Impacts of land-use land cover and urban canopies on Meteorology and Air Quality from WRF modelling

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Overview

• Introduction

• Case studies about impact of LULC on weather and Air Quality

• Field Campaigns over Delhi

• WRF-Modelling including landuse landcover and urban canopies

• Conclusions
Introduction

• 50% of the global population lives in the urban areas
  – projected to reach around 69% by 2050.

• Primary drivers of LULC changes
  – Continuous population growth → economic expansion

• Environmental changes across the globe mainly in the developing countries.

• Rapid worldwide change of the green and agricultural land to urban settlements.

• Urbanization significantly impacts regional near-surface air temperatures, wind fields, the evolution of the planetary boundary layer (PBL), and precipitation, subsequently influencing air quality, human comfort, and health.
Role of land use/land cover

• Fluxes of energy, momentum, water, heat are parametrized in NWP models as functions of
  – Surface albedo
  – Surface moisture availability
  – Surface emissivity
  – Surface roughness
  – Surface thermal inertia
Which are specified for a given LULC.

• Thus, Land use/cover determines inputs to be used by land surface models which compute land-atmosphere fluxes.
LU changes across the megacities of world

Dubai (1990-2007)
Shanghai (1990-2010)
Panama (1930-2009)
Tokyo (1960-2010)
Impact of LULC Changes: Case Studies

(i) Extreme heat events in Phoenix Metropolitan Area*

Here, the WRF/Noah UCM modeling system is applied to analyze the effects of urban land use changes on the magnitude of day- and nighttime temperatures during the Extreme heat events.

Landsat derived land use data for 1973, 1985, 1998, and 2005 are used to provide the basis for model parameter values.

Topography (contours from 0 to 3000 m; interval 250 m) and LULC for 1973, 1985, 1998, and 2005. Based on Landsat satellite-derived LULC data. To emphasize the urban land use changes the colors are grouped together for the rural land use classes (grassland, shrubland, deciduous broadleaf forest, evergreen needle leaf forest).

Average difference in air temperature 2 m 2005 LULC and historic LULC data 1973, 1985, and 1998) for (top) 0500 LST and (bottom) 1700 LST. Also included are topography contours (from 0 to 3000 m; interval 250 m).

Results show that urban land use characteristics that have evolved over the past about 35 years in the Phoenix metropolitan region have had a significant impact on extreme near-surface air temperatures occurring during EHEs in the area. Simulated maximum daytime and minimum nighttime temperatures were notably higher because of the conversion of agricultural to urban land use.

A month-long simulation were conducted by Xuemei et al., (2009) using WRF-Chem to investigate the effects of urban expansion on surface meteorology and ozone concentrations in two rapidly expanded urban areas located in slightly different climate regimes: Pearl River Delta (PRD) and Yangtze River Delta (YRD) regions of China.

Fig: The land-use data sets used for the WRF-Chem simulations:
Upper panel is for 1992–1993 USGS data of PRD (left) and YRD (right)
Lower panel is for 2004 MODIS data of PRD, PRD (left) and YRD (right)
The only change between upper and lower panel for both the regions is the urban areas marked in red.

Simulation results indicate that urbanization (corresponding regions of PRD and YRD highlighted by green circles in the figures):

(1) increases both day- and night-time 2-m temperatures by about 0.6°C and 1.4°C, respectively;

(2) decreases both day- and night-time 10-m wind speeds, and the daytime reduction (by 3.0 m s\(^{-1}\)) in wind speed is larger than that for the nighttime (by 0.5 to 2 m s\(^{-1}\))

As in above figure, but for the difference of the monthly-averaged 10-m wind speeds.

Urbanization increases surface ozone concentrations by about 4.7%–8.5% for the nighttime and by about 2.9%–4.2% for the daytime in the PRD and YRD regions (highlighted by green color in the figures).

