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Attribution of 2022 early-spring heatwave in India and Pakistan to climate change: lessons in assessing vulnerability and preparedness in reducing impacts

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Abstract

In March 2022, large parts over the north Indian plains including the breadbasket region, and southern Pakistan began experiencing prolonged heat, which continued into May. The event was exacerbated due to prevailing dry conditions in the region, resulting in devastating consequences for public health and agriculture. Using event attribution methods, we analyse the role of human-induced climate change in altering the chances of such an event. To capture the extent of the impacts, we choose March–April average of daily maximum temperature over the most affected region in India and Pakistan as the variable. In observations, the 2022 event has a return period of ∼1-in-100 years. For each of the climate models, we then calculate the change in probability and intensity of a 1-in-100 year event between the actual and counterfactual worlds for quantifying the role of climate change. We estimate that human-caused climate change made this heatwave about 1 °C hotter and 30 times more likely in the current, 2022 climate, as compared to the 1.2 °C cooler, pre-industrial climate. Under a future global warming of 2 °C above pre-industrial levels, heatwaves like this are expected to become even more common (2–20 times more likely) and hotter (by 0 °C–1.5 °C) compared to now. Stronger and frequent heat waves in the future will impact vulnerable groups as conditions in some regions exceed limits for human survivability. Therefore,

mitigation is essential for avoiding loss of lives and livelihood. Heat Action Plans have proved effective to help reduce heat-related mortality in both countries.

1. Introduction

Towards the end of spring of 2022, large parts of South Asia including India and Pakistan began experiencing prolonged periods of hot weather, which continued into summer. The month of March was the hottest in India since observed records began in 1901, according to the India Meteorological Department (IMD; Madaan 2022). Temperatures were consistently 3 °C–8 °C above the long period average (L.P.A, 1981–2010 climatology), breaking many decadal and some all-time records in several parts of the country, including the western Himalayas, the plains of Punjab, Haryana, Delhi, Rajasthan and Uttar Pradesh (IMD 2022c). The states of Odisha, Madhya Pradesh, Gujarat, Chhattisgarh, Telangana and Jharkhand also experienced heatwaves, in some areas quite severe, with temperatures ranging from 40 °C to 44 °C in the last days of March (IMD 2022c). In Pakistan many individual weather stations recorded monthly all-time highs in March (Pakistan Meteorological Department (PMD), 2022b). The heatwave conditions persisted into April, reaching a preliminary peak towards the end of the month. Around 300 large forest fires occurred in India on April 28, a third of these in the state of Uttarakhand (Rajeevan 2023). These months were also extremely dry, with rainfall at 62% and 73.6% below the L.P.A over Pakistan (PMD 2022a), and 71% and 3% below L.P.A over India for March and April, respectively (IMD 2022a, 2022b). By April 29, almost 70% of India was affected by the heatwave. Temperatures above 49 °C were recorded in Jacobabad in Sindh, Pakistan (Ilyas 2022b), and 30%of the country was gripped by the heatwave. Towards the end of April and in May, the heatwave extended into the coastal areas and eastern parts of India (IMD 2022c). Even though inhabitants in these regions are used to high ambient temperatures, temperatures exceeding 40 °C can increase mortality (Desai *et al* 2015, Rathi and Sodani 2021, Rathi *et al* 2021). The heatwave coincided with the holy Ramadan period, which affected the coping capacities of those fasting, particularly in Pakistan, thus exacerbating health impacts. The updated death toll for the 2022 from India event is 33 (Datt 2023) which is 8 more than the initial estimate. The number of heat-related deaths recorded in Pakistan, where temperature records were broken in several places remain at 65 (Irfan 2023). A particularly notable effect is the impact on wheat crops and yields in the wheat-growing regions in the northern plains of India and Southern Pakistan. Anomalously high temperatures during the wheat harvest season in these parts (February–May) are known to adversely affect grain filling and cause early senescence (Lobell *et al* 2012), thereby reducing yields (Zachariah *et al* 2021). The country had been aiming for 111.32 million tonnes of wheat for 2022–23; however, the actual production was 106.84 million tonnes, with the shortfall of ∼20% (Arora and Bhardwaj 2022, Gupta 2023). The export ban imposed by India on wheat due to concerns about domestic food security reportedly added further stress on global food prices and food security in an already tight market given the war in Ukraine (AFP 2022). Atleast 16 glacial lake outbursts in Pakistan during 2022 was linked to the heatwave as compared to annual average of 5–6 (Fox 2022, Janjua 2022). Figure 1 illustrates the far-reaching impacts of the 2022 extreme heat event, and in particular the varied ways in which the heightened (lessened) vulnerability and exposure (V&E) to the event is expected to have heightened (lessened) the associated impacts.

While heatwaves are not uncommon in this part of the world during the later months of the pre-monsoon (MAMJ) season (Chaudhury *et al* 2000, Sharma and Mujumdar 2017, Zahid and Rasul 2012, India Meteorological Department 2016, 2017), an increase in such conditions in the earlier, March–April period is observed in recent decades (Zahid and Rasul 2012, Singh *et al* 2021). The heatwave during March–April 2022 was characterised by anomalously high temperatures in large parts of India and Pakistan (figure 2(a)) due to the persistence of an upper atmospheric high-pressure system (anticyclone) (National Weather Forecasting Centre 2022a, 2022b). In a recent study Rashid *et al* (2022) found that in early summer, La Niña conditions favour development of anticyclonic systems in this region. This may have been the case during the 2022 event considering that the Pacific was in the La Niña phase at that time.

Another important feature of this event was the extremely dry conditions that accompanied the hot weather, thereby making the conditions favourable for enhanced surface heating. Upper-level synoptic scale systems embedded in the subtropical westerly jet stream called western disturbances (Hunt *et al* 2018, 2019) that are responsible for precipitation during December–April in northwest India and Pakistan were absent during March and April, 2022, causing a large rainfall deficit during this period (Express News Service 2022a; figure 2(b)). Thus, the 2022 heatwave was a dry event, in contrast to the previous, major heatwave of 2015 that occurred later in the season in June, concurring with high humidity levels and resulting in 3500 direct heat-related deaths in both countries (Saeed *et al* 2021).

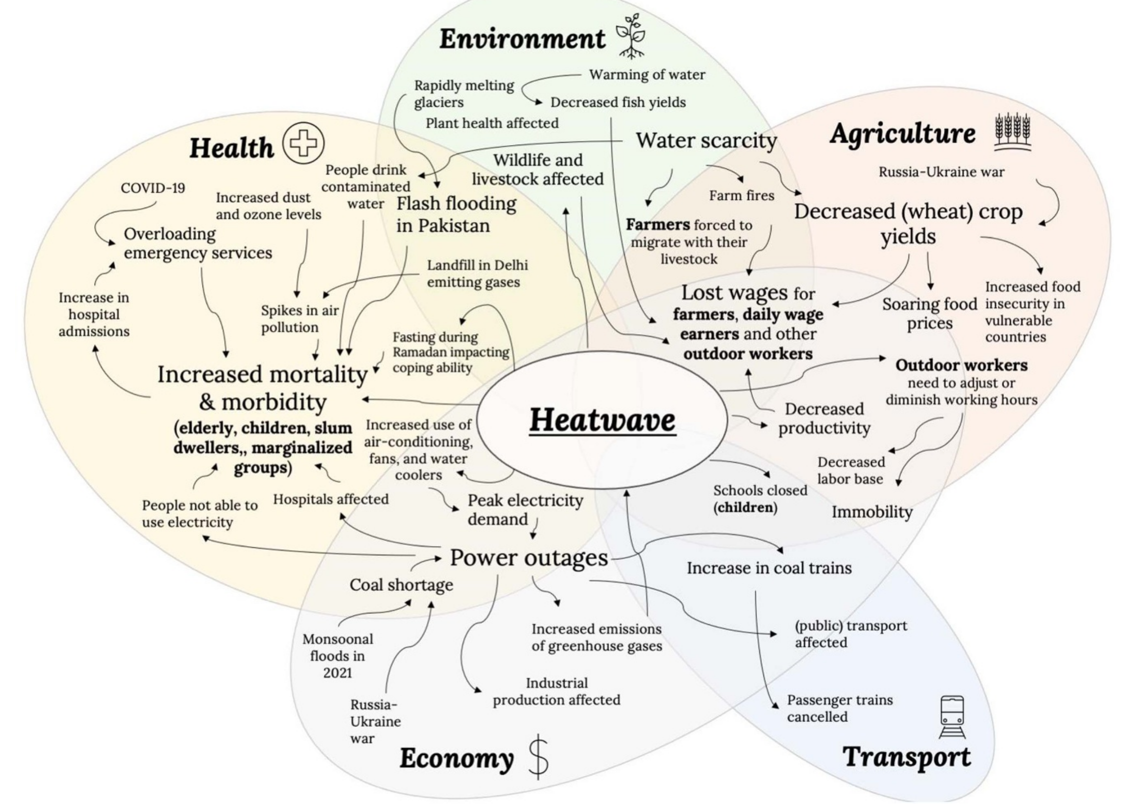

Figure 1. Conceptual map of impact pathways during the heatwave.

