



Surface Urban Heat Island (SUHI) Over Riverside Cities Along the Gangetic Plain of India

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Abstract—Rapid urbanisation in India has led to increased land use and energy demand, and the consequent uncontrolled development and increased human-induced activities are changing the micrometeorology and the local environment. Of late, the surface urban heat island (SUHI) effect is quite evident in India. It is known that river banks are where the most densely populated cities can be found around the globe, and the River Ganga (Ganges) in India is no exception. Town/cities located over the Gangetic Plain are witnessing a fast urbanisation, and associated perturbation is taking place in the micro/meso-scale meteorology/environment. Discussion about the influence of the river on the SUHI and dynamics over different cities along a single major river is needed, and therefore this study is undertaken to investigate the SUHI effect on riverside towns/cities over the Gangetic Plain, India. For this purpose, the observation data for the period of 2001–2014 from the Terra-MODIS satellite are used. The study quantifies the land surface temperature (LST) under different zones namely urban, suburban, and rural, delineated on the basis of International Geosphere Biosphere Programme-Land Cover (IGBP-LC) products. The intensity and trend of SUHI are measured as an indicator of environmental and micro-climate change. The study found a prevailing regime of nighttime SUHI intensity (SUHII) as well as the daytime formation of SUHI. The interaction of the wind blowing from the river and other land cover to towns/cities was examined with respect to the SUHII of Kanpur and Patna and was found to be quite important.

Keywords: SUHI, riverside cities, India, MODIS, ERA-interim.

1. Introduction

The urban heat island (UHI) phenomenon was first introduced by Howard (1833). The phenomenon occurs when a town/city shows comparatively

warmer temperatures than nearby rural areas. The difference in surface temperature between urban and rural areas normally measures the intensity of the UHI. Based on the data and estimation techniques (Bahi et al. 2016; Lockoshchenko and Korneva 2015; Voogt and Oke 2003), the UHI is categorised under three groups, namely (1) atmospheric UHI (AUHI), which is further divided into two subgroups, urban canopy Layer UHI and urban boundary layer UHI; (2) underground UHI (UUHI); and (3) surface urban heat island (SUHI). To exemplify the climatic effect of urbanisation, the quantification of SUHI is widely used at various locations in the world, as it is the most effective and uniform method (Bahi et al. 2016; Henry et al. 1989; Kumar et al. 2017; Matson et al. 1978; Meng and Liu 2013; Rao 1972; Shastri et al. 2017; Sultana and Satyanarayana 2018) for capturing the thermal perturbation in a microclimate. In SUHII estimation, the land surface temperature (LST) is considered as the indicator for measuring SUHI (Singh et al. 2014; Voogt and Oke 2003). LST is the skin temperature (Bhattacharya and Dadhwal 2003), which is influenced by several factors including soil temperature, vegetation canopy, vegetation body, surface albedo, and moisture content, and is also linked to other features (Qin and Karnieli 1999; Choi and Suh 2018). The land use/land cover change (LULCC) is another major factor regarding SUHII study (Bahi et al. 2016; Kalnay and Cai 2003; Meng and Liu 2013; Voogt and Oke 2003). The LST changes and formation of SUHI often with special reference to LULCC is discussed by Kotharkar et al. (2018), Zhou et al. (2019), Nesarikar-Patki and Raykar-Alange (2012), Ding and Shi (2013), Chen et al. (2014), Bhati and Mohan (2016), Bahi et al. (2016), Shirani-bidabadi et al. (2019), Freitas et al. (2007), Hart and Sailor (2009), Singh et al. (2014), Sharma et al. (2017), Shastri et al. (2017), Cosgrove

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and Berkelhammer (2018) and Fu and Weng (2018). The UHI Intensity (UHII), measured as SUHII, is sometimes termed as an indirect measure (Voogt and Oke 2003), yet it is considered one of the most valid ways to analyse the characteristics of urban thermal environments (Bahi et al. 2016; Sheng et al. 2017; Weng 2009). When the UHI needs to be measured with special reference to the land use/land cover (LULC), the SUHI approach is considered to be one of the best methods (Bahi et al. 2016; Balcik 2014; Dihkan et al. 2015; Li et al. 2012) due to its spatial resolvability. Furthermore for estimation of UHI through other approaches, the rural reference area (installation site of meteorological sensor) is needed to be free from influence of urban thermal environment (Lokoshchenko 2014), while SUHI being site independent and as the both urban and rural reference can be spatially adjusted, the SUHI approach is more readily applicable to any terrain. This flexibility of reference site selection is greatly helpful in studying the characteristic of urban thermal environment for agglomerations on the bank of a river, because an urban area may be influenced by cooling effects by the river just like coastal towns experience land/sea breeze, and fixed urban and rural reference points may be ineffective to study those effects.

In previous studies on SUHI, there was little discussion of the characteristics of UHI/SUHI with special reference to the riverside cities, despite the presence of large human settlements located on the banks of the river. However, there are some in-depth studies of the UHI over cities located on the banks of rivers around the world, such as Hiroshima by the Ota River (Murakawa et al. 1991), Manaus by the Amazon River (Maitelli and Wright 1996), Paris (Sarkar and De Ridder 2011; Sarrat et al. 2006), Seoul by the Cheonggye River (Kim et al. 2008), Sheffield by the river Don (Hathway and Sharples 2012), Jinan (Meng and Liu 2013), Beijing (Chen et al. 2014), and New Delhi by the Yamuna River (Bhati and Mohan 2016; Singh et al. 2014). Some of these studies quantify the influence of water bodies while others discuss the LST profile with respect to different land cover including areas near water bodies. However, due to the short time span of consideration in these studies, there is still a need for more in-depth studies. Some research involving multi-city studies (Kumar et al.

2017; Peng et al. 2011; Shastri et al. 2017; Sultana and Satyanarayana 2018) has quantified SUHI of multiple riverside cities but without any special analysis referring to the influence of the riverfront. Ashraf (2015), Ghosh and Mukhopadhyay (2014), Barat et al. (2018) and others have quantified LST and SUHI over the towns/cities on the bank of the River Ganga in the northern plains of India, including the urban area around the city of Patna, and other towns/cities of the state of Bihar, India, but without any reference to riverside cities. In the global context, a dearth of studies on the relationship between rivers and UHI was also reported by Hathway and Sharples (2012).

Thus, although studies are available for different riverside cities, the collective approach on the similarities of SUHI between the riverside towns/cities is seldom discussed, not only in India but also in a global context. Therefore, the present research will try to estimate the SUHI dynamics alongside a single river to elucidate the characteristics of SUHI and the influence of rivers on SUHII in one of the most densely populated regions of the world. The current paper is aimed at investigating (a) the temporal and spatial distribution of SUHI over riverside cities along the Ganga River, and (b) the riverfront of the Ganga and the influence on the SUHI intensity over towns/cities in India. The study area is focused on cities along the holy river Ganga in northern India. Section 1 is focused on the introduction and literature review. Section 2 describes the study area, data and methodology. Section 3 presents the results and discussion, respectively. Section 4 concludes the work.

2. Study Area, Data, and Methodology

2.1. Study Area

Important towns/cities, mostly listed in the Namami Gange Project of Government of India (<https://www.nmcg.nic.in>), along the Ganga River (Fig. 1), India, are selected for the study. These towns/cities are believed to be important as point sources of pollution, since they are major settlements and are directly linked with fast urbanisation. Hence, studying these towns/cities may in turn provide clues

