Supplemental Information

Heat wave exposure in India in current, 1.5°C, and 2.0°C worlds

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Section S1: Anthropogenic influence on the frequency of heatwaves in India

In order to be a tool for understanding past, current, and future trends in heatwaves over India, we must understand the extent to which climate models are capable of reproducing observed characteristics. We examine the frequency of heatwaves (above magnitude 3) in simulations from seven models from the CMIP5 archive driven with observed variations in radiative forcings (e.g. greenhouse gases) and land surface properties ("Hist") (see Table S2). For the period of 1980-2005, when simulation data are available from seven models that have data for both Hist and HistNat (without anthropogenic forcing) scenarios, the climate models produce about 3-8 heatwaves of at least magnitude 3 at each grid cell in the entire period of 1980-2005 under the Hist scenario (Fig. S1c) and underestimate observed frequency of heatwaves (Fig. S1a).

Over the 1951-2005 period during which observations and "Hist" simulations are available, the "Hist" simulations from the seven CMIP5 models (Table S2) all produce an increase in 3-day annual maximum temperature (an alternative index for heat wave) (Fig. S1h). The CMIP5 models, however, underestimate trends in 3-day AMT and do not capture regional variability (Fig. S1f, h). The CESM-LENS ensemble also shows an increasing trend in 3-day annual maximum temperature during the period of 1951-2005 (Fig. S1i-j). We notice a decline in the observed 3-day AMT in the Indo-Gangetic Plain, which may be associated with the presence of atmospheric aerosols (Menon et al 2002) or irrigation (Roy et al 2007, Sacks et al 2009) (Fig S1f). The HistNat simulations (Table S2) of these same CMIP5 models run without anthropogenic forcing show no systematic change in 3-day AMT indicating an anthropogenic contribution in the observed trend (Fig. S1f-j).

References:

Menon S, Hansen J, Nazarenko L and Luo Y 2002 Climate Effects of Black Carbon Aerosols in China and India Science 297 2250

Roy S S, Mahmood R, Niyogi D, Lei M, Foster S A, Hubbard K G, Douglas E and Pielke R 2007 Impacts of the agricultural Green Revolution–induced land use changes on air temperatures in India J. Geophys. Res. Atmospheres 112 D21108

Sacks W J, Cook B I, Buening N, Levis S and Helkowski J H 2009 Effects of global irrigation on the near-surface climate Clim. Dyn. 33 159–75
Figure S1. Anthropogenic influence on frequency of heat waves in India. (a) Frequency of heat waves (F-HW; in 26 years) with magnitude more than 3 from the observed daily Tmax data during the period 1980-2005. (b) multimodel ensemble mean F-HW with magnitude more than 3 in the historical natural (HistNat, CMIP5), (c) historical (Hist) scenarios for the period of 1980-2005 based on seven CMIP5 models (Table S2), (d) 20th Century scenario based on 7 members from CESM-LENS, (e) empirical kernel density functions for the observed F-HW (blue) and the multimodel ensemble mean F-HW estimated using all the grid cells for the HistNat (black) and Hist (red) scenarios based on the seven CMIP5 models, and 20th Century (brown) scenarios based on 7 CESM-LENS-runs during the period of 1980-2005. For the CMIP5-GCMs, heatwave magnitude was calculated based on the HistNat (1971-2000) as the reference period. Heatwave characteristics for the observed and 7-runs CESM-LENS 20th Century scenarios were also estimated using the reference period of 1971-2000. (f) trend (per year, °C) in 3-day annual maximum temperature (AMT) in the observed record of 1951-2005, (g, h, and i) multimodel ensemble mean trend in 3-day AMT for the 7 CMIP5-GCM's HistNat, Hist scenarios, and 7 runs CESM-LENS 20th Century scenarios (h) kernel density function estimated using trend in 3 day AMT for each grid in the observed, CMIP5-Hist, CMIP5-HistNat, and CESM-LENS 20th Century scenarios.
Figure S2  (a) All India averaged 3-day annual maximum temperature (Tmax) anomaly for the period of 1951-2015. 3-day annual Tmax anomaly was estimated against the reference period of 1971-2000. (b) change in 3-Day AMT during the period of 1951-2015 estimated using the nonparametric Mann-Kendall trend test and Sen’s slope method. Stippling in (b) indicates statistically significant trend in 3-day AMT at 5% significance level assuming uncorrelated noise. (c) and (d) 3-day AMT Anomaly for the year 1998 and 2015, respectively as estimated against the reference period of 1971-2000.
Figure S3 (a, b, and c) Gridded population of India in the year 2000, 2050, and 2100, respectively, for SSP1 scenario. (d-f) same as in (a-c) but for SSP2 scenario. (g-f) same as in (a-c) but for SSP3 scenario.
Figure S4 (a-h) same as in Figure 2(a-h) but for duration.
Figure S5 All India aggregated MPEHWd (millions) based on 11 ensembles of CESM-2C.
Table S1. Duration for which daily maximum temperature (Tmax) and monthly global mean temperature data are available for the Historical and RCP8.5 (ensemble: r1i1p1) scenarios from 27 CMIP5 climate models

