# LONG TERM SPATIO-TEMPORAL VARIATIONS OF URBAN ENERGY FLUXES USING EARTH OBSERVATION DATA FOR DELHI

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**KEY WORDS:** Urbanization, Surface Energy Balance, Urban Energy Fluxes, Earth Observation, Anthropogenic heat

**ABSTRACT:**

The rapid urbanization and population growth in Delhi have led to significant changes in the land and land cover, resulting in increased emissions and alterations in the urban energy balance. To understand these long-term trends and identify contributions factors, a study was conducted using Landsat series data and meteorological data from the ECMWF ERA-5 reanalysis. The study focused on estimating urban energy fluxes, including Net Radiation, Sensible heat flux, Latent heat flux and Ground heat flux with anthropogenic heat considered as the residual. The findings reveal a substantial increase in the anthropogenic heat flux, rising from 172 W/m$^2$ in 1990 to 281 W/m$^2$ in 2022. Seasonal variations were also observed, with the highest energy flux values occurring during the summer season, followed by post monsoon and winter season. Net radiation ranged from 650 to 700 W/m$^2$, sensible heat flux ranged between 250-300 W/m$^2$, latent heat flux ranged between 250-300 W/m$^2$ and ground heat flux ranged 30-120 W/m$^2$. Urban areas exhibited higher energy fluxes, emphasizing the importance of effective planning interventions to mitigate emissions in such areas. The study highlights the potential of Earth observation based approaches in estimating and balancing urban energy fluxes, while also emphasising the need to consider seasonal and spatial variations in the land use pattern when formulating strategies to mitigate emissions in the urban areas.

## 1. INTRODUCTION

World is urbanising at a rapid rate where the population living in urban areas has increased from 28.3% in 1950 to 55% in 2020 and is expected to increase by 68% by 2050 as per UN DESA (United Nations, 2019). India is also experiencing rapid urbanization with an urban population increase from 17.35% in 1951 to 31.4% in 2011 as per 2011 census of India (Government of India, 2022). Urbanization causes rapid changes in the Land Use Land Cover (LULC) and also leads to increase in the surface and atmospheric temperatures due to increased energy consumption and activities of human, change in the surface type by decreasing the vegetation cover, water and pervious surfaces (natural land surface into impervious surface), high albedo materials and change in roughness characteristics. The exchange of energy between the land surface and atmosphere within urban areas is impacted by all of these changes (Lin and Xu 2020). LST is one of the other important factors which changes the air temperature of the urban atmosphere and also determines the surface radiation, energy exchange in the cities which depends on many parameters such as building heights, roughness, trees, traffic, land use and land cover (Weng 2009).

Anthropogenic heat refers to the heat released by human and their related activities in factories, residents, buildings and transportation which is emitted into the surrounding environment in the form of different heats such as sensible, latent and ground heat (Kato et al. 2008; Kato and Yamaguchi 2005). AH Flux is termed as the energy emitted because of the human activities per unit area and time. Urban anthropogenic heat is causing change in the energy flow between surface and atmosphere and causing urban ecological imbalance which is affecting the local climatic conditions, increasing air pollution and atmospheric environment (Zheng et al. 2021). Therefore estimation and quantification of the anthropogenic heat is of great importance to control and mitigate the factors causing urbanization on the climate and find surface energy balance (Peng et al. 2021). It has been observed that the artificial heat generated is leading to Urban Heat Islands (UHIs) by more than 50% & resulting in a rise in temperature by 0.5 Degree in Beijing , Tokyo , Guangzhou & other cities (Peng et al. 2021).

Urban energy fluxes can be estimated using different methods such as inventory approach, in situ method, earth observation method etc. The inventory approach requires inventory data of different sectors such as industries, buildings and vehicles, which is generally not available at a finer resolution. The In situ methods requires measurements of the fluxes using instrument which is an intensive task, requires large capital and cannot be carried out for a large cities (Hu et al. 2012). Earth Observation (EO) data are used in order to estimate urban energy fluxes for large areas and deemed as a reliable and potential source to estimate the urban energy fluxes continuously for large areas.

EO data along with the meteorological data are combined in empirical equations using Surface Energy Balance (SEB) method where the anthropogenic heat is the additional heat released mainly due to the human and their related activities and is considered as the residual. It is also useful in monitoring the spatio - temporal variations. Kato & Yamaguchi (2005) were the first one to introduce a method which separates Anthropogenic heat from sensible heat using ASTER and Landsat data Urban Energy Fluxes were computed using MODIS and Landsat and observed Increase in population and intense anthropogenic activities resulted in high temperature and high anthropogenic heat flux in Delhi (Chakraborty, Kant, and Mitra 2015).

