November 2020

# Analyzing Future Climatic Changes in Temperature and Precipitation Using CMIP6 for Kolkata, India

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## Abstract

Climate change poses serious threats to India's agriculture and economy(Chaturvedi et al., 2012) while imposing challenges such as widening the existing social inequality and causing cross-border refugee migrations. Kolkata, a megacity in India, has been singled out as one of the urban centers vulnerable to climate risks such as temperature and precipitation changes and their extremes(Dasgupta et al., 2013). To better understand and quantify these changes, scientists have newly developed Shared Socioeconomic Pathways (SSPs) under the updated Coupled Model Intercomparison Project phase 6 (CMIP6). Here, we provide multi-scenario temperature and precipitation projections for Kolkata for the period 1950-2100 based on the recently released and state-of-the-art CMIP6 climate models. We find that annual mean temperatures for Kolkata are projected to increase by 0.4-3.9°C depending on the SSP considered. Moreover, we identify significant projected declines in cold nights (<15°C) and significant increases in heatwave days (>40°C). Meanwhile, the CMIP6 models analyzed project total annual precipitation and frequency of extreme precipitation days to be roughly similar to 1960-1990 baseline conditions across all SSP scenarios considered. We also observe a clear divergence among the three SSP scenarios for all variables considered only after the years 2050-2060. This work emphasizes the urgency to consider climate change risks in policy-making for agriculture and urban activity in Kolkata.

## Introduction

Vulnerability to climate extremes is a pressing issue in India. In recent years, India has ranked the fifth most vulnerable of 181 countries to the effects of climate change (Bhasker Tripathi, 2019), with the poorest Indians being at the highest risk. India has also recorded the highest number of deaths due to climate change impacts with over 2000 deaths in 2018 alone (Global Climate Risk Index, 2020).

Recent studies also propose an increasing trend in heat waves over India; (Rohini et al., 2019; Jaswal *et al. 2015;* Rohini *et al. 2016)*. These trends of heatwaves are significant both over the northwestern parts of India and the southeastern coast of India (Rohini et al., 2019; Ratnam *et al. 2016;* Rohini *et al. 2016*). Variability of heat waves over India is linked to El Nino/Southern Oscillation (ENSO) and the Indian Ocean SST anomalies (Rohini et al., 2019; Ratnam *et al. 2016;* Rohini *et al. 2016*).

India’s east coast has further been plagued by extreme precipitation in the form of tropical cyclones. In October and November 2018, the coast was hit by the cyclones Titli and Gaja. With wind speeds of up to 150km per hour, cyclone Titli killed at least eight people and left around 450,000 without electricity (BBC news, 2018). In May 2019 and May 2020, respectively, cyclones Fani (Category 4 tropical cyclone) and Amphan (Category 5 tropical cyclone) rampaged through the east coast again.

Both Fani and Amphan recorded wind speeds over 250 km/h, caused damages amounting to $8.1 billion (2019 USD) and $13.6 billion (2020 USD) (CNN News, 2020) and recorded fatality counts above 89 and 128, respectively.

In light of these challenges posed by climate change over India, the Union Ministry of Earth Sciences of the Government of India recently released its first report on Climate Change over the Indian region following the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (Krishnan et al., 2020). The IPCC is the United Nations body for assessing the science related to climate change. This report showed significant damage due to climate change events such as tropical cyclones and extreme rain (Krishnan et al., 2020) The Union Ministry of Earth Science further identifying a 49% increase in tropical cyclones in the Bay of Bengal region, placing states like

West Bengal at high risk to such extreme events (Krishnan et al., 2020).

With respect to these climate change reports, extreme events, and increased impacts of anthropogenic climate change in India, we believe that it is essential to examine the change in temperature and precipitation over regions that are particularly vulnerable to climate change in the coming decades. Kolkata, the capital city of the state West Bengal, is one such region home to 14.9 Million people in 2020(World Population Review, 2020). Furthermore, agriculture accounts for the largest share of the labor force in regions surrounding urban Kolkata and in the state of West Bengal at large. For these reasons, we chose to analyze future climate change trends in Kolkata, and discuss their impacts on both urban and agricultural settings.

