A SYNERGISTIC STUDY OF URBAN LAND COVER DYNAMICS-PREMONSOONAL RAINFALL RELATIONSHIPS IN KOLKATA, INDIA USING CLIMATOLOGICAL, REMOTELY-SENSED, AND MODELING METHODOLOGIES

by

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(Under the Direction of J. Marshall Shepherd)

ABSTRACT

Empirical and modeling studies show that increasing population in cities around the world and related anthropogenic activities have an impact on coupled human-natural systems. The focus of this study is the city of Kolkata, which is located in the eastern part of the India. The Kolkata megalopolis had an initial population of 100,000 in 1735 and has grown to 14.79 million in 2007, reflecting largely uncontrolled growth over the past 300 years, especially after India's independence in 1947. Such population growth has been accompanied by intensive conversion of natural land cover to impervious surfaces.

The objectives of this study were to: (1) delineate urban land cover change in Kolkata using historic cartography and remote sensing data; (2) analyze historical rainfall data and quantify trends in the spatio-temporal premonsoonal rainfall (PMR) climatology of the area; (3) explore potential associations between urban land cover growth and PMR trends; (4) project future growth of Kolkata in the next 25 years using the CA Markov urban growth model; and (5) investigate possible mechanisms associated with possible urban rainfall effects in and around

Kolkata, under different urban land cover scenarios in a coupled atmosphere-land surface modeling system.

The methodology is a synergistic blend of historical cartographic analysis, satellite remote sensing, urban growth modeling, and numerical weather modeling. Statistical analyses suggest that PMR amounts have increased at urban stations in Kolkata over the past 50 to 60 years (i.e., the period of rapid urbanization); while there is no discernible precipitation trend in rural stations, the Gangetic plain, or India itself. Growth model results suggest continued urbanization along lines of communication and transportation, so it is plausible to expect future changes in Kolkata's PMR as a function of such changes alone.

A novel set of coupled atmosphere-land surface modeling experiments explored the interactions between urban land cover and the well-known "Norwester" mesoscale storm systems common to the premonsoon study period. Results clearly establish a linkage between urban land cover and precipitation evolution. Further, the results suggest that trends in urbanization patterns and tendencies will further modify precipitation distributions in the future. Analyses indicate that augmentation of land cover affects precipitation processes through alteration of surface convergence, sensible-latent heat flux, and boundary layer thermodynamic processes. Overall, the results highlight that "climate change" in the Kolkata region may be a function of urbanization and land cover change in addition to broader forcing related to greenhouse gases.

INDEX WORDS: Kolkata, urbanization, Premonsoon season rainfall, CA-Markov urban growth model, GIS-Remote sensing techniques, mesoscale model, Norwester, precipitation trends.

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DEDICATION

This dissertation is dedicated to my family members and friends. To my mother, Kanak Mitra, and my father, Sanjib Chandra Mitra, for their unconditional love and encouragement. Even though my father is no longer with us, his calm voice and advice always gives me the strength to persevere. To my mother, who is my greatest inspiration and my biggest cheerleader -- I stand in awe of the sacrifices you have made in your life, so that I can be my very best. Ma, without you I wouldn't have been where I stand now. I thank you both for giving me the strength to embrace life.

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I cannot end my dedication by not mentioning my friends, who have been beside me through all ups and downs of life. I dedicate this to Irani Sen, Arundhati Banerjee, Arpan Sharma, Priyanka Chakraborty, Biswajit Bandyapadhyay, Ujwal Bagal and Sanjeev Kumar, who are like family to me and I value them in life. I dedicate this to all my friends in the US and back in India who have always thought well for me and kept me in their prayers.

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction:

The world population is expected to be on the order of 70 percent urban by 2050. Between 2007 and 2025, the urban areas of the world are expected to gain 1.3 billion people, including 261 million in China and 197 million in India, which together account for 35 percent of the total growth (UN 2007a). There is a steady transformation of villages and towns to urban centers. Population growth and industrialization are the key factors behind such phenomenal change in the spatial structure. The propensity of the populace to settle in cities has added to the increase of anthropogenic activities that impact the natural system. Thus cities, directly and indirectly, are responsible for global change in the atmosphere, hydrosphere, geosphere and biosphere (Mills 2007) and are examples of a complex, coupled human-natural system. One example following Mills (2007) is the depiction (Figure 1.1) of the global emission of carbon dioxide due to fossil fuel use calculated for a 1 x 1° longitude-latitude grid (Andres et. al 1996). The geography of emissions corresponds closely to the locations of larger, more affluent cities. For example, it is interesting to note the distribution of carbon injections, often referred to as CO_2 domes (Jacobson 2010), into the atmosphere in Western Europe, the tall spikes in Japan and the lower peaks in eastern China. By contrast, much of Africa and India is characterized by the absence of these carbon peaks despite the enormity of some cities (e.g. New Delhi and Lagos) located in these regions. This unique example sets the stage for further discussion on the contribution of cities although it might be anticipated that cities in developing nations will increasingly become carbon contributors as well.

In developing countries, unplanned or poorly-planned urbanization can have profound effects on the overall environment, climatic pattern, and ethical character of the city. According to Roth (2007) climate-related environmental problems in (large) tropical urban agglomerations include (1) poor dispersion of air pollutants (generally low wind speeds and a lack of ventilation), (2) high levels of heat stress which decreases productivity, reduces human comfort and increases mortality due to heat related illnesses and (3) space cooling needs which increases energy usage and further exacerbate climate change. Thus it is extremely important and the right time to expand the focus from urban areas of the temperate region to faster growing tropical cities and the cities of the Arctic region, where climate change could have the most adverse impact.

The focus of this dissertation is India, which is a tropical country. India is the second most populated country in the world, experiencing large-scale development in and around urban areas. In 2007, out of the world's thirty largest urban agglomerations, India had three cities within the top ten (UN 2007b). Kolkata, in eastern India, has being aggressively multiplying in size over the past few decades. The city of Kolkata (Figure 1.2) ranked eighth, with a population of 14.787 million in 2007 (UN 2007b). However, the real population explosion took place between 1940 and 1950, during the Indian independence phase, although growth is still continuing (Chakraborty 1990).

The area of study falls broadly under the tropical monsoon rainfall regime (June to September). The winters are normally dry with very little rainfall (Lohar and Pal 1995). This study focuses on the premonsoonal rainfall (PMR) season when sporadic thunderstorms or the

Nor'westers are the primary sources of rainfall (March, April and May). The formation of Nor'westers or "Kalbaishaki" is attributed to a warm, moist, southerly low-level flow from the Bay of Bengal and an upper-level dry, cool, westerly or north-westerly flow giving rise to an atmosphere with high instability. These storms cause havoc yearly in West Bengal, including Kolkata (Mukhopadhyay et al. 2005). The PMR season contributes approximately 12% of the annual total rainfall in this region (Sadhukhan et al. 2000a). As the overarching objective of the research is to explore the possibility that Kolkata's urban land cover growth influences the precipitation distribution and variability in the region, the PMR season is most suitable. In the PMR season, it is less likely that large-scale phenomenon like the monsoons mask the urban forcing on the hydroclimate system.

The prospect of continued growth in Kolkata raises a number of serious questions about urban growth and its environmental impact, in particular. For example, what happens when built up areas increase in a city? Will urban growth affect the environment? Will the uncontrolled growth and land use change of Kolkata have any impact on the regional hydroclimate in and around the city?

This scholarly dissertation addresses some of these questions. The study examines the growth of the city of Kolkata over 300 years and examines possible associations with spatio-temporal precipitation trends in the premonsoonal season. It also projects the future growth pattern of the city in 2025 using urban growth modeling. Further, the study couples aforementioned objectives using a coupled atmosphere-land modeling system with the goal of assessing how precipitation distributions respond to various representations of urban land cover (e.g. current urban land cover and pre-urban land cover). The study will also examine the physical mechanisms that explain how urban land cover can impact precipitation variability. And for the first time, the research examines urban-mesoscale interactions involving the primary precipitation mechanism, the Nor'wester, in the Gangetic region.

1.2 Literature Review

a. Urbanization of Kolkata, India:

During the last 50 years the population of India (1.2 billion in 2008) has more than doubled, but the urban population has grown by a factor of five (Taubenbock et al. 2008). Such growth calls for a better understanding of urbanization trends in India and assessment of how they will impact the overall environment or natural systems. Kolkata, one of the megacities of India, with a population of 14.3 million in 2005 had an average annual population growth rate of 2.0% between 1975 and 2000 (United Nations 2005).

Assessing urban extent has become a popular field of research for both developed (Maktav et al. 2005, Small 2002, Sutton 2003 and many others) and developing (Mass 1999, De Almeida et al. 2005, Taubenbock et al. 2007, Taubenbock et al. 2008a, Taubenbock 2009, Bhatta 2009) regions of the world. Compared to developed countries, less research has been done in developing countries where the impact of urbanization on local and regional levels may be more profound. Traditional methods for gathering demographic data, censuses and maps using samples, are impractical and unsatisfactory for urban management purposes. The application of remote sensing and Geographic Information Systems (GIS) techniques in urban studies in developing countries started in the 1970s (Maktav et al. 2005).

First generation satellite systems (1963 to 1972) consisted of Corona, Argon and Lanyard, however, they were limited in capability and resolution (Zhao and Kafatos 2002). Since 1972, numerous improvements in space technology ushered in a second generation of Earth observation satellites, such as LANDSAT, SPOT and IRS. After 1999, a third generation of

Earth observation satellites with very high geometric resolution (IKONOS-2, Quickbird-2, etc) (Maktav et al. 2005) emerged. The convergence of GIS, remote sensing, and database management systems has improved quantification, monitoring, modeling and subsequently predicting this phenomenon (Sudhira et al. 2004).

Mas (1999) tested six change detection procedures using Landsat Multi-Spectral Scanner (MSS) images for detecting areas of changes in the region of the TeÂrminos Lagoon, a coastal zone of the state of Campeche, Mexico. The change detection techniques considered were: image differencing, vegetative index differencing, selective principal components analysis (SPCA), direct multi-date unsupervised classification, post-classification change differencing and a combination of image enhancement and post-classification comparison.

Sutton (2003) used nighttime satellite imagery to delineate urban areas, focusing on cities in the United States having populations greater than 50,000. The data used to obtain areal extent and population were radiance calibrated Defense Meteorological Satellite Program (DMSP) Optical Line Scan (OLS) images of the United States (Elvidge et al. 1998) and a grid of population density derived from the U.S. census, both with 1 km resolution (Meij 1995). The regression line on the scatter plots of the Ln(Area) vs. Ln(Population) relationship represented a scale adjusted “Sprawl Line”. The cities above the sprawl line have no urban sprawl whereas the cities below the line are considered sprawling. Sutton’s study revealed how difficult it is to provide a single number that characterizes “Urban Sprawl” for any meaningful areal extent.

De Almeida et al. (2005) used GIS and remote sensing as tools for the simulation of urban land use change (1979 – 1988) on a medium-sized town, Baura, west of Sao Paulo, Brazil. To update the land use maps in the simulation, they used a LANDSAT Multispectral Scanner

(MSS) image of 22nd June 1979 and a LANDSAT Thematic Mapper (TM) image of 29 November 1988.

Small (2005) made a comparative Spectral Mixture Analysis (SMA) of the Landsat 7 Enhanced Thematic Mapper (ETM+) imagery for a collection of 28 urban areas worldwide to provide a physical basis for a spectral characterization of urban reflectance properties.

Maktav, Erbek and Jurgens (2005) attempted to highlight the importance of remote sensing as one of the most reliable mechanisms to assess the consequences of urbanization quickly and effectively in developed and developing countries. They showed that remote sensing can help in demarcating urban sprawl and quantifying both the sealed surface proportion and temporal change of urban growth.

Potere and Scheneider (2007) compared global maps describing urban land, which were created by six groups from government and academia in both the European Union (EU) and the US using remote sensing and GIS techniques. They found that the six maps created by six different groups differed at the scale of regions, countries, and urban patches.

Schneider and Woodcock (2008) quantified the spatial extent, rates of expansion, and patterns of urbanization using a combination of remotely sensed data, spatial pattern metrics and statistical census data of 25 mid-sized cities from different geographical settings and levels of economic development. Seto and Shepherd (2009) highlighted the widespread use of remote sensing data to measure urban extents, with a majority of studies superimposing one to three satellite images to quantify land use change or to monitor urban land-use change between two or three time points.

Sutton et al. (2010) used nighttime satellite imagery for mapping urban and peri-urban areas of Australia. They found that 82 percent of the population in Australia lived in urban areas, whereas in the US only 55 percent of the population lived in urban areas. In Australia, 15 percent of the population lived in peri-urban and 3 percent lived in rural areas.

It is evident that monitoring of urban land use change using remote sensing, GIS and modeling techniques is lacking in the context of India (Sudhira et al. 2004). Sudhira et al. (2004) used remote sensing and GIS to understand the pattern and sprawl of the city of Udipi in the Mangalore region of India. They found that the rate of development of land in Udipi was outstripping the rate of population growth which implied that land was being consumed at excessive rates (Sudhira et al. 2004).

Other Indian cities that have been the focus of studies employing GIS techniques and remote sensing include Ahmedabad, Surat and Vadodara (Jothimani 1997), Vadodara (Bhatt et al. 2006), Dhanbad (Srvastava 2000), Hyderabad (Lata et al. 2001; Taubenbock et al. 2007); Bhopal (Saxena 2003), Allahabad (Srivastava and Gupta 2003) and others.

In 2009, Taubenbock et al. conducted a spatio-temporal analysis using Landsat images from 1972 to 2001 for the 12 largest Indian urban agglomerations (Figure 1.3). The study sought to detect similarities and differences in spatial growth in the large Indian urban agglomerations. These cities, sharing the same cultural characteristics, range from 2.5 million inhabitants to 20 million (in the metropolitan region of Mumbai). The results paint a characteristic picture of spatial pattern, spatio temporal growth and future modeling of urban development in India (Figure 1.4).

A recent study by Bhatta (2009) was conducted on the Kolkata Municipal Corporation (KMC) area using Landsat and Indian Remote Sensing (IRS) images. He suggested that a single policy for the entire city never works with equal degrees of effectiveness and that each zone in the city has different patterns of growth. According to Bhatta, the theory and models of urban spatial growth pattern that are supported by the findings of the paper should prove useful for devising policy responses to the problems associated with preparing for urban expansion.

b. Growth Projections for Kolkata

Models are, perhaps, the best way of understanding the land change phenomenon and anticipating correct planning activities for sustainable cities (Cabral and Zamyatin 2006). A unique synthesis of urban systems theory linking location to transportation using the general concept of optimization and the time-dynamics problem was incorporated into the models (Batty and Xie 1994). However, this situation is changing rapidly since 1970s as dramatic advances in computer technology and the availability of large quantities of spatially-referenced data are stimulating a renewed interest in urban modeling in United States and throughout the world (Wegener 1994) (Figure 1.5).

The most commonly developed and applied techniques in understanding urban dynamics are the cellular automata models and agent-based models. Where cellular models are focused on landscapes and transitions, agent-based models focus on human actions. Agents are the crucial component in these models (Parker et al. 2003). Agents have been used to represent a wide variety of entities, including atoms, biological cells, animals, people, and organizations (Liebrand, Nowak, and Hegselmann 1988; Epstein and Axtell 1996; Conte, Hegselmann, and Terna 1997; Weiss 1999; Janssen and Jager 2000, Parker and Meretsky 2004). Cellular based models are inherently spatial models by their regular arrangement of cells in space, so it is easy to regard a cell as part of a regular intersected map (Figure 1.6). In this sense, every cell covers an attribute, which may be identified in the corresponding grid square in the city map (e.g., land use, population size) (Back et al. 1996).

Herein, we have employed a cellular automata model (CA Markov) within IDRISI Taiga (Eastman 1997, Eastman et al. 2005), an integrated GIS and Image Processing Software system, to predict the future growth of Kolkata. Modeling cities with cellular automata is a relatively new approach, and one that was virtually impossible without the management capabilities of GIS and powerful workstation technology (Clarke and Gaydos 1998). Cellular automata models have been used to study the urban expansion of a number of urban areas in the US like San Francisco, Charleston (Allen and Lu 2003), Savannah (Batty and Xie 1994), and Washington/Baltimore (Clarke and Gaydos 1998); and Southeast England (Wu and Martin 2002).

The IDRISI Taiga system has a built-in CA Markov model to predict the future growth of a city. The literature has shown that CA Markov models have been successful in predicting the future growth of cities. CA Markov was used to predict future urban growth or change for cities like Calgary (Sun et al. 2007) and Nenjiang County, China (Ye and Bai 2008). Falcucci et al (2008) used CA Markov to simulate a 2020 land-cover suitability map to assess habitat availability for the Apennine brown bear population in central Italy. Several comparative studies have been done to evaluate the importance and validity of the CA Markov model (Pontius and Malanson 2005; Pedro and Zamyatin 2006; Lee et al. 2008).

The future projection of Kolkata to 2025 conducted in this study could kindle a new interest in understanding the future state of cities in the developing parts of the world.

c. Linkages between Kolkata Urban Land Cover and Premonsoonal Precipitation

1. Studies on urban impact on precipitation (observational and modeling)

According to Landsberg (1970) the most pronounced and locally far-reaching effects of man’s activities on microclimate have been on cities. The heat gain due to heat storage in the urban structures, the reduction in local evaporation, and the anthropogenic heat alters the spatio-temporal pattern of temperature, the well-studied urban heat island (UHI). The UHI and other urban factors may actually lead to atmospheric interactions that also initiate or alter convection (Landsberg 1970, Changnon et al. 1981, Shepherd et al. 2002, Dixon and Mote 2003, Niyogi et al. 2006, Holt et al 2006). Diab (1978) in his review paper noted that urban induced changes in precipitation could result from one or more of the following possible modifications of the atmosphere: (1) increased thermal mixing due to the effects of the well-established heat island and anthropogenic heat input; (2) increased mechanical mixing due to the greater aerodynamic roughness of urban structures; (3) changes in the low-level atmospheric moisture content due to addition of water vapor from combustion processes, and to alternations in evapotranspirartion rates; and (4) the addition of condensation and ice nuclei from industrial and motor vehicle discharges. Recently, Shepherd (2005) has more aptly summed Landsberg and Diab's concepts in his review paper noting the possible mechanisms for urbanization to impact precipitation or convection including one or a combination of the following: (1) enhanced convergence due to increased surface roughness in the urban environment (e.g., Changnon et al. 1981; Bornstein and Lin 2000; Thielen et al. 2000); (2) destabilization due to urban heat island (UHI)-thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds (e.g., Shepherd et al. 2002; Shepherd and Burian 2003; Shepherd 2006; Mote et al. 2007; Baik et al. 2007); (Figure 1.7); (3) enhanced aerosols in the urban environment for cloud condensation nuclei sources (e.g., Moelders and Olson 2004); or (4) bifurcation or diversion of precipitating systems by the urban canopy or related processes (e.g., Loose and Bornstein 1977; Bornstein and Lin 1999; Bornstein and Lin 2000).

Early investigations (e.g. Horton 1921; Kratzer 1956; Landsberg 1956; Atkinson 1968; Changnon 1968; Landsberg 1970; Changnon 1971; Huff and Changnon 1972) highlighted the possibilities of urban effects on rainfall patterns. In the past 30 years, numerous observational studies (Dai et al. 1997; Bornstein and Lin 2000; Inoue and Kimura 2004; Shepherd et al. 2002; Changnon 2003; Dixon and Mote 2003; Burian and Shepherd 2005; Diem and Mote 2005; Shepherd 2006; Mote et al. 2007; Hand and Shepherd 2009, Kishtawal et al. 2009, Bentley et al. 2009) have been done to understand how urban land cover affects precipitation, a key component of Earth's climate and water cycle system. Modeling studies to understand urban impacts on precipitation have also emerged in the literature. Model simulations investigating urban rainfall effects dates back to the 1970s (Vukovich and Dunn 1978; Huff and Vogel 1978). Simulations related to UHI, humidity, fluxes and aerosols have also been conducted by Hjelmfelt (1982), Shafir and Alpert (1990), Thielen et al. (2000), Craig and Borstein (2002), Rozoff and Cotton (2003). Most of these studies investigated the role that the UHI and surface roughness associated with buildings play in generating or altering low-level convergence (Figure 1.8). Such convergence was hypothesized to affect the convective initiation process. More recent studies by Shem and Shepherd (2009) and Shepherd et al. (2010) have affirmed and extended this hypothesis by noting how low-level convergence establishes on the urban-rural interface.

A number of observational and modeling studies were done to understand the interactions between urban and sea breeze circulations in Houston (McPherson 1970, Bouvette et al. 1982, Orville et al. 2001, Shepherd and Burian 2003, Burian and Shepherd 2005, Shepherd et al. 2010), Japan (Yoshikado 1994, Kitada et al. 1998, Kusaka et al. 2000, Ohoshi and Kida 2002), Hong Kong (Lo et al. 2007) and Sydney (Gero and Pitman 2006).

Other city specific observational and modeling studies in the US have focused on Phoenix (Balling and Brazel 1987, Selover 1997, Diem and Brown 2003, Shepherd 2006), Atlanta (Dixon and Mote 2003; Bornstein and Lin 2000; Shepherd et al. 2002; Diem and Mote

2005; Mote et al. 2007, Bentley et al. 2009, Shem and Shepherd 2009), New York City (Bornstein and LeRoy 1990), Mexico City (Jauregui and Romales 1996), Oklahoma City (Niyogi et al. 2006), Indianapolis (Niyogi et al. 2010) and Chicago (Changnon and Westcott 2002). These studies continued to suggest that there is an association between rainfall and urban land cover. All of these studies showed some evidence of an increase in the precipitation, which they hypothesized to be related to heavy urban development.

Niyogi et al. (2006) conducted simulations using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) to investigate the impact of urban and land vegetation processes on the prediction of the mesoscale convective system (MCS) observed on 30 July 2003 in the vicinity of Oklahoma City (OKC), Oklahoma. The inclusion of the urban canopy model better represented the urban-rural heterogeneities and improved simulation of the moisture fluxes and upstream inflow boundaries. Ikebuchi et al. (2007) found that land cover change and increased anthropogenic activities enhanced rainfall intensity and location of heavy rainfall events over Tokyo (Japan). Baik et al. (2007) and Han and Baik (2008) used multi dimensional models to resolve that urban heat island circulation was relatively stronger during the daytime, which strengthens the downwind updraft cell, enhancing rainfall downwind. Zhang et al. (2009) in their modeling study have shown a decrease in rainfall due to increased temperatures and sensible heat and reduced evaporation.

2. Studies on precipitation in India with emphasis on premonsoon rainfall

Though the monsoons, June to September (Vines 1986; Kulkarni et al. 1992; Kripalani et al. 1995; Goswami et al. 2006; Dash 2005, Bhaskar Rao et al. 2004; Dash et al. 2006), are the most important source of rainfall in the Kolkata region, the focus of this study is the premonsoon (March-May) rainfall. During this period, large-scale atmospheric forcing like the monsoon is not of first-order importance and mesoscale forcing dominates precipitation processes. A mesoscale circulation spatially is defined as a system ranging in size from a few kilometers to hundreds of kilometers (Markowski and Richardson 2010). According to the American Meteorological Society *Glossary of Meteorology*, the mesoscale is defined as 2 – 2000 km scale, with subdivisions of 200 – 2000 km, 20 – 200 km and 2 – 20 km (Figure 1.9). As such, the PMR season is the most appropriate period to theoretically investigate how urban land cover, a mesoscale forcing mechanism, could affect precipitation in the Kolkata region. Further, most of the aforementioned studies in the literature have focused on weak large scale forcing environments or enhancement to mesoscale systems (Shem and Shepherd 2009, Niyogi et al. 2006, Niyogi et al. 2010).

Studies of PMR are limited because of the predominance of studies on the monsoon season, which is socio-economically vital for the Indian sub-continent. The three-month period (March, April, and May) preceding the monsoon season is characterized by hot days with sporadic thunderstorms (Sadhukhan et al. 2000b). Thunderstorms over West Bengal, also referred to as Nor'westers, appear frequently during the premonsoon period. Nor'westers (locally known as "Kalbaishaki" (IMD Report 1941, Weston 1972) are deep convective systems resulting from the dryline, which forms where the moist low-level southerlies meet arid westerlies (Figure 1.10). Mukhopadhyay et al. (2005) described the severity of two Nor'westers over Kolkata using Doppler radar observations and satellite images. The two dates were 16 and 30 April 2003. On the basis of the observations made by Mukhopadhyay et al. (2005), 16 April is chosen as a date for study in the third manuscript (Chapter 4). A similar paper by Mukhopadhyay et al. (2009), investigates the genesis, maturity and dissipation of two Nor'westers, one on 12 March 2003 and another on 22 May, 2003. In the US, Shem and Shepherd (2009) and Niyogi et al (2011) have noted that pre-existing convective systems can be influenced by urban land cover, but to our knowledge, this type of investigation is unprecedented for convective systems elsewhere in the world.

Studies on premonsoon rainfall have also been conducted by Sanderson and Ahmed (1979), Lohar and Pal (1995) and Sadhukhan et al. (2000). Sanderson and Ahmed (1979) conducted a study in the neighboring country of Bangladesh to understand the variability of premonsoon rainfall. Lohar and Pal (1995) carried out a one-station study on 20 years data of PMR. They concluded that irrigation reduced the low level moisture and increased soil moisture. They hypothesized that these processes decreased the intensity of sea breeze circulation and related convection. Sadhukhan et al. (2000) also conducted a study on the PMR (1901 – 1992) variability in the Gangetic West Bengal, which includes the study area of this dissertation. They found that there was no long term trend present in the data series, unlike the monsoons.

The limited literature related to Nor'westers and the premonsoon rainfall highlights the need for more studies to be conducted. Urban rainfall studies for India have been limited too. The first work of this kind was done by Khemani and Murthy (1973), who analyzed rainfall data from 1901 to 1969 for the city of Bombay and two other stations in the nearby rural region. Their study indicated that there was an increase of about 15% in total rainfall in the industrialized city of Bombay compared to nearby non-urban cities.

De and Rao (2004) conducted a study involving 14 major cities (over 1 million population) of India and the monsoons. They found that in the complete period between 1901 and 2000, seven cities including Kolkata had increasing trends during monsoons, excluding only Nagpur, which had a decreasing trend. The increasing trend in the monsoon season rainfall is most evident over Kolkata for the period 1951-2000, increasing at the rate of 83 mm/ 10 years.

Simpson (2006) employed a mesoscale model and observed rainfall data to investigate the impact of Chennai urban land use on the sea breeze circulation and rainfall amounts during the southwest monsoon. Observations indicate a tendency for occurrence of rainfall over the city during late evening and nocturnal hours, possibly due to the interaction between receding sea breeze circulation and the urban heat island. This process could not be simulated due to possible deficiencies in the model physics.

Devi (2006) discussed the nature and intensity of heat islands at Visakhapatnam, a tropical coastal city of South India, for over ten years. They also noted that there was interaction between land and sea breeze circulation and the heat island.

Kishtawal et al. (2009) found a positive correlation between heavy rain events and urban land cover growth for larger cities in India. On the other hand, Sen Roy's (2008) observational study on extreme hourly precipitation trends (1982–2002) for large urban areas in India with one million plus population showed that Kolkata had a negative trend in its rainfall pattern in the dry PMR months (March to May).

There is a minimal body of research on urban land use/ land cover modified rainfall in the monsoon and premonsoon season. Further, there is no previous study that has investigated the influence of urban land cover on the Nor'wester systems that dominate PMS rainfall. As such, this research addresses several gaps in the literature.

1.3 Research Objectives:

Very few studies have examined the effect of urban land use in developing nations yet the world's fastest growing urban areas are precisely in these regions. So this study will explore the effect of Kolkata's urban land cover change (one of the fastest growing urban areas) on premonsoon rainfall. The PMR period near Kolkata offers a nice framework for this type of study because urban effects on rainfall are most evident when strong large scale or synoptic forcing is not present (Shepherd 2005). This study is a unique synergy of urban land cover dynamics, premonsoonal climatology, urban growth model and a mesoscale weather model.

The first manuscript (second and third chapter) provides, to my knowledge, one of the most thorough spatio-temporal assessments of urban growth in Kolkata (India) over a span of 300 years approximately. 70% of world population will live in urban areas (UN 2007a), thus it is important to quantify the extent of land cover change of cities. Contemporary assessment of past, present and future growth of cities in developing countries is critical to future analysis of planning strategies, environmental impacts, and land management amongst others. As such, the research objectives of this paper are (1) to evaluate the growth of the city of Kolkata and determine the factors behind the population explosion, which took place after the Indian independence; (2) to quantify the extent of land cover change over the past 300 years i.e. from the time of its inception; and (3) to project how the urban land cover of Kolkata will grow in the next 25 years (2025) using the CA-Markov urban growth model.

In the second manuscript (fourth chapter), an assessment of spatio-temporal trends in urban land cover growth in Kolkata, India and possible relationships with aspects of the natural systems, specifically the premonsoonal precipitation climatology is performed. Time series analysis and trend detection using Mann-Kendall statistics on data from six stations are employed to establish whether trends in PMS rainfall are associated with rapid urban growth in the most recent 50-60 years. The research objectives are (1) to delineate urban land cover change using historic cartography and remote sensing data; (2) to analyze historical rainfall data and quantify the trend in the spatio-temporal PMR climatology of the area; and (3) to ascertain any link between trends in PMR rainfall over the last 50 years and urban land cover change.

The third manuscript (fifth chapter) investigates the physical mechanisms associated with urban land cover and precipitation processes. This paper is novel because it is possibly the first study to examine such issues from a modeling perspective in the Kolkata region. Furthermore, it is the first study of its kind to examine urban-mesoscale interactions involving the Nor'wester, the primary rainfall producer during the premonsoon season. Very recent papers (Shem and Shepherd 2009, Niyogi et al. 2011) have suggested that existing mesoscale systems can be altered by urban landscape. However, these papers examined two US cities, Atlanta and Indianapolis, respectively. Our study is the first to examine this issue outside of the US and to quantify how land-atmosphere interactions might alter the PMR associated with a Nor'wester-type system. The study employs the coupled WRF NOAH atmosphere – land surface model. The coupled atmosphere-land surface modeling system will be used to assess whether premonsoonal precipitation associated with typical Nor'wester might be influenced under two scenarios a) current urban and b) no urban (pre-Kolkata). It should be noted that this may be the first modeling study of a Nor'wester as they have been mainly studied from an observational perspective. We employ a case study approach using 16 April 2003 based on previous literature establishing this as a typical PMR "Nor'wester" case (Mukhopadhyay et al. 2005).

