Energy and water balance studies in the boundary layer over Delhi (India)

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Abstract: This paper describes the computation of various fluxes of energy and water balance components in the boundary layer over Delhi, for the years 1997–98 and 1998–99. Bulk-aerodynamic method has been used for the computation of sensible heat (H) and latent heat (LE) fluxes. Soil heat flux (G) has been directly measured using heat flux plate and also estimated using conductivity equation for comparison. Book-keeping procedure of Thornthwaite's has been used for water balance evaluation. Potential evapotranspiration (PE) is computed using Thornthwaite's method and compared with Penman's for the representative station. The results of the computed fluxes of energy and water balance components were compared with UREMBS-94 (Urban Rural Energy and Moisture Balance Studies - ES/63/018/84 – 1994) results for both the winter and summer seasons for urban (dry) and rural (moist) areas.

It was found that there persists an energy imbalance in both the seasons for urban/dry as well as rural/moist areas. However, urban areas showed positive ($+Ve$) energy imbalances and act as heat/pollution sources, whereas the rural/moist areas showed negative ($-Ve$) energy imbalances and act as heat/pollution sinks. These results are in good agreement with the UREMBS–94 results. On the other hand, water balance analysis for urban/dry and rural/moist areas showed the same ranges of moisture indices indicating hardly any shift in climate. However, UREMBS–94 results showed climatic shift in the urban regions.

Key words: energy balance, water balance, land use pattern, climatic types, seasons

1. Introduction

The importance of energy and water balance studies in the atmospheric boundary layer to the general circulation of atmosphere has long been well recognized. *Charney et al. (1977); Shukla and Mintz (1982); Sud and Smith (1985)* have shown the need for inclusion of energy and water exchange processes in the meteorological models. Over the complex urban agglomeration with changing land-use dynamics, the processes of heat and moisture exchanges and transport forms the basis of the urban meteorological studies *(Businger et al., 1971).* A central and recurring feature of much of the boundary layer meteorological research has been to establish and quantify the transfer and exchange processes of energy and water fluxes over different surfaces.

Urbanization produces changes in the earth–atmospheric radiation/energy and water balance relationship. Heat released due to various human activities supplements the natural sources of heat energy in the urban system causing surplus of energy where as its rural counterparts acts as heat sinks with deficit of energy *(Padmanabhamurty, 1999).* In urban areas, precipitation is augmented by water released through combustion and urban water supply piped in from rivers/reservoirs, because of this the water input to the urban system is greater. But in the rural surroundings there is no such occurrence (ignoring irrigation). Similarly, urban evapotranspiration is expected to be reduced because of the removal of vegetation and its replacement by relatively impervious materials. The poor infiltration properties of urban materials inspite of the larger convoluted surfaces of the interception areas there found smaller soil water storage in the urban areas as compared to its rural counterparts *(Oke, 1978).*

Experimental campaigns/programmes of international flavor viz. World Climate Research Programme (WCRP) and Global Energy and Water Cycle Experiment (GEWEX), Basel Urban Boundary Layer Experiment (BUBBLE) in Basel, Switzerland *(Baldocchi et al., 2002; Rotach, 2002; 2005)* and Experiments to Constrain Models of Atmospheric Pollution and Transport of Emissions/Urban Boundary Layer-Couche Limite Urbaine (ESCOMPTE/UBL-CLU) at Marseille, France *(Cros, 2004; Mestayer, 2005)* are noteworthy effort to increase the understanding of energy exchange and dispersion processes over urban, suburban, vegetated and rural areas of the complex mega city ecosystem/climatology. Studies in this field include *Enz et al. (1988)* who found out evapotranspiration to evaluate the energy balance components at different surfaces. *Tjernstrom (1989)* conducted some tests with surface energy balance scheme including bulk parameterization for vegetation in mesoscale mode. *Schmid et al. (1991)* studied the small-scale spatial variability of surface energy balance components within a residential suburban area in Vancouver, B. C. Canada. *Grimmond (1992), Oke and McCaughey (1983), Mills and Arnfield (1993), Lhome (1992)* studied extensively, through experiment and using a numerical simulation, the energy budget of an urban canyon and their rural counterparts. *Padmanabhamurty (1994)* noticed the surplus and deficit of energy in their respective dry (urban) and moist (rural) areas in both the winter and summer seasons. He attributed these differences to the urbanization. *Sasakibara (1996)* and *Hoyana et al. (1999), Terjung and Louie (1974)* and *Todhunter and Terjung (1990)* used urban canopy model "URBAN3" to study energy balance in an urban canyon under various synoptic weather conditions in an urban park and on a roof garden and with seasonal and latitudinal contrasts. *Camuffo and Bernadi (1982)* studied the partitioning of net radiation into convective and conductive heat fluxes. *Oke (1987), Thornes and Shao (1991), Sass (1992), Doll et al. (1985), Asaeda and Ca (1993)* also carried out such studies of partitioning of net radiation into different fluxes for concrete and asphalt surfaces.