## 2. STUDY AREA

The study area taken for the study is the Delhi urban agglomeration with surrounding villages located at 28º61’N and 77º23’E, lies on the Yamuna river bank (Figure1). It is the national capital of India which has experienced a tremendous growth of population from neighbouring towns. The population has increased from 2.5 billion in 2001 to 16 billion in 2011as per census of India. The city is one of the most polluted city in India due to the density which is 11,320 persons per sq.km, usage of large number vehicles, appliances and the complex urban structure of the city.

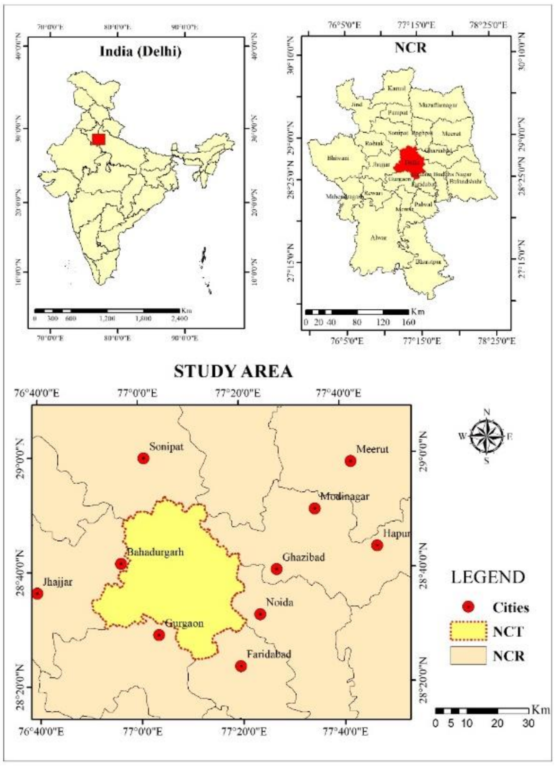


**Figure 1**.Study Area Map

## 3. MATERIAL AND METHOD

### 3.1 Dataset used

The data used in this study mainly includes, Landsat series data such as Landsat 5 and Landsat 8 with a spatial resolution of 30m for multispectral bands and the thermal bands has a resolution of 120 & 100m which were resampled to 30m. The meteorological data is taken from ERA5 Land hourly data from the ECMWF $5^{th}$ Generation Reanalysis data which has a spatial resolution of 11kms. These data sets were retrieved from GEE to calculate various input parameters such as LULC, NDVI, LST and albedo in order to give various energy fluxes.

| Data | Spatial Resolution (m) | Temporal Resolution |
|---|---|---|
| Landsat 5 TM (1984 -2013) | MSS- 30, TIR- 120 | 16 Days |
| Landsat 8 OLI/TIR (2013 -2022) | MSS- 30, TIR- 100 | 16 Days |
| ERA5 Land Hourly data | 11,000 | Hourly |

**Table 1.** Data sets used in the study

### 3.2 Estimation of Urban Energy Fluxes using Surface Energy Balance Method

The LULC classification is performed for all the seasons for different years from 1990 to 2022 using random forest classifier. Different classes such as Built-up, water bodies, vegetation, agriculture and bare soil. The overall accuracy achieved was more than 85% and kappa statistic is more 0.7.

The surface energy balance method is used to estimate the urban energy fluxes as shown in the equation (1)

$$Rn = G + LE + H \quad (1)$$

Where Rn is the Net radiation, G is the Ground heat flux, LE is the Latent Heat Flux and H is the sensible heat flux. For Natural land surface the Net Radiation is balanced by the remaining fluxes as shown in the Figure.2.