1.4 Summary:

Cities, as places where human activities are concentrated, are frequently cited as the chief causes of, and solutions to, anthropogenic global change (Mills 2007). The necessity to understand the growth pattern of cities in developed and developing part of the world is important along with their environmental impact. More than half of the annual growth currently occurs in six countries: India, China, Pakistan, Bangladesh, Nigeria, and the United States (Cohen 2003). Between 2007 and 2025, the urban areas of the world are expected to gain 1.3

billion people, including 261 million in China and 197 million in India, which together account for 35 percent of the total growth (UN 2007a). One main interest in cities lies in the question of whether cities can modify weather and climate. Additionally, global-scale forcings are superimposed on the effects of the built environment through local transfers of heat and moisture. Conversely, the impacts of cities on weather and climate may extend to regional scales too (Shepherd et al. 2010).

The uniqueness of this dissertation lies in the gamut of objectives which involves a synergistic analysis of past, present and future growth of the city and its impact on the premonsoon rainfall pattern using cartographic, GIS, remote sensing, and cellular automata modeling.

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Figures:

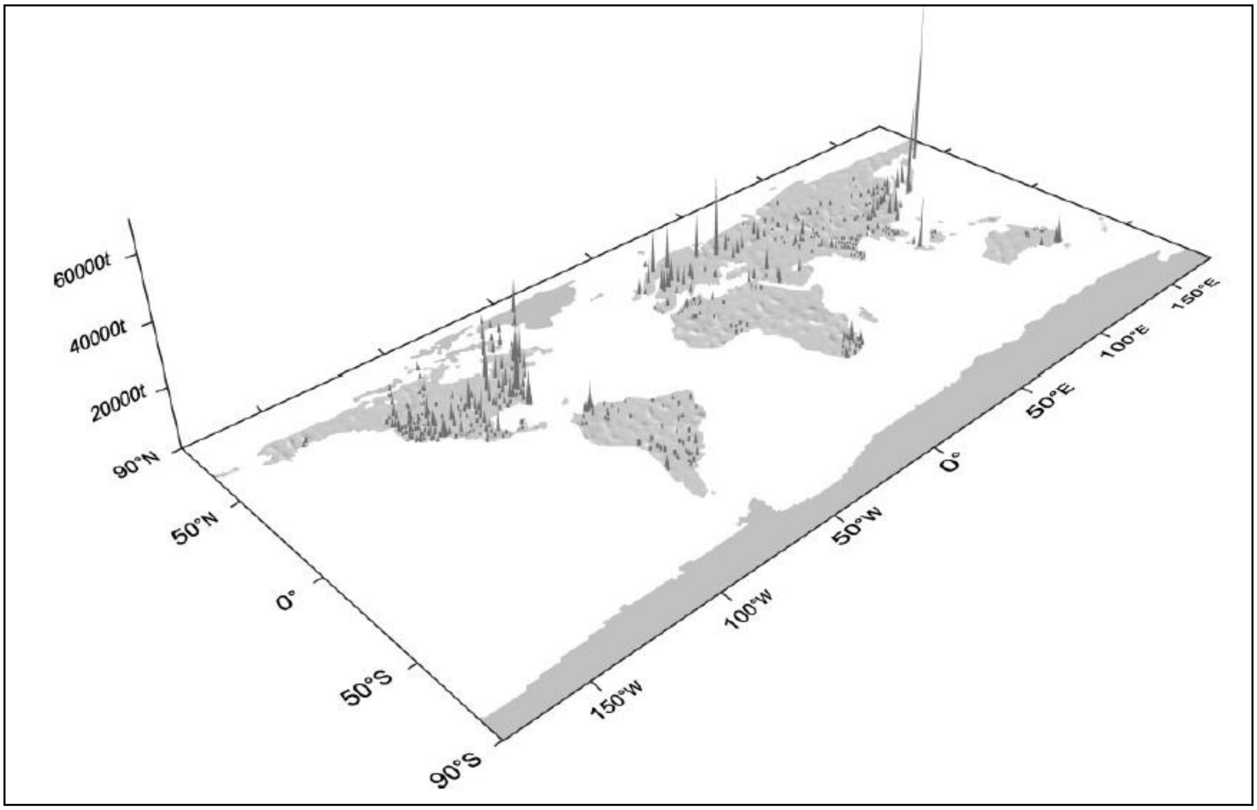

Figure 1.1: Estimated carbon dioxide emissions (1995) in 1000's of metric tons (t) of carbon per 1° x 1° latitude/longitude grid cell. Source: Andres el al. 1997

Figure 1.2: Location of Kolkata, India. Source: Mitra et al. 2011 (forthcoming)

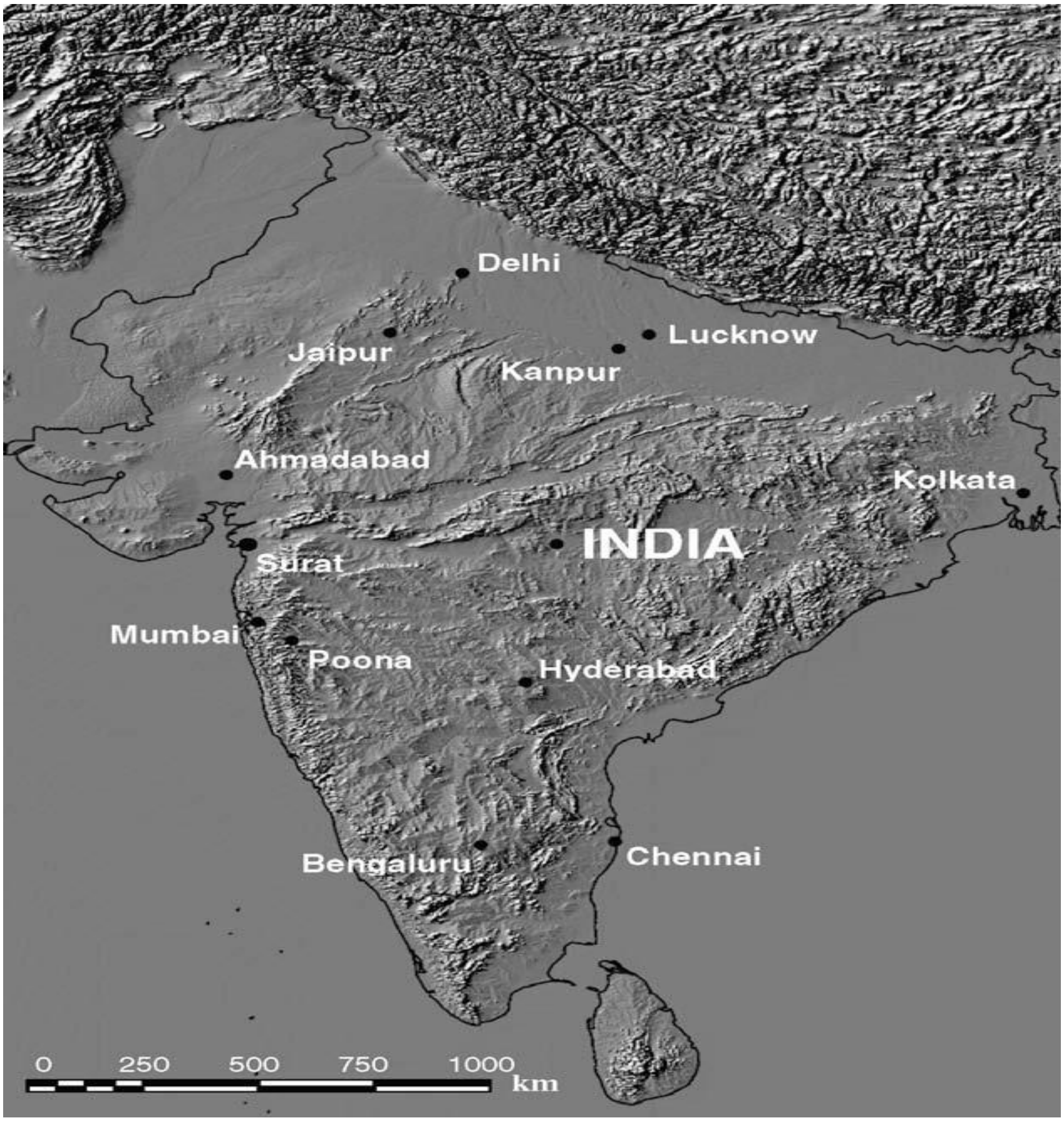

Figure 1.3: Location of India's large urban agglomerations. Source: Taubenböck et al 2009

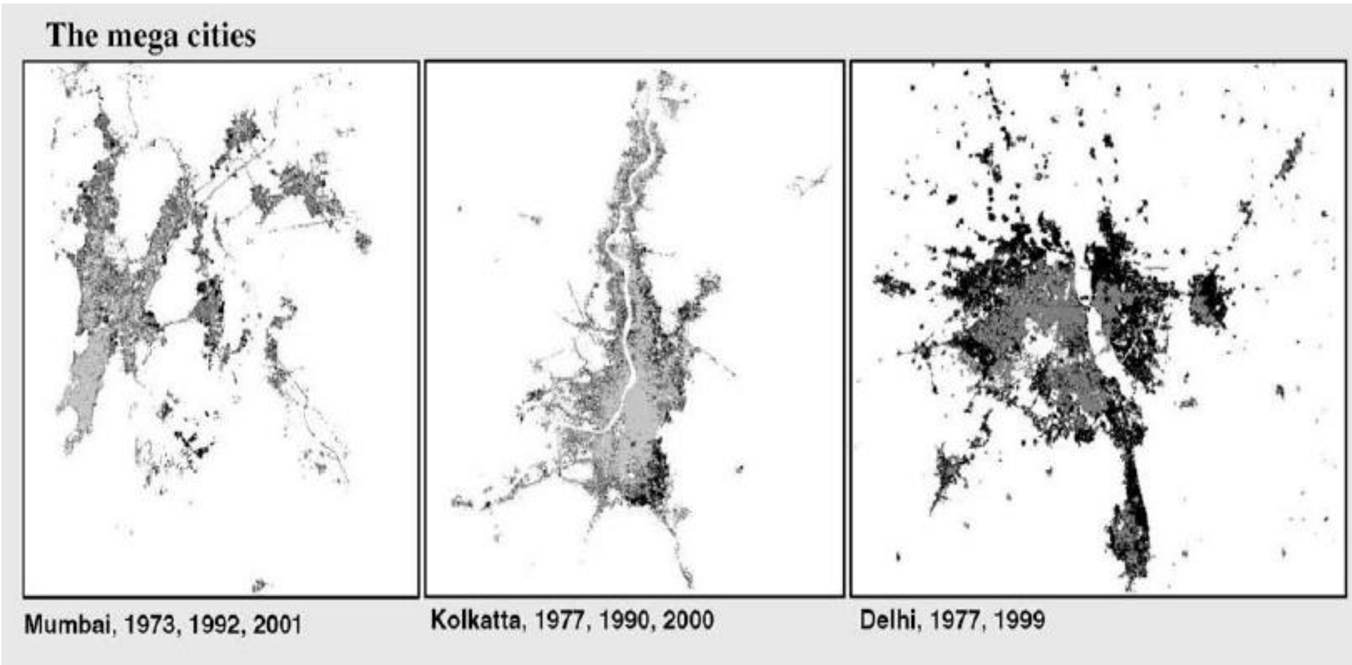

Figure 1.4: Spatiotemporal urban footprint of three large Indian cities. Source: Taubenböck et al 2009

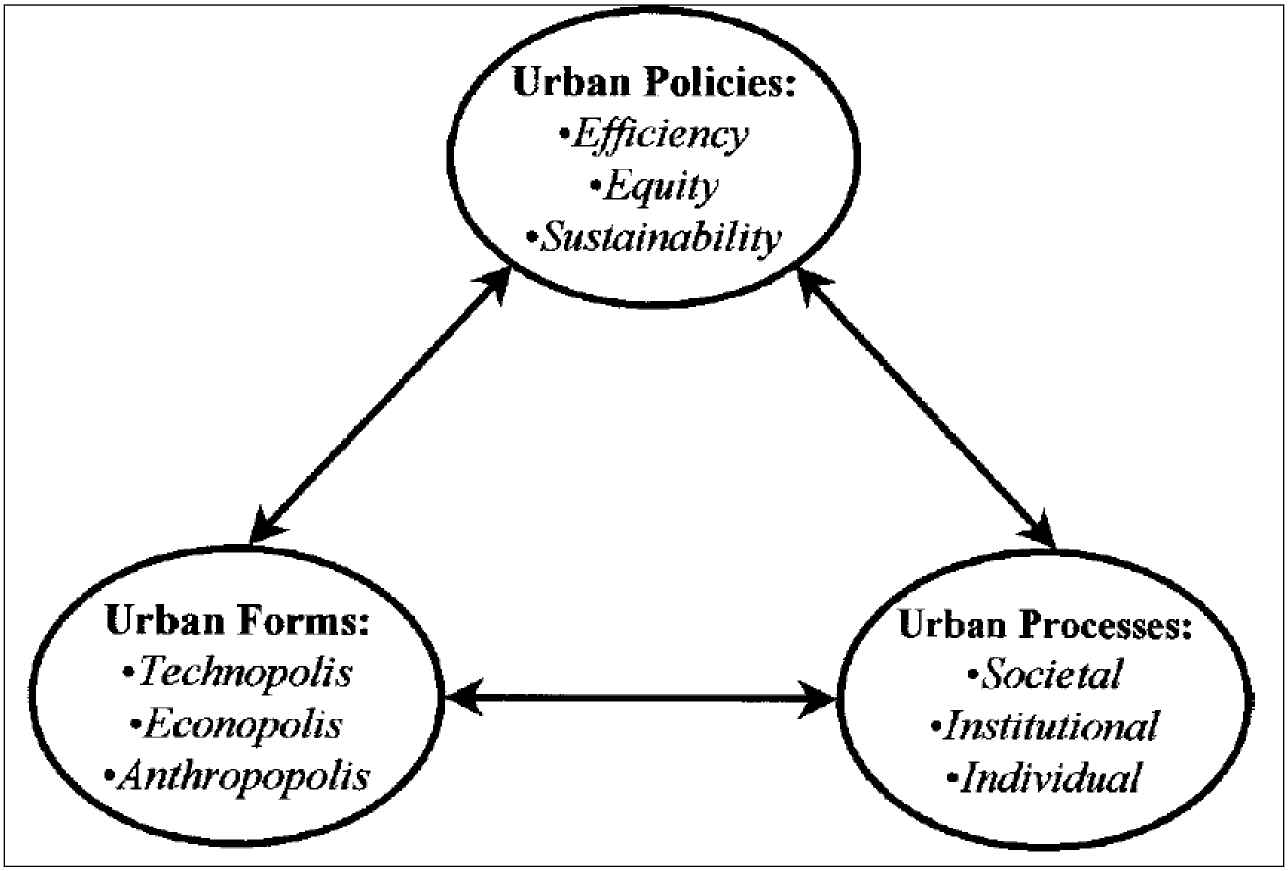

Figure 1.5: Elements of an integrated model for informational cities. Source: Sui 1998

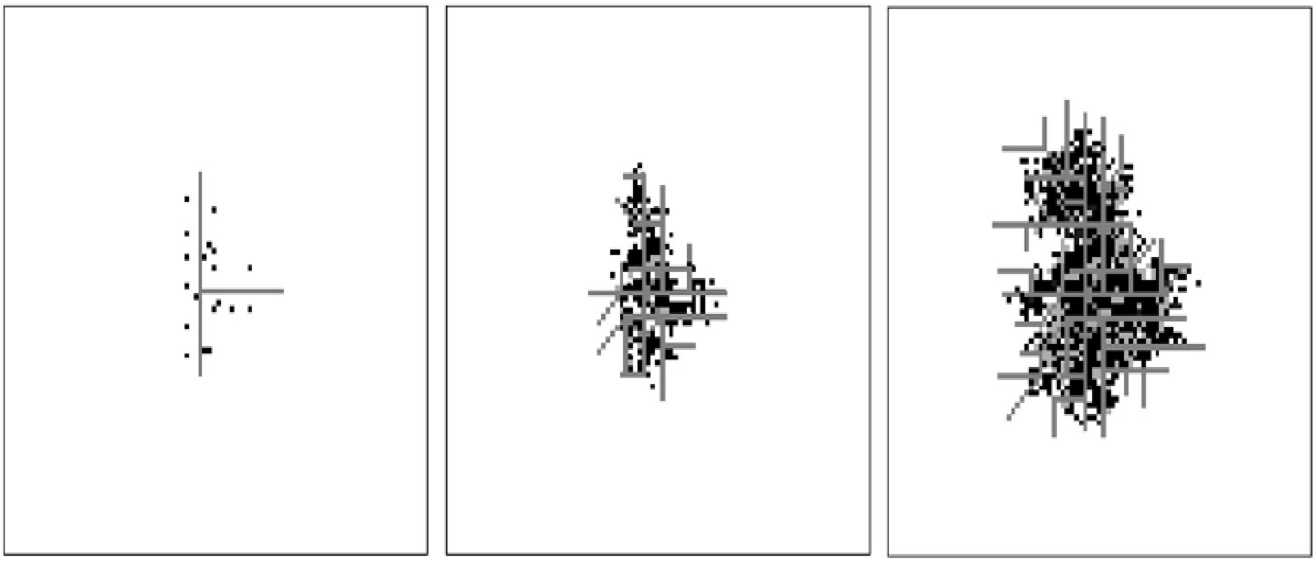

Figure 1.6: The growth of a village and town from a dispersed rural settlement using CA model.
Source: Batty et al 1999

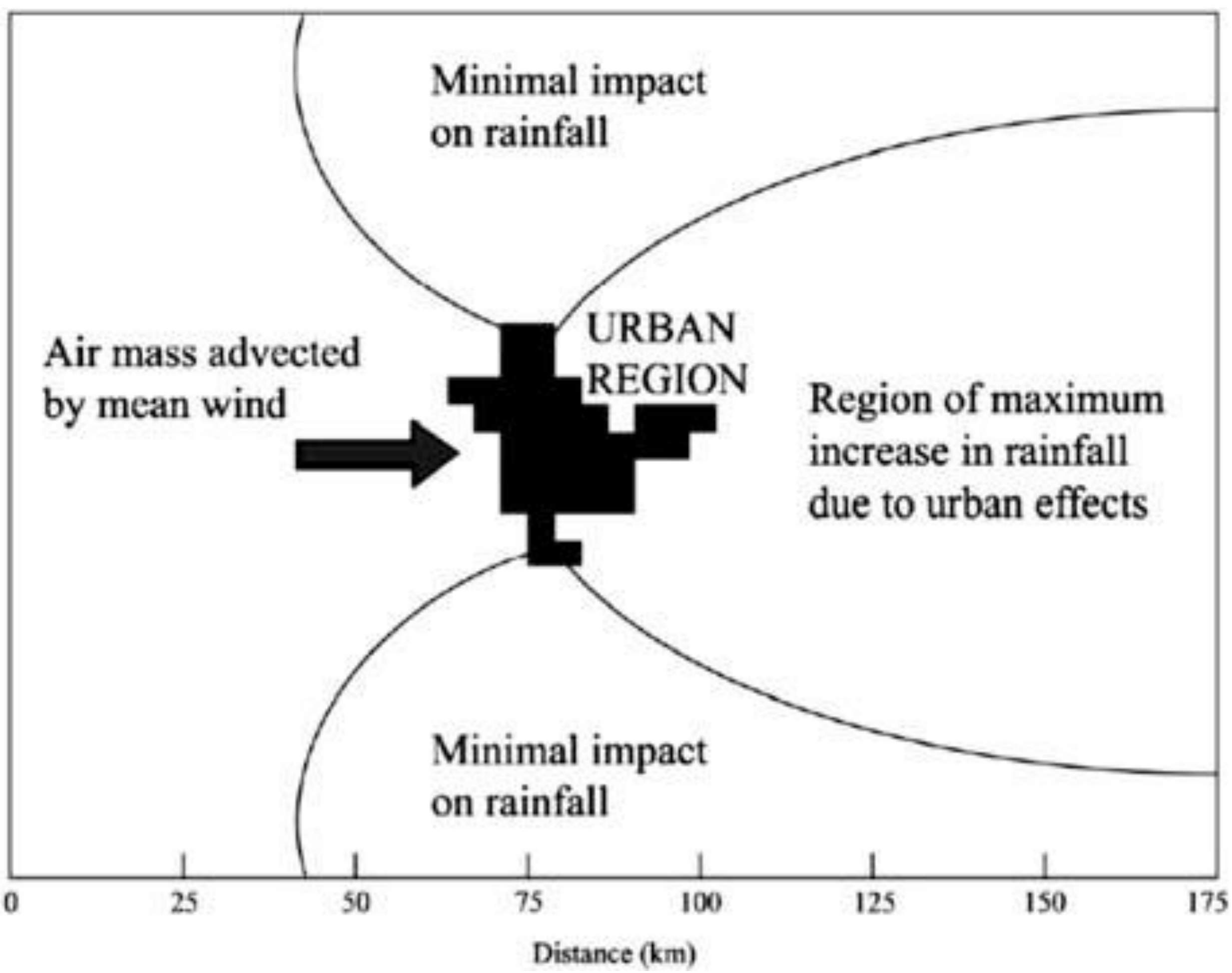

Figure 1.7: Conceptualization of spatial extent of urban rainfall effect (an adaptation from Shepherd et al. 2002). Source: Simpson 2006

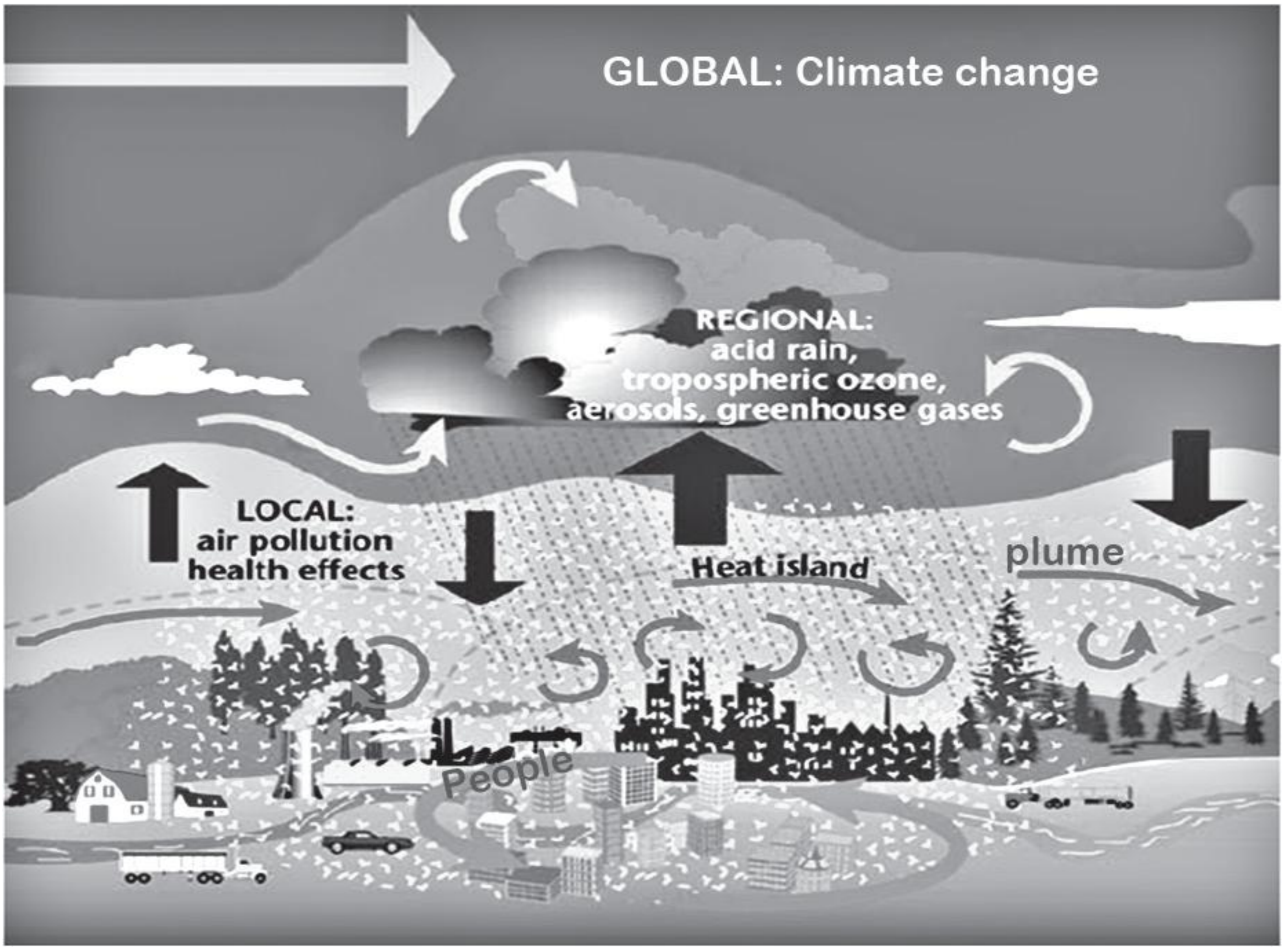

Figure 1.8: The coupling of the urban environment to the atmosphere at various scales. (Following GURME WMO 1995— 2008). Source: Hidalgo et al. 2008

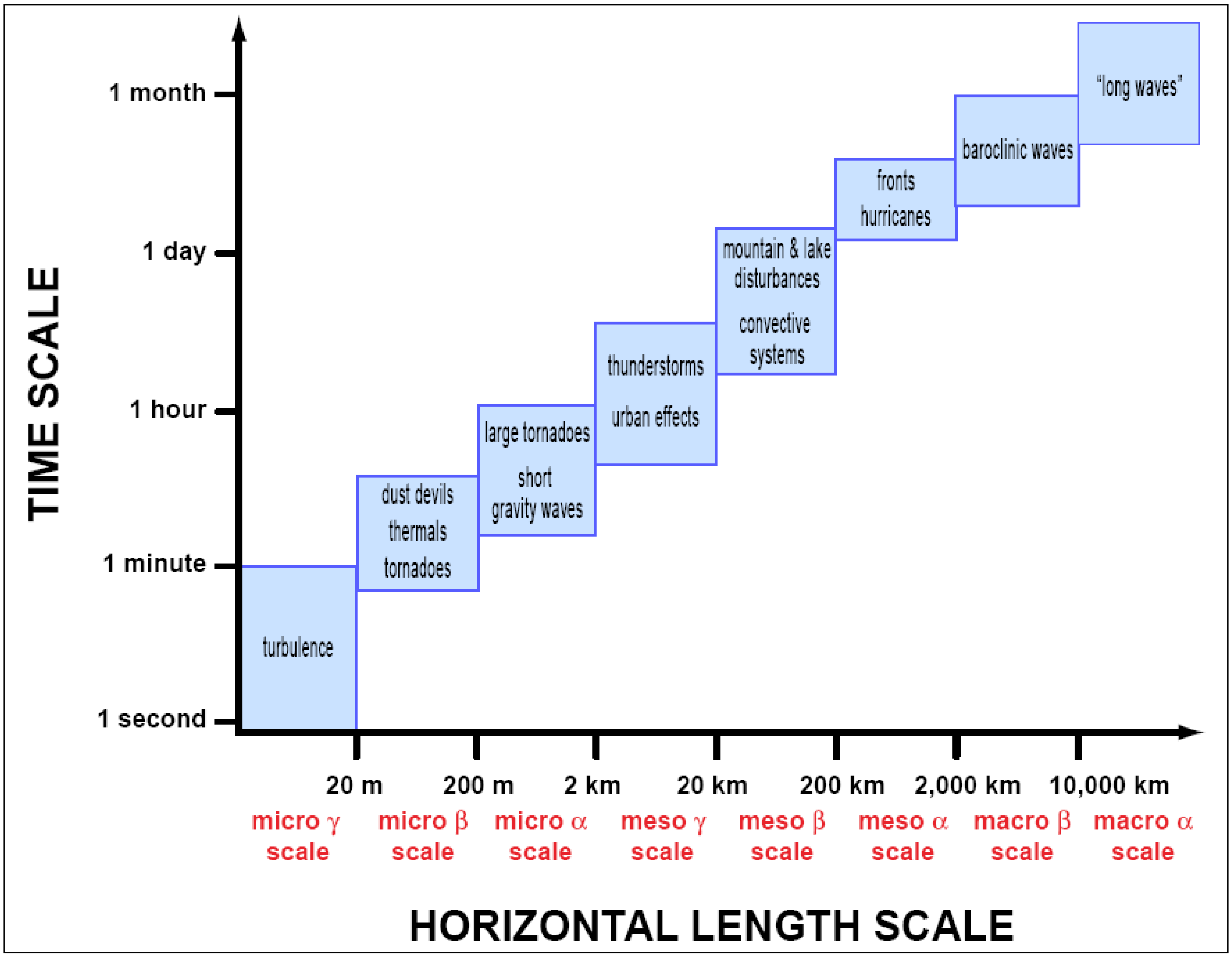

Figure 1.9: Scale definition and the characteristic time and horizontal length scales of a variety of atmospheric processes (Adapted from Orlanski 1975). Source: Markowski and Richardson 2010.

