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Natural Hazards and Earth System Sciences
Discussions

Brief Communication: Investigating trends in European hailstorm damage using CMIP6-DAMIP climate models

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Abstract

Warming seas around Europe have been driving recent upward trends in hailstorm severity. Therefore, learning more about changes to sea temperatures can give insights into hail climate too. Here, we use the DAMIP (Detection and Attribution Model Intercomparison Project) set of climate model experiments to explore how external forcings have modified Mediterranean temperatures. Climate models indicate external forcings caused most of the multidecadal changes in modern times, with anthropogenic aerosols explaining the cool period from about 1900 to the late 1970s, and greenhouse gas increases mainly responsible for the rapid 0.5 K/decade warming of the Mediterranean since then. Current trends in anthropogenic forcing are expected to continue warming seas which suggests European hailstorm risk will keep rising.

1 Introduction

Europe has experienced unusually large hailstorm losses in recent times. Thunderstorms in 2023 caused over five billion euros of insured loss, mostly in Italy (Swiss Re, 2024) which is all the more remarkable given very low insurance uptakes (e.g. Fitch Ratings article at https://www.fitchratings.com/research/insurance/european-insurers-more-exposed-to-weather-losses-as-reinsurers-retreat-17-11-2023). In 2022, French property and automobiles suffered five billion euros of loss due to hail (France Assureurs, 2023). A series of thunderstorms in June 2021 caused 4.5 billion USD of losses spread across a few countries (Swiss Re, 2021), though their effects may have been much greater by saturating soils prior to the immense damages from the storm Bernd flood in July 2021. In 2013 and 2014, hailstorms Andreas and Ela caused multi-billion euro losses, mainly to Germany and France respectively (Swiss Re, 2014 and 2015). This frequency of severe annual losses is in sharp contrast to the preceding 30 years with just one loss of a similar magnitude, namely the Munich hailstorm in 1984 (e.g. Pucik et al., 2019). Looking further back, there is no evidence of multi-billion hailstorm losses for a couple of decades prior to 1980, either from higher-quality loss records (e.g. VKG, 2022), or more anecdotally.

A variety of evidence indicates the recent spate of severe losses was part of an upward trend in hail risk over the past few decades. Raupach et al. (2021, hereafter R21) reviewed past hail trends, and found mixed results depending on the quantity (thunderstorms, any hail, or larger hail) and the geographic region being studied. However, if we confine our attention to studies of annual hail damage in the European area using longer datasets, then they tend to agree on a rising risk in recent decades, as now summarised.

R21 describe how large groups of long hailpad records are a highly valued source of ground-truth hail in Europe, and two major studies show signs of rising trends. Berthet et al. (2011) studied 457 hailpad stations in south and southwest France covering the period 1989-2009 and found annual hail kinetic energy growing by almost +3% p.a. over the period, while Eccel et al. (2012) analysed records from around 250 hailpad stations in the central-eastern Alpine area of Italy spanning 1975 to 2009, and reported an increase of about 1.5% p.a. in the mean kinetic energy of events. Positive trends in annual aggregate hail damage from earlier to later in the 20th century were documented in various early studies: tree-ring data from 1939 to 1996 in Switzerland (Hohl et al., 2002), crop insurance from 1920 to 1993 also in Switzerland (Willemse, 1995), and crop-hail insurance data in France from 1946 to 1992 (Dessens, 1995). A significant upturn in activity from about 1980 seems to be a main factor in these trends, as highlighted by Dessens (1995). More recently, Kunz et al. (2009) analysed insured losses to buildings in southwest Germany over the period 1986-2004 and found positive trends exceeding 5% p.a. in total hail losses, which was supported by significant increases in annual number of days with claims. More recently, some studies have examined how the hail-relevant environmental conditions evolved over the past few decades, and find that the basic atmospheric ingredients for large hail have become increasingly common since the 1970s (e.g. Mohr and Kunz, 2013; Radler et al., 2018; Taszarek et al., 2021). The hail model developed by Radler et al. (2018) indicated the annual amount of hail ≥ 2 cm increased at around 2.4% p.a. over 1979-2015 in a region covering Germany and the Alps, and up by 1.4% p.a. over the greater area of western and central Europe.