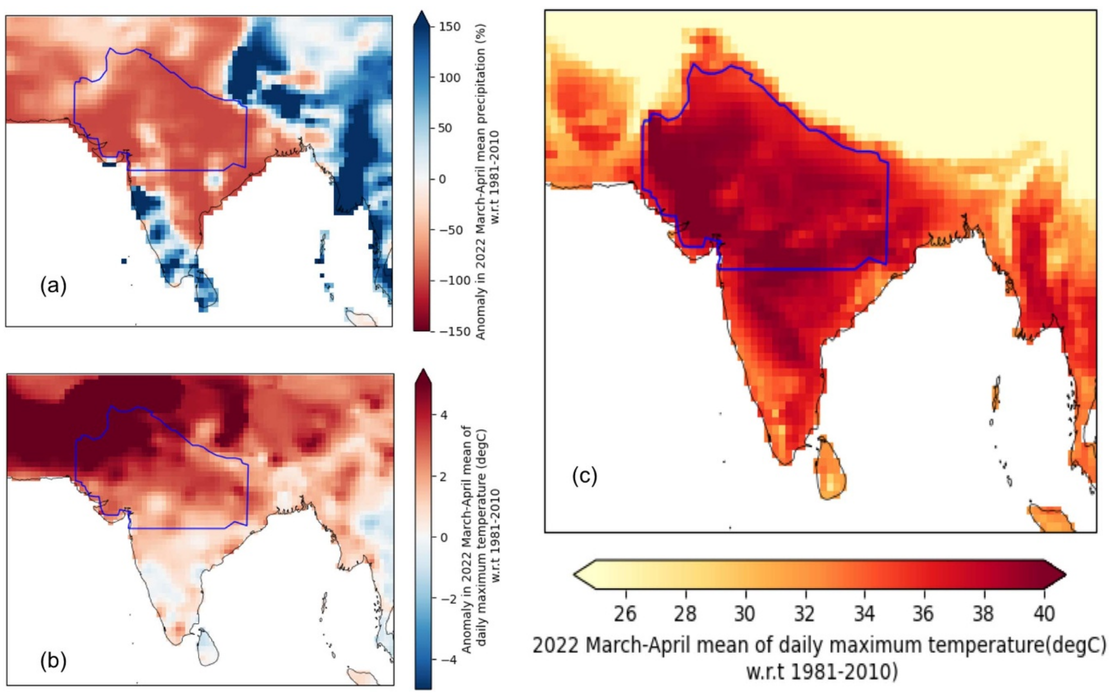

Figure 2. (a) Percentage deviation of observed (CPC) precipitation during March–April 2022 from the 1981–2010 climatology (%). (b) Observed (CPC) anomaly in March–April average daily maximum temperature for the year 2022 w.r.t. 1979–2022 climatology (°C). The study region is highlighted by the blue polygon. (c) March–April average of observed (CPC) maximum temperature for the year 2022 (°C).

Important concerns raised in the immediate aftermath of the event include (i) whether and to what extent can the 2022 heatwave be attributed to climate change (ii) whether heatwaves such as this one will become worse in the future, and (iii) what anticipatory strategies can be implemented for dealing with such extremes in the future. In this study, we attempt to answer these questions systematically, using the peer-reviewed protocol for event attribution and V&E analyses developed by Philip *et al* (2020). In keeping with the unusual timing of the heat episode, which occurred earlier in the year, the spatial extent and the associated widespread impacts, we define the event as the March–April average of daily maximum temperature, over the north Indian plains to the west of the Himalayas and the lowlands in southern Pakistan to the east of the Sulaiman range (highlighted in blue in figure 2). We choose to focus on the maximum air temperature, as opposed to a more complex metric for heat stress because (i) historical observations of humidity are less reliable (and are less available) than temperature measurements in the relevant regions, (ii) the question of model fidelity becomes more complex when assessing multivariate extreme events (Sippel *et al* 2016, Cannon *et al* 2020), and (iii) the concurrence of positive anomalies in temperature with negative rainfall anomalies (figures 2(a) and (b)) during March–April 2022 over India and Pakistan suggests that the event exhibits the characteristics of a 'dry heatwave'.

Over South Asia and other global regions, there is *high confidence* that the likelihood and intensity of extreme heat has significantly increased (Zahid and Rasul 2012, Sheikh *et al* 2015, Donat *et al* 2016, Rohini *et al* 2016, Chakraborty *et al* 2018, Dimri 2019, Roy 2019, Dunn *et al* 2020, Seneviratne *et al* 2021) and there is *robust evidence* confirming the role of human-induced climate change in driving them (Wehner *et al* 2016, Pattanayak *et al* 2017, Wang *et al* 2017, Dileepkumar *et al* 2018, 2021, van Oldenborgh *et al* 2018, Seong *et al* 2021). Nonetheless, at smaller scales, local factors can further exacerbate or alleviate the event characteristics. In parts of India, warming signals are attenuated due to the increased concentration of reflective sulfate aerosols in the atmosphere from burning fossil fuels, and the cooling from agricultural intensification and high irrigation activity in the region (Thiery *et al* 2017, 2020, van Oldenborgh *et al* 2018, Mishra *et al* 2020). On the other hand, absorbing aerosols, particularly black carbon that also results from fuel combustion and crop-burning, is found to intensify high temperatures in these areas (Mondal *et al* 2021). However, it should be noted that the studies that examine the link between irrigation and regional cooling account for soil moisture at field capacity or as a percentage of soil saturation, and use annual irrigated areas, thereby overlooking the fact that pre-monsoonal irrigation activities in India are only minimal when compared to the major monsoon (Kharif) and winter (Rabi) cropping seasons (Devanand *et al* 2019, Jha *et al* 2022). Combined, this evidence suggests that for the specific case of a March–April heatwave over these parts, the importance of increasing irrigation in suppressing the warming effect of greenhouse gases might be smaller than previously thought.

2. Data and models

2.1. Observational data

Gridded datasets for daily maximum temperature provided by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC), available at $0.5^\circ \times 0.5^\circ$ resolution for the period 1979–present (from https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html) are used as the primary dataset for observational analysis. Additionally, we use gridded datasets of observed daily maximum temperature at $1^\circ \times 1^\circ$ resolution for the period from 1 January 1951 to 30 April 2022 provided by the IMD (available at www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html) as a supplementary observational product although its spatial extent is limited to within the geographical borders of India. Both datasets are interpolated from station data using Shepard's interpolation algorithm (Xie *et al* 2007, Chen *et al* 2008, Srivastava *et al* 2009, Pai *et al* 2014).

For studying the effect of climate change on temperature, we assume that the location parameter of the best-fitted probability distribution for temperature varies with the global mean surface temperature (GMST), an accepted measure of anthropogenic climate change (e.g. van Oldenborgh *et al* 2017, Luu *et al* 2021). To this end, we use low-pass filtered estimates of GMST from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, Hansen *et al* 2010, Lenssen *et al* 2019) as the covariate.