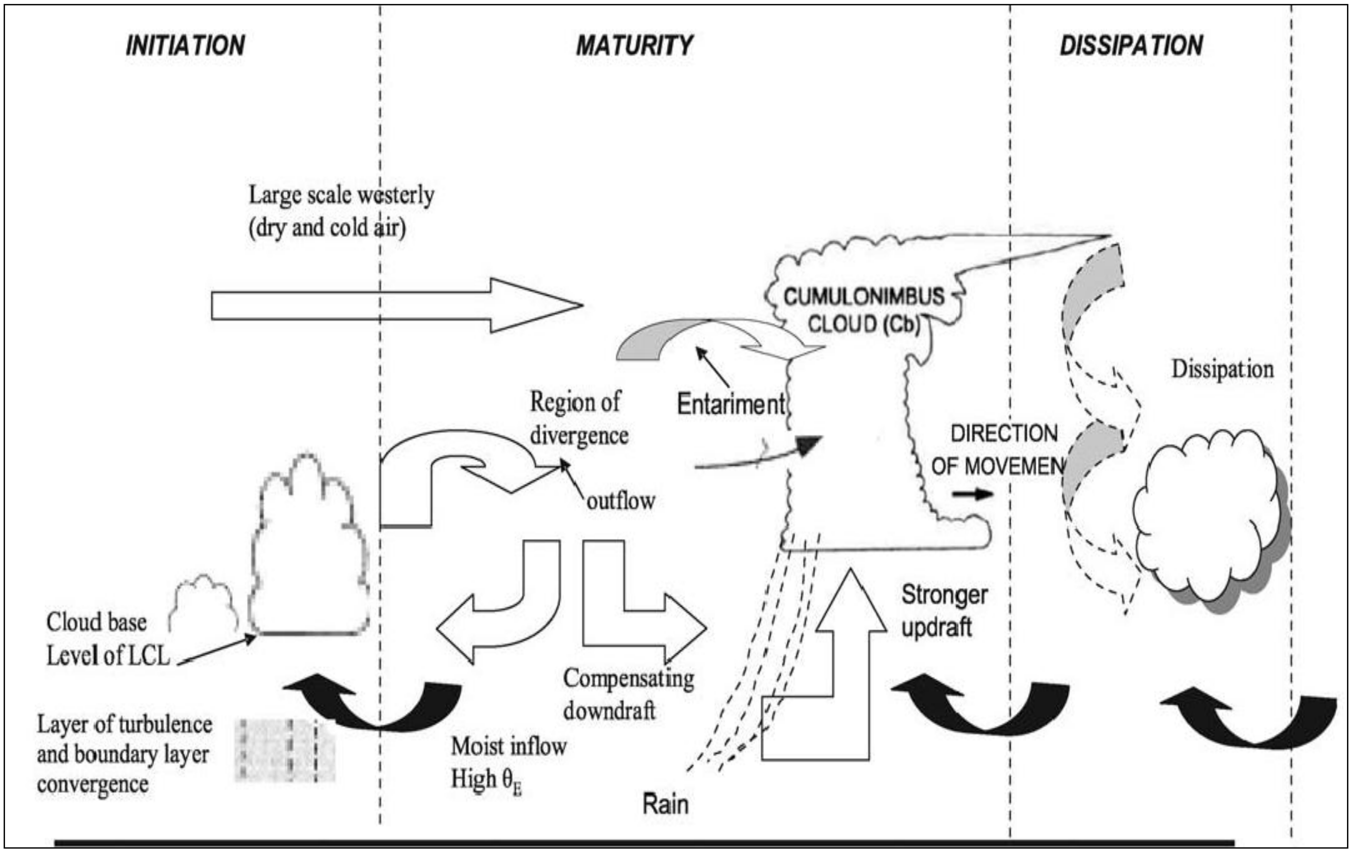

Figure 1.10: Schematic explaining the different processes at various stages of Nor'wester.
Source: Mukhopadhyay et al. 2009

CHAPTER 2

SPATIO TEMPORAL ASSESSMENT OF 300 YEARS URBAN GROWTH OF KOLKATA (INDIA)

[1] Mitra C., M. Shepherd and T. Jordan 2011. To be submitted to Professional Geographer.

2.1 Introduction:

The urban areas of the world, between 2007 and 2025, are expected to gain 1.3 billion people, including 261 million in China and 197 million in India, which together account for 35 percent of the total growth (UN 2007a). India, the second largest populated country in the world, has experienced large-scale development in and around urban areas. In 2007, out of the world's thirty largest urban agglomerations, India had three cities within the top ten. The city of Kolkata in eastern India (Figure 2.1) ranked eighth, with a population of 14.787 million in 2007. It is predicted that Kolkata will have a population of over 20 million by 2025 (UN 2007b). The population of Kolkata has being multiplying in the last three decades. However, the real population explosion took place between 1940 and 1950 during the Indian independence phase, though it is still continuing (Chakraborty 1990).

The morphology of any city is closely associated with its past and present populations that have adhered to certain social and economic customs and followed distinctive occupations (Dutt et al, 1989). Kolkata was the first major city developed by the British East India Company in the early 1700's. The East India Company built their first fortified construction, Fort William, to protect them from the other colonial power aspirants. The city expanded but retained the fortified concrete structure in the middle. Kolkata began as a garrison town first, and later became the company's town. The city then evolved into a provincial city and eventually became the headquarters of the British India government. It is now one of the four largest cities in India (Kundu and Nag 1996). This status established a level of importance for the city and stimulated significant growth in size over the years.

One of the primary objectives of this chapter is to quantify the land cover change of Kolkata from its time of inception to the present, over a period of 300 years using a combination of historical cartographic maps and satellite data, land cover change of Kolkata was quantified over the past 300 years. Even though the rainfall analysis (Chapter 4) spans a truncated period of roughly the last 50-60 years or so, the 300 year land cover analysis was critical for placing the explosive urban land cover dynamics in 1947 in proper historical context. There is no evidence from the inception of the city showing any preternatural period of growth before Indian independence (Mitra et al. 2011).

2.2 Data:

The delineation of the urban growth of Kolkata city is achieved using historical paper maps, Landsat images (1990 and 2000), and topographical maps. All maps used in this research, except Landsat images, have been collected from different Indian Government offices. The first image was a Landsat TM image, dated 11/14/1990. It was a WRS 2 image and the path/row is 138/044, respectively. The second image was a Landsat ETM satellite image, dated 11/17/2000. It is a WRS 2 image and the path/row is 138/044, respectively. The spatial and spectral details of the two images are provided in (Table 2.1). The reflected visible and infrared bands were used and the thermal bands were not considered for this analysis. A historical paper map of Kolkata city showing the growth of the city from pre-1756 to 1990 was also used (Figure 2.2). The scale of the map is 1:100.000. The source of the map is the National Atlas & Thematic Map Organization, India. Two topographical maps, # 79 B/6 & 79 B/7, showing Kolkata city and adjoining area are also used. The scale of the maps is 1:50,000. The source of the topographical maps is the Survey of India.

2.3 Method:

In this study, traditional cartographic sources like paper maps were employed due to lack of digitized historical maps of Kolkata. The results from digitization have been validated by remotely sensed images from recent years. The topographical maps and the city growth map were both paper maps. The first step was to scan the maps and have them digitally available. The scanned topographical maps were then rectified with the base paper maps using latitude/longitude coordinates found along the margins of the maps. The two topographical maps were mosaiced together to have a larger view of the area.

The Kolkata urban sprawl map did not have any coordinates, so it had to be georeferenced to the topographical map. For this process, 16 ground control points were chosen on both maps to georeference one to the other using Leica Geosystems Imagine 9.1 software. To facilitate further analysis, all datasets had to be precisely registered and transformed into the same coordinate system. The historical growth map was in geographic coordinates so it had to be transformed to UTM coordinates in order to facilitate comparison with the Landsat images. The study area is in the UTM system, Zone 45 N and cast on the WGS-84 datum. The transformation from geographic coordinates to UTM coordinates was done using the ArcGIS 9.1 software. The image registration accuracy for the two Landsat images was performed. Thirty points were chosen on both 1990 and 2000 images and the RMSE was calculated. The RMSE for these images was 16.08 km or approximately half a pixel.

All maps used in the analysis were published as paper products so none of the features of interest had been previously digitized. The extent of growth in the city was delineated using "heads-up" digitizing methods from the urban growth map and LANDSAT images using the ArcGIS software. Although the process of digitization was very time consuming and difficult, it was necessary to *reveal the phases of growth in different time frames beginning from before 1756 to 1990. The result was a unique and novel view of the land cover growth history of Kolkata over this time period*.

The next step was to overlay the digitized maps onto satellite images to further digitize and detect the changes in the growth pattern between 1990 and 2000. The overlaying of the digitized growth map over the 2000 satellite image showed an extension in area from the 1990 urban sprawl. An unsupervised classification was done on the 2000 image. Since the unsupervised classification did not give the desired result, a portion of the digitization was done based on visual interpretation. The areal extent of the city in different phases was calculated in the attribute table of ArcGIS 9.1, after the digitization was done.

2.4 Results:

Land cover change dynamics

Such rapid population growth inevitably drove the expansion of urban, impervious land cover. The digitization and overlaying of the maps revealed the phases of urban land cover growth in different time frames beginning from before 1756 to 2000. The city had been growing along the River Ganges and other centers at a regular pace up to 1947, after which there was a nearly fourfold increase in the change in area for the city of Kolkata from 225 sq. km. to 1102 sq. km (Mitra et al 2011). This fact is supported by the census data of the 1931 – 1941 decade when the population of Kolkata city increased by 77 % (Kundu and Nag 1996). The rate of change in urban land cover growth over the period 1947-1990 was 23.20 sq. km/year compared to 29.50 sq. km/year over the period 1856-1947. This rate of expansion continued for decades after the independence. Table 2.2 shows that between 1990 and 2000 the change in area per year for

Kolkata city was 29.50 sq. km., which was more than what was observed before 1990 (23.20 sq. km.) (Mitra et al 2009).

In Figure 2.3, the results from the digitization are shown. The first four figures show how the urban land cover before 1947, through influx of refugees, had already started from the 1930's. After 1947 the city rapidly expanded in all directions, which is likely a reflection of the sudden increase in population. Figure 2.4 is a graphical representation comparing the total area, total area change and area change per year up to the year 2000 for the city.

During the last two decades, the city of Kolkata has only been growing at the somnolent rate of 2 percent per decade in population. In contrast, the Kolkata Metropolitan District (KMD), which includes the rural tracts and townships that ring the city, has been expanding at a decadal rate of over 18 percent (Census of India, 1991; Roy, 2003). This information is alarming enough for the government and planners to evaluate the magnitude of damage such immeasurable expansion could have on the overall environment in the city of Kolkata.

The authorities have overlooked the possible environmental degradation caused by the gradual loss of wetlands east of the metropolitan region. Further, Mitra et al. (2011) have suggested that premonsoonal rainfall patterns and trends may have been altered due to urban land cover. Some of the fastest growth is occurring on the eastern fringes of the KMD. This involves state-controlled developments, such as Salt Lake City and the proposed New Calcutta at Rajarhat, as well as a flurry of private building activities, especially in the sphere of middle class housing (Roy, 2003). Salt Lake City now supports a population of 167,848 (Census of India, 2001).

2.5 Conclusions:

This chapter is an in depth study of the land cover change over the past 300 years and also of the future of the city of Kolkata. The first part of the research is based mostly on GIS and remote sensing techniques, followed in the next chapter by a growth model to predict the future growth of Kolkata. The quantification of the urban growth of Kolkata in 300 years shows that the maximum growth took place in the twentieth century between 1941 and 1981. The factors favoring the maximum growth during this period is elaborated on in chapter 3 of this dissertation. This study is possibly the most thorough spatio-temporal evaluation of Kolkata's urban dynamics, spanning several centuries. It paves the way for further studies in the following chapters related to future growth of Kolkata, its impact on pre-monsoon rainfall pattern and how urban land cover can modify convective activities.

Tables:

Table 2.1: Spectral and spatial details of the satellite images. Source: NASA (http://landsat.gsfc.nasa.gov/about/tm.html)

Details	**1990 TM Landsat Image**	**2000 ETM Landsat Image**
Sensor Type	opto-mechanical	opto-mechanical
Spectral Resolution	0.45 - 12.5 µm	0.45 - 12.5 µm
Spatial Resolution	30 m (120 m - thermal)	30 m (60 m - thermal, 15-m pan)
Temporal Resolution	16 days	16 days
Image Size	185 km X 172 km	183 km X 170 km
Swath	185 km	183 km

Table 2.2: Historical, current and projected change in urban land cover area of Kolkata city

Years	**Total Area (sq. km.)**	**Area change/ year (sq. km.)**
Before 1756	4.0	
1793	34	0.80
1856	136	1.60
1947	361	2.50
1990	1363	23.20
2000	1658	29.50
2025	2653	39.80

Figures:

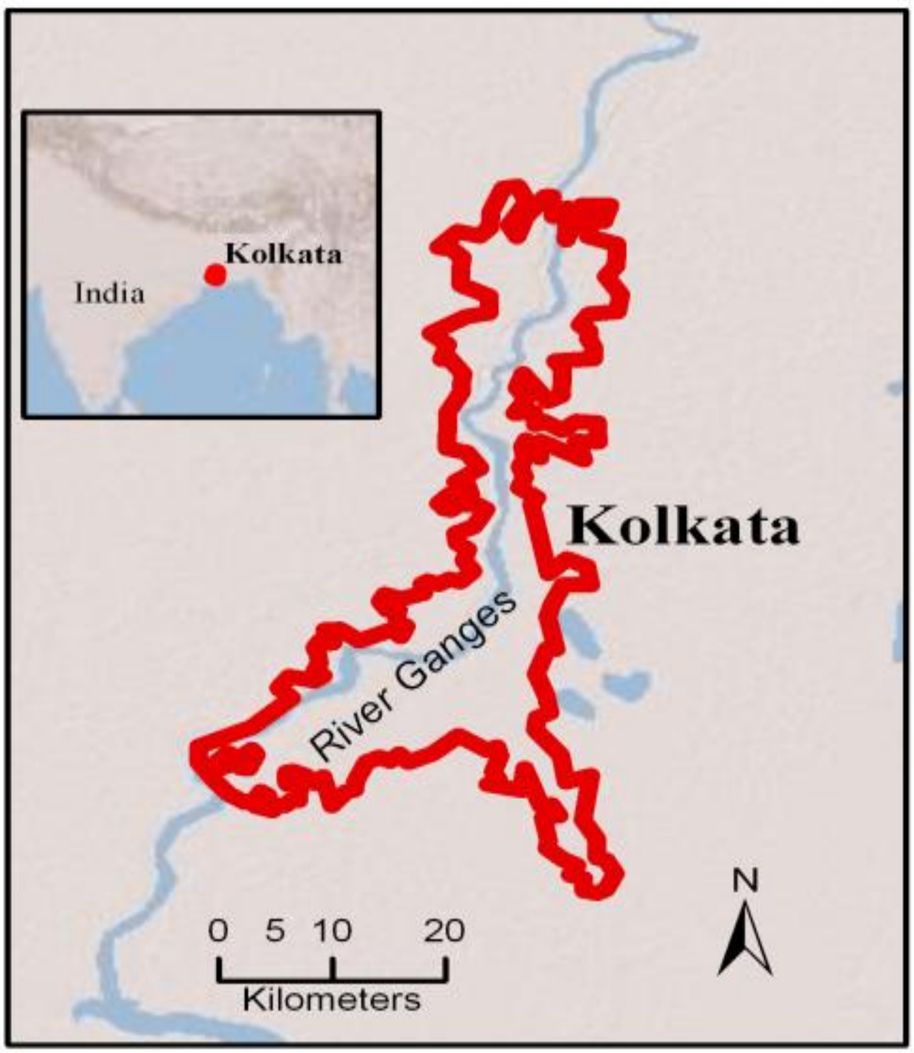

Figure 2.1: Location map – Kolkata City, India

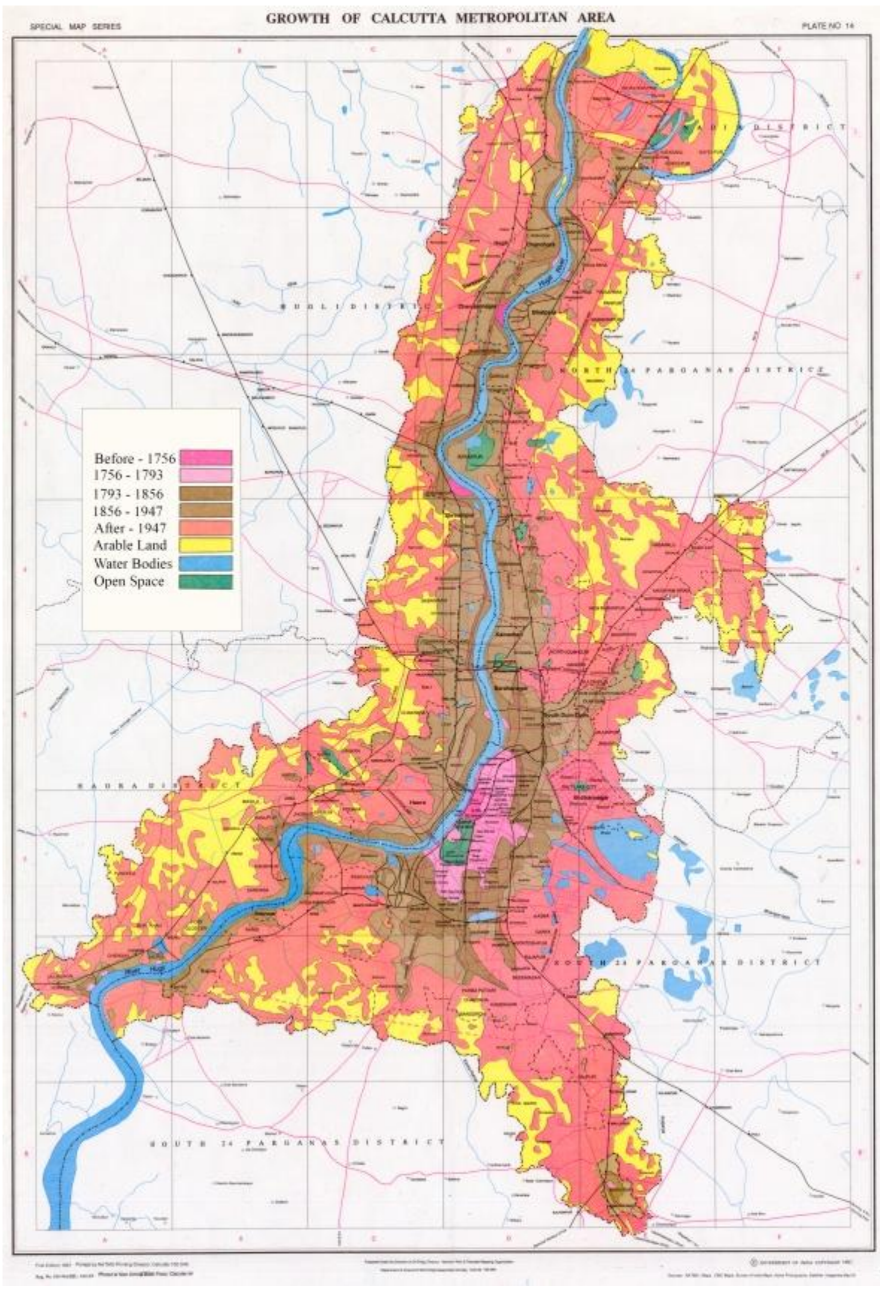

Figure 2.2: Growth of Calcutta Metropolitan Area, Plate No. 14, Special Map Series.
Source: National Atlas and Thematic Mapping Organization, Government of India

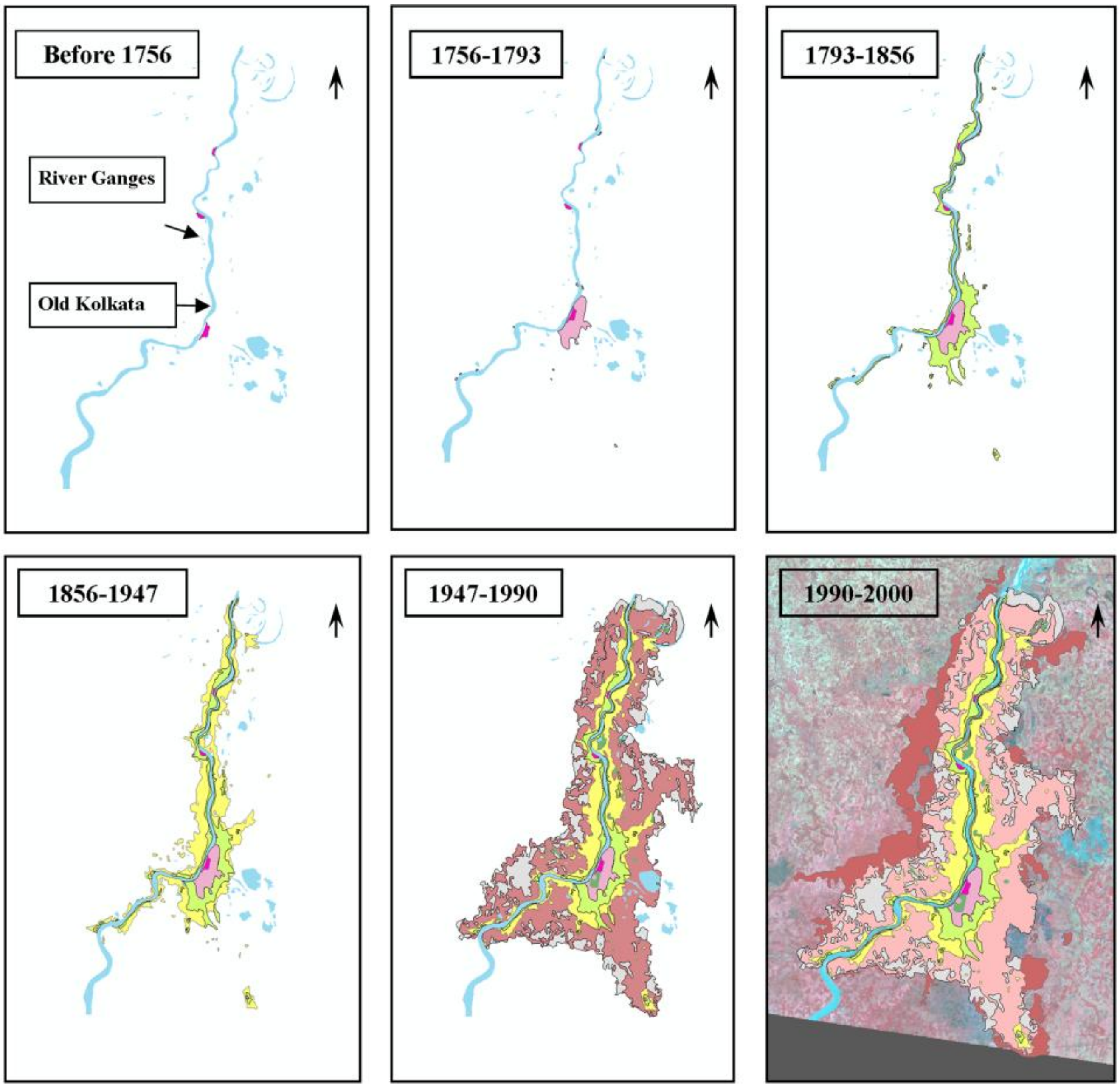

Figure 2.3: Phases of growth of Kolkata city in different time frames beginning from before 1756 to 2000

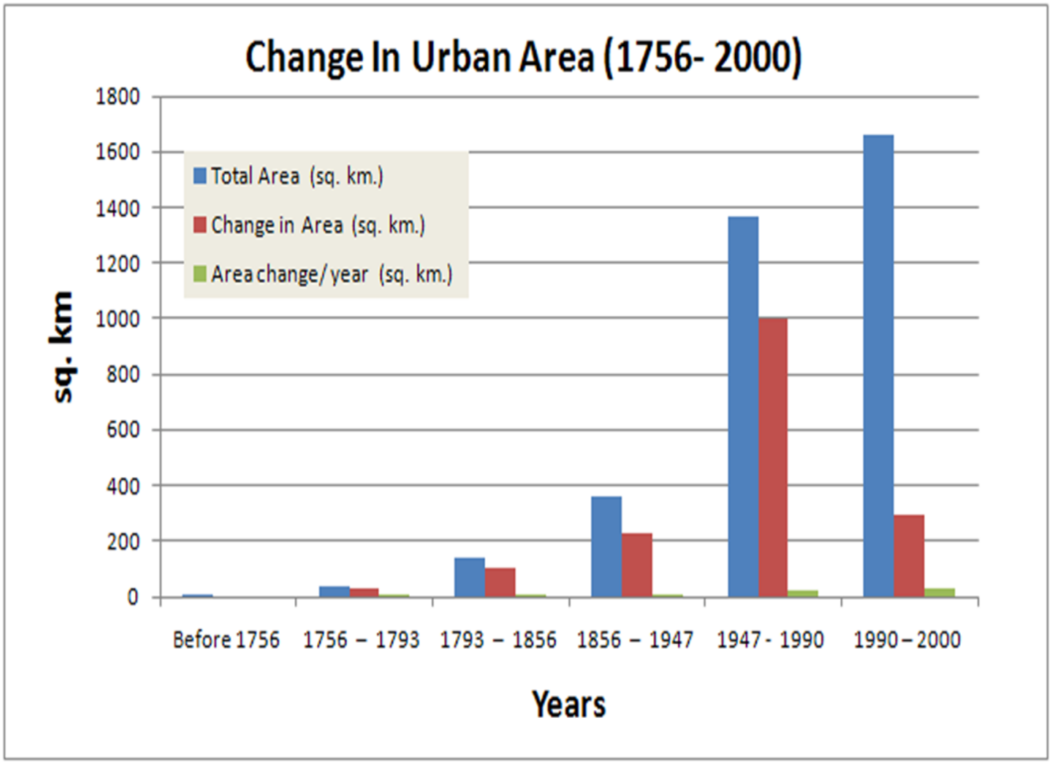

Figure 2.4: Graphical representation of change in urban land cover area for Kolkata city

CHAPTER 3

GROWTH OF KOLKATA, INDIA– PAST, PRESENT AND FUTURE: A SYNERGISTIC ANALYSIS USING CARTOGRAPHIC, GIS, REMOTE SENSING, AND CELLULAR AUTOMATA MODELING

[1] Mitra C., M. Shepherd and T. Jordan 2011. To be submitted to Professional Geographer.

Abstract:

This study provides, to our knowledge, one of the most thorough spatio-temporal assessments of urban growth in Kolkata (India). The objectives were (1) to ascertain factors behind Kolkata city's population explosion in the 20^{th} Century; (2) to project how the urban land cover of Kolkata will grow in the next 25 years (2025), using the CA-Markov urban growth model and (3) to project the growth of Kolkata to the present (2010) using CA-Markov and validating the image with present Google Earth scenario. The analysis shows that the maximum land cover growth occurred during and after India's independence in 1947, when millions of refugees migrated from Bangladesh and surrounding states. There has been a fourfold increase in urban land cover during that time period and the rate of growth continues. CA Markov model results suggest that the city will expand towards the south, southeast and along the river by 2025. This expansion will be mainly along lines of communication, primarily the river Ganges and the railway lines. The analysis also revealed that growth rates over the period 2000 to 2025 might exceed the growth rates in the most recent 20 years period. Contemporary assessment of past, present and future growth of cities in developing countries is critical to future analysis of planning strategies, environmental impacts, and land management amongst others.

Keywords: Urban land cover change, Kolkata city, CA Markov urban growth model, GIS-Remote sensing techniques, migration.

3.1 Introduction

A United Nation report verifies that the world population reached a landmark in 2008. For the first time in history the urban population equaled the rural population of the world. The world population is expected to be on the order of 70 % urban by 2050. Asia, in particular, is projected to see its urban population increase by 1.8 billion, Africa by 0.9 billion, and Latin America and the Caribbean by 0.2 billion (UN 2007a). Virtually all of the growth is and will be in the economically less-developed regions. More than half of the annual growth currently occurs in six countries: India, China, Pakistan, Bangladesh, Nigeria, and the United States (Cohen 2003). The rate at which urban areas are growing is of much concern to both social and natural scientists around the world. Rapid urbanization has led to an increase in built-up area and impervious surfaces, increased greenhouse gas emissions and more anthropogenic activities which are detrimental to the delicate yet complex environmental-climate system of the Earth. The impact will be more felt in developing countries as the standard of living is lower than in developed countries, and a large number of people remain below the poverty line. Thus, any change is likely to have implications on food production, water supply, coastal settlements, forest ecosystems, health, energy security, etc (Sathaye 2006). Rural areas have virtually stopped gaining population. Among regions as a whole, only in sub-Saharan Africa and Oceania will rural populations grow in the future (Hinrichsen et al. 2002)

The study discussed in chapter 2 provides, to our knowledge, one of the most thorough spatio-temporal assessments of urban growth in Kolkata (India). Keeping the growth of Kolkata in mind, we also aspire to project how the city will look in the next 25 years. The fact that 70% of world population will live in urban areas, it is important to quantify the extent of land cover change of cities (UN 2007a). Contemporary assessment of past, present and future growth of cities in developing countries is critical to future analysis of planning strategies, environmental impacts, and land management among others.

3.2 Quantifying the growth of Kolkata over 300 years

Assessing Urban Extent

A large body of research has been done in the field of assessing urban extent, especially in the developed countries of the West (Maktav et al 2005, Sutton 2003, Small 2005 and many others). Relatively little research has been done in the developing countries where the impact of urbanization on local and regional levels may be more profound. In the developing countries, overpopulation and unplanned development have given urbanization a more damaging outlook. According to Barba and Rabuco (1997) the three main causes of the rise in urban population in developing countries are rapid population growth by natural causes, rural-to-urban migration and reclassification of rural areas to urban areas (Barba and Rabuco, 1997).

Keeping this in mind, it seems necessary to analyze the extent of urbanization and highlight the significance of classifying urban land based images. Remote sensing and GIS techniques have long back replaced the traditional methods of quantifying urban extent. According to Maktav et al (2005) remote sensing – as a technique for observing the surface of the Earth from different platforms – and Geographic Information Systems (GIS) can mitigate the problems of traditional methods by providing up-to-date spatial information. In developing countries, this trend towards application of GIS and remote sensing in urban studies started in the 1970s (Maktav et al., 2005).

Literature has highlighted the major use of two techniques to delineate urban expansion and sprawl, one is the use of remotely sensed satellite images coupled with GIS techniques and the other is nighttime satellite imagery. Remotely sensed images from different satellite systems have brought about a remarkable improvement in understanding the changes on the earth's surface. First generation satellite systems (1963 to 1972) consisted of Corona, Argon and Lanyard, however, they were limited in capability and resolution (Zhao and Kafatos 2002). Since 1972, numerous technical improvements led to a second generation of Earth observation satellites, such as LANDSAT, SPOT and IRS (Landsat – Derived from Land Satellite; SPOT - Satellite Pour l'Observation de la Terre; IRS – Indian Remote Sensing Satellite). After 1999, a third generation of Earth observation satellites with very high geometric resolution (IKONOS-2, Quickbird-2, etc) (Maktav et al., 2005) emerged. The convergence of GIS, remote sensing, and database management systems has improved quantification, monitoring, modeling and subsequently predicting changes occurring on the surface of the earth (Sudhira et al., 2004).

Overlaying or superimposing of remotely sensed data is a common method to delineate urban growth. De Almeida et al. (2005) used GIS and remote sensing as tools for the simulation of urban land use change (1979 – 1988) of a medium sized town, Baura, west of Sao Paulo, Brazil. To update the land use maps used in the simulation, they used a LANDSAT Multispectral Scanner (MSS) image of 22 June 1979 and a LANDSAT Thematic Mapper (TM) image of 29 November 1988. Potere and Scheneider (2007) too employed a diverse set of methodologies that draw on a sometimes overlapping pool of remote sensing imagery, ground-based census results, and geographic information systems (GIS) data layers. They compared global maps describing urban land, which were created by six groups from government and academia in both the European Union (EU) and the US. Differences in these six maps persist at the scale of regions, countries, and urban patches. These large inter-map variances may be driven by a combination of several factors, including differences in the timing of map construction, differences in map resolution and class enumeration, and fundamental differences in each group's approach to urban land.

Remote sensing techniques were also utilized to quantify urban growth of 25 mid-sized cities from different geographical settings and levels of economic development (Schneider and Woodcock 2008). They quantified the spatial extent, rates of expansion, and patterns of urbanization using the combination of remotely sensed data, spatial pattern metrics and statistical census data. Seto and Shepherd (2009) highlighted the wide use of remote sensing data to measure urban extents, with a majority of studies superimposing one to three satellite images to quantify land use change or to monitor urban land-use change between two or three time points.

