TEMPERATURE TECHNICAL BRIEF

Projecting the Likely Rise of Future Heat Impacts Under Climate Change for Selected Urban Locations in South and Southeast Asia

AUTHORS

Caspar M. Ammann (NCAR)
Kyoko Ikeda (NCAR)
Ken MacClune (ISET-International)

CITIATION

Ammann, C., Ikeda, K., MacClune, K. (2014). Projecting the Likely Rise of Future Heat Impacts Under Climate Change for Selected Urban Locations in South and Southeast Asia (The Sheltering Series No. 9). Boulder, CO: Institute for Social and Environmental Transition-International.

ABSTRACT

The broad warming observed over the past decades across South Asia is likely to continue into the future. Multi-model projections indicate that mean temperature increases over the area are expected in the range of 2-3°C by 2050 compared to the late 20th century. Human perceived heat — the combination of temperatures with humidity — as expressed through the heat-index is likely to rise by significantly more, possibly 4 to 7°C, over the same time span. While heat is already an issue for the large fraction of the poor population that suffers from a lack of appropriate shelter and access to basic water and energy, the rapid rise in heat is likely to become an inescapable challenge. As the average daily heat-index reaches human body temperature, lack of cooling will significantly impact economic productivity and pose severely heightened health risks. Although South Asian populations have learned to cope with episodes of heat, future heat events will become relentless as the number of days of excessive heat increases and gaps between heat episodes shrink or even disappear.

Overall, the heat-season will start earlier in the year and last longer into the fall. Both daily and nighttime temperature and heat will reach unprecedented levels that are difficult to escape without access to active cooling. Daily maxima in the late afternoon can possibly be partially ameliorated through construction of simple forms of shade and through the use of evaporative cooling. For rapidly increasing nighttime minimum temperatures, however, which previously provided natural relief, there is no obvious, simple adaptive measure. A form of active but clean, low-energy cooling will be necessary to help the large populations of urban, peri-urban and even rural poor cope with the coming changes without leading to counterproductive increases in greenhouse gas emissions.

INTRODUCTION

Heat continues to accumulate near the Earth surface as global greenhouse gas concentrations reach higher levels every year. Measurements of CO_2 on Mauna Loa have surpassed 400ppm, higher than anything seen for at least a million years, and possibly not seen since before the repeated glaciations of the Quaternary geologic period 2.5 million years ago. It is well understood how greenhouse gases lead to warming, and it is now "extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC 2013).

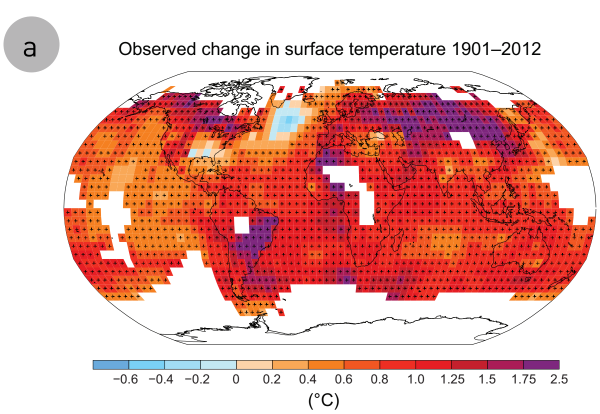
A hierarchy of factors can influence local and regional temperature trends. Natural climate variability on timescales of years to a few decades can mask global temperature trends, as can more local or regional radiative forcings such as large aerosol emissions or land use changes. To assess recent temperature observations at a given location it is therefore necessary to understand them in the context of local forcing and how that forcing influence global temperature trends. Looking forward in time however, increasing greenhouse gasses and their impact on global temperature will grow to dominate the climate of all locations; the scenarios offered by model-based projections will become dominant, overwhelming short term trends and variations.

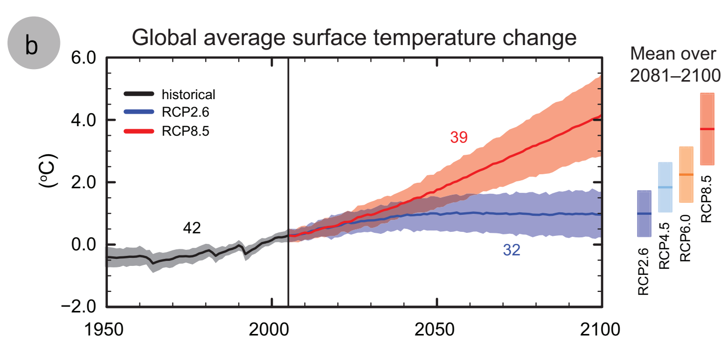
One of the more sensitive indicators of climate change is trends in extremes; the highs and lows in temperature and highs and lows in duration and intensity of precipitation. These events, that represent the tails of the variability distribution, express the range of potential physical processes under changing conditions. The literature has identified detectable changes in these events around the world (Alexander et al. 2006, Zhang et al. 2011) and the projections point to even stronger changes in the future (see Figure 1). Extreme events have much larger impacts on society and the environment than the slowly shifting average value. The impacts these extreme events have will be compounded for the poor, particularly in South Asia where increasingly intense heat exposure above body temperature thresholds and with fewer mitigating breaks will meet a limited capacity to adapt. Lack of adaptive capacity

FIGURE 1

TEMPERATURE CHANGES (HISTORIC AND PROJECTED)

(a) Observed surface temperature trends over 1901-2012 period with near global coverage. (b) Projected global mean temperature changes throughout the 21st century based on two scenarios, RCP2.6 a low emission scenario where the radiative forcing is quickly restricted to 2.6 Watts per square-meter, and RCP8.5, a high emission scenario essentially representing a continued growth in global greenhouse gas emissions. (Source: IPCC 2013)





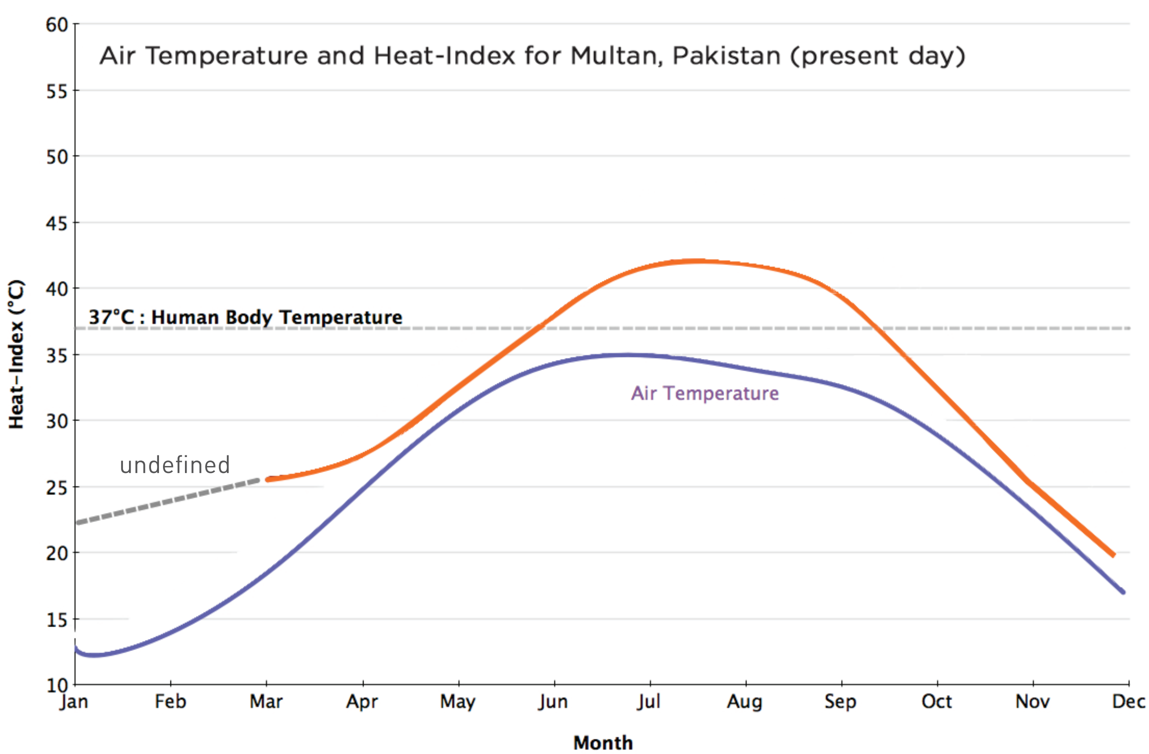
can be seen in the financial constraints of poverty, lack of access to infrastructure (ranging from protective shelter to reliable water and energy systems), institutional arrangements that fail to adequately represent vulnerable people, and lack of awareness of extreme events and their changing trends as an issue over which households and communities have some level of actionable space.

This report has been developed under a CDKN-funded project focused on the potential role that shelters play within climate-related vulnerability and how small modifications might increase resilience to high impact events. This report focuses on heat thresholds in selected emerging cities of South Asia and investigates current and likely future trends in heat-related stresses. This report initially focuses on the current climate context and observed changes in temperature over the past decades. It then introduces climate models as tools to assess potential future temperature changes. Temperature changes are compared with the "heat index", a value of perceived temperature that has correlations with impacts to health. The heat index is a measure that takes into account temperature and humidity of the air and how it affects the capacity of the human body's natural cooling mechanisms to maintain homeostasis (see Figure 2). A lack of cooling can lead to heat-related illnesses and even increased morbidity and mortality. The discussions here focused on South Asia are relevant because already today heat is recognized as having a significant impact on people, the local economic productivity and society overall.

FIGURE 2

COMPARISON OF PRESENT-DAY TEMPERATURE AND HEAT-INDEX AVERAGES OVER THE SEASONAL CYCLE FOR MULTAN, PAKISTAN

Comparison of present-day temperature and heat-index over the seasonal cycle for Multan, Pakistan illustrating the delay of the annual maximum in heat-index compared to temperature alone. The rising humidity throughout the monsoon season leads to the maximum heat impact in mid summer, well after the peak in air temperatures. In winter, temperatures are too low for the calculation of a useful heat-index.



DATA AND METHODS

This study focused on the cities of Gorakhpur, India, Islamabad/Rawalpindi, Lahore and Multan, Pakistan. These cities are reasonably representative of a much broader region spanning the gradient of the Indian Monsoon belt in the Ganges Valley in the East to the far reaches of the monsoon flow across the Punjab and the Indus Valley in the West. This is a region of generally high population density. Similar urban infrastructure is found across the region, and the resident population is composed of a large fraction of low-income and poor urban and peri-urban populations. These three cities were selected as representative of mid-sized urban centers with rapidly growing populations that are projected to receive the bulk of urban growth in the next several decades.

