Urbanization Effect's on Air Quality, Rainfall, and Climate Change

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- Studied about Urbanization effect's on Air Quality, Rainfall, Clouds, and Climate Change.

- Studied 8 articles on Effects of Urbanization on Climate from 2 June 2021 to 26 June 2021.

- During this time I Understood and prepared a power point presentation on 8 articles and discussed it with Dr. Chandan Sarangi.

- Important topics which I understood from the 8 articles are :-

- **Urbanization Impact on Precipitation -**

- Urbanization is accompanied by artificial changes in land use/land cover, creating substantial contrasts in land surface characteristics between urban areas and surrounding rural areas.

- The detection, understanding, and future projection of weather and climate changes due to urbanization are important aspects in the discipline of urban meteorology and climatology.

- Structure and movement of cloud systems can be influenced by urban areas. Air parcels ascend over a heat island and ascend on the downwind side.

- Perturbation velocity is larger in the shear flow case than in the larger flow case. Gravity waves are generated by heating in a stably stratified atmosphere, so the velocity perturbations induced by an urban heat island in the linear, theoretical studies are essentially gravity waves.

- Atmospheric stability plays an important role in enhancing or suppressing updrafts or convections.

- As the boundary layer-becomes less stable, the downwind updraft cell induced by an urban heat island strengthens and the vertical extent of the downwind updraft cell increases.

- Downwind updraft cell induced by an urban heat island can dynamically initiate moist convection and result in surface precipitation in the downwind region under favorable thermodynamic conditions.

- Among spatially varying surface sensible heat flux, surface latent heat flux, and roughness length, the surface sensible heat flux radiations were found to have most significant impact on the development of precipitation.

- It is not clear whether disrupted or bifurcated convective systems produce more precipitation over/or downwind of cities. It can increase/decrease depending on the water vapor supply and degree of urban roughness**.**

- The summer precipitation reduction in some areas is due to the reduction in surface water availability in the extensive urban areas of the region.

- **Role of Aerosols-**

- Aerosols can significantly affect the development of clouds and precipitation by acting as cloud condensation nuclei or ice nuclei as well as by absorbing and scattering solar radiation.

- Aerosols slow down the conversion of cloud water to precipitation over the urban area.

- A downwind shift of precipitation results from the fact that anthropogenic aerosols suppress the warm rain process and therefore more cloud ice and snow (due to condensation), which can be advected farther downwind because of their lower sedimentation velocities.

- The simulation results have shown that the development of stronger convective cloud under higher aerosol concentrations is mainly due to the release of an increased amount of latent heat resulting from the enhanced condensation process.

- The low collision efficiency of smaller cloud droplets and the resulting stronger updraft under higher aerosol concentration result in larger liquid water content at higher level, leading to the enhanced riming process, which produces large ice particles.

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- **Surface Roughness-**

- Spatial changes in surface roughness can lead to changes in airflow.

- Larger surface roughness in a city than in its surrounding rural area causes air approaching the city to slow down near the upwind city boundary and/or over the city.

- The air approaching a city tends to divert around it and the diverted air can converge on the downwind side of the city, yielding upward motion there. Precipitation (and upward motion) is enhanced with increased roughness.

- **Effect of Surroundings on UHI (Urban Heat Island) Intensity-**

- UHIs within urban areas vary spatially based on the properties of the surroundings.

- UHI's are calculated using a PWS (Public weather station) air temperature (T urban) minus the air temperature of the closest AWS (Automatic weather station) (T rural), which is written as-

- UHI = T urban – T rural.

- Maximum values, regardless of their frequencies of occurrence, may have the strongest impact on human life.

- The extreme precipitation intensities could be influenced by many factors, such as atmospheric dynamic advection processes, atmospheric moisture availability and other processes, however, an overall enhancement of the precipitation could be expected based on the temperature increases.

- Maximum capacity of an air mass for holding water vapor, increases by 6-7% per degree of temperature increase (and also depends on region, duration, season, temperature range).

- In the evening, the strengthened difference between urban and rural temperatures led to an increase in magnitude of UHI circulation with dynamically upward flow in urban areas, which could increase the possibility of precipitation occurrences in the evening and night-time.

- Many studies have shown that temperature has a greater impact on the intensity of extreme precipitation than on its frequency of occurrence.

- The highest values of the maximum hourly precipitation and UHI max are evident in the summer months, and the difference between urban and rural precipitation tends to be greater in months with larger values for UHI max.

