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Spatial and temporal distributions of radiation balance components over Delhi

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Abstract: The study area Delhi was divided according to land-use and the effect of urbanization on the spatial and temporal variations. Incoming shortwave (K↓), albedo (α), incoming longwave (L↓), outgoing longwave (L↑) and net radiation (Q*) were individually studied at five representative sites (Industrial, Commercial, Residential, Rural and Forest), for the winter and summer seasons. It was found that K↓ was higher in the rural areas with clearer skies and unpolluted atmosphere compared to congested and polluted urban areas. L↓ was higher in the industrial and commercial areas compared to their rural counterparts. Concrete surfaces of urban areas showed lower L↑ unlike the moist rural surfaces. Industrial and commercial areas showed lower α, whereas Q* was higher compared to other areas. However, on an average value of radiation balance components was more than double during summer as compared to winter.

Key words: radiation balance, spatial, temporal, land-use, urbanization

1. Introduction

With the increasing knowledge and scientific understanding of the fundamentals of the tropical urban climate, the study of the radiation balance on the earth - atmosphere interface draws a special attention, as few of the numerous studies of the urban climatic conditions so far have really focused on the radiation budgets *(Padmanabhamurty, 1994, 1999)*. The balance of radiation at the surface represents the most basic accounting of flux partitioning necessary to establish a sound physical understanding of the resulting thermal and moisture climates *(Oke, 1992)*.

Lack of enough focus on the radiation budget of cities could be a result of the difficulty in summing the average radiation characteristics, for the different land-use pattern of the urban complexes, which react to incoming solar radiation in different ways because of their varying reflection, refraction, scattering, absorbing, emission and albedo characteristics *(Adebayo, 1990).*

Urbanization and industrialization associated with modern construction techniques and materials, atmospheric pollution, 'heat & Humidity Island' etc. produce radical changes in the nature of surface and atmospheric properties of a region. These result in tremendous land cover change dynamics along with subsequent change in the components of the surface radiation balance. Urban weather anomalies are directly attributable to anthropogenic activities. The heat released due to various human activities supplements the natural sources of heat in the urban systems, which leads to change in radiation balance components.

This modification may be caused by:

- Direct effect of pollution e.g. Suspended Particulate Matter (SPM) in reducing $K\downarrow$.
- High level of Pollution and an increased urban temperature lead to an increase in $L\downarrow$.
- Low emissivity of city surface (concrete) compared to surrounding city side leads to a lower urban value of $L\uparrow$, for a similar surface temperature.
- Decrease in surface albedo (α) of the urban (Industrial, Commercial) area leads to absorption of more energy.
- Higher net radiation (Q^*) in the urban (Industrial, Commercial) centers due to reduction in albedo, increased $L\downarrow$ and reduction in the rate of diffusion of Q^* in the pockets of urban canyons *(Adebayo, 1990).*

Several studies have been conducted on the aspects of radiation balance over the mid latitude regions to assess the urbanization *(Peterson and Stoffel, 1980). Padmanabhamurty and Subrahmanyam (1964)* conducted experiments and observed the net and solar radiation at Waltiar and examined their relation. *Chacko et al. (1968)* compiled the surface radiation balance measurements at Poona, Calcutta and Delhi during International Quiet Solar Year (IQSY). *Idso et al. (1969)* observed various components of radiation balances over surfaces of short grass and bare soil at St. Paul Minnesota. *Trnka et al. (2005)* used seven methods for estimating daily global solar radiation and tested in the Central Europe case study area (Lowlands of Austria and Czech Republic) using several statistical relations. *Kelkar and Pradhan (1977)* presented the results of measurements of solar radiation and infrared fluxes in the upward and downward direction over a 20 m^2 evaporimeter tank. *Mani et al. (1980, 1981)* carried out the climatic study of radiation in India based on sunshine records and later on radiation instruments' data. *Mani and Rangrajan (1982)* studied the radiation climate of India for the entire year, which gives the heat balance at the surface. Considering the importance of radiation studies for the World Climate Programme (WCP) of World Meteorological Organization (WMO), a climatic study of warming/cooling of the atmospheric column by solar and terrestrial radiations over India in different seasons has been undertaken by Agnihotri and *Singh (1987)*. *Houshui (1980)* determined the global radiation from terrestrial radiation and the relative duration of sunshine to compute the radiation balance in tropics at Hainan Island in China. *Arnfield (1982)* used the radiation model for radiant flux studies. *Adebayo (1990)* in an urban area of Ibadan, and *Padmanabhamurty (1999)* in Delhi city conducted radiation balance studies, whereas *Jegede (1997)* estimated net radiation from atmospheric temperature for diffusion modeling application in the tropical areas. *Matazarakis (1999)* used *'RayMan'* radiation model to compute the radiation balance for biometeorological application in urban regions. *Rimoczi-Paal (2005)* used the digital images of METEOSAT satellite and radiosonde observation data for the modeling studies of radiation balance components over the territory of Hungary. *Al-Riahi et al. (2003)* measured the net radiation and its components in semi-arid climate of Baghdad simultaneously. The air temperature and relative humidity have also been measured in order to relate them with radiation balance components in different seasons. *Hollmann et al. (2002)* studied the surface shortwave radiation using the Li-Leighton algorithm. For these purposes data from the well calibrated Scanner for Radiation Budget (SCARAB) is used. *Bisht et al. (2005)* used Terra-MODIS data to estimate an instantaneous net radiation. In the suburban areas of Mexico City (Texcoco), day time net radiation has been forecasted using the simple parameterization scheme in which only global solar radiation and air temperature have been used as input parameter *(Sozzi et al. 1999)*.

Very little work have been done on the spatial and temporal distributions of radiation balance components over the tropical cities according to different land-use patterns comprising industrial commercial, residential, rural and forest areas. Therefore, a study was undertaken to find the effect of urbanization on each component of the radiation balance equation.

2. Materials and methods

Experiments were conducted through mobile surveys covering the entire length and breadth of the city of Delhi on different days of experiments during winter and summer seasons, respectively. Observations are made covering the total of 40 stations during winter (October to February) and 23 during summer (April to June) for the years 1997–98 over Delhi. Details of the experimental campaign, which was part of a project sponsored by the Ministry of Science and Technology, Govt. of India (No. ES/048/319/95), have been described by *Padmanabhamurty (1999), Das (2002), Das and Padmanabhamurty (2007)*.