Meteorological Station Data: Systematic weather and climate observations around South Asia were initiated during late British colonial times. But access to this station data, and particularly to temporally long (e.g. 30+ years) records of daily station data, remains challenging. To this day, some station records only exist on paper, while others have been digitized but not quality controlled. For India data for an increasing number of stations is readily available; for Pakistan the coverage of daily information is especially poor. Of particular use for the present study were data from the Global Historical Climatology Network (GHCN) retrieved through the National Climatic Data Center (NCDC of NOAA). For these station series, a reasonable amount of data quality testing has been performed (e.g., Peterson et al. 1998). These data series were augmented by a few local datasets provided by the Gorakhpur Environmental Action Group (GEAG) for the City of Gorakhpur, UP, India. Agreement between the GEAG and GHCN series was found to be quite good for temperature, but less so for moisture and precipitation. Data from Pakistan was more difficult to obtain as the GHCN stations were limited to Lahore. Station data was obtained by ISET-Pakistan from the Pakistani Meteorological Department for the cities of Multan and Islamabad. Moisture records were also downloaded from an online collection of observations provided by "TuTiempo" (www.tutiempo.net/clima/Pakistan/PK.html); however, these data series proved to be quite spotty at times, and homogeneity tests indicated some data quality issues. All data series used in this analysis cover the period from about the mid- to late-1970s to present.

The objectives of this study were not to assess discrete heat episodes but rather to analyze temperature and heat trends over time. Temperature and atmospheric humidity (moisture) data were collected and analyzed with climatological considerations in mind, as heat is a recurrent feature of the annual cycle. Daily and seasonal temperature evolution are, on average, smooth, large-scale processes with an accordingly smooth temperature field. Consequently, there is generally fairly high homogeneity among the station series around a city. Multi-station assessments can therefore quickly expose significant quality issues with the daily observations. Same-season differences between years can be found in the series and used to characterize the natural variability. Across the region, the observed trends were in good agreement.

GEAG Station: For the city of Gorakhpur, a nearly 1-year series of hourly observations taken from the roof of the GEAG building allowed for a clean documentation of the typical daily and seasonal cycle of a station in a Monsoon region. These observations show the typical pattern of rising daily maximum temperature during the summer season accompanied by lowering pressure as the Monsoon Trough is forming. By June, the trough is starting to attract moist air brought by shifting winds from the East as part of the onset of the Monsoon. Daily mean temperatures stop rising (or even decrease) as clouds become prevalent and rainfall sets in. With the increasing moisture, however, the heat-index keeps climbing throughout the summer. This hot and humid period is characterized by warm nights with 90% and higher relative humidity.

The Heat-Index: The calculation of the heat-index, or "apparent temperature", can be done in a number of different ways. For this paper, the Heat-Index from NOAA is applied (eq. 1), but other options would be possible (see e.g. Epstein and Moran 2006).

$$\text{heat-index } (^\circ F) = c1+(c2*t)+(c3*rH)+(c4*t*rH)+(c5*t^2) + c6*rH^2)+(c7*t^2*rH)+(c8*t*rH^2)+(c9*t^2*rH^2) \quad \text{(eq.1)}$$

where t is air temperature (°F) and rH represents relative humidity (%). The constants are:

c1=-42.379, c2=2.04901523, c3=10.14333127, c4=-0.22475541,c5=-6.83783e-3, c6=-5.481717e-2, c7=1.22874e-3, c8=8.5282e-4, c9=-1.99e-6

(source: National Oceanic and Atmospheric Administration, NOAA)

Further research is necessary to determine which is the most appropriate for the conditions encountered by the urban and peri-urban poor in South Asia. Comparison with air temperature is shown in Figure 2.

ReAnalysis Data: Reanalysis products, such as US NCEP-DOE Reanalysis II, the European ERA-Interims, and the Japanese Reanalysis JRA, are model-integrated observations that can also be used to verify climatologies. The low-resolution of reanalysis products prevents more detailed bias corrections, particularly in the vicinity of higher topography, which was the case for Gorakhpur, India and particularly Islamabad/Rawalpindi in Pakistan. Nevertheless, the NCEP reanalysis product was used to confirm the general climatological aspects of the seasonal cycle due to overall limitations in data availability.

Climate Models: To assess possible future climate, 14 global climate models with daily output from simulations coordinated through the Coupled Climate Model Intercomparison Project version 5 (CMIP5, Taylor et al. 2012) were used. Table 1 lists the models and the different ensemble members used in this analysis. Data obtained from CMIP5 (http://cmip-pcmdi.llnl.gov/cmip5/) covered the period 1950-2005 from the 20th century simulations, and future data was chosen from the high emissions scenario RCP8.5 to capture the full range for changes until 2050. To determine the climatology for 2050, data from the years 2041-2060 were averaged. Multiple ensemble members from the same model were obtained where available. Other emission scenarios were not included here. Climate changes associated with other emissions scenarios would be expected to be similar but somewhat lower in magnitude. The range of temperature changes due to different emission scenarios is relatively small over the next several decades; different emissions scenarios only begin to substantially diverge after 2050. Nevertheless, the RCP8.5 results presented here are widely considered to be at the upper end of future changes by 2050. Future changes under emissions somewhat lower than RCP8.5 would likely reach the same temperature and heat changes, they would just reach those changes a few years or decades later.

Nearly all climate models exhibit biases in one way or another. Commonly, their absolute depiction of the reconstructed historic temperature field over a selected city location (see Figure 3) differs, shows greater variability, or shows extremes that are not found in observations. Some of these biases result from the low resolution of the models (global circulation model cells are generally 100-300km on a side). This issue is of particular concern when looking at local impacts, particularly when the zone of interest is close to more substantial topographic relief such as along the Himalayan range (see low biases shown in Figure 3). Biases can also result from, for example, how land cover characteristics are represented or how the aerosol loading and distribution within the models matches the reality. Particularly in recent years, aerosol load in Asia has had substantial effects on the local and regional radiative balance, which in turn has had measureable impacts on local temperature trends. Aerosols are difficult to model due to the complexity of their interactions with incoming and outgoing radiation and their impacts on cloud cover. Responses to aerosol emissions and loading are quite different across the set

TABLE 1

CLIMATE MODELS FROM THE CMIP5 ARCHIVE USED IN THIS STUDY

Table of climate models used in this study organized by name, organization, and model run type, where 'r' represents the start time, 'i' represents initial conditions, and 'p' represents the physical characteristics of the atmosphere.

Model Name	Modeling Center	RCP8.5 Ensemble Members
ACCESS1-0	Australian Community Climate and Earth-System Simulator Version 1.0	r1i1p1
ACCESS1-3	Australian Community Climate and Earth-System Simulator Version 1.3	r1i1p1, r2i1p1, r3i1p1
bcc-csm1-1	Beijing Climate Center Climate System Model Version 1.1	r1i1p1, r2i1p1, r3i1p1
CanESM2	Canadian Earth System Model Version 2.0	r1i1p1, r2i1p1, r3i1p1, r4i1p1, r5i1p1
CCSM4	National Center for Atmospheric Research Community Climate System Model Version 4	r1i1p1, r1i2p1, r1i2p2, r2i1p1, r6i1p1
CESM1-BGC	National Center for Atmospheric Research Community Earth System Model - Biogeochemistry Version 1	r1i1p1
CESM1-CAM5	National Center for Atmospheric Research Community Earth System Model Version 1 - Community Atmosphere Model Version 5	r1i1p1
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization Model Version 3.6	r5i1p1, r6i1p1, r7i1p1, r8i1p1, r9i1p1
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, NOAA Earth System Model Version 2 - Modular Ocean	r1i1p1
HadGEM2-ES	UK Met Office Hadley Center Global Environment Model Version 2 with Earth System interactions	r1i1p1
IPSL-CM5A-LR	Institut Pierre Simon Laplace Climate Model Version 5A	r2i1p1, r3i1p1, r4i1p1, r5i1p1, r6i1p1
MIROC5	University of Tokyo Model for Interdisciplinary Research	r1i1p1, r2i1p1, r3i1p1 r4i1p1, r5i1p1
MPI-ESM-LR	Max Planck Institute for Meteorology, Hamburg Earth System Model	r1i1p1, r2i1p1
NorESM1-M	Norwegian Climate Centre Earth System Model Version 1	r1i1p1, r2i1p1, r3i1p1

of climate models used in this study. A third source of bias in model results is due to urban heat island effect. In this study, we are using available station data to identify and correct for model bias. However, the station data we are using is primarily from airport locations. Airport stations tend to have some of the longest data series but these locations are also on the outskirts of cities and are often a few degrees cooler than city centers. Consequently, the presented comparisons are likely conservative, reflecting the cooler airport temperatures and failing to include the full magnitude of the urban heat island effect.

As seen in Figure 3, the observed seasonal cycle (shown in pink) is broadly captured in all models (individual blue lines), though the modeled timing of onset of the summer warming, magnitude of peak temperatures, and retreat of the monsoon can all differ significantly from observations. The differences between modeled data and observations were used to determine a separate bias correction for each model. The bias correction was applied in a sliding four week window centered on each day to capture the proper climatological mean and its evolution over the seasonal cycle in a way that is insensitive to daily weather fluctuations.

This type of bias-correction is simple and can readily be applied without a high-resolution spatial network of observations, such as is generally used in spatially more extensive statistical downscaling (e.g., Maurer et al. 2002, Stoner et al. 2013). Indeed, for this application, because only single station observations at the periphery of the cities are available, and because the temperature is generally a smooth, large-scale field, further downscaling would not be very meaningful.

For daily temperature fluctuations, the models represent the general range and variations quite well and the bias correction eliminates systematic errors while preserving the simulated distributions

FIGURE 3

OBSERVED AND MULTI-MODEL ENSEMBLE PROJECTIONS OF DAILY MAXIMUM AND MINIMUM TEMPERATURES FOR GORAKHPUR, INDIA (NOT BIAS CORRECTED RESULTS)

Observed and simulated daily maximum (left) and minimum (right) temperatures for Gorakhpur, India. Model output is directly from GCMs without bias correction. Note the systematically cooler conditions in the models due to artificially high elevation for models cells in the proximity of the Himalayan mountain range. Errors in one model (see beginning of May) were eliminated prior to bias-corrections.

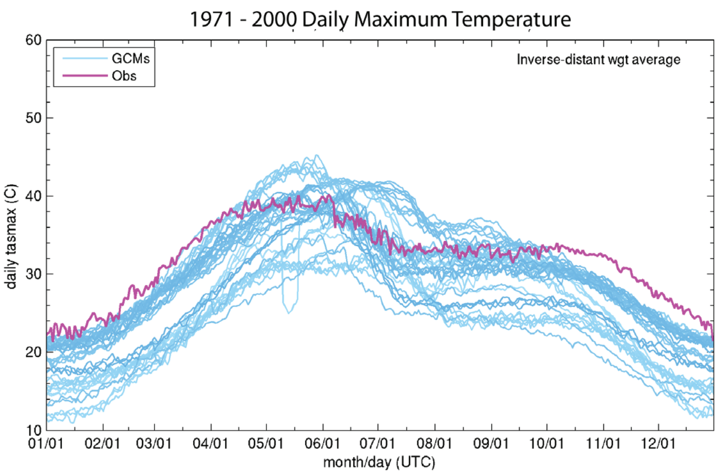


FIGURE 4

OBSERVED AND MULTI-MODEL ENSEMBLE PROJECTIONS OF DAILY MAXIMUM AND MINIMUM TEMPERATURES FOR GORAKHPUR, INDIA (BIAS-CORRECTED RESULTS)

Same as figure 3, but showing bias-corrected results (bright green) almost perfectly matching observations (dark blue). The multi-model ensemble mean of the un-corrected series is shown in pink (note, this line is different than the pink line in figure 3).

