Environmental Research Communications

LETTER

Decline in surface urban heat island intensity in India during heatwaves

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Keywords: urbanization, heat waves, land surface temperature, India, MODIS

Abstract

Heatwaves cause human mortality around the world and are projected to rise in the future. Despite the influence of urban heat island (UHI) on heatwaves, the role of UHI on heatwave intensification in urban areas in India remains unrecognized. Here using in situ, satellite observations, and model simulations, we show that urban areas in India do not intensify heatwaves. The frequency of hot-days has significantly increased in urban areas during 1951–2016. The frequency of hot-nights has also increased in the majority of urban areas in India except those located in Indo-Gangetic Plain (IGP). We show that a decline in the frequency of hot-nights (−4.5 ± 1.6 hot-nights) in IGP during 1951–2016 is mainly due to intensive irrigation in the region. We confirm the influence of irrigation on land surface temperature (LST) over IGP using simulations from Community Land Model (CLM4). Our results show that Surface Urban Heat Island (SUHI) intensity in major urban areas in India declines during heatwaves both during the day (−0.3 ± 0.7 °C) and night (−0.3 ± 0.4 °C) from the reference SUHIs. Surrounding non-urban areas (44.5 ± 5.5 °C) are warmer than urban areas (43.7 ± 6.8 °C) during heatwaves due to the absence of vegetation. Our results have implications for policy related to health impacts during heatwaves.

Introduction

About 33% of total population of India is currently living in urban areas, which is projected to reach 50% by 2050 (World Urbanization Prospects 2014). Urbanization contributes to regional warming (Zhao and Wu 2017) and can locally affect the intensity and severity of heatwaves (Fischer et al 2012, Li and Bou-Zeid 2013, Zhao et al 2014, Li et al 2015, Ramamurthy and Bou-Zeid 2017). Amplification of heatwaves in urban areas has been observed in the many regions across the globe (Li and Bou-Zeid 2013, Li et al 2015, Ramamurthy et al 2015, Ramamurthy and Bou-Zeid 2017). Moreover, urban areas can cause disproportionate heat stress in comparison to surrounding non-urban areas (Fischer et al 2012). The drop in temperature during night helps in the recovery from heat stress. However, during intense day-time heatwave, the chances of night time recovery reduces in urban areas (due to UHI) leading to a composite extremely hot-day and night event (Laaidi et al 2012).

Heatwaves are among the major causes of human mortality around the world (Patz et al 2005, Mazdiyasni et al 2017). The frequency of hot-days and hot-nights has increased in the last three decades around the world (Coffel et al 2017, Mazdiyasni et al 2017, Perkins-Kirkpatrick and Gibson 2017). In India, heatwaves have increased in the past and are projected to intensify in the future (Im et al 2017, Mishra et al 2017) causing increased heat related deaths. For instance, India witnessed a high heat-related mortality during the 2015 heatwave. Additionally, increased intensity and frequency of heatwaves over India can result in higher exposure and health risks (Mazdiyasni et al 2017, Mishra et al 2017, Panda et al 2017). Notwithstanding India faces frequent heatwaves (Mishra et al 2017, Panda et al 2017), it remains unknown if SUHI intensity in India (like in the USA (Li and Bou-Zeid 2013, Li et al, Ramamurthy and Bou-Zeid 2017, Zhao et al 2018) and...
China (Li et al 2015) gets amplified during heatwaves. Here using the observations and model simulations, we estimate SUHI intensity during heatwaves.

Data and methods

We used 56 m resolution Land Use Land Cover (LULC) from National Remote Sensing Center (NRSC) for the year 2011 and urban extent map derived from Moderate Resolution Imaging Spectroradiometer (MODIS) 500 m land cover data (Schneider et al 2010). The urban core or densely built-up areas were extracted by overlapping the MODIS urban extent maps and NRSA LULC for 89 major urban areas in India as described in Kumar et al (2017). The intersecting built-up area from both the datasets were considered as urban core area. We used 1 km resolution MODIS 8-day LST from the two satellites, Aqua and Terra, from 2003 to 2016 to estimate LST. The LST data are derived from known emissivity in different bands of spectrum, as observed from the satellites in clear sky conditions. The MODIS products also provide quality control flags, which were used to improve the reliability of LST (Wan et al 2015). More details on data quality and selection of urban areas can be obtained from Kumar et al (2017).