2.1. Radiation balance

The balance of net radiation close to the earth surface is represented by the algebraic sum of both the downward and upward components of shortwave and longwave radiation.

In the algebraic form the radiation balance equation is given as:

$$Q^* = K\downarrow (1-\alpha) + L\downarrow - L\uparrow,$$

where,
Q^* = Net radiation
$K\downarrow$ = Incoming shortwave radiation (Kdn)
α = Albedo
$L\downarrow$ = Incoming longwave radiation (Ldn)
$L\uparrow$ = Outgoing longwave radiation (Lup)

Net radiation (Q^*) was measured with the help of Net radiometer (Swissteco, Type S-1) with two replaceable plastic domes and a collapsible stand, which can be adjusted to desired height. The spectral range was 0.3 to 100 μm with direct output voltage of 1 mV corresponding to 66.6 W/m^2 with an accuracy of 5%. Incoming short wave radiation (K↓) was measured with the Eppley precision Pyranometer (spectral range 0.28 to 2.8 μm) with an accuracy of 2–5%. The output voltage is 1 mV, corresponding to 33.6 W/m^2. Albedo is obtained as a percentage ratio of the reflected radiation obtained by an inverted Pyranometer to that of the upward facing Pyranometer. Longwave radiation from the ground (upward) and the sky (downward) are obtained by exposing one side of the Net Radiometer and hermetically sealing the other side. Exposing upward gives the sky radiation (L↓) and by inversion the ground radiation (L↑) is measured.

Net radiometer and Pyranometer were erected at the height of 1.5 m from ground on a flat surface. Precautions were taken in installing the instruments to avoid the shadows of trees, buildings and other installations. Hourly observations were taken and later on averaged for daily basis and processed, following *Hakansson and Roberts (1995)* and *Backstrom (2006)*. Details of the instruments calibration procedures are given in *Das and Padmanabhamurty (2007)*.

3. Results and discussion

3.1. Spatial distribution of radiation balance components (24-hourly totals) over Delhi

3.1.1. Incoming shortwave radiation (K↓)

Several distinct pockets of high and low K↓ were observed during winter 1997–98 (Fig. 1). Multiple reflections by the buildings caused an increase in K↓ at Connaught Place, CGO Complex, Chanakyapuri, Pragatimaidan, Shahdara, Nangloi, Panjabibag, Anandparvat and Shaktinagar compared to other sites. Low K↓ was found in the areas such as Karolbagh, Chandnichowk, Naraina, Mayapuri, Janakpuri, Tilaknagar and Okhla, most of which fall in the industrial and commercial areas. This depletion of K↓ may be due to narrow urban canyons and scattering back to atmosphere by particulate matter present in these areas. Lower K↓ was found also in the rural and some vegetated areas like Palam, Deerpark and Budhagarden. This can be attributed to the circulation/transportation of particulate pollutants from nearby commercial and industrial areas, which drastically scattered and reduced the value of K↓. In this season, it is found that there is wide spatial variation of K↓. The open areas and industrial parks received more K↓ compared to densely built-up areas.

However, the spatial distribution of K↓ was quite different during summer 1998 compared to winter. From the isopleths (Fig. 2), it is evident that sites like Rohini, Sadipur, Naraina, Mayapuri, Janakpuri showed higher K↓ compared to the locations like Indiagate, CGO Complex, Nehru Place, Bhikajicama and Badarpur. Higher K↓ in these regions may be attributed to reflections by the concrete buildings. That is, multiple reflections in urban complexes diffuse shortwave radiation, which enhances K↓. Similarly, rural areas of Jawaharlal Nehru University (JNU), Saket received higher K↓ without depletion owing to clearer skies and unpolluted atmosphere compared to congested and built-up sites of commercial (Nehru Place), Industrial (Badarpur) and residential (CGO Complex) areas.

3.1.2. Incoming longwave radiation (L↓)

Spatial distribution of L↓ showed several pockets with high and low L↓ spread over the entire city during winter 1997–98. Isopleths (Fig. 3) clearly depict that industrial and commercial areas of Badarpur, Shahdara, Shaktinagar, and Anandparvat and the residential sites viz. Pragatimaidan, Panjabibag and Chanakyapuri showed higher L↓ due to polluted atmosphere and higher air temperature respectively. The peripheral and rural areas, city parks and vegetated areas showed relatively lower L↓, due to less polluted atmosphere and cooler air temperature than densely populated and congested built-up areas. However, rural areas like JNU and Nangloi showed higher L↓, which could be attributed to the transport of pollutants from neighbouring areas, enhancing L↓.

It is evident from the contour map (Fig. 4) that during summer 1998, areas viz. CGO Complex, Saket and Rohini showed lower L↓ compared to other parts of the city. Industrial areas of Badarpur, Naraina, Mayapuri and commercial areas of Shahdara exhibited higher L↓. This is due to the solar warming of overlying pollutant layers, enhancing the temperature in these areas. But surprisingly, L↓ was even higher in the rural (JNU) and

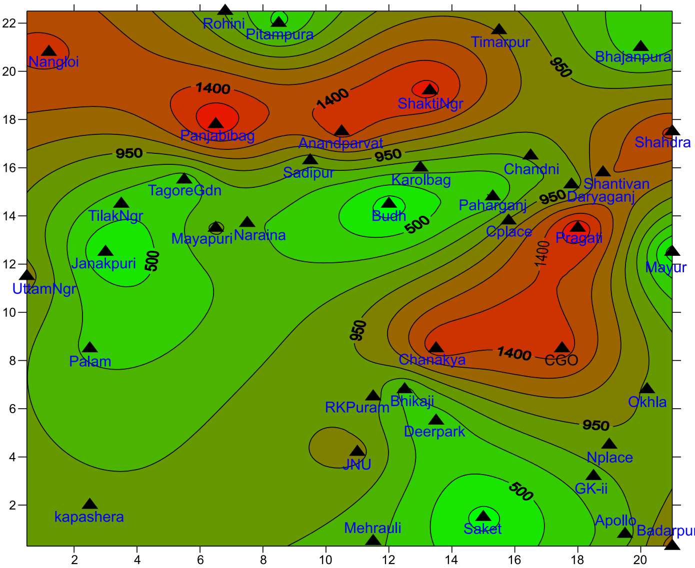

Fig. 1. Isopleth map of K↓ (W/m^2) over Delhi, winter 1997–98.