Barradas et al. (1999), Das and Padmanabhamurty (2007) studied the energy balance of a vegetated area. *Matejka et al. (2007)* have studied the potential evapotranspiration in relation to soil moisture of a maize stand in the south-east part of the Czech Republic. Similarly, the studies on water balance using the Thornthwaite's book-keeping procedure have been carried out by *Padmanabhamurty et al. (1970, 1981, 1994, 1999); Mather (1974), Rao et al. (1976). Subrahmanyam (1982)* used Thornthwaite's book-keeping water budgeting procedure and evaluated the water balance. *Kyuma (1971, 1972)* computed the water balance for Thailand and studied the climate using the method of *Thornthwaite (1948). Black (1966), Grigal and Bloom (1985), Kolka and Wolf (1998), Ward (1993)* studied the water balance and evaluated the moisture status. *Ratnam et al. (1996)* used the potential evapotranspiration computed by *Rao et al. (1971)* to compute the moisture Index (I_m) of Karnataka and applied the *Thornthwaite and Mather (1955)* techniques for climatic classification of the state.

Nevertheless, our understanding of the energy and moisture flux transfer and their role in mesoscale/regional climate models and associated biophysical processes involved in the generation of urban climates is limited. Direct observations of energy and mass exchanges in urban areas have been collected only in a restricted number of cities, with a small range of surface morphologies and climates *(Oke, 1988; Grimmond and Oke 1994).* Thus, to understand how urban morphology influences local climate (energy and water exchanges) it is necessary to undertake detailed investigations of local meteorology including water and energy balances in conjunction with an understanding of urban surfaces *(Grimmond et al., 1994).*

This paper describes our research conducted to study energy and water balance in the boundary layer over Delhi. Since such studies in a tropical city Delhi is semi-skeletal. Hence, the study has been carried out with the objective to see the energy imbalances and shift in climate of the city with the effect of urbanization, in addition to exchange our understanding of biophysical processes. These data could also be used to evaluate physically based meteorological models, which, in turn, will be used to investigate the effects of proposed changes in urban morphology on the urban climate.

2. Delhi - the study area

The study area, Delhi is situated in the north of North Indian Great plain, and influenced by the great Thar Desert in the west and the great Himalayan ranges in the north. Because of the human migrant influx, the city is dominated by a mixture of human settlements, Govt. offices, Residential and Commercial complexes with some vegetated areas. The climate of the region is controlled mainly by its inland position and continental air prevailing over most part of the year. Delhi's climate is semi-arid with extreme conditions. Winter is foggy with severe cold associated with cold waves due to western disturbances and summer with intense hot, sometimes heat wave called "luh" also makes the life threaten. In summer dust clouds make the entire city poor in visibility. Perhaps the dust from Rajasthan desert reaches to Delhi and reduces the visibility. Unseasonal rain sometimes with gusty winds is a common feature in Delhi. Southwest - monsoon brings good amount of rainfall. The predominant wind direction in most part of the year is northwesterly except during the monsoon season (July to mid-September) when it reverses to southeasterly. Day length in this latitude ranges approximately between 10.5 hrs in winter to 13.5 hrs in summer.

Maximum Global radiation occurs in May and minimum in Jan–Feb *(IMD, 1998)*.

The population of Delhi is more than 13 million. It is basically an administrative center, with Govt. offices, agricultural, medical institutions, etc. Lot of trading and commercial activities take place in the city. Being a capital of the country it is linked by rails and national highways with different parts of the country. Major industries like thermal power plants (at Badarpur, Rajghat and Indraprastha), chemicals, engineering, glass and ceramics, foundries and small industries like stone crushing, baking machine, food processing industries etc. causing air pollution. Delhi has the highest number of motor vehicles in India. The number is increasing at the rate of 14,000 per month. The vehicular population has increased phenomenally, from 2.35 lakhs in 1975 to 26.29 lakhs in 1996, and expected to touch 60 lakhs in 2011. Vehicular pollution contributes 67% of the total air pollution load (approximately 3,000 mt per day) in Delhi. Peripheral region of the city is characterized by rural population, whereas green spaces and forest areas are being scattered in southern and east central parts *(MoEF, 1999)*.

In this study, urban complexes comprising of Industrial, Commercial and Residential sites and Rural/Forest sites have been covered for the experimental campaign which are listed as follows:

- **Industrial:** Okhla, Naraina, Mayapuri, Ashram and Badarpur
- **Commercial**: Connaught Place, Nehru place, Karolbag, Chandnichowk, Daryaganj, Paharganj, Shahdara, Bhajanpura, Bhikajicama place, Sadipur and Shaktinagar
- **Residential:** CGO Complex, C.R. park (GK-II), Vasantkunj, Panjabibag, Rohini, Tilaknagar, TimarPur, Chanakyapuri, Janakpure, Mayurvihar, Pitampura, Pragatimaidan, RajauriGarden, RKPuram, Saket and Indiagate
- **Rural:** Jawaharlal Nehru University (JNU), Palam, Mehrauli, Nangloi and Kapashera
- **Forest**: Deer park, Budhagarden and Shantivana.