We use the state-of-the-art Coupled Model Intercomparison Project phase 6 (CMIP6) climate models and the newly developed Shared Socioeconomic Pathways (SSPs) [Table 1]. To our knowledge, we are the first to submit such an analysis.

| SSP | Name | Description of Pathway |
|---|---|---|
| SSP1-2.6 | Sustainability | Low emissions scenario. Challenges to mitigation and adaptation. Radiative forcing comparable to CMIP5 RCP2.6. |
| SSP2-4.5 | Middle of the Road | Medium challenges to mitigation and adaptation. Radiative forcing comparable to CMIP5 RCP4.5. |
| SSP5-8.5 | Fossil-Fueled Development | High emissions, business as usual scenario. High challenges to mitigation, low challenges to adaptation. Radiative forcing comparable to CMIP5 RCP8.5. |

***Table 1**: Description of the Shared Socioeconomic Pathways under the CMIP6 as used in the study* (Riahi et al., 2017)

# Validation of CMIP6 models over India

In our analysis we use the GFDL-ESM4 (Krasting et al., 2018)climate model participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) for projections of temperature and precipitation. The Geophyscial Fluid Dynamics Laboratory's (GFDL) Earth System Model 4 (ESM4) use advanced technology to capture comprehensive interactions between components such as physics and chemistry, atmospheric dynamics, ocean physics, biogeochemistry and ecosystems, sea ice, and land physics, biogeochemistry and ecosystems (Krasting et al., 2018). They have been previously successful in representing climate change dynamics in the 20th century for El Niño and the drying of the African Sahel (GFDL, n.d.)

We first validate the use of this climate model by comparing GFDL-ESM4 model-simulated baseline climatologies with the weather-station observed climatologies at Dumdum, Kolkata (obtained from the National Centres for Environmental Education website: https://www.ncdc.noaa.gov/) over the period 1980–2020 for both daily temperature and precipitation.

**Temperature Validation**

The CMIP6 GFDL-ESM4 simulates an annual mean temperature of 26.2°C for the period 1980-2020, which is close to the observed annual mean temperature of 26.4°C for the same period (Fig 1).

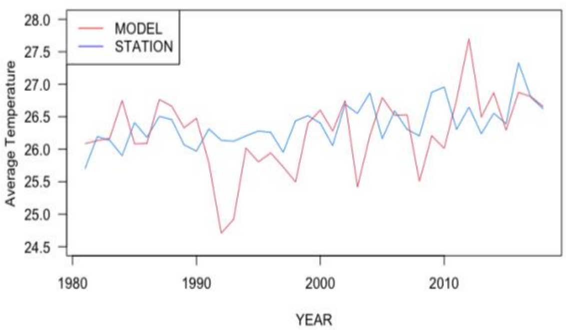



***Figure 1**: Observed (blue) and modelled (red) annual mean temperature at the Dumdum, Kolkata from 1980-2019.*

Furthermore, the long term pattern of the time series of annual mean temperatures over 1980-2020 simulated by the CMIP6 GFDL-ESM4 model plotted along with time series of the weather-station observed annual mean temperatures over Kolkata for the same period indicates results show a strong (relatively) correlation between the annual mean temperatures of the model and weather station over the 40 year period (Figure 1).

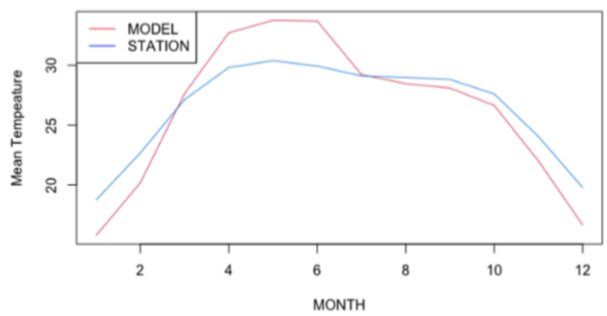



***Figure 2:** Comparing seasonal cycles. Observed (blue) and modelled (red) monthly mean temperature at the Dumdum, Kolkata from 1980-2019 from 1980-2019*

We further compare monthly climatologies of temperature over the 1980-2020 period at the weather station and the CMIP6 GFDL-ESM4 model simulations (Figure 2). These results show that the monthly mean temperatures simulated by CMIP6 GFDL-ESM4 model project 2-5°C hotter mean temperature during months April-June, and 1-3°C colder mean temperature during months November-February than the observed mean temperature at the weather stations. The months March, August, and September demonstrate best correspondence between model simulations and weather station recording in monthly mean temperature over the period 1980-2020. We caution the reader to consider these discrepancies in seasonal temperature ranges when interpreting the future simulation results.