(1) WRF/Chem model validation for Ozone

Gupta and Mohan; Atmos. Environ., (2015), 122, 220-229
Simulation Domains
# Description of selected sites

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Zone</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Site Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income Tax Office (ITO)</td>
<td>Central Delhi</td>
<td>28.63°</td>
<td>77.25°</td>
<td>Traffic Junction</td>
</tr>
<tr>
<td>SiriFort</td>
<td>South East Delhi</td>
<td>28.55°</td>
<td>77.21°</td>
<td>Residential site and sports complex</td>
</tr>
<tr>
<td>Delhi College of Engineering (DCE)</td>
<td>North Delhi</td>
<td>28.75°</td>
<td>77.11°</td>
<td>Institutional site</td>
</tr>
</tbody>
</table>
## Sources of Model Input

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Terrestrial Data</strong></td>
<td>USGS 24- category land use data</td>
<td>30''</td>
</tr>
<tr>
<td><strong>Meteorological Data</strong></td>
<td>NCEP FNL Operational Global Analysis data</td>
<td>1°</td>
</tr>
<tr>
<td><strong>Emission Data</strong></td>
<td>EDGAR</td>
<td>0.1°</td>
</tr>
</tbody>
</table>
Air Quality: Effect of Temperature on Ozone Production

• For temp ≥ 38°C,
  \[40 \, \mu\text{gm}^{-3} \leq \text{Observed Ozone} \leq 120 \, \mu\text{gm}^{-3}\] and Simulated Ozone > 90 \, \mu\text{gm}^{-3}.

• For temp ≤ 28°C,
  \[\text{Observed Ozone} \leq 30 \, \mu\text{gm}^{-3}\] and \[30 \, \mu\text{gm}^{-3} \leq \text{Simulated Ozone} \leq 70 \, \mu\text{gm}^{-3}.

*Gupta and Mohan; Atmos. Environ., (2015), 122, 220-229
O$_3$ concentration:

- Model performance for simulating O$_3$ concentrations is considered good.

- However, over prediction is observed in case of O$_3$.

- O$_3$ concentration levels are further evaluated in terms of its relationship with temperature.

<table>
<thead>
<tr>
<th>Parameter (Ideal Value)</th>
<th>Statistic Value</th>
<th>Reported Value [Ref.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOA (1)</td>
<td>0.82</td>
<td>0.66 to 0.9 [4]</td>
</tr>
<tr>
<td>RMSE (0)</td>
<td>32.97</td>
<td>≈ 35 [5]</td>
</tr>
<tr>
<td>FB (0)</td>
<td>-0.24</td>
<td>± 0.15 [6]</td>
</tr>
</tbody>
</table>
(iv) Impact on Indian Summer Monsoon Rainfall (ISMR)*

- Large-scale conversion from woody savannah to crop land in India from 1987 and 2005.

- Deforestation results in weakening of the ISMR because of the decrease in evapotranspiration and subsequent decrease in the recycled component of precipitation.

- Decrease in precipitation observed in Ganga Basin, Central India, and North East India corresponds to decrease in LAI over these areas.

*Paul et al, 2016, Scientific Reports | 6:32177
Sati and Mohan, 2014; IJRS
LULC Changes and Impacts
Case Study: Delhi
IPCC has recognized* connections between urbanization and the development of UHI in several cities of the world including Delhi. The report includes above studies in Delhi which have explored this relationship

- **Dynamics of Urbanization and LULC** (Mohan et al, 2011): shows there has been significant change in LULC which is expected to have led to changes in temperatures (ISRO, RESPOND Project; 2007-2010).

- **Urban Heat Island and Temperature Trends** (Mohan et al, 2011) wherein some signatures of heat island effect were obtained to relate urbanisation with change in temperature trends (ISRO, RESPOND Project; 2007-2010).

- **UHI based on ambient and satellite derived temperatures** (Mohan et al, 2012) in which systematic field campaign was carried out to estimate existing UHI effect (Indo-Japanese Cooperative Project on Heat Island Effect 2008-2015).

*IPCC WGII AR5 Chapter 8, 2014
Changes in LULC and urban expansion in Mega city Delhi were evaluated based on satellite data.

Major impacts of rapid urbanization and population growth on the land cover changes which needs immediate attention were highlighted.

Land use/Land cover distribution over Delhi for the years 1997 and 2008.

Land Cover changes (km$^2$) in Delhi for different classes from 1997-2008

Urban Heat Island and Temperature Trends

• A consistent increasing trend was seen in the annual mean minimum temperatures indicating an overall warming trend over the NCR especially after 1990.