3. Materials and methods

Experiments were conducted through mobile surveys covering entire length and breadth of the city of Delhi on different days of experiments during winter 1997–98/1998–99 and summer 1998/1999, respectively. This experimental campaign was part of a project sponsored by the Ministry of Science and Technology, Govt. of India (No. ES/048/319/95), aimed at acquiring experimental data for the study of radiation/energy/moisture budgets of urban ecosystem of the tropical city Delhi, according to different land use pattern *(Padmanabhamurty, 1999a, 1999; Das, 2002; Das and Padmanabhamurty, 2007).*

3.1. Energy balance

The energy balance equation at the earth–atmosphere interface in the absence of advection is given as

$$Q^* = H + LE + G \tag{1}$$

where Q^* = Net radiation, H = Sensible heat flux, LE = Latent heat flux, G = Soil-heat flux.

The energy imbalance at the atmosphere-land boundary layer is given by

$$Q^* - (H + LE + G) = 0 \tag{2}$$

3.1.1. Evaluation of convective fluxes (H&LE)

H and LE were calculated using Bulk-aerodynamic approach *(Oke, 1987).* Under neutral conditions the flux profile equations are

$$H = -\rho C_P K^2 Z^2 \left(\frac{\Delta u}{\Delta z} . \frac{\Delta T}{\Delta z}\right) \tag{3}$$

$$LE = -\rho Lv K^2 Z^2 \left(\frac{\Delta u}{\Delta z} . \frac{\Delta q}{\Delta z}\right), \tag{4}$$

where ρ = the air density, Cp = the specific heat of air at constant pressure, Lv = the latent heat of evaporation, K = the von Karman constant (0.4), Z = is the height under consideration, Δu = difference between two level mean wind speed, Δz = difference between two level height, ΔT = difference between two level mean temperature, Δq = difference between two level mean specific humidity.

The stability factor to be multiplied is $(\varphi_m \varphi_x)^{-1}$, where $\varphi_x = \varphi_q$ or φ_H, where φ_m = dimensionless stability factors for momentum flux, φ_q = dimensionless stability factor for moisture flux, φ_H = dimensionless stability factors for sensible heat flux.

With the substitution of φ_m and φ_x the above equations are transferred to

$$H = -\rho C_P K^2 Z^2 \left(\frac{\Delta u}{\Delta z}.\frac{\Delta T}{\Delta z}\right)(\varphi_m \varphi_H)^{-1} \quad (5)$$

$$LE = -\rho Lv K^2 Z^2 \left(\frac{\Delta u}{\Delta z}.\frac{\Delta q}{\Delta z}\right)(\varphi_m \varphi_q)^{-1}, \quad (6)$$

The Richardson number Ri is a convenient means of categorizing atmospheric stability in the lowest layer and is given as

$$Ri = \left(\frac{g}{T}\right)\left(\frac{\frac{\Delta T}{\Delta z}}{\left(\frac{\Delta u}{\Delta z}\right)^2}\right), \quad (7)$$

where g = acceleration due to gravity (9.8 m/s^2), T = mean temperature in layer (z), u = mean wind speed in the layer (z), z = height of the layer under consideration.

The empirical relations for different stabilities are *Dyer (1974), Oke (1978)*:
For stable conditions (Ri is positive ($+Ve$))

$$(\varphi_m \varphi_H)^{-1} = (\varphi_m \varphi_q)^{-1} = (1 - 5Ri)^2.$$

For unstable conditions (Ri is negative ($-Ve$))

$$(\varphi_m \varphi_H)^{-1} = (\varphi_m \varphi_q)^{-1} = (1 - 16Ri)^{3/4}.$$

3.1.2. Data collection

A soil heat flux plate ($HFT-3$, Campbell Scientific, Inc.) was used to measure the soil heat flux (G) on hourly basis and averaged for daily basis for analysis. The placement of the plate was difficult in the concrete or asphalt surfaces, as there was no possibility to dig the plate under the

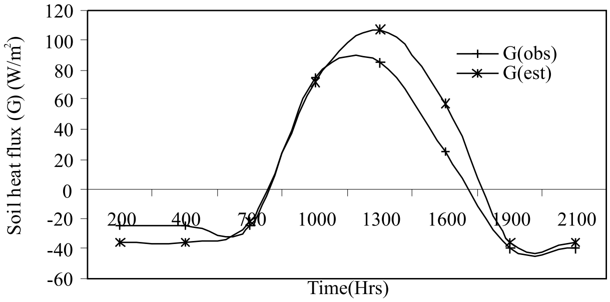

Fig. 1. Comparison of observed (obs) and estimated (est) soil heat flux (G).

