Global mean surface temperature anomalies in 2023/2024: Towards understanding the influencing factors

This section explores open science questions, and research on the topic is still evolving.

The records in global mean surface temperature set in 2023 and 2024 occurred in the context of rising temperatures driven by a continued increase in emissions of anthropogenic greenhouse gases (GHGs). However, despite the transition from La Niña to El Niño, the specific magnitudes of the anomaly in 2023 (and to a lesser extent that in 2024) drew attention for being at the edge of, or outside of, ranges from individual forecasts. According to some analyses (for example, that of Rantanen and Laaksonen[54]), they were at the far end of what has been expected from climate model estimates of trends plus internal variability.

A number of additional factors might help explain these records: a faster-than-expected onset of Solar Cycle 25, the developing impacts of the International Maritime Organization (IMO) rules on shipping fuel sulfur content that came into force in January 2020, the eruption of Hunga Tonga–Hunga Ha'apai (HTHH) in January 2022, and decadal decreases in aerosol emissions from East Asia (Figure 12). Anomalous patterns of internal variability in Saharan dust over the Atlantic and/or Antarctic sea-ice extents may also have played a role.

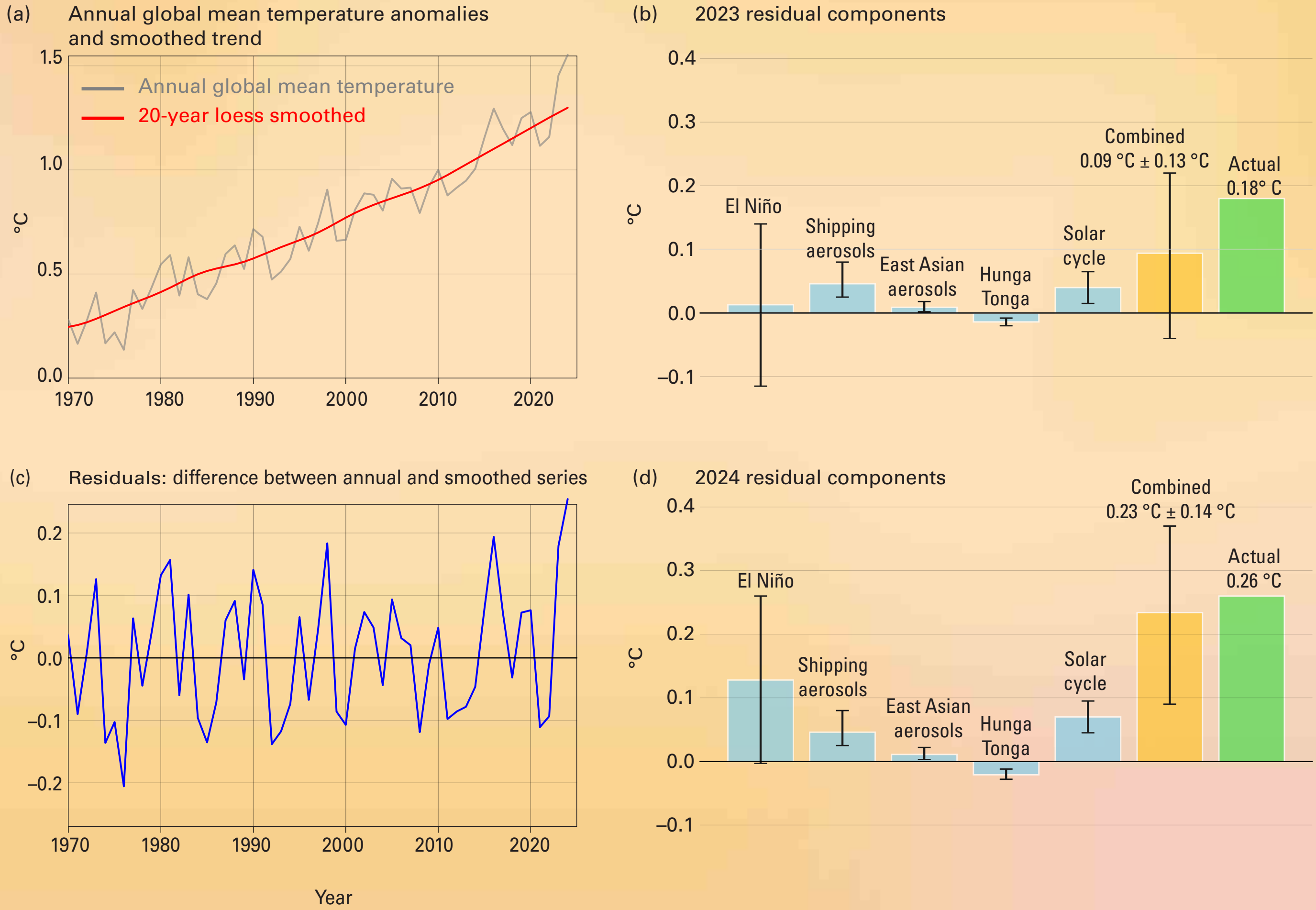

Figure 12. (a) Annual global mean temperature. Estimates of relative temperature residuals for (b) 2023 and (d) 2024 attributable to ENSO and four distinct forcings that were not (or were only partially) predicted. The (c) residuals are calculated by taking the difference between the annual global mean temperatures and the 20-year loess smoothed curve fitted to the data through to 2022. Uncertainties are nominally the 95% confidence level.

