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Why climate research still needs worst-case scenarios

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Why climate research still needs worst-case scenarios

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Abstract:
Reflecting concerns about the plausibility of SSP5–8.5, the Coupled Model Intercomparison Project has "retired" this "worst-case" scenario. Yet the marine heatwave off Baja California during September 2026 has been so extreme that comparable conditions are projected this century only by SSP5-8.5, and even then, only after 2075. This failure to project observed extremes challenges the wisdom of ignoring even apparently implausible scenarios when assessing risk, even in the near-term.

Main text:
Over recent decades, marine heatwaves (MHWs)—discrete periods of extreme ocean warmth lasting days to months[1]—have transformed marine ecosystems around the globe, causing widespread mass mortalities, habitat loss and shifts in species distributions[2–4], with associated impacts on the ecosystem services and livelihoods they support[2,5]. The trend toward more frequent, intense and protracted[6–8] MHWs is projected to continue throughout the century under all but the most optimistic scenarios[8–10]. Superimposed on the chronic threat caused by the

secular trend in warming, these intense and short-lived extreme events entail increasingly severe risks to marine systems[11,12].

Planning adaptation strategies to address future risks from MHWs depends on our capacity to project with reasonable skill when and where they will happen. MHW projections rely on outputs from Earth System Models (ESMs), coordinated by the Coupled Model Intercomparison Project (CMIP). The Sixth Phase of CMIP (CMIP6), which underpinned the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), considered climate scenarios that projected warming by 2100 (relative to the pre-industrial) of 1.5°C (SSP1–1.9) to 4.4°C (SSP5–8.5)[13]. More recently, CMIP7 has revised its approach to scenarios, effectively retiring SSP5–8.5, consistent with recent literature arguing that its emission levels are now considered implausibly high[14].

Nevertheless, there remains a strong rationale for retaining SSP5–8.5 to assess worst-case outcomes and low-probability–high-impact events in the long-term[15–17]. Consequently, most recent discussion in the literature has focused on whether SSP5–8.5 remains a relevant end-of-century projection[18]. Yet a different and largely unexplored question is whether climate extremes emerging today already approach the magnitudes projected by this high-end scenario towards the end of the century. Here, we address this question by comparing the MHW present along the Pacific coast of the Baja California Peninsula during September 2026 (Fig. 1) against projected MHWs in the region out to 2100 under four future CMIP6 scenarios, including SSP5–8.5. We show that the event is more intense over much of the affected region than any MHW projected before the final decades of the century, even under SSP5–8.5 (Fig. 2).

We compiled simulated daily sea-surface temperature time series, globally, using corresponding historical runs (1982–2014) and projections (2015–2100) from an ensemble of 12 CMIP6 Earth System models (ESMs; Table S1) under four CMIP6 scenarios: SSP1–2.6; SSP2–4.5; SSP3–7.0; and SSP5–8.5 (Table S2). For corresponding contemporary time series, we used the NOAA Daily Optimum Interpolation Sea Surface Temperature (OISST) reanalysis dataset[19], which is available globally at 0.25° resolution. We regridded ESM outputs to the OISST grid using bilinear interpolation, before filling missing values in both products to the coast using distance-weighted means (see Methods). From each of these timeseries, we computed the cumulative MHW intensity relative to a 30-year static baseline of 1983–2012 (see Methods). Using these data, we searched the projections from each ESM under each scenario for the first

year in which a cumulative monthly MHW intensity at least as intense as that for September 2026 was projected for each grid cell. We henceforth call this the projected “year of exceedance” for MHW intensity. Finally, we calculated the median year of exceedance across the 12 ESMs for each scenario. As a sensitivity test against over-interpolation of ESM projections, especially in coastal waters, we repeated the analysis using bilinear interpolation to regrid the raw ESM data onto a standard 1° grid, without filling to the coast, before disaggregating resultant data to 0.25° resolution by nearest neighbour to match OISST grid.

As the 2026 El Niño intensified through September 2026, the most extreme MHW yet recorded (Fig. S1A) along the Pacific coast of Baja California (Fig. 1) developed, with a maximum event intensity (i.e., aggregating across all cells in the MHW core) of 6.0°C and with peak cell-wise daily MHW intensities reaching 7.8°C at some locations (Fig. S1B). Early signs of ecological impacts had already emerged during September, with reports from local fishers and divers suggesting extensive loss of kelp forest, mass mortality of marine invertebrates, and the presence of more warm-affinity species (Fig. S2). These observations are consistent with impacts of previous, less-intense MHWs in the region, which caused declines in kelp-forest cover of up to 50%, persistent range contractions, shifts in community structure, and reductions in small-scale fisheries production[20–22].