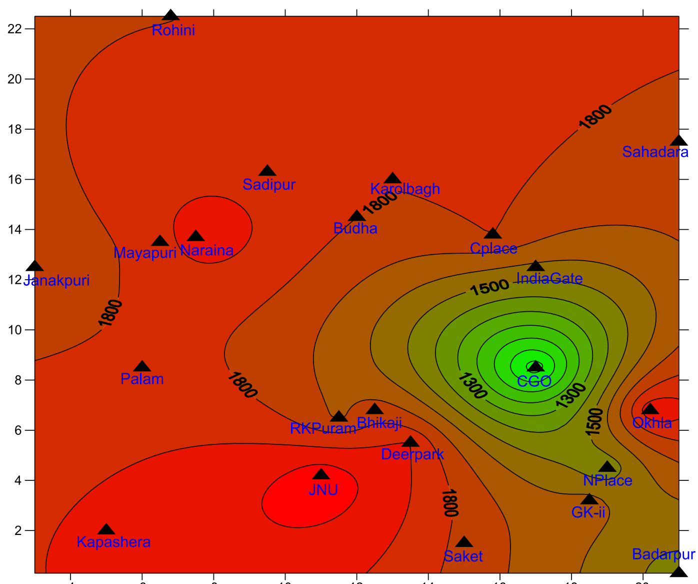

Fig. 2. Isopleth map of K↓ (W/m^2) over Delhi, summer 1998.

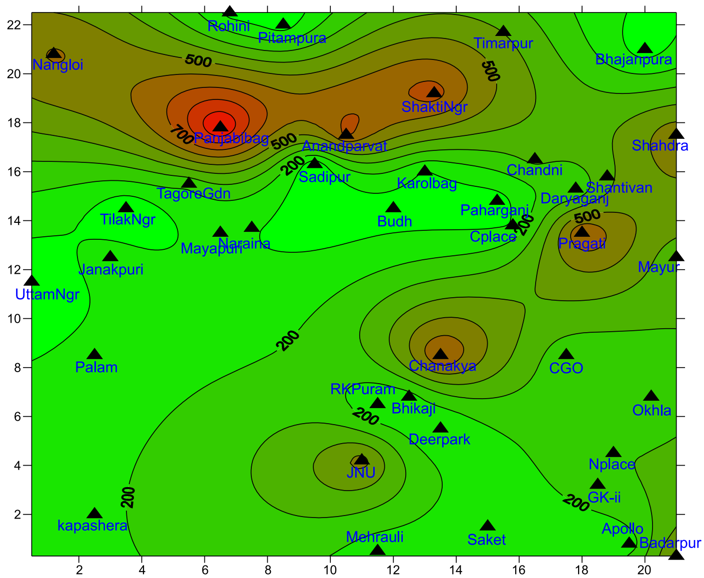

Fig. 3. Isopleth map of L↓ (W/m^2) over Delhi, winter 1997–98.

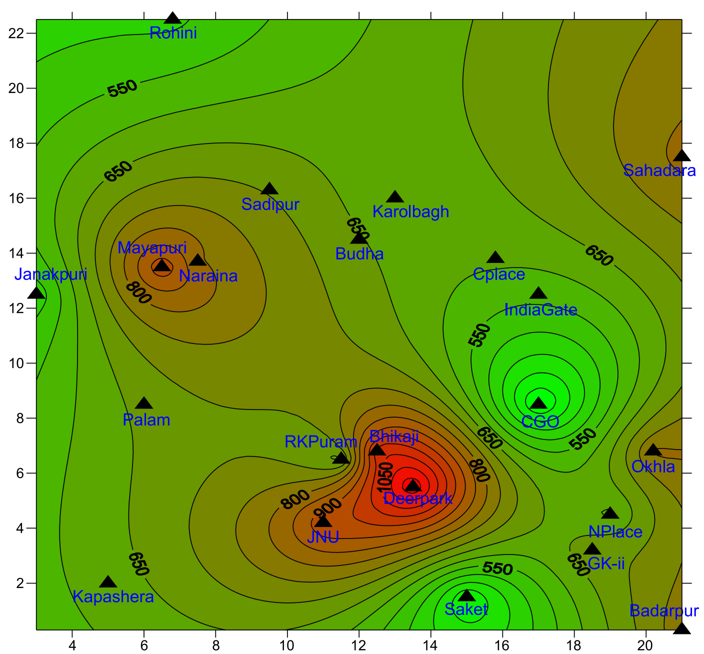

Fig. 4. Isopleth map of L↓ (W/m^2) over Delhi, summer 1998.

forest (Deerpark) areas, which could be attributed to the cellular circulation of air between polluted and warmer surroundings, and rural and forest areas.

3.1.3. Outgoing longwave radiation ($L\uparrow$)

The varied distribution pattern of $L\uparrow$ throughout the city during winter 1997–98, depicting the varied surface effect on $L\uparrow$, is shown in isopleth map (Fig. 5). Industrial areas of Shahdara, Shaktinagar and residential sites of CGO Complex, Chanakyapuri, Panjabibag, Tagoregarden, Pitampura showed higher $L\uparrow$ due to anthropogenic activities; these add up to $L\uparrow$, in spite of their low emissivity (due to concrete surfaces). However, moderate to high $L\uparrow$ values were observed in the urban parks and vegetated areas. In contrast, rural areas of JNU, Palam, Mehrauli and Saket showed lower values of $L\uparrow$ presumably due to moist ground (low surface temperature) and low emissivity.

However, the spatial distribution of $L\uparrow$ during summer 1998 is quite different from that during winter 1997–98. Isopleth map (Fig. 6) clearly indicates that industrial areas of Badarpur and Naraina showed moderate values of $L\uparrow$ due to low emissivity (concrete surface) of the area in spite of high surface temperature. Commercial areas of Sadipur, Karolbagh, Connaught Place, Shahdara, and Nehruplace showed moderate to high $L\uparrow$ due to built-up nature (causing high temperature and high emissivity), anthropogenically generated heat also adds up to it. Rural and vegetated areas (JNU, Palam, Kapashera and Deerpark) are unable to show high $L\uparrow$ due to wetness of the emitting surfaces.

