npj | climate and atmospheric science

Brief communication

Published in partnership with CECCR at King Abdulaziz University

https://doi.org/10.1038/s41612-025-01006-y

What made 2023 and 2024 the hottest years in a row?

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Global surface temperature reached a record high in 2023. Using a global climate model, we show that El Niño along with extratropical variability boosted 2023 to be the hottest year on a background warming of 0.2 °C/decade. Our model initialized in July 2024 correctly predicted that 2024 was on track to become yet another hottest year on record.

Global-mean surface temperature (GMST) has increased at a rate of 0.2 °C per decade since 1980 due largely to anthropogenic emissions of greenhouse gasses[1]. The rate of GMST increase varies on interannual to decadal timescales. Global surface warming slowed during prolonged periods of 1998–2013[2,3] and 2016–2022 but surged during the 2015-16 and 2023-24 El Niño events (Fig. 1a), with 2023 being the hottest year on record at the time this work was submitted. Strong warming over North America (Fig. 2a) unleashed widespread wildfires across Canada producing smoke that darkened the sky of New York City. Surface temperature increased over much of the globe (Fig. 2a), and the planet on fire begs the question of what caused the surge of global warming. Possible culprits range from reduced aerosol emissions[4,5], reduced low-cloud cover[6], to internal climate variability. El Niño is known to increase GMST but the contribution to the record global warming in 2023 remains to be quantified[7–9]. It is equally important to examine the spatial distribution of 2023 temperature anomalies and determine if it matches that of a typical El Niño outside the tropical Pacific. Major mismatches could indicate contributions from other climate modes. Here we use global climate models forced by radiative forcing and El Niño–Southern Oscillation (ENSO) to quantify the El Niño contribution to record-setting GMST in 2023.

Results

Tropical ocean effect

Here we use simulations with a global coupled ocean-atmosphere model (CM2.1)[10] in which sea surface temperature (SST) is nudged toward observations in the tropical Pacific (TP, marked in Fig. 2d; 10% of Earth surface area), but the ocean and atmosphere are otherwise fully interactive (Methods). The model is run 20 times, different only in initial conditions, over a 42.5-year period from January 1982 to June 2024. The ensemble mean represents the climate response to imposed radiative forcing and TP SST variability. A great advantage of the TP pacemaker simulation is that the results can be directly compared to observations to determine the TP contribution and underlying mechanisms[2]. The TP pacemaker ensemble mean tracks observed GMST very well (Fig. 1a), and the detrended time series are correlated at 0.73, significant at 99% level. A 10-member TP pacemaker ensemble with a newer climate model (CESM2)[11] yields very similar results (Fig. 2c, S1), confirming that ENSO is a major driver of interannual variability in GMST.

ENSO is often tracked by Niño3.4 SST anomalies (5°S-5°N, 170°W-120°W), which peak in the three-month season of November-January. A conventional annual averaging breaks one ENSO event into two calendar years, a more natural ENSO year is defined as 12 months from July 1 to the following June 30, which captures ENSO variability better than calendar years. Indeed, the model-observation correlation is higher (r = 0.76) for detrended GMST averaged for ENSO years (Fig. S2). Record GMST anomalies were observed during 13 months of June 2023-June 2024 (Fig. S3), a time window consistent with the development of the 2023-24 El Niño. El Niño-induced warming is efficiently communicated throughout the tropical troposphere, resulting in surface warming over tropical continents and the tropical Indo-Atlantic oceans at a time delay of 2-3 months due to the ocean's thermal inertia[12].

Observed GMST jumped by 0.31 °C from 2022 to 2023, a record since 1880 when GISTEMP data started. The TP pacemaker ensemble mean simulates a jump of 0.18 °C or 58% of what was observed (Fig. 1b). Almost all the 2022 to 2023 GMST jump in the TP pacemaker ensemble mean is due to that in the tropics (30°S-30°N, covering half Earth surface area). At 0.47 °C, the observed tropical warming is larger but within the range of the TP pacemaker ensemble (Fig. 1b). Indeed, intense SST warming was observed over the tropical North Atlantic from May 2023 onward (Fig. 2a), coupled with the weakened northeast trade winds (Fig. S4). Tropical North Atlantic SST warming began to develop in April 2023 and reached 2 °C, or 2.5 standard deviations off West Africa, aided by positive feedback of ocean-atmosphere interaction[13]. The pre-El Niño warming of the tropical North Atlantic explains the early commencement of tropical and global warming in 2023, and why the TP pacemaker ensemble mean under-simulates the observed warming magnitude.