Another remote sensing technique often used is the spectral characterization of urban reflectance properties. Remotely sensed data can give detailed information on the roof material, for example, by hyperspectral images (Heiden et al. 2001), which could influence heat transfer within the city. Different sensors on multiple platforms (HRSC-A, aerial cameras, LIDAR, satellite sensors) acquire high resolution three-dimensional (3D) surface information which was needed to model the air movement within a city in Heiden et al. (2001).

Small (2005) made a comparative Spectral Mixture Analysis (SMA) of the Landsat 7 Enhanced Thematic Mapper (ETM+) imagery for a collection of 28 urban areas worldwide to provide a physical basis for a spectral characterization of urban reflectance properties. His principal finding was that built-up urban areas occupy different but distinct regions of a common spectral mixing space. The implication of the spectral clustering is spectral consistency. This consistency can facilitate discrimination of built-up areas. In spite of the spectral heterogeneity at pixel scales, urban areas are distinguishable from undeveloped land cover within the mixing space. This type of spectral analysis is very helpful for any analysis of urban growth of a city (Small 2005).

Scholars like Imhoff et al. (1997), Sutton (2003), and Sutton et al. (2006) used nighttime satellite imagery to map urban areas and sprawl. Nighttime imagery has some advantages over daytime imagery in that it is measuring emitted rather than reflected radiation. This avoids some classification problems in separating developed vs. non-developed land cover. Sutton (2003) used nighttime satellite imagery to delineate urban areas in the United States that had a population of more than 50,000. In the study the data used to obtain areal extent and population was a radiance calibrated DMSP OLS image (DMSP OLS – Defense Meteorological Satellite Program Operational Linescan System) of the United States (Elvidge et al., 1998) and a grid of population density derived from the U.S. census (Meij, 1995), both having 1 km^2 resolution. The cities above the sprawl line (adjusted scale) have no urban sprawl whereas the ones below the line suffer from urban sprawl. Sutton et al. (2010) again used nighttime satellite imagery for mapping urban and peri-urban areas of Australia. They used a population-weighted measure of urban sprawl to categorize the different levels of sprawl for Australia's cities. They also compared the Australian situation with that of the US. They found that a large number of people (82 percent) in Australia lived in urban areas, whereas in the US only 55 percent of the populations lived in urban areas. Another unique study was done by Schneider et al. (2003) using a technique called boosting to improve supervised classification accuracy and provide a means to integrate Moderate Resolution Spectroradiometer (MODIS) data with the DMSP nighttime lights data set and gridded population data. They found that the fusion of these three data types improves urban classification results by resolving confusion between urban and other classes that occurs when any one of the data sets is used by itself.

The literature shows that the most important criteria in evaluating past, present and future urban extent is to acquire the best possible urban land use/ land cover images to classify and compare them. In fact, it is often the heterogeneity of urban land cover that distinguishes it from other land covers that are more spectrally pure and occupy distinct domains within the mixing space closer to the end member. Thus more studies comparing maps from different sources over longer temporal stretches are required to have a better understanding of how urban areas have expanded, setting a base for future predictions.

Assessing Urban Extent in India

It is evident that monitoring urban land use change using remote sensing, GIS, and modeling is lacking in the context of India (Sudhira et al., 2004). Sudhira et al. (2004) used remote sensing and GIS to understand the pattern and sprawl of the city of Udipi in the Mangalore region of India. They used standard image processing techniques such as image extraction, rectification, restoration and classification in the study. They found that the rate of development of land in Udipi was outstripping the rate of population growth. This implied that land was being consumed at excessive rates. Between 1972 and 1999, population in the region grew by about 54% (Census of India, 1971, 1981, 1991) while the amount of developed land grew by about 146% (Sudhira et al., 2004). Some of the other cities of India that have been the focus of studies employing GIS techniques and remote sensing include Ahmedabad, Surat and Vadodara (Jothimani, 1997), Vadodara (Bhatt et al., 2006), Dhanbad (Srvastava, 2000), Hyderabad (Lata et al., 2001; Taubenbock et al 2007); Bhopal (Saxena, 2003), Allahabad (Srivastava and Gupta, 2003) and others.

In 2009, Taubenbock et al did a spatiotemporal analysis using remote sensed Landsat images from 1972 to 2001 for 12 largest Indian urban agglomerations including Kolkata city.

The study aims to detect similarities and differences in spatial growth in the large Indian urban agglomerations. These cities in the same cultural area range from 2.5 million inhabitants to 20 million (in the metropolitan region of Mumbai). Ahead of the other metropolitan areas Mumbai and Kolkata show the highest built-up densities in zone 1, with little redensification since the 1970s. Delhi's pattern shows laminar ring-shaped growth; in contrast Kolkata shows very patchy growth. The results paint a characteristic picture of spatial pattern, gradients and landscape metrics, and thus illustrate spatial growth and need for future modeling of urban development in India.

A recent study by Bhatta (2009) was conducted on the Kolkata Municipal Corporation (KMC) area using Landsat and Indian Remote Sensing (IRS) images to understand the growth of the city between 1975 and 2005. He divided KMC into five zones based on land use: Northern; Central; Western; Southern and Eastern. He concluded that each different zone has a different level of compactness leading to different patterns of growth. Further, he suggested that a single policy for the entire city never works with equal degrees of effectiveness. According to Bhatta, the theory and models of urban spatial growth pattern that are supported by the findings of the paper should prove useful for devising policy responses to the problems associated with preparing for urban expansion.

The research herein complements and extends the results of Bhatta (2009). Bhatta deals with the KMC area which is 185 km^2 and for 30 years (1975 – 2005), whereas this study is done on the Kolkata Urban Agglomeration which consists of an area of 1750 km^2 (Bhatta 2009) for a period of 300 years. Further, our research is designed to provide two land cover scenarios (urban and no urban) to evaluate urban effects on environmental-climate factors (mainly precipitation) as reported in Mitra et al. (2011a) using coupled atmosphere-land surface models (Mitra and

Shepherd 2011, Manuscript 3). *Overall, it is clear from the review that further quantitative study of Kolkata, a city developing rapidly under the forces of incessant unplanned growth due to various political and social issues, is needed.*

Urban land cover of Kolkata change in the next 25 years

In spite of the choice of models to understand urban dynamics, the most commonly developed and applied techniques are the cellular automata models and agent-based models. Cellular automata are inherently spatial models by their regular arrangement of cells in space so it is easy to regard a cell as part of a regular intersected map. In this sense, every cell covers an attribute, which may be identified in the corresponding grid square in the city map (e.g. land use, population size) (Back et al. 1996). Modeling cities with cellular automata is virtually impossible without the management capabilities of GIS and powerful workstation technology (Clarke and Gaydos 1998). “Cellular models” are a promising approach for the adequate spatial modeling of complex urban socio-economic processes (Back et al 1996). Cellular automata models have been used to study the urban expansion of a number of urban areas in the US like San Francisco and Washington/Baltimore (Clarke and Gaydos 1998); in Guanzhou (Wu, 1998); Southeast England (Wu and Martin 2002); Savanna, Georgia (Batty and Xie 1994); Charleston area in South Carolina (Allen and Lu 2003).

Where cellular models are focused on landscapes and transitions, agent-based models focus on human actions. Agents are the crucial component in these models (Parker et al. 2003). Agents have been used to represent a wide variety of entities, including atoms, biological cells, animals, people, and organizations (Liebrand, Nowak, and Hegselmann 1988; Epstein and Axtell 1996; Conte, Hegselmann, and Terna 1997; Weiss 1999; Janssen and Jager 2000, Parker and Meretsky 2004).

Parker et al. (2003) discussed many land use land cover (LULC) models like mathematical equation-based, system dynamics, statistical, expert system, evolutionary, cellular, hybrid and agent based. He suggested that the best model to understand the complexities of urban systems are the multi-agent system models of land-use/cover change (MAS/LUCC) models that combine cellular and agent-based models. The cellular model is part of the agents' environment, and the agents, in turn, act on the simulated environment. In this manner, the complex interactions among agents and between agents and their environment can be simulated in a manner that assumes no equilibrium conditions.

In this study, we have employed a cellular automata model approach. The IDRISI Taiga, an integrated GIS and Image Processing software, has a built-in CA Markov model that can be used to project the future growth of a city, in this case, Kolkata City. The literature has shown that CA Markov models have been successful in predicting future growth of cities. Sun et al (2007) used the CA Markov model to predict the future urban sprawl of the City of Calgary based on the interactions between the land uses and the transportation network. Ye and Bai (2008) used the CA Markov model to predict the landuse of Nenjiang County, China in 2015 and 2030 in this region. In the paper they explain why CA and the Markov chain complement each other. One inherent problem with Markov is that it provides no sense of geography. The transition probabilities may be accurate on a per category basis, but there is no knowledge of the spatial distribution of occurrences within each category. So CA is used to add spatial character to the model. Falcucci et al (2008) used CA Markov to simulate a 2020 land-cover suitability map to assess habitat availability for the Apennine brown bear population in central Italy.

Several comparative studies have been done to evaluate the validity of the CA Markov model and recommend the use of the model (Pontius and Malanson 2005, Cabral and Zamyatin

2006, Lee et al. 2008). The comparisons were done between CA Markov, CA Advanced Models and Geomod.

The CA Markov model in IDRISI is a simple but realistic model applied to assess future land cover change in Kolkata city, India. We used it to predict the future land cover change of the city in the next 25 years. As this study is part of a broader effort to understand urban land cover-climate interactions, the intent was to acquire a representative land cover growth projection to feed into a coupled atmosphere-land surface model (WRF–NOAH), (Mitra and Shepherd 2011) without the complexities of other modeling approaches. Further, implementation of land cover in coupled atmosphere land models do not require the type socio-economic data inherent to agent-based approached.

In summary, there is a dearth of studies done using CA Markov model on cities of the developing countries, especially India, where the urban expansion is unconstrained. *Here this research will play a significant role by using the CA Markov model to make a projection of the future growth of Kolkata in 2025. The Kolkata in 2010 will also set the base for having a better understanding of the validity of projected future growth prediction. This analysis will be of first order significance in planning outcomes and assessing the role of urban land cover on Kolkata's regional hydroclimate (Mitra et al. 2011b, Mitra and Shepherd 2011; forthcoming manuscripts).*

3.3 Research Objectives

Efforts to understand the extent of damage caused by increased anthropogenic activities on local, regional and global environment is a difficult task. The apprehension lies in understanding the feedback of urban growth and population increase on the health condition of the cities. The literature review has shown that scientists have tried to assess the extent of growth of various cities using different techniques and also used predictive models to see how cities will grow in the future.

Kolkata city, from its days of inception, was never a planned city. It grew haphazardly around the port, the old fort and the ancient Barabazar market by the Hooghly River (Dutta 2003). Interestingly little research has been done to measure the dynamics and impact of the unprecedented urban growth. The objectives of this paper are (1) to evaluate the growth of the city of Kolkata and determine the factors behind the population explosion, which took place after the Indian independence; (2) to project how the urban land cover of Kolkata will grow in the next 25 years (2025), using the CA-Markov urban growth model and (3) to project the growth of Kolkata to the present (2010) using CA-Markov and validating the image with present Google Earth scenario. The hypotheses for this study is that the city has expanded hugely due to the enormous migration of people from Bangladesh during Indian independence and post-Independence economic opportunities and the future urban land cover growth will be in a north-south linear pattern with some east-west extensions due to how the current transportation lines (rail and highway) are oriented.

The methodology is a concerted blend of historical cartographic analysis,GIS techniques, satellite remote sensing (Chapter 2) and urban growth modeling. A CA Markov growth model is adapted to project the future growth of the city, which is the one of the first attempts to use a futuristic urban growth model in India. The data and methods used in the study will pave the way for further research in other similar cities, especially the coastal cities, which have similar flat terrain.

3.4 Data

The first research objective is a qualitative analysis of the factors behind the growth of Kolkata. The factors are social and politically-based but had a huge impact on the overall growth of the city. Migration and total population census data were also used to understand their inter-dependence (Kolkata Metropolitan Development Authority Report, 2001).

The second objective is a predictive analysis. The CA Markov urban growth model in the Idrisi Taiga software is a combined technique of Markov chain and Cellular Automata. The Markov Chain Analysis is a convenient tool for modeling landuse change when changes and processes in the landscape are difficult to describe. A Markovian process is simply one in which the future state of a system can be modeled purely on the basis of the immediately preceding state. Markov Chain Analysis will describe land use change from one period to another and use this as the basis to project future changes. This is accomplished by developing a transition probability matrix of land use change from time one to time two, which will be the basis for projecting to a later time period. (Eastman 2003)

To run the CA Markov model**,** we required two classified Landsat images. In this case we used the two images previously used in the first part of this research; i.e. Landsat images of 1990 and 2000.

For the third objective, the same classified Landsat images of 1990 and 2000 were used to project the future growth of Kolkata in 2010. Google Earth was accessed online (accessed on 17th February 2011) to validate the results of the CA-Markov output.

3.5 Methods

Research Objective 1

Kolkata was the first major city developed by the British in India and later became the headquarters of British India government. This established a level of importance for the city and stimulated significant growth in size over the years (Mitra et al 2011b). The population increase pattern of Kolkata for the past century was significant with a sudden outburst around 1930 – 1940s (Table 3.2). This requires a thorough literature analysis (Chatterjee, 1990, Roy, 1996, Roy, 2003, Mitra et al. 2011a, Kundu and Nag 1996) to understand the reasons behind increase in population and change in land cover in and around the city. Total population and migration data for decades were analyzed to understand the co-relation between them.

Research Objective 2

In the second part of the study, the cellular automata Idrisi Taiga model (Eastman 1997, Eastman et al 2005) was used to predict the future growth of Kolkata in the next 25 years. The two Landsat images (1990 and 2000) had to be classified. An unsupervised classification was done using Erdas Imagine software (Weng 2001, Stefanov et al 2001). First a supervised classification was done on the images but the complication was related to classification. Some of the vegetation/ agricultural land pixels got classified as urban. So an unsupervised classification was performed. Imagine uses the ISODATA algorithm to perform unsupervised classification, which is the default option in the software. The ISODATA utility continues to classify the cells of the image until either a maximum number of iterations have been performed or a maximum percentage of unchanged pixels have been reached between two iterations (Erdas 1999). An unsupervised classification was done into 20 classes followed by a reclassification into 4 classes: water, urban, vegetation or agricultural land, and wetland. The four classes were chosen to be ingested into the CA Markov model, which required specific classes. Thus additional classes were avoided. A classification accuracy assessment was performed on the classified images. Using the Hawths Tools, 100 random points were chosen. We used the random points created for the 2000 image to be the base for all the images (the original Landsat images as well as the classified images). The class values for the random points from the classified images were extracted to the original Landsat images. A visual assessment of the points on the original images were done and then compared with the help of the classification error matrix. The overall accuracy for the 1990 Landsat image and the 1990 classified image was 57 % and the overall accuracy for the 2000 Landsat image and the 2000 classified image was 86% (Table 3.3). The 1990 accuracy was not very good as the 1990 Landsat image was full of haze and of poor quality. To predict the future growth, it is important to know the extent of built-up area, vegetation/ agricultural land, which can be developed, and water, which cannot be developed. Here an additional class, wetland, is added, to represent the land cover east of Kolkata (Kundu and Nag 1996, Roy, 2003, Bose 2007). Urban expansion is rapidly occurring on them.

The Idrisi Taiga does not accept *.img images, so the two classified images had to be converted to *.tiff images and then *.rst format. *.rst is the format which is acceptable to Idrisi Taiga. To run the model, the images had to be: (1) derived from grids in the same projection, (2) derived from grids of the same map extent, (3) verified to be of the same resolution (row x column count is consistent), and (4) verified to be of the same class value (Idrisi Taiga). The next step was to import the images into Idrisi Taiga and convert them to *.rst images. Then, a Markov chain analysis was run on both images. The output from the Markov chain analysis was used to initialize the CA – Markov analysis. The images ran through a series of tasks to get the projection of the urban growth of Kolkata city up to 2025.

Research Objective 3

For the third objective, the CA-Markov model was run to predict the growth of Kolkata city in 2010 based on the same 1990 and 2000 images used in objective two. This was mostly done to see how accurate the output from the CA-Markov was, when validated against the present land cover scenario of Kolkata. This validation was done using the Google Earth 2010 image.

A classification accuracy assessment was performed on the 2010 CA-Markov output image and the Google Earth image. The same random 100 points used in objective two were imported to perform the accuracy assessment. In this case only 86 points could be plotted as the other points were outside the image. A visual assessment of the points on both the images were done and then compared with the help of the classification error matrix.

3.6 Discussion and results

Factors behind the growth of Kolkata

A major factor contributing to the influx of millions of refugees across the border was India's independence in 1947. Before independence, Bangladesh and West Bengal (a state in India whose capital is Kolkata) were unified as the same political entity, speaking the same language and sharing the same culture. This state was split on the basis of religion (i.e. the Hindus and Muslims) thereby leading to an exodus across the borders. An estimated four million people moved from Bangladesh to West Bengal between 1946 and 1971(Chatterjee, 1990). There has been a steady stream of refugees from Bangladesh consistently in the following decades. Without any planning, they settled on whichever plot of land available without restrictions.

Another factor contributing to the urbanization was the influx of people from the surrounding non-urban and less developed areas to the city (Roy, 2003). Kolkata is a vital city compared with other cities in the eastern part of India. It has become the target city for people of east India to migrate to and a source for financial advancement for many people. Population growth and the drive for economic development led to unplanned and sporadic expansion of the mega-city. A significant peculiarity of Calcutta's regional location is that, unlike Delhi and Bombay, Calcutta has no other major urban center within hundreds of kilometers. The other cities in the Eastern Region of India, outside of Kolkata are all provincial centers with small populations and limited ranges of economic activities and employment opportunities Most of the immigrants came from three states, Bihar (60.6 per cent), Orissa (8.4 percent) and Uttar Pradesh (15.6 per cent) (Lubell 1974).

Although there are no reliable statistics on this exodus, by the time of the 1951 census, only one-third (33.2 percent) of the inhabitants of Calcutta were recorded as having been born in the city, with everyone else classified as an immigrant: 12.3 percent were from neighboring villages, 26.6 percent from other Indian states, and 26.9 percent – more than a quarter of the population – were from East Pakistan, as a result of the communal troubles that had raged since 1907 and the 1947 partition (Dutta 2003). Some – about a quarter of the 1950 influx – settled in relief camps known as 'colonies'. In 1949, there were more than 40 colonies in southeast Calcutta and some 65 in the north. The platforms and concourses of the two main railway stations at Haora and Sealdah also filled up with refugees. Still more came after the dispute over Kashmir in 1951, and the entire city became a refugee relief center (Dutta 2003).

Table 3.2 shows the migrant population over the span of several decades. The maximum influx of migrants was between the years 1951 – 1961 (13.45 lakhs) and 1971-1981 (10.62

lakhs). Both decades are during and after the independence of India and the Bangladesh civil war, respectively (Curlin et al. 1976; Richard and Rose, 1991). It is interesting to note that in 1951 – 1961, the percent of migrant population to total population was 52.76. Figure 3.3 is a graphical representation showing the contribution of migrant population to the increase in total population within the city. It highlights that migrants are still coming into Kolkata to settle even after the influence of the two historical events of Indian Independence and Bangladesh Independence.

Kolkata city 2025

We used the CA Markov urban growth model to predict the future growth of Kolkata in 2025. The predictions were made based on two land cover images, one of 1990 and the other 2000. There is a significant increase in the land cover from 1990 to 2025 (Figure 3.6). The projection of the future growth of the city shows an increase of 995 sq. km. It increased from 1658 sq. km in 2000 to 2653 sq. km in 2025 (Table 3.4). The growth is 39.80 sq. km/year as compared to 23.20 sq km/year in 1990 and 29.50 sq. km/year in 2000. The 2025 image shows that the city expands towards the south-southeast. There will be expansion along River Ganges also. The main lines of communication are the river and the railway lines along the river and to the southeast (Kundu and Nag 1996). The results from the CA-Markov model reinforce the fact that growth is more generally along the lines of communication. The 2025 image shows that the city will also expand towards the east, though the east is covered by wetlands (Kundu and Nag 1996, Bose 2007). The encroachment into the wetlands started from the time the Eastern Metropolitan Bye-pass was constructed. The properties were changing hands very fast (Kundu and Nag 1996), which is supported by the 2025 CA-Markov image.

According to Bhatta (2009), within the KMC area (185 km²), the north and central zones show a very high concentration of built-up area since 1975 (Table 3.4). But further expansion has stagnated due to built-up saturation in these two zones. The expansion of built-up area shows alarming increases in the south and east zones. This is confirmed by the results from the 2025 CA-Markov projections that the expansion will be more towards the south and east of the city.

To further strengthen the case of Kolkata's growth as projected by the CA-Markov model, a visual validation technique was used to compare the 2010 image with present Google Earth scenario. The accuracy was tested using the four classes of water, urban, vegetation and wetlands. The overall accuracy for the 2010 image and Google Earth 2010 image was 74% (Table 3.5), which shows that the CA-Markov projection of Kolkata in 2010 is on par with the actual present growth condition of the city.

3.7 Conclusions

The quantification of the urban growth of Kolkata in 300 years shows that the maximum growth took place in the twentieth century between 1941 and 1981. They were mainly due to two main historically important incidents, one is the independence of India and the second is the Bangladesh Civil War in 1971, followed by Bangladesh's independence too. But the analysis also highlights the continued growing of the city even in the later years till present.

The 2025 results from the CA-Markov model are a cause of concern. The expansion from 1990 to 2025 is significant. The rate of annual growth was 29.50 sq. km/year over the period 1990 – 2000. This rate increases to approximately 40 sq km/year over the period, which appears to represent acceleration in growth compared to the most recent two decades. Such information is essential for government policy makers and planners.

Mitra et al (2011b) recently established, in a climatological assessment, that premonsoonal rainfall (PMR) variability and trends might be associated with urban land cover change during the most recent 50 years of explosive growth. Mann – Kendall trend analysis on the last 50 years of PMR data showed that there was an increasing trend in the PMR for the two urban stations (Alipore and Dumdum) and the Midnapore station (located in the possible downwind region). Using the two output images (1990 and 2025) from running CA- Markov urban growth model, Mitra and Shepherd (2011; Manuscript 3) will investigate how urban land cover growth affects the region's PMR, specifically, the Nor'wester system and what physical mechanism explain such relationships. Future work will also seek to couple future projected land cover into the coupled WRF-NOAH land cover-atmospheric model. Overall, these studies complement each other in understanding the role of urban land cover change and its impact on the hydrological cycle.

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Tables:

Table 3.1: Migrants to Kolkata City during 1921 – 1991 (1 lakh = 100,000)
Source: Kolkata Metropolitan Development Authority (2001), Vision 2025: Perspective Plan of CMA (Interim Draft), Kolkata Metropolitan Development Authority.

Year	Total Population(in lakh)	Migrant Population (in lakh)	Percentage of migrants
1921	10.31	3.25	31.52
1931	11.41	3.57	31.29
1941	21.09	6.64	31.48
1951	25.49	13.45	52.76
1961	29.14	7.58	26.01
1971	31.36	10.62	33.86
1981	33.05	9.28	28.08
1991	33.8	7.12	21.06

Table 3.2: Historical, current and projected change in urban land cover area of Kolkata city

Years	**Total Area** (sq. km.)	**Area change/ year** (sq. km.)
Before 1756	4.0	
1793	34	0.80
1856	136	1.60
1947	361	2.50
1990	1363	23.20
2000	1658	29.50
2025	2653	39.80

Table 3.3: Classification Error Matrix (Classified and original Landsat images)

Landsat Image points 1990	Image Classification points 1990					
		1	**2**	**3**	**4**	**Row total**
	1	3	1	5	0	9
	2	0	4	3	0	7
	3	0	14	49	13	76
	4	0	1	5	1	7
	Column total	3	20	62	14	99
					Overall Accuracy	57/99 =57%

Landsat Image points 2000	Image Classification points 2000					
		1	**2**	**3**	**4**	**Row total**
	1	6	3	4	0	13
	2	0	6	2	0	8
	3	0	4	55	13	72
	4	0	1	4	1	6
	Column total	6	14	65	14	99
					Overall Accuracy	86/99 =86%

Table 3.4: Percentage of built-up area in Kolkata city (KMC). Source: Bhatta 2009.

Table 4. Percentage of built-up area						
	Zone					
Year	**N**	**C**	**W**	**S**	**E**	**KMC**
N, Northern zone; C, Central zone; W, Western zone; S, Southern zone; E, Eastern zone; KMC, Kolkata Municipal Corporation.						
1975	80.15	77.89	28.37	11.39	24.81	43.08
1990	84.21	85.61	50.62	58.25	34.44	63.56
2000	86.26	85.63	52.89	63.94	51.33	68.20
2005	87.59	85.63	54.18	70.31	69.33	72.89

Table 3.5: Classification Error Matrix (2010 and Google Earth Image)

Google Earth random points	2010 random points					
		1	**2**	**3**	**4**	**Row total**
	1	4	0	0	1	5
	2	0	5	16	0	21
	3	1	0	51	0	52
	4	0	1	3	4	8
	Column total	5	6	70	5	86
					Overall Accuracy	64/86 =74%

Figures:

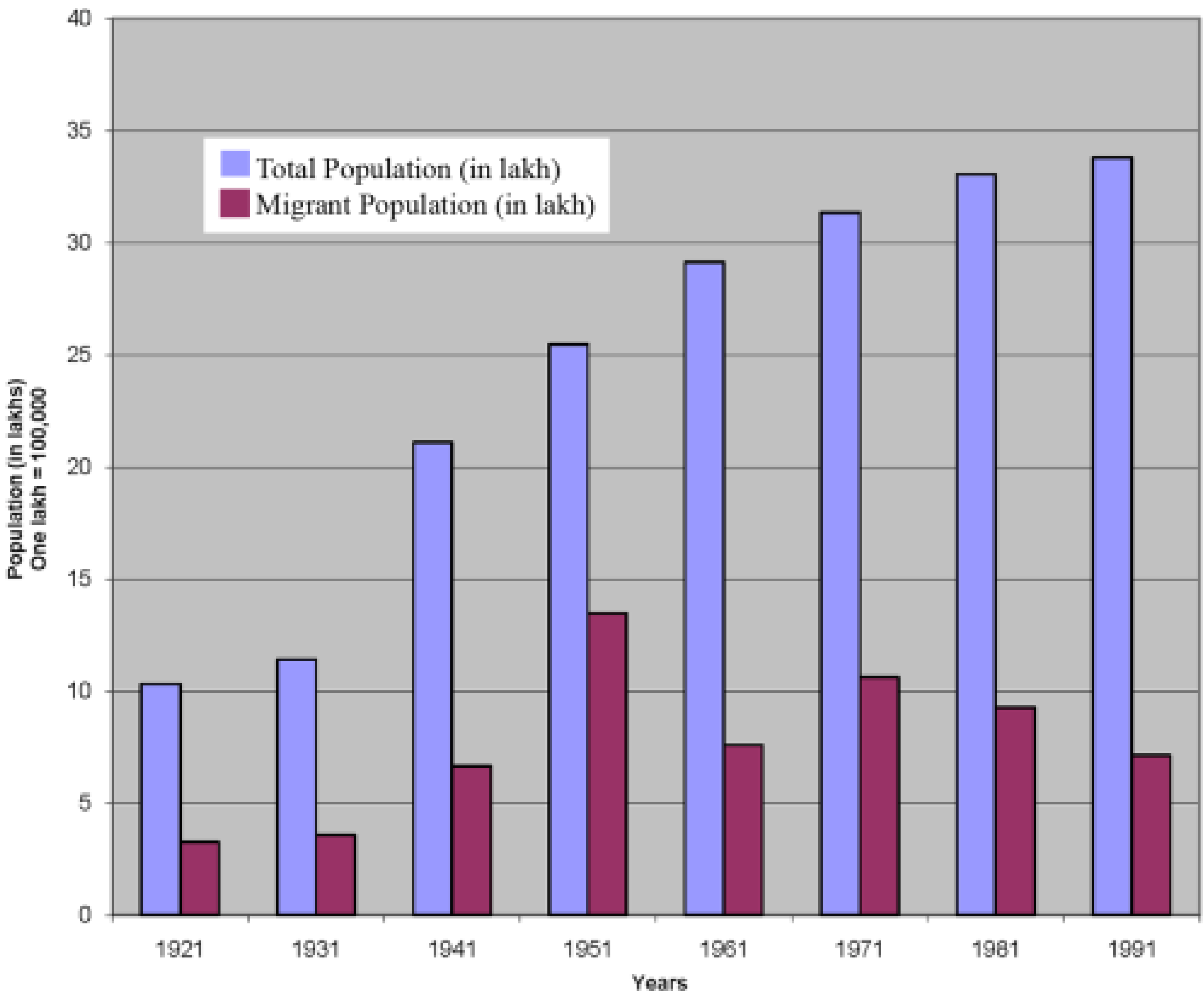

Figure 3.1: Bar Graph showing the total population and migrant population of Kolkata city (1921 – 1991). Source: Kolkata Metropolitan Development Authority (2001), Vision 2025: Perspective Plan of CMA (Interim Draft), Kolkata Metropolitan Development Authority

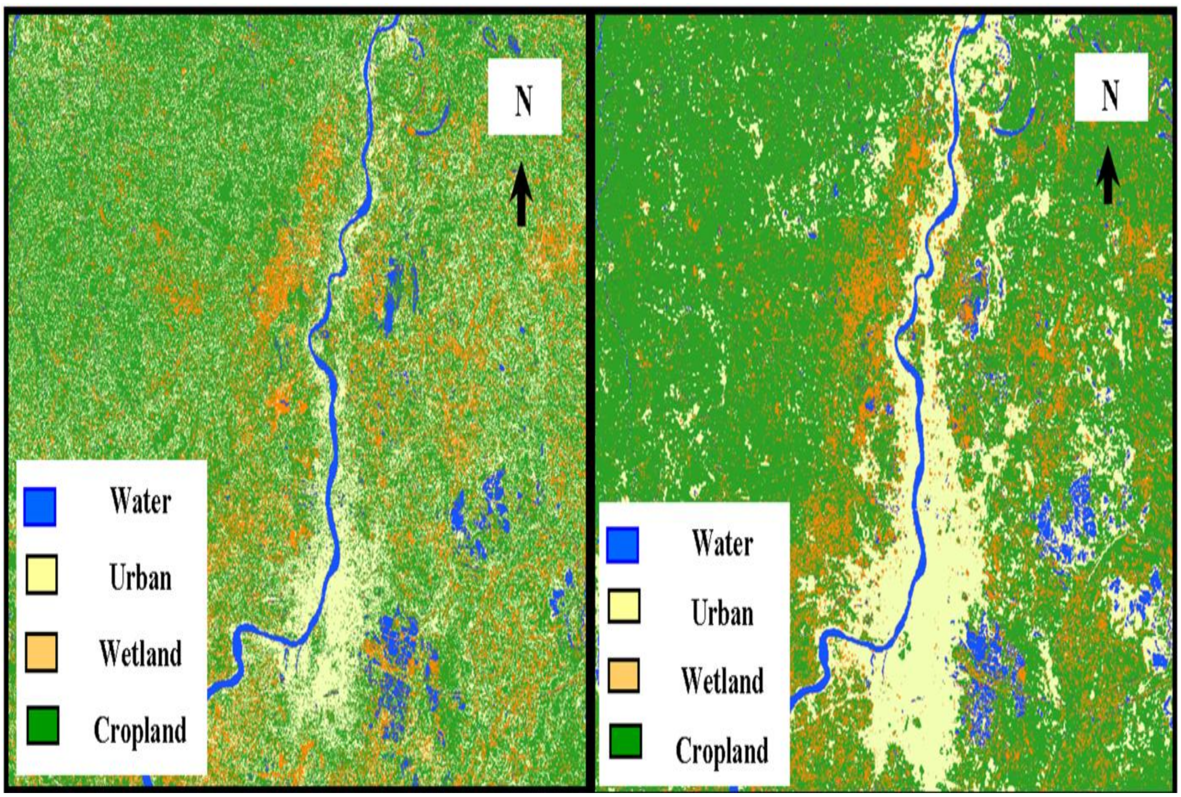

Figure 3.2: A comparison of land cover area of 1990 and 2025 for Kolkata city

CHAPTER 4

ON THE RELATIONSHIP BETWEEN THE PREMONSOONAL RAINFALL CLIMATOLOGY AND URBAN LAND COVER DYNAMICS IN KOLKATA CITY, INDIA

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Abstract:

Empirical and modeling studies show that urbanization can have an impact on the environment. Relatively few studies have investigated urban effects on precipitation in India or other developing countries experiencing rapid urbanization. Further, most precipitation related studies for India focus on monsoonal rainfall. However, premonsoonal periods (March to May) account for 12-14% of the annual cumulative rainfall in eastern India. The majority of premonsoonal rainfall (PMR) is convective and caused by mesoscale forcing, which may include urban effects. In this study, the area under scrutiny is a large urban area in eastern India, Kolkata City. Herein, our goal was to (1) produce a comprehensive characterization of historical land cover dynamics associated with the Kolkata megalopolis, (2) provide a spatio-temporal climatology of PMR in the Kolkata region, and (3) identify possibly associations between Kolkata's land cover and PMR. The analysis shows that the rate of change of urban land cover has increased ten fold from what it was before India's independence in 1947. Time series trend detection with Mann-Kendall statistics indicated statistically-significant upward trends in rainfall over the last fifty years for two Kolkata stations and a nearby downwind station. Further, there was no significant trend for cumulative PMR in less urbanized stations, the country of India or the East- Gangetic region. This finding suggests that the anomaly of the three stations, showing increasing trend in PMR, could be the effect of urban land cover change.