3.1.4. Albedo (α)

Isopleths of albedo, (Fig. 7), showed several pockets with high to moderate values of albedo spread over the city during winter 1997–98. Residential areas of CGO complex, Tilaknagar, Rohini, Timarpur, Tagoregarden and Chanakyapuri showed higher values of albedo due to high surface reflectivity (light coloured surfaces). Similarly, rural areas (JNU) show higher albedo due to reflectivity of rocky surfaces. But industrial and commercial areas showed lower albedo due to trapping of $K\downarrow$ in the urban canyon, reduced sky view factor, and dark/pitch coloured surfaces (having low reflectivity).

During summer 1998, the spatial variation of albedo was fairly different

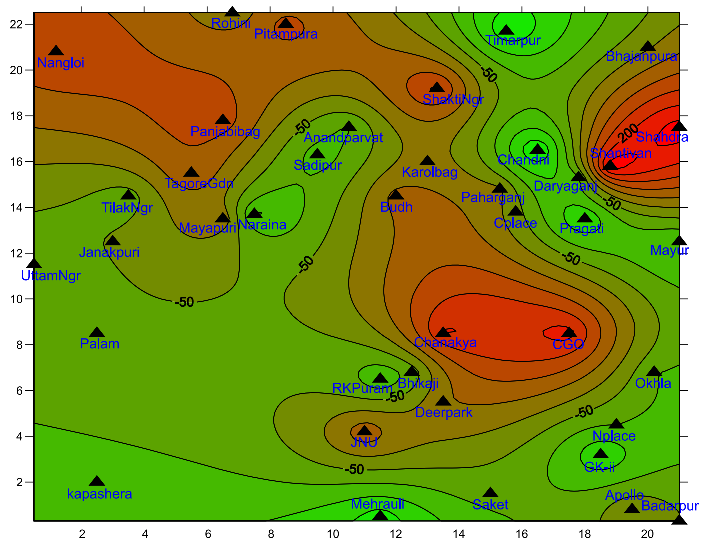

Fig. 5. Isopleth map of L↑ (W/m^2) over Delhi, winter 1997–98.

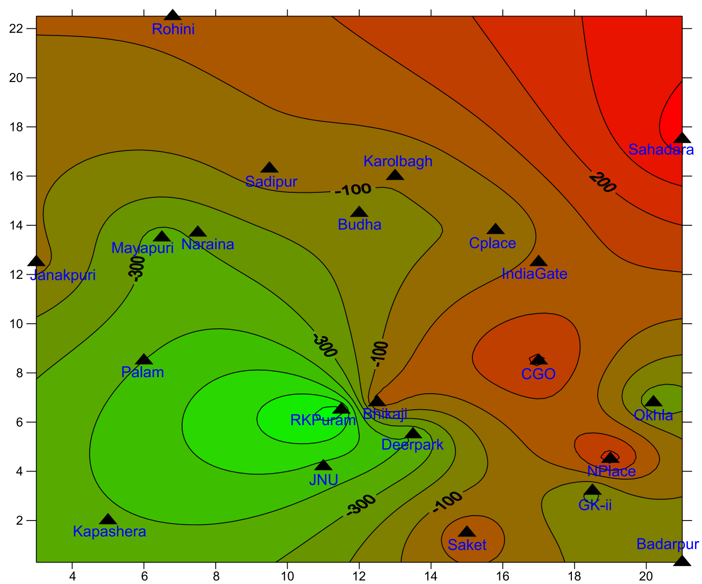

Fig. 6. Isopleth map of L↑ (W/m^2) over Delhi, summer 1998.

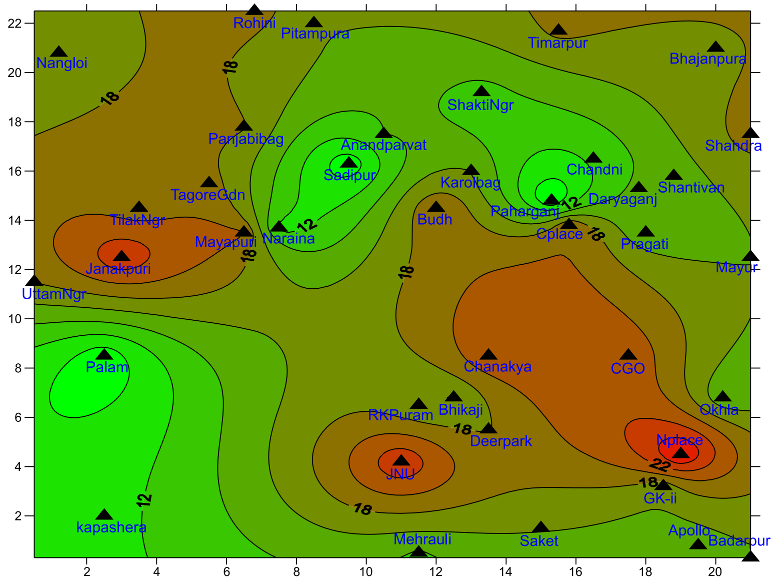

Fig. 7. Isopleth map of of albedo (%) over Delhi, winter 1997–98.

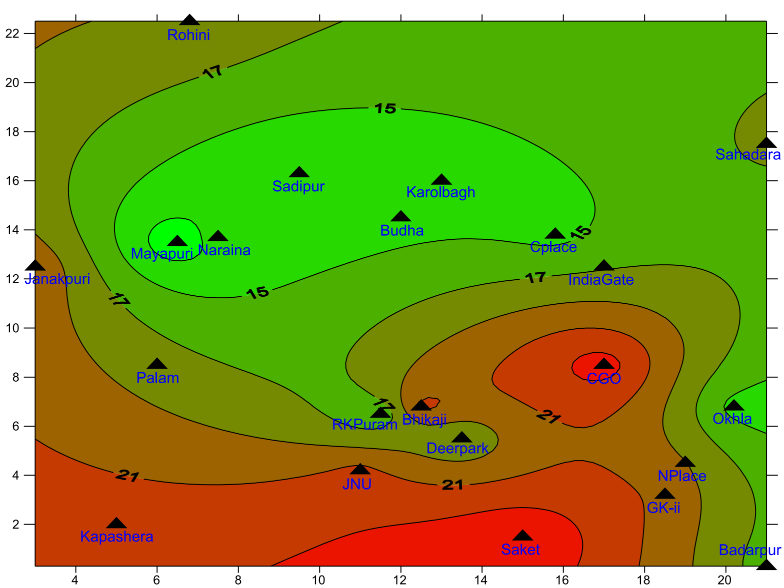

Fig. 8. Isopleth map of albedo (%) over Delhi, summer 1998.

than during winter 1997–98 as shown in the contour map (Fig. 8). Isopleths clearly indicate that residential complexes (CGO complex, Greater Kailash-II (GK-II), Janakpuri, Saket) and rural (JNU, Kapashera) areas had higher albedo due to high shortwave radiation and higher reflectivity. However, the industrial and commercial areas with congested and densely built-up areas showed low albedo due to trapping of most of the incoming shortwave radiation in the urban canopy set-up and low surface reflectivity.