We obtained observed daily near Surface Air Temperature (SAT) gridded at 2 m height from India Meteorological Department (IMD) for the period 2003–2016 to analyse extreme temperature during hot-days/night and heatwaves. The gridded data was developed using 395 stations from 1951 to present using Shepherd’s angular distance weighting algorithm (Srivastava et al 2009). For our study, we regridded the IMD data from 1° to 0.25° spatial resolution using bilinear interpolation as described in Shah and Mishra (2016). Daily gridded dataset from IMD was used to determine hot-days, hot-nights, and heatwaves. We considered a hot-day as a day with a maximum SAT greater than the 95th percentile of summer (April, May, and June) daily maximum SAT ($T_{\text{max}}$) for the reference period of 1970–2010. Similarly, a hot-night occurs when daily minimum SAT ($T_{\text{min}}$) exceeds 95th percentile of $T_{\text{min}}$ of the reference period during summer. We define heatwave as a continuous spell of three or more hot-days. We compared amplification of LST during a heatwave against reference LST days in the period 2003–2016. Here, the reference LST days were all the non-heatwave days during the summer, which coincide with a particular heatwave period.

Estimation of surface temperature from MODIS LST and surface Urban heat Island (SUHI)

We used 5 km buffer from the boundary of each urban area with a variable distance (based on the size of urban area) from the center (table S2). The buffer is provided to avoid any spillover effect of the urban area on the surrounding non-urban area. Water bodies were excluded from both the urban and nonurban areas. For urban areas that are close to each other, the nonurban areas were reshaped to remain out of each other’s buffer gap.

To reduce the cloud contamination, we used 8-day composite LST from both Aqua and Terra satellites. The local overpass time of the satellites is approximately around 10:30 and 22:30 h. for the Terra satellite and 01:30 and 13:30 h. for the Aqua satellite. The availability of LST at a different time of the day helped in estimating SUHI intensity variation during heatwaves.

We evaluated the quality of MODIS LST datasets with relevant quality control data provided along with it. To reduce the effect of cloud contamination, LST images with more than 10% cloud cover in either urban or non-urban areas were excluded from the analysis as described in Kumar et al (2017). We used associated quality control flags in the MODIS dataset to compute the weighted areal average LST for the urban and non-urban areas. This is done to ensure that variability form the poor quality pixels are not lost while calculating the areal average. The weights are higher for better quality data and lower for poor. The weighted areal average of a region (LST) can be determined as,

$$\text{LST} = \frac{\sum_{p=1}^{n} w_{p} \text{LST}_{p}}{\sum_{i=1}^{n} w_{p}}$$

Where, $w_{p}$ and $\text{LST}_{p}$ are weights and LST of pth pixel respectively. The pixel-wise weights ($w_{p}$) is defined as

$$w_{p} = \begin{cases} 
3, & \text{good quality LST} \\
2, & \text{fair quality LST} \\
1, & \text{poor quality LST} 
\end{cases}$$

Urban and non-urban temperature contrast can be quantified using Surface Urban Heat Island (SUHI) intensity. SUHI can be defined as the difference of urban and surrounding non-urban weighted average LST.

$$\text{SUHI} = \text{LST}_U - \text{LST}_\text{NU}$$

Where LST$_U$ and LST$_\text{NU}$ represents weighted average LST for urban and surrounding non-urban region, respectively.
Community land model (CLM) simulations

We used the Community Land Model (CLM4) (Levis et al. 2012), a component of the Community Earth System Model (CESM) developed by the National Center for Atmospheric Research (NCAR) to simulate SAT at 2° spatial and 4-times in a day temporal resolutions for both urban and non-urban biomes. An urban canyon model (Oke 1973) represents the urban environment in CLM4 wherein radiation, sensible, and latent heat fluxes are transferred between the walls, surface, and atmosphere of the canyon (Oleson et al. 2011).