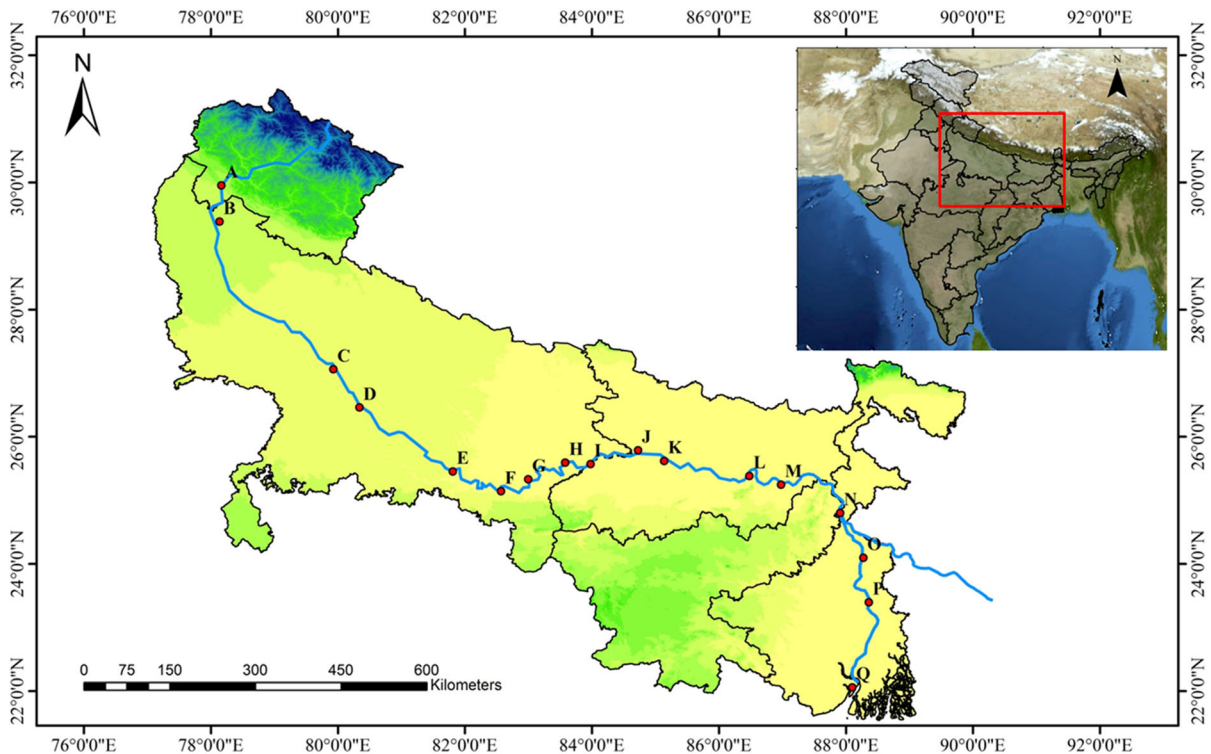


Figure 1

Location of considered stations [(A) Haridwar; (B) Bijnour; (C) Kannauj; (D) Kanpur; (E) Allahabad (we request that for future reference, the city be identified as Prayagraj; we have used the older name which was in use in the time period of the MAIRS mission); (F) Mirzapur; (G) Varanasi; (H) Ghazipur; (I) Buxar; (J) Chhapra; (K) Patna; (L) Munger; (M) Bhagalpur; (N) Farakka; (O) Baharampur; (P) Nabadwip; and (Q) Haldia] over the Gangetic plain of India

about other possible threats of urbanisation such as the formation of SUHI. The Gangetic Plain being one of the world's most populous regions, the need for monitoring of climate on a microscale is greatly needed, as it impacts the health of a large human population. The Ganges (or Ganga) is a major world river, flowing across different terrains and climate zones; hence it is very interesting to quantify the SUHI over different cities of the study area, as they will possess both similarities and dissimilarities. In the present study, many of the smaller towns were considered for documentation of the initial phase of SUHI dynamics, which will in turn help the scientific community in enriching the existing knowledge about heat islands. In most cases, these small towns are excluded by traditional filters or selection criteria, which target only larger cities, for example > 1 million population (Peng et al. 2011), > 0.1 million population (Shastri et al. 2017), and smart cities of

India (Kumar et al. 2017). However, the smaller towns are equally important, as they are in their initial phase of growth, and hence mitigation measures can be applied in a timely manner.

2.2. Data Sources

The data from Terra-MODIS under the Monsoon Asia Integrated Regional Study (MAIRS) were collected from the National Aeronautics and Space Administration (NASA) via the Giovanni online data system (Acker and Leptoukh 2007). The LST data and LULC data were both taken from the MAIRS project to ensure better synchronisation of datasets. The MAIRS project data are available in finest MODIS resolutions ($\sim 1 \text{ km}^2$ for LST and $500 \text{ m} \times 500 \text{ m}$ for LULC), duly geoprocessed and cleaned, over the Monsoon Asia region under the MAIRS programme and are distributed as Level 3

(L3) products. Hence this dataset is extremely useful for application to the present study area; the only drawback is the short time span of the dataset (~ 15 years). The Giovanni products are found to be used globally for different terrestrial and oceanic (Suwannathatsa and Wongwises 2013) studies, climatological analyses (Mohan et al. 2012), and LULC studies (Zhou et al. 2013). The base maps used for city demarcation are the De_Lorme world base map and the topographic base map from the user resources of arcgisonline.com for ArcGIS 10.1. The summer monsoon months (June–September) are excluded because the data are not available due to cloud cover. Similarly, representative data for each month are selected based on data availability over each city. The wind data at a surface resolution of $0.125^\circ \times 0.125^\circ$ ($\sim 12 \text{ km} \times 12 \text{ km}$) are taken from ERA-Interim reanalysis datasets from the European Centre for Medium Range Forecasting (ECMWF) (Dee et al. 2011). The wind data are further processed to visualise the prevailing mesoscale circulation at finer resolutions. We have chosen ERA-Interim data over ERA5 data, because the available ERA-Interim data has much finer resolution than ERA5 for the end user, although surprisingly ERA5 has a finer native resolution. The details of the datasets utilised are given in Table 1.

2.3. Methodology

To categorise the SUHI, the methodology is adopted as discussed by Barat et al. (2018). Each city and its immediate vicinity is divided into three major categories, i.e. urban (U), suburban (SU), and rural (R), based on the land cover data of the MODIS product MCD12Q1_MAIRS_IGBP.005 of the base

year 2001. The continuous area under the “urban and built-up” class is taken as the urban core; the difference from the urban periphery to suburban periphery and from suburban to the rural periphery is taken as an optimised distance of 2 km or around $+0.018^\circ$ on each side (the water pixels were not considered in zone delineation). This type of three-segment categorisation is widely used in micro-climatic studies (Barat et al. 2018; Chen et al. 2014; Cheval and Dumitrescu 2009; Ding and Shi 2013; Lowry 1977; Meng and Liu 2013). It is worth mentioning that some of the previous studies (Peng et al. 2011; Shastri et al. 2017) quantified SUHI over some of the present stations; however, both of these studies opted for a bi-zonal approach for the sake of simplicity and mass applicability as both were focused on the greater picture of SUHI. In the present study, we have opted for a tri-zonal approach (Barat et al. 2018), because we have fewer stations, so the current research model can incorporate this complexity. As we are interested in smaller towns too, it was also necessary to address the noise in a rural reference due to fast outward growth of the smaller towns. For the purpose by applying the tri-zonal approach, we damped any urban influence in the rural zone using a sub-urban buffer in between the two zones (urban and rural). For the sake of more consistent results we have opted for uniformly averaged temperatures for each zone, in place of taking a single point representative data.

The SUHII for urban to rural difference is calculated (Hoffmann et al. 2012; Oke 1973; Shigeta et al. 2009; Zhang et al. 2014) as follows

$$SUHII_{u-r} = \Delta T_{ur} = T_u - T_r$$

where T_u is urban LST and T_r is rural area LST.

Table 1

Datasets used and their spatial resolution, time period, and sources

| Dataset | Spatial resolution | Time period | Source |
|---|--|---|------------------------|
| IGBP land cover types (MCD12Q1_MAIRS_IGBP.005) | 0.5 km \times 0.5 km | 2001 | Terra-MODIS (MAIRS) |
| Land surface temperature (night and day) (MOD11A2_MAIRS.005) | 1 km \times 1 km | 01/01/2001–31/12/2014 | Terra-MODIS (MAIRS) |
| Wind components at 10 m (u and v) | $0.125^\circ \times 0.125^\circ$ (interpolated further for visualisation) | Different time steps as per the experiment | ERA-Interim |

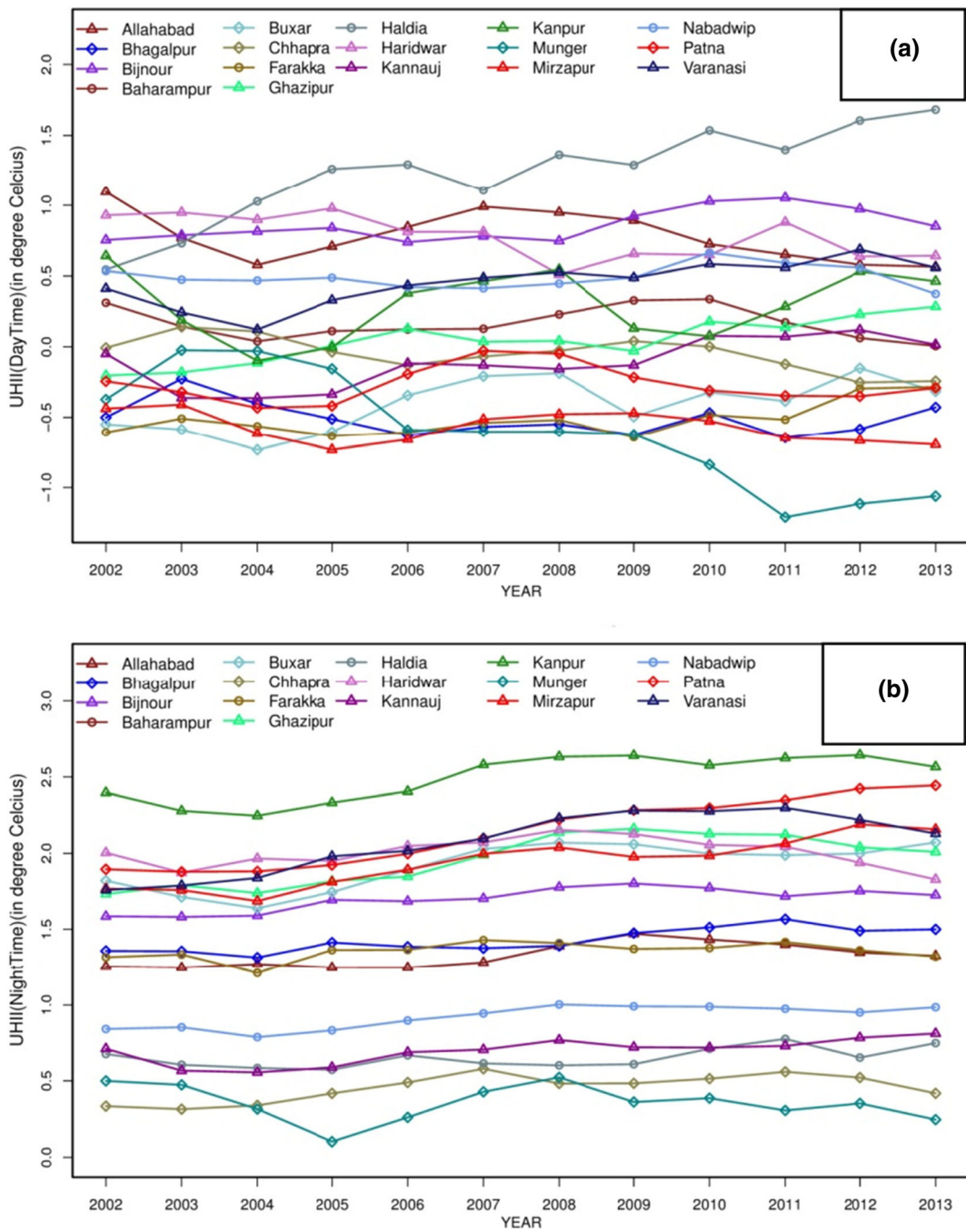


Figure 2
a, b Yearly variations of SUHII for **a** daytime and **b** nighttime over the considered stations