surface. The heat flux plate was placed on the non-natural surfaces and was covered with the rock-less concrete mix and care was taken to ensure that the top and bottom of the plate was in full contact with the material covered with. Details of the methodological limitations and error corrections have been given by *Asaeda and Ca (1993); Anandakumar (1999); Kotani and Sugita (2005); Weber (2006); Philip (1961).* In contrast, the plate was embedded in the top soil of the natural earth surface to measure the soil heat flux in rural parts of the experimental area. The output voltage of soil heat flux plate corresponded to 1 mV = 60.6 W/m^2. G is also estimated by conductivity equation as given by *Van Wijk (1965), Fritschen and Gay (1979).*

$$G = -K\left(\frac{\Delta T}{\Delta z}\right), \tag{8}$$

where K = thermal conductivity of soil = 7.12×10^{-1} Wm^{-1} K^{-1}, as used by *Saxena et al. (1996).* $\frac{\Delta T}{\Delta z}$ = is the temperature gradient between surface and 10 cm level. Observed and estimated G have been compared (Fig. 1) and R^2 is 0.9478.

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 100μm with direct output voltage of 1 mV corresponding to 66.6 W/m^2. Wind speed and dry and wet-bulb temperatures were measured at two heights (0.5 and 3.0 m) using a portable mast of 3.5 m height. Net radiometer and wind speed sensors were mounted separately. Net radiometer was 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 and other installations.

Hourly observations were taken and later on averaged for daily basis and processed following *Håkansson and Peters (1995)* and *Backstrom (2006)*. Details of the instruments calibration processes are given in *Das and Padmanabhamurty (2007)*. The errors associated with the measured terms were about 5% for net radiation and soil heat flux and 10–12% for latent heat flux (LE) and sensible heat flux (H) *(Webb et al., 1980; Munn, 1966)*. LE and H calculated using dry- and wet-bulb temperatures and wind speed measured at two different heights (0.5 and 3.0 m) from the bulk-aerodynamic method mentioned as above *(Saxena et al., 1996; Padmanamhamurty, 1999a, 1999b; Das, 2002)*.

3.2. Water balance

The moisture balance is expressed by the so-called "storage equation" of the hydrologist as

$$P = PE + R + \Delta S, \tag{9}$$

where P = water supply to the region as precipitation in all its forms or from other sources, PE = total water loss by evaporation and transpiration (Potential evapotranspiration), R = runoff from the area by subsurface or overload flow and ΔS = change in the moisture status of the soil (Soil moisture storage).

3.2.1. Methods of PE evaluation for water balance computation

To compute the water balance at a place it is necessary to have i) Mean monthly/daily potential evapotranspiration ii) Mean monthly/daily precipitation, and iii) Information on the water holding capacity of the depth of soil for which the balance is to be computed.

3.2.1.1. Thornthwaite's formulae for PE

According to the method of Thornthwaite the relation between mean monthly temperature and PE adjusted to a standard mean of 30 days each having 12 hours of possible sunshine is given by the equation:

$$PE = 1.6\left(\frac{10T_a}{I}\right)^a, \tag{10}$$

where PE = monthly potential evapotranspiration in Cms.
T_a = mean monthly air temperature (° C),
a = cubic function of I.
Given as, $a = (6.75\times10^{-7})\times I^3-(7.71\times10^{-5})\times I^2+(1.792\times10^{-3})\times I+0.49$
I = annual heat index, given by

$$I = \sum_{n=1}^{n=12}\left(\frac{T_a}{5}\right)^{1.514}, \quad \left(\frac{T_a}{5}\right)^{1.514} = i = \text{mean heat index of the } n^{\text{th}} \text{ month.}$$

These formulae give unadjusted values of PE since the number of days in a month ranges from 28 to 31 (nearly 11%) and the number of hours such as in the day between sunrise and sunset (when evapotranspiration principally takes place) varies with the latitude and seasons of the year. It thus becomes necessary to reduce or increase the unadjusted PE by a factor that varies with the latitude and the month under question.

3.2.1.2. Penmans' formulae for PE

$$E = \frac{\frac{\Delta}{\gamma}\left[(1-r)R_A\left(a+b\frac{n}{N}\right)-\sigma T^4(0.56+0.092\sqrt{e_d})\left(0.1+0.9\frac{n}{N}\right)\right]}{\frac{\Delta}{\gamma}+1} + \frac{35(e_a-e_d)\left(1+\frac{u}{100}\right)}{\frac{\Delta}{\gamma}+1} \tag{11}$$

where E = potential evaporation in mm/day with surface reflection of 5% to open water, R_A = incident radiation outside the atmosphere on a horizontal surface expressed in mm of evaporable water per day, n = duration of sunshine during the interval of estimate, N = maximum duration of sunshine during the same time, σ = Stefan–Boltzmann constant, T = temperature in degrees absolute, e_d = vapour pressure in mm of mercury, e_s = saturation vapour pressure in mm of mercury, u = daily wind run at 2 m above the ground in statute miles, γ = psychrometric constant, Δ = rate of change with temperature of s.v.p. These values are reduced by a factor of 0.7 as suggested by Penman to obtain PE.