| Sl No. | Model                  | Tmax Historical period through RCP8.5 | Global Mean Temperature Historical period through RCP8.5 |
|--------|------------------------|--------------------------------------|----------------------------------------------------------|
| 1      | ACCESS1-0              | 1850-2100                            | 1850-2100                                                |
| 2      | ACCESS1-3              | 1850-2100                            | 1850-2100                                                |
| 3      | CanESM2                | 1850-2100                            | 1850-2300                                                |
| 4      | CCSM4                  | 1850-2100                            | 1850-2300                                                |
| 5      | CESM1-BGC              | 1850-2100                            | 1850-2300                                                |
| 6      | CESM1-CAM5             | 1850-2100                            | 1850-2300                                                |
| 7      | CMCC-CM                | 1850-2100                            | 1850-2300                                                |
| 8      | CMCC-CMS               | 1850-2100                            | 1850-2300                                                |
| 9      | CNRM-CM5               | 1850-2100                            | 1850-2300                                                |
| 10     | CSIRO-Mk3-6-0          | 1850-2100                            | 1850-2300                                                |
| 11     | EC-EARTH               | 1850-2100                            | 1850-2300                                                |
| 12     | GFDL-CM3               | 1860-2100                            | 1860-2100                                                |
| 13     | GFDL-ESM2G             | 1861-2100                            | 1861-2300                                                |
| 14     | GFDL-ESM2M             | 1861-2100                            | 1861-2300                                                |
| 15     | HadGEM2-AO             | 1860-2100                            | 1860-2300                                                |
| 16     | HadGEM2-CC             | 1860-2100                            | 1860-2300                                                |
| 17     | HAdGEM2-ES             | 1860-2100                            | 1860-2300                                                |
| 18     | inmcm4                 | 1850-2100                            | 1850-2300                                                |
| 19     | IPSL-CM5A-LR           | 1850-2100                            | 1850-2300                                                |
| 20     | IPSL-CM5A-MR           | 1850-2100                            | 1850-2300                                                |
| 21     | MIROC-5                | 1850-2100                            | 1850-2300                                                |
| 22     | MIROC-ESM              | 1850-2100                            | 1850-2300                                                |
| 23     | MIROC-ESM-CHEM         | 1850-2100                            | 1850-2300                                                |
| 24     | MPI-ESM-LR             | 1850-2100                            | 1850-2300                                                |
| 25     | MPI-ESM-MR             | 1850-2100                            | 1850-2300                                                |
| CMIP5 Model               | Historic Natural (HistNat) | Historic (Hist) | RCP8.5  |
|--------------------------|---------------------------|----------------|---------|
| CNRM-CM5                 | 1950-2005                 | 1950-2005      | 2006-2099 |
| GFDL-ESM2M               | 1946-2005                 | 1946-2005      | 2006-2100 |
| IPSL-CM5A-LR             | 1850-2005                 | 1850-2005      | 2006-2205 |
| IPSL-CM5A-MR             | 1950-2005                 | 1950-2005      | 2006-2100 |
| MIROC-ESM                | 1850-2005                 | 1850-2005      | 2006-2100 |
| MIROC-ESM-CHEM           | 1850-2005                 | 1850-2005      | 2006-2100 |
| MRI-CGCM3                | 1950-2005                 | 1950-2005      | 2006-2100 |

**Table S2.** Duration for which data are available for the HistNat, Hist, and RCP8.5 (ensemble: r1i1p1) from the seven CMIP5 climate models used in the analysis.
Table S3. All India heat waves and their magnitude, duration, and time of occurrence, based on gridded daily station measurements and the methodology of Russo et al. (2015) (/). Heatwaves were estimated using the gridded maximum temperature data for the period of 1951-2015.

| Year | Duration (year) | Magnitude | Start Date | End Date |
|------|-----------------|------------|------------|----------|
| 1956 | 3               | 0.9        | 09-May     | 11-May   |
| 1958 | 5               | 5.2        | 02-Jun     | 06-Jun   |
| 1960 | 3               | 0.8        | 11-May     | 13-May   |
| 1962 | 3               | 1.5        | 27-May     | 29-May   |
| 1966 | 10              | 9.0        | 19-May     | 28-May   |
| 1967 | 7               | 3.8        | 30-May     | 05-Jun   |
| 1969 | 4               | 2.3        | 25-May     | 28-May   |
| 1970 | 7               | 6.8        | 12-May     | 18-May   |
| 1972 | 4               | 2.4        | 12-Jun     | 15-Jun   |
| 1973 | 8               | 4.7        | 25-Apr     | 02-May   |
| 1974 | 3               | 0.8        | 08-May     | 10-May   |
| 1978 | 7               | 6.4        | 17-May     | 23-May   |
| 1979 | 6               | 7.3        | 05-Jun     | 10-Jun   |
| 1980 | 4               | 3.5        | 24-May     | 27-May   |
| 1984 | 10              | 9.9        | 18-May     | 27-May   |
| 1985 | 4               | 1.8        | 18-May     | 21-May   |
| 1988 | 7               | 7.2        | 08-May     | 14-May   |
| 1989 | 4               | 2.5        | 20-May     | 23-May   |
| 1992 | 3               | 1.7        | 05-Jun     | 07-Jun   |
| 1993 | 7               | 3.0        | 02-May     | 08-May   |
| 1994 | 4               | 2.3        | 29-May     | 01-Jun   |
| 1995 | 13              | 18.4       | 29-May     | 10-Jun   |
| 1998 | 15              | 17.9       | 20-May     | 03-Jun   |
| 1999 | 10              | 4.1        | 25-Apr     | 04-May   |
| 2002 | 3               | 1.1        | 09-May     | 11-May   |
| 2003 | 7               | 10.7       | 30-May     | 05-Jun   |
| 2009 | 6               | 5.1        | 27-Apr     | 02-May   |
| 2010 | 9               | 6.8        | 10-May     | 18-May   |
| 2012 | 11              | 11.6       | 23-May     | 02-Jun   |
| 2013 | 9               | 9.3        | 17-May     | 25-May   |
| 2014 | 5               | 5.2        | 04-Jun     | 08-Jun   |
| 2015 | 8               | 7.5        | 20-May     | 27-May   |
**Table S4** Total number of severe heat waves (with magnitude greater than 16) for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) based on the 27 CMIP5 climate models listed in Table S3. Heat waves were estimated using the 1971-2000 as the reference period.