More evidence of rising trends in European hail have been uncovered since the review by R21. Battaglioli et al. (2023) described a model which had been calibrated to observed lightning and large hail reports, and indicated increasing trends of large hail throughout most of the western and central European mainland. They highlighted how hail ≥ 5 cm is now three times more likely than in the 1950s in northern Italy. Research within the insurance industry (Stormwise Ltd., at https://stormwise.co.uk/climate-change-and-hail and Partner Re, at https://www.partnerre.com/perspectives/the-contribution-of-climate-change-to-europes-increasing-hail-losses/), using models similar to those of Radler et al. (2018) and Battaglioli et al. (2023), find increases in annual hail risk of 1 to 1.5% p.a. over much of mainland Europe.

Insurance losses are also a valuable source of information on damaging hail in Europe. Insurance associations often monitor losses to their national market, and some records now extend to a few decades. The German Insurance Association (GDV) issue annual losses for combined wind and hail perils, all indexed to 2023 inventory and prices (available at https://www.gdv.de/gdv/statistik/datenservice-zum-naturgefahrenreport). Figure 1a shows the annual losses in the 1973-2023 period for automobiles, the vast majority of which are due to hail, and an annual growth rate of 3.1% is found over the past 50 years, or 2.2% p.a. since 1980. Figure 1b presents annual hail losses to all insured buildings in France, using data from France Assureurs (2023), with an indexation to 2023 values using the standard FFB Index (at https://www.outils.ffbatiment.fr/federation-francaise-du-batiment/le-batiment-et-vous/en_chiffres/indices-index/Chiffres_Index_FFB_Construction.html). The best-fitting annual growth rate of +6.0% p.a. in hail losses from 1990 to

https://doi.org/10.5194/nhess-2024-210
Preprint. Discussion started: 25 November 2024

2022 drops to +4.8% p.a. when excluding the final year with its huge hail losses. Figure 1c shows annual hail loss costs in Switzerland for the 1980 to 2023 period for all buildings in the 19 Swiss cantons covered by public insurance. In Fig. 1c, historical data are transcribed from Fig. 15 in VKG (2022), with more recent data from https://cms.vkg.ch/media/tutg0vgg/elementarschaeden-an-gebaeuden-2004-2023_de.pdf. The best-fitting annual growth rate of loss is 2.8% p.a. over the past 44 years.