3.1.5. Net radiation (Q)*

Several distinct pockets of high and low Q* values spread over the city were observed during winter 1997–98. Isopleths (Fig. 9) clearly indicate that industrial and commercial areas like Okhla, Naraina, Mayapuri, Shahdara, Shaktinagar, Anandparvat showed high Q*. This may be due to high L↓ and low L↑ values. Residential areas like CGO Complex, GK-II, Chanakyapuri, Pragatimaidan, Panjabibagh showed moderate to high Q*. Rural and forest areas of JNU, Palam, Kapashera, Mehrauli, Deerpark, Budhagarden, Shantivana showed lower Q* due to high emissivities and low L↓.

However, during summer 1998, the nature of spatial distribution of Q* was different than in winter (Fig. 10). High Q* was found in the industrial (Okhla, Naraina, Mayapuri, Badarpur) and commercial (Connaught Place, Karolbagh, Nehruplace, Bhikajicamaplace, Sadipur) areas due to low albedo, high L↓ and low L↑. Residential areas comprising CGO Complex, GK-II, Janakpuri, Indiagate showed low to moderate Q*. Rural and forest areas like JNU, Kapashera, Saket, Deerpark showed low Q* due to reduced value of L↓ and high upward long and short wave radiation.

3.2. Temporal variation of radiation balance components at five representative sites

3.2.1. Okhla (Industrial Site)

During winter 1997–98, the diurnal variations of radiation budget components peak at around noon (12:00 IST) (Fig. 11). K↓ varied from about 0 W/m^2 (minimum) to about 181.5 W/m^2 (maximum). Q* is the dominant component of radiation budget. It showed maximum (372 W/m^2) value at noon and minimum (-66 W/m^2) in the morning (06:00–07:00 IST) and

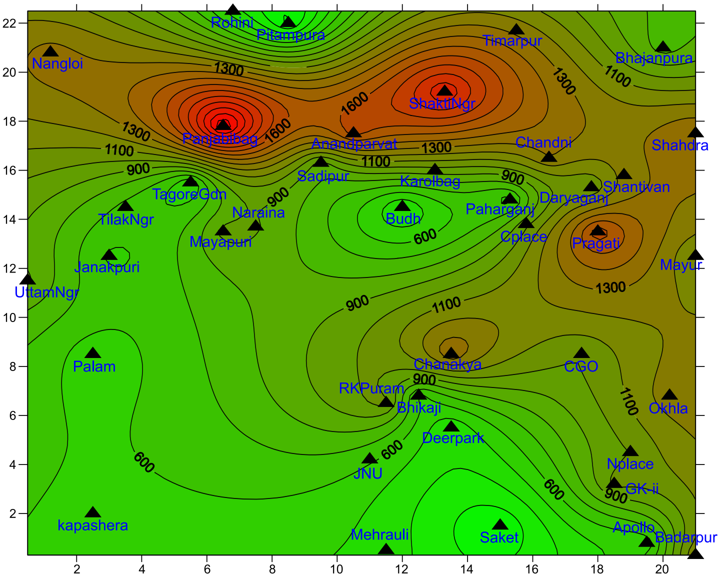

Fig. 9. Isopleth map of Q* (W/m^2) over Delhi, winter 1997–98.

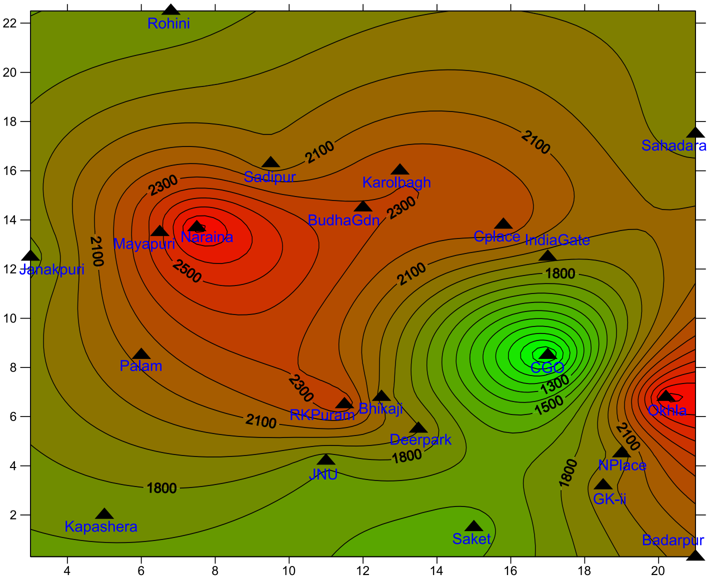

Fig. 10. Isopleth map of Q* (W/m^2) over Delhi, summer 1998.

evening (18:00–20:00 IST). The diurnal variation of L↓ is similar to K↓. Its maximum value was at noon of 183 W/m^2 and the minimum was -48 W/m^2 in the morning and evening. K↑ showed small diurnal variation, its maximum value was 26.6 W/m^2. Similarly, L↑ showed the negative magnitude (-91 W/m^2) at noon, indicating high emissivity compared to morning and evening hours.

During summer 1998, K↓ varied from 0 W/m^2 in the morning and evening to 275 W/m^2 at noon. Q* varied from -90 W/m^2 in the morning and evening to 560 W/m^2 in the afternoon (12:30–13:00 IST). Variation of L↓ was similar to K↓. Its hourly values ranged from -54 W/m^2 in the morning and evening to around 238.8 W/m^2 in the afternoon. K↑ showed comparatively small variation and ranged from 0 W/m^2 in the morning to about 41.8 W/m^2 at noon. L↑ showed negative trend at noon, amounting to about -100 W/m^2 (Fig. 12).