Keywords: Premonsoon season rainfall, Kolkata, landcover change, urbanization, anthropogenic climate change, precipitation trends.

4.1 Introduction:

By the middle of the twenty-first century, almost two-thirds of the world's population will be living in towns and cities. Although currently only 1.2% of the Earth's land is considered urban, the spatial coverage and density of cities are expected to rapidly increase in the near future. It is estimated that by the year 2025, 60% of the world population will live in cities (UNFP, 1999). An estimated 90% of this increase will occur in developing countries (Committee for International Cooperation in National Research in Demography, 2003; Maktav et al., 2005). By 2030, Asia and Africa will each have more urban dwellers than any other major area, with Asia (including China, Japan and Korea) alone accounting for over half of the urban population of the world (Roth, 2007).

Urban precipitation studies date back to Horton (1921), who noted that cities are associated with increased thunderstorm activity. Horton observed thunderstorms over some cities (e.g., Albany, N.Y. and Providence, R.I.), which originated immediately over the city and affected surrounding areas. Early investigations (e.g., Landsberg 1956; Atkinson 1968; Changnon 1968; Landsberg 1970; Huff and Changnon 1972) highlighted the possibility of urban effects on rainfall patterns. In the past 30 years, numerous observational studies (Dai et al. 1997; Bornstein and Lin 2000; Inoue and Kimura 2004; Shepherd et al. 2002; Changnon 2003; Dixon and Mote 2003; Diem and Mote 2005; Burian and Shepherd 2005; Shepherd 2006; Mote et al. 2007; Hand and Shepherd 2009; Lacke et al. 2009) and modeling studies (Hjemfelt 1982; Yoshikado 1994; Thielen et al. 2000; Craig and Bornstein 2002; Rozoff et al. 2003; Shepherd et al. 2007; Shem and Shepherd 2008; Trusilova et al. 2008; Shepherd et al. 2010) have been conducted to understand how urban land cover affects precipitation, a key component of Earth's climate and water cycle system.

This study presents a robust and detailed assessment of spatio-temporal trends in urban land cover growth in Kolkata, India and possible relationships with premonsoonal precipitation. The growth of the Kolkata Metropolitan Area over nine decades (Table 1) is significant, though the maximum was in the last three decades. However, the real population explosion took place between 1940 and 1950 during the Indian independence phase and is still continuing (Chakraborty, 1990). Such rapid expansion provides a favorable period to conduct a spatio-temporal analysis of the premonsoon rainfall climatology.

Climatologically, the area under study (Figure 2.1) is located in the tropical Indian monsoon region in eastern India. The monsoon season rainfall initiates in early June and continues through September. There is very little rainfall during the winter season (Lohar and Pal 1995). Monsoon season rainfall is of great concern to scientists in India because of its impact on the agricultural economy. The three-month period (March, April, May) leading into the monsoon season is characterized by hot days with sporadic thunderstorms. The precipitation that falls during this period is called the premonsoon rainfall (PMR) (Sadhukhan et al. 2000b). PMR contributes approximately 12% of the annual total rainfall (Sadhukhan et al. 2000a) in the study area. Figure 2.2 is a climatological analysis of rainfall for the region and it clearly supports the notion that PMR is a contributor to the annual rainfall budget. During the premonsoon season, large-scale atmospheric forcing like the monsoon is minimal. As such, it is an appropriate period to investigate how urban land cover could affect precipitation in the study region. However, the predominance of monsoonal studies has substantially limited the number of climatological studies on the PMR, and there are essentially no studies from the perspective of urban effects.

In the present study, the research objective is to analyze climatological precipitation data (premonsoon rainfall period) to assess current trends in premonsoon precipitation over the past 50 to 100 years, for urban and rural weather stations. Also we seek to quantify the extent of change in urban land use/land cover change in the past 300 years and determine any link between urban land cover growth and cumulative PMR. It is important to note that we did not include aerosol effects (e.g, see Shepherd 2005; Lacke et al. 2009; Rosenfeld 2008) on precipitation in the analysis. Historical aerosol data is fairly limited in the study region. Additionally, the intent of the study was to isolate urban land cover effects, independently. Mitra and Shepherd (2011) employ a mesoscale model with various urban land cover scenarios to investigate the physical mechanisms coupling urban land-atmosphere interactions. Future analysis should certainly consider the synergistic land cover and aerosol effects; however, the approach herein is instructive.

2.2 Background:

Urbanization of Kolkata

The city of Kolkata, a 300-year old city, is located in the eastern part of India at 22°82′N 88°20′E. It has spread linearly along the banks of the river Hooghly. Kolkata was the first major city developed by the British East India Company in the early 1700s. The city ultimately evolved into a provincial city and eventually became the headquarters of the British India government (Kundu and Nag 1996). This established a level of importance for the city and stimulated significant growth in size over the years. The magnitude of its population, its volume of trade and commerce, the avenues of employment that it offers, the variety of its inhabitants speaking diverse languages that give it a cosmopolitan character, and its continued importance as a centre of art and culture attracts people from everywhere (Roy, 1996).

A major factor contributing to the influx of millions of refugees across the border was India's independence in 1947. An estimated four million people moved from Bangladesh to West Bengal between 1946 and 1971 (Chatterjee, 1990) and in subsequent decades.

Another factor contributing to the urbanization was the influx of people from the surrounding non-urban and less developed areas to the city (Roy, 2003). Kolkata has become the target city for people of east India to migrate to and a source for financial advancement for many people. Population growth and the drive for economic development have led to unplanned and sporadic expansion of the mega-city. Mitra et al. (2011) examine the physical and societal drivers behind past, present, and future urban land cover patterns in Kolkata.

Urban precipitation effects

The Metropolitan Meteorological Experiment (METROMEX) was a landmark field experiment started in the 1970s to investigate the effect of St. Louis on convective processes and precipitation. Examination of historical data at St. Louis and other cities in the United States revealed that summer rainfall was larger in quantity in the immediate downwind area. METROMEX results also suggested that areal extent and magnitude of urban and downwind precipitation anomalies were related to size of the urban area (Changnon et al. 1971).

Other observational studies in the late 1900's focused on the cities of Phoenix (Balling and Brazel 1987, Selover 1997), New York City (Bornstein and LeRoy 1990), Mexico City (Jauregui and Romales 1996), and Chicago (Changnon and Westcott 2002). These studies continued to suggest that there was an upward trend in the rainfall amount in relation to the growth of the cities.

Shepherd et al. (2002) used data from a rain-measuring satellite to identify warm season rainfall anomalies downwind of Atlanta; Dallas and other cities. This study served as a catalyst for more recent studies in this area. A number of studies were conducted on cities like Atlanta (Dixon and Mote 2003; Bornstein and Lin 2000; Diem and Mote 2005; Mote et al. 2007); Houston (Bouvette et al. 1982; Shepherd and Burian 2003; Burian and Shepherd 2005) and Phoenix (Diem and Brown 2003). All of these studies showed some evidence of an increase in the precipitation, which they hypothesized to be related to heavy urban development. More, recently Shepherd et al. (2010) reviewed studies for cities around the world and established that the "urban rainfall effect" is now conclusive though mechanisms are not well understood.

Coupled numerical modeling studies have investigated some physical mechanisms that may lead to urban hydroclimate effects. Studies are done using two-dimensional (2D) models (Yoshikado (1994) in Japan, Thielen et al. (2000) in Paris, Baik et al. (2001)), as well as three-dimensional models (Ohashi and Kida (2002) in Japan, Craig and Bornstein (2002) in Atlanta). These studies provided valuable insight but with the exception of Rozoff et al. (2003), the land surface representation was simple or nonexistent (Shepherd 2005). Even with such simple urban representations, the studies suggested that enhanced convergence, sensible heat flux, and atmospheric destabilization were factors in convective forcing under relatively weak large-scale forcing. For Atlanta (Shem and Shepherd 2008) the Weather Research and Forecasting (WRF) model was employed to simulate both urban and non-urban situations for two case days and found 10 – 13 % more rainfall to the east of the city for the urban scenario as compared to the non-urban scenario. This finding emphasized that Atlanta may have enhanced pre-existing storms through convergence and flux enhancement. Another recent study by Shepherd et al. (2010) used a coupled atmosphere-land surface model to investigate a typically sea breeze convection day near Houston. Simulations were run using two scenarios: “urban land cover” and “no urban land cover.”The “urban” simulation showed evidence of heavier rainfall over the city and just northwest of the city, which was confirmed by radar observations on that day. This study established how enhanced convergence and destabilization occurred over Houston even within a region experiencing sea-breeze forced convergence. In many ways, the urbanization and coastal geography associated with Kolkata is similar to Houston and thus, it is plausible that similar processes may be occurring. Mitra and Shepherd (2011) examined this hypothesis in a novel urban rainfall study focused on Kolkata.

Urbanization and Premonsoonal Precipitation in the East Gangetic Region

India is an agriculture-based economy that is dependent on seasonal precipitation. The monsoons (June-September) play a very important role in this cycle (Figure 2.2). Previous and current investigations have studied the dynamics of the monsoons (Krishnamurti and Bhalme 1976; Krishnamurti et. al. 1981; Krishnamurti 1985; Vines, 1986; Kulkarni *et al*. 1992; Kripalani *et al*. 1995; Goswami et al. 2006). India monsoon studies are not limited to observational approaches. Numerical prediction experiments and modeling approaches have also been conducted (Krishnamurti and Ramanathan 1982; Bhasar Rao et al 2004; Dash et al. 2006). Though the monsoons are the most important source of rainfall in the Kolkata region, the focus of this study is the premonsoon (March-May) rainfall.

The PMR is characterized by mesoscale phenomenon, that is, thunderstorm activity. There are mainly two types of thunderstorms: i) deep convection resulting from the dryline, which forms where the moist low-level southerlies meet arid westerlies causing severe thunderstorms (locally known as “kalbaishaki” (IMD Report 1941, Weston 1972)) and ii) thunderstorm convection initiated at the sea-breeze front (Lohar 1996).

An analysis of the near surface (1000 hPa) and mid-level (500 hPA) flow regime during the premonsoon season was done (Figure 2.3 (a & b)). In this analysis, we composited the NCAR/NCEP reanalysis 1000 hPa (mb) and 500 hPa (mb) vector winds for the period 1950-2008. It is evident that the prevailing 500 hPA flow is zonal with a westerly component. The surface flow in the Gangetic plain is characterized by moist southerly flow from the Indian Ocean. This analysis corroborates the notion that the formation of nor'westers or "Kalbaishaki" is attributed to a warm, moist, southerly low-level flow from the Bay of Bengal and an upper-level dry, cool, westerly or north-westerly flow giving rise to an atmosphere with high latent instability (Mukhopadhyay et al 2005).

Sanderson and Ahmed (1979) conducted a study in neighboring Bangladesh to understand the variability and significance of premonsoon rainfall. They concluded that premonsoonal rainfall was less significant than monsoon rainfall, but provided 20 to 90 cm of rainfall annually. Lohar and Pal (1995) carried out a one-station study on a 20-year dataset of PMR. They concluded that irrigation reduced the low level moisture and increased soil moisture. They hypothesized that these processes decreased the intensity of sea breeze circulation and related convection. Sadhukhan et al. (2000a) also conducted a study on the PMR (1901 – 1992) variability in the Gangetic West Bengal, which includes this study area. They found that there were no long-term trends present in the data series, unlike the monsoons, though there was an increase in PMR in 1970s and afterwards. Short-term fluctuations were present, which they linked to PMR being mainly dependant on local features. Sadhukhan et al. (2003) investigated the changes in land use pattern by using satellite data over Gangetic West Bengal extending from 20º N to 25º N and 85º E to 89º E and its possible impact on the local climate through numerical modeling. They found, similar to Lohar and Pal (1995), that changes in vegetation patterns have an influence on the moisture content of the inland moving sea breeze and development of convective thunderstorms in coastal and neighboring areas.

These studies theorize that land cover dynamics related to deforestation, agricultural use (Sadhukhan et al. 2000a, Sadhukhan et al. 2003) or irrigation (Lohar and Pal 1995) could account for precipitation changes, yet the limited studies have been contradictory or lacked robustness. Further, none of these studies considered the influence of urban-related land cover. Our synergistic studies, coupled with accompanying model simulations seek to quantify the impacts of urban land cover extent and dynamics on the PMR rainfall in Mitra and Shepherd (2011).

Urban rainfall studies for India have been limited. The first work of this kind was done by Khemani and Murthy (1973), who analyzed rainfall data from 1901 to 1969 for the city of Bombay and two other stations in the near by rural region. Their study indicated that there was an increase of about 15% rainfall in the industrialized city of Bombay compared to nearby non-urban cities. The increase was observed during 1941-1969, which was a period of intensive industrialization. No data related to a possible heat island effect in the Bombay region were available to consider urban effects.

Simpson (2006) employed a mesoscale model and observed rainfall data to investigate the impact of Chennai (a large city in the south-east of India) urban land use on the sea breeze circulation and rainfall amounts during the southwest monsoon. Rainfall was more pronounced during late evening and nocturnal hours, possibly due to the interaction between the receding sea breeze circulation and the urban heat island.

Devi (2006) discussed the nature and intensity of heat islands at Visakhapatnam, the tropical coastal city of South India, for over ten years. The study revealed that the intensity of the heat island varies from 2°C to 4°C and intensity is high during winter season compared to summer and monsoon seasons. They also noted that the land and sea breeze circulations interact with the heat island as recently described by Shepherd et al. (2010). De and Rao (2004) conducted a study involving 14 major cities (over 1 million population) of India. They divided the data sets into two subsets, 1901-1950 and 1950-2000, and used the techniques suggested in WMO (1969). Although their analysis was restricted to the monsoon season, De and Rao found that between 1901 and 2000, seven cities including Kolkata had increasing trends, excluding only Nagpur, which had a decreasing trend. The increasing trend in the monsoonal rainfall is most evident over Kolkata for the period 1951-2000. Rainfall increased at an approximate rate of 80 mm per decade. This period was characterized by an intense change in land cover due to post-independence refugee influx, but the linkage between anthropogenic land cover and precipitation increases has not been quantified. Finally, Kishtawal et al. (2009) have shown a positive correlation between heavy rain events and urban land cover growth for large urban areas in India. On the other hand, Sen Roy's (2008) observational study on extreme hourly precipitation trends (1982–2002) for large urban areas in India with one million plus population showed that Kolkata had a negative trend in its rainfall pattern in the dry PMR months (March to May).

2.3. Research Objectives

The PMR period with sporadic thunderstorms offers an appropriate framework for this type of study because urban effects on rainfall are most evident when strong large scale or synoptic forcing is weak and mesoscale processes are more dominant (Shepherd 2005). Furthermore, very few studies have examined the effect of urban land use in developing nations yet the world's fastest growing urban areas are precisely in these regions.

Previous studies highlighted an anomaly in rainfall but did not identify the possibility of any causal effect of urbanization on precipitation. In some cases, the results were also conflicting. Such studies motivated this study of urbanization and its effects on PMR. Specifically, the research objectives are (1) to delineate urban land cover change using historic cartography and remote sensing data; (2) to analyze historical rainfall data and quantify the trend in the spatio-temporal PMR climatology of the area; and (3) to ascertain any link between trends in PMR rainfall over the last 50 years and urban land cover change. Mitra and Shepherd (2011) is a modeling study that complements this climatological assessment and provides insight into physical mechanisms.

4.4 Data and Methodology:

Data

Data from the National Data Centre-Indian Meteorological Department has been acquired for several stations in the study area. Most of the data covers the period of 1900-2003, however there are several stations with gaps. In this study, only five stations were analyzed, demarcating a time period spanning 1950 to 2000. Additionally, data from the Tropical Rainfall Measuring Mission Multisatellite Precipitation Analysis (Huffman et al. 2007) and the Delaware surface dataset (Legattes and Willmott 1990; Legates 1995; Willmott and Robeson 1995; Willmott and Matsura 1995) were employed for spatio-temporal precipitation analysis in the region. Further, the NCAR-NCEP reanalysis data (Kalnay et al. 1996) archived by the NOAA Earth System Resource Laboratory (ESRL) was composited to provide the climatological flow patterns during the premonsoon period. Compositing was accomplished using the ESRL online compositing tool (http://www.cdc.noaa.gov/).

Data used to delineate the urban growth of Kolkata city include historical paper maps, Landsat images (1990 and 2000), and topographical maps. All maps used in this research, except Landsat images, have been collected from different Indian Government offices.

The first remotely sensed image was a Landsat TM image, dated 11/14/1990. It was a WRS 2 (Worldwide Reference System) image and the path/row is 138/044, respectively. The second remotely sensed image was a Landsat ETM (Enhanced Thematic Mapper) satellite image, dated 11/17/2000. It is a WRS 2 image and the path/row is 138/044, respectively. The Landsat images were used as they provide a mechanism to monitor land cover and land use globally by remote sensing from space (Lillesand and Kiefer 1987; Morain 1998).

A historical paper map of Kolkata city showing the growth of the city from pre-1756 to 1990 was also used. The scale of the map is 1:100.000. The source of the map is the National Atlas & Thematic Map Organization, India. Two topographical maps, # 79 B/6 & 79 B/7, showing Kolkata city and adjoining area were also used (1:50,000; Survey of India).

Methodology

Urban growth delineation

Digitization of paper maps was validated by remotely sensed images from recent years. The scanned paper maps were rectified with the base paper maps, mosaiced together and georeferenced to have a larger view of the area. The extent of growth in the city was delineated using "heads-up" digitizing methods from the urban growth map and LANDSAT images using the ArcGIS software. Although the process of digitization was laborious, it was necessary to delineate the extent of growth of Kolkata city over 300 years. The next step was to overlay the digitized maps onto satellite images to further digitize and detect the changes in the growth pattern between 1990 and 2000.

Trend Analysis

Statistical trend analysis, primarily Mann-Kendall trend test, was conducted on the IMD (Indian Meteorological data) and Delaware data to determine whether statistically significant trends in PMR exist for urban and non-urban stations. The Mann Kendall is a non-parametric test that helps determine trends in the time series (Mann 1945; Kendall 1955). The non-parametric trend tests require only that the data be independent and can tolerate outliers in the data, unlike parametric tests, which requires data to be independent and normally distributed (Hamed and Rao 1997). Hipel and McLeod (1994) documented that Mann Kendall was more powerful as compared to log-one series correlation tests when dealing with normally distributed data. Yue et al. (2002) and Yue and Pilon (2004) also comparatively tested the robustness of the Mann Kendall method for trend detection and concluded that it was equally as effective as other trend detection methods like the Bootstrap tests and t tests. Mann Kendall test has been used to analyze precipitation trends in China and US (Karl and Knight 1998; Gemmer et al.2004).

Our analysis was done using a 3-year running mean to eliminate yearly variations in the time series. Similar analyses were conducted on regional (India and East Gangetic Plains) PMR rainfall in order to compare individual station trends to regional trends. The six stations are Alipore and Dumdum within the Kolkata urban area and Bankura, Midnapore, Krishnanagar and Sagar Island, which are classified as semi-urban areas (Figure 2.4 and 2.5).

The stations, Alipore and Dumdum, are situated within the city of Kolkata. If there is convection at both Alipore and DumDum stations then it is considered as a single convective event for Kolkata regardless of the nature and intensity of convection at the two places (Dasgupta and De 2007). The stations Bankura, Midnapore, Krishnanagar are located inland, within 100 – 200 km of the city of Kolkata. The Sagar Island is a coastal station located at the edge of the Bay of Bengal, where the influence of sea breeze is significant.

TRMM Multisatellite data (Huffman et al. 2007) was used to extend the Delaware rainfall data from 1999 to 2003 for the India and East Gangetic trend plots. A correlation analysis was conducted for a 24-month period was done, in which the Delaware data and TRMM data overlapped. The correlation coefficients (r^2) values were greater than 0.95. This suggests that the data extension technique was sound.

Spatial analysis

Two different spatial analyses were performed. In the first analysis, we plotted a proportional symbol map in the Kolkata region using the IMD stations. The method was to simply plot proportional symbols representing the strength of the trends at the stations. The goal was to determine if there were spatial regions of preference for the increasing PMR. A similar technique was employed by Hand and Shepherd (2009) but only for cumulative rainfall totals not trends.

The second analysis utilized ten years of TRMM Multisatellite analysis. We composited the premonsoon months for the period 1998-2007 and plotted the "mean" PMR map for the country of India. The goal of this analysis was to provide a comprehensive spatial climatology of PMR over India.

2.5. Results and Discussion

Land Cover Dynamics

The digitization and overlaying of the maps revealed the phases of growth in different time frames beginning from before 1756 to 2000. The result was a unique sketch of the growth history of Kolkata over this time period, which is shown in the table (Table 1) below. The table indicates that the city was growing consistently until 1947. After 1947, there has been a nearly fourfold increase in the change in area for the city of Kolkata from 225 sq. km. to 1102 sq. km. The rate of change in urban land cover growth over the period 1947-1990 was 23.20 sq. km/year compared to 2.50 sq. km/year over the period 1856-1947. This reflects a roughly tenfold increase in expansion in the last five decades. Such urban area expansion is linked with India's independence in 1947 after which four million refugees moved in from neighboring Bangladesh (Chatterjee; 1990). This rate of expansion continued for decades after the independence. The table shows that between 1990 and 2000 the change in area for Kolkata city was 29.50 sq. km., which was more than what was observed before 1990 (23.20 sq. km.). Such urban land cover dynamics establishes the basis for the second and third objective, namely, to determine if there is any trend in the PMR over the same period and ascertain any link between land cover change and rainfall.

PMR trends

We analyzed the time series of the premonsoon rainfall of India, the East Gangetic plains and individual stations. The Mann-Kendall analysis was performed on mean PMR for (1) the entire country of India, (2) the East Gangetic region, and (3) the six stations within the East Gangetic region. For the East Gangetic and India trends the blended Delaware-TRMM dataset is employed.

The time series plot (Figure 2.6a) of the mean PMR for India (1951 – 2003), with Mann-Kendall analysis, shows no significant climatological trend in the distribution of PMR over the entire country. Similarly, the East Gangetic region (Figure 2.6b) does not show any statistically-significant increasing or decreasing trend of PMR over the 50-year period (Table 2). Thus on a regional scale there is no statistically discernible large-scale trend over the study area that might mask or explain a more local or regional trend.

By contrast, analysis of individual stations revealed three station time series with statistically-significant increasing trends, two within the city Kolkata and one Midnapore, which is a fairly sizeable city, slightly west of the Kolkata Metropolitan region. In all three cases the p-value is less than 0.05, which establishes that it is significant at the 95% level. The Mann–Kendall analysis appears to support the hypothesis that large urban areas like Kolkata have influenced cumulative rainfall in the premonsoonal season. The Midnapore result is consistent with previous findings, which often suggested an anomaly not only over the city but on the downwind fringe of the urban land cover extent. These results support some of the findings that have been cited earlier in the paper inferring that land cover change in the Gangetic West Bengal might influence precipitation (Sadhukhan et al. 2000a, 2002; Lohar and Pal 1995), though none of the studies were related to urban land cover change. Urban rainfall studies conducted on Indian cities like Bombay (Khemani and Murthy 1973); Chennai (Simpson 2006); Visakhapatnam (Devi 2006); Kolkata (De and Rao 2004) all show increasing trends in rainfall. Mention must be made of a study done by Sen Roy (2008) where Kolkata showed decreasing trends in extreme hourly precipitation, as it is related to Kolkata, our study area.

It is to be noted, as mentioned earlier, that a precipitation event in either the Alipore or Dum Dum station is considered as one precipitation event for Kolkata. In this study the two stations, Alipore and Dum Dum are considered separately to gather independent evidence and validate results from each station of urban effect on precipitation.

Trend lines for each station (Figure 2.7) with the Mann-Kendall statistical analysis show that the stations Alipore and Dum Dum show increasing trends. But the other stations, with an exception of Midnapore, are not showing any significant trend. This suggests that urban land cover could be a driving factor for these increasing trends in Alipur and Dumdum stations. The Midnapore station, though not as urban as the other two, shows an increasing trend. We hypothesize that Midnapore is in a downwind anomaly region of the Kolkata urban area and thus may experience some of the urban enhancement. Further study is required to examine the possible mechanisms but is beyond the scope of this manuscript.

The spatial distribution of the trends (Figure 2.8) at each station with significant trends (at the 95% level) is in the city of Kolkata and in the climatologically downwind (relative to the low-level wind flow) region. Numerous studies have suggested that urban-induced rainfall anomalies appear over and downwind of the urban land cover (Shepherd et al. 2009; Mote et al. 2007).

A spatial analysis of composite PMR rainfall (1998-2007) is interesting for multiple reasons. First, it is possibly the first time that a spatial presentation of PMR has been presented. Previous studies investigate individual station records or trends. TRMM Multisatellite precipitation analysis (MPA), a blended satellite product incorporating TRMM, infrared, and gauge-derived precipitation dataset revealed an anomalously high region of rainfall extending from the Kolkata region southwestward along the coast (Figure 2.9). This finding establishes that the TRMM MPA at approximately 25 kilometer spatial resolution can identify mesoscale or topographically forced precipitation signatures, such as those associated with mountainous terrain (e.g., Himalayas) or the sea breeze front (along the coast). Of greater importance, the figure raises the question as to why the entire coastal plain does not display significant rainfall totals in response to sea breeze forcing whereas regions around the Kolkata metropolis do. Shepherd and Burian (2003), Burian and Shepherd (2005), and Shepherd et al. (2010) have shown that coastal cities like Houston, Texas (USA) may amplify the precipitation signature through urban- mesoscale (Nor'wester, seabreeze) interactions. However, it is more likely that urban enhancement of the "Nor'wester" storms could also explain this feature (Mitra and Shepherd 2011) because we did not find very strong sea breeze rainfall signatures in our analysis of PMR (not shown). Our future modeling studies will hopefully shed light on this finding and what synergistic role the sea breeze, dryline convergence, and urban forcing may play in this distribution.

2.6 Conclusions:

This study is a unique synergy of urban land cover dynamics and premonsoonal climatology. Using a combination of historical cartographic maps and satellite data, land cover change of Kolkata was quantified over the past 300 years. Even though the rainfall analysis spans a truncated period of roughly the last 50-60 years or so, the 300 year land cover analysis was critical for placing the explosive urban land cover dynamics in 1947 in proper historical context. There is no evidence from the inception of the city showing any anomalous period of growth before Indian independence. Further the study established the most current and robust assessment of PMR trends and climatology while suggesting a possible link between urban land cover change during the most recent 50 years of explosive growth. The analysis shows that the rate of change of urban land cover has increased ten fold from before India's independence in 1947. Before 1947 the growth rate was 2.50 sq. km/ year and after 1947 up to 1990 it was 23.20 sq. km/year. Between 1990 and 2000, the growth rate was 29.50 sq. km/year.

Time series trend detection over the last 50 years PMR data showed that there was an increasing trend in the PMR for the two urban stations and the Midnapore station (located in the possible downwind region) but not for three less urbanized stations around the region. Further, there was no significant trend for cumulative PMR over the entire country of India or the East-Gangetic region, in which Kolkata is located. This finding suggests that the anomaly of the three stations, showing increasing trend in PMR, could be the effect of urban land cover change. Mitra and Shepherd (2011) provide novel modeling experiments to test this finding from a physical mechanism perspective.

Mitra et al. (2011) has examined how and why Kolkata will grow in the next 25 years using the CA Markov growth model (Baoying and Bai 2008, Pontius and Malanson 2005). Further future work should focus on the role of urban aerosols on climate system (Ramanathan et al 2001, Lau et al 2006). It is also important to understand what will be the outcome if the same methods are applied to different cities under varied climate regimes. The implications and effects of this kind of research will provide a better understanding of what to expect in our future and what could be the possible feedback of today's increased anthropogenic forcings.

