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El Niño, La Niña and recorded heat deaths in India: index choice and early-warning value in a warming climate

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Title page (not sent to reviewers)

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Data availability. All source data are public, and each source is cited in Section 2 with its URL or publication in the reference list; Online Resource 1, Table S8 lists every National Crime Records Bureau edition and table used. The derived state-level panels of recorded heat/sun-stroke deaths, farming-sector suicides (aggregated state-year counts) and foodgrain production, the population denominators, the ENSO and climate exposure tables and the model inputs are openly available at https://github.com/hssling/elnino-heat-india and archived on Zenodo (Siddalingaiah 2026; https://doi.org/10.5281/zenodo.23556278), derived data under the CC BY 4.0 licence. The sources are the National Crime Records Bureau's *Accidental Deaths and Suicides in India* (https://www.ncrb.gov.in/accidental-deaths-suicides-in-india-adsi.html); the Open Government Data Platform India file of suicides by profession, 2001–2012; the Reserve Bank of India's *Handbook of Statistics on Indian States*, Table 54; the Census of India and the official population projections; the NOAA Climate Prediction Center's ENSO indices (https://www.cpc.ncep.noaa.gov/data/indices/); the NOAA Physical Sciences Laboratory's Dipole Mode Index; and India Meteorological Department gridded rainfall and temperature data (https://imdpune.gov.in/cmpg/Griddata/rainfall.php and https://imdpune.gov.in/cmpg/Griddata/maxtemp.php).

Code availability. The Python pipeline that builds the panels from the official sources and the R code that reproduces all analyses, supplementary tables and figure data are openly available in the same repository (https://github.com/hssling/elnino-heat-india; Zenodo, https://doi.org/10.5281/zenodo.23556278) under the MIT licence.

Ethics approval. Not applicable. This study used exclusively publicly available, de-identified, aggregated secondary data. No individual-level data were collected.

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Use of large language models. During the preparation of this work we used Claude Opus 5.5 (Anthropic) to assist with data-processing and analysis code and with drafting. After using this tool, we reviewed and edited the content as needed and take full responsibility for the content of the published article. As the journal asks, this use is also documented in the Methods (Section 2.12 of the manuscript).

Dataset reference (withheld from the anonymized manuscript; to be restored to its reference list at acceptance). Siddalingaiah HS (2026) El Niño, heat extremes, drought and mortality in India, 2001–2024: data and code (version 1.0.0). Zenodo. https://doi.org/10.5281/zenodo.23556278

El Niño, La Niña and recorded heat deaths in India: index choice and early-warning value in a warming climate

Abstract

We asked whether El Niño–Southern Oscillation (ENSO)–health estimates depend on the index, now adjusted operationally for tropics-wide warming, and whether ENSO, forecast before South Asia's April–June hot season, adds lead time to heat early warning. We analysed 23,821 heat/sun-stroke deaths recorded in 34 Indian states and union territories, 2001–2024, in negative-binomial mixed models; because a year random intercept was estimated at zero, year-level uncertainty was assessed with a national 24-year model, leave-one-year-out refits and a year-block bootstrap. Per 1 °C of the preceding December–February traditional Oceanic Niño Index (ONI), the rate ratio was 1.28, with a year-block 95% confidence interval (CI) of 1.06–1.50; it was 1.27 with the Relative Oceanic Niño Index (RONI) and 1.27 nationally. Fewer deaths followed La Niña winters in every specification reported (0.74, 95% CI 0.60–0.91, per 1 °C cooler), also without 2020–2023. The El Niño-phase estimate was fragile: 1.21 with the ONI, 1.13 with RONI and 1.13 without 2024. Withholding whole El Niño episodes, adding ENSO to a baseline without the previous year's count reduced forecast error by 0.6% (skill −1.1% without 2024), but not once observed local heat was known. Illustrative +2.0 °C scenarios implied 359–510 additional recorded deaths in 2027 with a separate El Niño term (including zero with RONI) and 586–725 with a single symmetric term, whose slope partly reflects La Niña winters; the indices' +2.0 °C values describe different events. ENSO–health studies should report both indices; whether ENSO outlooks improve heat-health preparedness beyond local temperature forecasts and surveillance remains untested.

Keywords: El Niño–Southern Oscillation; Relative Oceanic Niño Index; Heat-related mortality; Heat-health early warning; Forecast validation; India

1 Introduction

The El Niño–Southern Oscillation (ENSO) affects health in many regions (Kovats et al. 2003), and its state is forecast months ahead, so ENSO indices have been proposed as early-warning signals for climate-sensitive disease (Dhiman and Sarkar 2017). In South Asia the timing is favourable: the December–February ENSO state is known by March, before the April–June hot season. Indian heatwaves are linked to sea-surface temperatures in the tropical Indian Ocean and the central Pacific (Rohini et al. 2016), and monsoon onset, which ends the pre-monsoon heat, varies with El Niño (Joseph et al. 1994). One type of heatwave over coastal eastern India, however, follows Pacific cooling (Ratnam et al. 2016), so El Niño and La Niña need not act as mirror images. Heat is a major cause of death in India (Azhar et al. 2014; Fu et al. 2018; Mazdiyasni et al. 2017). A heat action plan has been associated with fewer deaths (Hess et al. 2018), and national guidelines exist (National Disaster Management Authority 2019), but city plans often frame heat as a time-limited disaster event (Dasgupta et al. 2025), so a seasonal signal that arrives early could help.

Two questions decide whether such a signal is useful in a warming climate. The first is early-warning value. Whether a Pacific index known before the hot season adds information can only be judged out of sample, withholding whole El Niño events rather than single years, and the answer depends on what the index is added to: the season's observed local heat, or only information available in March.

The second question is index choice. Warming across the tropics biases the traditional Oceanic Niño Index (ONI) as a measure of ENSO, and the Relative Oceanic Niño Index (RONI), which expresses the Niño-3.4 anomaly relative to the tropical-mean sea-surface temperature anomaly, was proposed to remove this drift (L'Heureux et al. 2024). The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) announced in February 2026 that RONI would become its official ENSO index

(Climate Prediction Center 2026a). Published ENSO–health associations were estimated with the traditional index, and whether they survive the switch is unknown.

India is a demanding test case. Heat/sun-stroke deaths recorded by the National Crime Records Bureau (NCRB) are available for every state over two decades and have been described (Kumar and Singh 2021; Kumar and Tiwana 2026), and ENSO has been linked to Indian heatwave hotspots (Banerjee et al. 2026). We are not aware of a study that has modelled these recorded deaths across all Indian states against ENSO, tested the added value of ENSO out of sample by withholding whole El Niño episodes, or compared the traditional ONI, RONI and Niño-3.4 as exposures. We therefore asked, across 34 state-level units over 24 years, whether recorded heat/sun-stroke deaths follow the preceding December–February ENSO index, whether El Niño and La Niña phases contribute differently, how much the answers depend on the index, and whether ENSO improves out-of-sample prediction, with and without observed local heat. ENSO is a pathway of climate variability, not a measure of climate change; this study concerns how that pathway is measured and used as the climate warms, and it does not attribute any deaths to anthropogenic climate change.

2 Materials and methods

2.1 Study design, pre-specification and reporting

This was an ecological panel study (Morgenstern 1995) of 34 state-level units, covering all Indian states and union territories, with annual data, reported following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement and its REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) extension (von Elm et al. 2007; Benchimol et al. 2015). Three units pool states that sources report jointly in some years and separately in others: Andhra Pradesh with Telangana, Jammu and Kashmir with Ladakh, and Dadra and Nagar Haveli with Daman and Diu.

The written analysis plan (15 October 2026) specified one primary estimand: a single symmetric term for the preceding December–February ONI, with unit random intercepts and slopes, a smooth year trend and indicators for the 2014 change in cause label and for 2020. It specified one hypothesis for this outcome: deaths are higher in El Niño-decaying years, mainly through heatwave days, judged consistent with the data only if the lower 95% confidence bound of the decaying-year rate ratio exceeded 1 and heatwave days had the largest proportion mediated of three mediators, with a bootstrap lower bound above 0. On the same day, before the analysis code was written or any result was seen, a dated amendment added separate El Niño and La Niña terms and made them primary, with the symmetric term as a sensitivity analysis; the record of that decision was committed two days later. After the first results, the symmetric estimate was reported in its own row rather than within the El Niño sensitivity range, because it is a different estimand; no estimate changed. For this revision, before any new model was fitted, although with the first-round results known, we returned to the pre-specified symmetric term as the lead estimate; the change restores the originally specified estimand. The traditional ONI and RONI are reported side by side; the separate El Niño and La Niña terms are secondary, and the Niño-3.4 model, the national model and the leave-one-year-out refits are sensitivity analyses. A further dated amendment, committed before its models were fitted, added the year-block, 2020–2023 and lead-time analyses described below. P values are unadjusted and descriptive. The dated plan, amendments and decision log are available to reviewers in Online Resource 2 and will be in the public repository.