| Model                  | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|------------------------|----------------------|-----------------------------|------------------------------|
| ACCESS1-0              | 0.5                  | 6.1                         | 24.5                         |
| ACCESS1-3              | 0.1                  | 4.0                         | 24.0                         |
| CanESM2                | 0.2                  | 1.8                         | 20.2                         |
| CCSM4                  | 0.5                  | 3.2                         | 19.8                         |
| CESM1-BGC              | 0.2                  | 2.3                         | 20.0                         |
| CESM1-CAM5             | 0.2                  | 3.8                         | 25.3                         |
| CMCC-CM                | 0.6                  | 5.2                         | 26.4                         |
| CMCC-CMS               | 0.2                  | 1.7                         | 16.2                         |
| CNRM-CM5               | 0.6                  | 8.0                         | 28.2                         |
| CSIRO-Mk3-6-0          | 0.7                  | 8.7                         | 25.3                         |
| EC-EARTH               | 0.8                  | 6.0                         | 23.1                         |
| GFDL-CM3               | 0.3                  | 6.9                         | 28.2                         |
| GFDL-ESM2G             | 0.6                  | 2.8                         | 19.8                         |
| GFDL-ESM2M             | 0.5                  | 3.2                         | 20.1                         |
| HadGEM2-AO             | 0.3                  | 3.2                         | 24.7                         |
| HadGEM2-CC             | 0.4                  | 7.0                         | 27.4                         |
| HAdGEM2-ES             | 1.0                  | 9.3                         | 27.7                         |
| inmcm4                 | 1.6                  | 15.2                        | 29.5                         |
| IPSL-CM5A-LR           | 0.6                  | 9.3                         | 29.1                         |
| IPSL-CM5A-MR           | 0.1                  | 0.8                         | 13.7                         |
| MIROC-5                | 0.1                  | 1.0                         | 15.0                         |
| MIROC-ESM              | 0.8                  | 2.9                         | 13.2                         |
| MIROC-ESM-CHEM         | 0.6                  | 5.0                         | 26.7                         |
| MPI-ESM-LR             | 0.2                  | 4.4                         | 25.5                         |
| MPI-ESM-MR             | 0.4                  | 3.3                         | 20.4                         |
| MRI-CGCM3              | 0.4                  | 3.0                         | 21.5                         |
| NorESM1-M              | 0.1                  | 0.9                         | 13.1                         |
Table S5 Total number of severe heat waves (with magnitude greater than 16) for the current period, mid-21st century, and end-21st century based on the 11 members from CESM-LENS RCP8.5 scenario. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-----------------------------|
| 1   | 0.2                 | 2.6                         | 20.3                        |
| 2   | 0.6                 | 2.3                         | 22.3                        |
| 3   | 0.3                 | 2.7                         | 21.7                        |
| 4   | 0.1                 | 2.6                         | 22.1                        |
| 5   | 0.3                 | 3.5                         | 21.4                        |
| 6   | 0.2                 | 2.7                         | 23.4                        |
| 7   | 0.5                 | 4.6                         | 21.5                        |
| 8   | 0.1                 | 3.2                         | 22.0                        |
| 9   | 0.4                 | 4.1                         | 23.1                        |
| 10  | 0.1                 | 3.2                         | 22.7                        |
| 11  | 0.3                 | 4.0                         | 21.7                        |
Table S6  Total number of severe heat waves (with magnitude greater than 16) for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) based on the 11 runs from LENS Low warming 2°C scenario. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-----------------------------|
| 1   | 0.2                 | 3.1                         | 20.6                        |
| 2   | 0.6                 | 2.3                         | 22.3                        |
| 3   | 0.4                 | 2.6                         | 6.6                         |
| 4   | 0.2                 | 2.1                         | 4.8                         |
| 5   | 0.2                 | 1.3                         | 5.5                         |
| 6   | 0.3                 | 1.5                         | 4.0                         |
| 7   | 0.1                 | 2.7                         | 7.7                         |
| 8   | 0.1                 | 1.8                         | 4.9                         |
| 9   | 0.4                 | 3.2                         | 8.4                         |
| 10  | 0.2                 | 1.7                         | 4.9                         |
| 11  | 0.3                 | 3.2                         | 5.6                         |
Table S7: Total number of severe heat waves (with magnitude greater than 16) for the current (1986-2015) period, mid-21st century (2021-2050), and end-21st century (2071-2100) based on the 11 members from CESM-LENS Low warming 1.5°C scenario. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-----------------------------|
| 1   | 0.1                 | 1.1                         | 2.4                         |
| 2   | 0.4                 | 1.5                         | 2.4                         |
| 3   | 0.3                 | 1.8                         | 3.0                         |
| 4   | 0.5                 | 0.9                         | 2.5                         |
| 5   | 0.5                 | 1.3                         | 2.9                         |
| 6   | 0.4                 | 1.4                         | 3.1                         |
| 7   | 0.5                 | 2.5                         | 4.4                         |
| 8   | 0.1                 | 1.3                         | 1.9                         |
| 9   | 0.3                 | 2.6                         | 3.0                         |
| 10  | 0.1                 | 1.4                         | 1.9                         |
| 11  | 0.4                 | 1.7                         | 2.0                         |
Table S8 Duration of severe heat waves (with magnitude greater than 16) for the current period, mid-21st century, and end-21st century based on the 27 CMIP5 climate models listed in Table S3. Heat waves were estimated using the 1971-2000 as the reference period.