2.2. Reliability of the observed datasets for the study region

Figures 3(a) and (b) shows the linear trends in March–April average daily maximum temperature for the period 1979–2022, from the CPC and IMD datasets, respectively. We find strong positive trends in this season almost everywhere in the study domain. The CPC dataset exhibits negative trends further south (figure 3(a)) as opposed to no significant trends in the IMD data (figure 3(b)). This suggests the need to consider both datasets in the analysis, to account for the uncertainties from differences in the trends.

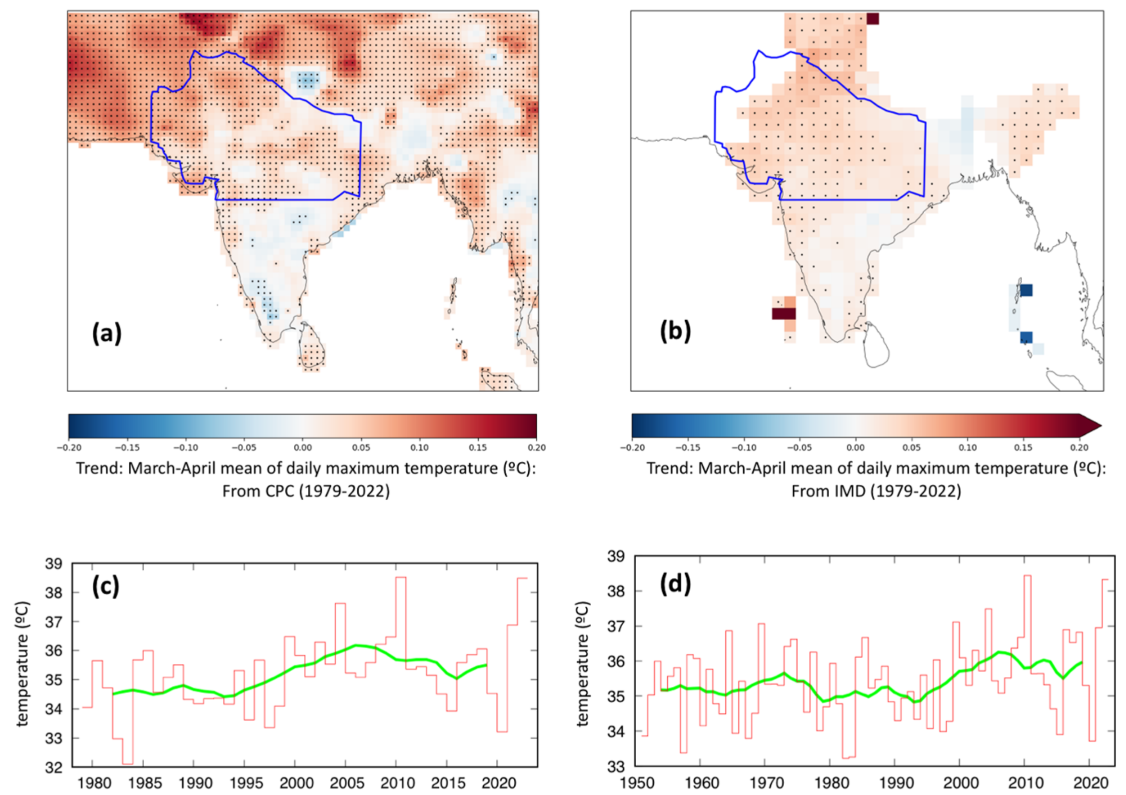

Figure 3. Trends in observed daily maximum temperature averaged over March–April from the (a) CPC and (b) IMD datasets, considering the years 1979–2022. Stippling indicates trends that are significant at the 10% significance level. Time series of area-averaged March–April average of observed daily maximum temperature along with the ten-year running mean (shown by the green line) based on the (c) CPC and (d) IMD datasets.

Figures 3(c) and (d) shows the time series of March–April average daily maximum temperature, averaged over the study region, from CPC (1979–present; figure 3(c)) and for the Indian part of the region only from IMD (1951–present; figure 3(d)). Overall, these datasets agree with each other in terms of magnitudes, year-to-year variability and the positive trend between 1979 and 2022, thus attesting to the homogeneity in the larger region, and further justifying their use as complementing datasets for the rest of the analysis.

2.3. Model simulations

We use multi-model ensembles from six climate modelling projects that use different framings such as sea surface temperature (SST) driven global circulation high resolution models, coupled global circulation models and regional climate models. Specifically, we consider simulations from the following projects: (i) Half a degree Additional warming Prognosis and Projected Impacts (HAPPI, Wehner *et al* 2018), (ii) Coordinated Regional Climate Downscaling Experiment (CORDEX-CORE, Teichmann *et al* 2021), (iii) IPSL-CM6A-LR global climate model large ensemble (Boucher *et al* 2020, Bonnet *et al* 2021), (iv) GFDL Forecast-oriented Low Ocean Resolution version of CM2.5 (FLOR; Vecchi *et al* 2014), (v) High Resolution Model Intercomparison Project (HighResMIP; Haarsma *et al* 2016) and (vi) Coupled Model Intercomparison Project version 6 (CMIP6; Eyring *et al* 2016). More details about these models and the experiments that are used in this study are provided in supplementary section S1.

The 1979–2022 period for which the observed data (CPC) is available is chosen for model evaluation, while the entire length of simulations up to the year 2022 is considered for the attribution analysis. As with observations, for the SST-forced simulations, we use observed GMST as covariate, whereas for the coupled models, we use the corresponding model-based GMST estimates.

3. Methods

We use a standard, peer-reviewed probability-based framework developed for rapid attribution assessments (Philip *et al* 2020), for quantifying whether and to what extent the frequency and/or magnitude of a class of extremes at least as extreme as the event of interest is attributable to climate change. Such results can help inform decision-makers in planning adaptation/mitigation strategies against future impacts. This is complementary to the 'storyline approach' which is also interesting in itself, separating the climate change contributions to the thermodynamic and the dynamic aspects of the event (Otto *et al* 2016, Vautard *et al* 2016). Although the storyline approach is important from a research perspective, this is not easily automated and therefore, not within the immediate scope of a rapid attribution study.

For quantifying attribution of the event to climate change, we calculate its return period and the changes in the event's probability (given by the probability ratio PR) and intensity between the climate of today ($clim_1$) and a hypothetical past before anthropogenic activities began altering the climate ($clim_0$). PR is the ratio of the probability of an event as strong or stronger than the event of interest in $clim_1$ to its probability in $clim_0$ and can take values in $(0, \infty)$. A value of PR more (less) than 1 implies that the event is made more (less) likely by human-induced climate change whereas PR $= 1$ suggests that there is no evidence of climate change in the likelihood of the event. Following the same framing, the change in intensity is the difference in the variable threshold for a given probability or return period between $clim_1$ and $clim_0$. See supplementary figure S1 for an illustration of how these metrics are calculated.

In the main method, we fit the data with a non-stationary probability distribution with GMST as covariate. This distribution is then shifted up to the 2022 climate when the event was observed and shifted down to the pre-industrial (late 19th century) climate that is 1.2 °C below the 2022 levels (see Global Warming Index; www.globalwarmingindex.org). Additionally, we analyse the expected changes in probability and intensity in a future warmer climate scenario that is +2.0 °C above pre-industrial GMST levels (or 0.8 °C warmer than 2022 levels).

We select the Gaussian distribution for modelling the March–April mean of daily maximum temperature in the study region. This is a justified choice, on account of the short length of the CPC dataset resulting in sparsely populated tails (Philip *et al* 2018). The Gaussian distribution is assumed to shift due to global warming without changing its shape. This is a first-order assumption that is made when performing attribution analyses of temperature events. The assumption has been validated in past studies, using climate models with long length of data by checking the past and present distributions from the non-stationary fits against distributions of the past and present climate in independent time slices (e.g. Uhe *et al* 2017, van Oldenborgh *et al* 2018, Kew *et al* 2019). The shift is factored into the analysis by linearly varying the location parameter (μ) of the distribution with (low-pass filtered) GMST while holding the scale parameter (σ) constant, as shown in equation (1),

$$\mu = \mu_o + \alpha T \text{ and } \sigma = \sigma_o \quad (1)$$

where T is the 4 year smoothed GMST anomaly, and α is the trend.