However, the magnitudes of all the radiation balance components were less during winter compared to summer at the representative industrial site due to lees intense solar radiation associated with foggy/cloudy weather conditions.

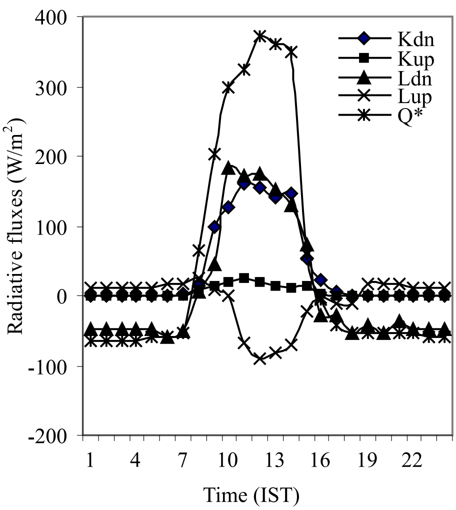

Fig. 11. Diurnal variation of radiation balance components at Okhla (industrial site), winter 1997–98.

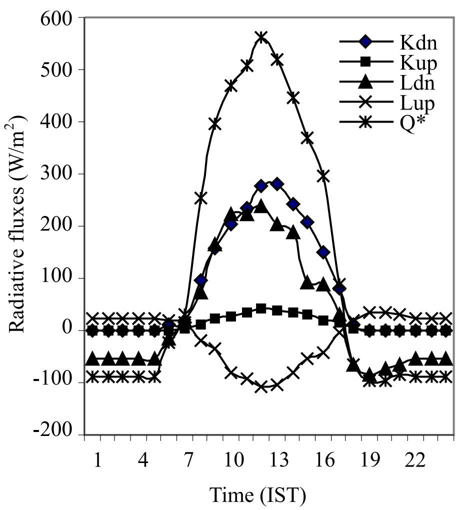

Fig. 12. Same as Fig. 11, for summer 1998.

On average, K↓ was more by twice in summer '98 compared to winter '97–98. In winter '97–98, K↓ was less by 53.09%. The winter to summer ratio was 0.47. In summer, Q* was also more than twice. It was less by 55.79% in winter '97–98 than summer '98, the winter to summer ratio being 0.44. L↓ was 3 times higher in summer '98 than winter '97–98, i.e., it was less by 72.20% in winter '97–98, the winter to summer ratio being 0.28. The winter to summer ratio for K↑ was found to be 0.47. It was about 52.70% less in winter '97–98 than summer '98.

3.2.2. Connaught Place (Commercial site)

It is evident from Fig. 13 that during winter 1997–98 K↓ varied from 0 W/m^2 (minimum) during morning and evening hours to 171.6 W/m^2 (maximum) at noon. Q* ranged from about −60 W/m^2 (minimum) in the morning and evening to about 390 W/m^2 (maximum) at noon. Diurnal variation of L↓ clearly indicates that its value peaked at around noon with maximum value of 193.5 W/m^2, minimum value being −36 W/m^2 in the morning and evening hours. K↑ showed small variation throughout the day compared to other component amounting to about 34.2 W/m^2. At this site too the magnitude of L↑ was negative at noon, indicating the high emissivity compared to morning and evening hours. Magnitude of maximum diurnal L↑ is about −64.2 W/m^2 at noon.

During summer 1998 all the parameters are varying with their varied degree. K↓ varied from 0 W/m^2 in the morning and evening to around 257.4 W/m^2 at noon. Q* was also fairly high. It varied from around −78 W/m^2 (minimum) to about 450 W/m^2 at noon, which is maximum in the daytime. L↓ varied from −45 W/m^2 to 258.6 W/m^2. In the afternoon there is a sudden drop of L↓ due to synoptic weather conditions. Small variations of K↑ were seen at this site too. During peak hours of the day it amounted to about 30 W/m^2. L↑ shows negative values at noon, and positive in the morning and evening (Fig. 14).

At the representative commercial site, K↓ was less by 45.24% in winter '97–98 compared to summer '98, the winter to summer ratio being 0.55. For Q*, the winter to summer ratio was found to be about 0.43. It was about 57.33% less in winter '97–98 compared to summer '98. L↓ was less by 82.72% in winter than summer, the winter to summer ratio for L↓ being 0.17. K↑ was less by 25% in winter '97–98 than summer '98, the winter to

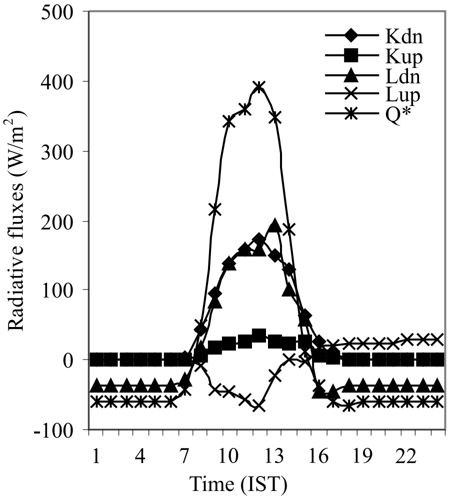

Fig. 13. Diurnal variation of radiation balance components at Cannought Place (commercial site), winter 1997–98.

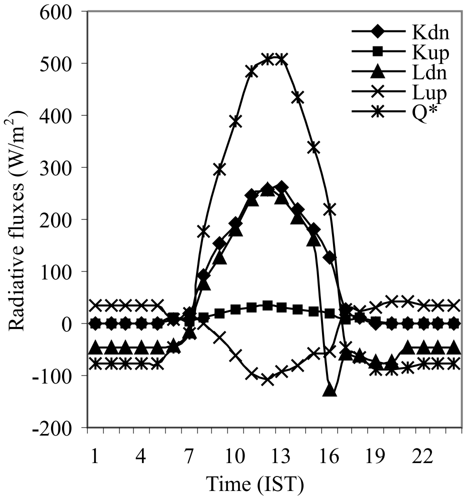

Fig. 14. Same as Fig. 13, for summer 1998.

summer ratio being 0.76. For L↑ the ratio of winter to summer was about 0.11.