**Precipitation Validation**

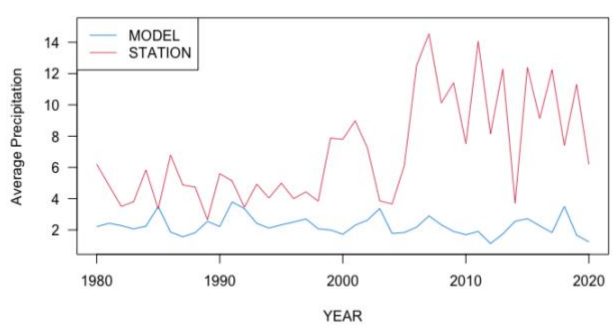



***Figure 3**: Observed (blue) and modelled (red) annual mean precipitation at the Dumdum, Kolkata from 1980-2019.*

The CMIP6 GFDL-ESM4 simulates an annual mean precipitation of 2.3 mm for the period 1980-2019, which is far from the observed annual mean precipitation of 6.0 mm for the same period (Figure 3). Furthermore, the pattern of the time series of annual mean precipitation over 1980-2019 simulated by the CMIP6 GFDL-ESM4 model is plotted along with time series of the weather-station observed annual mean temperatures over Kolkata for the same period (Figure 4) and shows a weak correlation between the annual mean precipitation of the model and weather station over the 40 year period.

We also compare the (seasonal cycle) observed by time series of the monthly mean precipitation over the 1980-2019 period at the weather station to the CMIP6 GFDL-ESM4 model simulations (Figure 6). These results show that the CMIP6 GFDL-ESM4 model projections highly underestimates monthly precipitation from real recordings.

A key takeaway from this comparison is that although there is a vast difference between magnitudes of estimated and actual precipitation, the model projects the seasonal cycle quite accurately, i.e both model and station data represent June-October as monsoon months and November-May as relatively drier months.

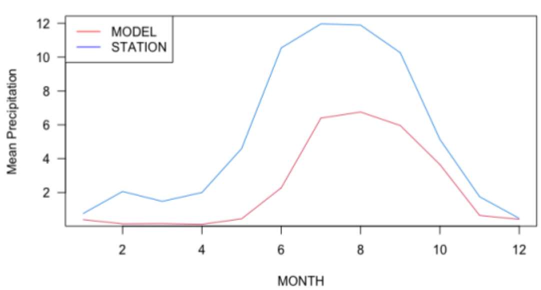



***Figure 4:*** *Comparing seasonal cycles. Monthly mean precipitation at the station (recorded) and models (projected) from 1980-2019.*

# Historical and Projected Climate Change over Kolkata: A Time Series View

1. **Temperature Time Series**

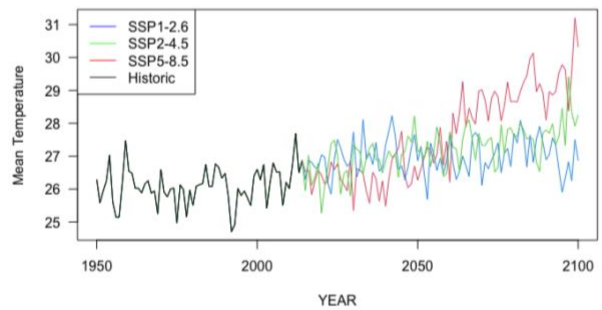



***Figure 5:*** *CMIP6 GFDL-ESM4 model-based time series of temperature projections from 1950 to 2100.*

The CMIP6 GFDL-ESM4 model-based historical and projected annual mean temperature in Kolkata is shown in Figure 5. The historically observed variability is well represented by the model. The range of temperature increase for all the SSP scenarios by 2100 compared to the 1950-1980 period is 0.7°-3.9°C. Figure 5 suggests that:

1. SSP1-2.6 (low emissions scenario) shows the least change in annual mean temperature by the year 2100. It predicts a 0.7-1.2°C rise compared to 1950-1980 baseline.
2. SSP2-4.5 (moderate emissions scenario) predicts a 1.9-2.3°C rise in annual mean temperature by the year 2100 compared to 1950-1980 baseline.
3. SSP5-8.5 (high emissions scenario/ business as usual) shows the highest and most dramatic increase in annual mean temperature by the year 2100, predicting a 3.4-3.9°C rise compared to 1950-1980 baseline.