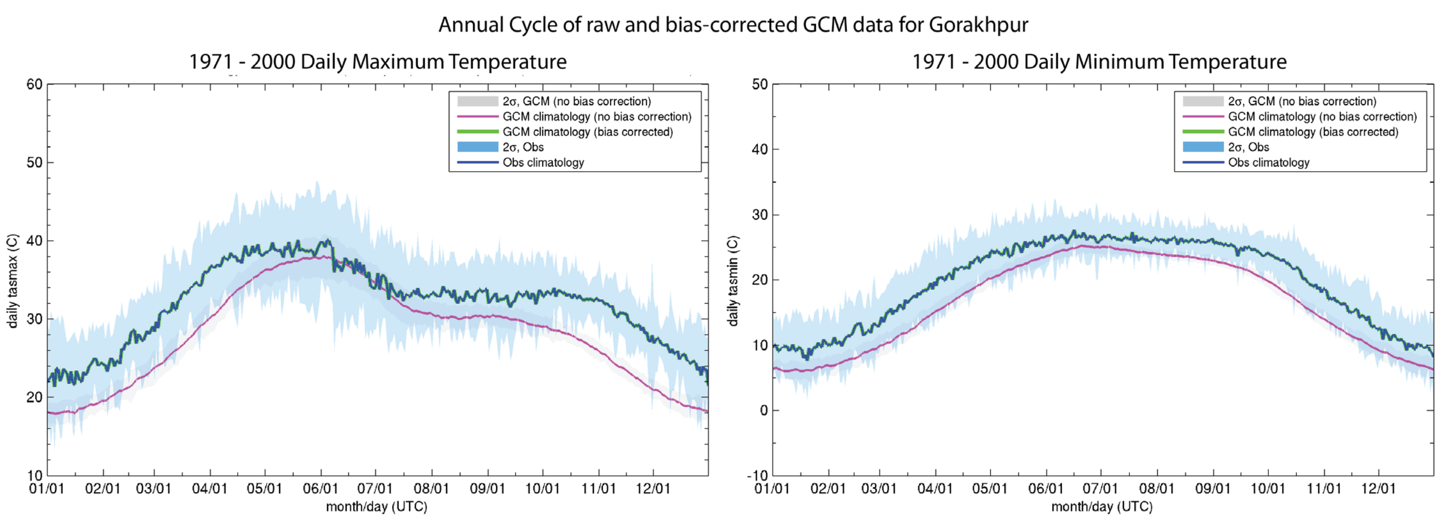
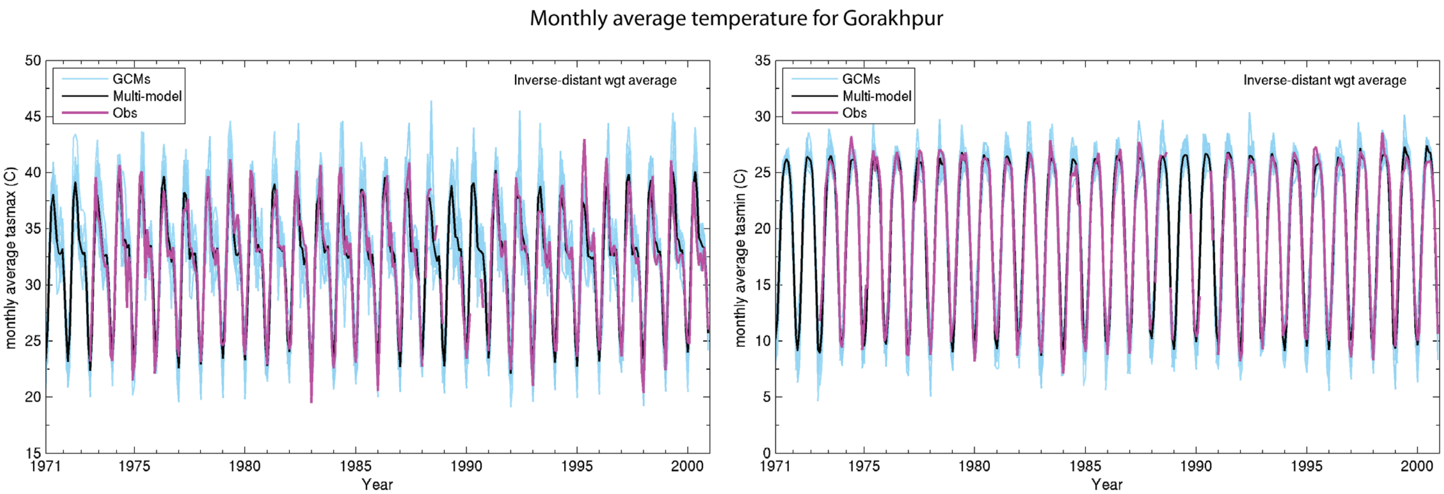


FIGURE 5

COMPARISON OF OBSERVED AND SIMULATED DAILY MAXIMUM AND MINIMUM TEMPERATURES FROM 1971–2000

Comparison of observed (pink) and simulated (black) daily maximum (left) and daily minimum (right) temperatures over the historical period. The range from individual models is shown in light blue.



of variations around the mean. Figure 4 shows the effectiveness of bias correction in the climatological means, as well as the inter-annual variability around the center expected value. Figure 5 compares the time series of observations at a monthly resolution (pink) with the ensemble mean of the bias-corrected model output (black) embedded in the range of individual models (light blue). While some individual models have a larger year-to-year variability than the multi-model mean (black), the multi-model mean for both daily maximum (left panel) and daily minimum temperatures (right panel) is very close to the observations. This example demonstrates the power of multi-model ensembles, where individual model differences tend to average out and the multi-model ensemble mean performs better compared to observations than any individual model. In the following presentation of results, all model data shown is drawn from the bias-corrected ensemble mean (unless otherwise stated) because of this property.

RECENT CLIMATE, EMERGING TRENDS, AND PROJECTIONS

Using bias correction ensures that the mean temperature over the historical period will agree between models, the multi-model ensemble, and the observations. Another important comparison between observations and model output concerns inter-annual to decadal variability. While bias corrections can eliminate deviations in the mean conditions, no corrections or downscaling can generate "structure" in the temporal variability around that mean if it wasn't present in the model in the first place. In the case of Gorakhpur, India (Figure 6), the inter-annual variability of model simulated hot days (right panel) is much smoother across the years than what can be read out of observations (left panel) where distinct years, and in fact decadal episodes, stand out as particularly hot.

FIGURE 6

COMPARISON OF WARMEST 1% OF DAYS OBSERVED VERSUS MODELED

Comparison of the number of days per month for which the daily maximum temperature is in the warmest 1% of observed days over the common period of 1971-2000. Shown is the example for the city of Gorakhpur, India with observations (left panel) and model output for the NCAR-CCSM4 model prior to bias correction (right panel). In observations the range from only few days per year to a very high number of days in a few or group of years is much more distinct across time than in the climate model where the years are much more alike.