2.2 Outcomes

The outcome was deaths recorded as accidental heat/sun-stroke deaths in the NCRB's annual *Accidental Deaths and Suicides in India* (ADSI), state tables of deaths due to natural causes, 2001–2024 (National Crime Records Bureau n.d.). ADSI compiles deaths reported to the

police, so it captures only deaths that enter medico-legal records and are attributed to heat; official statistics substantially under-report heat-related deaths in India (Narang and Gadgil 2026). The cause label was “Heat Stroke” until 2013 and “Heat/Sun Stroke” from 2014; no change of coding is documented. A dash was read as zero. Values for 2017–2021 agreed for every unit-year with a Ministry of Earth Sciences annexure (Ministry of Earth Sciences 2023); because the annexure reproduces ADSI data, this confirms transcription only. We report relative measures, which are protected against under-recording only if it is constant within a unit and unrelated to ENSO (Section 4.5).

Farming-sector suicides, 2001–2023 (National Crime Records Bureau n.d.; National Crime Records Bureau 2013), and foodgrain production, 1997–2016 (Reserve Bank of India 2019), were secondary outcomes describing the drought pathway; their data and methods are in Online Resource 1, Section S2. Population came from the 2001 and 2011 censuses, linearly interpolated between them, and from official projections for 2012–2027 (Office of the Registrar General & Census Commissioner, India 2011; National Commission on Population 2019). Missing values were never set to zero; a row missing any variable a model used was dropped and reported (Online Resource 1, Table S1), and nothing was imputed.

2.3 ENSO and Indian Ocean exposures

The traditional ONI is CPC’s 3-month running mean of the Niño-3.4 sea-surface temperature anomaly from the Extended Reconstructed Sea Surface Temperature dataset, version 6 (ERSSTv6); RONI is CPC’s ERSSTv6-based relative index (Climate Prediction Center 2026c; L’Heureux et al. 2024). The exposure was the index for December of the previous year to February of the current year (the preceding December–February). The symmetric form entered the index as one term (rate ratio per 1 °C over its whole range). The piecewise form entered an El Niño term, max(index, 0), and a La Niña term, min(index, 0), reported per 1 °C cooler. An El Niño episode was at least five consecutive overlapping seasons with ONI

≥+0.5 °C; a year was El Niño-decaying if its December–February season belonged to an episode that began in an earlier year, and El Niño-developing if its July–September season belonged to an episode. The Indian Ocean Dipole, which modifies the monsoon's response to ENSO (Saji et al. 1999; Ashok et al. 2001), entered as the September–November mean of the Dipole Mode Index (DMI) of the preceding year (NOAA Physical Sciences Laboratory 2026).

2.4 Local climate

Daily India Meteorological Department (IMD) gridded rainfall (0.25°) and maximum temperature (1°), 1981–2025 (Pai et al. 2014; Srivastava et al. 2009), were area-weighted over the state polygons of the Database of Global Administrative Areas (GADM) version 4.1 India file (GADM 2022), including that file's disputed-area polygons, and pooled to the 34 units; areas that GADM places in other countries' files are not covered. A heatwave day was a day with maximum temperature ≥45 °C, or ≥40 °C and ≥4.5 °C above the 1981–2010 calendar-day normal, following IMD's plains criteria (India Meteorological Department n.d.) but without its station, duration, hill and coastal conditions; annual counts were area-weighted means. The other local variables were the March–June mean maximum-temperature anomaly and the monsoon onset anomaly (positive values are later onsets), against 1981–2010; their construction is described in Online Resource 1, Section S1.

2.5 Models for heat deaths

Heat deaths were modelled with negative-binomial generalized linear mixed models with the quadratic variance function (NB2): log E[deaths] = log(population) + ENSO term(s) + natural cubic spline of year with 4 degrees of freedom (df) + indicator of the 2014 cause-label change + indicator of 2020 (coronavirus disease 2019 disruption) + unit random intercept and slope on the ENSO term. If the correlated random-effect fit did not converge with a positive-definite Hessian, uncorrelated and then intercept-only unit structures were used, and the

structure was recorded. Separate models replaced the ENSO terms with the decaying-year indicator, added the DMI and its interaction with the ONI, or replaced ENSO with heatwave days or the March–June temperature anomaly. The ENSO models give total associations, not conditional on local climate. Results are incidence rate ratios (IRR), the proportional change in the rate of recorded deaths, with Wald 95% confidence intervals (CI).

2.6 Year-level inference

ENSO takes one value per year, shared by all 34 units, so the effective sample size for ENSO associations is the number of years (24), not the number of unit-years. Year fixed effects are collinear with ENSO and were not used. Instead, every ENSO model was refitted with a year random intercept in addition to the unit random effects, for the symmetric and piecewise forms and for the ONI, RONI and Niño-3.4; the unit structure followed the fallback rule, and the year intercept was never dropped; most of these fits used uncorrelated or intercept-only unit structures (Online Resource 1, Table S1). As checks we fitted a national negative-binomial time series of the 24 annual totals with the same exposures, a 3-df spline of year and the two indicators; refitted the piecewise ONI model with the year random intercept 24 times, each time leaving out one calendar year; and re-derived the intervals of the four headline models (symmetric and piecewise terms, ONI and RONI) and of the heatwave-days mediation with a year-block bootstrap (500 resamples for the headline models; Section 2.7).

2.7 Mediation

Mediation used the product of coefficients (VanderWeele 2016): the change in each mediator per 1 °C of the preceding December–February ONI (Gaussian mixed model) multiplied by the mediator's coefficient in a negative-binomial model that also contained the ONI (symmetric term), both with unit random intercepts, the year spline and the indicators. The proportion mediated is the indirect over the total log rate ratio; this decomposition is descriptive, not causal, as it assumes no exposure–mediator interaction and no unmeasured

mediator–outcome confounding. Intervals were percentiles of 1,000 bootstrap resamples of units and, for heatwave days, also of 500 year-block resamples, each drawing the 24 years with replacement and keeping all units of a drawn year; if more than 10% of refits failed, no interval was reported.

2.8 Out-of-sample validation and the lead-time test

Five nested models were fitted to identical rows. Model A, the trend-and-persistence baseline, had unit random intercepts, the trend, the indicators and the previous year's log(1 + deaths). Model B added the predicted year's observed heatwave days and March–June temperature anomaly, which no forecaster knows in March. Model C added the El Niño and La Niña terms of the ONI and the DMI to Model B. Model D was Model A plus the El Niño and La Niña terms; apart from the previous year's recorded count (published by NCRB late in the following year or later), it uses only information available before the hot season, so it is an optimistic test of lead-time value. Model C-noDMI was Model C without the DMI. Models A and D were also refitted without a lagged count (Models A0 and D0, using only information available in March: the lead-time test reported first) and with the count from two years earlier (Models A2 and D2). Leave-one-El-Niño-out folds each withheld one episode's decaying year(s) and the following year (2003–04, 2005–06, 2007–08, 2010–11, 2015–17, 2019–21 and 2024, the last scoring 2024 only); training excluded the year(s) whose lagged count would carry withheld information. Rolling-origin validation trained on years up to $t-1$ and predicted year t, for 2015–2024. Coefficients not estimable in a training set were set to zero for prediction.

Point accuracy was the mean absolute log error (MALE) on log(1 + count), a typical proportional error. Probabilistic accuracy was the mean negative-binomial log score (Gneiting and Raftery 2007), and the coverage of nominal 95% prediction intervals from 200 joint draws of fixed and unit random effects plus negative-binomial noise. Skill of a model

over its reference was $100 \times (1 - \mathrm{MALE}_{new}/\mathrm{MALE}_{ref})$, and the log-score gain was the reference score minus the new score; for both, positive values favour the model with ENSO terms. We also counted the folds in which each model did better, and repeated every comparison with the 2024 rows removed from scoring.