An interesting takeaway from this analysis is that the annual mean temperature across all SSP scenarios is expected to be roughly constant till the year 2050. The model predictions begin to diverge around 2050-2060. All SSP scenarios predict that the annual mean temperature is expected to rise when compared to the 1950-1980 mean of ~26°C.

2. **Precipitation Time Series**

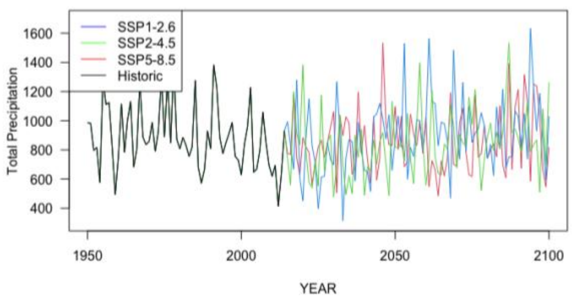



***Figure 6:*** *CMIP6 GFDL-ESM4 model-based time series of precipitation projections from 1950 to 2100.*

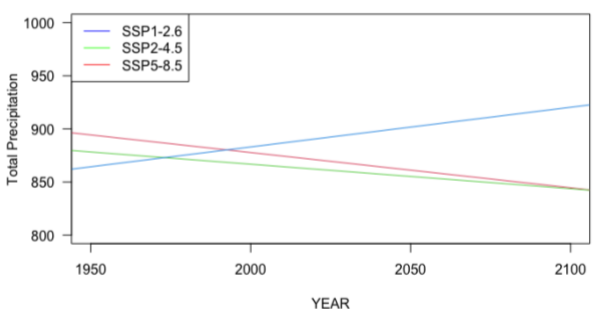



***Figure 7:*** *CMIP6 GFDL-ESM4 model-based time series of the regression lines of precipitation projections in Figure 6.*

The CMIP6 GFDL ESM4 model-based historical and projected annual total precipitation in Kolkata is also shown in Figure 6 and 7. The total annual precipitation is expected to be roughly constant by the end of the century, with some decline (from 1980-2040) followed by a slight increase after the year 2040.

Only the SSP1-2.6 projects an increase in total annual precipitation by ~100mm/year by 2100, while the other scenarios project near constancy compared to the 1960-1990 baseline of about 923mm/year. SSP1-2.6 scenario further shows higher variability in total annual precipitation compared to the other scenarios. The SSP2-4.5 scenario projects moderate variability, and the SSP5-8.5 low variability. (Variability is defined here as the spread across the y-axis).

The study of annual mean precipitation reveals similar findings. Compared to the 1960-1990 baseline of 2.5 mm/day, the SSP1-2.6 scenario projects an increase to 2.8 mm/day by 2090-2100, while the SSP2-4.5 and SSP5-8.5 scenarios project near constancy to the baseline with projections of 2.4 mm/day and 2.5 mm/day during the 2090-2100 period.

**Time Series of Temperature and Precipitation Extremes**

In this study, we analyse 4 types of temperature and precipitation extremes: heatwave days, cold nights, high precipitation days, and extreme precipitation events. The logical definitions of these events in the scope of this study are given below:

1. Heatwave days: Number of days in a year recording maximum temperatures > 40℃.
2. Cold nights: Number of days in a year recording minimum temperatures < 15℃.
3. High precipitation days: Number of days in a year recording rainfall > 20mm/day.
4. Extreme precipitation events: Number of days in a year recording rainfall > 60mm/day.

The study of these metrics are essential in understanding and implementing policy in the region.