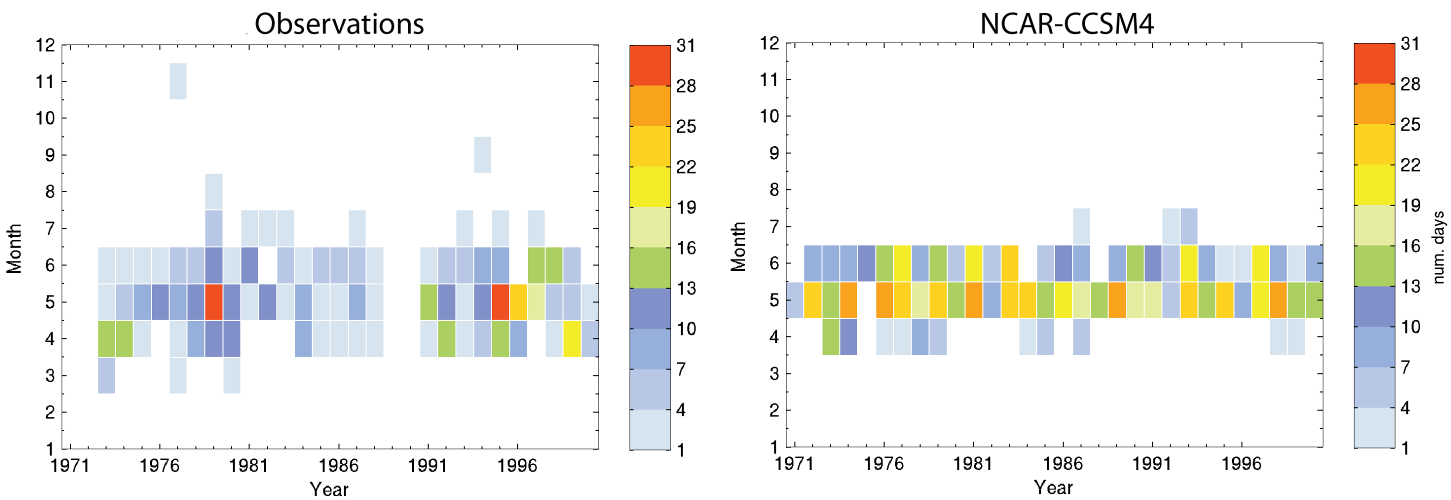


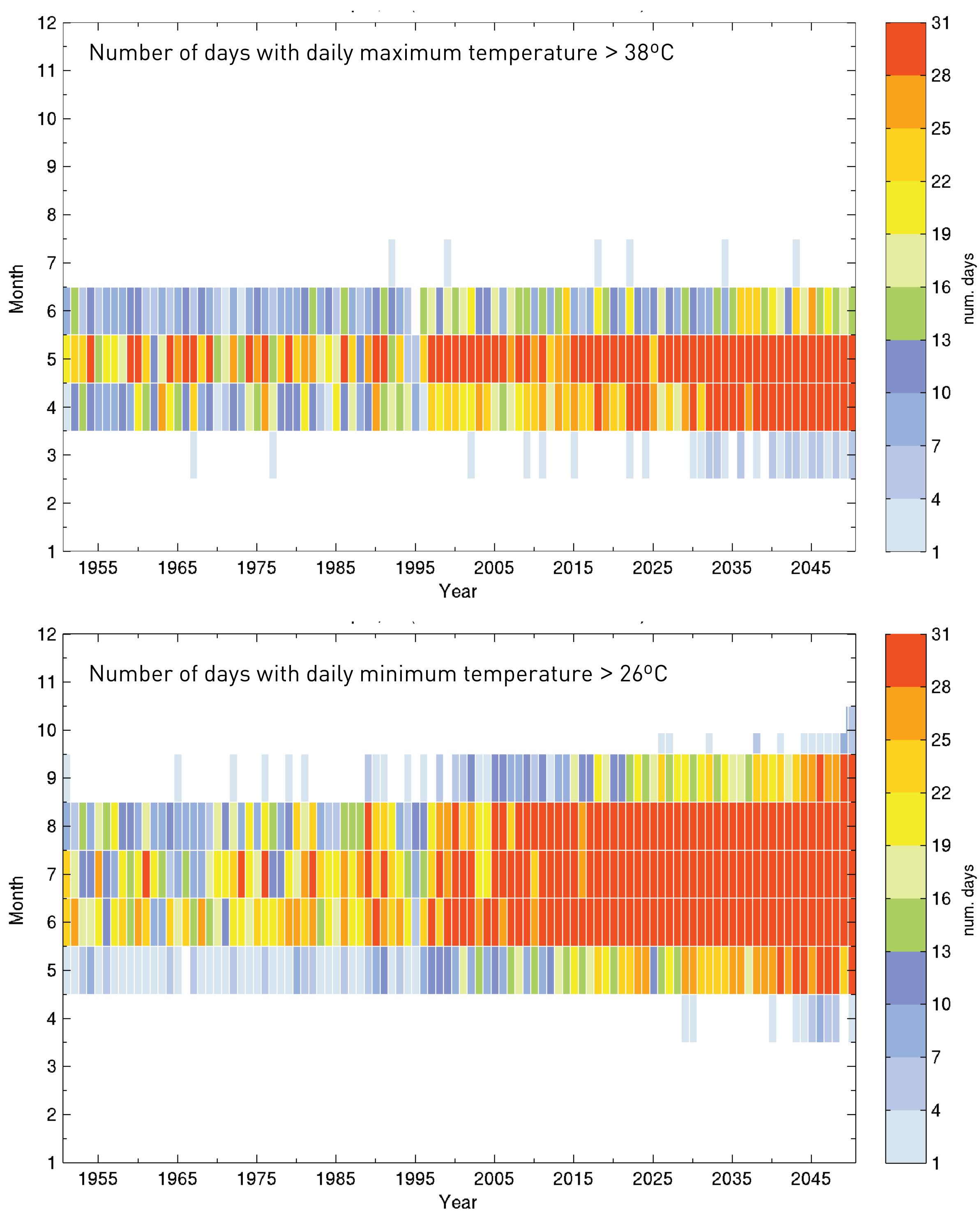
Figure 7 looks at how temperature trends may behave in the future. In the CMIP5 multi-model ensemble shown in Figure 7, both daily maximum (top) and daily minimum (bottom) temperatures in Gorakhpur transition from a relatively slow warming over the 20th century to a rapid intensification of heat conditions towards 2050. Figure 7 shows the change in the number of days per month that exceed fixed temperature thresholds. Emerging from community discussions the daily maximum temperature threshold was set to 38°C and the daily minimum temperature threshold to 26°C. Both are thresholds that currently are exceeded in Gorakhpur every year, but will be more so in the future. Looking at the projected number of days the thresholds will be exceeded in the future, it becomes clear that high maximum and minimum temperatures are going to intensify. These high temperatures will become regular to daily during the central months of the monsoon season, and the multi-model ensemble indicates that the heat season will likely expand into the transition (or shoulder) seasons. By mid-21st century, the part of the year in which such hot conditions occur expands from just one-quarter (Tmax) or one-third (Tmin) of the year today to roughly one-third and one-half of the year in the next 40 years, respectively. In this time, periods that currently are punctuated by cooler spells, bringing much needed relief, will likely remain hot, potentially for 2 to 3 months without cease.

The temperature trends projected by the models are already telling a powerful story. What today are high temperatures during both day and night may become average days over the next few decades. But temperature alone is not what causes most direct human health threats or even the highest discomfort. The other critical factor is humidity. The human body uses perspiration to cool when surrounding temperatures get too high. As long as evaporative cooling from the skin can happen, the body doesn't overheat and dangerous health impacts are prevented. But when the humidity in the air is high, the efficiency of perspiration and evaporation decreases and the body is exposed to an apparent heat that is significantly higher than what the temperature itself would suggest. The Heat Index captures these conditions by combining temperature with relative humidity (see Eq. 1).

FIGURE 7

HOTTEST DAYS >38°C AND WARMEST NIGHTS >26°C FOR GORAKHPUR (HISTORICAL AND PROJECTED)

Historical and projected occurrence of hottest days (>38°C) and warmest nights (>26°C) by month in Gorakhpur as seen in the multi-model ensemble for the period 1950 to 2050. An increase in intensity of heat waves is accompanied by a lengthening of the heat season, particularly for warm nights (minimum temperatures >26°C).

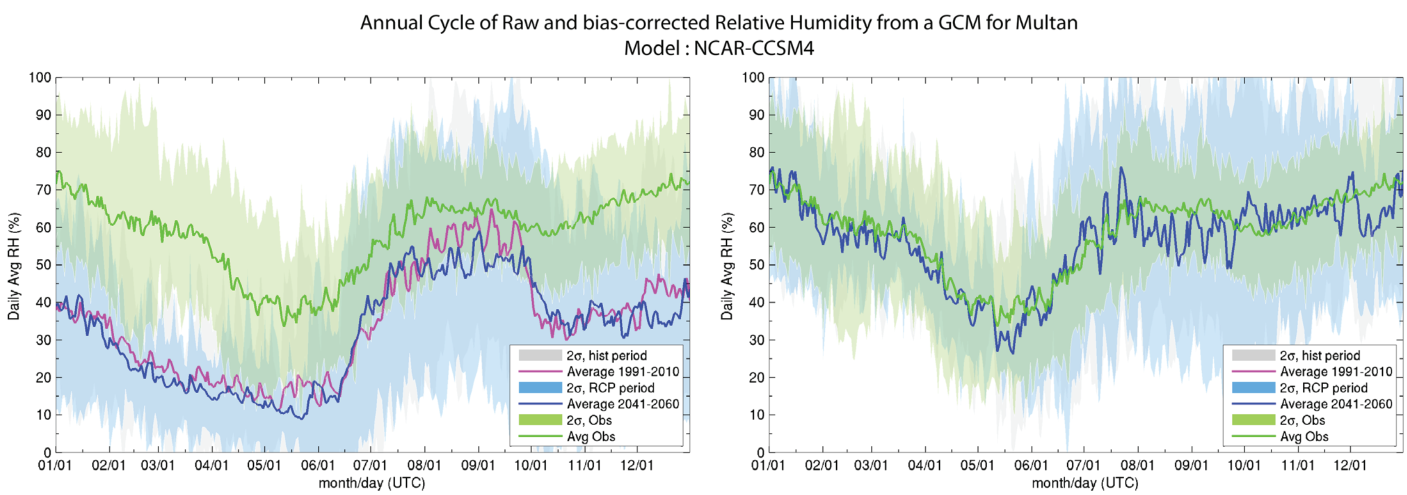


To calculate the Heat Index from climate model output, humidity data needs to be bias corrected as well. Figure 8 illustrates for one climate model (the NCAR CCSM4) how the annual cycle of humidity is structurally captured in the monsoon environment of Multan, Pakistan in South Asia. Figure 8 (left-hand side) also illustrates that the systematic errors in modeled humidity can be quite large. In the case of the NCAR CCSM4, only during the peak of the monsoon does the model come close to the correct daily mean relative humidity in this region. For most of the year, the model systematically under-predicts observed values by almost 30%. Such errors would lead to significant errors in inferred heat indices. After applying the same strategy for bias correction as used for the temperature data, the right hand side panel of Figure 8 shows the bias corrected annual cycle for Multan.

FIGURE 8

RELATIVE HUMIDITY FOR MULTAN, PAKISTAN (OBSERVED AND MODELED)

Raw (left-hand side) and bias-corrected (right-hand side) relative humidity for Multan, Pakistan from the NCAR CCSM4 model. Figure show a typical annual cycle of relative humidity for this region, which lies in a region of Pakistan where the monsoon nearly tapers out. Daily average observed relative humidity is shown in green; two standard deviation variability is shown in light green. Daily average modeled relative humidity is shown for 1971 - 2000 in pink and for 2041 to 2060 in dark blue; two standard deviation variability in modeled relative humidity is shown is light blue.



As seen for temperatures, the correct mean can be recovered by the bias correction, but extremes may still substantially differ. This can be seen in the pale green (two standard deviation envelope around the observed mean) vs. pale blue (two standard deviations from the modeled mean) sections of the right-hand side of Figure 8. The excessively high daily and inter-annual variability produced by the model will likely lead to an over prediction of days with highest (extreme) humidity. However, when used to calculate the Heat Index (Figure 9), the range of modeled annual and inter-annual variability (pink line; grey shading shows two standard deviations from the modeled mean) matches observations (green line; light green shading shows two standard deviations from the observed mean) quite closely, despite both temperatures and humidity being bias corrected independently. This is likely due to the almost direct offset of temperature and moisture. When moisture is too low in the model for a day or a period, this allows the model temperatures to rise sharply because of weak negative feedbacks that would arise from clouds. Conversely, if the humidity is excessively high, then the temperatures are dampened through formation of clouds and possibly rain. Both systematic offsets counteract and offset each other.