3.2.3. Greater Kailash – II (Residential site)

At the representative residential site all the radiation budget components peak at around noon, followed by sudden drop of components due to cloudiness or shadow of trees/buildings. The trends of variation of components are similar to the other sites mentioned above. The K↓ values varied from about 0 W/m^2 in the morning to about 181.5 W/m^2 at noon. Q* also ranged from about -30 W/m^2 in the morning to about 338 W/m^2 at noon and -54 W/m^2 in the evening. Diurnal variation of L↓ ranged from -30 W/m^2 to 244.5 W/m^2. There was very small diurnal variation of K↑ compared to other components, its maximum daytime value being about 30.4 W/m^2 at around noon. L↑ showed negative values at noon, indicating large outgoing longwave radiation (Fig. 15).

During summer 1998, incoming shortwave radiation (K↓) ranged from -20 W/m^2 in the morning and evening to 264 W/m^2 at noon. Q* shows fairly high values. It varied from about -48.2 W/m^2 in the morning to about 402 W/m^2 in the afternoon and -50 W/m^2 in the evening. The variation of L↓ is quite obvious. It varied from -34 W/m^2 to 230 W/m^2 during daytime. The variation of K↑ was very small compared to other parameters. Its hourly maximum value at noon was about 35 W/m^2. Likewise, at noon, L↑ showed negative values (Fig. 16).

The variation pattern and corresponding magnitudes depend on urban morphology and other factors of urbanization.

During summer '98, K↓ was more than in winter '97–98 at the residential site. The ratio of winter to summer was 0.46, which indicates that K↓ was less in winter than summer by 54.14%. Q* was also about twice in summer '98 compared to winter '97–98. The ratio of winter to summer was 0.53, indicating lower value (47.26%) in winter than summer. For L↓, the ratio of winter to summer came out to be about 0.38. It was less by about 61.53% in winter compared to summer. K↑ too showed pronounced seasonal variation at this site. It was less by 62.50% in winter compared to summer, the winter to summer ratio being 0.38. The winter to summer ratio of L↑ came out to be 0.87, indicating lower values (12.81%) in winter '97–98 than summer '98.

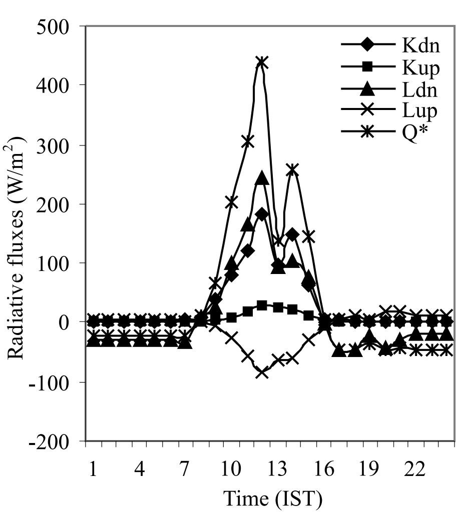

Fig. 15. Diurnal variation of radiation balance components at Greater Kailash (residential site), winter 1997–98.

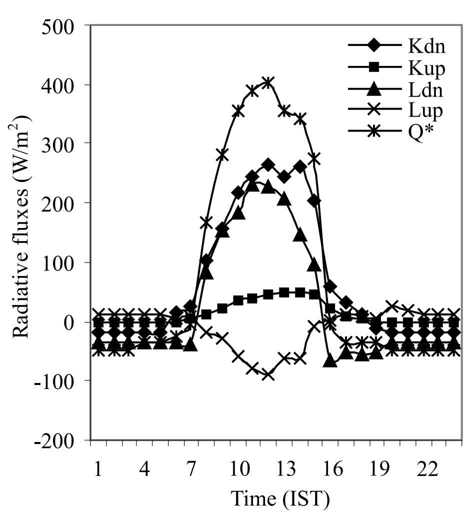

Fig. 16. Same as Fig. 15, for summer 1998.

3.2.4. *Jawaharlal Nehru University (Rural site)*

Figure 17 shows the diurnal variation of radiation budget components at the representative rural site. It is clear that the trends of variation of radiation budget components are similar to other sites and peak at around noon. K↓ showed minimum of 0 W/m^2 in the morning and evening and maximum of 191.4 W/m^2 at noon. The values of Q* ranged from about −36 W/m^2 in the morning to about 264 W/m^2 at noon and about −54 W/m^2 in the evening. L↓ attained maximum (186.6 W/m^2) value at around noon. K↑ showed small diurnal variation similar to those above sites amounting to about 45.6 W/m^2. Its maximum daytime value was 45 W/m^2. During noon hour L↑ showed negative magnitude (−33.6 W/m^2).

From Fig. 18 it is clear that hourly values of K↓ varied from 0 W/m^2 in the morning and evening to about 273.9 W/m^2 at noon. Q* ranged from −48 W/m^2 in the morning and evening to around 386 W/m^2 in the afternoon. At this site, L↓ showed slightly higher variability hourly. Its minimum value was about −48.6 W/m^2 (morning and evening) and maximum about 242.1 W/m^2 at noon. K↑ showed small hourly variation. Similarly,

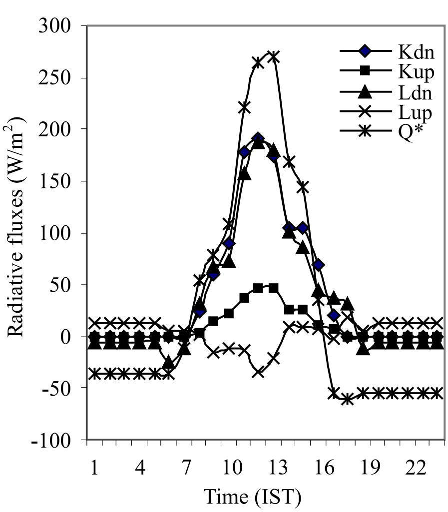

Fig. 17. Diurnal variation of radiation balance components at J. N. University (rural site), winter 1997–98.