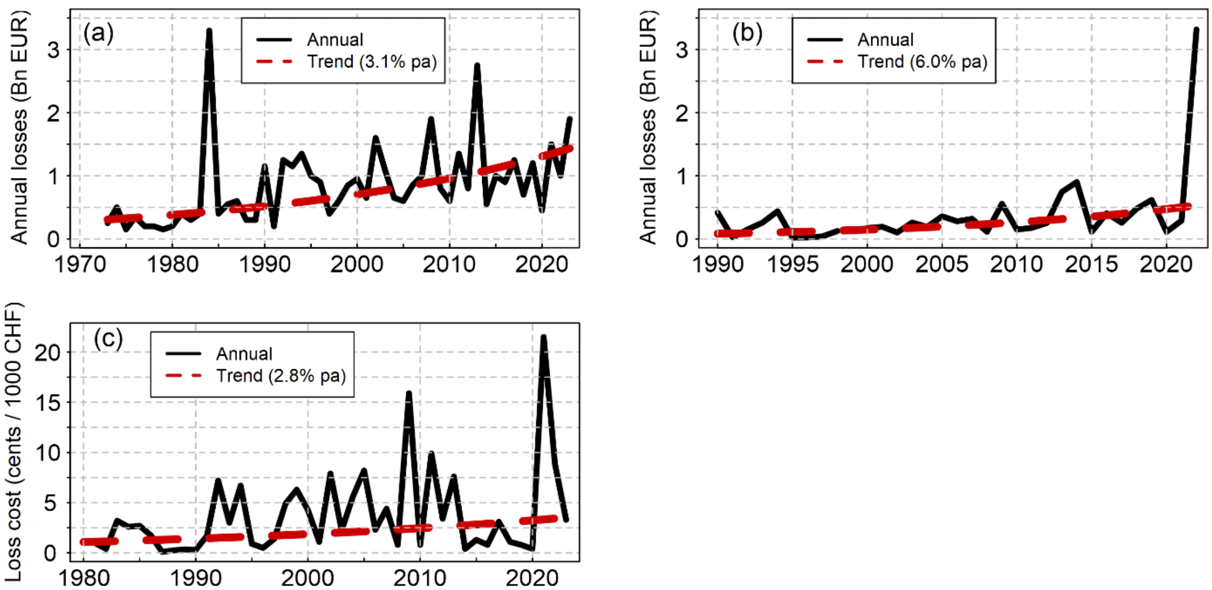

Figure 1: timeseries of insured hail damages for (a) automobiles in Germany, (b) buildings in France, and (c) buildings in Switzerland.

In general, national insurance losses trending upward at 2 to 5% per year over the past few decades. This is faster than the 1 to 2% range suggested by hazard-based studies. Both methods contain uncertainties: repair costs may be inflating faster than industry estimates, while those hazard methods trained to point occurrences of hail may not fully capture slow trends. Future investigation of the errors in both methods would help reduce uncertainty in how fast hail damage is increasing.

The causes of the rising hail risk in Europe have been investigated too. Dessens (1995) described a strong relation between annual hail loss in France and summertime minimum temperatures, which suggested rising wet-bulb temperatures in a warming climate were responsible for increasing hail risk. Berthet et al. (2011) found rising trends in hail kinetic energy from their hailpad network were mainly associated with nighttime warming, and dominated by trends in April and May. Kunz et al. (2009) found the growing hail risk over southwest Germany was accompanied by rising wet-bulb temperatures, while more accurate measures of convective instability such as CAPE were also increasing. Mohr and Kunz (2013) analysed

CAPE values based on radiosonde observations in 1978-2009 and reported significant upward trends in CAPE throughout most of Europe. Further, they identified a positive trend in low-level moisture as the main driver of intensifying CAPE and thunderstorms over Europe. More recent research using modern weather reanalyses calibrated to improved datasets of hail reports (e.g. Radler et al., 2018; Taszarek et al., 2021; Battaglioli et al., 2023) also implicate the humidification of low-level air in the rising trends of large hail.

Past research points to a warming climate causing more damaging hail in Europe. The key area is the Mediterranean Sea (the Med), because it is the main source of the high dewpoints which produce damaging hail (e.g. Kunz et al., 2020). Therefore, more knowledge of temperature anomalies in the Med can provide insights into hail trends too. This article explores drivers of past Med warming using climate models. The DAMIP (Detection and Attribution Model Intercomparison Project; Gillett et al., 2016) sub-project of CMIP6 was created to estimate how various external forcings, both natural and anthropogenic, force the climate system. DAMIP results from a set of climate models will be analysed to find how Med temperatures respond to different forcings of the climate system. Section 2 contains a description of the data and its processing, followed by the main results from DAMIP in Section 3. A discussion and summary are presented in Section 4.

2 Data and methods

The sixth version of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016) was a huge effort by the global climate community to understand and quantify climate change both in the past and future. CMIP6 contains 23 independent sub-projects targeting specific questions covering a wide range of climate topics. In particular, the DAMIP sub-project (Gillett et al., 2016) was created to investigate the impacts of various external forcings on global and regional climate. In the main, its tests explore the modern industrial period from 1850 to 2014, and its Tier 1 model simulations set one type of forcing to suitable values for the historical period with all others fixed at pre-industrial values. Initial conditions are taken from pre-industrial control runs (from the main CMIP6 model experiments), and Tier 1 historical forcings are split into three distinct types: natural forcings (solar and volcanic, hereafter Nat), greenhouse gases (GHG), and anthropogenic aerosols (Aero). This study used climate models from six different modelling centres providing monthly-mean near-surface temperature diagnostics, for at least five different ensemble members, for all three forcing tests. In addition, the Historical experiments with all forcings (Hist) performed as part of the central CMIP project are also analysed. Table 1 summarises the simulations analysed in this study. More information on the climate models is provided in the CMIP webpage: https://wcrp-cmip.org/cmip-model-and-experiment-documentation/.

