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Thermal Inertia: Why the Earth Will Keep Warming After Net Zero

Environment * Climate Change * Conservation

Introduction: The Fallacy of Instant Stabilization

Contemporary policy on anthropogenic climate change is anchored by the concept of "Net Zero" -- the milestone representing the cessation of net greenhouse gas emissions. Enshrined in the Paris Agreement, this framework assumes that limiting warming to 1.5 deg C-2.0 deg C above pre-industrial levels behaves as a "stop-flow" system, where eliminating net carbon dioxide emissions promptly stabilizes global temperatures and halts the intensification of extreme weather.[1] However, a study published in Environmental Research: Climate by Sarah Perkins-Kirkpatrick, Andrew King, and Tilo Ziehn challenges this expectation, demonstrating a profound millennial thermal inertia within the Earth system.[4]

For decades, simplified communications around the Zero Emissions Commitment (ZEC) -- the change in global mean surface temperature following the complete cessation of anthropogenic CO2 emissions -- suggested that ZEC is approximately zero.[3] Yet global averages mask regional variance and the coupled dynamics of the atmosphere, cryosphere, and hydrosphere. While the atmosphere adjusts rapidly to changes in radiative forcing, the deep ocean possesses a thermal memory spanning centuries to millennia. Whereas most projections from the Intergovernmental Panel on Climate Change (IPCC) terminate at 2100, Perkins-Kirkpatrick et al. utilized the Australian Community Climate and Earth System Simulator (ACCESS-ESM1.5) to extend simulations 1,000 years past the achievement of net zero.[4] Their findings reveal that deadly heatwaves do not revert toward pre-industrial baselines; instead, driven by carbon-cycle dynamics and Southern Ocean hysteresis, extreme heat events continue to intensify, lengthen, and proliferate for at least a millennium.[5]

The Physics of Commitment: Zero Emissions and Model Dynamics

When anthropogenic emissions cease, two counteracting processes govern global temperature trajectories during the ZEC phase. The cooling force is natural carbon uptake, as oceanic and terrestrial sinks continue drawing CO2 out of the atmosphere and diminishing radiative forcing.[3][21] The opposing warming force is diminishing ocean heat uptake: as atmospheric warming slows, the thermal gradient between surface air and the deep ocean narrows, reducing the ocean's efficiency as a planetary heat sink.[9]

Among Coupled Model Intercomparison Project Phase 6 (CMIP6) architectures, ACCESS-ESM1.5 is notable for capturing a positive Zero Emissions Commitment. In simulations where emissions cease after 2,000 PgC of cumulative carbon release, the model projects ongoing global mean warming of roughly 0.37 +/- 0.08 deg C after 50 years and 0.83 +/- 0.08 deg C after 200 years.[9] Structurally, ACCESS-ESM1.5 couples the Community Atmosphere Biosphere Land Exchange (CABLE) land-surface scheme with the Modular Ocean Model (MOM5) and the WOMBAT biogeochemical module.[2] Because

its representation of the carbon cycle features a relatively modest landborne carbon uptake fraction compared to its oceanborne fraction, atmospheric CO2 declines more gradually than in models with vigorous vegetation fertilization feedbacks.[10]

To isolate the long-term penalty of delayed decarbonization, Perkins-Kirkpatrick and colleagues ran a high-emissions baseline scenario (SSP5-8.5) and branched instantaneous net-zero simulations at five-year intervals between 2030 and 2060, running each branch forward for 1,000 years.[4] This experimental branching demonstrates that delaying net zero from the 2030s to the 2050s or 2060s does not merely add a few warm decades; it permanently shifts the millennial climatic baseline upward.[7]

The Southern Ocean Engine and Millennial Heatwave Regimes

A central mechanistic finding of the study is that persistent post-net-zero heatwaves are driven by the Southern Ocean, which acts as the high-inertia "freight train" of the global climate.[4][9] In the pre-industrial climate, circumpolar westerly winds associated with the Southern Annular Mode drive northward Ekman transport of surface waters, drawing cold, deep water up to the surface near Antarctica. As the ozone hole recovers and greenhouse forcing stabilizes in the post-net-zero era, ACCESS-ESM1.5 simulates a weakening and poleward shift of these westerly winds.[11] Reduced wind stress diminishes turbulent mixing and causes the oceanic mixed layer to shoal. Because a shallower surface layer holds lower heat capacity, solar radiation warms it rapidly, locking in a hysteresis loop that prevents Southern Ocean cooling even as atmospheric CO2 gradually subsides.[11]