Determining the impact of each of these effects on global temperatures has been complicated by the time needed to assemble estimates of historical emissions; hence, no fully comprehensive syntheses have yet been published. Nonetheless, a rough estimate can be made by combining the results of recent studies. For details of the methods, see Data sets and methods.

Here, we focus on "residuals" (Figure 12c), that is the differences from a smoothly rising trend calculated over the period through to the end of 2022. The residuals for 2023 and 2024 are 0.18 °C and 0.26 °C, respectively. We estimate the contribution to the residuals in 2023 and 2024 from five quantifiable external drivers (GHGs, shipping aerosols, East Asian aerosols, the HTHH volcanic eruption and the solar cycle), and additionally include an estimate for the impact of ENSO, which went from a multi-year La Niña at the beginning of 2023 to El Niño at the end of 2023 and back to neutral or mild La Niña conditions at the end of 2024. The impact of GHGs on the residuals in these two years is small (<0.01 °C), as changes from GHGs are represented in the smoothly rising trend line. They dominate the anomaly with respect to the pre-industrial period.

In total, there is an additional radiative forcing from these drivers in recent years of ~0.14 W m^{-2}, and the consequent warming (~0.1 °C) combined with the effect of ENSO come close to explaining the residuals (taking into account the uncertainties), although this is more true for 2024 than for 2023 (Figure 12(b) and (d)). The warming contribution of shipping and East Asian aerosol reductions are likely to persist, contributing to a slight jump in long-term temperatures not fully accounted for in existing projections.

Fuller analyses of these factors and the role of internal variability will require coordinated Earth system model experiments, which are currently underway. The sensitivity of the attribution to the strength of each model's cloud feedbacks, aerosol–cloud interactions, etc. remains to be seen. We stress that this is a preliminary estimate that will be refined as more sophisticated studies are undertaken.

SIDE BAR – GLOBAL MEAN SURFACE TEMPERATURE ANOMALIES IN 2023/2024: TOWARDS UNDERSTANDING THE INFLUENCING FACTORS

The global temperature series used is the average of the six global temperature datasets described in Global temperature data. The smoothly rising trend was estimated using a 20-year loess smoothed curve fitted to the data through 2022 and projected to 2024.

The impact of ENSO on the temperatures can be estimated in multiple ways. A linear regression of the annual mean relative anomaly on the February/March Niño 3.4 index is used here and suggests an impact of −0.07 °C, 0.01 °C and 0.13 °C for 2022, 2023 and 2024, respectively (95% CI, ±0.13 °C). Some results from pre-industrial control climate model simulations[56] suggest a transition from triple-dip La Niña to El Niño can produce an anomalous jump of up to 0.25 °C in the year of transition, but it is unclear how to apply this to 2023, since one would need to condition the effect on the ENSO change that was actually experienced.

The IMO regulation change in 2020 led to a quick reduction of about 7 $TgSO_2$ per year and a step change of radiative forcing of 0.15 [0.1–0.2] W m^{-2} (with a range estimated from a selection of studies[57,58,59,60,61]). The temperature impacts in 2023 calculated by the respective studies reviewed are between 0.03 °C and 0.08 °C, and they are slightly larger in 2024.

Solar cycle 25 was both slightly earlier and slightly stronger than had been expected, and the impact of the total solar irradiance (TSI) anomaly of 0.97 W m^{-2} in 2023 relative to the mean of the prior 20 years is a radiative forcing of approximately 0.17 W m^{-2} and an estimated impact of 0.07 °C [0.05–0.10] °C on surface global mean temperatures with a one to two year lag.[62] Thus, the impacts on 2023 and 2024 are around 0.04 °C and 0.07 °C, respectively (±0.025 °C).

East Asian sulfate aerosol emissions have fallen sharply from their peak in 2006 (38 $TgSO_2$ per year) – a third by 2014 (23 $TgSO_2$ per year) and then by an additional 50% since then (in 2022 it was 11 $TgSO_2$ per year). On its own this would lead to additional radiative forcing of 0.14 W m^{-2} and warming of 0.06 °C (±0.04 °C) in 2023 compared to a world where East Asian aerosol emissions remained at 2006 levels. But some of this decline will have already affected the long-term trends, and so the anomaly in 2023 relative to 2020 is only 0.01 °C (calculated using the Finite Amplitude Impulse Response (FaIR) model[63] (Leach et al., 2021)).

The HTHH volcanic event added both SO_2 and water vapour to the stratosphere (up to 56 km in altitude). The rapid oxidation of SO_2 to sulfate aerosol dominated the radiative forcing for the first two years after the eruption, and so the net radiative forcing at the tropopause was likely negative: −0.04 W m^{-2} and −0.15 W m^{-2} in 2022 and 2023, respectively,[64] implying a temperature impact of −0.02 °C [−0.01 °C to −0.03 °C], calculated using the FaIR model.