| Model            | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|------------------|----------------------|-------------------------------|-------------------------------|
| ACCESS1-0        | 7.3                  | 17.6                          | 31.4                          |
| ACCESS1-3        | 0.9                  | 12.6                          | 28.8                          |
| CanESM2          | 2.0                  | 12.0                          | 20.5                          |
| CCSM4            | 3.5                  | 12.7                          | 19.7                          |
| CESM1-BGC        | 2.8                  | 12.7                          | 20.9                          |
| CESM1-CAM5       | 2.1                  | 14.3                          | 27.8                          |
| CMCC-CM          | 7.7                  | 16.7                          | 32.2                          |
| CMCC-CMS         | 2.2                  | 8.6                           | 17.2                          |
| CNRM-CM5         | 6.9                  | 16.4                          | 45.7                          |
| CSIRO-Mk3-6-0    | 7.7                  | 17.3                          | 28.0                          |
| EC-EARTH         | 8.8                  | 17.9                          | 25.7                          |
| GFDL-CM3         | 3.2                  | 18.4                          | 41.3                          |
| GFDL-ESM2G       | 6.3                  | 13.0                          | 20.4                          |
| GFDL-ESM2M       | 3.9                  | 13.8                          | 21.9                          |
| HadGEM2-AO       | 3.8                  | 13.2                          | 28.6                          |
| HadGEM2-CC       | 5.5                  | 17.3                          | 39.5                          |
| HadGEM2-ES       | 12.2                 | 17.7                          | 37.4                          |
| inmcm4           | 9.8                  | 22.7                          | 54.4                          |
| IPSL-CM5A-LR     | 6.0                  | 20.3                          | 44.6                          |
| IPSL-CM5A-MR     | 0.8                  | 5.3                           | 19.9                          |
| MIROC-5          | 2.0                  | 6.1                           | 23.6                          |
| MIROC-ESM        | 8.7                  | 14.5                          | 22.3                          |
| MIROC-ESM-CHEM   | 6.8                  | 16.2                          | 33.6                          |
| MPI-ESM-LR       | 2.1                  | 16.3                          | 27.3                          |
| MPI-ESM-MR       | 3.5                  | 11.9                          | 21.0                          |
| MRI-CGCM3        | 4.3                  | 14.2                          | 22.3                          |
| NorESM1-M        | 2.0                  | 8.5                           | 16.7                          |
Table S9 Duration of severe heat waves (with magnitude greater than 16) for the current year (1986-2015), mid- 21st century (2021-2050), and end- 21st century (2071-2100) based on the 11 members from CESM-RCP8.5. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|------------------------------|-----------------------------|
| 1   | 2.3                 | 11.5                         | 20.2                        |
| 2   | 5.4                 | 12.3                         | 22.9                        |
| 3   | 4.9                 | 10.9                         | 21.7                        |
| 4   | 1.0                 | 13.4                         | 22.6                        |
| 5   | 4.0                 | 12.3                         | 21.4                        |
| 6   | 3.1                 | 12.8                         | 23.7                        |
| 7   | 6.0                 | 12.9                         | 21.4                        |
| 8   | 1.1                 | 11.9                         | 20.9                        |
| 9   | 3.5                 | 14.3                         | 23.6                        |
| 10  | 0.9                 | 13.2                         | 22.5                        |
| 11  | 3.4                 | 14.8                         | 21.5                        |
**Table S10** Duration of severe heat waves (with magnitude greater than 16) for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) based on the 11 members from CESM-2C. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|----------------------|-------------------------------|-----------------------------|
| 1   | 3.0                  | 12.1                          | 21.1                        |
| 2   | 5.4                  | 12.3                          | 22.8                        |
| 3   | 5.3                  | 12.6                          | 13.9                        |
| 4   | 3.5                  | 12.2                          | 15.4                        |
| 5   | 3.4                  | 11.0                          | 15.0                        |
| 6   | 4.1                  | 11.7                          | 14.0                        |
| 7   | 1.0                  | 9.9                           | 15.4                        |
| 8   | 1.7                  | 10.2                          | 14.0                        |
| 9   | 5.2                  | 12.1                          | 16.2                        |
| 10  | 3.2                  | 10.8                          | 14.1                        |
| 11  | 3.5                  | 12.7                          | 15.3                        |
Table S11 Duration of severe heat waves (with magnitude greater than 16) for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) based on the 11 members from CESM-1.5C. Heat waves were estimated using the 1971-2000 as the reference period.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-------------------------------|
| 1   | 2.1                 | 9.8                         | 12.2                          |
| 2   | 5.0                 | 11.6                        | 13.4                          |
| 3   | 4.8                 | 10.2                        | 11.2                          |
| 4   | 5.3                 | 8.3                         | 13.1                          |
| 5   | 6.1                 | 8.5                         | 12.9                          |
| 6   | 5.3                 | 9.0                         | 13.0                          |
| 7   | 5.7                 | 10.1                        | 13.3                          |
| 8   | 1.9                 | 9.3                         | 10.6                          |
| 9   | 3.9                 | 10.0                        | 11.9                          |
| 10  | 1.6                 | 9.6                         | 11.0                          |
| 11  | 6.4                 | 10.1                        | 12.0                          |
Table S12 MPEHWd for the SSP3 scenario for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) scenarios based on the 27 CMIP5 climate models listed in Table S3.