- Population density has a stronger link to building topology and the characteristics of the cities than does population number, and PD is further linked to sky visibility factor.

- A linear regression is obtained using least square estimation comparing UHI and PD.

- For very small population density, the averaged observed UHI is close to zero.

- The relationships between UHI and PD for the daytime and diurnal cycles tend to have weak correlation coefficients. In contrast, a significant positive relationship between UHI and PD was obtained for the night-time cycle.

- A greater intercept values is obtained for UHI max showing that a strong positive deviations of temperature could exist even when UHI ave is close to zero degree Celsius.

- **Spatial Rainfall Variability in Urban Environments -**

- Rainfall–runoff models are frequently used for restructuring, controlling, maintaining, and planning new urban water management infrastructure and strategies.

- Therefore, it is crucial to account for temporal and spatial rainfall variability of rainfall events as accurately as possible so as to avoid misleading simulation results. One solution to gain more spatial rainfall information is to utilize radar data, if available.

- Their drawback is that these measurements cannot account for factors that might change the rainfall intensity near the surface (because these are situated on an elevated surfaces).

- Further, the common resolution of C-band radars is 1 km2 per pixel, which can be too coarse for some model objectives.

- X-band radar systems with resolutions down to 1 ha that scan closer to the surface can solve a lot of the problems of C-band radar systems.

- These systems are not widely used in urban environments due to high investment and maintenance costs. Further, they also need local rain gauges to accurately account for precipitation volume as well.

- Most severe storms are categorized as convective summer storms and are the main challenge for local infrastructure management.

- The more rain gauges that are set up, the more accurate the information about the spatial variability of the rainfall will be.

- The amount of all possible combinations calculates as-
- Summation(k = 1 to n) $\binom{n}{k}$
- n = number of all available rain gauges
- k = number of rain gauges used to generate combinations
- n ranges from 1 to all available rain gauges for the current event with all combinations that fulfill a diversity criterion.
- The criterion means to reflect common sense in setting up a measurement network and limits the number of combinations to a manageable size.

- The diversity criterion for each combination within a number of rain gauges is:

$$\text{Summation } (i = 1 \text{ to } x) \; d_i / x \geq d_{all}$$

- x = number of all possible paths between rain gauges for the current combination.
- di = distance between 2 rain gauges.
- d all = mean of all distances between all available rain gauges.
- More intense rainfall shows a much higher spatial variability than the less intense ones.
- Spatial variability of rainfall decreases with decreasing temporal resolutions (12 hourly or daily rainfall).

- The only factor which shows a strong decreasing correlation is the interstation distance. The farther the rain gauges are apart from each other the worse there correlation is with each other, which will show spatial heterogeneity of measured rainfall values.

- Spatial rainfall variability affects the total variability especially for longer return periods of storms.

- Studies showed that rainfall increases not only downwind of the city but also over the city.

- Overwhelming number of daytime storms have showed urbanization impact (as compared to the less number of for the night). Storms tend to split when they approach the urban area and reemerge downwind of the city as a more powerful storm.

- **Meta-Analysis of Urbanization Impact on Rainfall Modification-**

- Even though it is known that Urbanization affects rainfall, studies vary regarding the magnitude and location of rainfall change.

- To develop a comprehensive understanding of rainfall modification due to urbanization, a systematic meta-analysis was undertaken.

- Results showed that Urbanization modifies rainfall, such that the mean precipitation is enhanced by 18% downwind of the city, 16% over the city, 2% on the left and 4% on the right with respect to the storm direction.

- The rainfall enhancement occurred approximately 20-50km from the city center.

Summary of Different papers -

- The studies were classified under two groups- those based off climatological assessments or those involving case studies-

- For the quantitative statistical part, case and climatological studies are together grouped and are used to calculate the summary effects (by summarizing the precipitation change in different locations such as upwind, downwind of the city) based on all the studies.

- A separate analysis regarding case studies and climatological precipitation under each subgroups of summer versus winter, observation versus model, day versus night is taken.

- However, because of the sample size considerations, studies restricted the quantitative meta-analysis for climatological studies only, and resort to descriptive discussion with respect to the case studies.

- An ANOVA is performed for different studies considering following main effects -

- A) Method: model and observations
- B) Event: case and climatology
- C) Diurnal : day versus night
- D) Season: summer and winter
- E) location of the rainfall change: upwind, downwind, center, right side or left side of the city.