## Temperature and Precipitation Extremes

### *3.1 Heatwaves*

For all SSP scenarios in the CMIP6 GFDL-ESM4 model, the number of heatwave days occurring per year is projected to increase by 10-38 heatwaves/year compared to the 1950-1980 baseline by the end of the century (Figure 5). The 1950-1980 baseline averages 37 heatwaves/year. The specific findings per SSP scenario are listed below:

(i) The SSP1-2.6 (low emissions scenario shows the least increase in the days affected by heatwaves every year, projecting an increase by an average of 12 heatwave days/year by the end of the century (2070-2100) compared to the 1950-1980 baseline. It projects that the heatwave days will increase to ~ 48 days/year by the end of the century. This scenario also shows the highest variability in its future predictions.

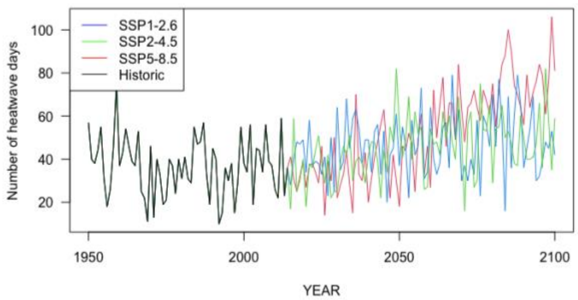



***Figure 8:*** *CMIP6 GFDL-ESM4 model-based time series of heatwave projections from 1950 to 2100.*

(ii) The SSP2-4.5 (moderate emissions) scenario shows a similar increase as the SSP1-2.6 scenario by an average of about 12 heatwave days/year by the end of the century compared to the 1950-1980 baseline. It projects that heatwave days will increase to ~50 days/year by the end of the century. GFDL-ESM4 SSP2-4.5 scenario shows a moderate range in its future predictions.

(iii) The SSP5-8.5 (high emissions, business as usual) scenario shows the sharpest increase in the number of heatwave days per year by 2100 when compared to the other two scenarios. The SSP-8.5 scenario predictions are very distinct, showing an increase by an average of 36 heat wave days per year at the end of the century (Figure 10). The scenario projects that heatwaves occurring per year will increase to ~72 days/year (a two-fold increase) by the end of the century. Moreover, the GFDL-ESM4 SSP5-8.5 scenario shows the lowest range in its future predictions, when compared to SSP1-2.6 and SSP2-4.5 scenarios. This can be observed by noticing that the distribution of black lines along the y axis is the lowest.

Interestingly, the number of days affected by heat waves is expected to be similar across the three SSPs considered till the 2060s, only after which we observe a pronounced divergence in the three cases.

### *3.2 Cold nights*

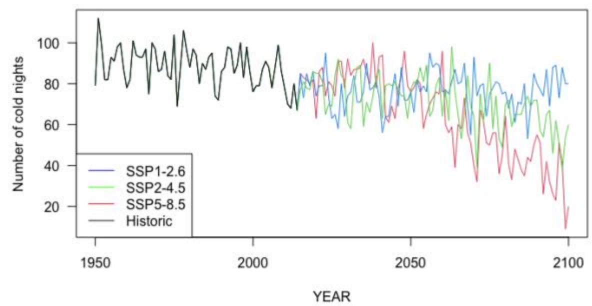


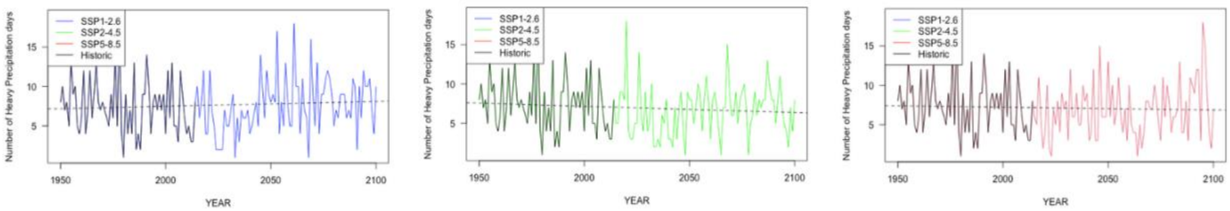

***Figure 9:*** *CMIP6 GFDL-ESM4 model-based time series of cold nights projections from 1950 to 2100*

The CMIP6 GFDL-ESM4 model projects that the number of cold nights occurring per year will decrease significantly (by 15-49 days) by the end of the century under all 3 SSP scenarios when compared the 1950-1980 baseline of ~91 cold nights/year (Fig.9).