The values of PE computed by Penman's method *(Padmanabhamurty et al., 1970; Das, 2002)*, for the representative station Delhi have been compared with Thornthweaite's method. On comparison with Thornthwaite's a 0.8% deviation from Penman (Table 3) is found. Precipitation and mean temperature (for computation of PE using Thornthwaite's) data have been obtained from the India Meteorological Department (IMD) and Centre for Studies in Regional Development (CSRD) of Jawaharlal Nehru University (JNU). Runoff is assumed to be zero. The field capacity is assumed to be 300 mm as measurement of this quantity is not readily available *(Thornthwaite, 1948)*. The complete water balance is evaluated by following an elegant book-keeping procedure given by C. W. Thornthwaite *(Subramanyam, 1982)*.

3.2.2. Computation of moisture indices and climatic classification

Studies of the water balance (which is the principle of mass conservation applied to exchanges of water) ensure the magnitudes of the various water exchanges processes, and allow investigation of the interaction between the elements of the hydrologic cycles. The purpose of water balance studies is to investigate climate shift and to classify the region into climatic categories based on availability of moisture surplus (WS) and deficit (WD) by computing moisture indices through water balance analysis.

Moisture indices determine the moisture status and climatic type of a region. The moisture index (I_m), humidity index (I_h) and aridity index (I_a) are computed as

$$I_h = \sum_{i=1}^{12} \left(\frac{WS}{PE} \right) \times 100 \tag{12}$$

$$Ia = \sum_{i=1}^{12} \left(\frac{WD}{PE} \right) \times 100 \tag{13}$$

and

$$I_m = (I_h - I_a) \quad (Carter\ and\ Mather,\ 1955). \tag{14}$$

Table 1. Energy balance 24-hourly totals (W/m^2) represented as source ($+Ve$) and sinks ($-Ve$) over Delhi, 1997–99

SEASON	STATION	*G*	*H*	*LE*	*Q**	(*G*+*H*+*LE*)	IMBALANCE		
Winter' 97-98	Dry (Urban)	195	453.08	515.52	1260	1163.57	96.43	(+Ve)	Source
	Moist (Rural)	90	204.81	494.38	618	789.20	-171.20	(-Ve)	Sink
Summer' 98	Dry (Urban)	635	1197.88	416.28	2331	2249.10	82.23	(+Ve)	Source
	Moist (Rural)	475	1175.13	550.82	1710	2200.94	-490.94	(-Ve)	Sink
Winter' 98-99	Dry (Urban)	260	441.68	519.82	1380	1221.50	158.45	(+Ve)	Source
	Moist (Rural)	195	299.99	627.75	954	1122.74	-168.74	(-Ve)	Sink
Summer' 99	Dry (Urban)	655	1206.15	658.69	2700	2519.83	180.17	(+Ve)	Source
	Moist (Rural)	150	1057.20	504.79	1554	1711.98	-157.98	(-Ve)	Sink

where i = months.

The total annual water surplus is the summation of all the monthly water surpluses during the year. Similarly, the annual water deficit and annual PE are obtained by summing the respective monthly values for the whole year from the book-keeping procedure for water balance.

4. Results and discussion

4.1. Energy balance

Urban areas (comprising of Industrial, Commercial and Residential sites) with concrete, asphalt and paved surfaces show higher values of G due to high heat capacity, thermal conductivity and surface temperature as compared to their rural counterparts. The higher surface to air temperature differences in such surfaces gives rise to higher H, as compared to rural/moist areas. On the contrary, LE is smaller in urban areas due to dryness nature of the evaporating surfaces where most of the natural earth surfaces for evaporation is built-up. Moreover, the apportionment of net available energy (Q^*) into G, H and LE in the complex urban morphology with changing land use pattern show diverse pattern of energy imbalance.

The difference between the net radiation observed directly and sum of the energy fluxes is termed as energy imbalance $[Q^* - (G + H + LE)]$. Positive imbalances suggest the creation/generation of heat sources while negative imbalances are deemed as cool pool/sinks of heat. Contour map

(Figs. 4 and 5) for the winters 1997–98/98–99 show the co-existence of pockets where the sum of the energy fluxes exceeded net radiation and vice-versa. Urban areas/complexes i.e. Industrial and Commercial sites of Badarpur, Okhla, Naraina, Mayapuri, Paharganj, Connaught Place, Shadipur, Shahdara, Bhajanpura and residential areas of GK-II, CGO Complex, Chanakyapuri, Janakpuri, Tilaknagar and Mayurvihar during winter 1997–98 and sites like Chandnichowk, Karolbagh, Daryaganj, Shahdara etc. including above mentioned sites during winter 1998–99 showed positive energy imbalances and act as warm pockets or heat sources. In contrast, rural and forest areas/parks representing moist regions viz. JNU, Palam, Kapashera, Nangloi, Deerpark, Budhagarden and Shantivana showed negative imbalances and act as a cool pool/sink of heat/pollution in both the years of 1997-98/1998-99. As shown in Table 1 and Fig. 2 the energy surplus and deficit represent heat source and sinks in the representative urban (dry) and rural (moist) areas in both the winters. However, winter 1998–99 showed more energy surplus by about 62% at the representative urban areas. This could be due to advection of heat due to western disturbances which appeared more frequent during this season. But the corresponding deficit showed not much difference during the season in their representative rural areas. These results of heat source and sinks in their respective urban and rural areas match very well with UREMBS-94 results (Table 2 and Fig. 3), though there is a difference in their magnitudes due to the prevailing synoptic weather conditions and surface characteristics which control the partitioning of available net energy. As since, UREMBS–94 data sets comprised of tower data installed at two locations (urban and rural sites) separately with automatic recording devices the isopleth distribution could not be produced.