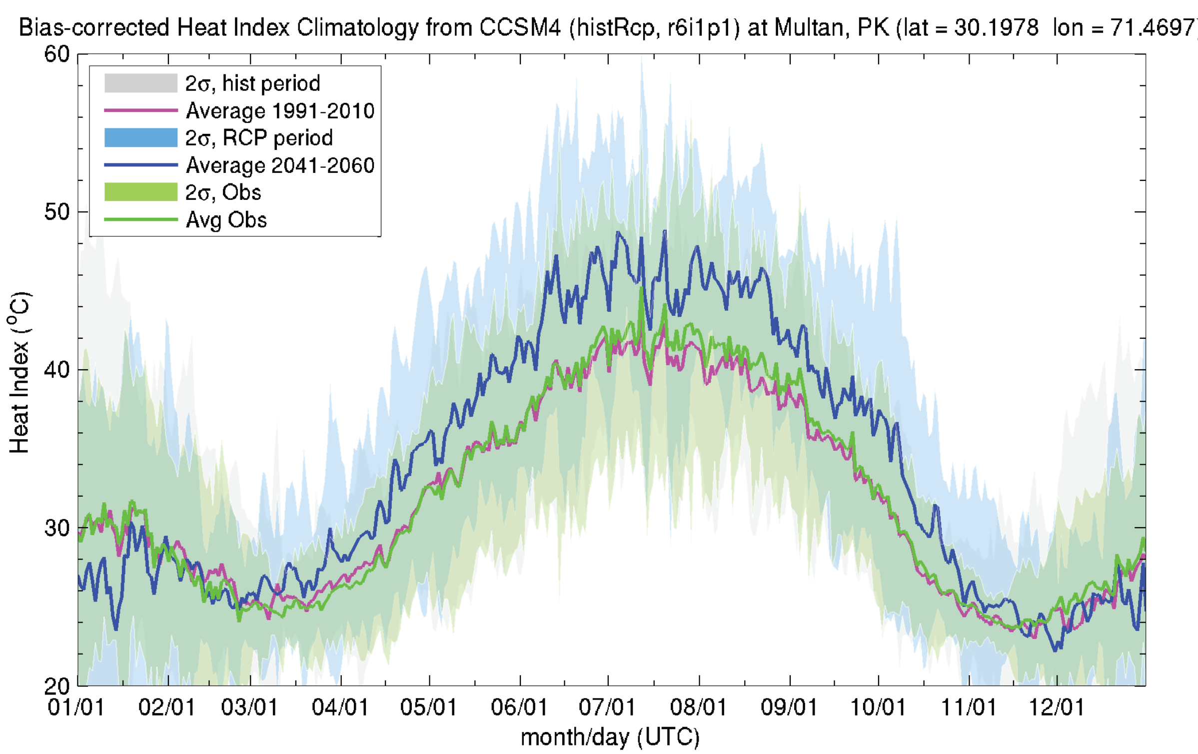
CURRENT AND FUTURE TEMPERATURE AND HEAT

The Heat Index has been used extensively to assess heat-related health issues (e.g. Epstein and Moran 2006, Kim McMichael et al. 2008, Huang et al. 2010). Here, we apply this perspective to discuss how future heat thresholds might be assessed for the cities in South Asia. Using the multi-model average, we compare the present day annual cycle of Heat with the projected

FIGURE 9

BIAS-CORRECTED HEAT INDEX CLIMATOLOGY FROM CCSM4 CLIMATE MODEL

Heat Index (see Eq. 1) for observations (green line and associated range) and NCAR CCSM4 climate model for the present climatology (pink line and light gray range). Also shown are the model-projected changes of the mean (dark blue line) and range (light blue shading) of future Heat Index by 2050.



future annual Heat cycle in 2050. In considering the impacts of Heat, we use 37°C as the threshold Heat Index. This is average body temperature for humans and the threshold at which health impacts begin to be significant. Table 2 illustrates the Heat Index, using a color scale to indicate the level of heat impact. The"strong discomfort", centered at 37°C, is where recommendations to restrict physical activity begin.

Using the Heat Index as a baseline, we assess current and future Heat in three cities that align in a transect, from Gorakhpur in the East through Islamabad/Rawalpindi to Multan in the West. Each city has a different geographic and topographic setting, with Gorakhpur experiencing the longest monsoon and with it the potential for the highest Heat Index season. Islamabad/Rawalpindi benefits from a significantly shorter monsoon and its location along the mountains offers cooler and drier ventilation. At the farthest reach of the monsoon flow is Multan where moisture is lower but the temperatures are very high; Multan is historically known as an extremely hot place.

TABLE 2

TABLE OF HEAT INDEX VALUES

37°C is the center of the range of the strong discomfort level where recommendations are to start to restrict physical activity.

HUMIDEX INDEX OF APPARENT TEMPERATURE (degree C)

	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
42°	48	50	52	55	57	59	62	64	66	68	71	73	75	77	80	82
41°	46	48	51	53	55	57	59	61	64	66	68	70	72	74	76	79
40°	45	47	49	51	53	55	57	59	61	63	65	67	69	71	73	75
39°	43	45	47	49	51	53	55	57	59	61	63	65	66	68	70	72
38°	42	44	45	47	49	51	53	55	56	58	60	62	64	66	67	69
37°	40	42	44	45	47	49	51	52	54	56	58	59	61	63	65	66
36°	39	40	42	44	45	47	49	50	52	54	55	57	59	60	62	63
35°	37	39	40	42	44	45	47	48	50	51	53	54	56	58	59	61
34°	36	37	39	40	42	43	45	46	48	49	51	52	54	55	57	58
33°	34	36	37	39	40	41	43	44	46	47	48	50	51	53	54	55
32°	33	34	36	37	38	40	41	42	44	45	46	48	49	50	52	53
31°	32	33	34	35	37	38	39	40	42	43	44	45	47	48	49	50
30°	30	32	33	34	35	36	37	39	40	41	42	43	45	46	47	48
29°	29	30	31	32	33	35	36	37	38	39	40	41	42	43	45	46
28°	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
27°	27	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
26°	26	26	27	28	29	30	31	32	33	34	34	35	36	37	38	39
25°	25	25	26	27	27	28	29	30	31	32	33	34	34	35	36	37
24°	24	24	24	25	26	27	28	28	29	30	31	32	33	33	34	35
23°	23	23	23	24	25	25	26	27	28	28	29	30	31	32	32	33
22°	22	22	22	22	23	24	25	25	26	27	27	28	29	30	30	31

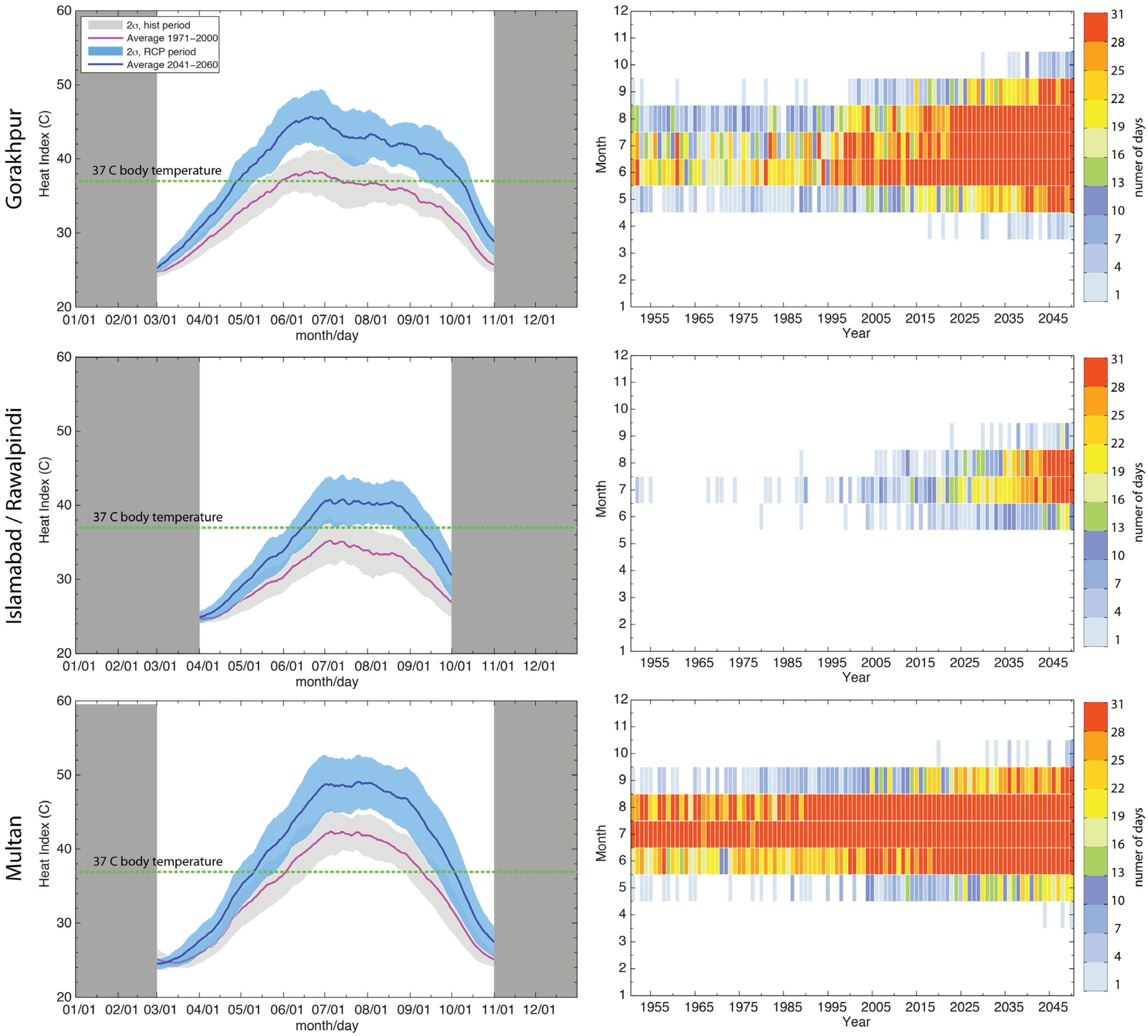
Up to 29 C°	No discomfort
From 30 to 34 C°	Slight discomfort sensation
From 35 to 39 C°	Strong discomfort. Caution: limit the heaviest physical activities
From 40 to 45 C°	Strong indisposition sensation. Danger: avoid efforts
From 46 to 53 C°	Serious danger: stop all physical activities
Over 54 C°	Death danger: imminent heatstroke

The left-hand column of Figure 10 shows the annual cycle of present day Heat Index (pink line with light gray shading for the variability) and the future projected Heat Index from the CMIP5 multi-model ensemble (blue line with light blue range) for the cities of Gorakhpur, Islamabad/ Rawalpindi and Multan. The right-hand column marks the number of days in each month from 1950 to 2050 for which the daily average Heat Index surpasses 37°C. For all locations, the multi-model projections suggest a

FIGURE 10

HEAT INDEX CLIMATOLOGIES FOR EACH LOCATION (MODELED)

The left-hand column shows Heat Index climatologies drawn from the bias corrected multi-model ensemble from CMIP5 for present day (pink line; light gray shading shows two sigma variability) and future (blue line; light blue shading shows two sigma variability) for Gorakhpur, India (top), Islamabad/Rawalpindi, Pakistan (center) and Multan, Pakistan (bottom). The right-hand column shows the number of days in the multi-model ensemble for which the daily mean Heat Index surpasses 37°C.



dramatic increase in the Heat Index during the summer season. While temperature changes are expected to be in a range from 1 to maybe 3°C, the projected increase in Heat Index could be as much as 5-7°C! Figure 11 shows the changes for Multan from as projected by the NCAR CCSM4.

The combination of continued high humidity in the monsoon period with higher background temperatures will intensify temperature-related health issues in these three cities. Residents of all three cities already struggle with heat waves and their impacts. This is especially problematic for the poor, who have less access to active cooling, may work outdoors, or, often more problematically, may be confined to primary shelters which are often poorly ventilated and cannot be due to external conditions.