The scenario specific findings for cold nights (Figure 9) are listed below.
(i) The SSP1-2.6 scenario predicts the annual cold nights to decrease by roughly 15 occurrences per year (compared to the 1950-1980 baseline) to an average of 76 cold nights/year by the end of the century (2070-2100). The rate of decline promises to remain roughly constant till 2040s, after which it, interestingly, shows a gentle increase during the 2080s till the end of the century. This SSP scenario shows the least amount of variability among the other scenarios.
(ii) The SSP2-4.5 scenario projects that annual cold nights will decrease by roughly 30 days/year (compared to the 1950-1980 baseline) to an average of 62.6 annual cold nights by the end of the century. This SSP scenario is closer to the SSP1-2.6 scenario in predictions than the SSP5-8.5 scenario, but shows more y-axis variability than the former.
(iii) The SSP5-8.5 scenario shows the sharpest decline in the number of cold nights per year by 2100. The scenario projects that annual cold nights will decrease by roughly 49 days (compared to the 1950-1980 baseline)to an average of 42 recorded cold nights at the end of the century. This scenario also shows the highest variability in its future projections, predicting a range of 9-51 annual cold nights for the final decade of the 21st century. The SSP-8.5 scenario predictions are also most distinct and extreme when compared to the 2.6 and 4.5 scenarios (Fig. 9). The beginning of a stark divergence of the SSP5-8.5

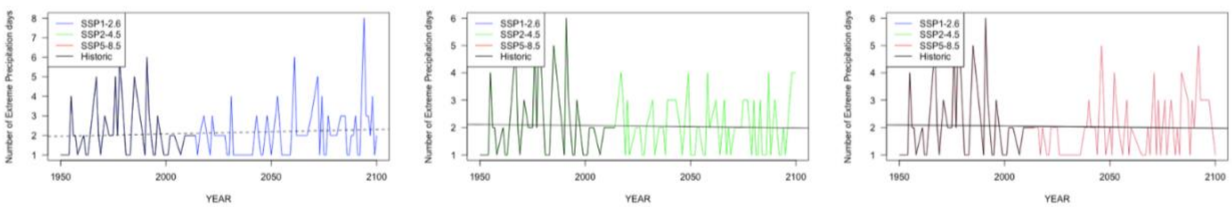
scenario from SSP2-4.5 and SSP1-2.6 in the graph is noted from the 2050s.

One key take-away from the analysis of this temperature minimums index is that daily minimum temperatures are declining at a rate faster than the rate the daily maximums (heatwaves) are increasing by.




(a) Annual Heavy Precipitation days (SSP1-2.6 scenario) (b) Annual Heavy Precipitation days (SSP2-4.5 scenario) (c) Annual Heavy Precipitation days (SSP5-8.5 scenario)

***Figure 10:*** *Annual Heavy Precipitation days (>20mm/day) under SSP1-2.6 (a), SSP2-4.5 (b) and SSP5-8.5(c)*




(a) Annual Extreme Precipitation days (SSP1-2.6 scenario) (b) Annual Extreme Precipitation days (SSP2-4.5 scenario) (c) Annual Extreme Precipitation days (SSP5-8.5 scenario)

***Figure 11:*** *Annual Extreme Precipitation days (>60mm/day) under SSP1-2.6 (a), SSP2-4.5 (b) and SSP5-8.5(c).*

***Heavy Precipitation Days and Extreme Precipitation Events***

Figure 8 shows the time series of heavy precipitation days *(>20mm/day*) under the various SSP scenarios and Figure 9 shows the time series of extreme precipitation events (>60mm/day) under the various SSP scenarios. Heavy precipitation days signify days with more than monsoon rainfall, while extreme events signify storms, cyclones, and other precipitation events that occur. We choose to study heavy precipitation under two different metrics to analyse how the occurrence of heavy precipitation corresponded with cyclonic rainfall through the century and to ensure our analysis of climate change impacts on extreme precipitation is robust to differences in extreme thresholds considered.

From these figures, we observe that both the number of annual heavy precipitation days and extreme events promise to remain roughly similar to the 1960-1990 baseline values by the end of the century (2070-2100). The baseline average for annual heavy precipitation days is found to be 8 days/year, while the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios project 8, 7, and 8 days per year respectively.