A substantial proportion of the core area affected by the Baja California MHW (red polygon in Fig. 2) had no analogue in our climate projections before 2100 (in such cases, we assumed that median year of exceedance was beyond 2100). These no-analogue areas covered >90% of the MHW core under SSP1–2.6, shrinking progressively under higher-emission scenarios and contracting toward the coast. Under SSP5–8.5 no-analogue areas covered ~ 8% of the MHW core, mainly close to the coast (Fig. 2; Table S3). Sensitivity tests using data regridded to 1° and clipped to the ESM land mask (Fig. S3) yielded similar results under SSP1–2.6. As with projections interpolated to finer-scales, the no-analogue area in this sensitivity test progressively shrank and contracted towards the coast under SSP2–4.5 and SSP3–7.0, but it disappeared under SSP5–8.5 (Fig. S3; Table S4). Nevertheless, even under this extreme scenario, no part of the MHW core had median years of exceedance before 2050. Further, for >42% of the area with available projections, exceedance was not detected until 2075 or later (Fig. S3; Table S4).

The observation of a MHW in the contemporary ocean that is more intense than any MHW projected for any time this century under SSP1–2.6 is concerning, particularly given that this

scenario approaches the upper warming limit of the Paris Climate Agreement (Table S2). These concerns are exacerbated when noting that current observations across a smaller, but still substantial area of coastal Baja California, are more extreme than conditions projected until the last 25 years of the century under what is now considered the implausibly high-emission SSP5–8.5 scenario (Fig. 2D; Fig. S3D).

Importantly, it should be noted that historical runs of CMIP6 ESMs reproduce the extreme-value distributions of observations sufficiently well to be confident in using them to project MHWs[23], and such projections have been used to assess future risks to coastal species, including corals and kelps[9,24]. Moreover, although finer-scale interpolation of ESMs does not robustly resolve coastal processes[25,26], our results remained qualitatively unchanged in our sensitivity test at 1° resolution without coastal filling, which more closely matches the resolution of most ESMs (Table S1). Finally, although ESMs are more skillful in simulating changes in the statistics of extremes than projecting acute, localised extreme events[27], our focus on the MHW intensity accumulated over a month, rather than over a shorter MHW period, makes it more likely that ESMs would adequately capture phenomena of this scale. We are therefore confident that a MHW of this intensity in the region would be unprecedented this century for climate projections as extreme as SSP3–7.0, and at least until 2075 under SSP5–8.5.

Regardless of whether the failure to project such an intense MHW arises from model limitations or from an exceptionally rare realised event, the practical implication is the same: adaptation strategies should consider the extreme conditions represented by the highest-magnitude temperature projections of SSP5–8.5. If extreme anomalies such as the “Super El Niño” in 2026[28,29] are inadequately modelled by present-generation ESMs, we should be questioning what other unanticipated extreme events might be associated with intensifying El Niños, or with other phenomena lying in the outer tails of projections from even the most extreme climate scenarios. The wide-ranging impacts of MHWs on biodiversity, habitats and people are severe[4], but without adequate planning, the manifestation in the contemporary ocean of other extreme events not captured in near- or mid-term projections could have worse consequences for nature, infrastructure and human life. These concerns are amplified by the reality that all climate scenarios capable of delivering futures compatible with the Paris Climate Agreement rely on Carbon Dioxide Removal, which is both inadequately implemented[30] and potentially risky[17]. Solar Radiation Management is increasingly appealing to policymakers wishing to delay climate action while still meeting end-of-century temperature commitments, but this approach introduces

further unknowns and potentially greater risk[17,31,32]. Our results suggest that we are not adequately quantifying the risks of extreme events in the contemporary ocean, and they emphasise the value of including high-emission climate scenarios in ecological risk assessments. Even if very high-emissions scenarios are now considered unlikely or implausible, they remain essential for exploring the upper bounds of climate extremes and their potential consequences in an uncertain future.

