00571-y>

717 Su B, Huang J, Kundzewicz ZW, et al (2026) Trajectories of climate scenarios:
 718 historical foundations and emerging trends. *Science Bulletin*
 719 S2095927326004536. <https://doi.org/10.1016/j.scib.2026.04.053>

720 Sutanto SJ, Vitolo C, Di Napoli C, et al (2020) Heatwaves, droughts, and fires:
 721 Exploring compound and cascading dry hazards at the pan-European scale.
 722 *Environ Int* 134:105276. <https://doi.org/10.1016/j.envint.2019.105276>

723 Tabari H, Willems P (2023) Global risk assessment of compound hot-dry events in the
 724 context of future climate change and socioeconomic factors. *npj Clim Atmos*
 725 *Sci* 6:74. <https://doi.org/10.1038/s41612-023-00401-7>

726 Tebaldi C, Debeire K, Eyring V, et al (2021) Climate model projections from the
 727 Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth*
 728 *System Dynamics* 12:253–293. <https://doi.org/10.5194/esd-12-253-2021>

729 Tripathy KP, Mukherjee S, Mishra AK, et al (2023) Climate change will accelerate the
 730 high-end risk of compound drought and heatwave events. *Proceedings of the*
 731 *National Academy of Sciences* 120:e2219825120.
 732 <https://doi.org/10.1073/pnas.2219825120>

733 Venmans F, Carr B (2024) Literature-informed likelihoods of future emissions and
 734 temperatures. *Climate Risk Management* 44:100605.
 735 <https://doi.org/10.1016/j.crm.2024.100605>

736 Wu X, Hao Z, Tang Q, et al (2021) Projected increase in compound dry and hot events
 737 over global land areas. *International Journal of Climatology* 41:393–403.
 738 <https://doi.org/10.1002/joc.6626>

739 Yao L, Leng G, Yu L, et al (2024) Observational constraint on climate model projections
 740 of global compound hot–dry events and the socioeconomic risks under climate
 741 change. *Environ Res Lett* 19:114027. <https://doi.org/10.1088/1748-9326/ad7f72>

743 Zhang G, Zhang S, Wang H, et al (2024) Evaluating vegetation vulnerability under
 744 compound dry and hot conditions using vine copula across global lands. *Journal*
 745 *of Hydrology* 631:130775. <https://doi.org/10.1016/j.jhydrol.2024.130775>

746 Zhang X, Zhong J, Zhang X, et al (2025) China can achieve carbon neutrality in line
 747 with the paris agreement’s 2 °C target: Navigating global emissions scenarios,
 748 warming levels, and extreme event projections. *Engineering* 44:207–214.
 749 <https://doi.org/10.1016/j.eng.2024.11.023>

750 Zhong J, Zhang X, Zhang D, et al (2025) Plausible global emissions scenario for 2 °C
 751 aligned with China’s net-zero pathway. *Nat Commun* 16:8102.
 752 <https://doi.org/10.1038/s41467-025-62983-5>

753 Zscheischler J, Martius O, Westra S, et al (2020) A typology of compound weather and
 754 climate events. *Nat Rev Earth Environ* 1:333–347.
 755 <https://doi.org/10.1038/s43017-020-0060-z>

756 Zscheischler J, Seneviratne SI (2017) Dependence of drivers affects risks associated
 757 with compound events. *Science Advances* 3:e1700263.
 758 <https://doi.org/10.1126/sciadv.1700263>

759 Zscheischler J, Westra S, Van Den Hurk BJJM, et al (2018) Future climate risk from
 760 compound events. *Nature Clim Change* 8:469–477.
 761 <https://doi.org/10.1038/s41558-018-0156-3>

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