Similarly, we observe the extreme precipitation event projections of 2 days/year (SSP1-2.6 scenario), 2 days/year (SSP2-4.5 scenario), and 2 days/year (SSP5-8.5 scenario) to be similar to the baseline value of 3 extreme events per year. However, it is interesting to note that both heavy precipitation days and extreme precipitation events show decadal trends.

# Key Results

**For Temperature and its Extremes**

- Mean temperature over Kolkata is projected to rise in the range of 0.7-3.9°C rise compared to 1950-1980 baseline.
- For cold nights, the SSP1-2.6 scenario projects a decrease of ~15 days, the SSP2-4.5 scenarios projects a decrease of ~30 days, and

the SSP5-8.5 projects a decrease of ~50 days compared to the 1950-1980 baseline (91 cold nights).

- For heatwaves, the SSP1-2.6 scenario projects an increase of ~10 days, the SSP2-4.5 scenarios projects an increase of ~12 days, and the SSP5-8.5 projects an increase of ~35 days compared to the 1950-1960 baseline (43 heatwave days).
- We observe that the rate of decrease of cold nights per year is faster than the rate of increase in the number of heat waves per year.

**For Precipitation and its Extremes**

- Mean, heavy and extreme precipitation are projected to remain constant over the coming decades until the end of the century.

# Discussions and Conclusions

In 2015, the United Nations Member States adopted 17 Sustainable Development Goals (SDGs) in order to "to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030" (UNDP, n.d.). Among the 17 SDGs, Goal 13 specifically calls for Climate Action and aims to mobilize US$100 billion annually by 2020 to address the needs of developing countries to both adapt to climate change and invest in low-carbon development (UNDP, n.d.).

Climate change is a pressing issue that concerns almost every nation on the planet. The United Nations Framework Convention on Climate Change (UNFCCC) , adopted in May 1992, aimed to address this challenge of climate change (United Nations Framework Convention on Climate Change, n.d.). The UNFCCC aims to "achieve the stabilization of green-house gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations Framework Convention on Climate Change, n.d.). The Durban (2011) and Cancun (2010) agreements made at the 16th and 17th Conference of Parties of the UNFCCC recognized the need to hold the increase in global average temperature between 1.5° and 2°C above pre-industrial levels (Gao et al., 2017). Out of the three scenarios discussed in this article, SSP1-2.6 is consistent with the goal of limiting warming at 2°C (Riahi et al., 2017; Gao et al., 2017). However, an analysis by Arora *et al* (Arora et al., 2011) indicates that "limiting warming to roughly 2°C by the end of this century is 'unlikely' since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration in the second half of this century" (Chaturvedi et al., 2012).

Regarding Kolkata, climatic changes in temperature call for immediate attention of policy makers and governing bodies. As mean temperature is projected to rise above 29°C and heatwaves look to surge to 72 days per year under the SSP5-8.5 business-as-usual scenario according to our analysis, we expect severe impacts on human health, agriculture, and energy consumption. Mortality rates can be expected to rise as well (Mazdiyasni et al., 2017)

With a dramatic decrease projected in cold nights occurrence, we expect greater risk to agriculture and also a possible change in crop season timing. For example, the kharif and rabi cropping seasons, two dominant crops in the region, are heavily dependent on the timing and frequency of cold nights (Bapuji Rao et al., 2014).

It is also surprising to note that the GFDL-ESM4 models do not predict much variation in mean, total, or extreme precipitation over Kolkata, which is contradictory to much of the other work in the region and India that projects an increase extreme precipitation and a decline in total precipitation (Chaturvedi et al., 2012). Those studies analyzed an ensemble of climate models, and it is possible other CMIP6 models project differing trends in precipitation than those presented here for the GFDL-ESM4 model.

It is important to note that climate projections are generally more reliable at the regional and global scale than at smaller scales like a single city. To that end, one could alternatively explore regional climate models focused on climate in eastern India for more detailed results.

# Future Directions

In the coming 6-8 months, we plan to analyze more CMIP6 climate models for our station. Since the GFDL-ESM4 model underestimates observed precipitation, we wish to undertake analyses of other CMIP6 models to further evaluate the robustness of our findings.

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