| Model            | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|------------------|----------------------|------------------------------|------------------------------|
| ACCESS1-0        | 3853                 | 90966                        | 1219700                      |
| ACCESS1-3        | 771                  | 49509                        | 1002300                      |
| CanESM2          | 3019                 | 24530                        | 644130                       |
| CCSM4            | 6397                 | 43336                        | 640220                       |
| CESM1-BGC        | 1657                 | 24645                        | 663210                       |
| CESM1-CAM5       | 1592                 | 50282                        | 1047000                      |
| CMCC-CM          | 8849                 | 81333                        | 1392400                      |
| CMCC-CMS         | 1440                 | 16300                        | 393830                       |
| CNRM-CM5         | 7554                 | 130110                       | 2038100                      |
| CSIRO-Mk3-6-0    | 5040                 | 139680                       | 1124200                      |
| EC-EARTH         | 6370                 | 98082                        | 1007400                      |
| GFDL-CM3         | 5621                 | 296680                       | 2617600                      |
| GFDL-ESM2G       | 6009                 | 51678                        | 568400                       |
| GFDL-ESM2M       | 3724                 | 74682                        | 708260                       |
| HadGEM2-AO       | 3944                 | 37571                        | 1044700                      |
| HadGEM2-CC       | 2535                 | 104170                       | 1635200                      |
| HAdGEM2-ES       | 7483                 | 149710                       | 1615500                      |
| inmcm4           | 12400                | 360480                       | 3003300                      |
| IPSL-CM5A-LR     | 3300                 | 187510                       | 2489400                      |
| IPSL-CM5A-MR     | 695                  | 13727                        | 717550                       |
| MIROC-5          | 1187                 | 22580                        | 865300                       |
| MIROC-ESM        | 5029                 | 32611                        | 396920                       |
| MIROC-ESM-CHEM   | 6383                 | 73888                        | 1379300                      |
| MPI-ESM-LR       | 1443                 | 74097                        | 1095700                      |
| MPI-ESM-MR       | 4744                 | 43166                        | 751180                       |
| MRI-CGCM3        | 4808                 | 42929                        | 798950                       |
| NorESM1-M        | 7017                 | 9396                         | 330410                       |
Table S13 MPEHWd for the SSP3 scenario for the current year (1986-2015), mid-21st century (2021-2050), and end 21st century (2071-2100) scenarios based on the 11 members from CESM-LENS RCP8.5 (CESM-RCP8.5) scenario.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-----------------------------|
| 1   | 1094.2              | 28826.0                     | 644620.0                    |
| 2   | 3243.5              | 26444.0                     | 817420.0                    |
| 3   | 1792.4              | 31180.0                     | 727610.0                    |
| 4   | 318.3               | 31789.0                     | 775860.0                    |
| 5   | 1828.9              | 34743.0                     | 718540.0                    |
| 6   | 1500.6              | 32802.0                     | 867090.0                    |
| 7   | 3176.2              | 55895.0                     | 731570.0                    |
| 8   | 906.4               | 38911.0                     | 732280.0                    |
| 9   | 2727.4              | 46178.0                     | 839050.0                    |
| 10  | 781.0               | 37143.0                     | 814600.0                    |
| 11  | 2862.5              | 48538.0                     | 725890.0                    |
**Table S14** MPEHWd for the SSP1 scenario for the current year (1986-2015), mid-21st century (2021-2050), and end-21st century (2071-2100) scenarios based on the 11 members from CESM-LENS Low warming 2 °C (CESM-2C) scenario.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|----------------------|-----------------------------|-----------------------------|
| 1   | 1615.6               | 39826.0                     | 493950.0                    |
| 2   | 3246.2               | 27801.0                     | 577270.0                    |
| 3   | 2160.0               | 33044.0                     | 108400.0                    |
| 4   | 1113.2               | 28092.0                     | 88643.0                     |
| 5   | 1423.1               | 16512.0                     | 87643.0                     |
| 6   | 2128.6               | 20223.0                     | 62302.0                     |
| 7   | 674.8                | 26334.0                     | 132950.0                    |
| 8   | 873.3                | 25502.0                     | 85269.0                     |
| 9   | 3059.6               | 39830.0                     | 141240.0                    |
| 10  | 2437.4               | 19757.0                     | 75471.0                     |
| 11  | 2404.4               | 39920.0                     | 104910.0                    |
Table S15 MPEHWd for the SSP1 scenario for the current year (1986-2015), mid-21st century (2021-2050), and end 21st century (2071-2100) scenarios based on the 11 members from CESM-LENS Low warming 1.5 °C (CESM-1.5C) scenario.

| Run | Current (1986-2015) | Mid-21st century (2021-2050) | End-21st century (2071-2100) |
|-----|---------------------|-----------------------------|-------------------------------|
| 1   | 1088.7              | 15049.0                     | 33416.0                       |
| 2   | 2978.8              | 18925.0                     | 39774.0                       |
| 3   | 1827.0              | 19574.0                     | 50867.0                       |
| 4   | 3073.1              | 11011.0                     | 36094.0                       |
| 5   | 2446.7              | 14640.0                     | 42009.0                       |
| 6   | 2558.2              | 15795.0                     | 45154.0                       |
| 7   | 2848.4              | 27616.0                     | 66566.0                       |
| 8   | 804.2               | 15244.0                     | 28987.0                       |
| 9   | 1661.7              | 28439.0                     | 44180.0                       |
| 10  | 942.0               | 17268.0                     | 31800.0                       |
| 11  | 3334.2              | 19177.0                     | 38313.0                       |
Table S16: MPEHWd for the SSP3 scenario based on CMIP5-RCP 8.5, CESM-RCP 8.5, CESM-1.5C, and CESM-2C.