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Tables:

Table 4.1: Change in urban land cover area over 300 years in Kolkata city

Years	Total Area (sq. km.)	Change in Area (sq. km.)	Area change/ year (sq. km.)
Before 1756	4.0		
1756 – 1793	34	30	0.80
1793 – 1856	136	102	1.60
1856 – 1947	361	225	2.50
1947 - 1990	1363	1002	23.20
1990 – 2000	1658	295	29.50

Table 4.2: Mann Kendall analysis of rainfall data for the six study stations; East Gangetic plain and India. P-Value > 0.05 (not significant); P-Value < 0,05 (significant)

Stations	**P- Value**	**Tau correlation**
Alipore (within Kolkata)	0.0167	0.227
Dumdum (within Kolkta)	0.0129	0.236
Bankura	0.0881	0.173
Krishnanagar	0.3982	-0.081
Sagar Island	0.6032	0.051
Midnapore	0.0007	0.323
India	0.0872	0.163
East Gangetic	0.1795	0.128

Figures:

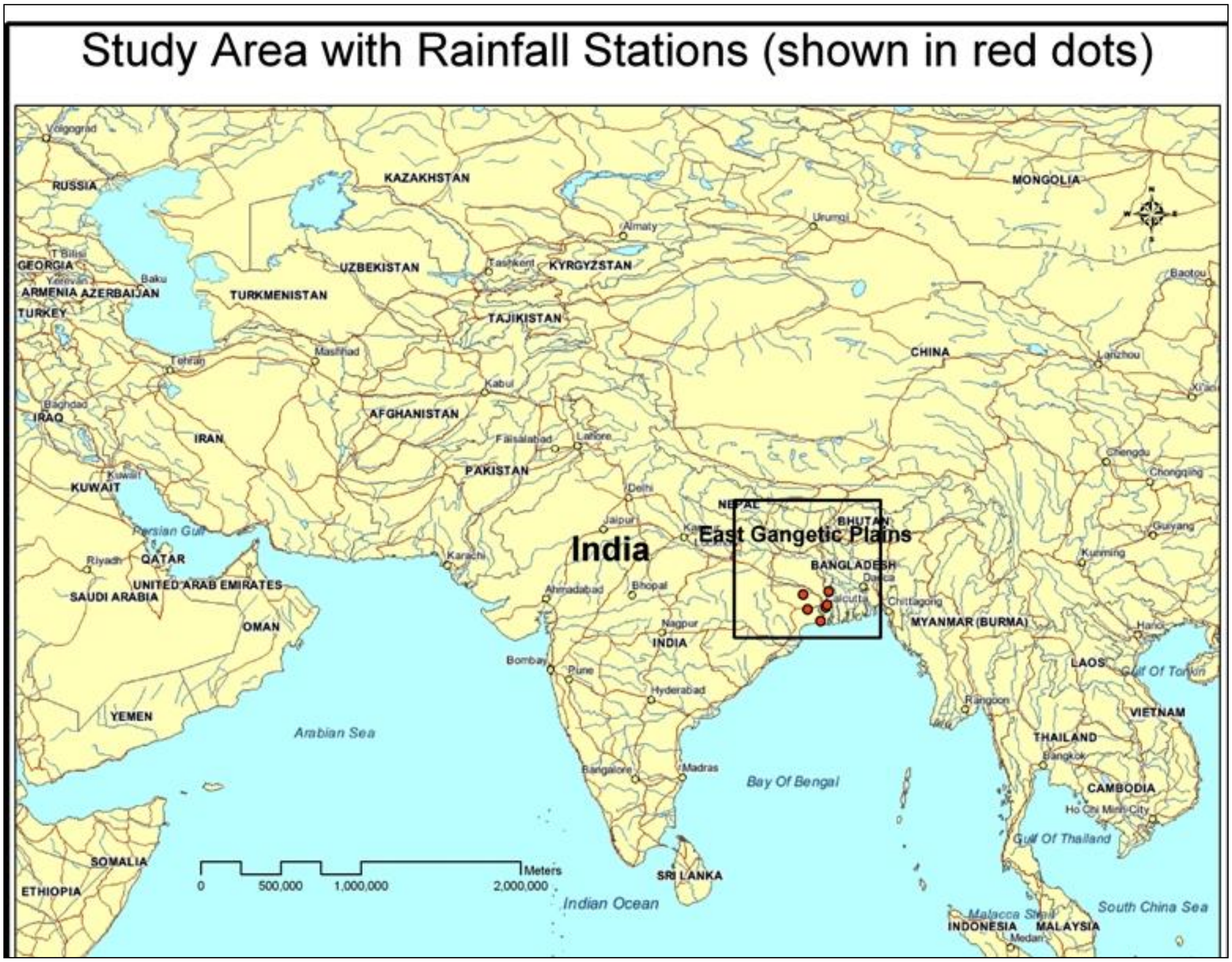

Figure 4.1: Map showing India, East Gangetic Plain and rainfall stations (orange circles) used in the study.

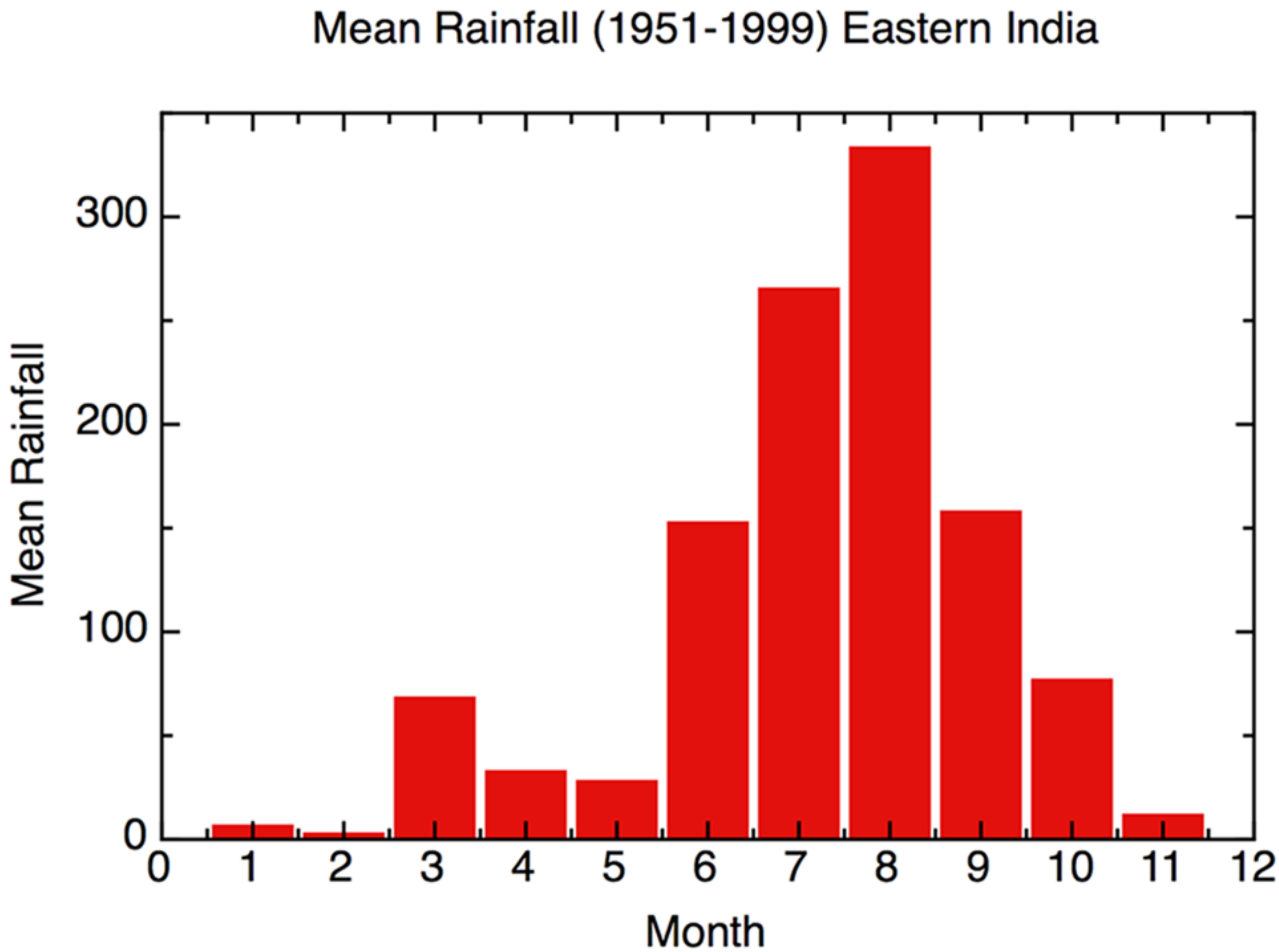

Figure 4.2: Mean monthly rainfall for the area (82-89 E, 19-26 N) using Legates and Willmott (1990b) data set.

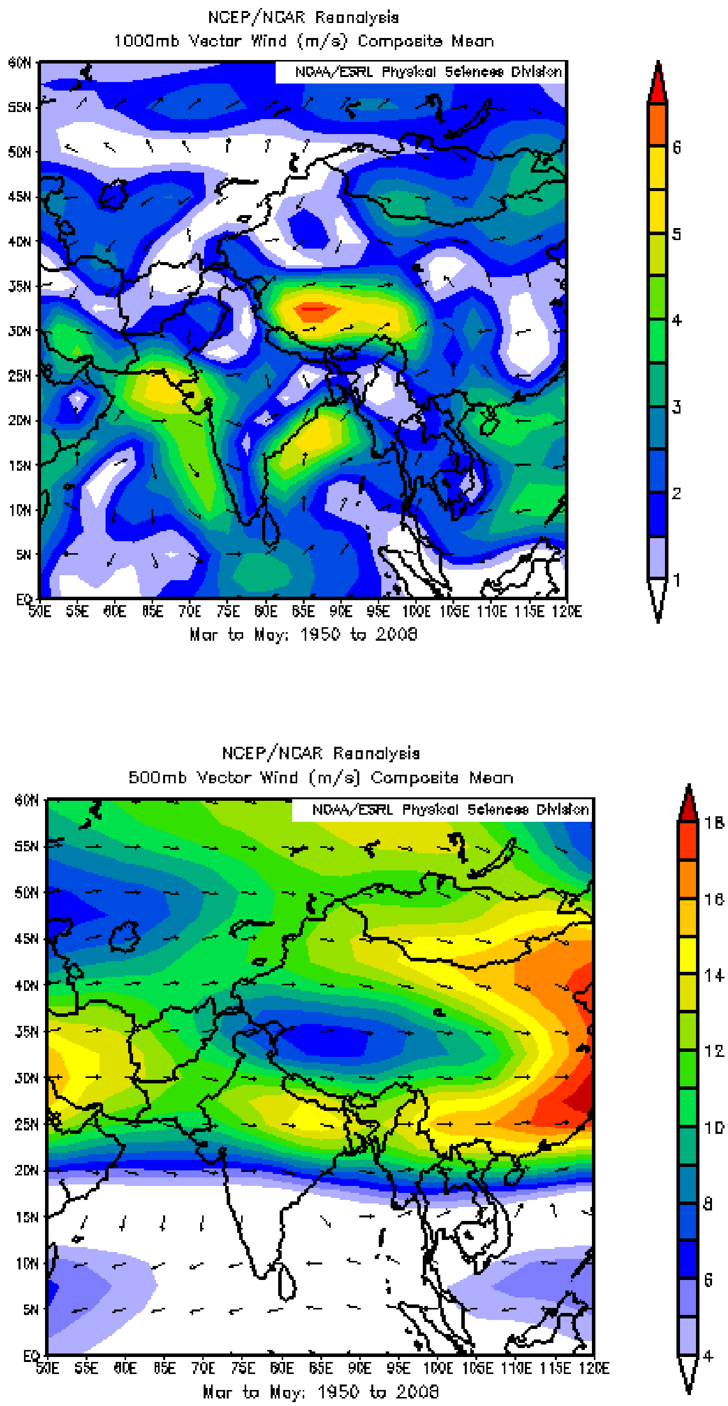

Figure 4.3: (top) Mean 1000 mb vector winds and (bottom) mean 500 mb vector winds in the premonsoonal season (1950-2008).

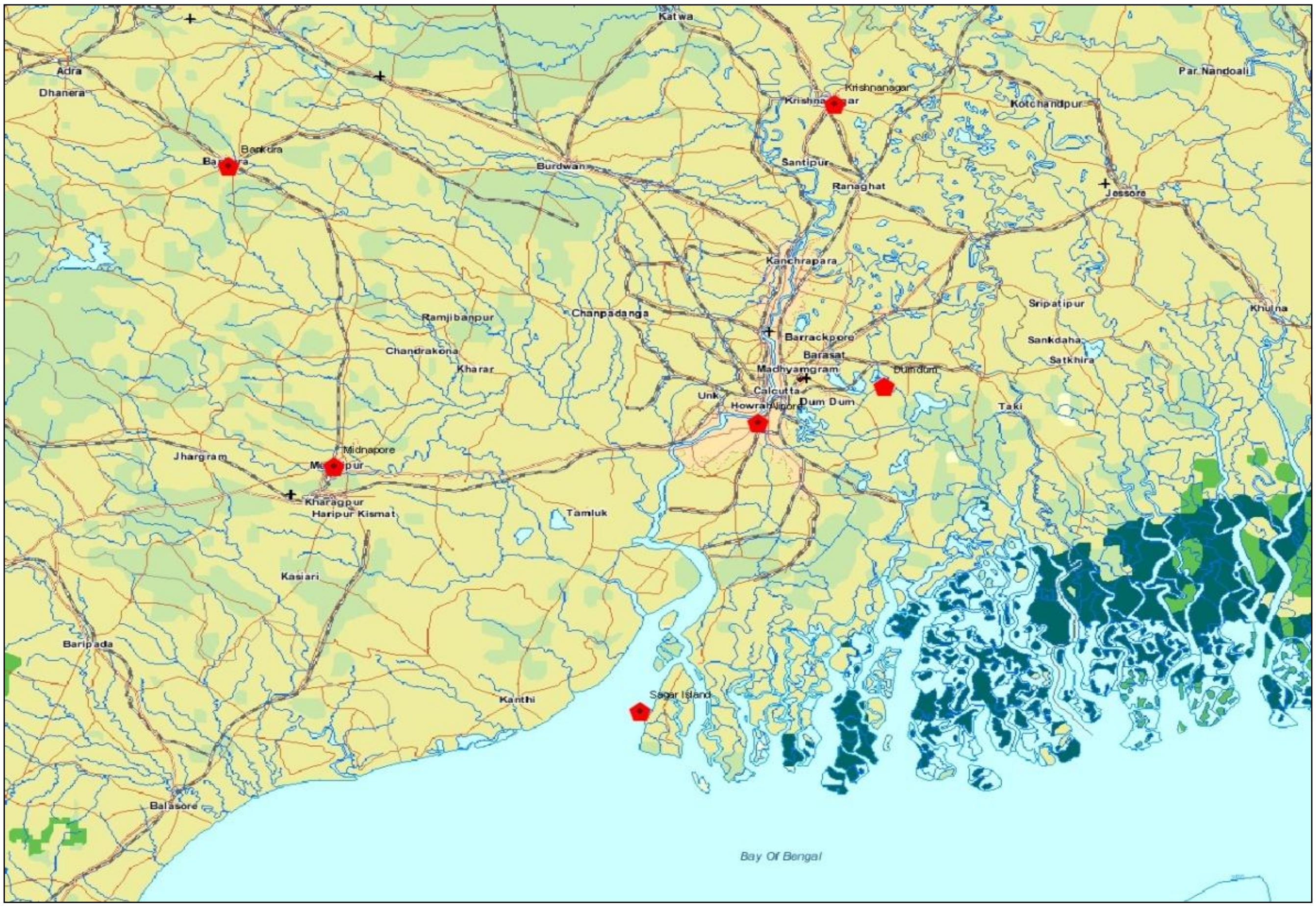

Figure 4.4: Map showing location of the six stations in the East Gangetic Plains.

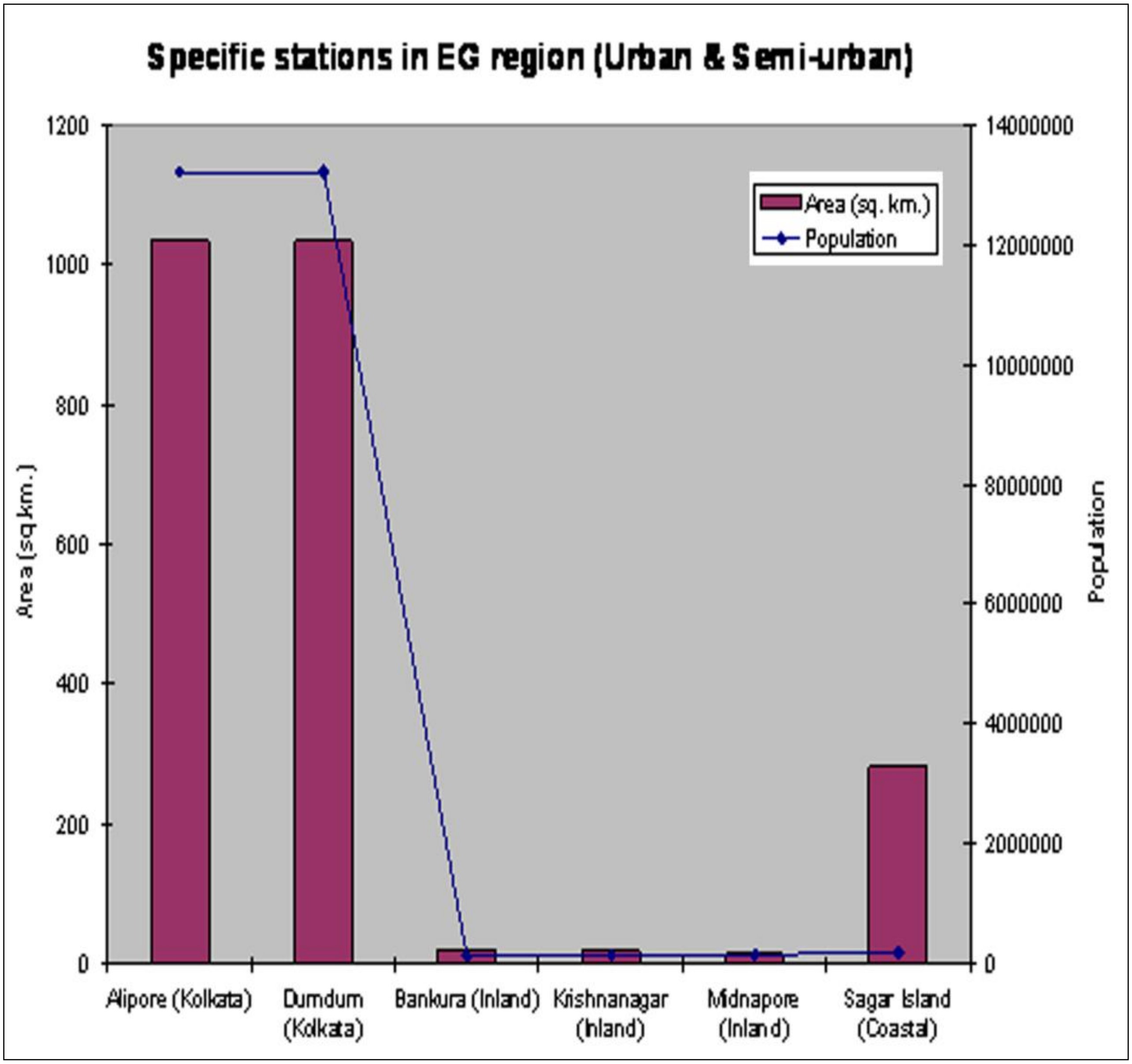

Figure 4.5: Comparison of population and area covered by the five study stations.

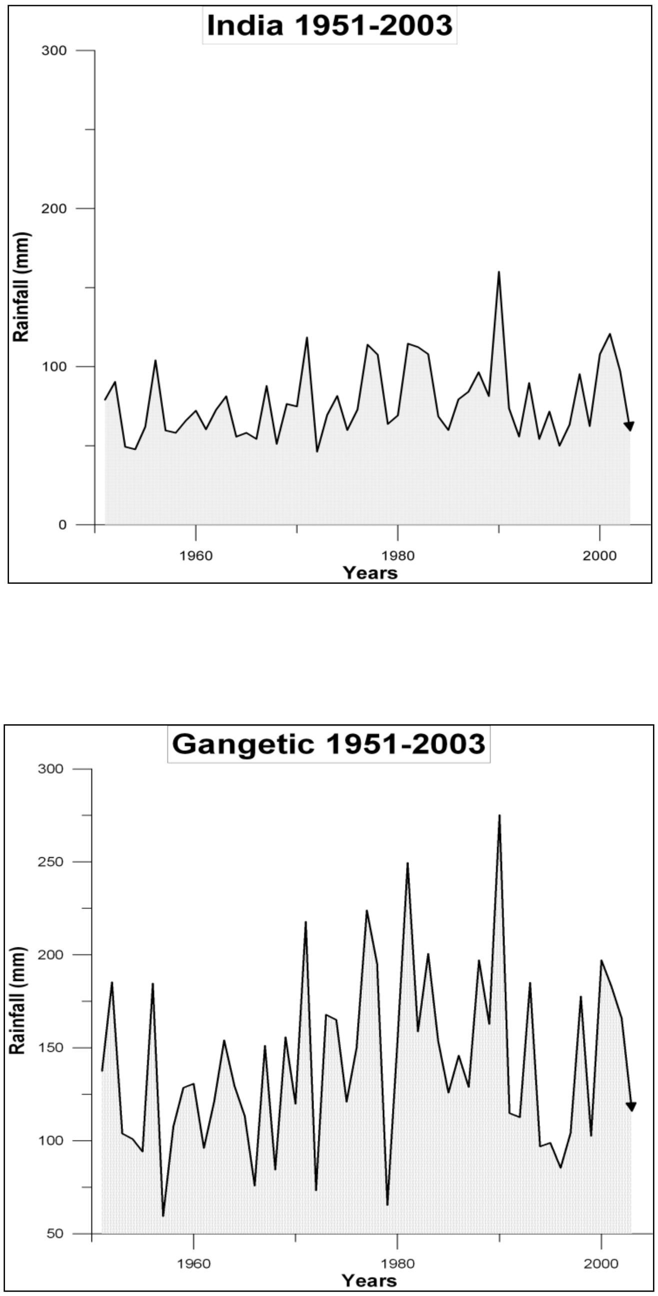

Figure 4.6 a. (top) Time series of cumulative pre monsoonal rainfall (3-year running mean) for India. b. (bottom) Time series of cumulative pre monsoonal rainfall (3-year running mean) for East Gangetic Plain.

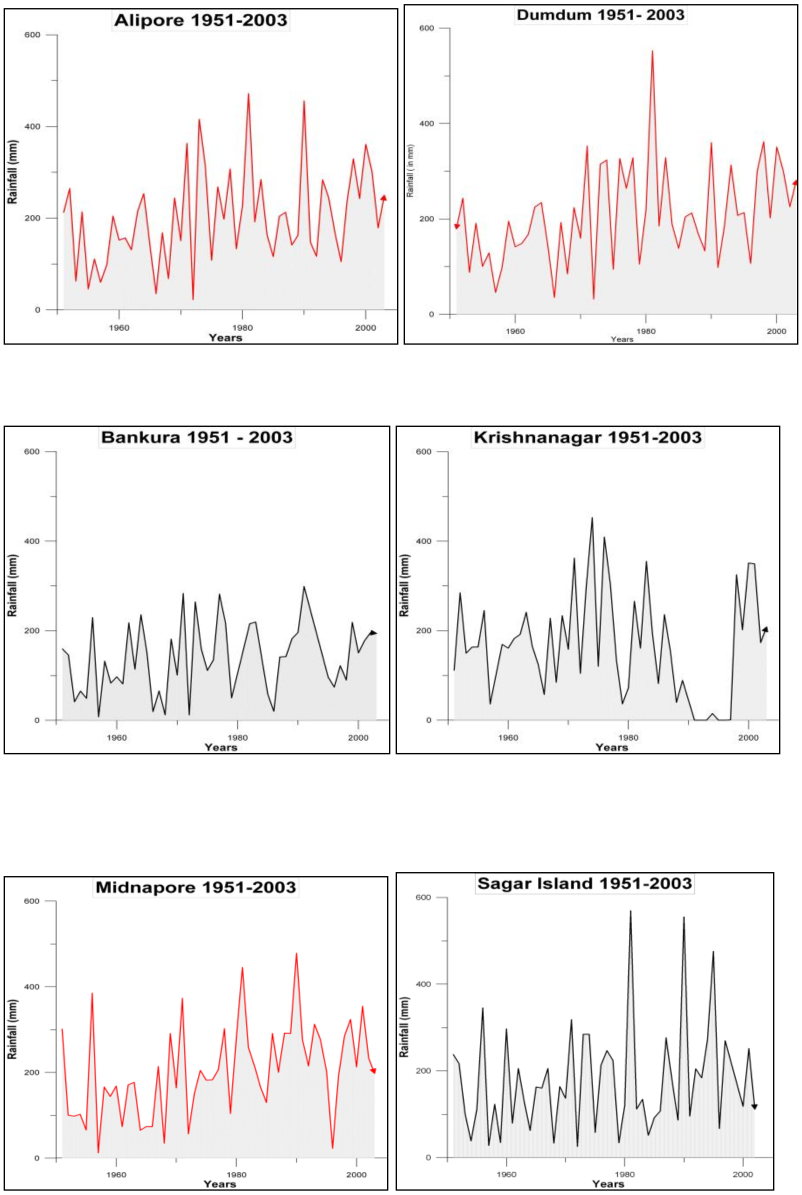

Figure 4.7: Time series of cumulative pre monsoonal rainfall (3-year running mean) for the six study stations (IMD data).

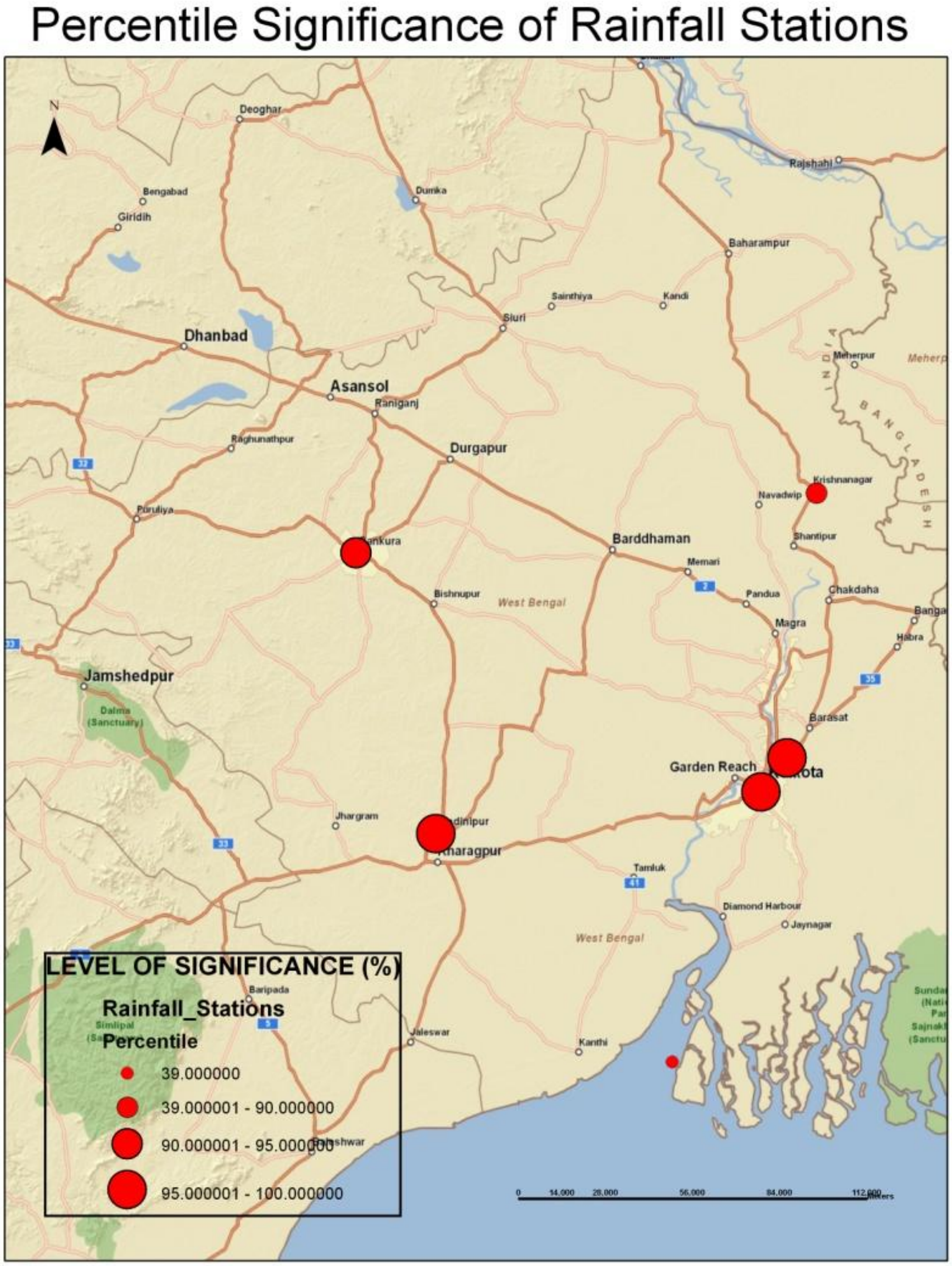

Figure 4.8: Spatial plot showing the distribution of statistically significant trends for PMR over the past 53 years.