The control simulation only has unmanaged rain fed crops. We use this version rather than the more recent CLM4.5 because the irrigation model is operational for India in CLM4 only. We incorporated two crops types with unmanaged rainfed and unmanaged irrigated schemes in a generic crop model. The models were spun up using Climate Research Unit and National Centers for Environmental Prediction (CRUNCEP) reanalysis driving datasets (Kalnay et al. 1996, Mitchell and Jones 2005), cycling over 1991–2010 for 500 years considering two scenarios, one with crop on and irrigation off and the other with crop on and irrigation on. The long spin up period is required to stabilize land surface and atmospheric components in CLM4. We calculated drift in globally averaged surface temperature using $-0.005 \, ^\circ C/\text{century}$ for our irrigation simulation, and $0 \, ^\circ C/\text{century}$ for the control run, which indicate the suitability of the CLM4 for application.

The CRUNCEP is an atmospheric forcing dataset prepared by combining two datasets, Climate Research Unit (CRU) TS3.2 (0.5 degree, monthly, 1901–2002) and National Centers for Environmental Prediction (NCEP) reanalysis (2.5 degree, 6 hourly, 1948–2016). The forcing dataset has been used to run CLM for a long term in studies related to vegetation growth, evapotranspiration, crop production and trends in land-atmospheric carbon-exchanges. The dataset was developed by Natural Environment Research Council (NERC) and United States Department of Energy. With these initial equilibrium conditions, we ran our experiment with CRUNCEP 2000–2014.

Results and discussion

We first examine the changes in the frequency of extreme hot-days and hot-nights for the 89 urban areas using gridded daily SAT data from IMD for 1951–2016. We find that a majority of urban areas experienced about five hot-days and nights per year during 1951–2016 (figures 1(a) and (d)). About 44% of the selected locations show a significant ($P < 0.05$) rise in the frequency of hot-days while 34.8% of the total urban areas show a significant decline in the frequency of hot-nights. Our results show that urban areas in IGP show a contrasting pattern in the changes in the frequency of hot-days and hot-nights. Most of the urban areas experience an insignificant ($P > 0.05$) rise in the frequency of hot-days over IGP. In contrast, a majority of urban areas experience a significant decline in the frequency of hot-nights in comparison to the urban areas located in the other parts of the country (figures 1(b) and (e)). Between 1951 and 1980 (pre-1980), urban areas in non Gangetic plain region (NGR) experienced lesser hot-days and hot-nights in comparison to urban areas located in IGP (figures 1(c), (f)). However, in the post-1980, the frequency of hot-days in urban areas located in IGP has declined. We find that the frequency of hot-nights in urban areas in NGR is higher than for those located in IGP. The differences in the frequency of hot-days and hot-nights for urban areas located in IGP and NGR can be due to the presence of intensive irrigation over IGP (Ambika et al. 2016).

To further examine the role of irrigation on LST, we used simulations from CLM with irrigation on and off scenarios. We find summer median cooling of 1.2 °C and 1.6 °C in IGP region due to irrigation at day and night-time, respectively (figures 2(a) and (d)). However, for locations in less intensively irrigated NGR, cooling is only 0.37 °C and 0.4 °C for the day and nighttime, respectively. Irrigation induced cooling of surface temperature has been observed in many regions such as in India (Bonfilis and Lobell 2007, Roy et al. 2007, Cook et al. 2011), China (Han and Yang 2013, Shi et al. 2014) and California, USA (Kueppers et al. 2007, Lobell et al. 2008). Apart from irrigation induced cooling, Padma Kumari et al. 2007 and van Oldenborgh et al. 2017 argued that aerosols are also a major factor for the decline in maximum SAT. Kumar et al. (2017) reported that aerosols play a relatively minor role in temperature modulation over IGP in comparison to irrigation, therefore, we did not estimate their influence on surface temperature during heatwaves.