| Year | Mean Population per 30 year (SSP3) | Ensemble mean MPEHWd based on CESM-LENS | Ensemble mean MPEHWd based on CMIP5-RCP8.5 |
|------|------------------------------------|------------------------------------------|------------------------------------------|
|      |                                    | CESM-1.5C      | CESM-2C      | CESM-RCP8.5   |                          |
| 2009 | 718.78                             | 1472.9         | 1308.6       | 1334.5        | 3111.3                   |
| 2010 | 731.12                             | 1706           | 1565.4       | 1427.1        | 3315.4                   |
| 2011 | 743.51                             | 1685.5         | 1502.2       | 1343.4        | 3425.9                   |
| 2012 | 755.97                             | 1699.5         | 1575.7       | 1358.2        | 3504.7                   |
| 2013 | 768.48                             | 1762.3         | 1689.1       | 1622.1        | 3762.6                   |
| 2014 | 781.05                             | 1875.3         | 1837.5       | 1716.6        | 4095.3                   |
| 2015 | 793.68                             | 2140.3         | 1924.3       | 1839.2        | 4550.4                   |
| 2016 | 806.37                             | 2145.8         | 2012.3       | 1860.6        | 4998.4                   |
| 2017 | 819.12                             | 2394.1         | 2299         | 1942.6        | 5616.3                   |
| 2018 | 831.93                             | 2479.8         | 2370.7       | 2007.5        | 6109.9                   |
| 2019 | 844.8                              | 2722.5         | 2445.2       | 2223.1        | 6988.3                   |
| 2020 | 857.72                             | 2855.2         | 2713.9       | 2669.7        | 7445.4                   |
| 2021 | 870.74                             | 3058.2         | 2977.4       | 2898.2        | 8574.7                   |
| 2022 | 883.87                             | 3120.9         | 3196.3       | 3023.8        | 9511.1                   |
| 2023 | 901.42                             | 3483.4         | 3251.9       | 3165.6        | 10373                    |
| 2024 | 923.84                             | 3707.5         | 3375.8       | 3687.5        | 11162                    |
| 2025 | 937.36                             | 3908.6         | 3660.3       | 3881.1        | 12297                    |
| 2026 | 950.98                             | 4088.1         | 3854.6       | 4144          | 13273                    |
| 2027 | 964.7                              | 4263           | 4242.7       | 4651.5        | 14220                    |
| 2028 | 978.52                             | 4461.7         | 4613.7       | 5080.2        | 15429                    |
| 2029 | 992.44                             | 4969.6         | 4917.7       | 5430.7        | 16892                    |
| 2030 | 1006.4                             | 5634.1         | 5275.1       | 6079.3        | 18221                    |
| 2031 | 1020.5                             | 5937.9         | 5836.1       | 6419.6        | 19958                    |
| 2032 | 1034.5                             | 6044.1         | 6600.2       | 6543.3        | 21582                    |
| 2033 | 1048.7                             | 6293.5         | 7030.5       | 7045.7        | 24051                    |
| 2034 | 1062.9                             | 6758.6         | 7593.3       | 7524.9        | 25304                    |
| 2035 | 1077.2                             | 6977.3         | 7911.5       | 8602.1        | 27256                    |
| 2036 | 1091.5                             | 7295           | 8551.8       | 9245.8        | 29660                    |
| 2037 | 1105.8                             | 7983.2         | 9447.7       | 10647         | 32375                    |
| 2038 | 1120.3                             | 8375.4         | 10784        | 12826         | 34616                    |
| 2039 | 1134.8                             | 9327           | 10868        | 13768         | 37735                    |
| 2040 | 1149.2                             | 9607.3         | 12377        | 15312         | 41959                    |
| 2041 | 1163.5                             | 10217          | 13402        | 17053         | 46185                    |
| 2042 | 1177.8                             | 11095          | 14891        | 19479         | 49943                    |
| 2043 | 1192.1                             | 11942          | 16072        | 22030         | 55453                    |
| 2044 | 1206.2                             | 12308          | 17962        | 23760         | 59496                    |
| 2045 | 1220.3                             | 13276          | 19322        | 26054         | 64607                    |
| 2046 | 1234.3                             | 13573          | 20872        | 28247         | 69443                    |
| 2047 | 1248.3                             | 14732          | 22739        | 31612         | 74967                    |
| 2048 | 1262.2                             | 14798          | 24724        | 34673         | 80242                    |
| 2049 | 1276                               | 16736          | 25786        | 37495         | 86246                    |
| 2050 | 1289.8                             | 17869          | 27944        | 42378         | 93941                    |
| 2051 | 1303.5                             | 18623          | 29666        | 46642         | 101580                   |
| 2052 | 1317.2                             | 19445          | 30582        | 50278         | 109290                   |
| 2053 | 1330.8                             | 19664          | 32539        | 54662         | 117900                   |
|    |     |     |     |     |     |
|----|-----|-----|-----|-----|-----|
| 2055 | 1344.4 | 20899 | 36084 | 59844 | 127810 |
| 2056 | 1357.9 | 22313 | 38161 | 63946 | 137900 |
| 2057 | 1371.3 | 22775 | 42534 | 69803 | 146980 |
| 2058 | 1384.7 | 24141 | 45824 | 76457 | 157210 |
| 2059 | 1398.1 | 24923 | 49060 | 84081 | 167780 |
| 2060 | 1411.4 | 25320 | 53247 | 92055 | 179360 |
| 2061 | 1424.6 | 25729 | 56201 | 98317 | 191290 |
| 2062 | 1437.8 | 27884 | 59895 | 106250 | 203020 |
| 2063 | 1450.8 | 29448 | 63507 | 114310 | 216220 |
| 2064 | 1463.8 | 30701 | 65464 | 121760 | 229900 |
| 2065 | 1476.7 | 32089 | 69803 | 129360 | 243990 |
| 2066 | 1489.6 | 32372 | 71093 | 139400 | 260020 |
| 2067 | 1502.3 | 33418 | 75003 | 153270 | 276060 |
| 2068 | 1515.0 | 33839 | 79024 | 166880 | 291930 |
| 2069 | 1527.6 | 34540 | 81277 | 176800 | 304800 |
| 2070 | 1540.1 | 34272 | 86689 | 189780 | 327420 |
| 2071 | 1552.5 | 35371 | 90064 | 194320 | 345290 |
| 2072 | 1564.9 | 35484 | 95346 | 206680 | 364230 |
| 2073 | 1577.3 | 36296 | 100300 | 213260 | 384170 |
| 2074 | 1589.5 | 36589 | 106790 | 224690 | 400840 |
| 2075 | 1601.7 | 37111 | 111030 | 236040 | 423270 |
| 2076 | 1613.8 | 37173 | 115950 | 247560 | 444710 |
| 2077 | 1625.9 | 39152 | 118620 | 259070 | 466890 |
| 2078 | 1637.9 | 38729 | 121680 | 261030 | 491990 |
| 2079 | 1649.8 | 40418 | 126030 | 275200 | 515150 |
| 2080 | 1661.7 | 38871 | 132060 | 281650 | 538750 |
| 2081 | 1673.4 | 39186 | 139300 | 293000 | 563330 |
| 2082 | 1685.0 | 41430 | 144310 | 325200 | 588180 |
| 2083 | 1696.4 | 41887 | 152800 | 341970 | 615200 |
| 2084 | 1707.7 | 42447 | 159180 | 342180 | 639150 |
| 2085 | 1718.8 | 41933 | 160860 | 349930 | 665130 |
| 2086 | 1729.8 | 41676 | 166910 | 364080 | 693020 |
| 2087 | 1740.6 | 43273 | 169830 | 385170 | 722580 |
| 2088 | 1751.2 | 43445 | 173120 | 505020 | 750520 |
| 2089 | 1761.7 | 44325 | 177610 | 522730 | 781540 |
| 2090 | 1772.1 | 45684 | 182200 | 539860 | 811880 |
| 2091 | 1782.4 | 46779 | 186340 | 561430 | 842380 |
| 2092 | 1792.8 | 44604 | 192750 | 584110 | 878820 |
| 2093 | 1803.1 | 43460 | 201860 | 609270 | 909390 |
| 2094 | 1813.5 | 43941 | 206710 | 629270 | 940780 |
| 2095 | 1823.8 | 44234 | 214210 | 655760 | 975460 |
| 2096 | 1834.1 | 46743 | 217070 | 682700 | 1011400 |
| 2097 | 1844.4 | 47307 | 223120 | 704060 | 1043000 |
| 2098 | 1854.7 | 49839 | 227980 | 721950 | 1081600 |
| 2099 | 1864.9 | 51265 | 234750 | 744320 | 1117000 |
| 2100 | 1875.2 | 53455 | 240860 | 763140 | 1155200 |
Table S17: MPEHWd for the SSP1 scenario based on CMIP5-RCP 8.5, CESM-RCP 8.5, CESM-1.5C, and CESM-2C.