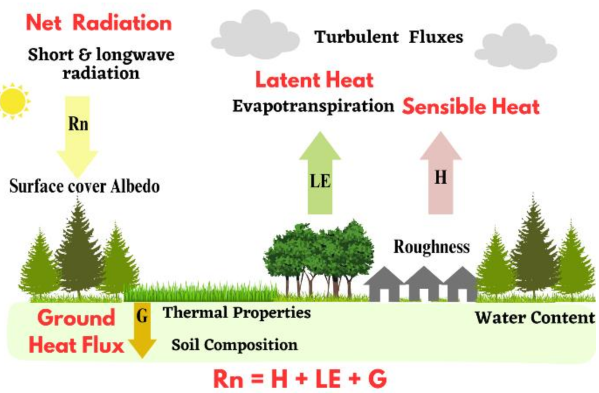


**Figure 2**.Rural Surface Energy Balance (source: author)

Anthropogenic heat is the additional heat released due to the human's activities as represented in the Figure 3. The heat is discharged in the form of Latent, sensible and ground heat from the vehicles, industries and living activities of the human beings. The equation (2) is modified as given bellow (Oke 1982).

$$Rn + AH = G + H + LE \quad (2)$$

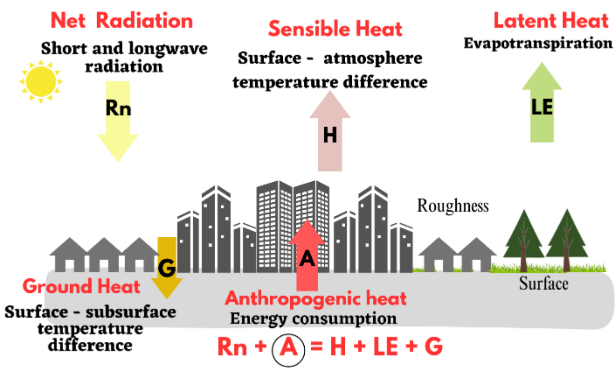


**Figure 3**.Urban Surface Energy Balance Equation

**3.2.1 Net Radiation:** Net radiation is represented as the amount of solar shortwave radiation and longwave radiation reaching the earth surface. It can be driven by subtracting all the outgoing radiation fluxes from all the incoming radiation fluxes and it can also be defined as the amount of radiation gained and lost from the earth surface as given below in the equation (3) (Kato and Yamaguchi 2007).

$$Rn = \left( (Rs\downarrow + Rl\downarrow) - (Rs\uparrow + Rl\uparrow) \right) \quad (3)$$

The equation is simplified as the following equation (4)

$$Rn = (1-\alpha)Rs\downarrow - (\varepsilon o \sigma Ts^4) + (\varepsilon a \sigma Ta^4) \quad (4)$$

$Rs\downarrow$ is the incoming shortwave radiation ($W/m^2$) .LST, α and ε is the surface albedo and emissivity which can be derived from the remote sensing data. Surface albedo is calculated using the SEBAL formulae using the path radiance (Waters et al. 2002). $\varepsilon a$ is the atmospheric emissivity which is estimated using empirical equation given by kato and Yamaguchi which is given below (Kato and Yamaguchi 2005).

$$\varepsilon a = 0.85 * (-\mathrm{In}\tau_{sw})^{0.09} \quad (5)$$

**3.2.2 Land Surface Temperature (Ts)**

Thermal band of Landsat 8 is used to estimate the Land Surface temperature using the radiative transfer equation method as equation (6).

$$Ts = \frac{C_1}{\lambda_i * \mathrm{In}\left( \lambda_i^5 * \frac{C_2}{\left[ \frac{L_\lambda - L_\uparrow - \tau_i * (1-\varepsilon) * L_\downarrow}{\tau * \varepsilon} \right]} + 1 \right)} \quad (6)$$

Where Ts is the LST in K and $L_\lambda$ is the at sensor radiance value in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$ units. ε is the surface emissivity . $L\uparrow$, $L\downarrow$, τ are the up-welling , down welling path radiance and atmospheric transmittance respectively which have been extracted from the online atmospheric correction tools from NASA (https://atmcorr.gsfc.nasa.gov/). The value of $C_1$ = 14,387.7μmK, $C_2$ = $1.19104*10^8\ W\mu m^4\ sr^{-1}\ m^{-2}$. $\lambda_i$ is the effective band wavelength of the respective band that is 10.896μm for band 10.