Observed sea surface temperatures are taken from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST; Rayner et al., 2003), a global dataset of monthly sea surface temperature values at 1° x 1° resolution from January 1870 and continually updated to the present day.

https://doi.org/10.5194/nhess-2024-210
Preprint. Discussion started: 25 November 2024

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

Table 1: summary details of the DAMIP climate model simulations.

Model	Reference ID in text	No. of ensemble members per 1850-2014 forcing test
CNRM-CM6-1	1	10
CanESM5	2	15
GISS-E2-1-G	3	5
HadGEM3-GC31-LL	4	15
MIROC6	5	10
MPI-ESM1-2-LR	6	15

Both observed and modelled data are processed similarly. Monthly mean values are initially area-averaged over the northern half of the Mediterranean Sea (referred to as the northern Med, see Figure 2), then combined to form an extended summertime average (May-September) corresponding to the annual peak of hail risk, and ensuring the most relevant seasonal warming trends are used (García-Monteiro et al., 2022). Observed and model values were converted into anomalies using the climate from the common baseline period of 1870-2014. Anomalies for all model forcing simulations were computed with respect to the climatology of the Hist experiment over this common 1870-2014 period. Finally, a second-order low-pass Butterworth filter with a 5-year cutoff was applied to all timeseries to reduce large amounts of interannual noise obscuring longer-term trends. The 5-year cutoff was chosen to retain potential signals from Nat forcings such as 11-year solar cycles and major volcanoes, as well as the slower changes from GHG and Aero.

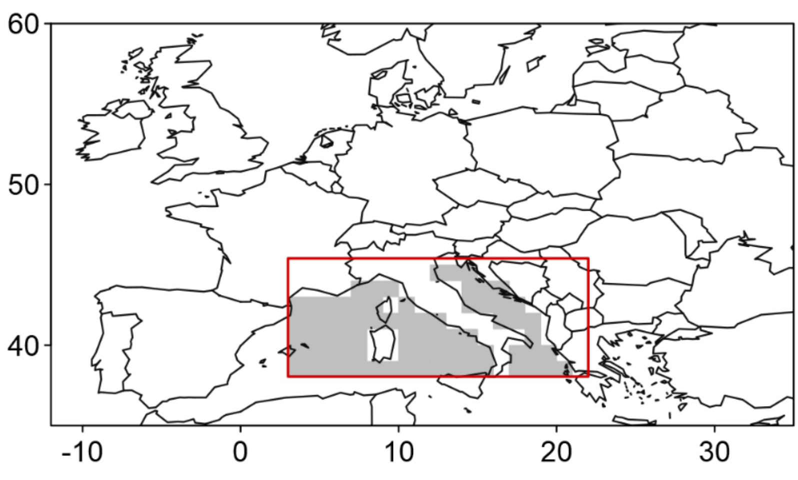

Figure 2: the region of the Mediterranean Sea used in the analysis.

https://doi.org/10.5194/nhess-2024-210
Preprint. Discussion started: 25 November 2024

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Discussions

3 Results

Figure 3a shows the timeseries of northern Med temperature anomalies over the extended historical period for observed and multi-model ensemble means for the Historical and three distinct DAMIP forcing experiments.

The most notable feature in HadISST observations (solid black) is the recent sharp upward trend from a near-minimum coolness in the late 1970s to a maximum in the present day which greatly exceeds earlier temperatures. Prior to this rapid warming, the timeseries contains a multidecadal variation, with minima around 1910 and the late 1970s, and a local maximum from about 1930 to the early 1960s.

The multi-model ensemble mean signal from all forcings (Hist – solid red) is similar to observed values over the whole period. Specifically, the modelled rate of warming in the northern Med since the 1970s closely follows HadISST data, and the earlier multidecadal oscillation in observations is replicated, albeit with reduced amplitude. Control simulations (part of the main CMIP6 protocol) have an interannual standard deviation (□) of 0.38 K, hence a 70-member mean has □=0.046 K, and the simulated multidecadal oscillation in Hist with amplitude of 0.5 K is significant. Therefore, the 20th century multidecadal cycle in northern Med warmth is a feature caused in some part by external forcing, according to climate models. Research by Booth et al. (2012) in the broader North Atlantic, and Aizawa et al. (2022) in the Arctic, also concluded that external forcing contributed substantially to pronounced multidecadal variations in near-surface heat in their study areas in the 20th century. We note how the sum of responses to individual forcings are consistent with Hist signals, suggesting Med warmth has a mostly linear response to forcings. Having established the validity of CMIP6 climate models to simulate temperature anomalies in the northern Med, we now discuss the contribution of individual forcings to the total signal.

