

# Mesoscale moisture convergence drives stronger rainfall extremes

High-resolution global climate simulations reveal that mesoscale moisture convergence, rather than thermodynamic effects alone, drives much of the projected intensification of extreme rainfall under warming. These results demonstrate that better representing mesoscale dynamics substantially improves the robustness of future rainfall projections, offering critical insights for flood-risk assessment and climate adaptation.

## This is a summary of:

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## The question

Extreme precipitation has intensified across much of the world as the climate warms, but the physical causes of this amplification are only partly understood. Thermodynamic theory predicts that rainfall extremes should increase by 7% per degree of warming as the atmosphere's capacity to hold moisture rises. However, observations show that the response is often stronger, more regionally variable, and closely linked to changes in atmospheric circulation<sup>1</sup>. These discrepancies point to the critical role of dynamical processes, particularly mesoscale updrafts that fuel moisture into intense storms<sup>2</sup>.

Conventional global climate models from the Coupled Model Intercomparison Project (CMIP), which typically have ~100 km horizontal resolution, cannot explicitly resolve these mesoscale updrafts and instead rely on parameterized subgrid-scale convection. Kilometre-scale storm-resolving models can resolve deep convection but remain prohibitively expensive for century-long global simulations. However, a new generation of global high-resolution climate models operating at 10–25 km is bridging this gap and provides the first practical framework to investigate the dynamical controls of extreme precipitation. Yet the mechanisms behind these improvements, and whether these new models yield more reliable projections than standard models, remain open questions.

## The discovery

We have used a new suite of historical and future climate simulations featuring a high-resolution (~25 km) atmosphere and land model coupled with an eddy-rich (~10 km) ocean and sea-ice model, based on the Community Earth System Model version 1.3 (CESM-HR<sup>3</sup>). This CESM-HR suite comprises a 10-member ensemble spanning 1920–2100, following the CMIP5 protocol in two scenarios: representative concentration pathways 8.5 (high emission) and 6.0 (medium-to-high emission). Parallel low-resolution (~100 km) simulations (CESM-LR) following identical protocols enabled direct assessment of resolution effects. To isolate the physical drivers, we applied a column moisture-budget analysis together with a feature-tracking framework<sup>4</sup> that identifies key precipitation-producing systems such as mesoscale convective systems (MCSs), tropical cyclones and atmospheric rivers.

The CESM-HR simulations reproduce the historically observed global distribution

and intensity of daily precipitation extremes with much greater fidelity than the CESM-LR. Moisture-budget analysis revealed that the improvement arises primarily from enhanced representation of mesoscale moisture convergence, which strengthens mesoscale updrafts and convective organization. In addition, CESM-HR realistically captures the occurrence of MCSs and their multiscale interactions with other weather systems, which are largely absent in the CESM-LR.

Historical validation demonstrates that, even without explicitly resolving convection, the ~25 km resolution delivers a step-change improvement in the spatiotemporal representation of mesoscale processes that drive extreme precipitation. Under high-emission forcing, CESM-HR projects a 41.2% increase in global land daily precipitation extremes by 2100, compared with 24.8% in CESM-LR. Notably, the thermodynamical contribution to these changes exhibits similar spatial patterns and magnitude in both models, whereas the dynamical contribution related to mesoscale moisture convergence is stronger in CESM-HR, at 25.8%, than in CESM-LR, at 8.9% (Fig. 1). This highlights the dominant role of dynamical amplification in shaping future precipitation extremes.

## The implications

Our results highlight that mesoscale moisture convergence, rather than thermodynamics alone, govern much of the projected intensification of extreme precipitation in a warming climate. This finding has broad implications for flood-risk assessment, water-resource planning and climate adaptation strategies, particularly in regions where organized convection dominates precipitation. By demonstrating that high-resolution global models provide more credible projections than conventional CMIP-class models, this work offers new insights for improving climate prediction, constraining uncertainty and guiding the development of next-generation climate modelling frameworks.