**3.2.3 Ground Heat Flux:** Ground Heat flux is the rate of heat storage into the soil and vegetation by conduction. It is computed using the empirical formula developed by the Bastiaanssen in 2000 by first finding the ratio of G/Rn which is given as follows in the equation (7) (Waters et al. 2002) (Sauer and Horton 2005).

$$\frac{G}{Rn} = \frac{Ts}{\alpha}(0.0038\alpha + 0.0074\alpha^2)(1 - 0.98NDVI^4) \quad (7)$$

**3.2.3 Sensible and Latent Heat Flux:** Sensible heat is the difference in the air and land surface temperature due to transfer of heat (Kato et al. 2008).

$$H = \frac{\rho \times Cp \times dT}{ra} \quad (8)$$

Sensible heat is the rate of heat loss from land to air due to the transfer of heat (Waters et al. 2002). It is computed using the equation (8), where $\rho$ is the air density, Cp is the specific heat at constant pressure, dT is the Temperature difference, ra is the aerodynamics resistance.

The aerodynamic resistance is calculated using the equation (9) where z2 and z1 is the maximum and minimum height of the urban built-up obstacles in the study area, k is the von Karman's constant (k = 0.41), u is friction velocity constant (m/sec) (Allen et al. 1998).

$$ra = \frac{\mathrm{In}\left(\frac{z2}{z1}\right)}{u * \times k} \quad (9)$$

Friction velocity constant (u*) is calculated using the known wind speed (ux) which is been estimated using the ERA5 Land hourly data. zom is the roughness height for momentum transfer in meters as given in the equation (10).

$$u* = \frac{kux}{\mathrm{In}\left(\frac{zx}{zom}\right)} \quad (10)$$

**3.2.4 Latent Heat Flux:** Latent heat is expressed as following equation (11) (Kato, Yamaguchi 2005).

$$LE = \frac{\rho Cp(es - ea)}{\gamma(ra + rs)} \quad (11)$$

ρ is the air density (1.2 kg/m3 ) , $Cp$ is the specific heat of the air at constant pressure (1005 J/Kg) , ɣ is the psychrometric constant (0.67 hPa/K), ra is the aerodynamic resistance and rs is the stomatal resistance . Where (es) and (ea) are saturated vapour pressure and actual vapour pressure in hPa.

Nishida et al. (2003) has modified the rs formula by using only remote sensing parameters as given in the equation (12).

$$\frac{1}{rs} = \frac{f1(Ta)f2(PAR)}{rs_{min}} + \frac{1}{r\ cutile} \quad (12)$$

Where $rs_{min}$ is the minimum resistance values that have been taken from study conducted by kato and yamaguchi (2007). f1(Ta) and f2(PAR) are the functions of temperature and photosynthetic active radiation (PAR) respectively which is estimated using the following set of formulas (13),(14).

$$f1(Ta) = \left(\frac{Ta - Tn}{To - Tn}\right) \times \left(\frac{Tx - Ta}{Tx - To}\right)^{\left(\frac{Tx - To}{To - Tn}\right)} \quad (13)$$

$$f2(PAR) = \frac{PAR}{PAR + A} \quad (14)$$

The Anthropogenic heat is estimated with the sensible heat which consists of artificial energy and expressed as Hn (15) and is estimated using the radiant heat balance equation (16) as follows

$$Hn = Rn - G - LE \quad (15)$$

$$Has = Has - Hn \quad (16)$$

Where anthropogenic heat is the net increase in the sensible heat flux in the form of artificial sensible heat. Where the total H is smaller than Hn the following formulae (17) is used to estimate the Anthropogenic heat.

$$Has = Hn - H \text{ or } Has = H - Hn \quad (17)$$

## 4. RESULTS AND DISCUSSION

### 4.1 Annual Urban Energy Fluxes

**4.1.1 Net Radiation:** Net Radiation is the energy present at the earth surface. It is generally high in vegetation and agricultural areas due to the high albedo and low surface temperature values. The annual net radiation ranges from 450-600W/m² as shown in the Figure 4. There is no significant trend in the net radiation observed in the Mann Kendall test, which is a statistical tool to identify the monotonic trend.

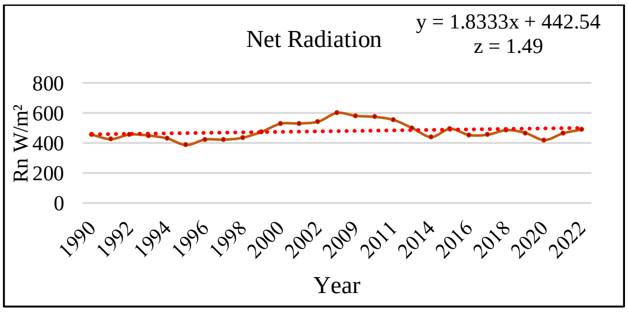


**Figure 4.** Annual Net Radiation

**4.2.2 Ground Heat Flux:** Annual Ground heat flux ranges from 40-100 W/m² as shown in the Figure 5. It is mostly high in the built-up class due to the good heat storage capacity of the materials and structures. The ground heat flux showed an increasing trend in the Mann Kendall test due the increase in the built class from 1990 to 2022 with the increasing population. The annual mean ground heat flux is ranges from 30 to 100 W/m².