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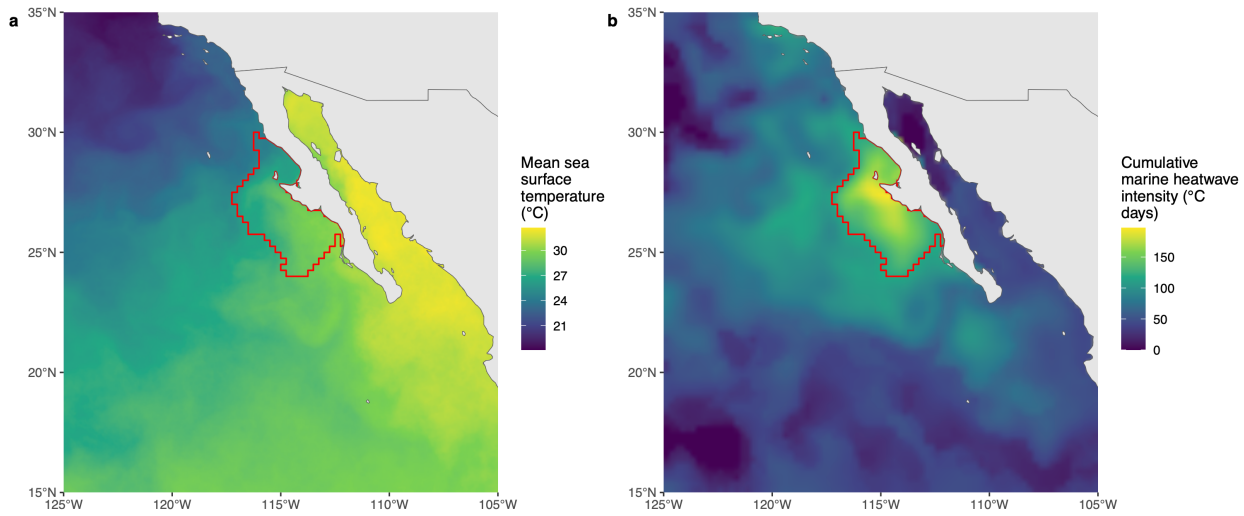

Figure 1 | The marine heatwave off the coast of Baja California, September 2026. a, mean sea-surface temperature (SST) from the NASA JPL Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST) dataset at 0.01° resolution, and **b**, cumulative marine heatwave intensity based based on NOAA Daily Optimum Interpolation Sea Surface Temperature (OISST) dataset at 0.25° resolution. The polygon outlined in red in both panels represents the core of the marine heatwave present along the Pacific coast of Baja California in September 2026 (computed as the contiguous area within which all grid cells had cumulative monthly marine heatwave intensities in the upper 5th percentile across the plotted area). Marine heatwave intensity could not be computed for MUR SST, because this dataset is available only from 2002, whereas the baseline period upon which marine heatwaves were based spans the 30-year period 1983–2012. Note that higher temperatures in the Gulf of California do not result in substantial marine heatwave intensity.