2.9 Comparison of ENSO indices

As a pre-specified secondary aim, the piecewise model was refitted with RONI and with the December–February mean of CPC's monthly Niño-3.4 anomaly (ERSST version 5, 1991–2020 base period) in place of the traditional ONI, and compared by the same validation and by Akaike's information criterion. The Niño-3.4 series differs from the other two in both dataset version and anomaly convention.

2.10 Illustrative scenario outlook

Four models with a year random intercept (ONI and RONI, symmetric and piecewise) gave model-implied additional recorded deaths in 2027 relative to a neutral index of zero, under scenario values of +1.5, +2.0 and +2.5 °C of each model's own index, with 2027 covariates (cause-label indicator 1, 2020 indicator 0, projected 2027 population) and the 2027 year effect at zero. Means and nominal 95% intervals came from 1,000 joint parameter draws; a secondary interval also drew the 2027 year effect from its estimated distribution, and scenario values outside the training range of the index were flagged. These are conditional scenarios, not forecasts or climate projections, and they extrapolate the trend.

2.11 Sensitivity analyses

These were: a single symmetric ONI term without a year random effect, as originally specified; RONI; random intercepts only; excluding 2020–2021; and excluding Dadra and Nagar Haveli and Daman and Diu, whose post-2011 population projection is implausible (Online Resource 1, Table S5). With the year random intercept, the ONI and RONI models

were refitted excluding 2020–2023 and with an indicator for 2020–2022 added, and the piecewise models were tested for equal El Niño and La Niña slopes (Wald test).

2.12 Software and AI use

Analyses used R 4.5.3 with glmmTMB 1.1.15.2, MASS, data.table and splines (R Core Team 2026; Brooks et al. 2017), and Python 3.14.0 with pandas 2.3.3. We used Claude Opus 5.5 (Anthropic) to assist with data-processing and analysis code and with drafting; we checked all code, numbers and citations and take responsibility for the content. Every number in the text is filled from the analysis output files. The derived data, the analysis code and the dated analysis records are provided for review as Online Resource 2, an anonymized copy of the public repository.

2.13 Ethics

Ethics approval was not applicable: only publicly available, de-identified, aggregated secondary data were used, and no individual-level data were collected.

3 Results

3.1 Data

The heat panel included 816 unit-years from 34 units and 23,821 recorded heat/sun-stroke deaths (Fig. 1). Of 24 years, 9 were El Niño-decaying (2003, 2005, 2007, 2010, 2015, 2016, 2019, 2020 and 2024). The national rate of recorded deaths per 10 million population had a median (range) of 9.8 (3.9–15.0) in El Niño-decaying years and 6.7 (2.7–10.2) in other years (Table 1). The piecewise model without a year random effect used the uncorrelated random intercept and slope unit structure (Online Resource 1, Table S1; ENSO and Dipole combinations by year in Table S2).

3.2 ENSO and recorded heat deaths

With a year random intercept, the rate ratio of recorded deaths per 1 °C of the preceding December–February ONI (symmetric term; Table 2) was 1.28 (95% CI 1.16–1.42). It was 1.27 (95% CI 1.17–1.37) with RONI and 1.26 (95% CI 1.16–1.35) with Niño-3.4, and the national 24-year time series gave 1.27 (95% CI 1.16–1.38) with the ONI and 1.27 (95% CI 1.16–1.39) with RONI. The variance of the year random intercept was estimated at 0.000 in this model and in every other year-random-effect model, a boundary estimate, so these state-panel intervals equal those without the year effect (1.28, 95% CI 1.16–1.42). With the year-block bootstrap, the 95% CI of the symmetric term was 1.06–1.50 with the ONI and 1.15–1.48 with RONI, against Wald intervals of 1.16–1.42 and 1.17–1.37 (Table 2); in the mediation model the total association was 1.27 (95% CI 1.15–1.46), against 1.27 (95% CI 1.17–1.37) with a Wald interval. Recorded deaths were higher in El Niño-decaying than in other years (1.57, 95% CI 1.33–1.85), and each additional heatwave day had a rate ratio of 1.07 (95% CI 1.04–1.10) and each 1 °C of March–June temperature anomaly 1.26 (95% CI 1.08–1.46), in models without ENSO terms.

3.3 El Niño and La Niña phases

The La Niña term was consistent across specifications: per 1 °C cooler, the rate ratio was 0.74 (95% CI 0.60–0.91) with the ONI, 0.69 (95% CI 0.56–0.85) with RONI and 0.71 (95% CI 0.57–0.88) with Niño-3.4, and 0.64 (95% CI 0.52–0.80) and 0.58 (95% CI 0.48–0.71) in the national model (Table 2). The El Niño term was not. Per 1 °C above zero it was 1.21 (95% CI 1.05–1.40) with the ONI but 1.13 (95% CI 0.93–1.36) with RONI and 1.16 (95% CI 0.99–1.35) with Niño-3.4, and in the national model 1.11 (95% CI 0.95–1.29) with the ONI and 0.95 (95% CI 0.79–1.14) with RONI. With year-block intervals, the ONI El Niño term was 1.21 (95% CI 1.02–1.63) and the La Niña term 0.74 (95% CI 0.54–0.97); with RONI they were 1.13 (95% CI 0.86–1.64) and 0.69 (95% CI 0.52–0.93). The year-block intervals

were wider, but none included 1 where the Wald interval did not. In the leave-one-year-out refits (24 of 24 converged), the ONI El Niño term ranged from 1.13 (without 2024) to 1.36 (without 2016); its interval included 1 without 2024 (1.13, 95% CI 0.98–1.32) and without 2010 (1.19, 95% CI 0.98–1.44) (Online Resource 1, Table S10). Across the published sensitivity analyses it ranged from 1.13 to 1.21 (Online Resource 1, Table S5). The standard deviation of unit-specific El Niño slopes was estimated at 0.00 (likelihood-ratio test against random intercepts, P=1.000; Online Resource 1, Fig. S1), so the data had no power to detect between-state differences. The DMI term had a rate ratio of 1.26 (95% CI 0.93–1.71) and its interaction with the ONI 1.12 (95% CI 0.82–1.53). Three La Niña winters (2021–2023) followed the 2020 disruption. Excluding 2020–2023, the La Niña term was 0.76 (95% CI 0.61–0.94) with the ONI and 0.75 (95% CI 0.60–0.93) with RONI (Online Resource 1, Table S5), and the El Niño term 1.12 and 1.09. With an indicator for 2020–2022, the La Niña term was 0.78 with the ONI and 0.75 with RONI. A Wald test did not reject equal El Niño and La Niña slopes (P=0.483 with the ONI and P=0.171 with RONI).

3.4 Mediation

Per 1 °C of the preceding December–February ONI, heatwave days changed by 0.44 (95% CI 0.27–0.60), the March–June temperature anomaly by 0.21 (95% CI 0.16–0.26) °C and monsoon onset by 1.16 (95% CI 0.15–2.17) days (Table 3). Heatwave days accounted for 9% (95% CI 4–18%) of the total association on the log scale with unit resampling and 9% (95% CI 0–22%) with year-block resampling, the March–June temperature anomaly for 11% (95% CI 2–23%) and onset for 0% (95% CI −3 to 4%). By the pre-specified rule the results were not consistent with the hypothesis: deaths were higher in El Niño-decaying years, but heatwave days did not have the largest point estimate of the proportion mediated. The intervals for heatwave days and temperature overlap, so the data do not discriminate between the two mediators.

3.5 Out-of-sample skill and lead time

Refitted Models A–C reproduced the published pooled scores (reproducibility check: identical). Without a lagged count (Model D0 against Model A0), adding the El Niño and La Niña terms reduced typical error by 0.6% under leave-one-El-Niño-out validation and 3.4% under rolling origin (log-score gains +0.057 and +0.097; Table 4); without 2024 the skill was −1.1% and 1.5%, and the 2024 rows contributed 82% and 72% of the summed log-score gain. With the count from two years earlier (Model D2 against Model A2) the skill was 4.2% and 5.1% (4.2% and 5.2% without 2024).