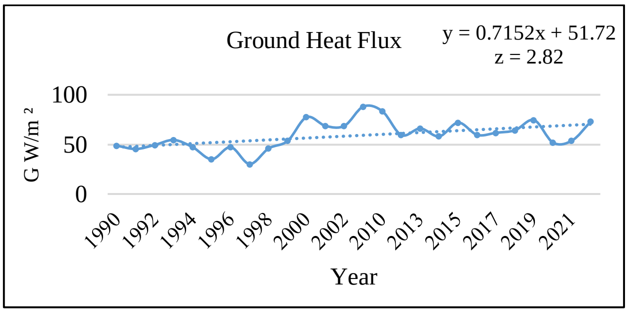


**Figure 5**. Annual Ground Heat Flux

**4.2.3 Sensible Heat Flux:** Sensible heat flux showed a significant increase in the Mann Kendal test due to the continuous increase in the difference between the air and land surface temperature as shown in the Figure 6. The growth of the city might be one of the reason for the increase in the sensible heat flux as it changes agriculture and vegetation into built-up and bare soil. The annual mean sensible heat flux ranges from 50 – 200 W/m².

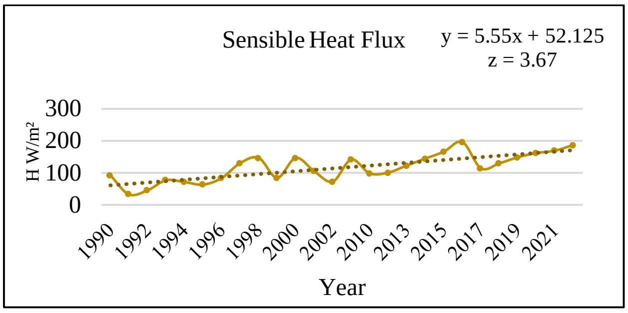


**Figure 6**.Annual Sensible Heat Flux

**4.2.4 Latent Heat Flux:** Latent Heat flux showed an inverse pattern of sensible heat flux as shown in the Figure 7. The latent heat flux mostly depends on the amount of water content in the leaves and rate to evapotranspiration. The latent heat flux did not show any trend in the Mann Kendall test.

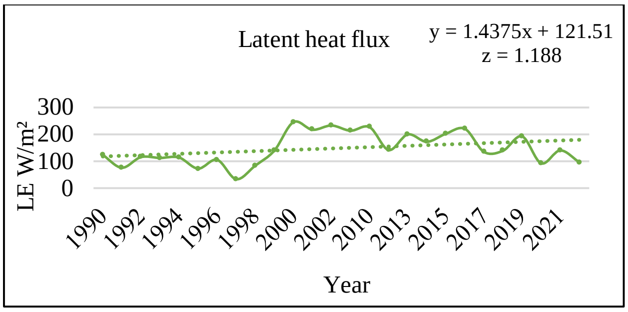


**Figure 7.** Annual Latent heat flux

**4.2.6 Anthropogenic Heat Flux:** The anthropogenic heat flux generated due to the human activities showed crests and troughs pattern as shown in the Figure 8. The overall anthropogenic heat flux showed an increasing trend with a z value of 3.10. The dips in the anthropogenic heat flux might be due to the planning interventions that have taken place in Delhi to reduce the emission. It has showed a significant drop in the year 2020 due to COVID pandemic.