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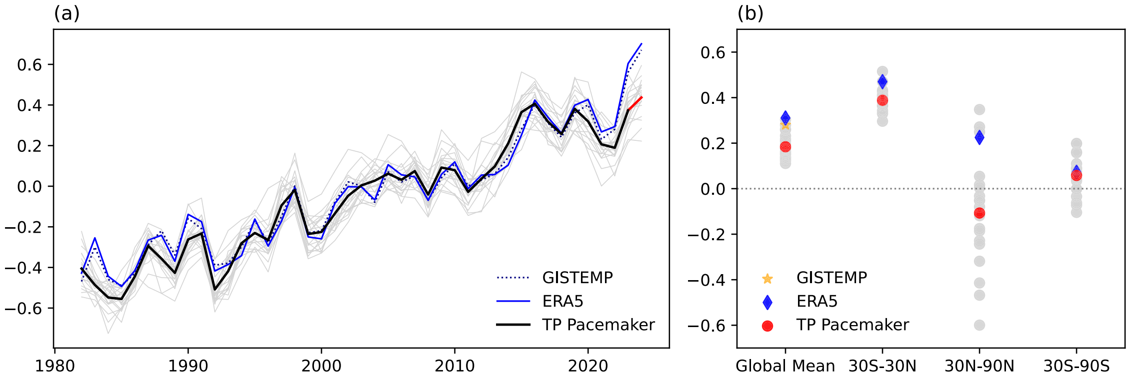
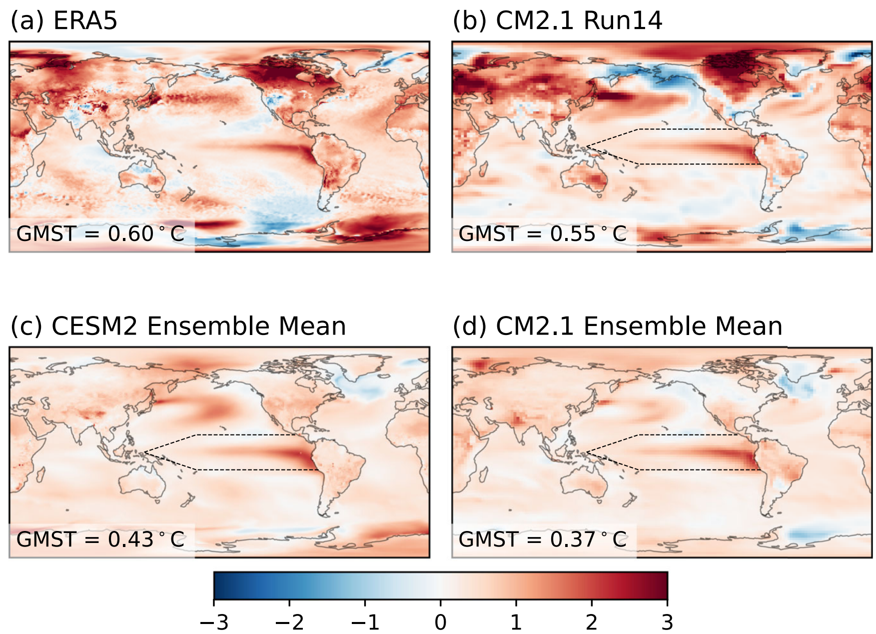


Fig. 1 | Evolution of global temperature and the relationship with ENSO. **a** Annual-mean GMST anomalies (ref. 1991–2020): observations (ERA5 in solid blue; GISTEMP in dotted blue) and the TP pacemaker ensemble mean (black) with 20 member runs in grey. The 2024 forecast is in red. **b** Surface temperature changes from 2022 to 2023 averaged over the globe, tropics, and extratropical Northern and Southern Hemispheres (from left to right). Red dots denote the TP pacemaker ensemble mean (20 members in grey dots). Unit is °C.