With the previous year's count, an optimistic version of the test (Model D against Model A), the skill was 2.6% and 4.4%, with log-score gains of +0.057 and +0.067 (Fig. 2). Without 2024 the skill fell to 0.9% and 2.4%, and Model D had the better log score in 3 of 6 folds and 4 of 9 rolling years (4 of 7 and 5 of 10 with 2024). The 2024 split alone contributed 63% (leave-one-El-Niño-out) and 81% (rolling origin) of the pooled log-score gain, and adding ENSO worsened prediction in the 2015–17 episode (skill −12.8%). Once observed local heat was known, ENSO added no point skill: Model C-noDMI against Model B gave −0.2% and −0.4%, with log-score gains of +0.035 and +0.033 that fell to +0.011 and −0.005 without 2024. For the ENSO and Dipole model (Model C against Model B), skill was −0.8% under leave-one-El-Niño-out validation (7 folds, 510 unit-years; lower error in 3 of 7 folds) and 4.7% under rolling origin; its log score was better in 6 of 7 folds, but 2024 contributed 78% of that gain, without 2024 the gain was +0.009 and the skill −2.7%, and in the 2015–17 fold the skill was −0.7%. Coverage of nominal 95% intervals was 96.1% and 95.3% for Model C (Online Resource 1, Tables S3 and S9).

In the index comparison, leave-one-El-Niño-out MALE of the piecewise model, which contains no local weather, was 0.514 with the traditional ONI, 0.508 with RONI and 0.513 with Niño-3.4, and Akaike's information criterion differed by at most 0.59 (lowest with the

traditional ONI), so the indices could not be distinguished by fit or prediction (Online Resource 1, Table S4).

3.6 Illustrative scenario outlook

At a scenario value of +2.0 °C, the model-implied additional recorded deaths in 2027 were 586 (nominal 95% interval 258–1,132) with the symmetric ONI model, 510 (nominal 95% interval 153–969) with the piecewise ONI model, 725 (nominal 95% interval 375–1,234) with the symmetric RONI model and 359 (nominal 95% interval −194 to 1,078) with the piecewise RONI model, whose interval includes zero (Fig. 3; Online Resource 1, Table S11). Because the El Niño-phase estimate was fragile, the separate-term models are the more appropriate basis for an El Niño scenario. Values on the RONI and ONI scales are not interchangeable: in 2024 the traditional ONI exceeded RONI by 0.71 °C. Scenario values outside the training range were +2.5 °C (training maximum +2.14 °C) for the RONI models and none for the ONI models. Because the year-level variance was estimated at zero, these intervals omit year-to-year variation (with the 2027 year effect drawn, 586, nominal 95% interval 258–1,132, for the symmetric ONI model). Unit-level values are in Online Resource 1, Table S7.

3.7 Drought-pathway outcomes

Farming-sector suicides were not distinguishable from no association with the 3-month Standardized Precipitation Index for September (rate ratio 1.03, 95% CI 0.98–1.08, per 1-unit decrease) or with El Niño-developing years (1.07, 95% CI 0.95–1.21). Foodgrain production deviated from trend by −6.5 (95% CI −9.3 to −3.6) percentage points in El Niño-developing years (Online Resource 1, Section S2 and Tables S6 and S12).

4 Discussion

4.1 Principal findings

Across all Indian states and union territories over 24 years, recorded heat/sun-stroke deaths followed the preceding December–February ENSO index: the pre-specified symmetric estimate was 1.28 per 1 °C (Wald 95% CI 1.16–1.42; year-block bootstrap 95% CI 1.06–1.50), with similar point estimates with RONI, Niño-3.4 and a national time series. The year random-intercept variance was estimated at zero, so the Wald intervals do not reflect year-to-year variation; the year-block intervals do. Fewer recorded deaths followed La Niña winters in every specification reported, and the La Niña-phase association was at least as strong as the El Niño-phase association (test of equal slopes, P=0.483 with the ONI and P=0.171 with RONI). Three La Niña winters (2021–2023) follow the coronavirus disease 2019 disruption, and excluding 2020–2023 gave La Niña-term rate ratios of 0.76 with the ONI and 0.75 with RONI, both with intervals below 1 (Section 3.3). The El Niño-phase estimate was fragile: it depended on the index, on the level of aggregation, on 2024 and on the 2020–2023 block. ENSO added little lead-time skill, and none once observed local heat was known.

4.2 Climate variability in a changing climate

These results describe a climate-variability pathway and attribute no heat deaths to anthropogenic climate change; the smooth year trend in the models was an adjustment, not an estimate of a warming signal. Their relevance to a changing climate lies in how the pathway is measured. RONI removes the tropics-wide warming that biases the traditional index (L'Heureux et al. 2024). The symmetric estimate barely changed between the two indices (1.28 and 1.27), but the El Niño-phase estimate fell from 1.21 to 1.13 and its interval included 1. The two sensitivities are linked. The 2023–24 winter is where the indices differ most (traditional ONI +1.84 °C, RONI +1.13 °C; Fig. 1b), so moving to RONI reduces the weight of 2024, the year on which the El Niño-phase estimate depends (1.13, 95% CI 0.98–

1.32, without 2024). The index result therefore rests largely on one recent event. That is also why it matters: warming inflates the traditional index most in recent strong events. The traditional index has run above RONI since 2013, by 0.19–0.71 °C, in El Niño and La Niña winters alike, with the largest gaps in 2024 and 2020 (Fig. 1b); the more negative RONI values in 2021–2023, years of low recording after the coronavirus disease 2019 disruption, may contribute to the stronger La Niña estimate with RONI (0.69, against 0.75 without 2020–2023). Index choice therefore matters most for the quantity that ENSO-based warnings would use, the expected excess in an El Niño year. The indices could not be distinguished by fit or prediction, so ENSO–health studies should report both, to stay comparable with earlier work and with current operational classification.

4.3 Early-warning value of ENSO

The lead-time test asks whether the winter index, known in March, improves on a forecast from the trend and the reporting indicators. Without the previous year's count, which is not yet published in March, the gain was small and depended on 2024; with the count from two years earlier it was larger and changed little without 2024; with the previous year's count it depended on 2024 and was negative in the 2015–17 episode (Section 3.5). An operational version would replace the previous year's recorded count, which is not yet published in March, with an earlier count or with surveillance data. Given the season's observed local heat, ENSO added no point skill. Annual data cannot show when within the season risk peaks, and we evaluated observed rather than forecast local temperature. Our interpretation, which is consistent with these data but was not tested, is that ENSO outlooks can set the preparedness calendar, prompting the review of heat action plans before April, while local temperature forecasts and heat-illness surveillance carry the warning.

4.4 Mechanisms, recording and comparison with earlier work

Measured local heat explained a small share of the association: heatwave days accounted for 9% (95% CI 0–22%) with year-block resampling, and the interval overlapped with that for March–June temperature. Heat exposure was measured coarsely, by area-weighted state means of a simplified heatwave definition, which would understate mediation; and heat deaths may be recorded more completely in widely publicized heat years, many of which follow El Niño, which would produce an association without any change in mortality. The La Niña result runs against the coastal heatwave type that follows Pacific cooling (Ratnam et al. 2016), which would predict more deaths after La Niña winters; we found fewer. The La Niña winters of 2021–2023 also follow the coronavirus disease 2019 disruption; excluding 2020–2023 left the La Niña estimate essentially unchanged with the ONI and slightly weaker with RONI (Section 3.3). Our relative estimates complement city studies of all-cause excess mortality (Azhar et al. 2014; Hess et al. 2018) and national temperature–mortality estimates (Fu et al. 2018), which describe a much larger burden than the recorded counts.

4.5 Strengths and limitations

The strengths are a harmonized 34-unit panel covering every state, pre-specified analyses with a documented deviation ledger, year-level inference, out-of-sample validation by withholding whole El Niño episodes, and a direct lead-time test. Three limitations could change the conclusions. First, ENSO varies only by year. The year random-intercept variance was estimated at the boundary under a shared negative-binomial dispersion, so it did not widen the intervals, and the national model, the leave-one-year-out refits and the year-block bootstrap are the more informative checks on year-level uncertainty. The national model nonetheless showed residual year-to-year variation (negative-binomial θ 22–32, a year-level coefficient of variation of 0.18–0.21), so the zero estimate in the state panel more likely reflects the shared dispersion parameter absorbing year-level variation than its absence.