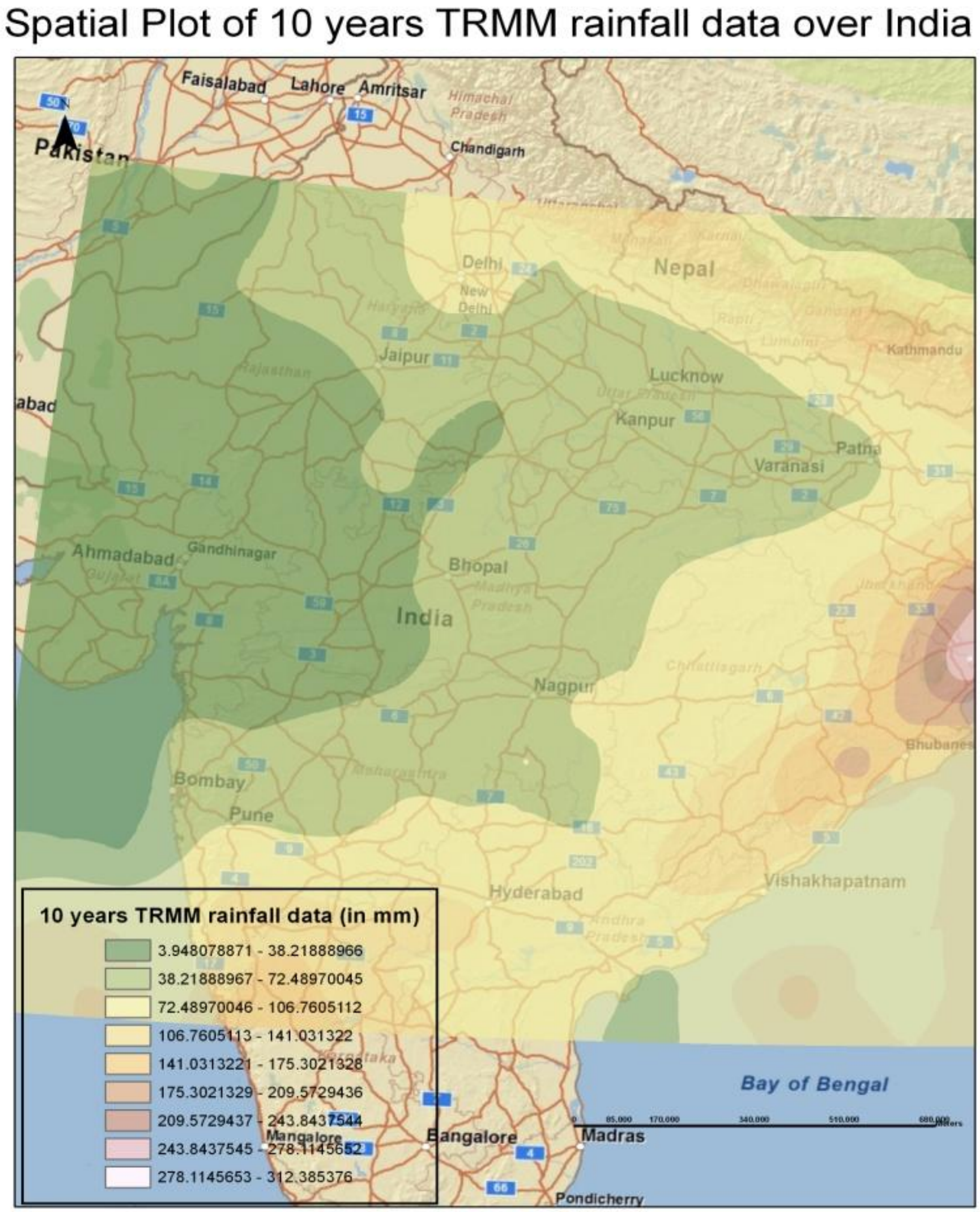

Figure 4.9: TRMM multi satellite precipitation analysis data (1998 – 2008) illustrating the climatology of PMR over India (25 km spatial resolution).

CHAPTER 5

THE ROLE OF URBAN-MESOSCALE INTERACTIONS ON PREMONSOONAL PRECIPITATION IN KOLKATA, INDIA: A COUPLED ATMOSPHERIC-LAND SURFACE MODELING STUDY

[3] Mitra C. and M. Shepherd. 2011. To be submitted to Atmospheric Research.

Abstract:

Studies continue to link urbanization (e.g., land cover, aerosols) with regional hydroclimate variability. This study investigates how urban land cover physically influences mesocale forced precipitation during the premonsoonal period in Kolkata, India. The study employs the coupled WRF NOAH atmosphere – land surface model to assess whether premonsoonal precipitation trends in Kolkata can be explained by the presence of urban land cover. The framework for the investigation is the Nor'wester mesoscale system, which is the primary precipitation mechanism during the premonsoon period in this region. Such systems have been recently investigated from observational perspectives but have not been simulated using numerical modeling. Further, there has been no quantitative analysis of urban-mesoscale interactions associated with these systems although the premonsoon period is optimal for urban land cover-precipitation interactions. The goal is to investigate whether precipitation associated with a typical Nor'wester might be influenced under two scenarios a) current urban and b) no urban (pre-Kolkata). A case study for 16 April 2003, a "Nor'wester" case day (Mukhopadhyay et al. 2005), is chosen during the premonsoon rainfall regime, which is characterized by weaker large scale forcing. Results from the simulations have shown that the total accumulated rainfall for the urban scenario is enhanced (i.e., producing up to 4 mm more rainfall in some locations) relative to the no-urban scenario. We also examine key physical mechanisms (sensible heat flux, vertical motion (via convergence), moisture, and other thermodynamic variables) that might describe how urban land cover influences atmospheric convection. Results showed that urban expansion in Kolkata area is associated with larger sensible heat fluxes, less water vapor at 2 meters height, lower albedo, and

a deeper boundary layer. All these physical mechanisms and increased vertical velocity (due to enhanced low-level convergence), enhances the lifting of warm unstable air required to increase convection enough to produce slightly more rainfall in the Nor'wester system when passing over Kolkata city. This result is consistent with recent US studies on enhancement of pre-existing convection but may be the first report outside of the U.S. and is unquestionably the first study of its kind focused on the Nor'wester.

Keywords: Urban precipitation, Kolkata, Nor'westers, WRF-NOAH model, land cover change, urban – mesoscale interactions.

5.1 Introduction:

Urbanization is increasing and alteration of the coupled human-natural systems of cities by anthropogenic activities is an important issue being addressed by the scientific community. To measure the extent of urban growth's influence on the overall environment, it is important to understand its impact on the individual elements of weather and climate like clouds, precipitation and associated hazards (e.g., lightning, flash flooding) (Shepherd et al. 2010a). According to Lowry (1998), in most of the reviews on urban climatology the primary foci are air quality, radiation, temperature and wind (Kratzer 1937, 1956); Landsberg (1956, 1981); Lee (1984) and Goldreich (1996). But there is a need to understand other aspects of the climate system. More recently, the scientific community has focused on how urban environments affect precipitation variability and the hydroclimate (Shepherd et al. 2010a). Water is an essential element of urban life and significant variations in rainfall, spatially or temporally, may affect the populace in critical ways related to water resource management, health, flooding, and agriculture.

According to Landsberg (1970) the most pronounced and locally far-reaching effects of man's activities on microclimate have been on cities. The heat gain due to heat storage in the urban structures, the reduction in local evaporation, and the anthropogenic heat alters the spatio-temporal pattern of temperature, the well-studied urban heat island (UHI). The UHI and other urban factors may actually lead to atmospheric interactions that also initiate or alter convection (Landsbert 1970, Changnon et al. 1981, Shepherd et al. 2002, Dixon and Mote 2003, Niyogi et al. 2006, Holt et al. 2006). Diab (1978), in his review paper, noted that urban induced changes in precipitation could result from one or more of the following possible modifications of the atmosphere: (1) increased thermal mixing due to the effects of the well-established heat island and anthropogenic heat input; (2) increased mechanical mixing due to the greater aerodynamic roughness of urban structures; (3) changes in the low-level atmospheric moisture content due to additions of water vapor from combustion processes, and to alternations in evapotranspirartion rates resulting from land use changes; and (4) the addition of condensation and ice nuclei from industrial and motor vehicle discharges. Recently Shepherd (2005) more aptly summed Landsberg and Diab's concepts in his review paper noting the possible mechanisms for urbanization to impact precipitation or convection including one or a combination of the following: (1) enhanced convergence due to increased surface roughness in the urban environment (e.g.,Changnon et al. 1981; Bornstein and Lin 2000; Thielen et al. 2000); (2) destabilization due to urban heat island (UHI)-thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds (e.g., Shepherd et al. 2002; Shepherd and Burian 2003; Shepherd 2006; Mote et al. 2007; Baik et al. 2007; Han and Baik 2008; Rose et al. 2008; Hand and Shepherd 2009; Shem and Shepherd 2009; Shepherd et al. 2010a); (3) enhanced aerosols in the urban environment for cloud condensation nuclei sources (e.g., Rosenfeld 2000; Moelders and Olson 2004; Givati and Rosenfeld 2004; Lensky and Drori 2007; Rosenfeld et al. 2008; van den Heever and Cotton 2007; Jin and Shepherd 2008); or (4) bifurcation or diversion of precipitating systems by the urban canopy or related processes (e.g.Loose and Bornstein 1977; Bornstein and LeRoy 1990; Bornstein and Lin 2000).

5.2 Urban influenced precipitation:

There has been considerable interest amongst scholars to understand the dynamics of urban induced precipitation anomalies.The first documented study on urban precipitation dates back to as early as 1921 when Horton mentioned that cities are sometimes breeders of thunderstorms. Horton observed thunderstorms over some cities (e.g., Albany, N.Y. and Providence, R.I.), which originated immediately over the city and affected surrounding areas (Horton 1921).

Other early investigations (e.g., Kratzer 1956; Landsberg 1956; Atkinson 1968; Changnon 1968; Landsberg 1970; Huff and Changnon 1972) highlighted the possibilities of urban effects on rainfall patterns. Earlier studies on the La Porte anomaly (Stout 1962; Changnon 1968) investigated and found some interesting results in La Porte, Indiana situated 48 km east of Chicago. Over the period 1951 – 1965, the suite of studies indicated a 31% increase in mean annual rainfall over surrounding areas, a 38% increase in thunderstorm days, and a 246% increase of hailstorm days (Diab 1978). Owing to the magnitude of the percentage increases, the 'La Porte Anomaly', provoked a great deal of controversial discussion in meteorological circles (Diab 1978). This controversy set the stage for the major North American field study, the Metropolitan Meteorological Experiment (METROMEX), which provided the first formal hypotheses about urban-convective relationships (Shepherd et. al. 2010a). The three main salient findings of the METROMEX were (Shepherd 2010a):

- Precipitation was enhanced by urban effects typically 25 to 75 km downwind of a city during summer months (Huff and Vogel 1978; Changnon 1979; Braham 1981).
- Cumulative amounts were enhanced between 5 and 25% over background values (Changnon et al. 1981, 1991).
- The size of an urban area influenced the horizontal extent and magnitude of urban enhanced precipitation (Changnon, 1992).

In the past 30 years, numerous observational studies (Dai et al. 1997; Bornstein and Lin 2000; Inoue and Kimura 2004; Shepherd et al. 2002; Changnon 2003; Dixon and Mote 2003; Burian and Shepherd 2005; Diem and Mote 2005; Shepherd 2006; Mote et al. 2007; Hand and Shepherd 2009; Kishtawal et al. 2009; Bentley et al. 2009) have been conducted to understand how urban land cover affects precipitation, a key component of Earth's climate and water cycle system. Modeling studies to understand urban effects on precipitation are less prevalent in the literature. Model simulations addressing urban rainfall effects dates back to the 1970s (Vukovich and Dunn 1978; Huff and Vogel 1978). Simulations related to the UHI, humidity, fluxes and aerosols have also been conducted by Hjelmfelt (1982); Shafir and Alpert (1990); Theinen et al. (2000); Craig and Bornstein (2002); Rozoff and Cotton (2003). Most of these studies investigated the role that the UHI and surface roughness associated with buildings plays in generating or altering low-level convergence. Such convergence was hypothesized to affect the convective initiation process. More recent studies by Shem and Shepherd (2009) and Shepherd et al. (2010a) have affirmed and extended this hypothesis by noting how low-level convergence establishes on the urban-rural interface.

A number of observational and modeling studies were done to understand the interactions between urban and sea breeze circulations in Houston (McPherson 1970; Bouvette et al. 1982; Orville et al. 2001; Shepherd and Burian 2003; Burian and Shepherd 2005; Shepherd et al. 2010a), Japan (Yoshikado 1994; Kitada et al. 1998; Kusaka et al. 2000; Ohoshi and Kida 2002), Hong Kong (Lo et al. 2007) and Sydney (Gero and Pitman 2006).

Other city specific observational and modeling studies in the US have focused on Phoenix (Balling and Brazel 1987; Selover 1997; Diem and Brown 2003; Shepherd 2006), Atlanta (Dixon and Mote 2003; Bornstein and Lin 2000; Shepherd et al. 2002; Diem and Mote

2005; Mote et al. 2007, Bentley et al. 2009, Shem and Shepherd 2009), New York City (Bornstein and LeRoy 1990), Mexico City (Jauregui and Romales 1996), Oklahoma City (Niyogi et al. 2006), Indianapolis (Niyogi et al. 2011) and Chicago (Changnon and Westcott 2002). These studies continued to suggest that there is an association between rainfall and urban land cover. All of these studies showed some evidence of an increase in the precipitation, which they hypothesized to be related to heavy urban development.

Niyogi et al. (2006) conducted simulations using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) to investigate the impact of urban and land vegetation processes on the prediction of the mesoscale convective system (MCS) observed on 30 July 2003 in the vicinity of Oklahoma City (OKC), Oklahoma. The inclusion of the urban canopy model better represented the urban-rural heterogeneities and improved simulation of the moisture fluxes and upstream inflow boundaries. Ikebuchi et al. 2007 found that land cover change and increased anthropogenic activities enhanced rainfall intensity and location of heavy rainfall events over Tokyo (Japan). Baik et al. 2007 and Han and Baik 2008, used two and three dimensional models to resolve that urban heat island circulation was relatively stronger during daytime, which strengthens the downwind updraft cell, enhancing rainfall downwind. Zhang et al. (2009) in their modeling study have shown a decrease in rainfall due to increased temperatures and sensible heat and reduced evaporation.

Four studies which are of special relevance to this study are Shem and Shepherd (2009); Shepherd et al. (2010a); Goswami et al. (2010) and Niyogi et al. (2011). Similar to this study, all four are modeling studies incorporating urban and no-urban scenarios, except Goswami et al. (2010) who have used partial and fully urban scenarios. Shem and Shepherd (2009) performed experiments over Atlanta, Georgia with urban and no-urban scenarios using the WRF model. In the urban run, the model captured well the convective evolution of the two case days. Similarly the no-urban run also caused distinct differences in temporal and spatial evolution of precipitation. Shepherd et al. (2010a) used a coupled atmosphere-land surface model to investigate a typical sea breeze convection day near Houston, Texas. The day considered was 25 July 2001. Simulations were run using three scenarios: urban land cover, no urban land cover and urban 2025.Future land cover growth of 2025 was projected using the UrbanSim (Wadell 2002) and fed into the WRF NOAH model to simulate cumulative rainfall. The “urban” simulation showed evidence of heavier rainfall over the city and just northwest of the city, which was confirmed by radar observations on that day. The study established how enhanced convergence and destabilization occurred over Houston even within a region experiences sea-breeze forced convergence. This result also suggests that climate changes, as indicated by precipitation changes, can be a function of factors beyond the scope of greenhouse gases. In many ways, the urbanization associated with Kolkata is similar, geographically, to Houston and thus, it is plausible that similar processes may be occurring (Mitra et al 2011a). Both cities are large near-coastal, urban regions with frequent convection associated with mesoscale forcing (e.g., sea breeze fronts, drylines).

Goswami et al (2010) examined the impact of urbanization on the evolution and dynamics of three heavy rainfall events that occurred over Indian cities (Mumbai, Bangalore and Chennai) in different seasons using the mesoscale atmospheric model MM5, version-3. Simulations were carried out for two scenarios; partially urban and fully urban. In general it was found that urbanization increases the Diurnal Temperature Range (DTR). Partial urbanization was found to be associated with more total rain, larger spatial extend of distribution and less intensity, while the converse is true for the fully urban scenario. The impact of the spatial extant of urbanization (large city vs. megacity) was also examined through an additional set of numerical experiments; the size of the city was found to have a marked influence on both the intensity and distribution of rainfall. Niyogi et al. (2011) investigated storm characteristics over the Indianapolis region and four peripheral rural counties. Using radar imagery, storm structure, synoptic setting, orientation and storm motion was studied. Again using MM5 model, an urban and another no-urban simulation was conducted, which showed that the no-urban run did not simulate the storm of interest over the region. These three studies highlight the fact that urban areas have a strong climatological influence on regional thunderstorms.

Though the general consensus is that urbanization has been effective in increasing rainfall there is a few which show contradictory results. Guo et al. (2006) found that the total accumulated precipitation in the Beijing region decreases when they modified the land surface conditions. Rainfall distributions tend to become concentrated and also intensified along the borderline between urban and non-urban region. Zhang et al. (2007, 2009) argued that urban expansion in Beijing area produced less evaporation, higher surface temperatures, larger sensible heat fluxes, and a deeper boundary layer. This led to less water vapor, more mixing of water vapor in the boundary layer, and hence reduction in rainfall. Kaufman et al. (2007) using econometric and statistical modeling revealed that urban development in the Pearl River Delta of China has reduced local precipitation. They suggested that such reductions might be due to changes in surface hydrology that extend beyond the urban heat island effect and energy-related aerosol emissions. Trusilova et al. (2008) used a coupled atmosphere– land surface model to investigate the effects of urban land on the climate in Europe on local and regional scales. They found statistically significant increases (decreases) in winter (summer) precipitation in their urban simulations as compared to the pre-urban simulations. But these studies did not consider the contribution of aerosols in enhancing or suppressing rainfall in urban areas.

Though it is beyond the scope of this study but mention must be made of the recent studies related to urban aerosols and precipitation. Research groups have shown that aerosols play a role in either enhancing (large condensation nuclei) or suppressing (small condensation nuclei) rainfall over or downwind of the urban areas (Rosenfeld 2000; Givati and Rosenfeld 2004; Rosenfeld et al. 2007, 2008; Lensky and Drori 2007; van den Heever and Cotton, 2007, Jin and Shepherd 2008).

Urban Rainfall Studies in India

Urban rainfall studies for India have been very limited. Khemani andMurthy (1973) analyzed rainfall data from 1901 to 1969 for the city of Bombay and two other stations in the near by rural region. Their study indicated that there was an increase of about 15% rainfall in the industrialized city of Bombay compared to nearby non-urban cities. In an unpublished doctoral dissertation, Simpson (2006) investigated the impact of Chennai urban land use on the sea breeze circulation and rainfall amounts during the southwest monsoon. Observations indicate occurrence of rainfall over the city during late evening and nocturnal hours, possibly due to the interaction between the receding sea breeze circulation and the urban heat island. De and Rao (2004) conducted a study involving 14 major cities (over 1 million populations) of India focusing the monsoon season. De and Rao found that in the complete period between 1901 and 2000, seven cities including Kolkata had increasing trends, excluding Nagpur, which had a decreasing trend. The increasing trend in the Monsoon season rainfall is most evident over Kolkata for the period 1951-2000, increasing at the rate of 83 mm/ 10 years. This period was characterized by the maximum change in landcover due to post independence refugee influx (Mitra et al. 2011b) and is also consistent with trends reported in Mitra et al. (2011a). In a recent study, Kishtawal et al. (2009) have shown a positive correlation between heavy rain events and urban land cover growth for large urban areas in India. Goswami et al. (2010), mentioned earlier, also strengthens the notion that increased urbanization affects both intensity and spatial distribution of rain.

Though the majority of the limited literature suggests that urbanization in India is associated with enhanced local-regional precipitation, Sen Roy's (2008) observational study on extreme hourly precipitation trends (1982–2002) for large urban areas in India with one million or greater population showed that Kolkata had a negative trend in its rainfall pattern in the premonsoonal months (March to May). The limited literature and conflicting results necessitates further in-depth studies to more effectively comprehend the urban impacts on the hydrological cycle over Indian cities.

5.3 Study Area and Research Objectives:

This study focuses on a major urban center on the Indian subcontinent (Kolkata, India) in a developing part of the world, where future urban growth is expected to be significant (Figure 5.1). Asia, in particular, is projected to see its urban population increase by 1.8 billion. Between 2007 and 2025, the urban areas of the world are expected to gain 1.3 billion people, including 261 million in China and 197 million in India, which together account for 35 percent of the total growth (UN 2007a). The city of Kolkata is predicted to have a population of 20 million by 2025 (UN 2007b). Mitra et al. (2011b) also predicts the future growth of Kolkata in 2025 using the CA-Markov urban growth model. According to them, there is a significant increase in the land cover from 1990 to 2025. It increased from 1363 sq. km in 1990 to 2653 sq. km in 2025. As such, the objective of the study is to investigate whether Kolkata's urban land cover might influence the premonsoon season precipitation as suggested by the climatological and observational analyses of Mitra et al. (2011a). More specifically, we focus on the well-known, though poorly studied, mesoscale system known as the Nor'wester, a dryline-induced convective system that is a primary source of rainfall around Kolkata during the premonsoon season. Only a few observational studies have documented the Nor'wester (Lohar 1996; Sadhukhan et al. 2000a; Sadhukhan et al. 2000b; Mukhopadhyay et al. 2005). Recently, Shem and Shepherd (2009) and Niyogi et al. (2011) have established that pre-existing convective systems can be enhanced by the urban environment. Yet, these studies were focused on squall-type systems in the US. Two novel aspects of this work are the focus on the Nor'wester itself and also, the possible interactions with the urban land cover.

As likely the first scholarly study to examine such issues from a modeling perspective in the Kolkata region, we investigate the physical response of the precipitating Nor'wester system to two land cover scenarios using the coupled WRF NOAH atmosphere – land surface model. The two scenarios are: a) no urban, indicative of the pre-urbanized period and b) an urban, representative of the current urban land cover (circa mid-2000s). Furthermore, it is the first study of its kind to examine urban-mesoscale interactions involving the Nor'wester, the primary rainfall producer during the premonsoon season. The coupled atmosphere-land surface modeling system will be used to assess whether premonsoonal precipitation associated with the typical Nor'wester might be influenced under two scenarios a) current urban and b) no urban (pre-Kolkata). Further, we examine key physical mechanisms (sensible heat flux, vertical motion (a proxy for low-level convergence), moisture, and other thermodynamic variables) that might describe how urban land cover influences atmospheric convection.

Our hypothesis is that the precipitation associated with the Nor'wester system may be altered as a function of the existence of urban land cover. More specifically, we hypothesize that rainfall will be enhanced in response to enhanced surface fluxes and vertical motion triggered by convergence.

5.4 Meteorological conditions for 16 April 2003 over Kolkata Metropolitan Area:

Climatologically, Kolkata is located is in the tropical Indian monsoon region**.** The monsoon season rainfall (Krishnamurti et. al. 1981; Krishnamurti 1985; Vines 1986; Kulkarni *et al.* 1992; Bhasar Rao et al 2004; Dash et al. 2006 and many others) is important because of its impact on the agricultural economy. The monsoon season rainfall initiates in early June and continues through September. There is very little rainfall during the winter season (Lohar and Pal 1995). The three-month period (March, April, May) leading into the monsoon season is characterized by hot days with sporadic thunderstorms (Sadhukhan et al. 2000b).

The premonsoon rainfall (PMR)(March, April, May) is characterized bymesoscale forcing which leads to thunderstorm activity. There are mainly two types of thunderstorms: i) deep convection resulting from the dryline, which forms where the moist low-level southerlies meet arid westerlies causing severe thunderstorms (locally known as "Kalbaishaki" or Nor'wester (IMD Report 1941; Weston 1972) and ii) convection initiated at the sea-breeze front, causing thunderstorms (Lohar 1996). Our qualitative analysis, not shown, suggests that sea breeze convection is quite minimal relative to the more dominant Nor'wester in the premonsoonal rainfall over the region. The formation of Nor'westers or "Kalbaishaki" is attributed to a warm, moist, southerly low-level flow from the Bay of Bengal and an upper-level dry, cool, westerly or north-westerly flow giving rise to an atmosphere with high latent instability (Figure 5.2) (Mukhopadhyay et al. 2005). Historically speaking, possibly the first documentation of such a storm was made by Floyd (1838). He documented a storm that affected east of Kolkata on 8 April 1838. He gave a brief explanation about the movement of the storm along with an account of damage by visiting the site after the passage of the storm. These systems are formed over the Bihar, Jharkhand region travel south-eastward to strike Kolkata and surrounding areas. With respect to Kolkata, these storms appear from the northwest direction hence the name ‘Nor’wester’ (Desai 1950; Mukhopadhyay et al. 2005; Mukhopadhyay et al. 2009).

These storms are meteorological hazards annually in West Bengal, including Kolkata. The storms cause damage to aviation, rail, traffic, power supply and agriculture, along with loss of life (Mukhopadhyay et al. 2005). PMR (Mitra et al. 2011a) contributes approximately 12% of the annual total rainfall (Sadhukhan et al. 2000a) and our analysis of historical rainfall totals confirms this notion as well (Figure 5.3).Because these storms are a predominant mechanism for PMR, we use a case study to investigate, likely for the first time, how a Nor’wester may interact with urban landscape. Further, Shepherd et al. (2005) noted that modeling studies should select periods when large scale forcing is weaker. Additionally, Holt et al. (2006), Shem and Shepherd (2009) and Niyogi et al. (2011) illustrated how existing convective systems can be modified by the urban environment. As such, it is an appropriate period to investigate how urban land cover could affect PMR in the study region (Mitra et al. 2011a) and time frame.

5.5 Data used to validate16 April 2003 rainfall event:

An analysis of satellite-based rainfall revealed that the month of April was the premonsoon month with the maximum total cumulative rainfall. We used the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA), which comes as monthly (3B43) or daily (3B42) data as described by Kummerow et al. (1998) and Huffman et al. (2007). TMPA provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25°

_ 0.25° and 3 hourly). TMPA is available both as a research and real time product (Huffman et al. 2007).We used the daily data (3B42 V6 derived) to plot the total accumulated rainfall on 16 April 2003 (Figure 5.4). The data were plotted using the NASA online TOVAS/GIOVANNI system (http://disc2.nascom.nasa.gov/Giovanni/tovas/). For the case study, 16 April 2003 was chosen based on the paper by Mukhopadyay et al. (2005), which utilized the hourly images of Doppler radar at Kolkata and satellite images (Figure 5.5) to document the initiation, maturity, dissipation, vertical extent of the cloud and movement of two, severe Nor'westers on 16 and 30 April 2003. The total cumulative rainfall from the TMPA was around 35- 40 mm, which is consistent with the Indian Meteorological Department's Dopplar Radar record for the same day (i.e., 34mm of total rainfall (Mukhopadyay et al. 2005).

To establish that 16 April 2003 was a typical Nor'wester thunderstorm event, daily composite maps were plotted using the NCEP (National Center for Environmental Prediction) Daily Global Analyses data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/data/histdata/). The geopotential heights at 500 hPa (Figure 5.6) show that there was no large amplitude feature in the overall Rossby wave pattern on that particular day. The surface level pressure plot (Figure 5.7) validates the same fact with low pressure in the southern region of the area and higher pressure towards the north. The surface vector wind field (Figure 5.8) illustrates mainly light southerly flow, which tends to advect moist air from the Indian Ocean. This is also reflected by the large precipitable water values (Figure 5.9) that can support convection, if there is a trigger. Thunderstorms are associated with environments with convective instability, abundant moisture at low levels, strong wind shear and a dynamical lifting mechanism that can release the instability (Kessler 1982). So, all of the above conditions were conducive to produce a Nor'wester thunderstorm on our case day.

5.6 The WRF-NOAH model:

This study utilizes a series of coupled WRF-NOAH simulations of the atmosphere. The Weather Research and Forecasting model (WRF) is a next generation mesoscale model with the advanced dynamics, physics and numerical schemes (Kusaka and Hayami 2006). The WRF model was developed as a collaborative effort by the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), Oklahoma University (OU) and the university community. The version of the model used is the Advanced Research WRF (WRF-ARW) version 2.2. The ARW dynamic core is designed to integrate the compressible, nonhydrostatic Euler equations using a terrain following mass vertical coordinate (Skamarock et al. 2005) and is structured to perform case studies based on real input data. Three map projections are supported for real data simulations: polar stereographic, Lambert-Conformal, and Mercator (Kusaka and Hayami 2006).

NOAH is the land surface model (LSM) used in this study. It is a unified model between the National Center for Atmospheric Research, National Oceanic and Atmospheric Administration's (NOAA's) National Center for Environmental Prediction (NCEP), and the Air Force Weather Agency (AFWA) (Kusaka and Kimura 2004). This LSM simulates soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack depth, snowpack water equivalent (and hence snowpack density), canopy water content, and the energy flux and water flux terms of the surface energy balance and surface water balance (Mitchell 2005).

In this study the meteorological input data used to initiate the WRF model was provided by the National Center of Environmental Prediction (NCEP). The data was Global Forecast System (GFS) data in GRIB format. GFS was formerly known as the Medium Range Forecast or MRF (Seo et al. 2005). The current operational GFS model has undergone substantial changes since 1996. These include modification of the physics package such as the inclusion of prognostic cloud water, boundary layer turbulence and convective parameterization, a modification of the evaporation formulation for convective rain, inclusion of cumulus momentum mixing, enhanced gravity wave drag, etc. The data resolution (latitude and longitude) is 1 degree. For each case, the model is run for the duration of the case study period, totaling 36 hours, ingesting updated input data every six hours, which simulates the assimilation of data from real world surface and upper air meteorological data sources.

5.7 WRF-NOAH Model 16th April 2003 Simulations:

To understand the physical mechanism associated with urban land cover and precipitation processes, two distinct scenarios were chosen. The two scenarios were ‘urban’ (present) and ‘no-urban’ (pre-urbanization). The urban criteria represent Global Land Cover Characteristics (GLCC) data created from images acquired during 1992 and 1993 for surface characteristics (Sertel et al. 2009). In the urban run no changes were made to the landuse and vegetation parameters. In the no-urban scenario, modifications were made in the tables (LANDUSE.TBL and VEGPARM.TBL) to remove Kolkata city and replace it with the dominant landcover type of the surrounding rural areas, i.e., irrigated cropland and pasture. (Tables 5.1 and 5.2). One unique aspect of our study is that irrigated cropland is the dominant native land cover around Kolkata. Studies in Atlanta (Shem and Shepherd 2009), Houston (Shepherd et al. 2010a), and Indianapolis (Niyogi et al. 2011) replaced the urban category with the most predominant surrounding landcover type, dryland-cropland-pasture category for the no-urban scenario.

In this research, the Lambert-Conformal projection was used for three nested, telescoping, 2-way interacting grids. The outermost domain had a spatial resolution of 111 km.

that was interpolated to 35 km in the domain wizard pre-processing tool. Each domain increases the resolution by a factor of 5, such that the third domain, centered on the city of Kolkata, has a resolution of 1.4 km (Figure 5.10). The outermost domain covers most of south Asia including India, Bangladesh, Nepal, Bhutan, Myanmar, parts of China, Laos and Thailand. The second domain covers most of central and eastern India and the third domain cover lower Gangetic basin centered on Kolkata city.

For both the urban and no-urban scenarios, the physics packages (Table 5.3) used were Kain-Fritsch cumulus cloud parameterization scheme and Ferrier (Eta) microphysics (Figure 5.11). The Kain-Fritsch scheme includes shallow convection, low level vertical motion, updrafts, downdrafts and also entrainment and detrainment (Chen and Dudhia 2000). The Ferrier scheme was used for the innermost domain (Ferrier et al. 2002) where explicit convection occurs. The value of the new Eta microphysics is that multiple phases and moments of liquid and frozen hydrometeors are explicitly calculated and stored. Some assumptions are made about cloud ice that prevents the need for ice nucleation processes (Shem and Shepherd 2009).