For the diurnal dynamics of SUHII, the diurnal difference of SUHII ($\Delta\text{SUHII}_{\text{diurnal}}$) is calculated as follows

$$\Delta\text{SUHII}_{\text{diurnal}} = \text{SUHII}_{\text{night}} - \text{SUHII}_{\text{day}},$$

where $\text{SUHII}_{\text{night}}$ is nighttime SUHII and $\text{SUHII}_{\text{day}}$ is daytime SUHII.

Table 2

Highest value of SUHII achieved during 2001–2014 over the considered stations

| S. no. | Station | Month | Year | Peak SUHII (°C) |
|--------|------------|----------|------|-----------------|
| 1 | Haridwar | May | 2005 | 3.901 |
| 2 | Bijnour | April | 2008 | 2.69 |
| 3 | Kannauj | April | 2001 | 1.772 |
| 4 | Kanpur | March | 2012 | 4.031 |
| 5 | Allahabad | February | 2013 | 2.186 |
| 6 | Mirzapur | October | 2009 | 3.136 |
| 7 | Varanasi | March | 2010 | 3.695 |
| 8 | Ghazipur | November | 2010 | 3.214 |
| 9 | Buxar | November | 2003 | 3.876 |
| 10 | Chhapra | February | 2014 | 1.589 |
| 11 | Patna | November | 2010 | 4.179 |
| 12 | Munger | October | 2005 | 1.559 |
| 13 | Bhagalpur | December | 2010 | 2.442 |
| 14 | Farakka | December | 2009 | 2.365 |
| 15 | Baharampur | February | 2013 | 2.599 |
| 16 | Nabadwip | October | 2009 | 1.991 |
| 17 | Haldia | May | 2014 | 1.864 |

The non-parametric Mann–Kendall test is used to determine the existence and significance of a trend in the data (Ezber et al. 2007; Kumar et al. 2010; Singh et al. 2008). The Mann–Kendall test checks the null hypothesis of no trend against the alternative hypothesis for the existence of any increasing or decreasing trend. It is defined for N data points as follows:

$$\text{MKTestStatistic}(S) = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sgn}(x_j - x_i),$$

where,

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases}$$

The significance of the Mann–Kendall test is checked at 95% confidence level.

To remove excessive fluctuations in the time series and trend of SUHIIu-r, the moving average technique is applied over the entire period. The wind data is also studied for the top two cities. These cities are selected as they exhibit a well-developed SUHI system for an in-depth multi-parameter (e.g. SUHII and wind flow) analysis.

Figure 3

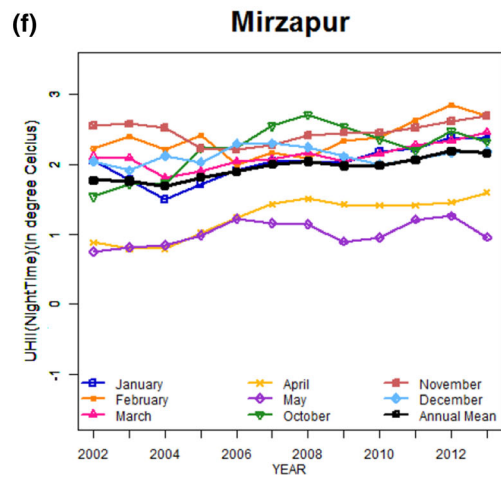
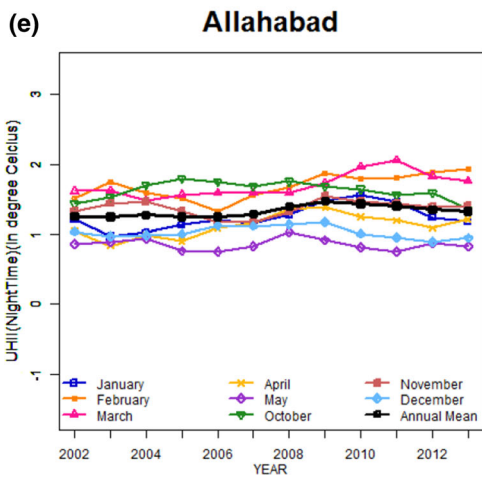
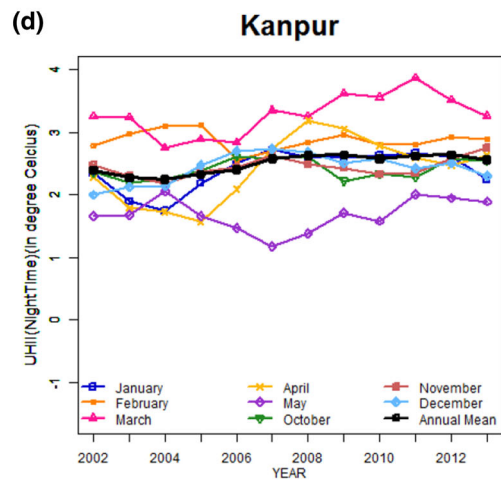
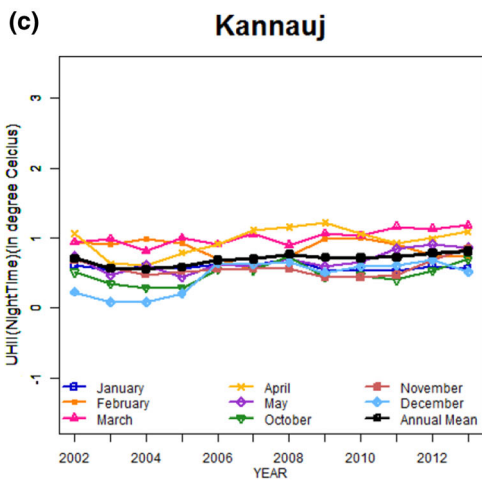
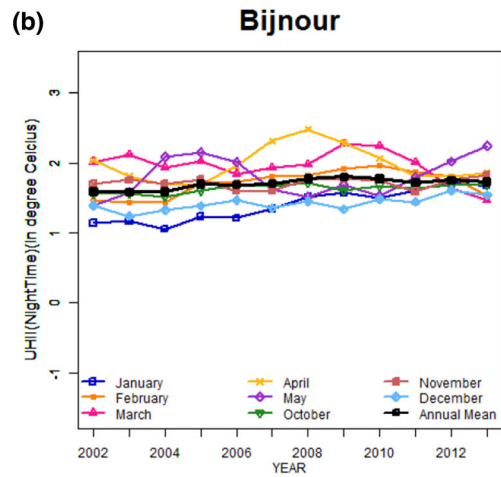
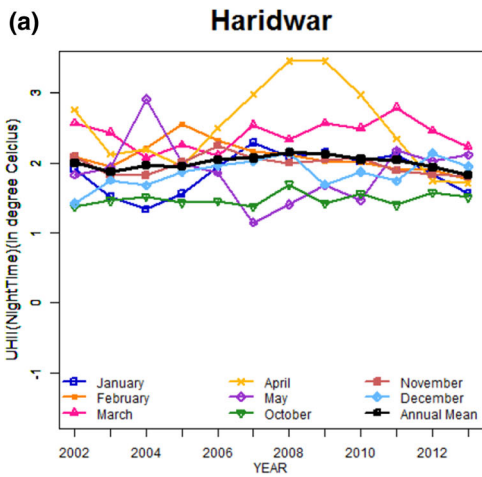
a–q Three-year moving average time series of nighttime SUHII over **a** Haridwar; **b** Bijnour; **c** Kannauj; **d** Kanpur; **e** Allahabad; **f** Mirzapur; **g** Varanasi; **h** Ghazipur; **i** Buxar; **j** Chhapra; **k** Patna; **l** Munger; **m** Bhagalpur; **n** Farakka; **o** Baharampur; **p** Nabadwip; and **q** Haldia, respectively