Second, recording. NCRB heat deaths are an administrative undercount (Narang and Gadgil 2026), possibly recorded more in well-publicized years; the national ratio of observed to model-expected recorded deaths (symmetric ONI model with the year random intercept) was 0.65 in 2001–2008, 0.92 in 2009–2013, 1.39 in 2014–2019 and 1.24 in 2020–2024, which suggests changes in recording that a smooth trend absorbs only in part. No negative-control outcome was analysed. Third, there are few El Niño episodes, which limits every El Niño-phase estimate. Heat was also area-weighted rather than population-weighted, the heatwave definition simplifies IMD's criteria and ignores humidity, a dash was read as zero, the estimates are ecological and annual, and heat-illness surveillance data could not be obtained as a cross-check.

4.6 Transferability and the 2026–27 season

The design can be applied in other settings; whether the result transfers is untested. A ministry considering ENSO-based heat warnings would need recorded heat deaths by region over several ENSO cycles, both indices, and benchmarks scored on whole withheld El Niño events, with and without observed local heat. In late 2026, CPC favoured a strong to very strong El Niño persisting through January–March 2027 (Climate Prediction Center 2026b), and India's June–September monsoon was at 87% of the long-period average (India Meteorological Department 2026). The scenario outlook is conditional, differs by index and model form, has wide intervals, and will be superseded by the observed December–February 2026–27 index in early March 2027.

5 Conclusions

Recorded heat/sun-stroke deaths in India follow the ENSO cycle, with fewer deaths after La Niña winters in every specification reported. The El Niño-phase estimate is smaller and uncertain with the warming-adjusted RONI, so ENSO–health studies in a warming climate should report both indices. Adding ENSO to information available in March reduced forecast

error by 0.6% when whole El Niño episodes were withheld, but the skill was −1.1% without 2024; with the previous year's count, which is not published by March, it worsened prediction in the strongest episode (2015–17); once observed local heat was known, ENSO added no point skill. These data therefore give no firm evidence that ENSO improves heat-death prediction at lead time: the gain depended on the baseline and, without a lagged count, on 2024. Using ENSO outlooks to time preparedness, with local temperature forecasts and surveillance carrying the warning, is a reasonable approach that this study did not test.

References

Ashok K, Guan Z, Yamagata T (2001) Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophys Res Lett 28:4499–4502. https://doi.org/10.1029/2001GL013294

Azhar GS, Mavalankar D, Nori-Sarma A, Rajiva A, Dutta P, Jaiswal A et al (2014) Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave. PLoS One 9:e91831. https://doi.org/10.1371/journal.pone.0091831

Banerjee S, Padmakumari B, Ramana MV (2026) Intensification and spatial shifts of heatwave hotspot across India under climate and ENSO influences with health risk assessment. Sci Rep 16:8437. https://doi.org/10.1038/s41598-026-38289-x

Benchimol EI, Smeeth L, Guttmann A, Harron K, Moher D, Petersen I et al (2015) The REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) statement. PLoS Med 12:e1001885. https://doi.org/10.1371/journal.pmed.1001885

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A et al (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400. https://doi.org/10.32614/RJ-2017-066

Climate Prediction Center (2026a) CPC adopts Relative Oceanic Niño Index (RONI) for reliable, responsive monitoring and tracking of ENSO. NOAA/National Weather Service, College Park (MD). https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso/roni/announcement.php. Accessed 15 October 2026

Climate Prediction Center (2026b) ENSO diagnostic discussion, 8 October 2026. NOAA/National Weather Service, College Park (MD).

https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_disc_oct2026/ensodisc.shtml. Accessed 15 October 2026

Climate Prediction Center (2026c) Monthly atmospheric & SST indices: Oceanic Niño Index, Relative Oceanic Niño Index and monthly Niño-3.4 data files. NOAA/National Weather Service, College Park (MD). https://www.cpc.ncep.noaa.gov/data/indices/. Accessed 14 October 2026

Dasgupta R, Dasgupta P, Dayal V, Mishra A, Murali A, Sharma G et al (2025) Heat action plans in eight Indian cities: knowledge gaps & opportunities for intersectoral heat governance. Indian J Med Res 162:330–341. https://doi.org/10.25259/ijmr_1019_2025

Dhiman RC, Sarkar S (2017) El Niño Southern Oscillation as an early warning tool for malaria outbreaks in India. Malar J 16:122. https://doi.org/10.1186/s12936-017-1779-y

Fu SH, Gasparrini A, Rodriguez PS, Jha P (2018) Mortality attributable to hot and cold ambient temperatures in India: a nationally representative case-crossover study. PLoS Med 15:e1002619. https://doi.org/10.1371/journal.pmed.1002619

GADM (2022) GADM data, version 4.1: India (gadm41_IND.gpkg) (July 2022). GADM. https://geodata.ucdavis.edu/gadm/gadm4.1/gpkg/gadm41_IND.gpkg. Accessed 17 October 2026

Gneiting T, Raftery AE (2007) Strictly proper scoring rules, prediction, and estimation. J Am Stat Assoc 102:359–378. https://doi.org/10.1198/016214506000001437

Hess JJ, Sathish LM, Knowlton K, Saha S, Dutta P, Ganguly P et al (2018) Building resilience to climate change: pilot evaluation of the impact of India's first heat action plan on all-cause mortality. J Environ Public Health 2018:7973519. https://doi.org/10.1155/2018/7973519

India Meteorological Department (2026) Salient features of the 2026 southwest monsoon season. India Meteorological Department, Ministry of Earth Sciences, New Delhi.

https://internal.imd.gov.in/press_release/20260930_pr_5361.pdf. Accessed 15 October 2026

India Meteorological Department (n.d.) FAQ on heat wave. India Meteorological Department, Ministry of Earth Sciences, New Delhi. https://internal.imd.gov.in/section/nhac/dynamic/FAQ_heat_wave.pdf. Accessed 15 October 2026

Joseph PV, Eischeid JK, Pyle RJ (1994) Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Niño, and sea surface temperature anomalies. J Clim 7:81–105. https://doi.org/10.1175/1520-0442(1994)007<0081:IVOTOO>2.0.CO;2

Kovats RS, Bouma MJ, Hajat S, Worrall E, Haines A (2003) El Niño and health. Lancet 362:1481–1489. https://doi.org/10.1016/S0140-6736(03)14695-8

Kumar A, Singh DP (2021) Heat stroke-related deaths in India: an analysis of natural causes of deaths, associated with the regional heatwave. J Therm Biol 95:102792. https://doi.org/10.1016/j.jtherbio.2020.102792

Kumar A, Tiwana AS (2026) Heat wave mortality, administrative visibility and disaster risk governance in India, 2013–2022. Environ Hazards 1–17 (published online 24 August 2026). https://doi.org/10.1080/17477891.2026.2720079

L'Heureux ML, Tippett MK, Wheeler MC, Nguyen H, Narsey S, Johnson N et al (2024) A relative sea surface temperature index for classifying ENSO events in a changing climate. J Clim 37:1197–1211. https://doi.org/10.1175/JCLI-D-23-0406.1

Mazdiyasni O, AghaKouchak A, Davis SJ, Madadgar S, Mehran A, Ragno E et al (2017) Increasing probability of mortality during Indian heat waves. Sci Adv 3:e1700066. https://doi.org/10.1126/sciadv.1700066

586 Ministry of Earth Sciences (2023) State/UT-wise number of accidental deaths due to heat/sun
587 stroke during 2017–2021 (annexure, Lok Sabha, 26 July 2023). Press Information Bureau,
588 New Delhi.
589 https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/jul/doc2023726228
590 401.pdf. Accessed 15 October 2026
591 Morgenstern H (1995) Ecologic studies in epidemiology: concepts, principles, and methods.
592 Annu Rev Public Health 16:61–81. https://doi.org/10.1146/annurev.pu.16.050195.000425
593 Narang P, Gadgil A (2026) Estimating heatwave-induced excess mortality in India's districts.
594 Front Environ Health 5:1789071. https://doi.org/10.3389/fenvh.2026.1789071
595 National Commission on Population (2019) Population projections for India and states 2011–
596 2036: report of the Technical Group on Population Projections (November 2019).
597 Ministry of Health & Family Welfare, New Delhi.
598 https://nhm.gov.in/New_Updates_2018/Report_Population_Projection_2019.pdf.
599 Accessed 15 October 2026
600 National Crime Records Bureau (2013) State/UT-wise professional profile of suicide victim
601 during 2001–2012 (released 10 October 2013, updated 17 April 2014). Open Government
602 Data Platform India, New Delhi. https://www.data.gov.in/resource/stateut-wise-
603 professional-profile-suicide-victim-during-2001-2012. Accessed 15 October 2026
604 National Crime Records Bureau (n.d.) Accidental deaths & suicides in India, 2001–2024
605 editions (editions and tables used are listed in Online Resource 1, Table S8). National
606 Crime Records Bureau, Ministry of Home Affairs, New Delhi.
607 https://www.ncrb.gov.in/accidental-deaths-suicides-in-india-adsi.html. Accessed 15
608 October 2026
609 National Disaster Management Authority (2019) Guidelines for preparation of action plan –
610 prevention and management of heat wave. National Disaster Management Authority,