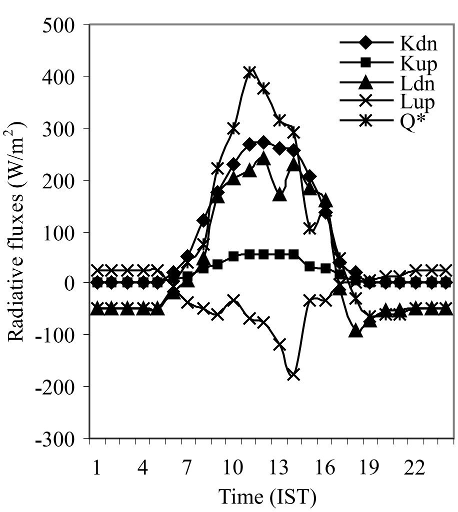

Fig. 18. Same as Fig. 17, for summer 1998.

negative flux of L↑ was observed in the afternoon whereas it was positive in the morning and evening.

By comparison we find that in the rural site K↓ was more than twice in summer '98 compared to winter '97–98. The ratio of winter to summer, i.e. 0.49, indicates that K↓ was less by about 50.64% in winter than summer. Q* was about 64% less in winter '97–98 compared to summer '98. L↓ was less by 42.22% in winter compared to summer. The ratio of winter to summer was 0.58. K↑ was found to be decreasing dramatically at this site in winter. It was about 45.35% less in winter than summer.

3.2.5. Deerpark (Forest site)

The diurnal variations of radiation budget components during winter at the representative forest site have been shown in Fig. 19. The maximum value of K↓ at noon was 52.8 W/m^2, whereas that of Q* was about 110 W/m^2. The variation of L↓ was also similar to K↓ at this site. Its hourly values are coinciding with K↓, but the average daily totals are different. The hourly variation of K↑ is very small, varying from 0 to 52.8 W/m^2. The hourly values of L↑ during daytime at noon showed negative magnitude (flux), varying from -6 to -17.4 W/m^2.

Figure 20 shows the diurnal variation of radiation budget components during summer 1998. From this figure it is obvious that all the parameters peak at afternoon. K↓ showed a pronounced hourly variation from about 0 W/m^2 in the morning and evening to about 273.9 W/m^2 in the afternoon. Q* also showed a pronounced hourly variation and ranged from -54 W/m^2 in the morning and evening to 392 W/m^2 (maximum) at noon. L↓ showed large daytime variation and varied from about -24 W/m^2 in the morning and evening to 296 W/m^2 in the afternoon. From the figure it is clear that K↑ showed smaller magnitudes and variability at this site also. L↑ showed negative flux during the noon hours and varied from 18 W/m^2 in the morning and evening to about -103.4 W/m^2 at noon.

K↓ was found to be much lower (87%) at the forest site in winter '97–98 compared to summer '98. The ratio of winter to summer for Q* was 0.21, which indicates that Q* was about 79% less in winter '97–98 compared to summer '98. L↓ was much lower (85%) than at other sites in winter compared to summer. During winter L↑ was less by 83% than in summer at this site. K↑ also showed a pronounced variation at this site and was less

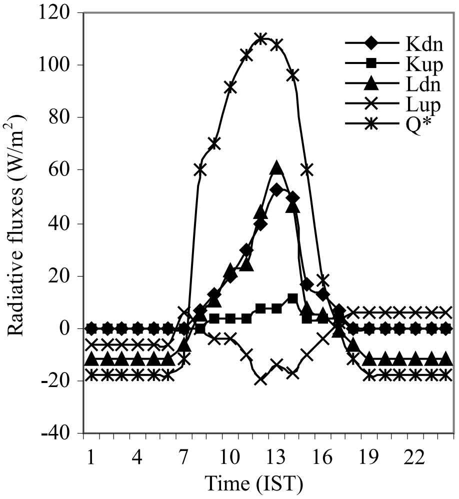

Fig. 19. Diurnal variation of radiation balance components at Deer Park (forest site), winter 1997–98.

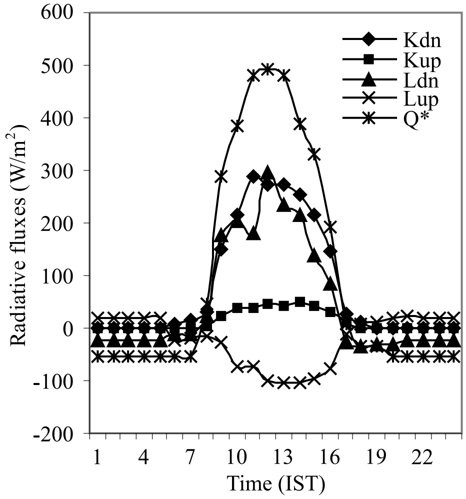

Fig. 20. Same as Fig. 19, for summer 1998.

by 84.71% in winter than summer.

4. Conclusions

Both in winter and summer, incoming shortwave radiation (K↓) showed wide spatial variation. However, during summer, except for the fringes of the city in the northeast and southwest, the entire area received strong radiation. Open areas, and industrial parks receive more global radiation compared to densely built-up areas.

The corresponding net radiation (Q*) during these seasons also showed distinct spatial variability. Rural areas, sparsely built-up localities and some industrial pockets showed lower net radiation. Consequently Q* was higher in those regions where vegetation was minimum or scanty during summer.

Albedo varied spatially due to differences in surface characteristics and the sky view factor. Sprawling areas and locations/areas devoid of vegetation/foliage exhibited higher albedo. During cloudy/foggy winter lower albedo was observed.

Downward longwave radiation (L↓) due to atmosphere also exhibited numerous pockets of high, moderate and low radiation during summer. The sky radiation (L↓) in winter was lower. These pockets were distributed over the entire city.

Upward longwave radiation (L↑) also presents similar features of downward longwave radiation. The upward radiation (L↑) during the winter shows lower value due to either overcast or cloudy sky for most of the time.

The creation of warm pockets (higher air temperature/radiation) during the winter reduces energy demands for heating the buildings. The warm pockets during summer are well spread over an axis from southeast to northwest, covering areas of either pollution sources/densely populated areas/densely built-up areas with cement and concrete. Areas that are covered by more vegetation, less population, less cement and concrete buildings emitted less radiation, hence resulted in lower air temperature and are cooler. Cooler areas closely follow the warm pockets. It is this co-existence of warm and cold pools associated with pollution sources, rendering pockets of high/low pollution (heat sinks/cold pools). Therefore, it is essential to undertake studies within the tropical areas on the spatial and temporal variations of radiation (energy) balances and corresponding warm and cool pools vis-à-vis pollution distribution to develop multi source regional air quality models, which are unique to the tropics.

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