This framework is detailed in the peer-reviewed World Weather Attribution protocol (www.worldweatherattribution.org/pathways-and-pitfalls-in-extreme-event-attribution, Philip *et al* 2020, van Oldenborgh *et al* 2021) and has been successfully applied in recent studies (Ciavarella *et al* 2021, Luu *et al* 2021).

In addition to the above method, we use simulations from three fixed climate model experiments from the HAPPI project- one for current conditions (Hist), and two counterfactuals for the world that would have been in the absence of anthropogenic emissions (Nat) and a +2.0 °C warmer world with adjusted concentrations of CO_2, other greenhouse gases, and aerosols. For the observed return period (or probability) of the event in the 2022 climate, we first obtain the magnitude in the Hist climate for each of the models. Thereafter, the return period of this magnitude in the counterfactual scenario is calculated for the respective models. The PR is the ratio of the probability (or return period) of the event in +2.0 °C warmer world to that in Hist. The intensity change attributable to climate change is the difference between these event magnitudes.

Finally, results from observations and the models that pass the validation tests are synthesised into a single attribution statement. See Philip *et al* (2020), Ciavarella *et al* (2021) and Li and Otto (2022) for details.

4. Results and discussions

4.1. Observational analysis: trend and return period

The left panels in figure 4 show the response of area-averaged March–April mean daily maximum temperatures to the GMST anomaly, for the CPC and IMD datasets. Despite the limited length of the data series, there are clear trends in temperature for both datasets (figures 4(a) and (c)) that suggest warming of the late spring and early summer in the study region consistent with global warming. Fitting these time series to a Gaussian distribution shifting with GMST (section 3) allows us to calculate the return period of the 2022 temperature in the 2022 climate as well as a past, 1.2 °C cooler climate, along with the change in intensity of the event between these climates for a quantitative appraisal of the role of climate change in causing this event.

The right panels (figures 4(b) and (d)) show the return period curves in the present, 2022 climate and the past climate when the global mean temperature was 1.2 °C cooler, for the two datasets, along with their

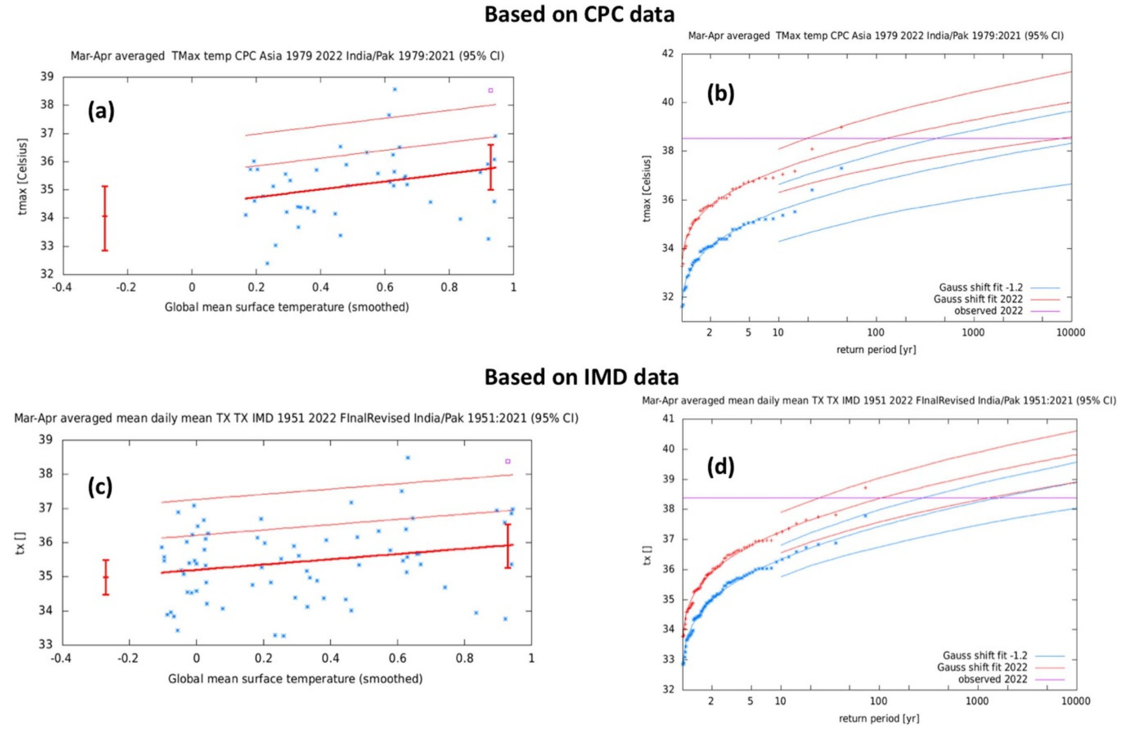

Figure 4. (a) Response of March–April mean daily maximum temperature averaged over the study region estimated from CPC records to change in global mean temperature. The thick red line denotes the time-varying mean, and the thin red lines show 1 standard deviation (s.d) and 2 s.d above. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2022 climate and the hypothetical, 1.2 °C cooler climate. The 2022 observation is highlighted with the magenta box. (b) Return periods for the 2022 climate (red lines) and the 1.2 °C cooler climate (blue lines with 95% CI), based on CPC data. (c) Same as (a), but using IMD data. (d) Same as (b), using IMD data.

confidence intervals (CI). The two-sided 95% CI for these curves is estimated using a non-parametric bootstrap, by repeating the fit 1000 times with (variable, covariate) pairs drawn from the original series, with replacement. Although the CPC dataset has high resolution over the study region, it is too short to estimate the return period with confidence. Therefore, we compare these estimates with those based on IMD dataset for the part of the study region in India. Upon fitting Gaussian distributions, the best estimates of the return period of the 2022 event in the current climate emerges as 1-in-130 year (uncertainty: 1-in-8000 to 1-in-20 year) for the study region based on CPC (figure 4(b)), and 1-in-103 year (uncertainty: 1-in-1250 to 1-in-25 year) for the region over India based on IMD (figure 4(d)) and 1-in-110 year (uncertainty:1-in- 4500 to 1-in-15 year) for the same region, again, based on CPC (table S5). These numbers imply that, based on available observed data, the March–April average maximum temperature in the study region during 2022 is best defined as a 1-in-100 year event in the current climate.

This event would have been highly unlikely in a world without climate change, with very high return periods of 20 000 and 1500 years with wide uncertainty bounds (see supplementary table S5), in the CPC and IMD datasets, respectively, indicating that climate change has increased the chances of the event. However, these numbers are many times higher than the length of the observational data (44 years long for CPC and 73 for IMD) and the 2022 value is an outlier in both the 1.2 °C cooler and 2022 climates. Therefore, we cannot rely on the precision of these numbers. A possible reason for these high numbers and the large uncertainties in the return period of the 2022 event could be due to the Gaussian distribution not being able to model the tail of the data distribution as seen in figures 4(b) and (d). The large uncertainties are also reflected in the PR and $\triangle I$ estimates from the datasets. The best estimate for PR between the 2022 climate and the 1.2 °C cooler climate is 155 (0.9–1000 000 with 95% CI; table 1) and 15 (0.7–600; table 1), from the CPC and IMD datasets, respectively, with change in intensity ($\triangle I$) estimates of 1.7 °C (−0.019 °C … 3.7 °C) and 0.92 °C (−0.12 °C … 2.0 °C), respectively (table 1). These bounds encompassing no change suggests that the trend may not yet have emerged from the noise in the observations even though the probability has changed. This is partially due to the short length of observations resulting in larger sampling uncertainties, along with other confounding factors including natural variability. Therefore, we repeat this analysis climate models as well, as discussed in section 4.2.