Similarly, isopleths distribution (Figs. 6 and 7) for the summers of 1998/1999 indicate that urban areas comprising Industrial and Commercial sites

Table 2. Energy balance 24-hourly total (W/m^2) represented as source ($+Ve$) and sink ($-Ve$) over Delhi, UREMBS–94, 1994

SEASON	STATION	G	H	LE	Q^*	$(G+H+LE)$	IMBALANCE		
Winter'94	Dry (Urban)	180	560	400	1380	1140	240	(+Ve)	Source
	Moist (Rural)	280	800	560	1500	1640	-140	(-Ve)	Sink
Summer'94	Dry (Urban)	720	1566	1100	3500	3386	114	(+Ve)	Source
	Moist (Rural)	700	1466	1500	3360	3666	-306	(-Ve)	Sink

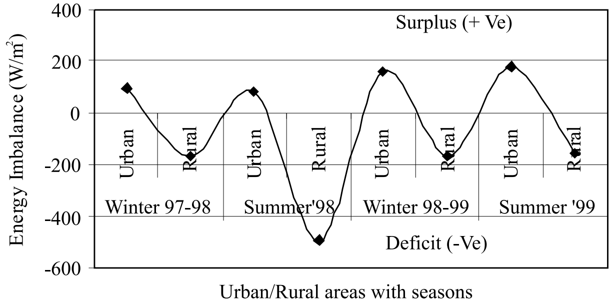

Fig. 2. Energy Imbalance (Surplus/Deficit) for the year 1997–1999.

of Okhla, Naraina, Mayapuri, Shahdara and Connaught Place during summer 1998 and sites viz. Badarpur, Sadipur, Shaktinagar, Karolbagh, Chandnichowk, Paharganj, Daryaganj and Nehru place and urban Residential areas of GK-II, CGO Complex, Vasantkunj, Janakpuri, Tilaknagar and Pitampura act as heat/pollution source including above mentioned sites during summer 1999. This could be attributed to the anthropogenic heat generated due to industrial and commercial activities in the urban agglomeration. Rural and vegetated areas of JNU, Palam, Kapashera, Deerpark and Budhagarden showed negative imbalance and act as cool pool/energy sinks. During summer 1999, Shantivana also acts like a cool pool/pollution sink including above mentioned sites. Also shown in the Table 1 and Fig. 2, during summer 1999, energy imbalance was greater by a factor of two times than in summer 1998. This may be due to more anthropogenic heat gen-

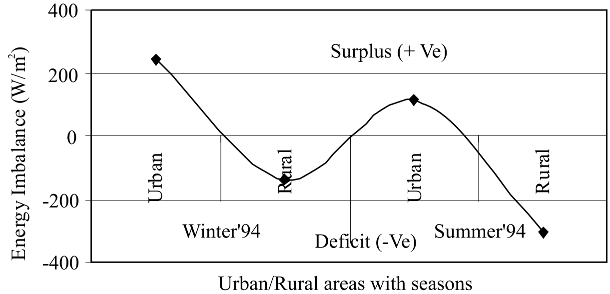

Fig. 3. Energy Imbalance (Surplus/Deficit) for the year 1994 [UREMBS–94].

eration during summer 1999 which contributes to the natural sources of heat energy causing more imbalance at the representative urban areas on an average. Similarly, corresponding heat/pollution sinks in the representative rural/moist site were more during summer 1998 compared to summer 1999. UREMBS–94 data sets also revealed similar results, indicating the heat sources in the urban regions and sinks in the rural areas (Table 2 and Fig. 3).

Where the sum of the fluxes is more than the net radiant energy received directly, the sources of additional energy are to be accounted for. This may be due to advection of energy from the neighborhood or anthropogenically generated. The anthropogenic heat is attributed to the density of population, buildings and traffic, commercial and industrial activities. The unique feature of the urban agglomeration is the presence of numerous pockets of heat sources and sinks as evident by the isoline map.

Therefore, the formation and existence of warm pockets and cold pools are mutually balancing and mitigating the mass/pollution rather than circulating the mass/pollution within the urban atmosphere.