Some regional biases persist, including underrepresentation of warm-season mesoscale convective systems over the central USA. Addressing these limitations will require kilometre-scale global storm-resolving models capable of explicitly simulating deep convection and the complex feedback that link atmospheric dynamics, moisture convections and land-surface processes<sup>5</sup>.

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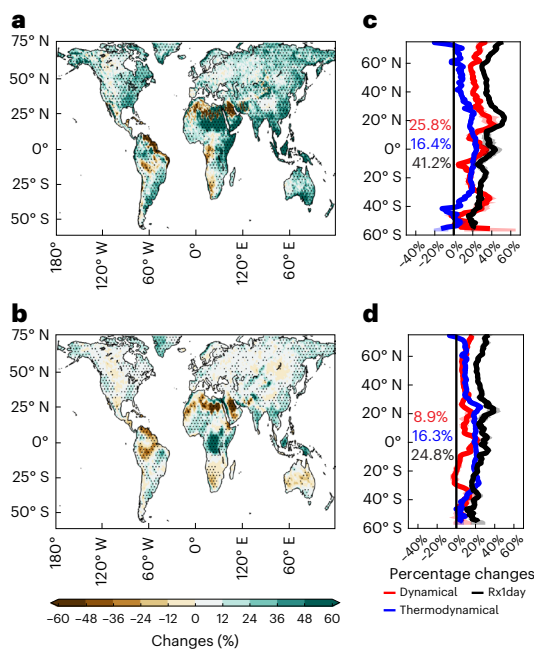
## EXPERT OPINION

“This study provides a convincing demonstration of the benefits of high-resolution global climate models in simulating the processes associated with extreme precipitation events more realistically. Importantly, these improved models predict substantially stronger

intensification of extreme precipitation in future warming scenarios compared with current models at coarser resolution — highlighting that these current models likely underestimate future climate risks.”

**Markus Donat, ICREA and Barcelona Supercomputing Center, Barcelona, Spain.**

## FIGURE



**Fig. 1 | Dynamical contributions to future extreme rainfall. a, b,** These maps show the global distribution of dynamical contributions to the projected fractional changes (%) in annual maximum daily precipitation (‘Rx1day’, in mm per day) for 2071–2100 relative to 1981–2010, calculated using the modelling ensemble Community Earth System Model version 1.3 (CESM-HR) with a resolution of ~25 km (a), and using a lower-resolution (~100 km) version (CESM-LR) (b). Stippling marks regions where at least three-quarters of the ten-member ensemble agree on the sign of the ensemble mean. c, d, Dynamical and thermodynamical contributions to Rx1day (global land-averaged values) versus latitude are shown for CESM-HR (c) and CESM-LR (d). The dynamical contribution — which is related to mesoscale moisture convergence — is much stronger in the higher-resolution model. © 2025, Chang, P. et al.

## BEHIND THE PAPER

Why do global climate models underestimate the observed intensity of extreme precipitation? Our discussions with colleagues suggested that the missing link lay in mesoscale convection and moisture convergence — processes that are poorly captured by coarse-resolution climate models. Running century-long, high-resolution (10–25 km) simulations proved to be a huge technical challenge, requiring sustained collaboration with the US National Science Foundation’s National Center for Atmospheric Research (NCAR) and access to advanced supercomputing

resources. When the CESM-HR results revealed that mesoscale dynamics overwhelmingly drive rainfall amplification, it was a genuine ‘eureka’ moment.

This project united scientists with complementary expertise in modelling, diagnostics, and extreme-event analysis. CESM-HR simulation data are now publicly available through NCAR’s Geoscience Data Exchange, providing a valuable resource for the broader community. We hope these datasets will foster new analyses and collaborations. **D.F. & P.C.**

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## FROM THE EDITOR

“As extreme precipitation events become more frequent with climate change, this paper offers a major breakthrough. The high-resolution (10–25 km) Earth system modelling designed to better capture local weather conditions reveals where these impacts will hit hardest — laying the groundwork for more accurate and reliable extreme-weather forecasts in a warming world.” **Aliénor Lavergne, Senior Editor, Nature Geoscience.**