Fig. 2 | Surface temperature anomalies in 2023. Annual-mean anomalies (°C, ref. 1991–2020) in (**a**) ERA5, (**b**) CM2.1 Run 14 chosen for high spatial correlation with observations in the extratropical Northern Hemisphere[14], (**c**) CESM2 and (**d**) CM2.1 ensemble means. The TP SST-restoring region is marked by dashed lines in (**b**–**d**).



Extratropical contribution

The TP pacemaker simulates large variability in extratropical Northern Hemisphere (NH) temperature change, ranging from −0.60 °C to +0.35 °C (Fig. 1b), equivalent to −0.15 ~ + 0.09 °C GMST. The temperature variability averaged over the extratropical NH is not significantly correlated with ENSO (Fig. S5). The observed extratropical NH temperature change stands far above the TP pacemaker ensemble mean, by 0.33 °C, equivalent to 0.08 °C GMST. The observed surface warming in 2023 is indeed much larger than the pacemaker ensemble mean over central Asia, the North Pacific Ocean east of Japan, and mid-high latitude North America (Fig. 2a vs. 2d). Remarkably, TP pacemaker run #14 produces a temperature distribution very similar to observations (Fig. 2b vs. 2a), while increasing GMST anomaly by a whopping 0.18 °C above the TP pacemaker ensemble mean. It indicates an important role of extratropical variability as well as El Niño in making the record GMST in 2023. Extratropical Southern Hemisphere temperature variability is smaller.

Among the contributors to GMST variability, ENSO is predictable a few seasons in advance, and tropical Indo-Atlantic SST variability is of seasonal persistence. The predictability of extratropical temperature variability remains to be fully determined.

Prediction

The Niño3.4 SST anomaly turned negative in August 2024, signaling the arrival of a La Niña state in the tropical Pacific. Nevertheless, the 2024 monthly GMST anomalies matched or exceeded those of 2023 for the first eight months (Fig. S3), stirring speculations that 2024 could become yet another hottest year on record. We have removed the SST nudging over the tropical Pacific on 1 July each year and integrated the freely running model for 12 months. The annual-mean forecast is obtained by combining January-June observations and the 20-member TP pacemaker ensemble mean for July-December. The correlation of detrended annual GMST amounts to 0.90 between observations and the forecast for 1982–2023, and it remains high at 0.64 for the July-December mean. The forecast skill originates from high predictability of Niño3.4 SST (r = 0.77 for November-January) and the associated Indo-Atlantic response through tropical cross-basin interactions.

Our forecast initialized on 1 July 2024 puts the 2024 GMST 0.08 ± 0.08 °C (ensemble mean ± inter-member standard deviation) higher than 2023 (Fig. 1a), despite the transition of the Pacific from an El Niño to a La Niña state. As validation, observed GMST was 0.10 °C higher in 2024 than 2023. We recently updated the CM2.1 TP pacemaker simulation through 2024. The simulated two-year change in GMST from 2022 to 2024 ranges from 0.17 to 0.46 °C, inclusive of the observed value of 0.40 °C.

The prediction initialized in July 2024 indicates that the 2024/25 ENSO year will be cooler by 0.18 ± 0.10 °C than the record-shattering 2023/24 ENSO year (Fig. S2). The model over-predicts the 2024 La Niña with a July-December Niño3.4 of −0.73 °C as opposed to the observed −0.24 °C. This would exaggerate the predicted GMST decrease for the 2024/25 ENSO year.

Discussion

2023 set a record for GMST by a large margin above the previous record set in 2016. Furthermore, the 2022 to 2023 increase in GMST is the largest since at least 1880. Our TP pacemaker simulation successfully captures this jump due to the La Niña to El Niño transition. Our results indicate that barring major volcanic eruptions, ENSO is the dominant driver of year-to-year GMST variability and identify internal variability in extratropical Northern Hemisphere surface temperature[14] as the second largest source of GMST variability. Since ENSO is predictable three seasons in advance ($r > 0.5$) in our prediction initialized from the TP pacemaker run, GMST can be predicted as much as 12 months in advance. Specifically, our TP pacemaker forecast initialized in July 2024 predicts a record-high GMST in 2024 because of the lingering 2023-2024 El Niño effect. Our model predicts, however, that the 12-month mean GMST from July 2024 to June 2025 (the 2024/25 ENSO year) is to decrease as the Pacific transitions to La Niña.