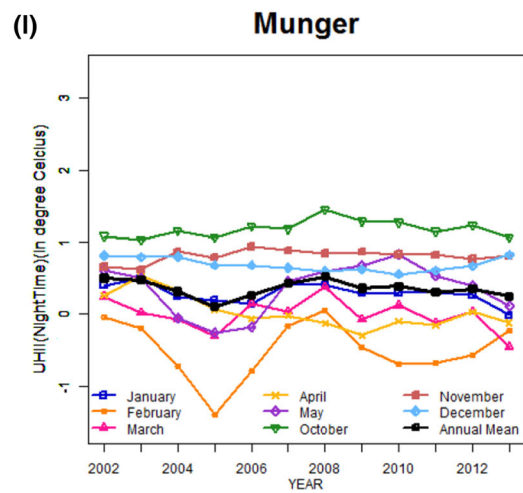
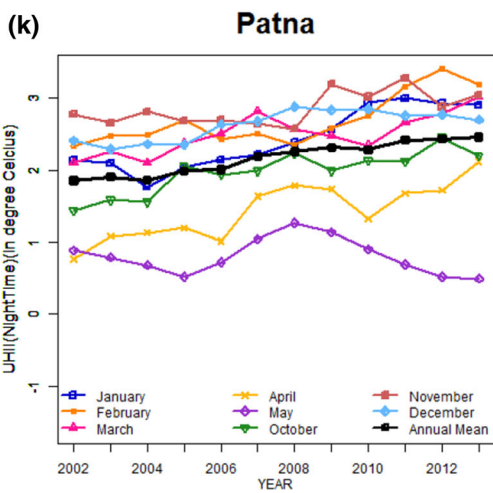
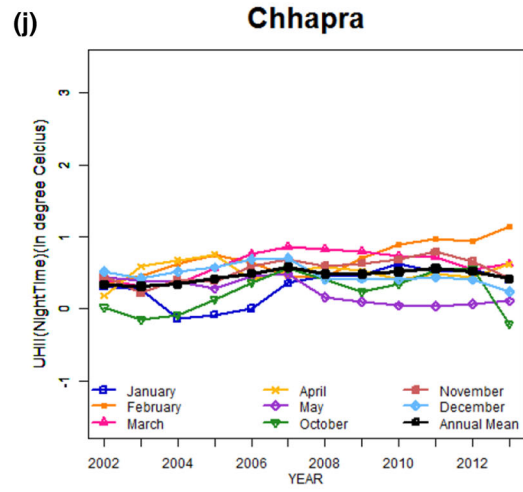
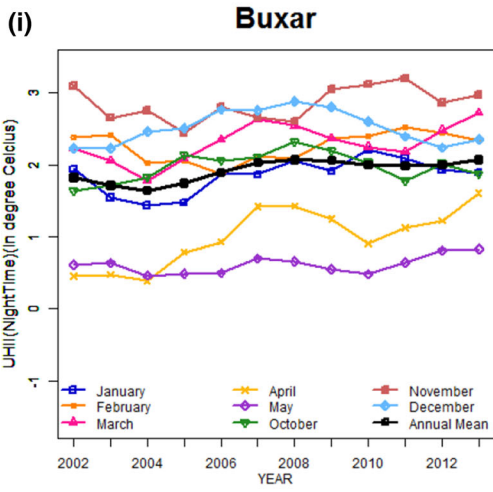
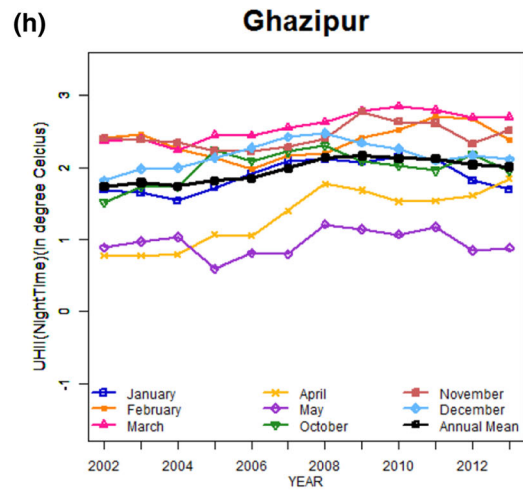
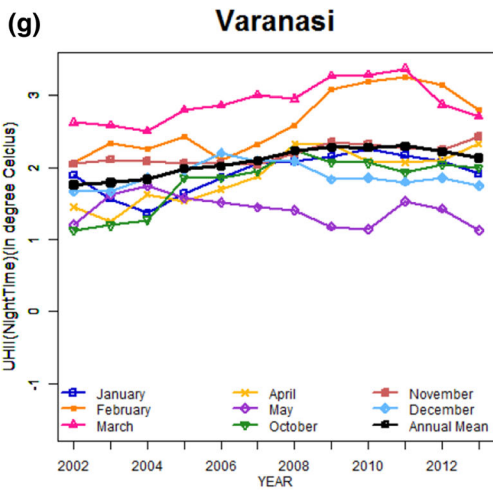
3. Results and Discussion

The dynamics of the SUHI over the riverside cities are studied over different time scales for the similarities and contrasts in their temporal and spatial behaviours in the following sections.

3.1. Temporal Variation of SUHII

The temporal (excluding June–July–August–September) variation of SUHII during day and nighttime is shown as 3-year moving average time series in Fig. 2a, b. The profile shows that stations with more SUHII at night may have less intense UHI during the day, except in few cases. The SUHII for day and night is found to be prominently different for all the stations, and it may be inferred that the station having more SUHII at night may have less intense SUHI during the day, except in a few cases. During nighttime, positive SUHII is observed across all stations, whereas in daytime, negative values are commonly found. This may be because of the thermal inertia phenomenon, as we are using Terra-MODIS data, so the overpass time is in early hours of morning and night (Crosson et al. 2012). Hence, due to the thermal inertia, the artificial structures are found to be cooler (hotter) in daytime (nighttime) than the surroundings, and in the daytime only a few stations show positive SUHII. This may be because of some other localised factors such as industry (Shirani-bidabadi et al. 2019; Mirzaei et al. 2020), and should be further investigated using imagery of even higher spatial resolution in city-specific studies to quantify the actual causes; however, this is beyond the scope of the present study and data products used. From the current analysis, we have found that the majority of stations show low to negative SUHII in daytime recordings. In Fig. 2a, the daytime SUHII shows a range of -1.5 to 1.5 °C, and 50% of the stations