611 Ministry of Home Affairs, Government of India, New Delhi.
612 https://ndma.gov.in/sites/default/files/PDF/Guidelines/heatwaveguidelines.pdf. Accessed
613 15 October 2026
614 NOAA Physical Sciences Laboratory (2026) Dipole Mode Index (DMI), HadISST. NOAA
615 Physical Sciences Laboratory, Boulder, CO.
616 https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data. Accessed 14 October
617 2026
618 Office of the Registrar General & Census Commissioner, India (2011) Census of India 2011,
619 Table A-02: decadal variation in population 1901–2011, India (updated 1 June 2022).
620 Office of the Registrar General & Census Commissioner, India, New Delhi.
621 https://censusindia.gov.in/nada/index.php/catalog/43333. Accessed 15 October 2026
622 Pai DS, Rajeevan M, Sreejith OP, Mukhopadhyay B, Satbha NS (2014) Development of a
623 new high spatial resolution (0.25° × 0.25°) long period (1901–2010) daily gridded rainfall
624 data set over India and its comparison with existing data sets over the region. Mausam
625 65:1–18. https://doi.org/10.54302/mausam.v65i1.851
626 R Core Team (2026) R: a language and environment for statistical computing, version 4.5.3.
627 R Foundation for Statistical Computing, Vienna. https://www.r-project.org/. Accessed 15
628 October 2026
629 Ratnam JV, Behera SK, Ratna SB, Rajeevan M, Yamagata T (2016) Anatomy of Indian
630 heatwaves. Sci Rep 6:24395. https://doi.org/10.1038/srep24395
631 Reserve Bank of India (2019) Handbook of statistics on Indian states, Table 54: state-wise
632 production of foodgrains – total foodgrains (3 March 2019). Reserve Bank of India,
633 Mumbai. https://rbi.org.in/Scripts/PublicationsView.aspx?id=18850. Accessed 15
634 October 2026

Rohini P, Rajeevan M, Srivastava AK (2016) On the variability and increasing trends of heat waves over India. Sci Rep 6:26153. https://doi.org/10.1038/srep26153

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363. https://doi.org/10.1038/43854

Srivastava AK, Rajeevan M, Kshirsagar SR (2009) Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmos Sci Lett 10:249–254. https://doi.org/10.1002/asl.232

VanderWeele TJ (2016) Mediation analysis: a practitioner's guide. Annu Rev Public Health 37:17–32. https://doi.org/10.1146/annurev-publhealth-032315-021402

von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP (2007) The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Lancet 370:1453–1457. https://doi.org/10.1016/S0140-6736(07)61602-X

Statements and Declarations

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Data availability. All source data are public, and each source is cited in Section 2 with its URL or publication in the reference list; Online Resource 1, Table S8 lists every National Crime Records Bureau edition and table used. The derived state-level panels of recorded heat/sun-stroke deaths, farming-sector suicides (aggregated state-year counts) and foodgrain production, the population denominators, the ENSO and climate exposure tables and the model inputs are openly available in a public repository with a persistent identifier [repository link provided on the title page to preserve anonymity] under the CC BY 4.0

licence (aggregates of India Meteorological Department gridded data under IMD's terms of use). For peer review, an anonymized copy, with the dated analysis plan, amendments and decision log, is Online Resource 2.

Code availability. The Python pipeline that builds the panels from the official sources and the R code that reproduces all analyses, supplementary tables and figure data are openly available in the same repository [repository link provided on the title page to preserve anonymity] under the MIT licence; the R code is included in Online Resource 2.

Ethics approval. Not applicable. This study used exclusively publicly available, de-identified, aggregated secondary data. No individual-level data were collected.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Use of large language models. Documented in Section 2.12, as the journal asks.

Tables

Table 1 El Niño-decaying and other years: recorded heat/sun-stroke deaths and local climate, 2001–2024

Measure	El Niño-decaying years	Other years
Years, n	9	15
Preceding December–February traditional ONI, °C, mean (range)	+1.15 (+0.62 to +2.50)	−0.64 (−1.76 to +0.34)
Recorded heat/sun-stroke deaths per year, national, median (range)	1,274 (530–1,908)	793 (374–1,248)
Recorded heat/sun-stroke deaths per 10 million population, national, median (range)	9.8 (3.9–15.0)	6.7 (2.7–10.2)
Heatwave days per unit, mean (SD)	1.8 (3.4)	1.2 (2.8)
March–June maximum-temperature anomaly, °C, mean (SD)	+0.35 (0.89)	+0.28 (0.76)
Monsoon onset anomaly, days, mean (SD)	+0.3 (11.8)	−1.7 (15.2)

ONI, Oceanic Niño Index; SD, standard deviation across unit-years. El Niño-decaying: the December–February season belongs to an El Niño episode that began in an earlier year. Deaths are National Crime Records Bureau counts; national values are sums over units. Climate values are unit means of India Meteorological Department gridded data (area-weighted), anomalies against 1981–2010; positive onset anomalies are later onsets. Developing-year comparisons for rainfall, drought, farming-sector suicides and foodgrain production are in Online Resource 1, Table S12.

Table 2 Associations of the preceding December–February ENSO index with recorded heat/sun-stroke deaths, by specification

Model and index	Term (unit)	IRR (95% CI)	Year-block 95% CI	P
State panel with a year random intercept, 2001–2024				
Traditional ONI	Symmetric term (per 1 °C)	1.28 (1.16–1.42)	1.06–1.50	<0.001
Traditional ONI	El Niño term (per 1 °C above 0)	1.21 (1.05–1.40)	1.02–1.63	0.008
Traditional ONI	La Niña term (per 1 °C below 0, cooler)	0.74 (0.60–0.91)	0.54–0.97	0.004
Traditional ONI, 2024 left out	El Niño term (per 1 °C above 0)	1.13 (0.98–1.32)	–	0.098
RONI	Symmetric term (per 1 °C)	1.27 (1.17–1.37)	1.15–1.48	<0.001
RONI	El Niño term (per 1 °C above 0)	1.13 (0.93–1.36)	0.86–1.64	0.210
RONI	La Niña term (per 1 °C below 0, cooler)	0.69 (0.56–0.85)	0.52–0.93	<0.001
Niño-3.4	Symmetric term (per 1 °C)	1.26 (1.16–1.35)	–	<0.001
Niño-3.4	El Niño term (per 1 °C above 0)	1.16 (0.99–1.35)	–	0.059
Niño-3.4	La Niña term (per 1 °C below 0, cooler)	0.71 (0.57–0.88)	–	0.002
National time series, 24 annual totals				
Traditional ONI	Symmetric term (per 1 °C)	1.27 (1.16–1.38)	–	<0.001
Traditional ONI	El Niño term (per 1 °C above 0)	1.11 (0.95–1.29)	–	0.188
Traditional ONI	La Niña term (per 1 °C below 0, cooler)	0.64 (0.52–0.80)	–	<0.001
RONI	Symmetric term (per 1 °C)	1.27 (1.16–1.39)	–	<0.001
RONI	El Niño term (per 1 °C above 0)	0.95 (0.79–1.14)	–	0.570
RONI	La Niña term (per 1 °C below 0, cooler)	0.58 (0.48–0.71)	–	<0.001
State panel without a year random effect (as first specified)				
Decaying year	El Niño-decaying vs other years	1.57 (1.33–1.85)	–	<0.001
Dipole	DMI, preceding Sep–Nov (per 1 °C)	1.26 (0.93–1.71)	–	0.133
Dipole	ONI × DMI interaction	1.12 (0.82–1.53)	–	0.472
Heatwave	Per additional heatwave day	1.07 (1.04–1.10)	–	<0.001
Temperature	Per 1 °C March–June maximum-temperature anomaly	1.26 (1.08–1.46)	–	0.003

CI, confidence interval (Wald, or percentile over 500 year-block resamples); DMI, Dipole Mode Index; IRR, incidence rate ratio (the proportional change in the rate of recorded deaths; values above 1 mean higher rates); ONI, Oceanic Niño Index; RONI, Relative Oceanic Niño Index. P values are unadjusted. State-panel models are negative-binomial mixed models with a log-population offset, a natural cubic spline of year (4 df), indicators for the 2014 cause-label change and for 2020, and unit random effects (symmetric ONI model: correlated unit

690 intercept and slope, year intercept; the structures of the other models are listed in Online
691 Resource 1, Table S1); the year random-intercept variance was estimated at 0.000 in every
692 model. The national model is a negative-binomial time series of 24 annual totals with a 3-df
693 spline of year and the same indicators. Symmetric and piecewise terms are separate models;
694 the last five rows are separate models without ENSO terms except the Dipole pair, which is
695 fitted with the ONI.