Change in LST during heatwaves

Next, we evaluate the SUHI intensity variation in major urban areas during heatwaves using LST from MODIS satellites. We estimated the changes in SUHI intensity during heatwaves from the reference SUHI at day and night-time for 89 urban areas in India. We find that most of urban areas experience day-time surface Urban Cool Island (SUCI) as nonurban areas are hotter than the surrounding urban areas (Kumar et al. 2017, Shastri et al. 2017). However, at night-time almost all the urban areas experience SUHI (figures 3(a) and (d)). We find that 63% and 74% of the total urban areas show a decline in SUHI intensities ($\text{SUHI}_{\text{UHI}} < \text{SUHI}_{\text{Ref}}$) during heatwaves with respect to the reference SUHI for both day and night-time, respectively (figures 3(b) and (e)).
Therefore, our results do not show an intensification of SUHI during heatwaves in urban areas. Kumar et al. (2017) reported that urban areas experience a cool island during day-time, which is linked with agriculture and irrigation. However, the variation of SUHI during heatwaves was unexplored. Our results show that in urban areas in India, in contrast to many other regions in the world, SUHI intensity does not intensify during heatwaves. Our results showing that SUHI intensity does not intensify during heatwaves are in contrast with earlier studies that show a synergistic response between UHI and heatwaves (Li et al. 2015, Ramamurthy et al. 2015, Zhao et al. 2018). For instance, Li et al. (2015) reported that urbanization causes intensification of heatwaves in Beijing, China using flux tower datasets. Similarly, Ramamurthy et al. (2017) and Zhao et al. (2018) found a similar intensification in urban areas located in the United States of America. Beijing has monsoon-influenced humid continental climate while the USA lies in temperate, continental, and dry climate zones (Peel et al. 2007). Irrespective of the background climate, previous studies conducted over other parts of the world highlight an intensification of heatwaves caused by urbanization (Li and Bou-Zeid 2013, Li et al. 2015, Ramamurthy and Bou-Zeid 2017, Ramamurthy et al. 2015).

Our results show that SUHI intensity does not increase during heatwaves in urban areas in India. To further understand if urban LST gets intensified during heatwaves, we estimated absolute LST amplification in urban and non-urban areas. We find that the reference day-time LST for non-urban areas was substantially higher than that of urban areas during summer. For instance, day-time mean reference LST during 2002–2016 in all the urban areas was 43.7 ± 5.5 °C in comparison to 44.5 ± 6.8 °C in surrounding nonurban areas (figures 3(a) and 4(a)). Day-time median reference LST for urban and non-urban areas in IGP was found to be as 43.9 °C and 44.3 °C, respectively. For locations in NGR, the median reference day-time LST for urban and non-urban areas was 47.0 °C and 49.0 °C, respectively (figures 3(c) and 4(c)). We find that mean amplification in LST during heatwaves in non-urban areas was 1.9 °C, which is substantially higher than that experienced by urban areas (0.14 °C) for all selected locations. The daytime median LST amplification is in the NGR 2.3 °C and 2.1 °C for nonurban and urban areas, respectively. However, the night-time analysis suggests that the reference LST of urban areas is higher than the surrounding non-urban areas (figures 4(d) and S1(d) is available online at stacks.iop.org/ERC/1/031001/mmedia).
Next, we estimated night-time amplification of LST during heatwaves for urban and non-urban areas. We find that urban areas experienced an amplification in LST of 0.7 °C and 0.8 °C during night-time in NGR and IGP, respectively. On the other hand, for non-urban areas, night-time LST amplification during heatwaves was 0.8 °C and 0.5 °C for NGR and IGP, respectively. A majority of the non-urban areas is located in the agriculture dominated regions (table S3). Both soil moisture and vegetation cover decline after the harvesting before the summer season. On the other hand, urban areas have perennial vegetation resulting in lower LST in urban areas than surrounding non-urban areas during summer. We focused on daytime as urban areas store heat during day-time, which may result in a higher absolute temperature in urban areas during heatwave. During night-time urban areas release the stored heat during night (Oke 1982). We find that amplification is lesser for urban areas in Western regions (Rajasthan, Gujarat, Madhya Pradesh and Maharashtra) with higher reference LST (figures 4(b) and S1(b)). At higher reference LST, the amplification during heatwaves is lower due to higher heat capacity (Kay and Goit 1975).

We estimated the change in LST during heatwaves as simulated by CLM for urban areas. Our results show that the LST amplification was higher for most of the locations during daytime in comparison to night time. We find that median LST amplification during heatwaves of 2.3 °C and 3.4 °C for urban areas in NGR and IGP, respectively (figure S2(c) and S2(f)). Additionally, our results based on CLM simulations show night time LST amplification of 1.6 °C and 2.7 °C for urban areas located in NGR and IGP, respectively. We find that LST amplification during heatwaves obtained from CLM are different from those based on MODIS LST, which can be explained by the difference in spatial resolution of the two datasets.