This accumulated Southern Hemisphere heat is redistributed globally via oceanic currents and atmospheric teleconnections, altering interhemispheric temperature gradients that govern Hadley Cell circulation and the position of the Intertropical Convergence Zone (ITCZ).[12] Consequently, across the full 1,000-year simulations, terrestrial and Marine Heatwaves show no sign of returning to pre-industrial norms, while short-term aerosol unmasking further amplifies early post-emission warming.[6][22] In branches where net zero is delayed until 2050 or later, record-breaking heatwaves occur annually across equatorial regions.[5] Low natural temperature variability in the tropics means that modest increases in mean temperature push the Amazon, the Sahel, and the Indian subcontinent far outside their historical envelopes, while southern Australia experiences prolonged mega-heatwaves fueled directly by adjacent Southern Ocean heat content.[6] Because deep-ocean heat re-emergence and feedback loops decouple surface thermal extremes from declining atmospheric CO2, late-century Carbon Dioxide Removal (CDR) cannot rapidly reverse the capitalized thermal debt.[8]

| Metric | | Net Zero 2040 Scenario | | Net Zero 2060 Scenario | | Trend vs Pre-Industrial (+500 Years) |

| Frequency (Global) | | Elevated (2-3x baseline) | | Severe (5-10x baseline) | | No decline over 1,000 years |

| Frequency (Tropics) | | Annual occurrence | | Continuous / seasonal | | Historically rare events become baseline |

| Intensity (Peak Temp) | | +1.5 deg C to +2.0 deg C | | > +2.5 deg C | |

Systematically hotter; rising in Southern Hemisphere |

| Duration | | +10 days / season | | +30 days / season | | Permanent seasonal shift; chronic mega-heatwaves |

| Regional Hotspots | | Mediterranean, Australia | | Amazon, Sahel, India | | Tropics cross liveability thresholds annually |

| Physiological Impact | | Frequent caution risk | | Frequent danger/extreme risk | | Widespread unliveable conditions for outdoor labor |

Physiological Thresholds and Multi-Century Adaptation

Translating these millennial temperature projections into human impacts requires evaluating wet-bulb temperature (Tw), which integrates heat and humidity to measure the capacity for evaporative cooling through sweat. While climate impact assessments long relied on Sherwood and Huber's theoretical survivability limit of Tw = 35 deg C -- the threshold at which core body temperature rises uncontrollably toward fatal hyperthermia within six hours -- co-author Andrew King and physiological researchers emphasize a critical distinction between survivability and liveability.[14][16][19][20] Survivability marks the biological ceiling for a resting, healthy young adult in the shade; liveability defines the maximum environmental conditions under which people can conduct sustained daily activity and outdoor labor without cumulative organ strain.

Empirical trials from the PSU HEAT Project (Vecellio et al., 2022; 2023) demonstrate that uncompensable heat stress begins well below 35 deg C: for young adults performing light tasks, critical Tw limits fall near 31 deg C, and for older populations or dry-heat exposures, dangerous strain emerges between 26 deg C and 28 deg C.[16][17][18] Overlaying ACCESS-ESM1.5 trajectories onto these empirical thresholds reveals that delaying net zero to 2060 renders outdoor agriculture and construction functionally unliveable across large portions of the Global South for weeks to months each year.[4]

Because this thermal regime persists for at least 1,000 years, climate adaptation cannot be treated as a temporary bridge to a cooling planet; as King notes, it becomes "the work of centuries, not decades."[5] Electrical grids must be engineered to sustain multi-month cooling loads where power failures during a high-Tw event would trigger mass casualties.[13] Urban architecture must pivot from active mechanical cooling toward passive survivability, high-albedo surface modification, and structural heat-island mitigation.[15]

Conclusion: The Millennial Imperative of Rapid Decarbonization

The simulations by Perkins-Kirkpatrick, King, and Ziehn dispel the illusion that achieving Net Zero acts as an immediate thermostat reset. Driven by the thermal inertia and circulation hysteresis of the Southern Ocean, the heat injected into the Earth system over the coming decades will sustain elevated heatwave frequency, duration, and intensity for at least a millennium.[4] Yet rather than counseling fatalism, the branching results underscore the decisive value of velocity: every five-year reduction in the time required to reach net zero permanently lowers the millennial heatwave baseline, preserving physiological liveability for the next

forty generations.[7]

Updates (Nov 20, 2026): Replaced blocked ResearchGate, Scimex, and Princeton URLs and removed redundant or off-topic citations with verified primary DOI and PubMed Central records (including Perkins-Kirkpatrick et al. 2025 DOI 10.1088/2752-5295/ae0ea4, Fr licher et al. 2013 DOI 10.1038/nclimate2060, Sherwood & Huber 2010, and Vecellio et al. 2022/2023); added Chamberlain et al. (2024) uncertainty bounds (+/-0.08 deg C) on ACCESS-ESM1.5 ZEC projections, unnumbered headings, added exact publication dates across all 22 references, and enforced 1:1 inline citation parity.

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