Nat forcing (green dotted line in Figure 3a) of northern Med temperatures is near-zero over the long-term. However, volcanic eruptions exert influence on northern Med anomalies at timescales shorter than about 10 years in DAMIP simulations. Six of the largest climate-changing eruptions in the simulation period are indicated as long red tick-marks on the x-axis (Krakatoa 1883; Santa Maria 1902; Novarupta 1912; Mount Agung 1963; El Chichon 1982; Pinatubo 1991), and their occurrences coincide with anomalies of up to -0.5 K for a few years. This size of perturbation is smaller than the recent GHG and Aero forcings, and of much shorter duration, hence Nat forcing is a minor consideration in the modern industrial period, according to DAMIP results.

GHG (gold dashed) acts to warm the northern Med throughout the period. The magnitude of its forcing was small up to around 1920, then it has grown continuously since then. DAMIP models indicate GHG has caused almost 2 K of warming by the end of simulations in 2014. This large forcing has overwhelmed the Med in recent times, leading to GHG being the main cause (almost three-quarters) of the total modelled warming from 1975 to 2014.

The northern Med cools in response to Aero forcing (blue dash-dotted line in Figure 3a). This driver dominated total climate forcing up to 1920, and outweighed GHG forcing for much of the 20th century. Its peak impact on the Med was reached in the late 1970s, then stabilised for a short time before reducing in magnitude from about 1990 onwards, in line with aerosol emissions (e.g. Lund et al., 2019). The net warming from 1990 to 2014 due to lowered aerosol burdens caused about one-

https://doi.org/10.5194/nhess-2024-210
Preprint. Discussion started: 25 November 2024

quarter of the total modelled warming in this recent period. Given the coupling between northern Med temperatures and thunderstorm severity, these results suggest Aero forcing led to significant reductions in hail damage during most of the 20th century, while the recent trend to cleaner, healthier air has raised hail risk. Anthropogenic aerosols have been found to drive substantial multidecadal changes in the climate of other perils, such as tropical cyclones (Murakami, 2022), and the profound multidecadal peak in European windstorm damages in the late 20th century (Cusack, 2024).