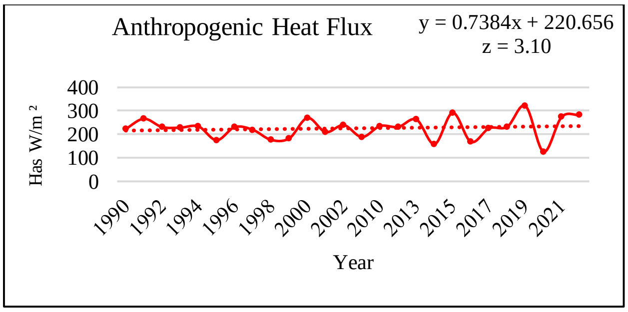


**Figure 8:** Annual Anthropogenic Heat Flux

**4.2.7 Mann Kendall Test for Annual Urban Energy Fluxes**

Mann Kendall test is a statistical test which detects the trend pattern in time series data and was performed for the energy fluxes which states monotonic upward or downward trend over a time (Hamed and Ramachandra Rao 1998). This test is preferable when there is missing data. The z value in the test represent the normalized test statistic values. The Theil Sen's slope is sub component of Mann Kendall test which is used to determine the magnitude of the trend (Kamal and Pachauri 2019). If the normalized test statistic value z is more than 2, the trend is increasing and if it is less than 0 it is decreasing. If the z value is between 0 and 2 then there is no trend. The table 2 represents the annual Mann Kendal test results of the different energy fluxes.

| Flux | Trend | z value | Sen's Slope |
|---|---|---|---|
| **Net Radiation** | No Trend | 1.49 | 1.83 |
| **Ground Heat Flux** | Increasing Trend | 2.82 | 0.71 |
| **Sensible Heat Flux** | Increasing Trend | 13.95 | 5.55 |
| **Latent Heat Flux** | No Trend | 1.18 | 1.43 |
| **Anthropogenic Heat Flux** | Increasing Trend | 3.10 | 0.73 |

**Table 2.** Mann Kendall Test of Annual Energy Fluxes

**4.3 Seasonal Urban Energy Fluxes:** Seasonal urban energy fluxes were performed to find the variations in the different seasons. The energy fluxes vary depending on the earth sun distance, amount of radiations received, humidity and amount of water content present on the surface. All the energy fluxes were dominant in the summer season, this is mostly because of the large volume of radiations received by the earth and the distance between them is less in the summer season.

Factors such as clear sky, no cloud cover, less precipitation, high albedo results in high net radiation as earth receive large amount of radiations in summer season. The mean net radiation in summer ranges between 500 $W/m^2$ to 680 $W/m^2$ followed by post monsoon and least in winter ranging from 300 $W/m^2$ to 450 $W/m^2$. No trend is observed in any season in the net radiation. The ground heat flux is high in summer season due to less moisture content in the soil and due to good heat storage capacity of the building materials. It is least in the winter season less than 50 $W/m^2$.

The sensible heat flux is high in summer season and showed an increasing trend in all the seasons due to the increased difference between LST and the air temperature mainly owing to the increase in the impervious surface. The sensible heat flux is about 200 – 350 $W/m^2$ in summer and least in winter season ranging less than 150 $W/m^2$. The anthropogenic heat flux also showed an increasing trend in all the seasons where as it is high in summer due to more usage of appliances for cooling. The anthropogenic heat flux in summer season ranges from 250 – 350 $W/m^2$ followed by post monsoon (200-250$W/m^2$) and least in winter ranging from (100-200$W/m^2$).