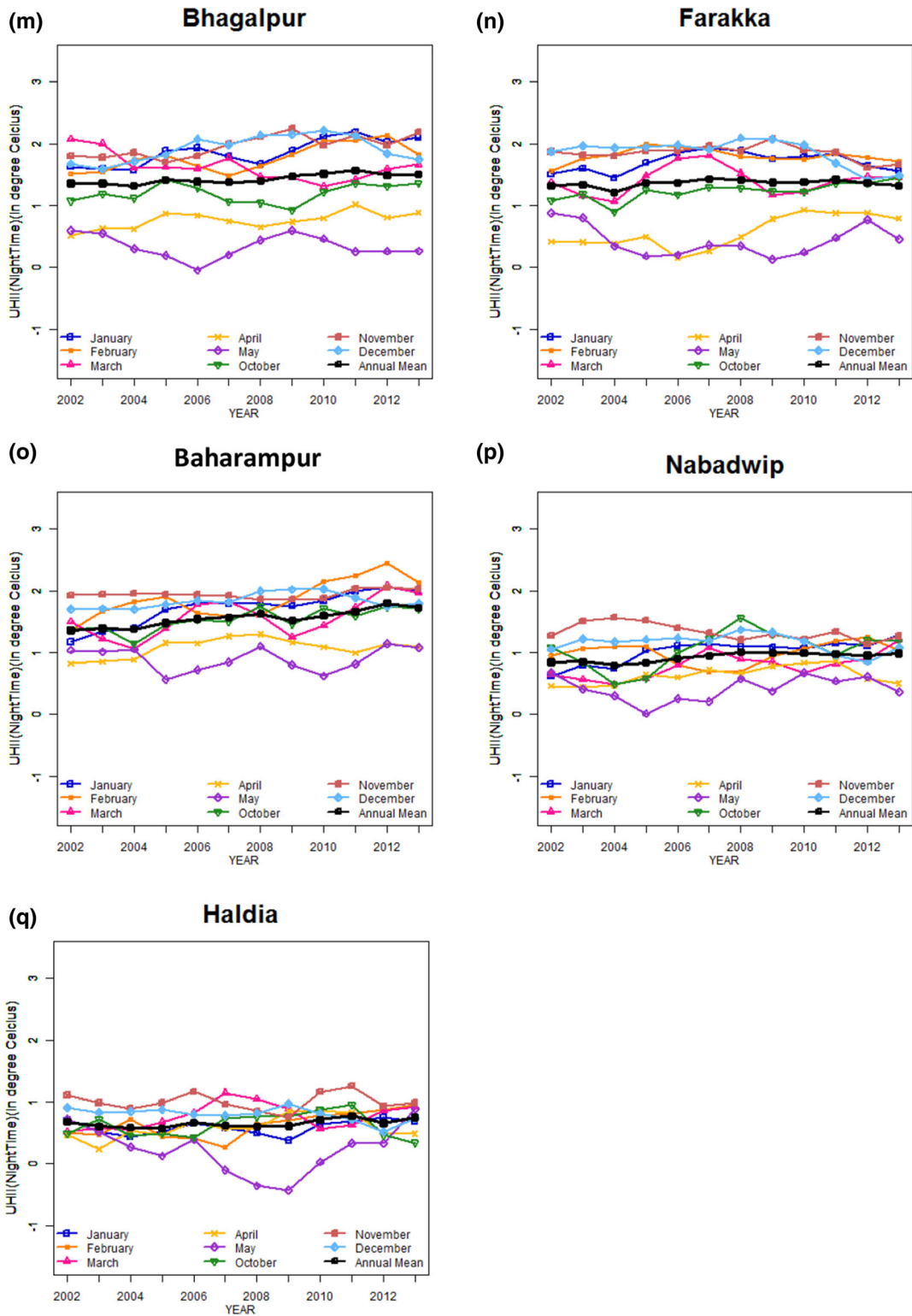


Figure 3 continued

exhibit negative SUHII from 2002 to 2013. The higher value of daytime SUHII is shown by Haldia and lower values are shown by Buxar. An important point is that the negative value of daytime SUHII is from towns/cities of relatively small size and located close to the Ganga River. The probable cause also may be thermal inertia (Carnahan and Larson 1990; Wang et al. 2007) and characteristics of the urban surfaces which act as a heat sink in the daytime (Watson 1982). Estimation of surface urban cool island intensity (SUCII) and its cause seems to be more appropriate for daytime data, instead of treating it as negative SUHII, and for the same reason this can be summarised in a separate study tailored for this aspect. Since nighttime SUHII is more important, it is examined in detail in the present study. Figure 2b reveals that nighttime SUHII varies from 0.2 to 2.5 °C and there has been an increase since 2005 over most of the stations. The nighttime SUHII remains higher over Kanpur compared to other locations, while Munger exhibits quite low values of SUHII. The peak values of SUHII during the considered period are recorded over each station as shown in Table 2. A high value of 4.0 (°C) of SUHII is observed over the cities of Kanpur and Patna, while a low SUHII value of 1.5 (°C) is seen in the small towns of Chhapra and Munger.

Figure 3a–q represents the monthly variation of nighttime SUHII during 2002–2013 over the 17 towns/cities located along the vicinity of the Ganga River. A 3-year moving average analysis is carried out to remove excess fluctuations in the data series. The monthly data analysis also provides some inkling of seasonality of SUHI in the study area. The Gangetic Plain is a very vast area comprising different climate zones, which also causes the onset date of a season to vary across the stations. For example, the meteorological conditions typical of winter season may be picked up in November in some areas, while in other areas, the same can be found later; hence, a study with strict demarcation of seasons delineated by a specific group of months may average out some of the features of this microclimatic phenomenon. It is known that the strong mesoscale phenomenon may damp the effect of microscale meteorology; hence, the seasonal averages will also mask out the important features of SUHII in an inter-

seasonal transition phase when mesoscale phenomenon is weakest. These features will be shadowed by a typical strong mesoscale phenomenon of the season as whole if seasonal averages are considered solely. Even though seasonal analyses have been done in the past, even at global scales (Peng et al. 2011), there lies a risk of trade-off with the peak values, as strong mesoscale phenomena are also reported to form cool islands in place of UHI system (Kumar et al. 2017) in some past studies. Hence we have analysed the data resolving the temporal step finer than seasonal scale for studying the SUHI dynamics, even while discussing its seasonal influences. The towns/cities, namely Bijnour, Kannauj, Allahabad, Chhapra, Baharampur, Nabadwip, and Haldia, show consistency in the monthly variation of nighttime SUHII during the period, while other towns/cities show large fluctuations in SUHII. Such variation may be due to different locations of the towns/cities from the river. Over most of the town/cities (except a few), the nighttime SUHII remains low in April and May. The SUHI appears to be more significant in the starting or ending months of winter over the cities from Allahabad up to Haldia (Fig. 3a–q), on the other hand, in towns/cities located over the upper Gangetic plain, like Haridwar, the peak value of SUHII is recorded in May, whereas April is found to be the warmest in a long time average. Interestingly, SUHI intensity is found to be strong in December over the towns/cities located along the middle to lower Gangetic plains, while it remains weak over the upper Gangetic plain which may be attributed to the winter cold wave phenomenon over the region. This type of contrast in the seasonality of SUHII is previously reported (Bahi et al. 2016; Sakaida et al. 2011; Wilby 2003; Zhou et al. 2014). Thus, it may be summarised that the spring months (February–April) are most conducive for strong SUHI formations over the entire Gangetic plain.

3.2. Trend Analysis of SUHII

It is important to understand the trend in the daytime and nighttime SUHII, as well as the diurnal ranges of SUHII (Sun et al. 2006), since it impacts the health and comfort (Papanastasiou et al. 2010) of

Table 3

Trend (Mann–Kendall test at 95% confidence level) in daytime SUHII(D), nighttime SUHII(N) and diurnal range of SUHII (DRU) (night SUHII–day SUHII) (Y = yes)

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Oct | | Nov | | Dec | | Annual Mean | | | |
|------------|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|-------------|---|-----|---|
| | D | N | D | N | D | N | D | N | D | N | D | N | D | N | D | N | D | N | DRU | |
| Haridwar | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Bijnour | – | Y | – | Y | – | – | Y | – | Y | – | – | Y | Y | – | – | Y | Y | Y | – | – |
| Kannauj | – | – | – | – | Y | Y | Y | – | Y | Y | – | – | – | – | – | Y | Y | Y | – | – |
| Kanpur | Y | Y | – | – | – | Y | – | – | – | – | – | Y | – | – | – | – | – | Y | – | – |
| Allahabad | – | Y | – | Y | – | Y | – | Y | – | – | Y | – | – | – | – | – | – | Y | Y | Y |
| Mirzapur | – | Y | – | Y | – | Y | – | Y | – | Y | – | Y | – | – | – | – | – | – | Y | Y |
| Varanasi | Y | Y | – | Y | Y | Y | Y | Y | – | – | – | Y | – | Y | – | – | Y | Y | – | – |
| Ghazipur | Y | – | – | – | Y | Y | – | Y | Y | – | – | – | – | – | – | – | – | Y | Y | – |
| Buxar | – | – | Y | – | Y | Y | – | Y | Y | Y | Y | – | – | – | – | – | Y | Y | – | – |
| Chhapra | Y | Y | – | Y | – | – | – | – | – | – | – | – | – | Y | – | – | – | Y | Y | Y |
| Patna | – | Y | – | Y | – | Y | – | Y | Y | – | – | Y | – | – | – | Y | – | Y | Y | Y |
| Munger | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | Y |
| Bhagalpur | – | Y | – | Y | – | – | – | Y | – | – | – | – | – | Y | – | Y | – | Y | Y | Y |
| Farakka | Y | – | – | – | – | – | – | Y | – | – | Y | Y | Y | – | – | – | Y | – | – | – |
| Baharampur | – | Y | – | Y | – | Y | – | – | – | – | – | Y | – | – | – | Y | – | Y | Y | Y |
| Nabadwip | – | Y | Y | – | – | Y | – | Y | – | – | Y | – | Y | – | – | – | – | Y | Y | Y |
| Haldia | Y | – | Y | Y | Y | Y | Y | – | – | – | Y | – | Y | – | – | – | Y | – | – | – |

the residents. Therefore, the daytime and nighttime SUHII trends and the diurnal range of SUHII are examined at the 95% confidence level by the Mann–Kendall test, as shown in Table 3. The increasing trend in daytime SUHII, especially from January to May, is observed at fewer stations, which is possibly due to factors such as diminishing urban greenery, which may in turn reduce the cooling effects over the urban core in the daytime (Peng et al. 2011). In summer, large-scale phenomena such as heatwaves also may be a contributor to the daytime SUHI. The extreme heat can easily breach the threshold of thermal inertia, which together with the loss of cooling with diminishing urban greenery can cause the urban core to become hotter more quickly than its rural counterpart. Thus cooler urban cores in the daytime are found to show an increasing SUHII trend (diminishing SUCII trend) under temporal trend analysis. However, if the mesoscale phenomenon becomes more intense, it may cause temperature homogeneity by damping the microscale effects in some cases. The significant increasing trend in the nighttime SUHII is observed over all of the stations, especially from January to April. Over a few stations, nighttime UHII is also observed in October and December. On an annual scale, almost all stations

attained a significant increasing trend. In the diurnal SUHII ranges, the majority of the stations, namely Allahabad, Mirzapur, Chhapra, Patna, Munger, Bhagalpur, Baharampur, and Nabadwip, over the middle and lower Gangetic plain show a significant increasing trend in the annual mean diurnal range of SUHII (Table 3). This is mainly because of the increase in nighttime SUHII. Other major stations such as Kanpur also show an increase in the nighttime SUHII, but there is a large fluctuation in the daytime; therefore, no significant trend in the diurnal range is found.

3.3. Spatial Variation of SUHII

The spatial distribution of the highest value of nighttime SUHII achieved in a particular month and year over the stations (Table 2) is shown in Fig. 4a–q. The maximum value nearing 10 °C is seen as the difference between highest value in the urban zone and lowest value in the rural zone (Fig. 4a–q). The cities of Patna, Varanasi, Farakka, Haldia, Allahabad, and Kanpur show peak values. SUHII up to 15 °C have been also reported in other parts of the world (Bahi et al. 2016; Lokoshchenko 2014). The extreme value of SUHII within a city may be linked with

intense urbanisation within the city and industrialisation in and around (only in area representing non-rural pixels) stations. The highest recorded values of SUHII during 2001–2014 are shown in Table 2. Densely built cities such as Patna and Kanpur are at the top of the list of highest SUHII. This indicates that these densely built cities possess their own microclimate over their built-up area and store heat energy in a great amount which is released during the nighttime along with other anthropogenic heat emissions (Peng et al. 2011).