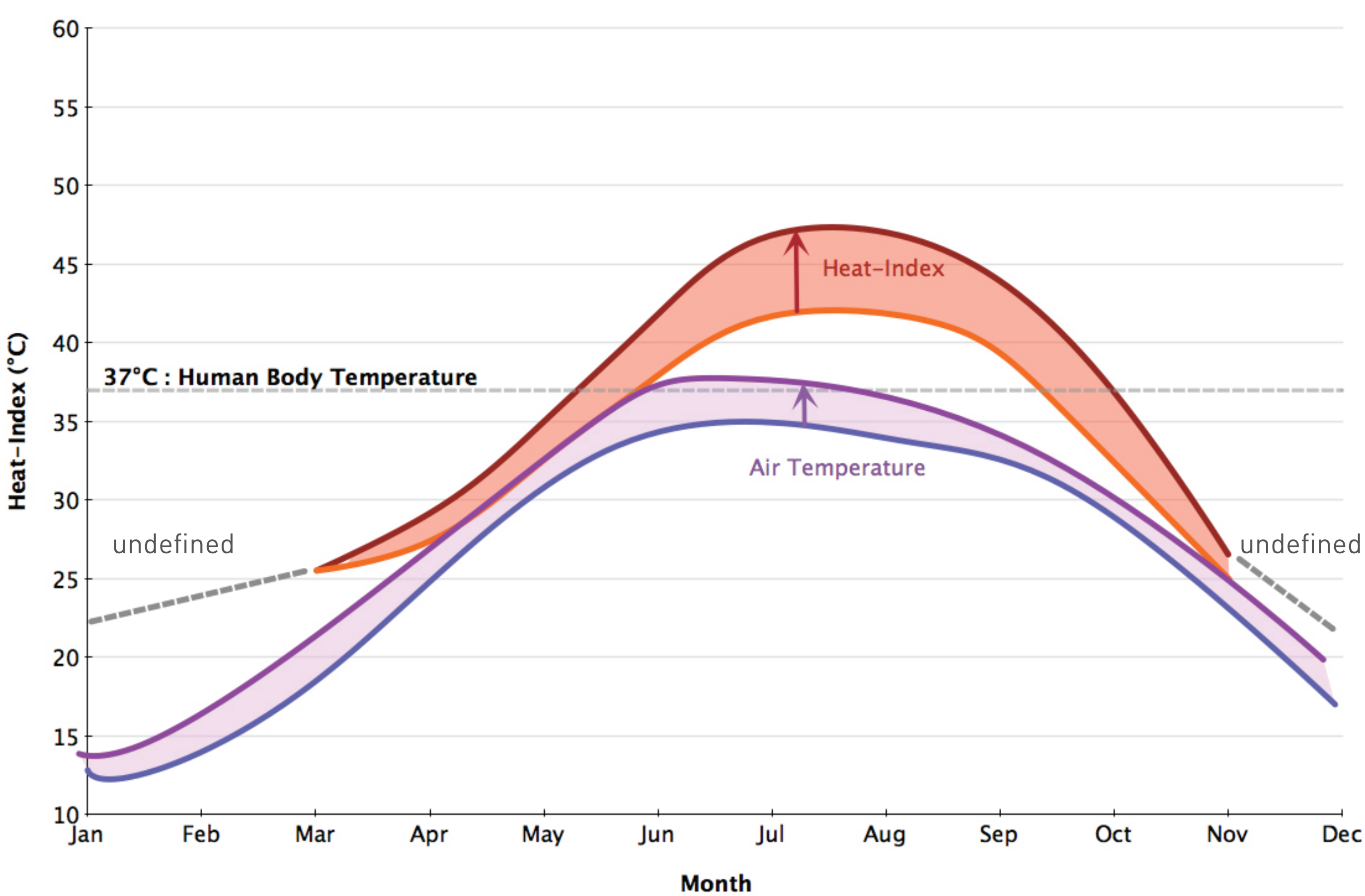
Future heat waves are not only projected to be significantly more severe, but heat will likely also become more sustained. Today, health effects are closely tied to the duration of exposure. During heat spells there are usually a couple of days where the heat breaks allowing people's body's to recover thus allowing them to cope better with the ensuing high heat. Model projects suggest, however, that breaks in hot weather that currently allow for recuperation will gradually give way to continual heat with little or no interruption. In the future the 37°C Heat Index threshold will be surpassed much more often than today; daily Heat Index during the core monsoon period could continuously exceed 37°C, particularly for Gorakhpur and Multan.

If in the future the current pattern of periodic temperature decreases no longer occur, the impacts on people

FIGURE 11

CHANGES IN AIR TEMPERATURE AND HEAT INDEX DECADAL AVERAGES OBSERVED AND PROJECTED FOR MULTAN, PAKISTAN

Air temperatures (blue) and heat index (red) for observed [1991–2010, lower bound]; and projected [2041–2060, upper bound] from the NCAR CCSM4.



will be severe, with the potential for rapid decrease in economic productivity. Heat-related morbidity and mortality will likely become a critical factor for the region (Huang et al. 2003, Nag et al. 2007, McMichael et al. 2008).

In addition to the intensity and relentless nature of projected future heat, climate change is likely to cause a significant expansion of the period of the year that is affected by heat. For all three cities studied here, the summer heat season is likely to expand into the shoulder seasons, beginning a month early than today and ending a month later. Gorakhpur, India may become dominated with a climate where the Heat Index is above the 37°C threshold for a third of the year or more. In Multan, although the intensity of projected heat is higher than in Gorakhpur, because less monsoon moisture reaches that area in Pakistan, evaporative cooling may be a more effective solution than in Gorakhpur and Islamabad/ Rawalpindi. Islamabad/ Rawalpindi may experience the most severe impacts. Currently this city only occasionally experiences days of high Heat Indices; consequently, of the three cities studies, their adaptive capacity for heat is probably lowest. If, by 2050, they have 60 days of continuous high Heat Indices, will they be able to adapt?

CAVEATS AND CAUTIONS IN INTERPRETATION

Observational data: The openly available observational record of daily data from South Asia is lacking spatial and temporal coverage and necessary data validation. For the purpose of this study, we relied on GHCN station information. Corroboration of the climatology was achieved with neighboring stations, by comparison with reanalysis data, and by comparison with a one year observational record recorded by GEAG at a station on the roof of their building in a newly developing area of Gorakhpur. The accuracy of the present day climatologies, and the associated bias-corrected projected temperature and Heat Index calculations therefore are somewhat uncertain. However, relative changes and the spatial and temporal structure of these changes should be robust against observational deficiencies in the calibration.

Length of observations: Based on the short observational records available, it is difficult to judge how well the few decades of available daily data represent the natural multi-decadal variability of this region. This issue is of particular relevance when working with extreme values where normally much longer climatological records would be desirable. As described in the analysis, the models generally illustrate larger interannual variability than observation. However, model output also lacks the decadal structure seen in the observations. What the implications are of these issues for projections over the next few decades is difficult to estimate at this point. From the presented results one might expect that instead of relatively continuous increases in the intensity and duration of heat stress, reality will likely be more volatile, possibly with less frequent but more intense heat waves than the models currently project.

Urban heat island: The meteorological stations from which we obtained data for this study are primarily located at airports at the periphery of the cities. These locations are expected to be somewhat cooler than conditions in the inner part of the cities. Absolute heat values to which the poor populations in the cities are exposed to are most likely higher.

Regional and local driving factors of change: The emission pathway chosen for this study was the high-end scenario following a Representative Concentration Pathway (RCP) of 8.5 W/m2 by the end of the 21st century. We used this pathway primarily to increase the signal to noise part of the climate change results. The consequences of this choice are still rather small by 2050; the separation of the climate signals when following different emission pathways is mostly concentrated in the second part of the century. Potentially more important are uncertainties in regional land use and land cover changes and local and regional emissions of aerosol in the future. Because land use, land cover and aerosols have an immediate effect on local conditions, there is a non-negligible opportunity for cities to modify their urban environments in ways that will reduce climate impacts. Increasing green space would offer both shading and evapo-transpirative cooling. Even strategies such as using white paint or chalk on roofs can have measurable impacts on the urban heat environment. Such adaptive approaches could help cities mitigate extreme daily maximum temperatures.

Challenge of high nighttime temperatures: Countering high daily minimum temperatures is more challenging than mitigating high daytime maximum temperatures. Because humidity is generally highest at night, passive cooling is hardest at night. Solutions applicable in other regions of the world, such as basements sunk into the generally cooler ground (deeper soils are closer to annual average temperature conditions) are not commonly possible in monsoon regions where flooding is common during the monsoon.

SUMMARY: THE HEAT INDEX AND ITS IMPLICATIONS

The global increase in greenhouse gases in the atmosphere is leading to a continued warming of the planet. Over the next decades, most regions of the world will experience warming. The rise in surface temperatures in the South Asia is expected to be 1-3°C. Figure 12 shows the global projections of the anomaly in maximum and minimum temperature for 2041-2060 mean versus the 1971 to 2000 climatological mean from an ensemble of IPCC CMIP5 models (IPCC 2013) for the Summer Monsoon period of June-July and August.

The increase in nighttime temperatures (associated with the daily minimum temperature) is likely to be somewhat larger than the increase in daily maximum

FIGURE 12

GLOBAL AND REGIONAL PROJECTIONS OF DAILY MAXIMUM AND DAILY MINIMUM TEMPERATURES (SUMMER MONSOON SEASON)

Projected changes in air temperature from ensemble CMIP5 models for the Summer Monsoon period of June, July, and August (JJA).