For testing the reliability of the Gaussian assumption, we separately fitted a Gaussian model and a Generalized-Pareto distribution (GPD; with a threshold of 90% of the data) to simulations of a multi

Table 1. (a) Probability ratio and change in intensity when compared with a 1.2 °C cooler climate, for models that passed the validation tests. (b) Projected probability ratio and change in intensity when compared with a 2 °C warmer climate, for models that passed the validation tests.

	(a) Present vs. past		(b) Future vs. present	
Model/observations	Probability ratio PR	Change in intensity ΔI (°C)	Probability ratio PR	Change in intensity ΔI (°C)
CPC (1979–2022)	$1.5 \times 10^{+2}$ (0.94 … $1.2 \times 10^{+6}$)	1.7 (−0.019 … 3.7)	—	—
IMD (1951–2022)-India only	15 (0.70 … $6.0 \times 10^{+2}$)	0.92 (−0.12 … 2.0)	—	—
ECEARTHr12-COSMOcrCLIM rcp85 (1)	35 (3.0 … $1.7 \times 10^{+3}$)	1.6 (0.53 … 2.7)	7.0 (5.0 … 11)	1.1 (0.95 … 1.2)
MPIr1-COSMOcrCLIM rcp85 (1)	$1.1 \times 10^{+2}$ (11 … $2.8 \times 10^{+3}$)	1.7 (0.87 … 2.4)	11 (7.0 … 19)	1.3 (1.2 … 1.4)
NORESMr1-COSMOcrCLIM rcp85 (1)	14 (0.70 … $3.5 \times 10^{+2}$)	1.2 (−0.16 … 2.4)	6.0 (4.0 … 9.0)	0.97 (0.84 … 1.1)
FLOR (5)	$6.2 \times 10^{+2}$ ($3.6 \times 10^{+2}$ … $1.2 \times 10^{+3}$)	2.4 (2.2 … 2.5)	13 (11 … 16)	1.6 (1.5 … 1.6)
HAPPI-CCCMA happi2.0 (10)	—	—	15 (14 … 17)	1.3 (1.2 … 1.4)
HAPPI-ETH happi2.0 (10)	89 (48 … $1.8 \times 10^{+2}$)	1.6 (1.4 … 1.8)	11 (10 … 13)	1.3 (1.2 … 1.4)
HAPPI-NCC happi2.0 (10)	—	—	15 (13 … 16)	1.6 (1.5 … 1.7)
HAPPI-MIROC happi2.0 (10)	8.4 (5.4 … 13)	0.87 (0.68 … 1.1)	9.8 (8.6 … 11)	1.3 (1.1 … 1.4)
ACCESS ESM1-5 Historical + SSP245 (1)	1.1 (0.27 … 4.7)	0.061 (−0.58 … 0.68)	—	—
INM-CM4-8 Historical + SSP245 (1)	$1.2 \times 10^{+2}$ (12 … $1.9 \times 10^{+3}$)	1.4 (0.78 … 2.0)	—	—
ACCESS-ESM1-5 (40)	2.1 (1.6 … 2.6)	0.30 (0.20 … 0.41)	3.0 (2.8 … 3.2)	0.46 (0.43 … 0.49)
BCC-CSM2-MR (1)	34 (4.4 … $2.3 \times 10^{+2}$)	1.3 (0.54 … 2.1)	10 (5.8 … 18)	0.93 (0.70 … 1.2)
CMCC-ESM2 (1)	12 (3.0 … 55)	0.83 (0.38 … 1.3)	17 (9.3 … 33)	0.93 (0.76 … 1.1)
EC-Earth3 (6)	8.3 (5.2 … 13)	0.80 (0.62 … 0.98)	4.7 (4.0 … 5.5)	0.59 (0.53 … 0.66)
EC-Earth3-CC (1)	4.1 (1.7 … 9.7)	0.56 (0.21 … 0.92)	4.1 (2.8 … 6.2)	0.57 (0.41 … 0.74)
EC-Earth3-Veg (7)	9.0 (6.0 … 14)	0.82 (0.66 … 0.98)	4.4 (3.8 … 5.1)	0.57 (0.51 … 0.63)
EC-Earth3-Veg-LR (3)	13 (5.6 … 29)	0.95 (0.63 … 1.3)	4.5 (3.5 … 6.0)	0.61 (0.50 … 0.72)
INM-CM4-8 (1)	7.0 (1.2 … 36)	0.62 (0.058 … 1.2)	8.6 (4.8 … 15)	0.68 (0.49 … 0.88)
INM-CM5-0 (1)	$4.3 \times 10^{+2}$ (42 … $4.3 \times 10^{+3}$)	1.6 (1.0 … 2.1)	28 (14 … 61)	0.99 (0.80 … 1.2)
UKESM1-0-LL (5)	17 (9.3 … 32)	0.96 (0.73 … 1.2)	6.7 (5.5 … 8.2)	0.68 (0.62 … 0.74)
IPSL-CM6A-LR (32)	58 (36 … 88)	1.4 (1.3 … 1.6)	6.5 (5.5 … 7.3)	0.94 (0.84 … 1.0)
CNRM-CM6-1-HR HighResMIP (1)	$2.3 \times 10^{+2}$ (9.9 … $2.1 \times 10^{+4}$)	2.5 (1.1 … 3.9)	—	—
HadGEM3-GC31-HM HighResMIP (1)	38 (2.1 … $9.9 \times 10^{+2}$)	1.4 (0.31 … 2.4)	—	—
HadGEM3-GC31-MM HighResMIP (1)	$3.8 \times 10^{+2}$ (20 … $2.6 \times 10^{+4}$)	2.4 (1.1 … 3.7)	—	—

ensemble climate model with long runs- the IPSL-CM6A-LR ensemble (see section 2.2 and supplementary section S1 for more details about the model), figure S9 shows the two fits- the Gaussian and the GPD (with a threshold of 90% of data) distributions. Although the best estimate of the return period shows the same order of magnitude as with the observations (∼100 years), there is a subtle departure from the data in the fitted Gaussian distribution far tail and the fit does not capture the curvature of the data, while this is captured by the GPD distribution. As a result, interestingly, this induces a large change in the probability ratio, with a best estimate of about 50 in the Gaussian case and 3300 in the GPD case. The results in terms of intensity changes are however not much changed (∼1 °C). This result suggests a potential underestimation of the PRs by the Gaussian model for temperatures.

4.2. Climate model analysis

We repeat the above analyses based on observed data with temperature simulations from the participating models (discussed in section 2.2) for estimating the model-based probability ratios and intensity changes. First, we evaluate the model simulations against observations for their suitability for the attribution analysis. The evaluation period considered is 1979–2022, the period common to the CPC and IMD observational datasets. The climate models are evaluated against the observations in their ability to capture-

(1). *Seasonal cycle*: The seasonal cycle of the daily maximum temperature for the study region from the climate models are qualitatively compared against the cycle from CPC dataset. A model is labelled as 'good' if the model-based cycles capture the shape and the seasonality of the observed seasonal cycle. It is labelled 'reasonable' if either the peaks are not well-defined or if the seasonality is out of phase. If the peaks are ill-defined and the seasonality is out of phase, the model is labelled as 'bad'.

(2). *Spatial pattern*: The spatial pattern of March–April average maximum temperatures for a larger region spanning 5° N–40° N, 60° E–100° E and encompassing the study region (figure 2) from the model simulations are qualitatively compared with the pattern based on observed data. Depending on how well the models are able to replicate the observed patterns-i.e. the north–south gradient in temperatures and patterns due to higher temperatures in arid/semi-arid regions (figure S2(b))—completely, at least in part or poorly, these are classified as 'good', 'reasonable' or 'bad', respectively.

(3). *Distribution parameters*: We check if the parameters of the fitted statistical distribution (Gaussian shifting with GMST for this study) from the model simulations are compatible with those from observations. A model is labelled as 'good' if the model parameter range lies within the observational range (95% confidence interval), 'reasonable' if the ranges overlap, and 'bad', if they diverge.