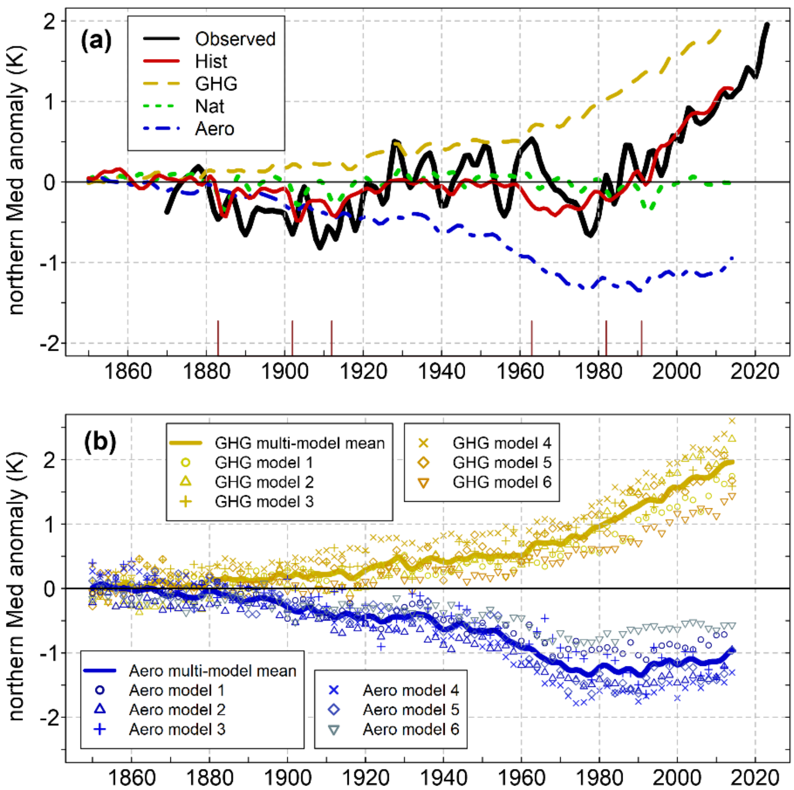

Figure 3: timeseries of northern Med temperature anomalies. (a) observed (solid black line) and multi-model mean anomalies for the various forcing experiments, with major volcanic eruptions indicated by long ticks on the time axis. (b) DAMIP multi-model mean (solid lines), and the mean of each of the six models (various symbols), for the Aero (blue) and GHG (gold) experiments.

DAMIP models suggest slow variations in the warmth of the northern Med during the modern industrial period was largely governed by the strengths of GHG and Aero forcings. In earlier times, aerosol cooling effects were dominant, and the northern Med dipped to a nadir in the late 1970s, then GHG forcing grew to become dominant and warm the Med, along with declining aerosol burdens adding a little to this warming. We can be quite sure that recent trends will persist into the near future (at least), with continued rises in GHG forcing, together with more clean-air policies implemented around the world. A continuation of the warming trend in the Med corresponds to further increases in European hail damage.

https://doi.org/10.5194/nhess-2024-210
Preprint. Discussion started: 25 November 2024

Natural Hazards and Earth System Sciences Discussions

Confidence in these DAMIP signals was assessed using the inter-model spread. Figure 3b contains mean signals for each of the six climate models, for the two main forcings of GHG and Aero. All six models agree on the respective sign of the two forcings, and signal amplitudes are similar too. We conclude that GHG and Aero forcings of northern Med temperatures are a robust feature of DAMIP models.

4 Conclusions

Evidence clearly points to a rising trend in the European hail climate over the past few decades, from hailpad observations, insured losses, and raw weather ingredients for large hail. Here, we presented new evidence of increasing hail damage in Europe, based on national insurance association surveys of building and automobile losses over the past few decades, and indexed to the present day. The largest remaining uncertainty concerns how positive this upward trend in hail damage has been in western and central Europe over the past few decades. Most of the hazard-based estimates are around 1 to 2% per year, whereas loss-based estimates contain steeper rises from about 2% to 5% per year.

Warming of the European area over the past few decades has driven the upward trend in hail risk. Rising temperatures of local seas humidify the low-level air, which intensifies thunderstorms leading to more severe hail. Therefore, knowing more about sea temperature variations would inform on the hail climate too. We found how climate models participating in the set of CMIP6-DAMIP experiments replicate most of the variations in observed northern Mediterranean temperatures at multidecadal timescales since 1870, building confidence in the realism of their simulations. They indicate anthropogenic forcings from greenhouse gases (GHG) and aerosols (Aero) dominate the slower changes in temperatures over the northern Med. The Aero effect dominated from 1850 to the late 1970s to produce a slight cooling, then clean-air acts reduced their impacts while GHG forcing continued to grow, resulting in a rapid warming of the Med of about 0.5 K / decade since 1980. GHG rises were responsible for about three-quarters of the warming in the northern Med over the past four decades, and the remaining portion is mostly due to reducing aerosol burdens. Major volcanoes can also change temperatures in the northern Med, but their peak cooling of -0.5 K, lasting for just a few years, suggests this forcing is minor compared to ongoing GHG and Aero forcing.

We can develop an outlook for hail climate in Europe based on the model results, and it is not encouraging. It is very likely that recent positive trends from rising GHG concentrations and less negative Aero forcing will persist over the next couple of decades, hence the current trend toward more severe hail is set to continue. The main unresolved issue is the size of the hail damage response to this ongoing warming of local seas.

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Preprint. Discussion started: 25 November 2024

Code/Data availability

HadISST data are available at https://www.metoffice.gov.uk/hadobs/hadisst/ (accessed on 24th October 2024). CMIP6-DAMIP climate model results were downloaded from the Earth System Grid Federation (ESGF): https://aims2.llnl.gov/search/cmip6/ (accessed July-October 2024).

Author Contribution

SC designed the tests and did the analysis. Both SC and TC prepared the manuscript.

Competing Interests

The authors declare no competing interest.

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