3.4. Influence of the Riverfront on the SUHI Intensity

To understand the influence of the riverfront on the SUHII, the two cities with the highest SUHII, namely Kanpur and Patna, are selected, and the riverfronts are identified using MODIS-IGBP data (Fig. 5a, b). In Fig. 5a, the city of Kanpur has one riverfront of the Ganga, whereas the city of Patna (Fig. 5b) has two rivers, the Ganga and the Sone, in its vicinity. To understand the influence of wind in the formation of SUHI on riverside cities, the mean value of SUHII for each month is taken and the month with the highest (mMxU) and lowest (mMnU) mean SUHI intensity is considered for both cities. Then the entire time series for each of these months (mMxU and mMnU) is analysed to find the event registering maximum (TUm_x) and minimum (TUm_n) magnitude of SUHII within each of these months. Thus, four cases for each city (as shown in Table 4), namely (a) TUm_x in mMxU, (b) TUm_n in mMxU, (c) TUm_x in mMnU and (d) TUm_n in mMnU, are considered. The mesoscale wind is assumed to be homogenous over the study area, so for better clarity, the $0.125^\circ \times 0.125^\circ$ (~ 12 km × 12 km) resolution wind data of ERA-Interim (Dee et al. 2011) are bilinearly interpolated to approximately 3 km × 3 km resolution. Figure 6a, h reveals the influence of wind on SUHII in a riverside city. The wind data are plotted over the MODIS derived IGBP LULC data.

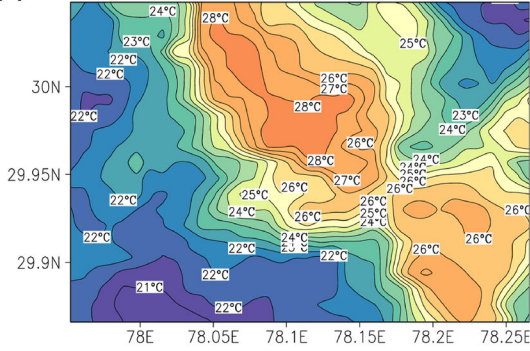
The city of Kanpur (Fig. 6e, h) shows that the wind blows towards the city from the river. The SUHII decreases in the peak month (mMxU) of March and in the lean month (mMnU) of May. The reversal of wind direction increases SUHII (also irrespective of the month). This shows that the river

Figure 4

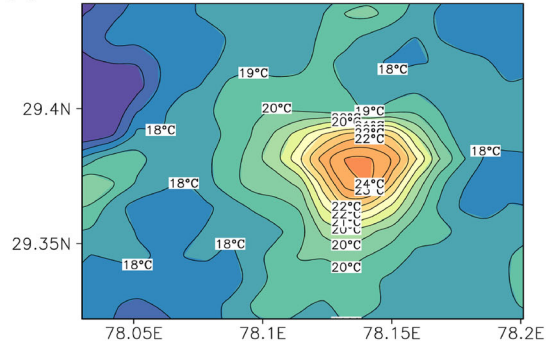
a, q Spatial distribution of highest value of nighttime SUHII (contour lines showing LST, while color bar depicting SUHII) as shown in Table 2 over **a** Haridwar; **b** Bijnour; **c** Kannauj; **d** Kanpur; **e** Allahabad; **f** Mirzapur; **g** Varanasi; **h** Ghazipur; **i** Buxar; **j** Chhapra; **k** Patna; **l** Munger; **m** Bhagalpur; **n** Farakka; **o** Baharampur; **p** Nabadwip; and **q** Haldia, respectively

may induce a cooling effect over the city of Kanpur. Over the city of Patna (Fig. 6a, d), SUHII appears to be influenced by complex land cover (LC) and wind speed and direction, rather than the simple river breeze. The SUHII in (mMnU) May is found to be influenced by the wind velocity, not by the direction. In mMxU (November), the maximum SUHII is observed when the wind blows from the direction of another urban core of a nearby town to Patna, and thus the wind is warmed before reaching Patna and the city is deprived of cooling relief. On the other hand, when the wind travels over agricultural fields and rural landscapes before entering Patna, the city experiences comparatively cooler conditions. Moreover, due to the wind direction, the heat of the city itself is also directed towards some extremely heated zones (Fig. 4k), whereas in both minimum cases these hotspots receive a cooling effect from nearby landscapes. A similar finding was reported in studies across different cities by Murakawa et al. (1991), Maitelli and Wright (1996), Webb and Zhang (1997), Kim et al. (2008), Hathway and Sharples (2012), Unger (1996) and Cammilloni and Barrucand (2012). In their field experiment over Hiroshima, Japan, Murakawa et al. (1991) reported that the rivers significantly reduce temperature by providing cooling effects up to 5 °C; moreover, the surface temperatures are also found to be proportional to their air temperature recordings. Similar findings of cooling effects by the river were also reported by Hathway and Sharples (2012) for the city of Sheffield, UK. In an experiment on Hiroshima (Murakawa et al. 1991), it was noted that the wind velocity and direction also influenced the UHI of the riverside city. In our present study, we found similar results also for the Indian context. Furthermore, the Ganges is a fairly wide river, and the cities selected have some of their densely built areas at the riverside; hence a

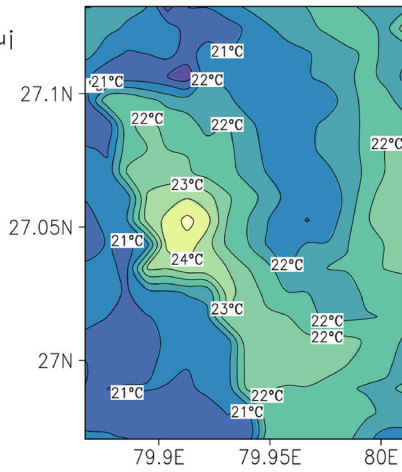
(a) Haridwar



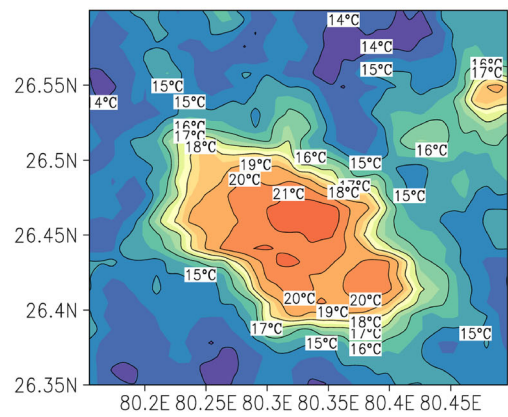
(b) Bijnour



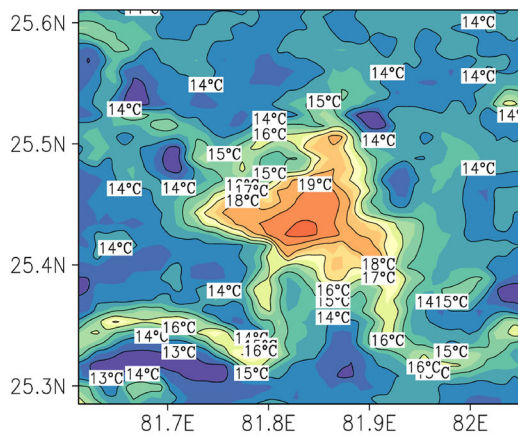
(c) Kannauj



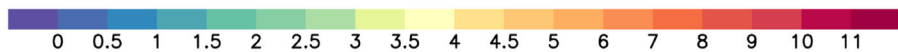
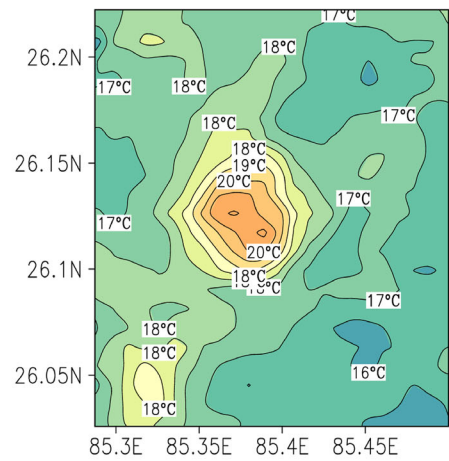
(d) Kanpur