Previous studies link urbanization to heatwave intensification using SUHI as a metric (Fischer et al 2012, Li et al 2015, Wang et al 2015, Peng et al 2018, Yu et al 2018, Zhao et al 2018) and report that urban population is at
higher risk. Here we show that the effect of urbanization during heatwaves in India by estimating LST amplification in urban and non-urban areas separately. We do not find an evidence of increase in SUHI in urban areas during heatwaves with respect to the reference non-urban system. We find a distinct pattern in urban areas in IGP for hot-days and hot-nights. The contrasting pattern in the frequency of temperature extremes in urban areas over IGP and NGR can be attributed to intensive irrigation in IGP. We find that cooling of SAT due to irrigation is strongly linked to the decline in hot-nights in urban areas in IGP. Our CLM simulation confirms the observed cooling in IGP due to irrigation. Therefore, in absence of intensive irrigation in IGP, temperature extremes can be more severe (Lu and Kueppers 2015).

Conclusions

Based on our work, we conclude the following:

1. We evaluated the changes in extreme hot-days/night and heatwave intensification at 89 major urban locations in India using in situ, satellite and simulation datasets. We observed that majority (44%) of the selected locations show significant rise in extreme hot-day frequency in the period of 1951–2016. While 35% of the urban locations experienced a decline in extreme hot-nights frequency in the same period. Our results show a significant decline in change in frequency of hot-nights concentrated in the IGP. Using CLM simulations we show that the intensive irrigation is associated with significant cooling in IGP, which can be attributed to the decline in frequency of extreme hot-nights as compared to the rest of India.

2. We further examined the amplification of difference in temperatures in urban and non-urban systems (SUHI) during heatwaves as an indicator of impact of urbanization on heatwave intensification using MODIS LST datasets (Li et al 2015, Ramamurthy et al 2015, Zhao et al 2018). We used changes in SUHI during heatwaves with respect to reference non-heatwave days, since LST is closely related to land use.
change and which can better explain the urban and non-urban temperature contrast. We show that majority of the urban locations (63% and 74%, respectively) show decline in SUHI intensities during heatwaves both at day and night times. Our observation are in contrast with studies showing synergistic response between heatwaves and UHI (Li et al. 2015, Ramamurthy et al. 2015, Zhao et al. 2018).

(3) The effect of urbanization can be explained by disentangling the urban and non-urban responses during heatwaves. We find that during heatwaves the day-time LST amplification in non-urban regions was significantly higher (1.94 °C) than the amplification in the urban areas (0.14 °C) for all selected locations (on top of higher non-urban base temperature than urban areas). Our results show that heatwaves do not amplify SUHI intensity in India have implications for urban planning in India.

Acknowledgments

The work was supported by the Ministry of Human Resources Development fellowship, Belmont Forum and Ministry of Earth Sciences (MoES). The land surface temperature datasets used in the study are freely available and can be obtained from NASA’s GSFC website (https://modis.gsfc.nasa.gov/data/dataprod/mod11.php). The authors would like to thank Jonathan Buzan and Mathew Huber for the help with CLM simulations. We appreciate comments from three reviewers.

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Wan Z, Hook S and Hulley G 2015 MOD11A2 MODIS/terra land surface temperature/emissivity 8-Day L3 Global 1km SIN Grid V006 [Data set]. NASA EOSDIS LP DAAC 10.5067/MODIS/MOD11A2.006

Wang L, Gao Z, Miao S, Guo X, Sun T, Liu M and Li D 2015 Contrasting characteristics of the surface energy balance between the urban and rural areas of Beijing 32 505–14

World Urbanization Prospects 2014 World Urbanization Prospects 2014 United Nations https://esa.un.org/unpd/wup/publications/files/wup2014-report.pdf

Yu Z, Xu S, Zhang Y, Jørgensen G and Vejre H 2018 Strong contributions of local background climate to the cooling effect of urban green vegetation. Scientific reports 8 6798

Zhao D and Wu J 2017 Contribution of urban surface expansion to regional warming in Beijing, China Journal of Applied Meteorology and Climatology 56 1551–9

Zhao L, Lee X, Smith R B and Oleson K 2014 Strong contributions of local background climate to urban heat islands Nature 511 216–9

Zhao L, Oppenheimer M, Zhu Q, Baldwin J W, Ebi K L, Bou-Zeid E and Liu X 2018 Interactions between urban heat islands and heat waves Environ. Res. Lett. 13 034003