A model is given an overall rating of 'good' if it is rated 'good' for all three characteristics. If there is at least one 'reasonable', then its overall rating will be 'reasonable' and 'bad' if there is at least one 'bad'. Supplementary table S6 summarises the model evaluation results for 66 model simulations from the various experiments. The seasonal cycles and spatial patterns for the observed dataset and the participating models that are used for the model evaluation are shown in supplementary section S2, figures S2–S8.

A 24 out of the 66 models that have an overall rating of 'good' (highlighted in green in table S5) and are selected for the attribution analysis. Out of these, there are 22 models that have simulations for the past 1.2 °C cooler climate and 19 models that cover the future 2 °C warmer world.

Table 1(a) (highlighted in blue) shows the PR and ΔI of the 1-in-100 year event for the present climate, relative to a 1.2 °C cooler climate, based on the observations and the 22 selected models. Table 1(b) (highlighted in red) shows these values for a future 2 °C warmer world relative to the present climate, from the 19 models. The individual model estimates of the change in event likelihood and event intensity are strongly correlated to each other i.e. models showing a large increase in the intensity of 100 year hot events also have correspondingly large probability ratios and vice versa (see supplementary figure S10). In the next section, we synthesize the results for observations and the models that pass validation.

4.3. Hazard synthesis

Here we present the synthesis for PR and ΔI for the present compared to the 1.2 °C cooler climate (figures 5(a) and (b)) and the future vs. present (figures 5(c) and (d)). The best estimates of the PR range from 1.1 in the ACCESS models to more than 600 in FLOR. The change in intensity goes from almost no change to more than +2 °C. Both are compatible with the highly uncertain observational analysis; therefore, we can use the weighted mean to indicate the main result of this study. Our synthesis concludes an event probability ratio of 30 (2–470) (figure 5(a)) and a corresponding change in intensity of 1 °C (0.2 °C–2.1 °C) (figure 5(b)).

The change in PR for a further 0.8 °C global temperature increase is 8 (3–12) (figure 5(c)) and an additional increase in intensity of 1 °C (0.3 °C–1.7 °C) (figure 5(d)). The simulations based on the HAPPI

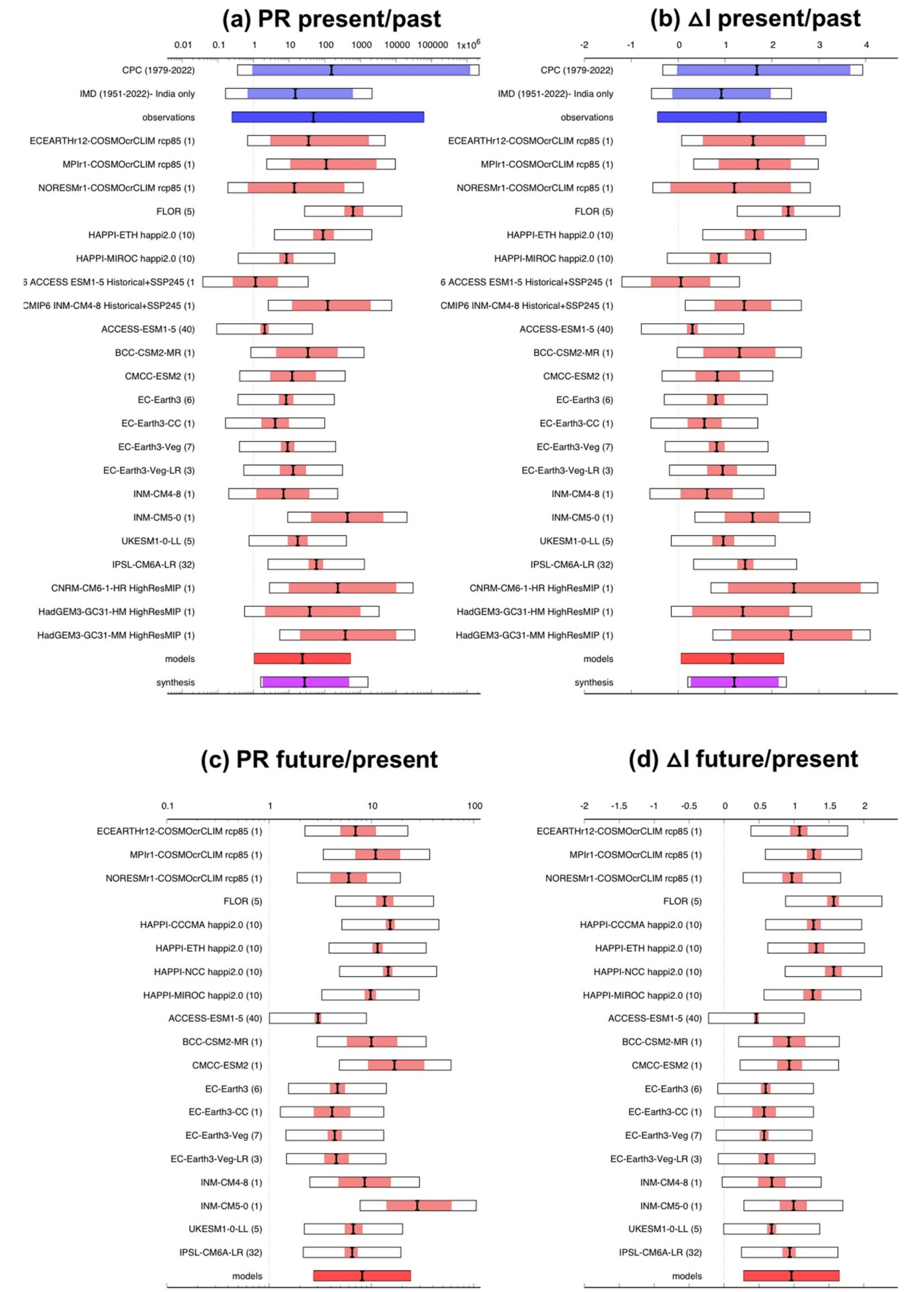

Figure 5. (a) Synthesis of intensity changes (ΔI) and (b) probability ratios (PR) when comparing the 100-year event in today's climate with a 1.2 °C cooler climate. (c) Same as (a) and (d) same as (b) when comparing the 100-year event in today's climate with a 0.8 °C warmer climate (equivalent to 2 °C of global warming).

ensemble are centred at 1 °C warming for the present day climate instead of 1.2 °C thus they show changes in likelihood and intensity for an additional 1 °C of global warming rather than 0.8 °C. Nevertheless, the discrepancy between the individual models is smaller than for the changes up until today.

Part of the uncertainties in the estimates from the participating models arise from differences in the aerosol representation and the GHG and non-GHG forcings in the individual models. For example, the PR and intensity change of the ACCESS-ESM1.5 model in figure 5 are relatively low. This may be due to the relatively large global-mean aerosol indirect effect for that model over the historical period that results in smaller historical warming as compared to the other models in the CMIP6 ensemble considered in the study (Wang *et al* 2021). The differences in external forcing (SSP245 and SSP585) that are used to obtain the future scenario runs in the participating models also contribute to uncertainties in PR and intensity changes for the future (figures 5(c) and (d)). Furthermore, the choice of a Gaussian fit rather than a GPD might have led to an underestimation of the changes in a relatively rare event such as this one (supplementary section S3; figure S9). We therefore conclude that our overarching results are conservative and the true influence of human-caused climate change is towards the higher end of the estimated changes in likelihood. On the other hand, the central estimate of $\triangle I$ that the 2022 is made $\sim$1 °C warmer due to climate change is consistent across both observations and models, and consistent with statements made in other dry regions (Li *et al* 2019, Daramola and Xu 2022), thus lending high confidence to our findings.

5. Vulnerability and exposure (V&E)

The overall risk associated with the heatwave event is governed by the hazard as well as the V&E factors that make people and human systems more or less susceptible to the impacts of the prolonged high temperatures. Heatwaves are 'silent disasters' because their impacts are difficult to ascertain. The 2022 heatwave is estimated to have led to around 98 deaths in India and Pakistan (Datt 2023, Irfan 2023). However, heat-related deaths are often undercounted across the globe; therefore the actual toll is likely higher (Ghumman and Horney 2016). A comprehensive review of the V&E factors that accompanied the 2022 heatwave is necessary for informing timely interventions and long-term strategies to address vulnerability and improve preparedness for avoiding future impacts in these regions. We carry out this review for five key areas revolving around demographics, informality in urban areas, heat action planning and preparedness, agriculture and other compounding risks.