Our TP pacemaker simulation uses Representative Concentration Pathway (RCP) 4.5 from January 2006 onwards. Remarkably, internal climate variability and crude RCP radiative forcing developed nearly 20 years ago without various recent variations are a recipe for the record GMST spike and the planet-on-fire temperature distribution in 2023 (Fig. 2a, b). On decadal and longer timescales, radiative forcing becomes important for GMST variations. In our TP pacemaker simulation, negative biases develop from 2016 on, possibly due to errors in RCP4.5 forcing. Satellite observations of planetary radiative imbalance at the top of the atmosphere display an increasing trend[6,15] that is systematically larger than atmospheric models forced with observed SST and sea ice can simulate[16]. More accurate radiative forcing along with better representation of cloud processes holds the promise of further improving the simulation and understanding of the GMST trend and variability.

Methods

Observational data

For observational datasets, we used the ERA5 global atmospheric reanalysis[17] for surface temperature and winds; the GISS Surface Temperature Analysis (GISTEMP) version 4[18] for GMST; the Optimum Interpolation Sea Surface Temperature (OISST) version 2[19] and Extended Reconstructed SST (ERSST) version 5[20] for SST.

Model simulations

We used the Geophysical Fluid Dynamics Laboratory coupled model version 2.1 (CM2.1)[10] for the simulations. Freely coupled historical (HIST) and the TP pacemaker runs are forced with the historical radiative forcing of Coupled Model Intercomparison Project phase 5 (CMIP5) for the 1982–2005 period and Representative Concentration Pathway 4.5 (RCP4.5) afterward. In our TP pacemaker experiment[21], tropical Pacific SST is restored to the daily HIST climatology plus observed interannual OISST anomaly with a 10-day e-folding time for a 50 m ocean mixed layer. The anomalies are defined from the 1982–2011 climatology. The restoring region spans 15°S–15°N from the American coast to the dateline and a triangle wedge extending to 135°E, with a 5° buffer zone in latitude. The ocean and atmosphere are fully coupled elsewhere. HIST and TP pacemaker runs have 40 and 20 members, respectively, with different initial conditions.

To assess the potential ENSO effect in the 2024-2025 GMST, CM2.1 was branched off from 1 July 2024 of the TP pacemaker simulation and run in fully coupled mode for 12 months. The 20 ensemble members share the same ENSO conditions through June 2024 but diverge thereafter due to internal variability outside of TP. The prediction skill was tested by conducting a hindcast from July 1 in each year from 1983 to 2023.

The 10-member TP pacemaker simulation using the Community Earth System Model version 2 (CESM2)[11] was conducted through 2019 by CESM Climate Variability and Change Working Group. We extended the CESM2 TP pacemaker simulation through December 2023. It uses ERSST monthly anomalies relative to the 1880–2019 climatology and the CMIP6 historical (through 2014) and Shared Socioeconomic Pathway (SSP3-7.0) radiative forcing. The corresponding 50-member radiative forcing-only simulations (CESM2 HIST) are obtained from CESM2 Large Ensemble Community Project.

Data availability

The observational data are publicly available: ERA5 (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5); GISTEMP (https://data.giss.nasa.gov/gistemp/); OISST (https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html); ERSST (https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html). Part of CESM2 simulations were downloaded from the Casper system in National Center for Atmospheric Research.

Code availability

All codes supporting the findings of this study are available from the corresponding authors upon request.

Received: 9 December 2024; Accepted: 13 March 2025;
Published online: 22 March 2025

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Acknowledgements
SPX is supported by the National Science Foundation (AGS 2105654); Y.K. by the Japan Ministry of Education, Culture, Sports, Science and Technology through the Program for Advanced Studies of Climate Change Projection (JPMXD0722680395) and the Arctic Challenge for Sustainability II (JPMXD1420318865), and by the Japan Society for the Promotion of Science (JP23K25937, JP23K25946, JP24H00261, and JP24H02223); Y.L. by the Schmidt AI in Science postdoctoral fellowship.

Author contributions
S.P.X. and A.M. conceptualized the study. A.M., P.Z., and Y.K., performed the CM2.1 simulations; A.M. extended the CESM2 simulation; A.M. and P.Z. performed the analysis. S.P.X. drafted the paper. All the authors participated in discussion and commented on the paper.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41612-025-01006-y.

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