4.2. Water balance

4.2.1. Moisture indices and climate

The climate of Delhi is classified following the scheme of *Thornthwaite and Mather (1955)* with the following limits of I_m%.

Classification	**Type**	**Limits of I_m%**
Perhumid	A	100 and above
Humid	B	20 to 100
Moist subhumid	$C2$	0 to 20
Dry subhumid	$C1$	−33.3 to 0
Semi-arid	D	−66.7 to −33.3
Arid	E	−100 to −66.7

The moisture index may be positive or negative; the positive values indicate moist/humid climates while the negative dry climates.

Different indices were calculated both for urban and rural locations for the years 1997 and 1998 (Table 5). Humidity Index (I_h) was found to be zero at urban (Safdarjung) as well rural (JNU) sites in both the years as there

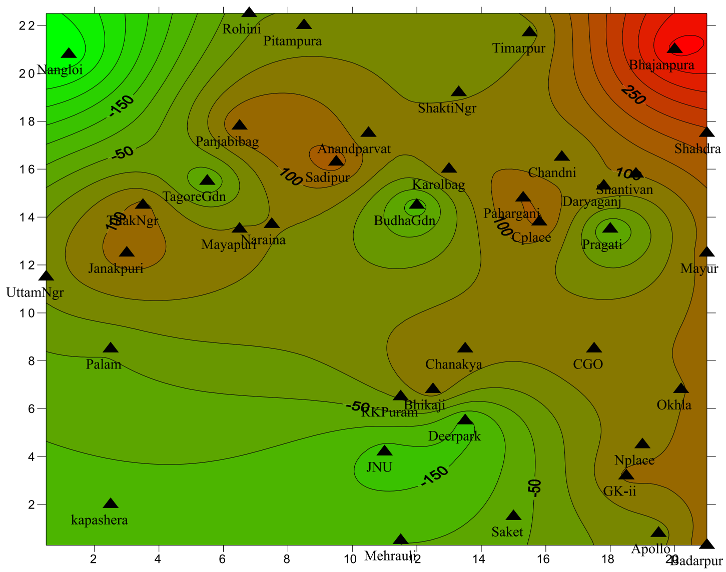

Fig. 4. Isopleth distribution of energy imbalance, winter 1997–98.

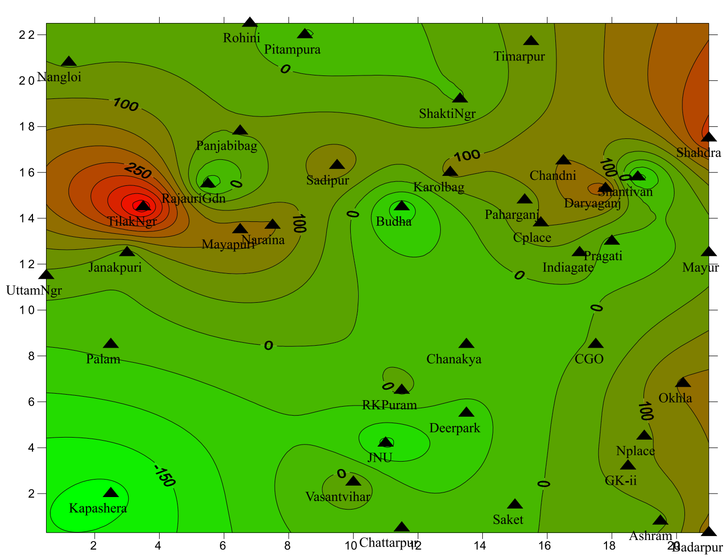

Fig. 5. Isopleth distribution of energy imbalance, winter 1998–99.

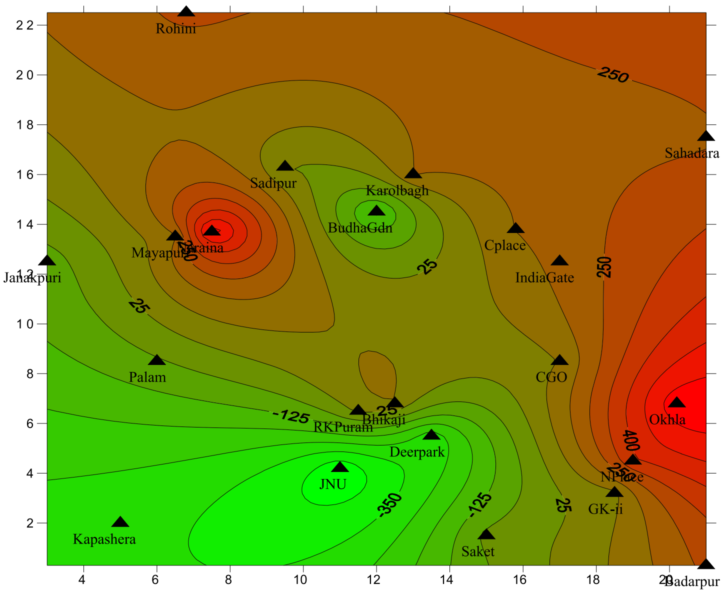

Fig. 6. Isopleth distribution of energy imbalance, summer 1998.