5.1. Demographics and vulnerable groups

The effects of the 2022 heatwave were primarily felt over northwestern India and Pakistan, where some of the largest and densest urban areas in the world are situated (Ul Haque *et al* 2021, The Global Statistics 2022). Between 1983 and 2016, urban population exposure to extreme heat is reported to have increased by approximately 200%, globally (Tuholske *et al* 2021). Three of ten cities that experienced the largest increase during this period are in our study region, namely, New Delhi, Karachi, and Lahore (Tuholske *et al* 2021). Although anybody can feel the impacts of extreme heat, vulnerable groups of people are affected disproportionately. The most affected groups include outdoor workers such as farm workers, labour migrants, low-income households, homeless people, daily wage earners, construction workers, street vendors, street sweepers and rickshaw drivers (Climate & Development Knowledge Network 2016, Mazdiyasni *et al* 2017), the elderly and young children, people with chronic conditions (cardiovascular, respiratory, and cerebrovascular), people with pre-existing mental illness, and people with cognitive and/or physical impairments (Carleton 2017, Mazdiyasni *et al* 2017, Swain *et al* 2019). Tourists, travellers and migrants are prone to additional risks due to missing warnings in local language, not knowing how to access cool spaces, or being less accustomed to the local temperatures (Hari *et al* 2021).

5.2. Informality in urban areas

Approximately 10 million Karachi residents and half of New Delhi's population live in informal, low-income settlements (Pabani 2021, World Population Review 2022) with building structures and roof types that significantly intensify indoor temperatures during the day (Mahadevia *et al* 2020, Mukhopadhyay *et al* 2021). In the absence of adequate cool roof retrofits (Vellingiri *et al* 2020), the urban poor rarely get respite from the extreme heat (Weitz *et al* 2022), especially those who spend most of their time indoors, such as the elderly, women, and people with physical impairments. The elderly low-income residents are up to 4.3 times more likely to be exposed to hazardous heat than their rural counterparts (Weitz *et al* 2022). Moreover, tin roofs in such settlements are known to further exacerbate the urban heat island effect (Padmanaban 2021). Half of India's workforce is estimated to be outdoor labourers (Jha and Kishore 2022). Therefore, it is not surprising that India faces the largest impacts of heat on heavy manual labour such as agriculture and construction, with over 101 billion working hours lost per year (out of the global sum of 228 billion; Parsons *et al* 2021). Under future warming, both India and Pakistan are amongst the top ten countries projected to experience the largest population-weighted labour losses, together with China, Bangladesh, Indonesia, Sudan, Vietnam, Nigeria, Thailand and Philippines (Parsons *et al* 2021).

The urban poor—in particular, daily wage earners who work outside are the worst-off during heatwaves, due to the effects of direct sunlight exposure being compounded by air pollution, limited access to healthcare facilities and inadequate mitigation practices (Bakhsh *et al* 2016, Anwar *et al* 2022, Barthwal *et al* 2022). At least four people found dead on the streets in the city of Nagpur in India, in April 2022, were suspected to be heat stroke-related fatalities (Mascarenhas 2022). The urban heat island effect, which can exacerbate heat by up to 12 °C locally, also contributes to the exposure risk among the urban poor (Razzak *et al* 2022). For peri-urban residents, the risk of exposure is largely due to the long-distance commute to work by foot, two-wheelers or public transportation, thus limiting their options to mitigate (Bakhsh *et al* 2016). Finally, it is important to note that this group had already been reeling under the effects of the COVID-19 pandemic (Raju *et al* 2021) before the 2022 extreme heat episode. The impacts of the heatwaves such as the 2022 event could therefore make the pandemic recovery even longer, highlighting the need for anticipatory humanitarian approaches (Thalheimer *et al* 2022).

5.3. Heat action planning, preparedness, and response

Given the propensity for heatwaves in the populous South Asian regions, the countries have implemented an arsenal of early warning systems and early action programmes at local to regional scales for mitigating impacts (Das and Smith 2012, Vahlberg *et al* 2022). For example, the South Asia Heat Health Information Network (https://climateandcities.org/about-us/south-asia-heat-health-information-network/#) was developed in 2020 to share lessons and increase capacity to deal with extreme heat across South Asia. Both India and Pakistan are making significant and rapid strides to combat extreme heat in particular, especially in recent decades.

5.3.1. Heat action planning, preparedness, and response in India

In the aftermath of the catastrophic heatwave in 2010, Ahmedabad in India became the first South Asian city to implement a Heat Action Plan (HAP); the city is now estimated to avoid approximately 1190 heat-related deaths annually (Hess *et al* 2018). Since then, over 120 Indian cities and states have developed HAPs that focus on building public awareness and capacity among health professionals, issuing safety alerts for residents, fostering inter-agency coordination, and enabling adaptive measures for vulnerable groups that include adopting cool roof technology, increasing green coverage in urban areas, assembling roofing structures at markets, and installing drinking water stations along highways (Padmanaban 2021, Natural Resources Defense Council 2022). Aimed at mitigating the increasing temperatures' toll on public health and building consensus around its management, India's Ministry of Health and Public Welfare (with support from other government departments and non-governmental actors) developed the National Action Plan on Heat Related Illnesses (National Centre for Disease Control 2021). Launched in 2021, it contains guidelines for the government, health care facilities and policymakers on managing and reporting heat-related illnesses. Stocktaking basic equipment and medicine and ensuring sufficient staffing are some of the recommended actions when faced with extreme heat.

In anticipation of the 2022 heat season, the National Disaster Management Authority held a national workshop on heat preparedness, mitigation and management, in March (Natural Resources Defense Council 2022). In a first, the IMD implemented an impact-based early warning system, providing accessible and actionable information for increasing heat risk preparedness and coping capacity (Natural Resources Defense Council 2022). The agency has been disseminating timely information to the public since 2020 via their mobile phone application 'Mausam'. Thus, there was an increased awareness of the weather and warnings this year (Natural Resources Defense Council 2022). Bulletins from the Ministry of Health and the Indian Institute of Public Health Gandhinagar advised people to wear lightweight clothing of natural fibres, avoid exposing one's head to direct sunlight and seek care if they recognize any signs of heat-related illness (PTI 2022). Preparing for a heavy inflow, hospitals across India set up special wards for heat-related illnesses, rolled out capacity-building training and sensitisation on heat risk and symptoms for medical staff, and were instructed to ensure uninterrupted electricity supply to guarantee the functioning of cooling devices (Mascarenhas 2022, Singh 2022a, TN National Desk 2022). Cooling centres and rooms were established in primary health centres, hospitals, places for worship, malls and other public buildings to provide visitors with drinking water, health care and respite from the heat, while fans and cooling structures were installed in schools (Lal 2022).

5.3.2. Heat action planning, preparedness, and response in Pakistan

The Start Network—a conglomeration of agencies from across the world for aiding humanitarian action, has a national disaster risk financing programme for Pakistan (https://startnetwork.org/disaster-risk-financing-pakistan) that funds early action in anticipation of heatwaves. Activities include training community leaders in disaster preparedness and first aid, opening shelters in schools and other communal spaces, spreading public awareness on heatstroke prevention and identification of symptoms, establishing helplines, and setting up health emergency camps that provide cold drinking water and medicines (Start Network 2021).