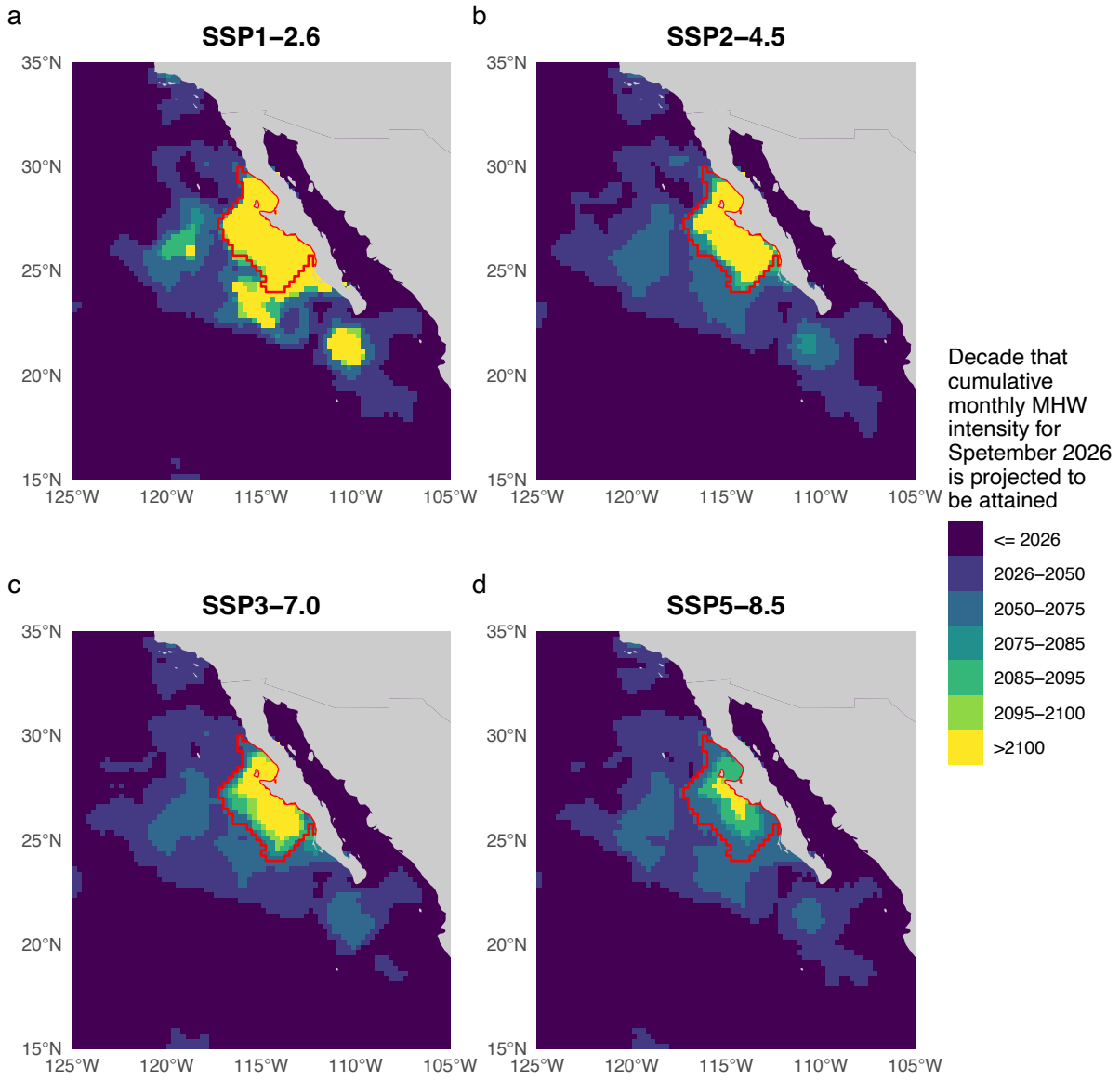

Figure 2 | The median year across 12 ESMs in which the cumulative monthly marine heatwave intensity observed during the marine heatwave off the coast of Baja California, September 2026, was reached under four CMIP6 scenarios. a, SSP1–2.6; **b**, SSP2–4.5; **c**, SSP3–7.0; and **d**, SSP5–8.5. The polygon outlined in red represents the core of the marine heatwave in September 2026, as in Fig. 1. Note that the scale in the legend is not linear.

Online methods:

Climate data

To represent observations, we collated daily sea-surface temperature (SST) estimates from the Optimum Interpolation Sea Surface Temperature (OISST v2.1) reanalysis[19] at 0.25° resolution (provided by NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov), cropped them to a bounding box of 15°N, 105°W to 35°N, 125°W and filled them to the coast using the distance-weighted means from nearest neighbors. For climate simulations, we downloaded historical (1985–2014) and projected future (2015–2100) daily SST (ESM variable "tos") from the first ensemble member (r1i1p1f1) of 12 Coupled Model Intercomparison Project Phase 6 (CMIP6) Earth System Models (ESMs; Table S1) for each of four CMIP6 scenarios: SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 (Table S2). These downloads were facilitated via the Earth System Grid Federation's Metagrid interface (ESGF; https://esgf.nci.org.au/search). Most (9) of these ESMs were selected (i) on the basis of data availability, and (ii) because of the plausibility of their climate sensitivity (Table S1), although we also included two ESMs with elevated transient climate sensitivities (IPSL-CM6A-LR and CanESM5) to reflect the tendency of some CMIP6 ESMs to "run hot"[33], and one ESM with depressed transient climate sensitivity (NorESM2-MM), to add diversity. Historical simulations and projections were spliced together directly, without any attempt at bias correction because marine heatwaves are computed as anomalies, so are unaffected by any uniform adjustment of the time-series mean. These data were cropped to the OISST bounding box, remapped to a standard 0.25° grid using bilinear interpolation and filled to the coast using the distance-weighted means from nearest neighbors. Although the primary focus of our analysis was on the simulations regridded to 0.25° and filled to the coast, we repeated the analysis using simulations regridded to 1° using bilinear interpolation, without filling to the coast. Our rationale was that this coarser resolution more closely matched the native resolution of the ESMs in our ensemble (Table S1), mirroring the approach in other studies of projected MHWs[34]. Moreover, this approach avoids the possibility that interpolation to the coast introduced unrealistic values. All netCDF files containing climate data were processed using CDO[35] software.

Marine heatwaves

For both the observational and the simulation datasets, we used the R package heatwaveR[36] to compute daily MHW intensities for each grid square relative to a baseline climatology of 1983–2012. For simulations, the baseline period was drawn from historical simulations rather than observations to ensure fidelity to the properties of each ESM. The daily MHW intensity was

computed as the anomaly between the SST for each day during a period classified as an MHW and the seasonally smoothed baseline climatology of SST for that day (where a MHW is defined as a period of five consecutive days or more during which the daily SST exceeded the 90th percentile of the seasonally smoothed SSTs for the corresponding day during the baseline period). We elected to use monthly cumulative MHW intensities because they are a good indicator of the exposure of kelp forests to warm anomalies[24]. The Core of the Baja California MHW was identified as the largest contiguous area covered by grid cells within the upper 5th percentile of daily MHW intensities within the bounding box of the study domain, and it is shown as a polygon outlined in red in the Figures 1, 2 and S2. All analyses were conducted in R6.4.1[37], with much of the technical processing relying on the *terra*[38] and *sf*[39] packages. For any analysis relying on computation of area, *SpatRasters* were first reprojected to UTM12N to ensure equal-area grid cells.

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