Table 3 Mediation of the association between the preceding December–February ONI and recorded heat/sun-stroke deaths

Mediator	Mediator change per 1 °C ONI (95% CI)	IRR per mediator unit (95% CI)	Indirect IRR per 1 °C ONI (95% CI)	Proportion mediated, % (95% CI)
Heatwave days (days)	0.44 (0.27–0.60)	1.05 (1.02–1.08)	1.02 (1.01–1.04)	9% (4–18%)
Heatwave days, year-block bootstrap intervals	as above	as above	1.02 (1.00–1.06)	9% (0–22%)
March–June maximum-temperature anomaly (°C)	0.21 (0.16–0.26)	1.13 (1.02–1.25)	1.03 (1.00–1.06)	11% (2–23%)
Monsoon onset anomaly (days)	1.16 (0.15–2.17)	1.00 (1.00–1.01)	1.00 (0.99–1.01)	0% (−3 to 4%)

CI, confidence interval (percentile; 1,000 bootstrap resamples of units, or 500 year-block resamples in which all units of a drawn year are kept together); IRR, incidence rate ratio; ONI, traditional Oceanic Niño Index (December–February before the year, single symmetric term). Each mediator was analysed separately. Mediator models are Gaussian and outcome models negative-binomial mixed models with unit random intercepts, a natural cubic spline of year and the 2014 and 2020 indicators. Total IRR per 1 °C ONI, Wald interval: 1.27 (95% CI 1.17–1.37); year-block bootstrap: 1.27 (95% CI 1.15–1.46). Proportion mediated = indirect ÷ total association on the log scale; positive onset changes are later onsets.

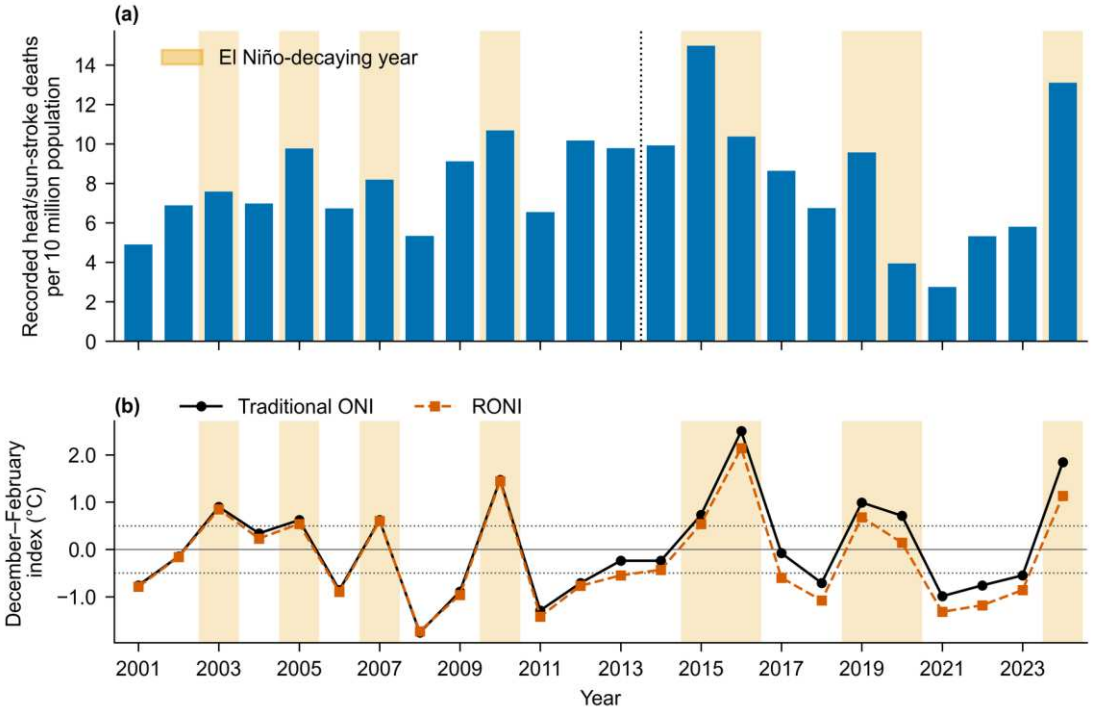
Table 4 Out-of-sample comparison of models with and without ENSO terms for recorded heat/sun-stroke deaths

Comparison	Validation	Unit-years scored	MALE skill	Log-score gain	Folds better, MALE	Folds better, log score
D0 vs A0: ENSO added to a trend baseline without a lagged count (information available in March)						
D0 vs A0	Leave-one-El-Niño-out	510	0.6%	+0.057	5 of 7	5 of 7
D0 vs A0	Leave-one-El-Niño-out, 2024 excluded	476	−1.1%	+0.011	4 of 6	4 of 6
D0 vs A0	Rolling origin	340	3.4%	+0.097	8 of 10	8 of 10
D0 vs A0	Rolling origin, 2024 excluded	306	1.5%	+0.030	7 of 9	7 of 9
D vs A: ENSO added to the trend-and-persistence baseline (previous year's count; optimistic)						
D vs A	Leave-one-El-Niño-out	510	2.6%	+0.057	5 of 7	4 of 7
D vs A	Leave-one-El-Niño-out, 2024 excluded	476	0.9%	+0.022	4 of 6	3 of 6
D vs A	Rolling origin	340	4.4%	+0.067	6 of 10	5 of 10
D vs A	Rolling origin, 2024 excluded	306	2.4%	+0.015	5 of 9	4 of 9
C-noDMI vs B: ENSO added to observed local heat						
C-noDMI vs B	Leave-one-El-Niño-out	510	−0.2%	+0.035	3 of 7	6 of 7
C-noDMI vs B	Leave-one-El-Niño-out, 2024 excluded	476	−1.9%	+0.011	2 of 6	5 of 6
C-noDMI vs B	Rolling origin	340	−0.4%	+0.033	5 of 10	6 of 10
C-noDMI vs B	Rolling origin, 2024 excluded	306	−2.7%	−0.005	4 of 9	5 of 9
C vs B: ENSO and Dipole model against observed local heat						
C vs B	Leave-one-El-Niño-out	510	−0.8%	+0.039	3 of 7	6 of 7
C vs B	Leave-one-El-Niño-out, 2024 excluded	476	−2.7%	+0.009	2 of 6	5 of 6
C vs B	Rolling origin	340	4.7%	+0.066	7 of 10	7 of 10
C vs B	Rolling origin, 2024 excluded	306	2.7%	+0.022	6 of 9	6 of 9

MALE, mean absolute log error on log(1 + deaths). MALE skill = 100 × (1 − MALE of the model with ENSO terms ÷ MALE of its reference); log-score gain = mean negative-binomial log score of the reference minus that of the model with ENSO terms; for both, positive values favour the model with ENSO terms. Folds better: leave-one-El-Niño-out folds or rolling-origin years in which the model with ENSO terms had the lower per-fold value. Model A: unit random intercepts, natural cubic spline of year, 2014 label and 2020 indicators, and the previous year's log(1 + deaths), unpublished by March; Model A0 omits it. Model B adds the