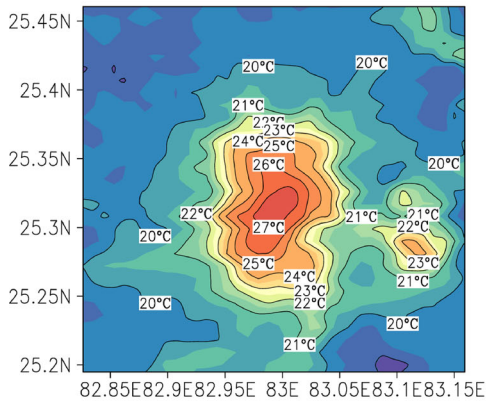
(e) Allahabad



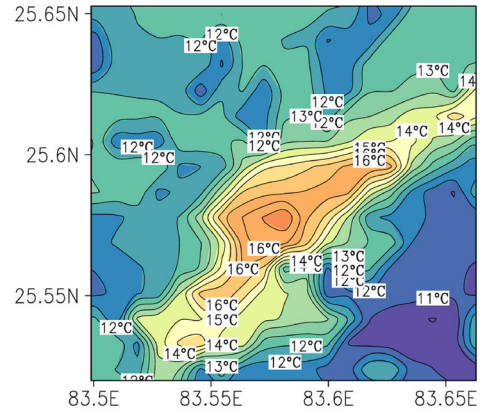
(f) Mirzapur



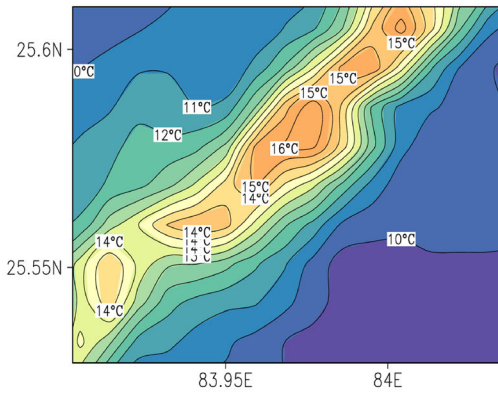
(g) Varanasi



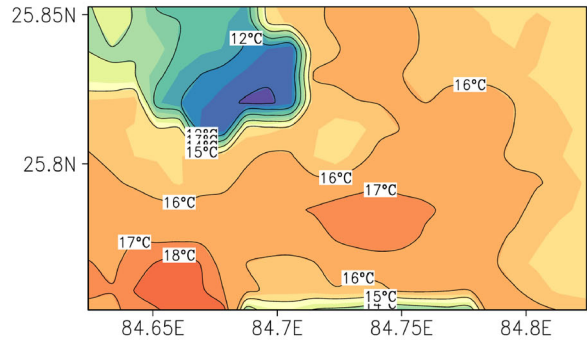
(h) Ghazipur



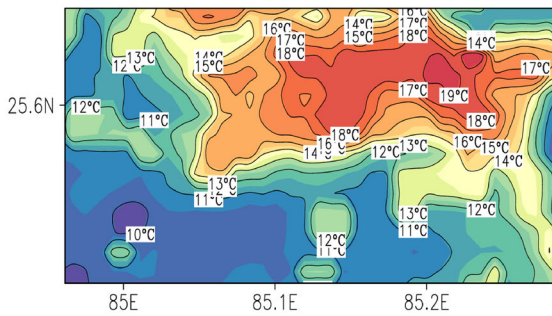
(i) Buxar



(j) Chhapra



(k) Patna



(l) Munger

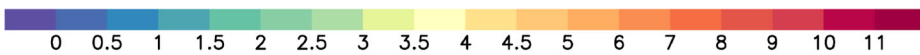
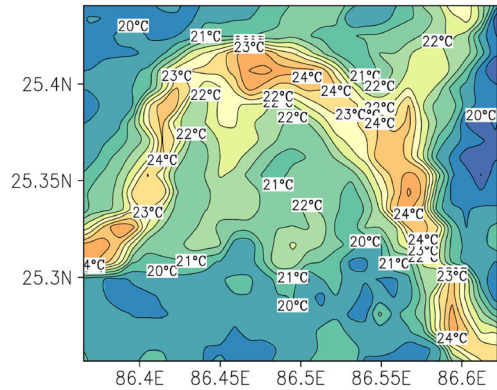


Figure 4 continued

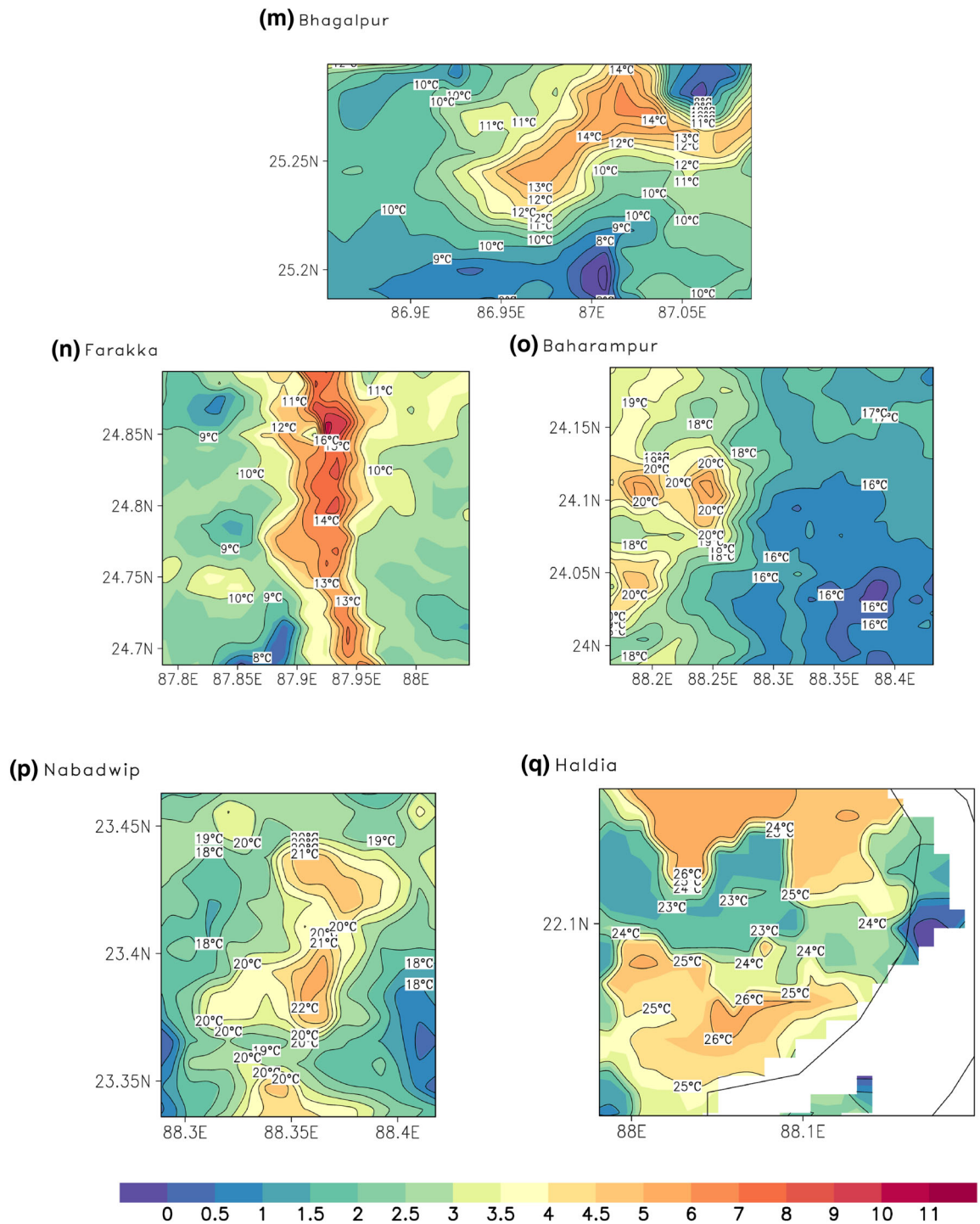
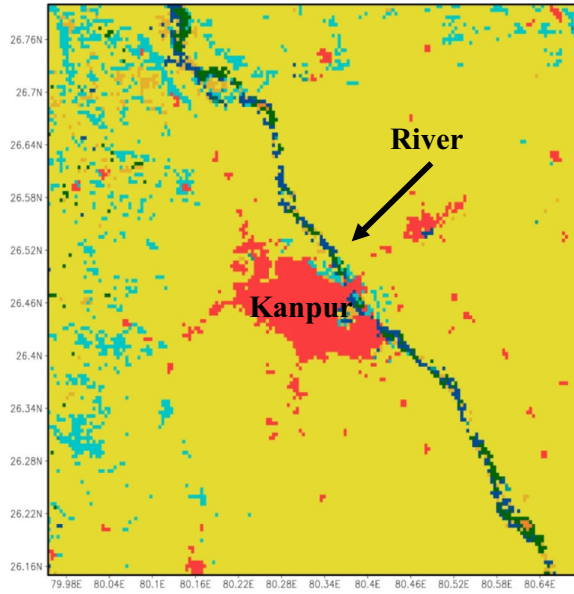


Figure 4 continued

substantial cooling effect of the river reaches some of the core heat zones, and this mitigating effect cannot

be ruled out. At the same time, winds also play a great role in dissipating the heat for the entire city

(a) Kanpur



(b) Patna

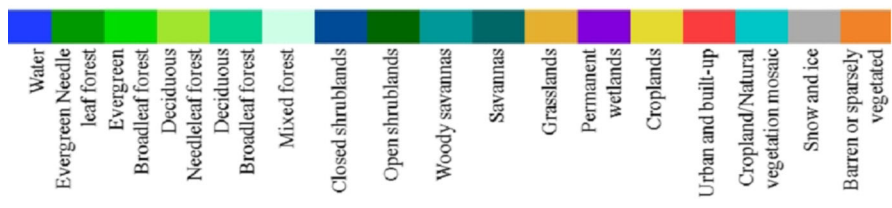
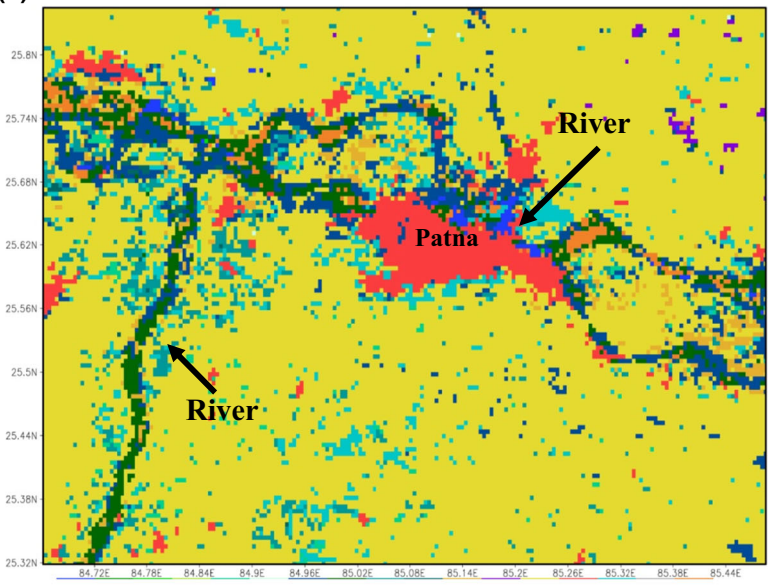