• Increasing warming trends in the night-time temperatures reflect the contribution of changing land-use patterns and additional anthropogenic heat that may enhance the urban heat island intensities in the city.

**Diurnal Temperature Range**

- Satellite based annually averaged DTR of entire Delhi shows a significant decreasing trend.

- Areas of Rapid urbanization exhibited a highly decreasing trend in DTR.

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Analysis of LULC Impacts using WRF Modelling System
The different koppens climate classification (Peel et al., 2007) found in India are - Tropical Monsoon (Aw), Tropical Savannah (Am), Arid Steppe Hot (BSh), Arid Desert Hot (BWh), Temperate Dry winter Hot summer (Cwa), Temperate Dry winter Warm summer (Cwb), Temperate without dry season Hot summer (Cfa). The climate classes have been broadly divided into three zones namely - Tropical, Arid, and Temperate.
Synoptic weather conditions – wind and geopotential height at 850hPa

- ERA Interim shows strong westerly winds of the order of 6–12 m/s over India during summer period.
- The simulated geopotential height almost overlaps with the ERA Interim during winter period and maximum difference ranging between 10 and 20 m is seen during summer.
- YSU, ACM2 and QNSE show positive bias (overestimation) for wind speed and higher differences for wind direction over sea compared to land.
- Higher positive bias over land area is seen around northern and north eastern India during summer.
- Overall ACM2 and MYNN show lower wind and geopotential bias at 850 hPa during summer, whereas YSU and MYNN work better in winter.

Reference: Gunwani and Mohan 2017; Atmospheric Research
## Statistical Performance, T2, Summer

<table>
<thead>
<tr>
<th>Climatic zones</th>
<th>YSU</th>
<th>MYJ</th>
<th>ACM2</th>
<th>QNSE</th>
<th>MYNN</th>
<th>Acceptable values</th>
<th>Best option</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tropical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IOA</td>
<td>0.85</td>
<td>0.88</td>
<td>0.84</td>
<td>0.88</td>
<td>0.80</td>
<td>&gt;0.8</td>
<td>MYJ, QNSE</td>
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<tr>
<td>Bias</td>
<td>1.55</td>
<td>0.68</td>
<td>1.23</td>
<td>0.74</td>
<td>2.45</td>
<td>≤±0.5</td>
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<tr>
<td>FB</td>
<td>-0.0051</td>
<td>-0.0022</td>
<td>-0.0041</td>
<td>-0.0024</td>
<td>-0.0079</td>
<td>≤±0.5</td>
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<tr>
<td>RMSE</td>
<td>3.12</td>
<td>2.83</td>
<td>3.47</td>
<td>2.80</td>
<td>4.18</td>
<td>&lt;2</td>
<td></td>
</tr>
<tr>
<td><strong>Arid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>IOA</td>
<td>0.62</td>
<td>0.73</td>
<td>0.73</td>
<td>0.74</td>
<td>0.65</td>
<td>&gt;0.8</td>
<td>ACM2, QNSE</td>
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<tr>
<td>Bias</td>
<td>4.98</td>
<td>3.25</td>
<td>3.15</td>
<td>3.20</td>
<td>4.75</td>
<td>≤±0.5</td>
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<tr>
<td>FB</td>
<td>-0.0162</td>
<td>-0.0106</td>
<td>-0.0103</td>
<td>-0.0104</td>
<td>-0.0155</td>
<td>≤±0.5</td>
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<td>RMSE</td>
<td>7.04</td>
<td>5.60</td>
<td>5.75</td>
<td>5.51</td>
<td>6.99</td>
<td>&lt;2</td>
<td></td>
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<tr>
<td><strong>Temperate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IOA</td>
<td>0.73</td>
<td>0.82</td>
<td>0.85</td>
<td>0.84</td>
<td>0.73</td>
<td>&gt;0.8</td>
<td>ACM2</td>
</tr>
<tr>
<td>Bias</td>
<td>5.96</td>
<td>4.23</td>
<td>3.24</td>
<td>3.79</td>
<td>6.14</td>
<td>≤±0.5</td>
<td></td>
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<tr>
<td>FB</td>
<td>-0.0196</td>
<td>-0.0139</td>
<td>-0.0107</td>
<td>-0.0125</td>
<td>-0.0201</td>
<td>≤±0.5</td>
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<tr>
<td>RMSE</td>
<td>7.33</td>
<td>5.57</td>
<td>5.23</td>
<td>5.36</td>
<td>7.59</td>
<td>&lt;2</td>
<td></td>
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<tr>
<td><strong>All Stations</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IOA</td>
<td>0.71</td>
<td>0.80</td>
<td>0.81</td>
<td>0.81</td>
<td>0.72</td>
<td>&gt;0.8</td>
<td>QNSE, ACM2</td>
</tr>
<tr>
<td>Bias</td>
<td>3.94</td>
<td>2.53</td>
<td>2.46</td>
<td>2.43</td>
<td>4.22</td>
<td>≤±0.5</td>
<td></td>
</tr>
<tr>
<td>FB</td>
<td>-0.0129</td>
<td>-0.0083</td>
<td>-0.0081</td>
<td>-0.0080</td>
<td>-0.0138</td>
<td>≤±0.5</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>5.99</td>
<td>4.76</td>
<td>4.89</td>
<td>4.65</td>
<td>6.27</td>
<td>&lt;2</td>
<td></td>
</tr>
</tbody>
</table>