Day and Night -

- Larger fraction of daytime storms are impacted due to the urban heat island effect.

- During the night, the land-atmospheric coupling is typically weaker as compared to the day, and as a result, the urban impact is also expected to be less dominant.

- **Model versus Observational studies -**

- Observational studies showed an increase in rainfall both at the center as well as downwind (19% and 22%), while model based climatological analysis showed a dominant increase over the center (by about 20%) and no significant increase downwind.

- The model result showed a relatively smaller change due to urban impact as compared to the observations.

- Whether this relatively muted response in the model is due to missing processes (e.g. Aerosol and land-atmosphere feedback) or the way results are analyzed (e.g. Station data in observations versus grid-averaged results in models) or the resolution (grid spacing) in the models which does not discretize the city-center and the downwind effect for an urban grid is not clear.

- The effect size is a standardized term, used for the comparison of results across different papers.

- **Effect Size -**
- $$ES = (P_u - P_{nu}) / P_{nu}$$

- Where the effect size is denoted as ES (precipitation change), Pu is the precipitation amount (mm) at a specific location (i.e., urban center or downwind) when urban area is present or under urban influence, While P nu is the precipitation amount (mm) at that location when urban area is not present (in model studies) or away from the urban influence (in observational studies).
- The effect size is for two specific precipitation attributes:
- (I) change in the amount, and
- (ii) change in the position.
- For case studies, it is typically based on daily data while for climatological studies, the rainfall volumes averaged over years/decades are typically taken.

- The meta-analysis consists of two steps:
- Homogeneous analysis and applying a summary model to articles-
- A homogeneity analysis was undertaken using the so-called ‘Q test’ to decide if the articles are consistent or not.
- By consistent, it means to determine if the results are similar or not (There may occur sampling errors).
- When there are larger sample, we need some quantitative measurement, which is obtained by examining Q-test results. If the articles are consistent, the fixed effect model is applied, otherwise the random effect summary model is applied.

- **Rainfall modification by Major Urban Areas-Observations from Spaceborne radar on TRMM satellite-**

- A potential Short coming of any study that attempts to link rainfall modification with urban areas is the difficulty of separating topographic and other effects (e.g.- sea breeze circulations, river-breeze circulations) from urban effects.

- These factors suggest caution when considering urban circulations against other mesoscale-induced circulations.

- To investigate the capabilities of satellite based measurements for identifying urban effects on rainfall, a working hypothesis was established.

- In this framework, hypothesized areas of urban effect and no effect on a climatological time scale were determined.

- This study identified the most frequent lower-tropospheric wind flow for each city and defined the hypothesized 'downwind affected region' and upwind control regions. This working hypothesis was a variation of this approach-

- 1) Areas within 25km of the city (e.g. The central urban area) will exhibit some level of enhanced precipitation due to the UHI effects.
- 2) Area within 25-75km downwind of the central urban area and within a 125 degree sector will exhibit the maximum impact area (MIA) of UHI effects.
- 3) Areas within 25-75km upwind of the central urban area are defined as the "upwind control area (UCA)".
- 4) Area within approximately 50km^2 orthogonal to the mean wind vector are considered to be minimal to no impact regions.

- The data examined in the Metropolitan Meteorological Experiment, provide evidence of mesoscale signatures of rainfall distributions and first steps in the use of satellite-based estimates in urban modification studies.

- This study utilized a spaceborne radar dataset from the TRMM satellite.

- Space-time averaged PR (precipitation radar) rainfall products were utilized to investigate rainfall modification by urban effects.

- The analysis was primarily conducted on mean monthly rainfall rates (mm h-1) at a height of 2.0km in 0.5 x 0.5 cells.

- **The rainfall rates were calculated as a part of the algorithm described as-**

- In the algorithm, unprocessed receiver counts are converted to calibrated received power with the standard radar equation.

- Conversion equations are then used to convert PR received power into radar reflectivity factor.

- This procedure is consistent with radar data processing with ground-based systems.

- The final steps in the processing involves conversion of reflectivity Z to rainfall rate estimates R using a Z-R relationship.

- As with ground-based radar systems, the specific Z-R relationship may vary depending on region, rain type, or season. The relationship selected is
- $$R= a*Z*b,$$
- In which a and b are functions of the rain type, freezing height, storm height, and absolute height.
- Effects of the difference in raindrop size distribution by rain type, phase state, temperature, and the difference in terminal velocity due to change in the air density with height are also accounted for.
- For more detailed Analysis, the mean rainfall rate value at each grid point was calculated over the 3-yr period for the months of May, June, July, August, and September. For a given point, a total of 15 mean monthly rainfall-rate values were averaged (3yrx5 months of data).