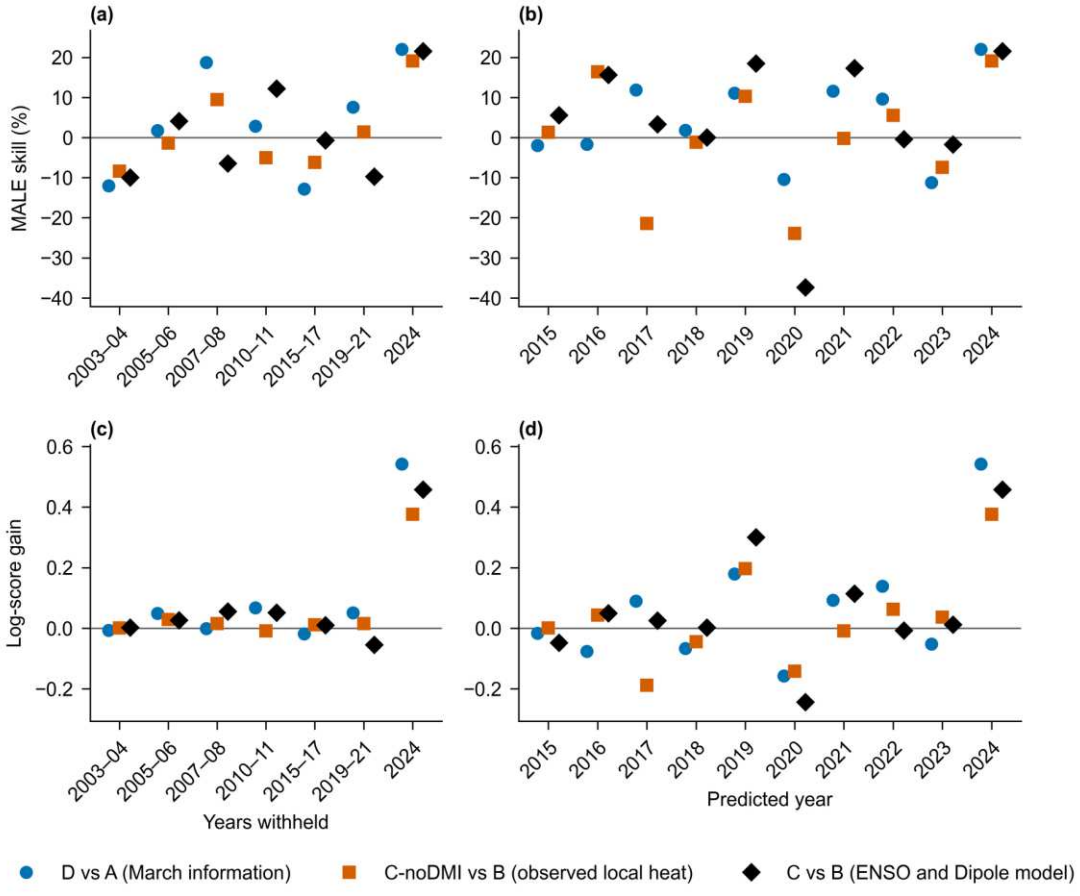
predicted year's observed heatwave days and March–June maximum-temperature anomaly. Models D and D0 add the El Niño and La Niña terms of the preceding December–February traditional Oceanic Niño Index to Models A and A0; Model C-noDMI adds them to Model B; Model C adds them and the preceding September–November Dipole Mode Index (DMI) to Model B. All models were scored on identical unit-years. "2024 excluded" removes the 2024 rows from scoring. Per-fold values are in Online Resource 1, Table S9.

721 **Figure captions**



722

723 **Fig. 1** Recorded heat/sun-stroke deaths in India and the preceding December–February
724 ENSO index, 2001–2024. **(a)** National deaths recorded by the National Crime Records
725 Bureau as accidental heat/sun-stroke deaths, per 10 million population (bars); El Niño-
726 decaying years are shaded; the dotted vertical line marks the change of cause label from
727 "Heat Stroke" (to 2013) to "Heat/Sun Stroke" (from 2014). **(b)** Traditional Oceanic Niño
728 Index (solid line, circles) and Relative Oceanic Niño Index (dashed line, squares) for the
729 December–February season before each year; dotted horizontal lines mark ±0.5 °C



730

731 **Fig. 2** Out-of-sample comparison, by fold, of models with and without ENSO terms. **(a, b)**
732 Point-forecast skill: percentage reduction in mean absolute log error of the model with ENSO
733 terms relative to its reference model. **(c, d)** Gain in mean negative-binomial log score
734 (reference minus model with ENSO terms). Panels (a) and (c) show leave-one-El-Niño-out
735 folds, labelled by the years withheld; panels (b) and (d) show rolling-origin predicted years,
736 2015–2024. Circles: Model D (trend-and-persistence baseline plus El Niño and La Niña
737 terms) against Model A; squares: Model C-noDMI (observed local heat plus El Niño and La
738 Niña terms) against Model B; diamonds: the ENSO and Dipole model C against Model B.
739 Positive values favour the model with ENSO terms; the horizontal line marks no difference

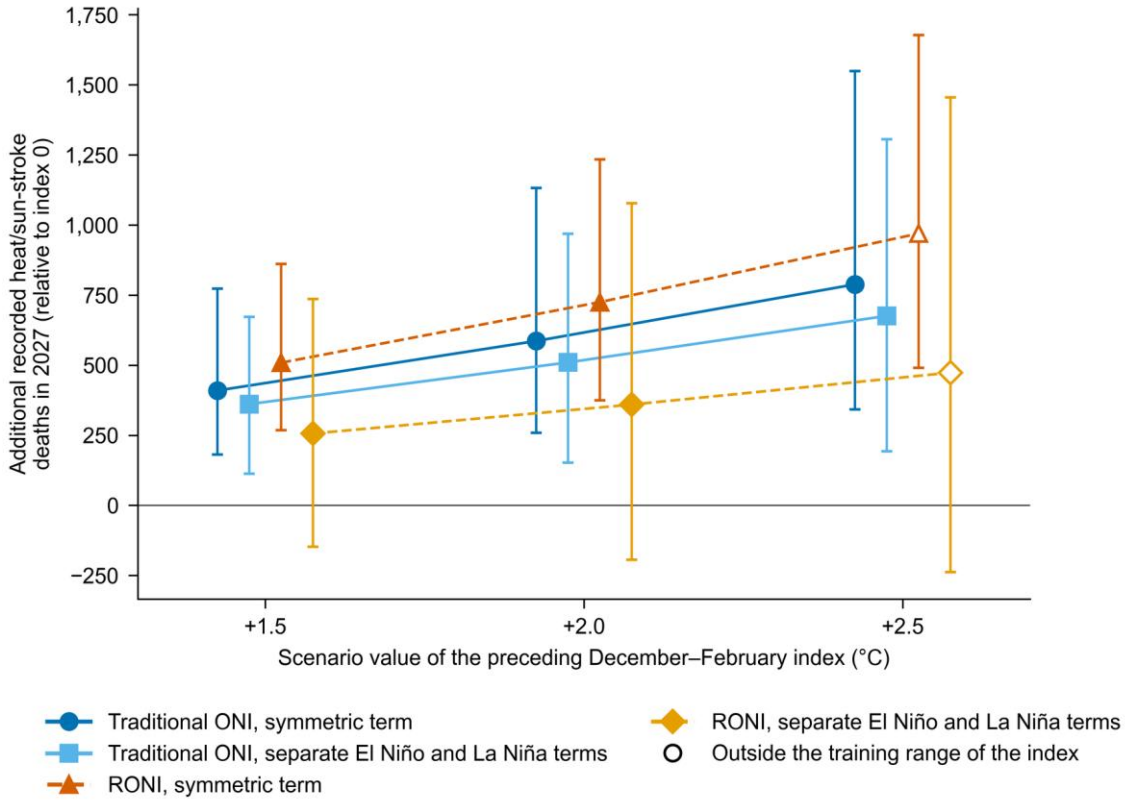


Fig. 3 Illustrative scenario outlook: model-implied additional recorded heat/sun-stroke deaths in India in 2027, relative to a neutral (zero) preceding December–February index, under scenario values of +1.5, +2.0 and +2.5 °C of each model's own index. Circles (symmetric term) and squares (separate El Niño and La Niña terms) joined by solid lines: traditional Oceanic Niño Index; triangles (symmetric term) and diamonds (separate terms) joined by dashed lines: Relative Oceanic Niño Index. Points are means and bars nominal 95% intervals from 1,000 joint parameter draws, reflecting parameter uncertainty only; open markers are scenario values outside the training range of the index. Values are on each index's own scale; equal values are not equal events. Values are recorded deaths, an under-count of heat-related mortality; these are conditional scenarios, not forecasts

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ESM1.docx