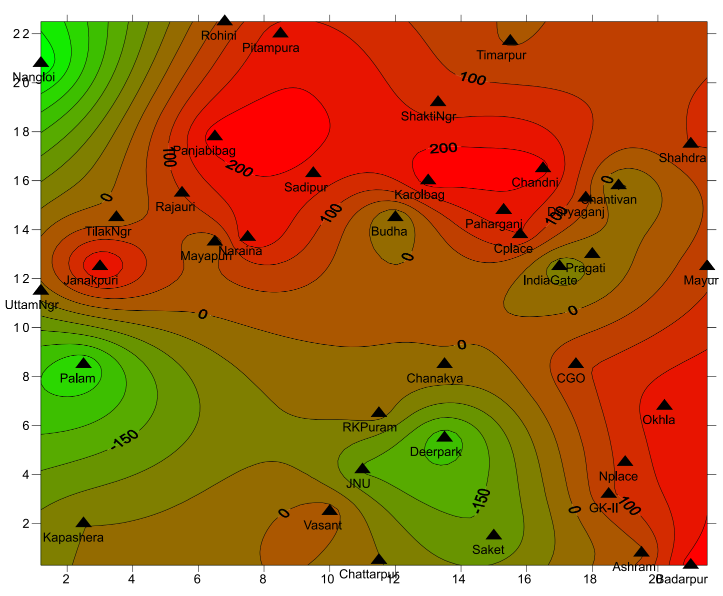

Fig. 7. Isopleth distribution of energy imbalance, summer 1999.

was no water surplus (WS). Aridity Index (I_a) was found to be greater in rural sites than urban sites in both years. On an average I_a was greater by about 28% in 1997 compared to 1998 in the urban locations. In contrast, it was about 17% more in 1997 in the rural locations. This indicates that the corresponding moisture index (I_m) tends to be more positive in the rural sites than urban sites when compared 1997 and 1998 and climatic type according to *Thornthwaite and Mather (1958)* revised scheme, and so remains as semi-arid. But the water balance analysis of UREMBS–94 data shows that moisture index (I_m) in the urban areas was –30.63% and in its rural counterpart it was about –38%. This shows that I_m is tends to be positive in the urban areas (as I_m was about 6% more) compared to rural parts in 1994. Thus, the climate of rural areas remained as semi-arid but that of urban area shifted to dry sub humid (Table 4).

Table 3. Comparison of PE computed by Thornthwaits and Penman methods and climatic type over Delhi for Climatological normal years

CLIM. YRS.	*PE*	*WS*	*WD*	*Ih* (%)	*Ia* (%)	*Im* (%)	Climatic type
Thornthwaits	1419.27	0.0	470.8	0.0	33.17	-33.17	semi-arid
Penman	1408.00	0.0	693.0	0.0	49.21	-49.21	semi-arid

PE = 0.8% departure from Penman's'

Table 4. Water balance climatic type (*Thornthwaits' and Mather 1958*, revised scheme), over Delhi, UREMBS–94

1994	*PE*	*WS*	*WD*	*Ih* (%)	*Ia* (%)	*Im* (%)	Climatic type
Urban	1436	77.4	517.3	5.38	36.02	-30.63	dry sub humid
Rural	1413	6.8	543.6	0.48	38.47	-37.99	semi-arid

Table 5. Water balance climatic type (*Thornthwaite and Mather, 1958* revised scheme), over Delhi, 1997–1998

1997	*PE*	*WS*	*WD*	*Ih* (%)	*Ia* (%)	*Im* (%)	Climatic type
Urban	1338.20	0.0	587.50	0.0	43.90	-43.90	semi-arid
Rural	1400.00	0.0	853.66	0.0	60.97	-60.97	semi-arid
1998							
Urban	1421.40	0.0	487.40	0.0	34.29	-34.29	semi-arid
Rural	1457.58	0.0	755.26	0.0	51.81	-51.81	semi-arid

5. Conclusion

- There persists energy imbalance in both the seasons, creating or generating heat/pollution sources and sinks in their respective urban and rural areas.
- The coexistence of sites of energy surplus and deficit mutually nullify and keep in balance.
- These surplus and deficit of energy in the tropical megacities could be attributed to the urbanization; sometimes the synoptic weather conditions prevail over the regions.
- Shift in climate in the urban areas during UREMBS–94 as compared to 1997/98-water balance analysis may be due to higher rainfall occurred during 1994. This supports the theory of augmentation of precipitation in the urban agglomeration due to thermal convection and increased condensation nucleii (suspended pollutants) as compared to their rural surroundings.

However, it is recommended to further investigate the energy and water exchange processes over tropical cities to draw the relationship among their various components and quantify the magnitude and direction of transport/exchange of the properties and examine the moisture status and resulting climate of the biophysical environment.

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