- The monthly rainfall rates at each grid point were aggregates of numerous pixels defined as 'rainy' by the algorithm over the 30-day period.

- The mean values were placed in the cartesian coordinates and contoured. In addition, an analysis of a parameter called the urban rainfall ratio (URR) was conducted, with
-
- RI / RBG
- Where R^I represents a given mean rainfall rate at a grid point and R^BG is the mean background value. This value is the average of all mean rainfall rates in the entire control coordinate system and encompasses values in the upwind control, maximum impact, minimum impact, and urban areas.

- Essentially, the URR is a measure of the relative magnitude of a given point to a background point, and values greater than one are considered to be positive anomalies.

- URR rates for all grid points in the control coordinate system for all cities in the study showed that 70% of the values above a reference value of 1 (i.e. the threshold for positive anomalies) were found in the downwind maximum impact area (MIA).

- It also revealed that majority of upwind control points (76%) have URR value less than 1. which indicated a downwind bias towards increased rainfall rate.

- The majority of the points in the minimum impact area fall below URR values of 1 and values over the urban center generally cluster close to 1.

- To evaluate the significance of the differences in warm-season rainfall rates between the upwind control area and hypothesized areas, statistical t tests were applied.
- The t test gives the probability that the difference between the mean of two groups is caused by chance rather than some forcing or circumstance.
- It is customary to establish that if this probability is less than 0.05, the difference is significant and not caused by chance.
- Significance testing indicates the following mean values for all cities in the study:
- 1) major impact area versus upwind control, probability = 0.034 (not due to random chance).
- 2) urban area versus upwind control, probability = 0.805.

- As experimental and real-time weather prediction models continue to approach smaller spatial scales, the researches may require mesoscale models to consider urban surfaces and their characteristics in surface-land parameterizations.

- **Observations of rainfall around greater Kanpur-**
- Four years of high-resolution(half-hourly) in situ rainfall measurements were conducted from a network of three AWSs over the greater Kanpur.
- Frequency-intensity comparison of rainfall measures at these sites was performed to establish the difference in frequency and magnitude of rainfall among the urban and rural sites within the network at various sites.
- Only measurements between June and September for days when all the three sites were operational were included in the analysis.
- Attenuation-corrected radar reflectivity factor (Ze) observations from the precipitation radar on board the Tropical Rainfall Measuring Mission satellite were used to gain a better overview of the spatial distribution of rainfall over the greater Kanpur region.

- Lower Ze values from TRMM-PR had high uncertainty.

- The high spatial resolution is important for determining the climatology and spatial variations of rainfall over the small area.

- **Data and Methods -**

- WRF (Weather research and Forecasting) has good ability in simulating the Indian Monsoon depressions.

- The WRF Model, was configured to simulate the regional weather prevalent over India using three nested domains during 4-20 August 2011.

- The outermost domain had a resolution of 27km and comprised the southeast Asian region.
- The innermost domain had a resolution of 3km, centered over the GB (Gangetic Basin).
- The intermediate resolution domain (9km resolution) bridged the resolution difference between the innermost and outermost domain.

- The CNN aerosol category is designed as a combination of sulfates, sea salts, and organic matter, while the IN aerosol category mainly resembles dust concentration.

- Multiyear global model simulations were performed with prescribed aerosols emitted by natural and anthropogenic sources.

- The simulated CCN concentration is used to predict cloud water droplet concentration spectrum in the microphysical spectrum.

- The 30 min Moderate-Resolution Imaging Spectroradiometer (MODIS) data set provided static geographical fields, such as terrain height, soil properties, vegetation fraction, land use, and albedo, which were interpolated to the domain grids by using the WRF preprocessing system.

- Good correlation between the in situ measured accumulated rainfall values and simulated accumulated rainfall over corresponding WRF was seen.

- The good correlation was mostly due to the stations over the plain regions of North India.

- Correlation Coefficient of the association is lower for the stations in Himalayan foothills.

- The urban regions of Kanpur received more rainfall compared to nearby rural regions upwind of Kanpur.

- The cities were arranged from left to right within each CCN bin in an ascending order of their longitudinal extent (east-west span).

- This is done to visualize the effect of increasing urban area on Enh raindownwind and Enh rainurban within the narrow availability in CCN values.