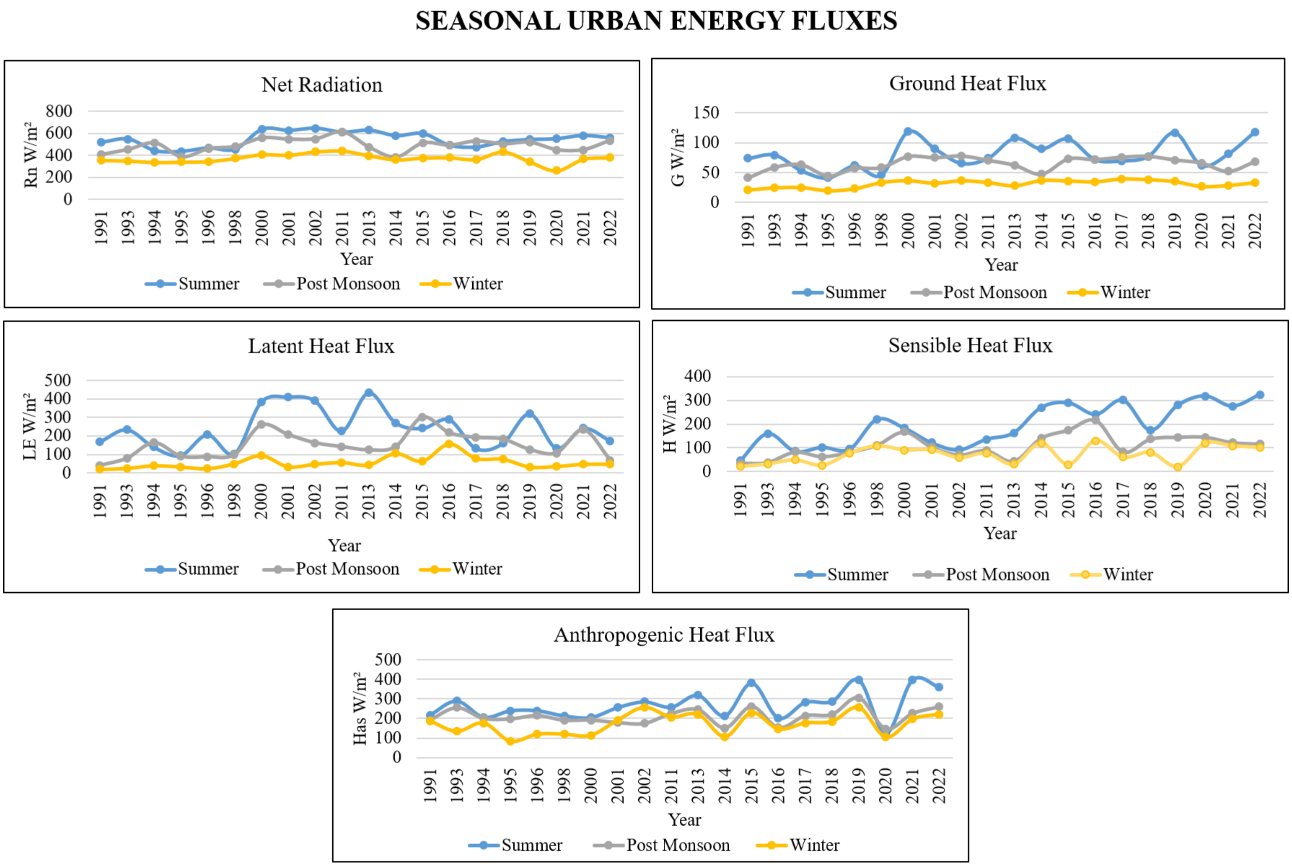


**Figure 9.** Seasonal Trend of Urban Energy Fluxes

### 4.3.1 Seasonal Mann Kendall Test

The Mann Kendall test is also performed for the seasonal urban energy fluxes to identify the trend pattern as represented in the Table 3. The net radiation did not show any trend in any season with the z value less than 2. Whereas Ground heat flux, Sensible heat flux and anthropogenic heat flux showed an increasing trend in all the seasons.

| Energy Flux | | Summer | Post Monsoon | Winter |
|---|---|---|---|---|
| Rn | Trend | No Trend | No Trend | No Trend |
| | z value | 1.25 | 1.44 | 0.97 |
| | SS | 2.85 | 2.46 | 0.77 |
| G | Trend | Increasing | Increasing | Increasing |
| | z value | 4.96 | 2.44 | 2.86 |
| | SS | 1.63 | 0.69 | 0.51 |
| H | Trend | Increasing | Increasing | Increasing |
| | z value | 2.44 | 2.73 | 3.71 |
| | SS | 12.30 | 4.43 | 2.94 |
| LE | Trend | No Trend | Increasing | Increasing |
| | z value | 0.54 | 2.22 | 3.34 |
| | SS | 1.79 | 4.61 | 1.86 |
| AH (Has) | Trend | Increasing | Increasing | Increasing |
| | z value | 12.21 | 6.34 | 4.35 |
| | SS | 5.36 | 1.52 | 3.54 |

**Table 3**.Mann Kendall Test for seasonal urban energy fluxes

## 5. CONCLUSION

The urban energy fluxes play an important role in the surface energy balance. Sensible, anthropogenic and ground heat flux showed an increasing trend which is analysed using Mann Kendall Test. The Mann Kendall test is a statistical approach and a valuable tool for analysing trends in the energy fluxes. All the seasons observed an increasing trend in the sensible, ground and anthropogenic heat flux and no trend in the net radiation. With the increase in the population and change in the land use land cover the thermal properties of the urban areas have influenced the trend and pattern of urban energy fluxes. The earth observation is considered as a potential source to estimate the energy fluxes and there is a future scope to estimate anthropogenic heat flux at a higher resolution.

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