- Similarly QNSE and ACM2 also show good performance during winter period

References: Gunwani and Mohan 2017; Atmos. Res.
Simulation Details

• Simulations over the study area of Delhi were carried out using WRF modeling system (v 3.5).

• Simulation Details
  – Time Period: 5 Mar 2010 0000 UTC – 11 Mar 0000 UTC
  – Analysis: 6 Mar 2010 0600 UTC – 11 Mar 0000 UTC
  – No. of Domains: 3 ; Resolution: 18 km, 6km, 2km

• Physical Schemes (*Mohan and Bhati, 2011, Advances in Meteorology*)
  – Microphysics: Lin
  – NOAH LSM
  – ACM 2 Boundary Layer
  – Kain Fritsch cumulus parametrisation
LULC Categories

• The built-in USGS 24 category land-use data in WRF is based on AVHRR satellite data spanning April 1992 through March 1993 using a resolution of ~ 1 km (Schicker, 2011; Sertel et al, 2009).

• Major differences, specially in terms of urban land cover, have been observed in USGS data and present LULC.

• Present study is aimed at analyzing impact of change in input land cover on model outputs such as air temperature and land surface temperature.

• MODIS IGBP is a 20 category land use data based on MODIS satellite data collected during years 2001-2005.

• Urban areas are more dominant in MODIS data.
Distribution of different land use types in input terrestrial data sets for WRF model

<table>
<thead>
<tr>
<th>Type</th>
<th>USGS</th>
<th>MODIS</th>
<th>UCM</th>
<th>Satellite (Mohan et al, 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban (built up/high-low residential/commercial/industrial)</td>
<td>25.17%</td>
<td>90.66%</td>
<td>49.83%</td>
<td>52%</td>
</tr>
<tr>
<td>Cultivated (Cropland and Pastures)</td>
<td>59.03%</td>
<td>6.08%</td>
<td>27.43%</td>
<td>20%</td>
</tr>
<tr>
<td>Natural (Grassland/Scrubland/Woodland)</td>
<td>14.58%</td>
<td>0.83%</td>
<td>18.92%</td>
<td>14%</td>
</tr>
<tr>
<td>Water</td>
<td>1.22%</td>
<td>2.43%</td>
<td>3.13%</td>
<td>12%</td>
</tr>
<tr>
<td>Barren/Sparingly vegetated/Sandy</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.69%</td>
<td>2%</td>
</tr>
</tbody>
</table>
Representation of different landuse/land cover

Land use of Delhi as simulated by WRF based on MODIS land use data with (a) WRF (b) modified LULC with UCM. * symbols followed by number indicate location of micrometeorological stations and their station code in the field campaigns.

UHI Field Campaigns*1,2

• DELHI (Delhi Experiments for Learning Heat Island)
  – DELHI-1 (23-28 May 2008)
  – DELHI-2 (4-10 March 2010)

• Urban heat islands in Delhi were assessed based on both air temperature as well as land surface temperature.