Cities covered by the programme include Karachi, Larkana, Multan, Sibi, Nawabshah and the city of Jacobabad which incidentally recorded the region's maximum temperature during the 2022 heatwave, at 49 °C on 30 April 2022 (Bhatti 2022). Following the devastating 2015 heatwave that led to over 1200 deaths Pakistan (Rafferty 2016) with more than 65 000 heatstroke-related hospitalisations in Karachi alone (Glum 2015), Karachi and other urban areas across Pakistan have developed HAPs (Commissioner Karachi n.d.) that outline the immediate actions following a heatwave warning, such as establishing cooling centres in places for worship, malls and other public buildings, increasing staffing at healthcare centres to accommodate a rise in patient influx and redistributing more ambulances to densely populated areas (Commissioner Karachi n.d.). Adaptive measures such as increased water consumption, staying in the shade or bathing more frequently, is paramount for reducing heat-related mortality in urban Pakistan (Bakhsh *et al* 2018). A Start Network evaluation on early action in response to a 2021 heatwave in the city of Sibi showed that most people tend to apply these strategies, except those for whom it would negatively impact livelihoods, such as rickshaw drivers or construction workers (Guyatt and Khan 2022). This dilemma to choose between safeguarding one's health and sustaining one's livelihood is characteristic of the most at-risk populations' exceptional vulnerability. In October 2021, as Pakistan updated its Nationally Determined Contributions, the government announced that it is developing a Cooling Action Plan to be adopted by 2026 (United Nations Climate Change n.d.). The plan will identify key cooling needs and outline sustainable actions for addressing those needs, both current and prospective.

In response to the 2022 heatwave, public health authorities in Pakistan instructed health units to open 'heatstroke centres' to help the public connect with the authorities, while also reminding people to avoid direct sunlight and increase their water consumption (Saeed 2022, Toheed 2022). Although the most rigorous action seems to have been taken in May (Web Desk- Geo News 2022), numerous trainings were rolled out in April. Between 18 and 29 April, the Provincial Disaster Management Authority Sindh and Pakistan Red Crescent Society jointly offered heat emergency training to traffic police and line department officials as well as representatives of civil society organisations.

5.4. Agriculture

The agriculture and related sectors are the major contributors to the national economies of India and Pakistan, with 60% and 40% of the respective population working in this sector (Statista 2022a, 2022b). The 2022 heatwave hit at a critical time, during the final period of the growing season for winter crops such as wheat and barley, and also affected summer crops such as pulses, coarse cereals, oilseeds, vegetables and fruits.

India, the second-largest wheat producer globally, is also a major consumer. Farms in the northern states of Punjab and Haryana of India that account for 25% of the country's total wheat production (United States Department of Agriculture 2022) and Uttar Pradesh lost an estimated 10%–35% of crop yields due to the heatwave (Ghosal 2022), affecting local market prices, that rose to 15% in some regions (Arora and Bhardwaj 2022). Global food prices also reached their highest level ever recorded in March 2022, with a 40% rise since the beginning of the year (FAO Food Price Index 2022), due to the Russian invasion of Ukraine, a major wheat producer (Parija and Bhatia 2022) and increasingly high fertiliser prices this year (Meyer 2022). Therefore, the Indian government was forced to retract its initial plan to boost its wheat exports to meet the global wheat shortages and to impose a ban on export, to protect India's internal food market—further affecting the global wheat market and food-dependent countries (Hoskins 2022). In Pakistan, exportable mango varieties have seen a 50% loss and 30% in local varieties, due to the extreme heat, which was followed by a pest attack, with yields per acre falling from 40 to 28 maunds (1 maund = 37.32 kg) (Ilyas 2022a).

Although advisories were sent to farmers to ensure frequent irrigation for the crops (e.g. AICRPAM *et al* 2022), functional electricity and water systems are also important during periods of extreme heat. At present, there is an urgent need for research, public policies and investments to focus on adaptation strategies to minimise the future impacts of extreme heat on agriculture.

5.5. Compounding risks

In addition to the direct impacts of extreme heat on public health, agriculture, socio-economic factors and urban planning discussed above, there are compounding risks such as cascading hazards and energy availability. Heatwaves are known to create cascading hazards, leading to secondary events of significant impact (Pescaroli and Alexander 2014, Tilloy *et al* 2019, Vogel *et al* 2020). For example, increased temperatures and evapotranspiration from heatwaves can result in both water shortages and floods from meltwater. Spikes in energy demand during heatwaves can result in shortages, thereby limiting means for cooling and irrigation.

In northern Pakistan and India, rapidly melting glaciers are putting thousands at risk of glacial lake outburst floods (GLOFs) and landslides as well as to decreased water supplies. GLOF risks were highlighted by the Pakistani government in their heatwave response (Government of Pakistan 2022) and a large one occurred on 7 May 2022, wiping out a bridge, houses and inundating farmland in the Hunza valley (Davies 2022). Heatwaves also increase the risk of forest-fires (Jain *et al* 2021). On April 27th, the Forest Survey of India reported 300 active large forest fires, a third of which were in the Uttarakhand province (NASA Earth Observatory 2022). In Delhi, a massive landfill caught fire for at least 9 d (Express News Service 2022b). Across Pakistan, multiple farm and village fires have been reported throughout April, resulting in loss of lives and properties (Provincial Disaster Management Authority 2022, The Third Pole 2022). In turn, these fires have a significant impact on air quality, which increases morbidity and mortality of extreme heat events. April was reported as the worst month for air quality in Delhi since 2015—the city recorded 29 d of 'poor air quality' (200–300 air quality index, AQI) (Paljor 2022). Throughout March and April, Lahore consistently measured AQI corresponding to levels 'unhealthy for sensitive groups' (151–200) and 'unhealthy' (201–300) (Environment Protection Department 2022). About 70% of India's electricity generation comes from coal (IEA 2021), with about 60% of energy provision from coal, oil and natural gas in Pakistan (IEA 2020). The 2022 heatwave increased the demand for coal imports in India due to shortages resulting in rolling blackouts (Chaturvedi 2022). At least 16 out of 28 states in India experienced power outages of two and ten hours duration (Bloomberg 2022), affecting the public, industry, and agriculture (Singh 2022b).

6. Concluding remarks

In 2022 India and Pakistan experienced an intense heatwave that began in early March and persisted into the month of May. Given the devastating impacts on human health and agriculture we set out to answer the question of whether and to what extent the event could have been influenced by climate change. Therefore, we performed an attribution analysis of the observed March–April average daily maximum temperature, using published peer-reviewed methods. Upon comparing the event characteristics—return period and intensity, in today's climate with counterfactual worlds without climate change (GMST 1.2 °C cooler as compared to now), the 2022 heatwave is found to be made 1 °C hotter and 30 times more likely by climate change. Notwithstanding the conflicting effects of local factors on magnitudes such as aerosol interactions among the different models, future projections also show consistently more intense heat waves of longer durations and occurring at a higher frequency over India (Murari *et al* 2015, Mishra *et al* 2020) and Pakistan (Nasim *et al* 2018, Saeed *et al* 2021). Our results show that under global warming of 2 °C above pre-industrial levels, the 2022 heatwave is expected to become 2–20 times more likely and 0.5 °C–1.5 °C hotter than now.

The urban poor in India and Pakistan are amongst the most exposed and vulnerable to extreme heat, and are left using coping mechanisms to withstand the extreme heat and earn a daily wage. Rising temperatures from more intense and frequent heatwaves will render coping mechanisms inadequate, as some regions meet and exceed limits to human survivability (Mora *et al* 2017). While some losses will inevitably occur due to extreme heat, it is misleading to assume that the impacts are inevitable (Raju *et al* 2022). This emphasises the need to record losses and damages occurring due to climate change related disasters (Boyd *et al* 2021). Adaptation to extreme heat has been shown to be effective in some cases (Hess *et al* 2018). HAPs that include early warning and early action, awareness raising and behaviour changing messaging, and supportive public services can reduce mortality, and India's rollout of these has been remarkable, now covering 130 cities and towns. There are, however, still large research gaps on adaptation to heat across India and Pakistan that will require further study to build a stronger evidence base for action (Pachure *et al* 2022). Heatwaves such as the event we analysed here are considered disasters due to people's vulnerabilities, an issue that needs to be tackled by society. Better urban and health planning, disaster insurances and livelihood protection mechanisms, investment in green spaces, energy grid strengthening, improved water infrastructure and pollution controls could all contribute to ensure that fewer people suffer as temperatures rise.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://climexp.knmi.nl/HeatwaveIndiaPakistan2022.cgi.

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