- Enh raindownwind is more closely associated with the CCN loading than the increase in Enh rainurban with CCN during storm passage over the cities.

- Increase in Enh raindownwind values with increase in CCN loading is relatively larger (~2 times) over bigger cities compared to that over smaller cities. But for Enh rainurban change is negligible suggesting saturation of CCN effect on Enh rainurban over big cities.

- Ground heat fluxes and Sensible heat fluxes were higher, but the latent heat flux were lower at urban center in the CNTEX simulations (urban LULC) compared to NOURBEX (natural LULC). Higher ground heat flux urbanization causes more storage of available energy at the surface and increases the soil temperature.

- At the same time reduction in vegetation and availability of natural surface under urbanization causes reduction in evapotranspiration and reduces the LHF (latent heat flux).

- This increases the soil-air temperature which coupled with reduction in evapotranspiration, results in favorable dissipation of available energy via SHF affects the near-surface layer and increases its temperature under urbanization, which causes UHI effect.

- Local Climate Zone classification is an effective method to quantify the UHI intensity. They are classified as regions of uniform surface-air temperature distribution at horizontal scale of 10^2 to 10^4 meters.

- On site measurements were carried out to record urban parameters which best match with those present in the city.

- The source area of each field was parametrized by the differentiating properties of the LCZ (local climate zone) classes. E.g.- sky view factor, canyon or building aspect ratio, building surface fraction, Impervious surface fraction, pervious surface fraction, mean building height were measured.

- The instantaneous difference between all observational points and the reference site is calculated in order to determine UHI intensity.

- UHI intensity of each zone is highly influenced by type of adjacent zones.

- As the radial distance to adjacent zones or area of the zones increases, the effect of that zone to the UHI intensity also dominates.

- UHI intensity of zones with large pervious surface (Example – SB) decreases as the area of the zone increases. Zone boundary distance represents the influence of each zone and nearest adjacent zone tells the control of adjacent zone on the UHI intensity.

- **Urban Heat Island and Mitigation Strategy -**

- Utilizing ENVI-met simulations and through Urban Futures Assessment Method (UFAM), it is easy to identify and test resilient and effective UHI mitigation strategies.

- Resilience of UHI refers to the extent to which these UHI mitigation strategies will be able to achieve their design purpose and sustain in the face of a changing future.

- ENVI-met is a three dimensional non-hydrostatic microclimatic model that allows for complex modelling and detailed investigation of urban microclimate. It shows a good resolution that satisfactorily models small-scale interactions between buildings, surfaces and plants.

- The UFAM is a 5-stage assessment methodology which assesses the ability of today's sustainable strategies to deliver their intended benefits in the future

- Selected Mitigation Strategies-
- Vegetation in the form of trees, shrubs, and grass.
- Presence of water in form of urban inland water bodies excluding rivers and waterways.
- Use of materials and high albedo rating (HAM).
- Other urban strategy that is used to mitigate urban heat island is cool colors and cool materials.
- Parks and green spaces help to mitigate the heat island effect and reduce energy consumption for cooling buildings in the summer, while also maintaining changes of temperature induced by building materials.

- Vegetation is awarded a resilience rating of 6.25 out of 10 and is therefore a reasonable choice when aiming for resilient UHI mitigation strategy.

- Albedo of green areas is 25% in comparison to traditional surfaces and buildings which is 15%.

- During nighttime, the temperature in planted species is higher than the temperature in non-planted space due to sky view factor. Low sky view trap more heat during nighttime.

- Therefore it is advisable to study the relationship between tree spread and streets ratio to provide more shade for sidewalks and keep sky view open (to make the heat escape to the atmosphere during nighttime). E.g.,- Palm trees.

Practical Part-

Analyzed rainfall increase or decrease on the downwind side of urban area, over a urban area, left and right side of a urban area, and upwind side of a urban area.

Used Python, Python GeoPandas, and different Python libraries such as Pandas, Numpy, Matplotlib, for analyzing and plotting the Mean temperature, Mean daytime and Mean nighttime temperature, mean minimum and mean maximum temperature, Mean Rainfall, Mean daytime and Mean nighttime Rainfall, mean minimum and mean maximum Rainfall, Mean Humidity, Mean daytime and Mean nighttime Humidity, mean minimum and mean maximum Humidity, on a Python basemap of Chennai and it's nearby cities (Total 18 different locations of and outside the Chennai city).

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Thank you!!