| year | Mean Population per 30 year (SSP1) | Ensemble mean MPEHWd based on CESM-LENS | Ensemble mean MPEHWd based on CMIP5-RCP8.5 |
|------|-----------------------------------|-----------------------------------------|------------------------------------------|
|      |                                   | CESM-1.5C | CESM-2C | CESM-RCP8.5 | CESM-RCP8.5 |
| 2009 | 726.95                            | 1468.9    | 1306.6  | 1333.6      | 3123.8      |
| 2010 | 739.56                            | 1703.5    | 1561.7  | 1423.8      | 3329.6      |
| 2011 | 752.14                            | 1682.6    | 1498.1  | 1339.9      | 3438.5      |
| 2012 | 764.69                            | 1696.7    | 1570.3  | 1354.4      | 3518        |
| 2013 | 777.2                             | 1759.8    | 1685.1  | 1620        | 3777.7      |
| 2014 | 789.67                            | 1873.8    | 1834.1  | 1716.3      | 4114.9      |
| 2015 | 802.11                            | 2142.1    | 1921.5  | 1842.2      | 4571.3      |
| 2016 | 814.52                            | 2151.5    | 2012.6  | 1867        | 5025.9      |
| 2017 | 826.9                             | 2400.4    | 2303.2  | 1951.7      | 5646.7      |
| 2018 | 839.24                            | 2489.5    | 2375.9  | 2019.3      | 6145.8      |
| 2019 | 851.54                            | 2741.6    | 2453.2  | 2236.3      | 7032.7      |
| 2020 | 863.82                            | 2876.2    | 2728.3  | 2691.8      | 7495.7      |
| 2021 | 875.97                            | 2896.4    | 2775.9  | 2777.6      | 8155.5      |
| 2022 | 888                               | 3093.4    | 3006.6  | 2937.8      | 8638.4      |
| 2023 | 899.91                            | 3169.5    | 3241.7  | 3074.5      | 9588.6      |
| 2024 | 911.7                             | 3559.6    | 3308.2  | 3229.1      | 10458       |
| 2025 | 923.37                            | 3807      | 3447.3  | 3765.8      | 11260       |
| 2026 | 934.92                            | 4022.6    | 3752.9  | 3979.8      | 12411       |
| 2027 | 946.34                            | 4222      | 3961.5  | 4250.4      | 13407       |
| 2028 | 957.65                            | 4418.4    | 4367    | 4782.3      | 14356       |
| 2029 | 968.83                            | 4639.7    | 4758.8  | 5241        | 15565       |
| 2030 | 979.9                             | 5179.5    | 5077.3  | 5622.8      | 17038       |
| 2031 | 990.84                            | 5892.2    | 5477.1  | 6341.8      | 18394       |
| 2032 | 1001.7                            | 6227.4    | 6103.5  | 6732.2      | 20150       |
| 2033 | 1012.4                            | 6389.3    | 6909    | 6900.5      | 21796       |
| 2034 | 1022.9                            | 6680      | 7386.9  | 7476.1      | 24230       |
| 2035 | 1033.4                            | 7242.1    | 8035.3  | 8041.4      | 25498       |
| 2036 | 1043.7                            | 7530.9    | 8413.4  | 9226.5      | 27506       |
| 2037 | 1053.9                            | 7924.7    | 9157.2  | 9973.5      | 29973       |
| 2038 | 1064                              | 8687.9    | 10182   | 11647       | 32666       |
| 2039 | 1073.9                            | 9148.2    | 11689   | 14071       | 34960       |
| 2040 | 1083.8                            | 10035     | 11842   | 15189       | 37967       |
| 2041 | 1093.4                            | 10382     | 13590   | 16951       | 42089       |
| 2042 | 1102.7                            | 11055     | 14773   | 18955       | 46203       |
| 2043 | 1111.8                            | 12001     | 16460   | 21745       | 50094       |
| 2044 | 1120.7                            | 12924     | 17898   | 24611       | 55790       |
| 2045 | 1129.3                            | 41560     | 19947   | 26664       | 59882       |
| 2046 | 1137.7                            | 13236     | 21507   | 29313       | 64934       |
| 2047 | 1145.9                            | 40277     | 23327   | 31836       | 69835       |
| 2048 | 1153.8                            | 14439     | 25407   | 35434       | 75299       |
| 2049 | 1161.5                            | 39905     | 27723   | 38910       | 80525       |
| 2050 | 1168.9                            | 14779     | 28804   | 42004       | 86549       |