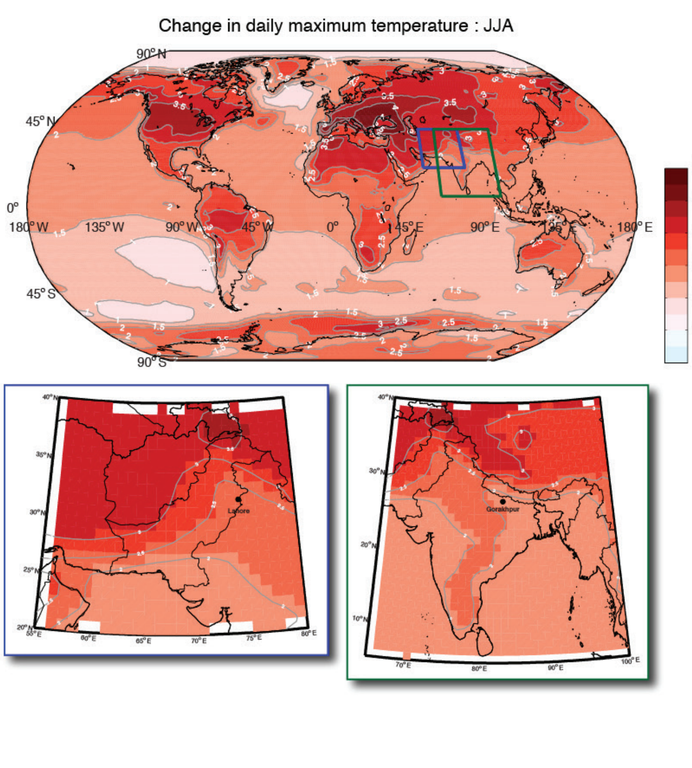
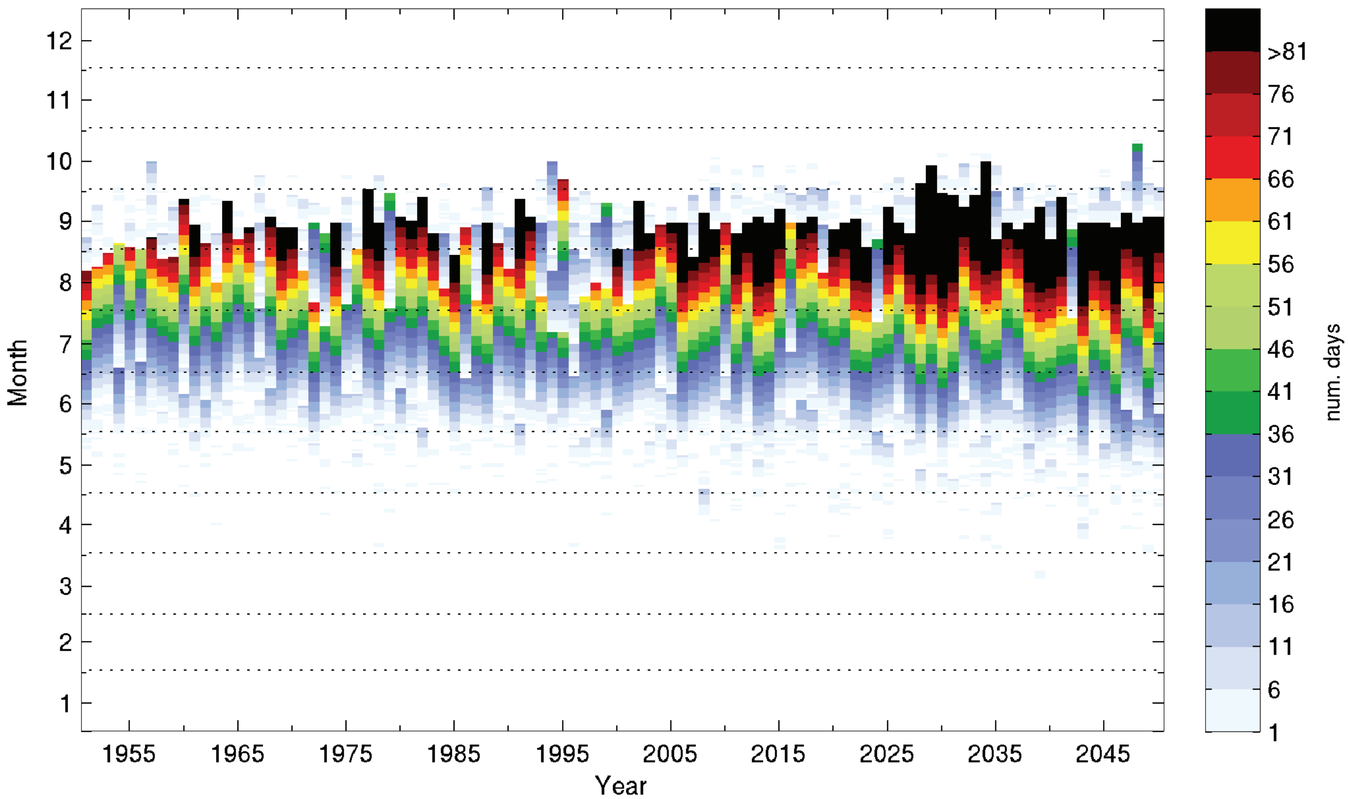


FIGURE 13

NUMBER OF CONSECUTIVE DAYS WITH DAILY MINIMUM TEMPERATURE >26°C FOR GORAKHPUR, INDIA (CCSM4 CLIMATE MODEL)

Projection of longest consecutive episodes per year with nighttime minimum temperatures remaining above 26°C. As can be seen, as we move into the future the onset of nighttime temperatures begins earlier in the year (first appearance of pale blue), high temperatures continue later into the year (color bars extending well above the 9 month marker), and an increasing portion of years have increasingly extended black periods, indicating 81 consecutive days or more with minimum temperatures above 26°C. Even in the next decade or two we begin to experience individual years with 3 to 5 month periods of uninterrupted nighttime heat above the human comfort level.



temperature because of negative feedbacks (mostly clouds, rainfall and evaporative cooling) that can act to reduce potential daily peak temperatures. However, humans experience heat not only as temperature. Atmospheric humidity plays a critical role in our perception of heat because perspiration is our primary mechanism to rid the body of excess heat. If atmospheric moisture is relatively low, then even extreme temperatures can be endured without too much discomfort or physical impact. If, however, the atmospheric relative humidity is high, evaporative cooling from the skin is suppressed and the apparent heat is significantly higher than the temperature alone. The Heat Index captures this combined effect.

Simulated changes in the Heat Index across a large multi-model ensemble agree with observations of already increasing heat threats to the population and the economies of South Asia. The next few decades are likely to witness the emergence of wide-spread heat threats across South Asia. Our case studies in the Gangetic Plain of India and the Indus Valley suggest that within a few years or decade these regions are likely to surpass key temperature thresholds and begin experiencing increasingly continuous Heat Index situations above 37°C. Individual heat events will likely become more severe than anything previously experienced. The average Heat Index is projected to rise twice as fast as air temperatures, significantly exacerbating heat impacts on people.

This highlights two critical issues for local and regional decision makers. First, the total number of days in which heat reaches health-threatening levels in going to rise rapidly over the next several decades. Compared to today, the projections suggest at least a doubling in the number of health-threatening days compared to historical averages. Embedded in this trend are extreme years when high nighttime temperatures (see e.g. Figure 13) remain above the level where comfort through cooling can be found. Particularly the nighttime heat poses challenges to adaptation.

Second, in the central summer months, high heat will become increasingly sustained. In figures A1–A3 (See Appendix) summarize these results for the three cities — Gorakhpur (India), Islamabad/Rawalpindi (Pakistan) and Multan (Pakistan) — for which daily heat indices were computed. Current high heat events are generally interspersed with cooler periods which allow for recuperation. Sustained periods of high heat prevent are likely to significantly increase heat stress and impact human health and productivity. The increasingly sustained nature of future heat episodes should be of immediate concern to planners and decision makers.

APPENDIX

FIGURE A1

HEAT THRESHOLD SUMMARY GORAKHPUR, INDIA

Overview of Heat conditions for Gorakhpur, India. Top: period of the year within which to expect days with a Heat Index above 37°C. Middle: Number of days per year with Heat Index above 37°C. Bottom: Annual cycle of the Heat Index and typical inter-annual variability for present day and 2050.

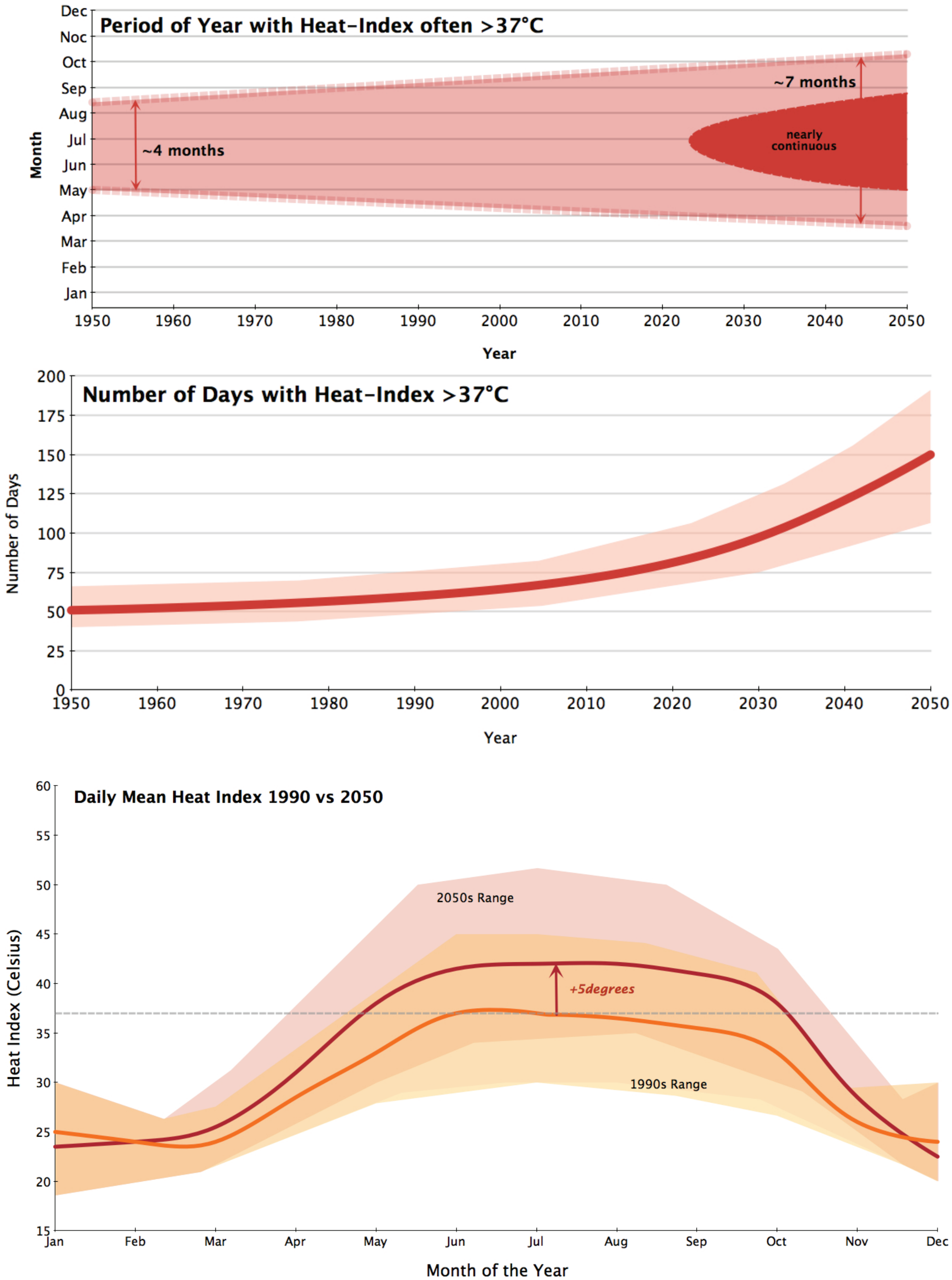


FIGURE A2

HEAT THRESHOLD SUMMARY ISLAMABAD/RAWALPINDI, PAKISTAN

Same as for Figure 14, but for the city of Islamabad / Rawalpindi, Pakistan.