• The studies revealed temperature hotspots in densely populated and commercial areas.


Set up of micrometeorological stations across the study area of Delhi. A 12 × 12 km sub domain with greater station density is shown in lower part of the grid network.

Mohan et al., 2012, Atmospheric and Climate Sciences, 2, doi:10.4236/acs.2012.22014
Local warming is here, and growing

Vicious Cycle

Hot zones use more ACs, become hotter still

The Hindustan Times, 26 September, 2009

Prof M Mohan
IIT Delhi, India
Prof M Mohan
IIT Delhi, India

Urban Meteorology and Climate Conference; Hongkong; 25-27 May 2017

METHODOLOGY
- 30 locations across the NCR were selected.
- Weather stations were installed on roof tops of buildings to collect data such as temperature, wind speed, wind direction and atmospheric pressure.
- Temperature and humidity measurements were taken from May 25 to May 28.

EFFECTS OF LIVING IN AN URBAN HEAT ISLAND
- Greater energy consumption due to increased use of cooling devices, which in turn generate more heat.
- Greater consumption of water.

Q. What is an urban heat island?
A. An urban heat island (UHI) is a metropolitan area that is warmer than its surroundings. A heavily urbanised or built up area has a lot of material that traps heat. This creates a UHI.

Q. How is UHI defined?
A. The UHI value of a particular site is the difference between its temperature at a given time and the minimum temperature of the entire study area. For example, if the UHI for place X is 8, then 8 is the difference between temperature of place X and the minimum temperature in the study area (NCR).

HOT - EVEN AT NIGHT
Hot zones like CP and Bhikaji Cama Place are hotter than the “cool” zones like Sanjay Van and Hauz Khas by 2.8 to 8.3 degrees C, around 9 pm. The range in temperature variation arises from changing weather conditions - from rainy to moderately hot.
Sites Under Urban Built Up Area

Neb Sarai

Bhikaji Cama

Dwarka

Noida Sec-19

Lajpat Nagar

Janakpuri
Green Areas

Hauz Khas Distt Park
Natural + Cultivated Green Area

Buddha Jayanti Park
Natural Green Area
(Medium Dense Forest)
Sailing Club *(River Bank)*

Riverside Areas

Majnu Ka Tila *(Near River Bank)*
Calibration Set Up of all Micro-Meteorological Instruments
**Reported intensity of the urban heat island in various cities across the world**

*Fig from Santamouris, 2015, Sci Total Env*
Incorporation of urban canopy features in WRF has shown improvement in both ambient temperatures as well as urban heat island intensity distribution.

All stations show an index of agreement above 0.8 for WRF-UCM temperatures.
Mean absolute errors for WRF-UCM temperatures are also lower than WRF for all temperatures.

Bhati and Mohan, 2015, Theoretical and Applied Climatology, pp 1-16. 10.1007/s00704-015-1589-5
Statistics for Relative Humidity, 6-10 Mar 2010

Index of Agreement

Mean Absolute Error (%)

Urban Areas Non-Urban Areas

WRF WRF-UCM

Max desirable MAE Min desirable IoA

Mean Absolute Error

Bhati and Mohan, 2015, Theoretical and Applied Climatology, pp 1-16. 10.1007/s00704-015-1589-5
PBL height

PBL Height 0530 IST

- Observed
- WRF
- WRF-UCM

<table>
<thead>
<tr>
<th>Date</th>
<th>Observed</th>
<th>WRF</th>
<th>WRF-UCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Mar 0530</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Mar 0530</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Mar 0530</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Mar 0530</td>
<td></td>
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</tr>
</tbody>
</table>
Diurnal range of UHI for different land use land cover types

Bhati and Mohan, 2015, Theoretical and Applied Climatology, pp 1-16. 10.1007/s00704-015-1589-5
Conclusions

- Significant changes in LULC observed across the globe due to urbanisation and developmental activities.

- NWP modelling shows significant impacts on temperature and air quality due to change in LULC across the globe.

- Performance of mesoscale numerical models can be significantly altered by appropriate incorporation of LULC and urban canopy features.
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