| 2051 | 1176                              | 38164     | 31102   | 47443       | 93941       |
| 2052 | 1182.9                            | 16057     | 33090   | 52255       | 101060      |
| 2053 | 1189.4                            | 38044     | 34185   | 56331       | 108570      |
| Year | Area    | Julian Day | Julian Day | Julian Day | Julian Day |
|------|---------|------------|------------|------------|------------|
| 2054 | 1195.6  | 16121      | 36320      | 61020      | 116760     |
| 2055 | 1201.6  | 36565      | 39915      | 66599      | 126130     |
| 2056 | 1207.2  | 18431      | 42194      | 70820      | 135590     |
| 2057 | 1212.5  | 37245      | 47071      | 77341      | 144070     |
| 2058 | 1217.6  | 19535      | 50386      | 84287      | 153390     |
| 2059 | 1222.3  | 36957      | 53602      | 92598      | 163280     |
| 2060 | 1226.8  | 20374      | 58216      | 101210     | 174140     |
| 2061 | 1230.8  | 38034      | 61121      | 107820     | 184760     |
| 2062 | 1234.6  | 21052      | 62835      | 115980     | 195140     |
| 2063 | 1238    | 40232      | 82583      | 131240     | 231590     |
| 2064 | 1241    | 21104      | 89462      | 138730     | 245470     |
| 2065 | 1243.7  | 39994      | 96966      | 148440     | 301280     |
| 2066 | 1246    | 22292      | 106220     | 151280     | 358380     |
| 2067 | 1248    | 39126      | 113240     | 159070     | 374840     |
| 2068 | 1249.6  | 23860      | 114930     | 163250     | 391080     |
| 2069 | 1250.9  | 38652      | 119490     | 168940     | 408360     |
| 2070 | 1251.8  | 24327      | 123850     | 174560     | 426240     |
| 2071 | 1252.3  | 39402      | 127650     | 183840     | 458370     |
| 2072 | 1252.5  | 25966      | 131240     | 193840     | 515610     |
| 2073 | 1252.4  | 38486      | 136940     | 203840     | 556190     |
| 2074 | 1251.9  | 26819      | 141640     | 213840     | 598630     |
| 2075 | 1251    | 39268      | 146340     | 223840     | 642470     |
| 2076 | 1249.8  | 27194      | 151040     | 233840     | 688310     |
| 2077 | 1248.2  | 39968      | 155740     | 243840     | 735070     |
| 2078 | 1246.2  | 27678      | 160440     | 253840     | 783870     |
| 2079 | 1243.9  | 39632      | 165140     | 263840     | 833670     |
| 2080 | 1241.3  | 29877      | 170440     | 273840     | 884370     |
| 2081 | 1238.3  | 39403      | 175140     | 283840     | 934070     |
| 2082 | 1235    | 31278      | 179840     | 293840     | 984770     |
| 2083 | 1231.5  | 37347      | 184540     | 303840     | 1035470    |
| 2084 | 1227.6  | 32389      | 190240     | 313840     | 1085170    |
| 2085 | 1223.5  | 37203      | 194940     | 323840     | 1134870    |
| 2086 | 1219    | 33811      | 200640     | 333840     | 1184570    |
| 2087 | 1214.2  | 39149      | 205340     | 343840     | 1234270    |
| 2088 | 1209.2  | 33928      | 210040     | 353840     | 1283970    |
| 2089 | 1203.8  | 37823      | 214740     | 363840     | 1333670    |
| 2090 | 1198.1  | 35066      | 219440     | 373840     | 1383370    |
| 2091 | 1192.2  | 38486      | 224140     | 383840     | 1433070    |
| 2092 | 1186.1  | 35372      | 228840     | 393840     | 1482770    |
| 2093 | 1179.6  | 36879      | 233540     | 403840     | 1532470    |
| 2094 | 1172.9  | 35968      | 238240     | 413840     | 1582170    |
| 2095 | 1166    | 37385      | 242940     | 423840     | 1631870    |
| 2096 | 1158.8  | 35960      | 247640     | 433840     | 1681570    |
| 2097 | 1151.4  | 36925      | 252340     | 443840     | 1731270    |
| 2098 | 1143.7  | 36759      | 257040     | 453840     | 1780970    |
| 2099 | 1135.7  | 37008      | 261740     | 463840     | 1829670    |
| 2100 | 1127.5  | 36698      | 266440     | 473840     | 1879370    |

Reference:

Menon S, Hansen J, Nazarenko L and Luo Y 2002 Climate Effects of Black Carbon Aerosols in China and India *Science* **297** 2250

Roy S S, Mahmood R, Niyogi D, Lei M, Foster S A, Hubbard K G, Douglas E and Pielke R 2007 Impacts of the agricultural Green Revolution–induced land use changes on air temperatures in India *J. Geophys.*
Russo S, Sillmann J and Fischer E M 2015 Top ten European heatwaves since 1950 and their occurrence in the coming decades Environ. Res. Lett. 10 124003

Sacks W J, Cook B I, Buenning N, Levis S and Helkowski J H 2009 Effects of global irrigation on the near-surface climate Clim. Dyn. 33 159–75