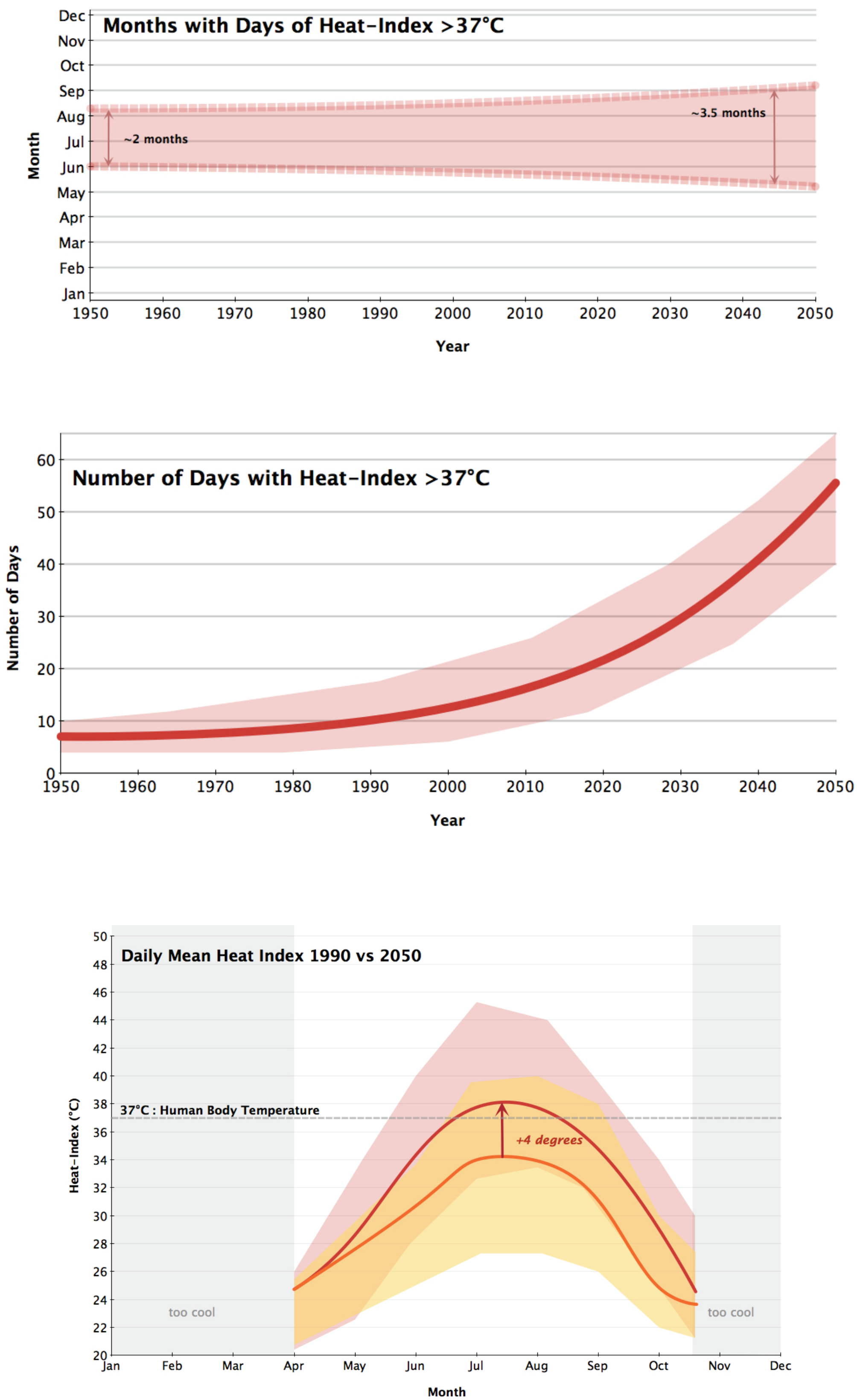
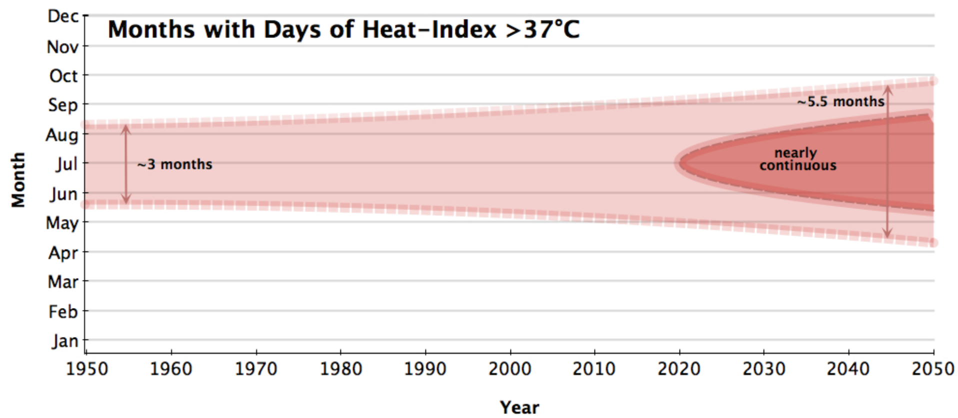
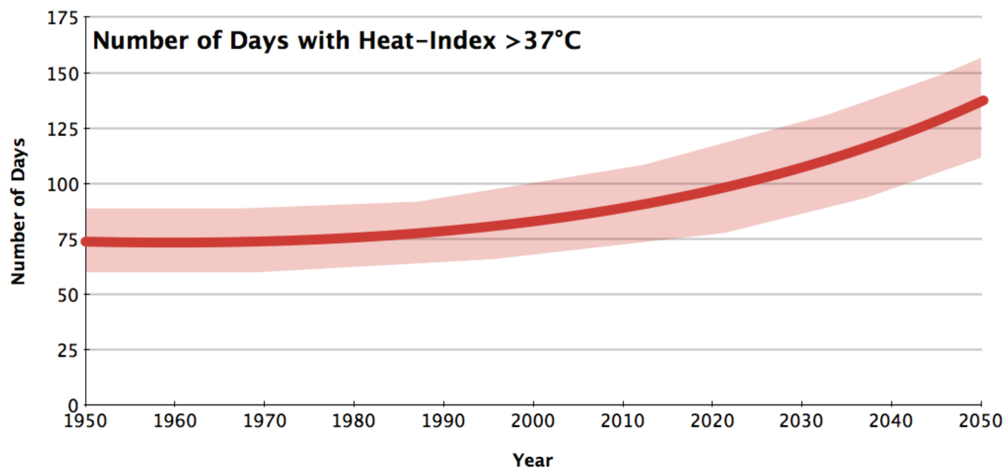


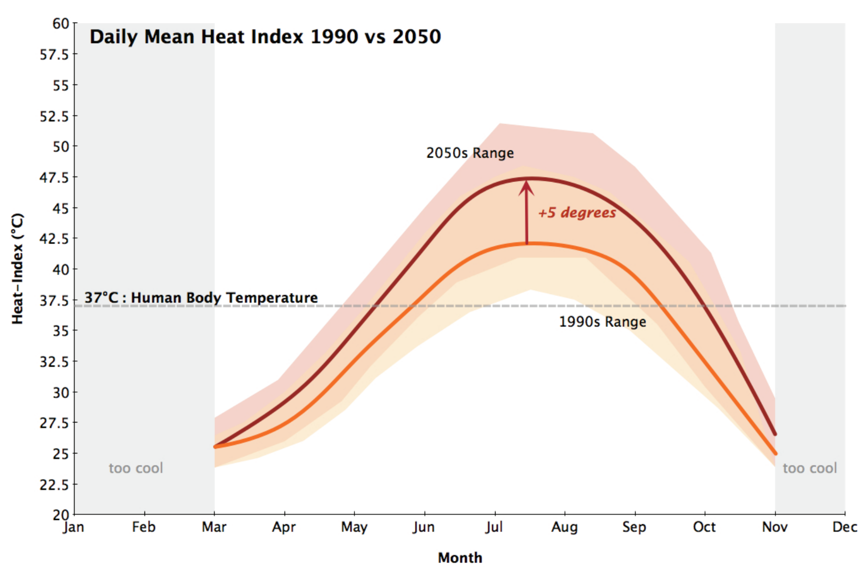
FIGURE A3

HEAT THRESHOLD SUMMARY MULTAN, PAKISTAN

Same as for Figure 14, but for the city of Multan, Pakistan.







REFERENCES

Alexander, L. V., et al., 2006: Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* 111, D05109, doi:10.1029/2005JD00629.

Epstein Y., and D. S. Moran, 2006: Thermal Comfort and the Heat Stress Indices. Review Article. *Industrial Health*, 44, 388-398.

Huang, W., H. Kan, and S. Kovats, 2010: The impact of the 2003 heat wave on mortality in Shanghai, China. *Science of the Total Environment*, 408 (11), 2418-2420.

Hyatt, O.M., B. Lemke, and T. Kjellstrom, 2010: Regional maps of occupational heat exposure: past, present, and potential future. *Global Health Actio*n, 3 (0).

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Kan, H., S.J. London, H. Chen, G. Song, G. Chen, L. Jiang, N. Zhao, Y. Zhang, and B. Chen, 2007: Diurnal temperature range and daily mortality in Shanghai, China. Environmental Research, 103 (3), 424-431.

Kim, H., J.-S. Ha, and J. Park, 2006: High temperature, heat index, and mortality in 6 major cities in South Korea. *Archives of Environmental & Occupational Healt*h, 61 (6), 265-270.

Maurer, E. P., et al., 2002: A long-term hydrologically based data-set of land surface fluxes and states for the conterminous United States. *Journal of Climate* 15: 3237-3251.

McMichael, A.J., P. Wilkinson, R.S. Kovats, S. Pattenden, S. Hajat, B. Armstrong, N. Vajanapoom, E.M. Niciu, H. Mahomed, and C. Kingkeow, 2008: International study of temperature, heat and urban mortality: the 'ISOTHURM' project. *International Journal of Epidemiology*, 37 (5), 1121-1131.

Nag, P.K., A. Nag, and S.P. Ashtekar, 2007: Thermal limits of men in moderate to heavy work in tropical farming. *Industrial Health*, 45 (1), 107-117.

Peterson T.C. et al., 1998: Homogeneity adjustments of in situ atmospheric climate data: A review. *International Journal of Climatology*, 18, 1493-1517.

Stoner, A. M. K., et al., 2012: An asynchronous regional regression model for statistical downscaling of daily climate variables. *International Journal of Climatology*, doi: 10.1002/joc.3603.

Taylor K., R. J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the Experimental Design. *Bull. Am. Met. So*c., 93, 485-498.

Zhang, X., et al. (2011). "Indices for monitoring changes in extremes based on daily temperature and precipitation data." *Wiley Interdisciplinary Reviews WIRE: Climate Change*: doi: 10.1002/wcc.147.