Figure 5
a, b Land use/land cover (LULC) pattern over the city of **a** Kanpur and **b** Patna, respectively

Table 4

Minimum (T_{Umn}) and maximum (T_{Umx}) value of nighttime SUHII in mean peak (mMxU) and minimum (mMnU) months (2001–14) for cities of Kanpur and Patna

| Stations | mMxU (mean SUHII value) ^a | mMnU (mean SUHII) ^a | T _{Umx} in mMxU Event occurrence [magnitude] ^a {percentage departure from mean value of the month} | T _{Umn} in mMxU Event occurrence [magnitude] ^a {percentage departure from mean value of the month} | T _{Umx} in mMnU Event occurrence [magnitude] ^a {percentage departure from mean value of the month} | T _{Umn} in mMnU Event occurrence [magnitude] ^a {percentage departure from mean value of the month} |
|-------------|--|--------------------------------------|---|---|---|---|
| Kanpur | March (3.26 °C) | May | (1.64 °C) | March 2012 [4.03 °C] {+23.61%} | March 2005 [2.25 °C] {-30.98%} | May 2012 [2.28 °C] {+39.02%} |
| May 2006 | [0.88 °C] | | {-46.34%} | | | |
| Patna | November (2.83 °C) | May | (0.79 °C) | November 2010 [4.18 °C] {+47.70%} | November 2011 [2.22 °C] {-21.55%} | May 2008 [1.5 °C] {+89.87%} |
| May 2013 | [0.35 °C] {-55.7%} | | | | | |

^aRounded up to two decimal places

area considered. In general, we can conclude that the winds play a very important role in SUHI formation; if flowing from the riverside, they even act as a cooling unit, resulting in mitigation of the SUHI by cool moist air.

4. Conclusions

The phenomenon of SUHI is discussed over towns/cities along the Ganga River in the northern and east-central parts of India. Each urban entity has a great extent of heterogeneity in their size, morphology, residing population and density of urban cover. Each zone, namely, urban (U), suburban (SU), and rural (R), exhibited a unique temperature profile independent of each other and dependent on prevailing local weather conditions.

It is found that stations with greater SUHII (0.2–2.5 °C) in the nighttime, which increased sharply after 2005, are marked by comparatively less intense SUHI (-1.5 to 1.5 °C) in the daytime, and a large number of stations show negative SUHII in the daytime. The monthly variations in SUHII are mostly influenced by the geographical locations of towns/cities. Many of them show a low value of nighttime SUHII in April and May. The SUHII appears to be more significant in the winter months over the cities

from Allahabad to Haldia. The SUHI intensity remains strong (weak) in December over the stations of the middle to lower Gangetic plains (upper Gangetic plain). The Mann–Kendall test, at a 95% confidence level, shows a non-increasing (significant) trend in the daytime (nighttime) for most of the stations, with some exceptions. On the annual scale, almost all stations attained a significant increasing trend. In the diurnal SUHII ranges, many stations over the middle and lower Gangetic plain show a significant increasing trend. The spatial distribution of SUHII over several stations reflects peak values nearing 10 °C. The highest recorded values of SUHII during 2001–2014 are observed in Patna and Kanpur, and therefore the effect of wind over them is analysed. Over Kanpur, the wind blows towards (away from) the city from (towards) the river, and SUHII decreases (increases), which appears to be the river-induced cooling effect over the city of Kanpur. Over the city of Patna, the SUHII appears to be influenced by complex land cover (LC) and wind speed and direction, rather than the simple river breeze. The SUHII in May is influenced by the wind velocity (not by the direction). In November, the maximum SUHII is observed when the wind blows towards the city of Patna carrying heat with it, while the wind travelling over agricultural fields and rural landscapes before entering Patna has a comparative cooling effect.

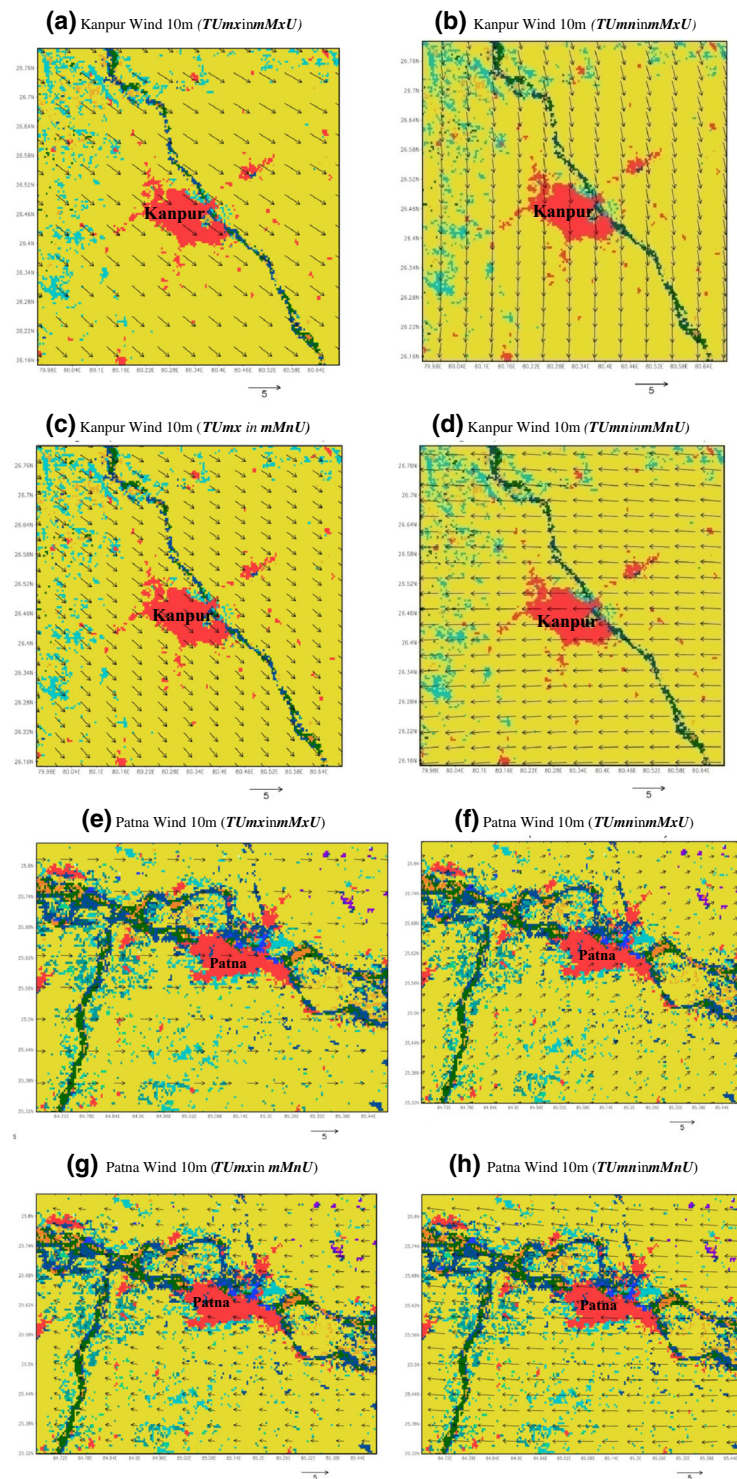


Figure 6

a, h Mesoscale wind circulation and LULC pattern in different cases of SUHII (as given in Table 4) over the riverside cities of Kanpur (**a, d**) and Patna (**e, h**), respectively, color scale used as per Fig. 5

From the present findings we can say that there is a need for further studies with respect to microscale circulation patterns to track complex interactions between the river and UHI. At present this can be achieved only through field studies or very high-resolution numerical simulations. It has been found that smaller cities may also have a strong risk of SUHI. Hence, future studies should examine not only large cities but also smaller towns that warrant the special attention of the scientific community. It may be concluded that because the SUHI significantly influences the unique thermal behaviour of a town/city, customised green town planning and environmentally sound development tailored for each city is much needed in the future, taking the influence of rivers and urban greenery into account.

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Author contributions AB conducted the experiments, framed the methods and codes, plotted the illustrations and graphs, and acted as lead author of the manuscript. PPS framed the research problem, authored and refined the manuscript and supervised

the entire research. SK contributed in obtaining and downloading data, graphics handling including graphics post-processing, and refined the manuscript. PK and AKS helped in code refinement for data extraction and R Coding for plots.

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Availability of data and material

Raw data requested from the concerned sources/authority can only be used for research purposes, and the original files cannot be redistributed. The data used in charts may be provided only on special request, if in accordance with the journal's policy and deemed to be necessary.

Code availability

Not Applicable. The research protocol involves the use of both GUI and CLI software.

Declarations

Conflict of interest The authors hereby declare that there is no conflict of interest/competing interests.

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