Both scenarios were run under the same meteorological conditions for 16 April 2003 to examine how the rainfall variability responds to the different land cover scenarios. The simulated rainfall is compared with available station or remotely sensed precipitation data for validation. We will also quantitatively analyze model-derived vertical motion (as a proxy for low-level convergence), sensible heat fluxes, and boundary layer structure to test hypotheses for how urban land cover in Kolkata may affect PMR patterns associated with a typical Nor'wester.

5.8 Results and Analysis: Urban and No-urban simulations

Total cumulative rainfall

The simulations for both urban and no-urban scenario are capturing the rainfall event on 16 April 2003. The TMPA daily rainfall product (3B42) is relatively consistent with the spatio-temporal rainfall pattern on this day (Figure 5.12). The radar data presented in Mukhopadhyay et al. 2005 also is consistent with the model generated precipitation distribution (Figure 5.13). The urban simulation shows total rainfall amounts on the order of 14.5 mm (maximum value) whereas the no-urban simulation is producing noticeably less rainfall as a whole (e.g., on the order of 11 mm). The model result has underestimated the total accumulated rainfall in comparison to the rainfall generated by TMPA daily rainfall product as well as radar data (Mukhopadhyay et al. 2005), but the model captures the characteristics of the convective system. As Shem and Shepherd (2009) noted, often model derived precipitation amounts will vary relative to actual amounts due to inadequacies in the model physics and temporal resolution of the model but the overall spatio-temporal representation is useful for sensitivity analysis like those herein. This result supports the hypothesis that the premonsoonal rainfall climatology in the urbanized region will be anomalously high compared to non-urban regions that experience similar meteorological forcing during this time frame.

A difference analysis between the urban and no-urban 13Z (18.30 LST) rainfall fields (Figure 5.14) clearly establishes that the urban simulation is producing roughly 3 - 4 mm more rainfall than no-urban. This finding suggest that when the Nor'westers move over an urban area, the storm may intensify as observed in US squall line type systems reported by Shem and Shepherd (2009) and Niyogi et al. (2011). A west-east cross section through the region (see figure 5.14 for cross section orientation) also reiterates that rainfall totals are greater in the urban scenario than in the no-urban scenario. The cross sectional time series captures the enhanced rainfall in the urban simulation than the no-urban simulation (Figure 5.15). Our experiments clearly establish that the spatio-temporal evolution of the rainfall can be a function of the urban land cover as has been previously reported. It also provides a possible explanation for why urban Kolkata sites exhibited statistically-significant upward trends in rainfall in the past 50-60 years as reported in Mitra et al. (2011a).

Physical parameters modifying the convective system

The enhanced rainfall in the urban runs motivates the second major component of this study, which is to examine the physical mechanisms that might govern the strengthening of the mesoscale convective system as it passes over the urban area. Urbanization is accompanied by the replacement of natural land surfaces by artificial surfaces that significantly change the original surface properties. The parameters that are uniquely modified by urbanization include land use, surface roughness, green vegetation fraction, albedo, volumetric heat capacity and soil thermal characteristics among others (Shem and Shepherd 2009). Here we will discuss how differences in sensible heat flux, water vapor content (a proxy for latent heat flux), near surface vertical velocity (a proxy for low-level convergence), albedo and planetary boundary height, all might explain how land-atmosphere interactions in the Kolkata region might explain convective enhancement.

A time series plot showing the sensible heat flux (HFX) (Figures 5.16) illustrates the transfer of heat from the surface to the lower convective boundary layer. Shepherd et al. (2010a), Huff and Vogel (1978), Thielen et al. (2000) and Rotach et al. (2005) all have noted that sensible heat flux has contributed to more convective activity in urban areas. Figure 5.16 shows that urban areas result in approximately 60 W/m^2 more sensible heat flux than the no-urban scenario.

This is expected as urban surfaces can significantly alter the energy balance in and around the cities (Shepherd et al. 2010a). Figure 5.17 represents the spatial difference field of albedo between urban and no-urban simulations. It clearly shows that the albedo is more in no-urban case than urban case. This result is consistent with the notion that urban surfaces have lower albedo surfaces than natural landscapes. As such, cities like Kolkata will absorb and retain more shortwave energy compared to a higher albedo region, which is more reflective.

The literature shows that moisture is reduced (e.g., latent heat or near surface moisture) in urban areas (Rozoff et al. 2003, Shem and Shepherd 2009). This is likely due to a reduction in vegetation and associated evapotranspiration due to replacement of natural surfaces with imperious surfaces. Herein, we use water vapor at 2 meters (Q2) as a proxy for latent heat flux because of inconsistencies with the latent heat flux field. All other fields were consistent with the expected literature and our own physical understanding so we concluded that the processing of latent heat flux was flawed. Figure 5.18 shows a difference plot of Q2 for urban and no-urban, which emphasizes that no-urban has more vapor at 2 meters than urban areas, approximately 6 kg kg-1 more. However, we should emphasize that this moisture reduction likely is of secondary or tertiary importance because there is still ample large scale moisture to support convection as noted previously.

Many aforementioned studies in the literature have identified low-level convergence, induced by the city, as a primary factor that could cause initiation or enhancement of convection. Herein, we establish near-surface vertical velocity as a proxy for divergence and convergence. Cho and Ogura (1974) and numerous other papers establish that this is a valid assumption (i.e., "Q α η (ρ) ω where ω is the vertical velocity at the top of the boundary layer, a measure of boundary layer convergence"). They found that the maximum low-level convergence is about one-eighth (~475 km) of a wavelength ahead (to the west) of the maximum deep cumulus convective heating. It is well known in mesoscale convective systems too. At low-levels the intense upward motion is found in front of the mesoscale precipitation maximum and mesoscale downdraft immediately behind the precipitation maximum (Chao and Deng 1997).

Figure 5.19 shows a spatial difference plot of vertical velocity between urban and no-urban scenario at 9Z, which is precedesthe convective activity by a couple of hours. In the plot the urban stretch of Kolkata city distinctly stands out showing the presence of pockets of enhanced vertical velocity, indicative of low-level convergence response to the increased surface roughness and sensible heat flux associated with the urban surface.

We also looked into the boundary layer structure (Figure 5.20) for both urban and no-urban scenarios. Boundary layer processes couple the urban land surface forcing to the atmospheric convective process (Shepherd et al. 2010a). The time series plot shows that the urban planetary boundary was higher (around 50 – 100 meters) than the no-urban boundary, especially during the daytime hours. Urban boundary layer doming has been commonly noticed, mentioned in studies done by Spangler and Dirks (1974), Hjelmfelt (1982), Rozoff et al. (2003) and Shepherd et al. (2010a).

According to Shepherd et al. 2010a, the dynamic source of enhanced lifting is able to release the convective energy and convert moisture-laden air to precipitating clouds. With regards to the Kolkata city case, this study, for the first time, has presented evidence that urban interactions with the Nor'wester system can physically alter the land-atmosphere exchange of heat, moisture, and momentum to modify convection. We should also note that even though the UHI is proportional to city size (Oke 1981) and more evident at night (Oke 1987), according to Shepherd et al. (2010a), its influence on meso-circulations is more clearly observed during the daytime than nighttime because of urban-rural pressure gradient and vertical mixing during daytime hours. Additionally, the convergent enhancement is likely also a function of building-induced mechanical turbulence or roughness, irrespective of diurnal cycle.

5.9 Conclusions:

The combined physical mechanisms in the urban region, namely increased sensible fluxes, and vertical velocity (through low-level convergence), enhances the lifting of warm unstable air required to increase convection enough to produce slightly more rainfall in the Nor'wester system. The study employs the coupled WRF NOAH atmosphere – land surface model. The coupled atmosphere-land surface modeling system was used to assess whether premonsoonal precipitation associated with Nor'wester might be influenced under two scenarios a) current urban and b) no urban (pre-Kolkata). The results were consistent with the hypothesis that precipitation associated with the Nor'wester system may be altered as a function of the existence of urban land cover. The urban run produced more rainfall than the no-urban run. The study also established that enhanced surface fluxes and convergence will contribute increased areas of positive vertical motion over the city.

This research paves the way for further to understand the implications of urban enhanced rainfall on society (e.g. flooding). Recent literature suggests that damage, loss of life, and costs from flooding have risen in recent decades (Brissette et al. 2003; Burian and Shepherd 2005; Ashley and Ashley 2008; Reynolds et al. 2008; Seager et al. 2009 and Shepherd et al. 2010b). Urban flooding will be on the rise in future with the pressure of increasing population and thus built-up area. A difference plot between urban and no-urban scenarios (Figure 5.21) in our experiments illustrates enhanced surface runoff in the urban experiment, which suggests that urban flooding might be a increasingly evident hazard. Kolkata city, with predictions of immense urban extension up to 2025 and beyond (Mitra et al. 2011b), may face the brunt of urban flooding very soon in future. So it is important to comprehend the nature and amount of change in precipitation, which can occur due to increased anthropogenic activities in future. Future work might consider integrating projected future land cover scenarios into the WRF-NOAH framework to assess how the regional hydroclimate responds to this aspect of anthropogenic forcing irrespective of greenhouse gases.

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Tables:

Table 5.1: Landuse Table in WRF-NOAH model (original)

USGS Categories	**ALBD**	**SLMO**	**SFEM**	**SFZO**	**THERIN**	**SCFX**	**SFHC**	
1	15.	.10	.88	80.	3.	1.67	18.9e5	Urban and Built-Up Land
3	18.	.50	.98	10.	4.	2.20	25.0e5	Irrigated Cropland and Pasture

.

Table 5.2: Vegetation Table in WRF_NOAH model (original)

USGS Cat	ALBEDO	ZO	SHDFAC	NROOT	RS	RGL	HS	SNUP	LAI	MAXALB	
1	.15	1.00	.10	1	200	999.	999.0	0.04	4.0	40.	Urban and Built-Up Land
3	.15	.07	.80	3	40.	100.	36.2	0.04	4.0	64.	Irrigated Cropland and Pasture

Table 5.3: Physics and dynamics options used for the simulations described herein

Option	**Selection**
Microphysics	Ferrier
longwave radiation	RRTM
shortwave radiation	Dudhia scheme
surface layer	Monin-Obukhov scheme
surface physics	NOAH Land Surface Model
boundary layer physics	Yonsei University Scheme
cumulus parameterization	Kain-Fritsch Scheme
turbulence and mixing option	simple diffusion
eddy coefficient option	2D deformation

Figures:

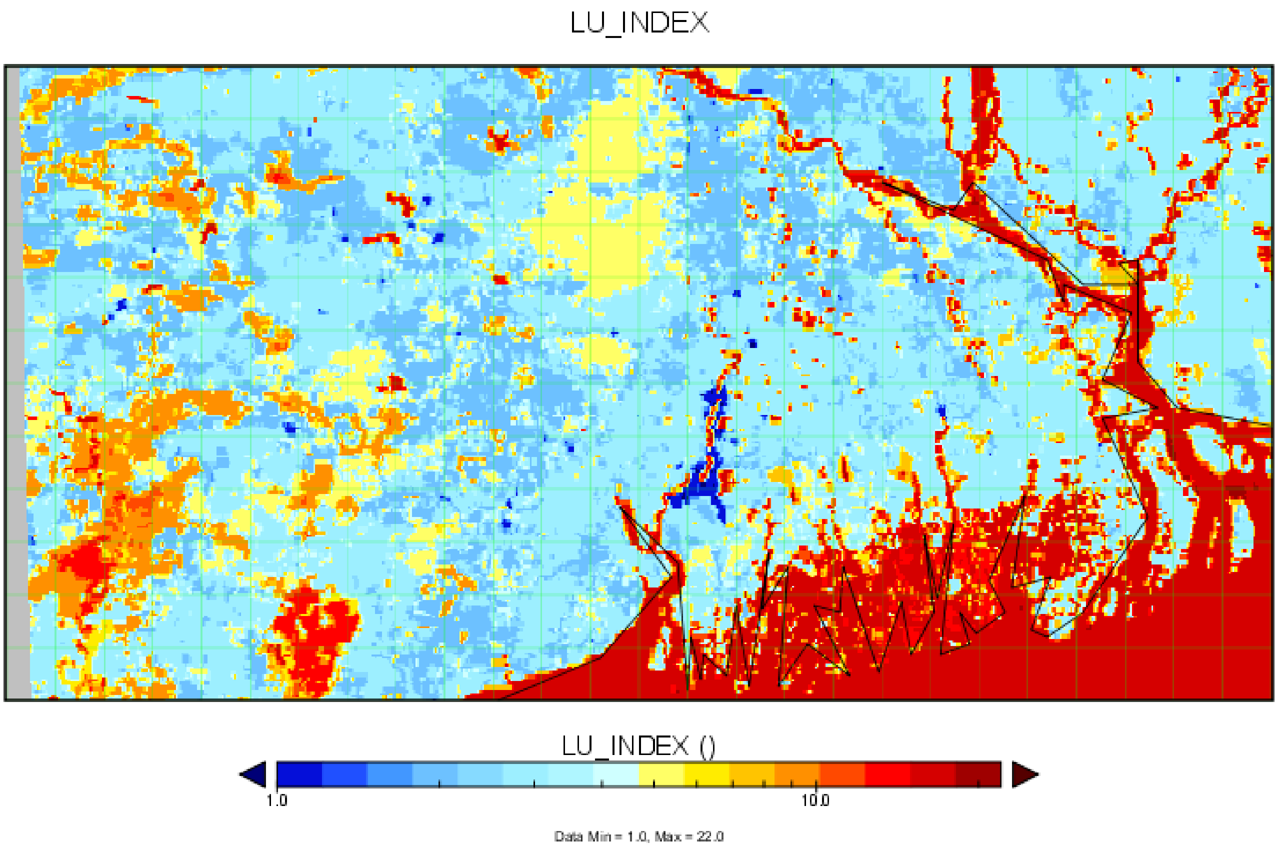


Figure 5.1: WRF initial land cover showing the Kolkata metropolitan area. (LU Index=Landuse Index, where the value 1(dark blue) stands for urban category; 16 (shades of red) stands for water and wetland category; 2, 3, 4 and 5 (shades of light blue, yellow stands for dry and irrigated cropland, scrubland, cropland grassland mosaic and pastures, 10 and 11 (shades of orange) stands for Savanna and Deciduous broadleaf forest.

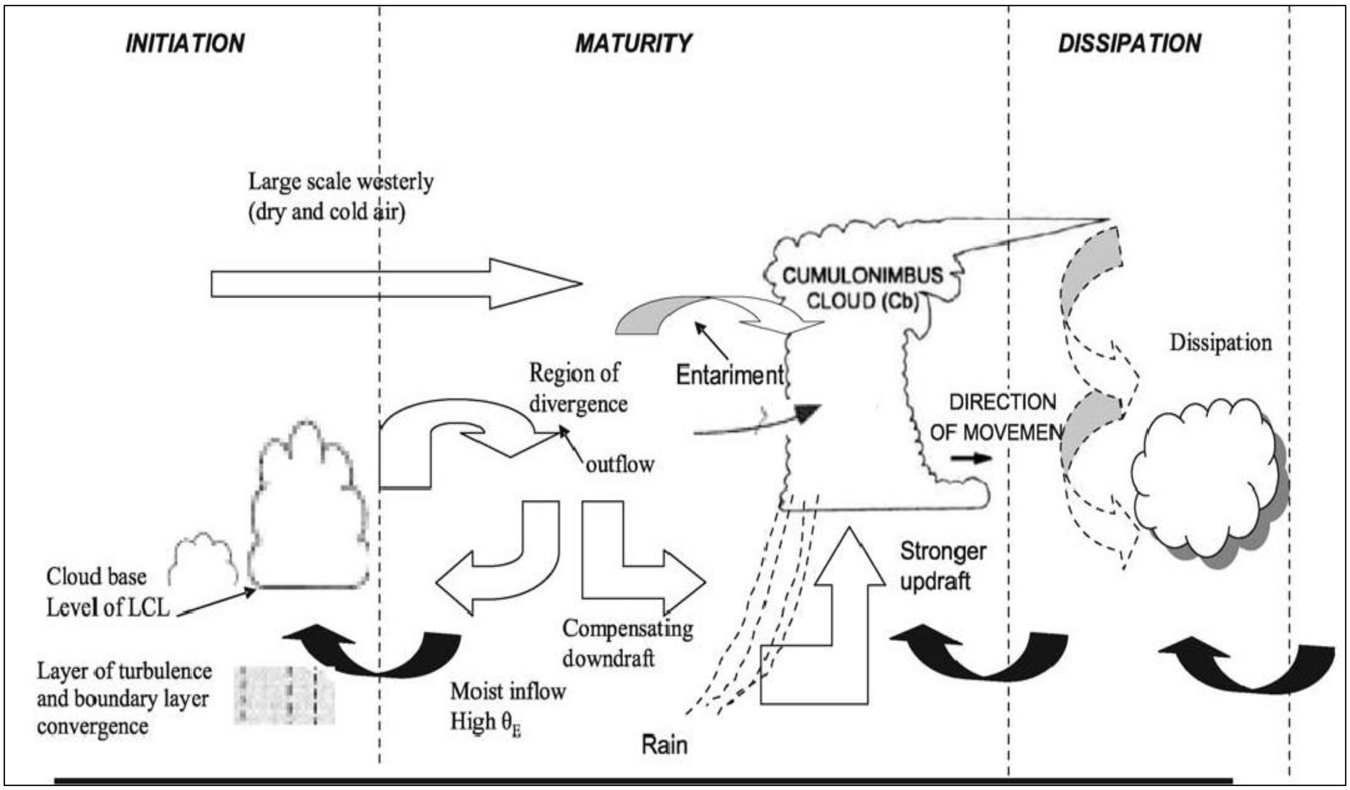


Figure 5.2: Schematic explaining the different processes at various stages of Nor'wester.
Source: Mukhopadhyay et al. 2009

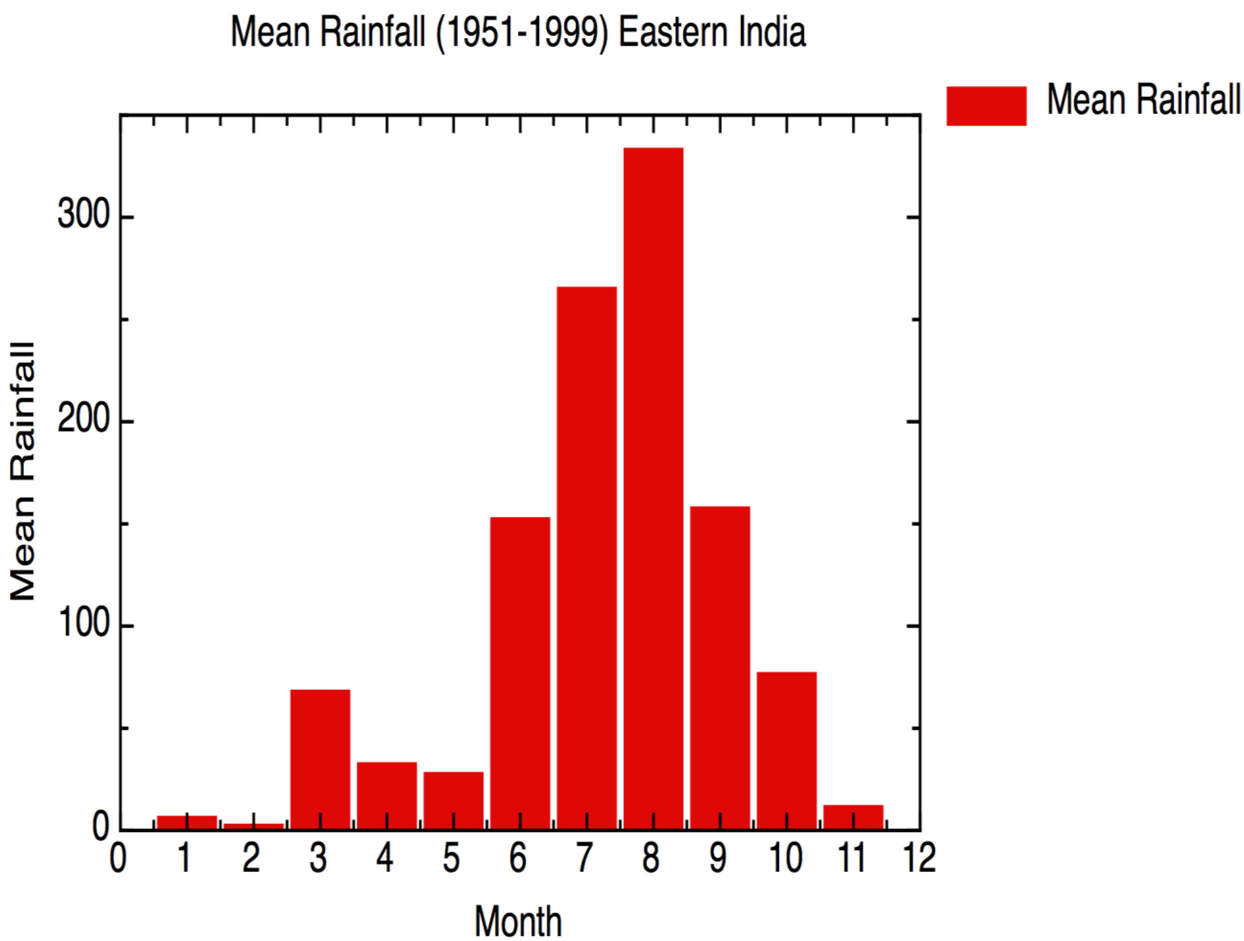


Figure 5.3: Mean monthly rainfall (mm) for the area (82-89 E, 19-26 N) using Legates and Willmott (1990b) data set.

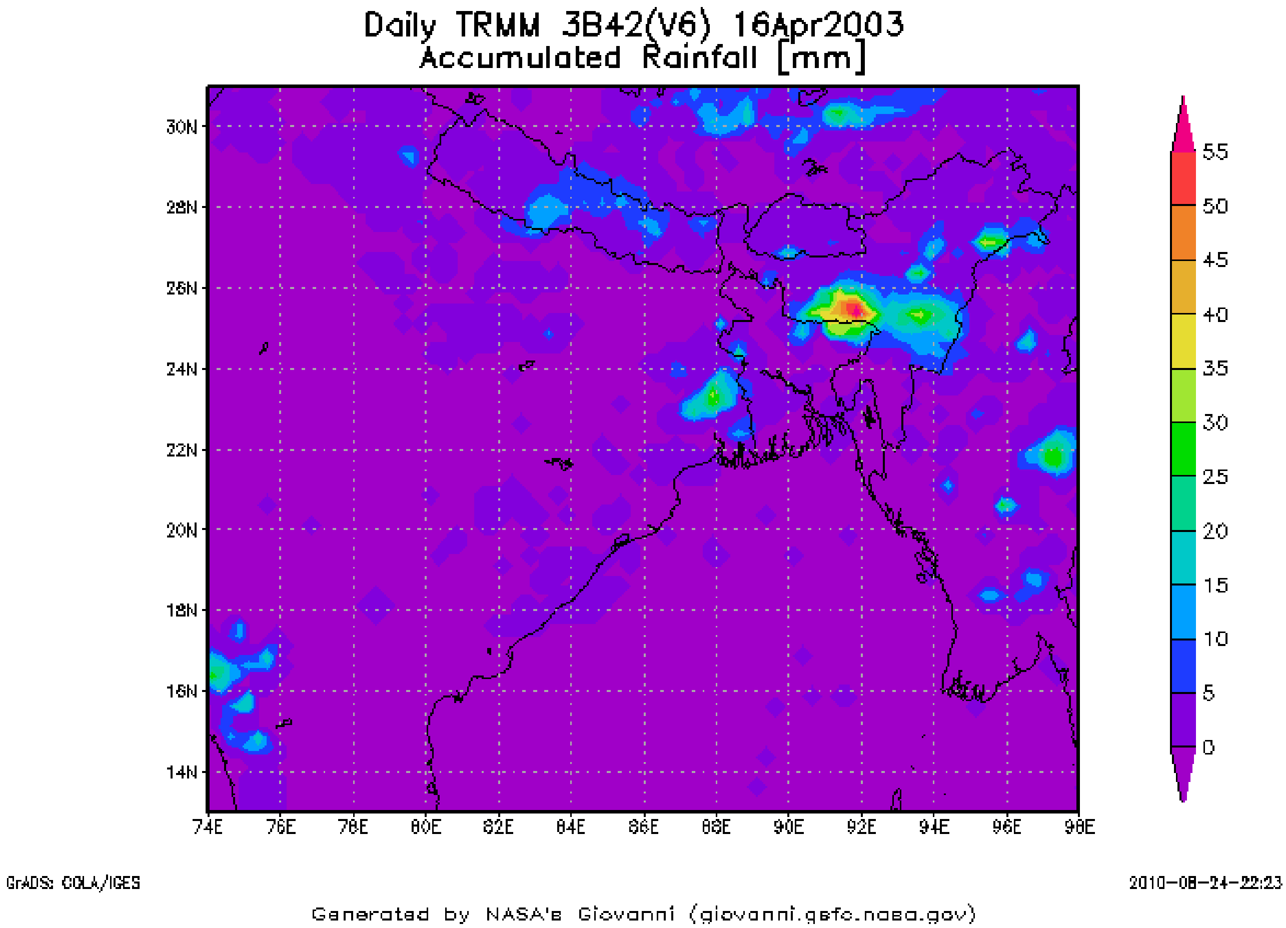
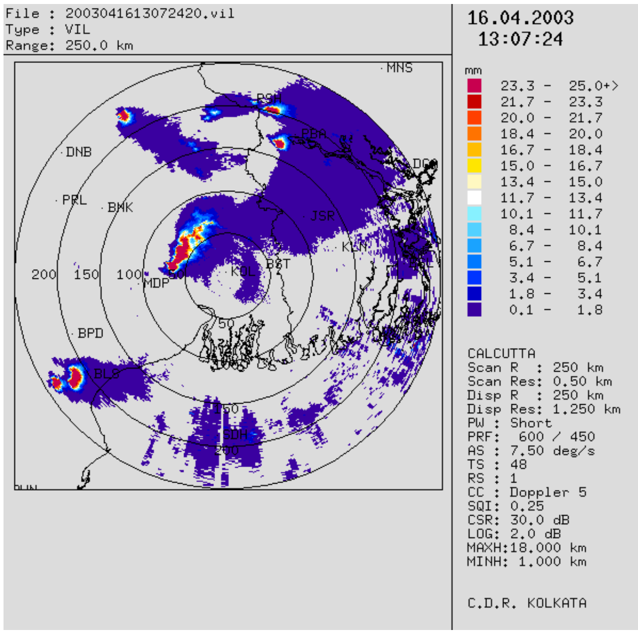


Figure 5.4: 16 April 2003 mesoscale rainfall (mm) associated with the Nor'wester case day in the study using the TRMM MPA (3B42) product.



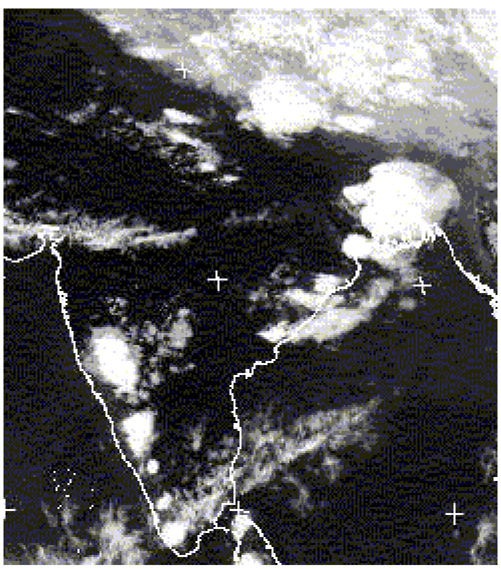


Figure 5.5: Top – Dopplar Radar image of 16th April, 2003, 13 Z, showing the Norwester event over the region. Bottom – Satellite image showing the same Norwester event.
Source: Top – India Meteorological Institute, Government of India; bottom - Dundee Satellite Receiving Station, Dundee University, UK

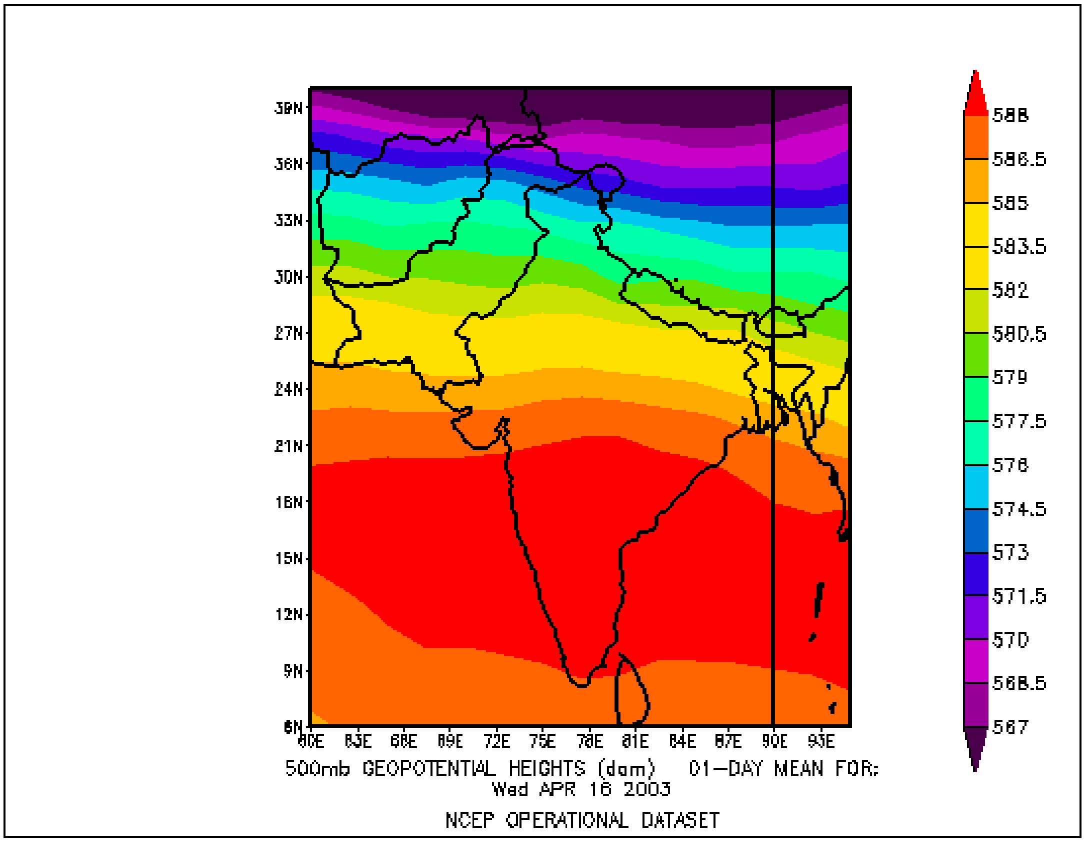


Figure 5.6: Geopotential Heights (500 mb level) calculated from the NCEP/NCAR Reanalysis Dataset.

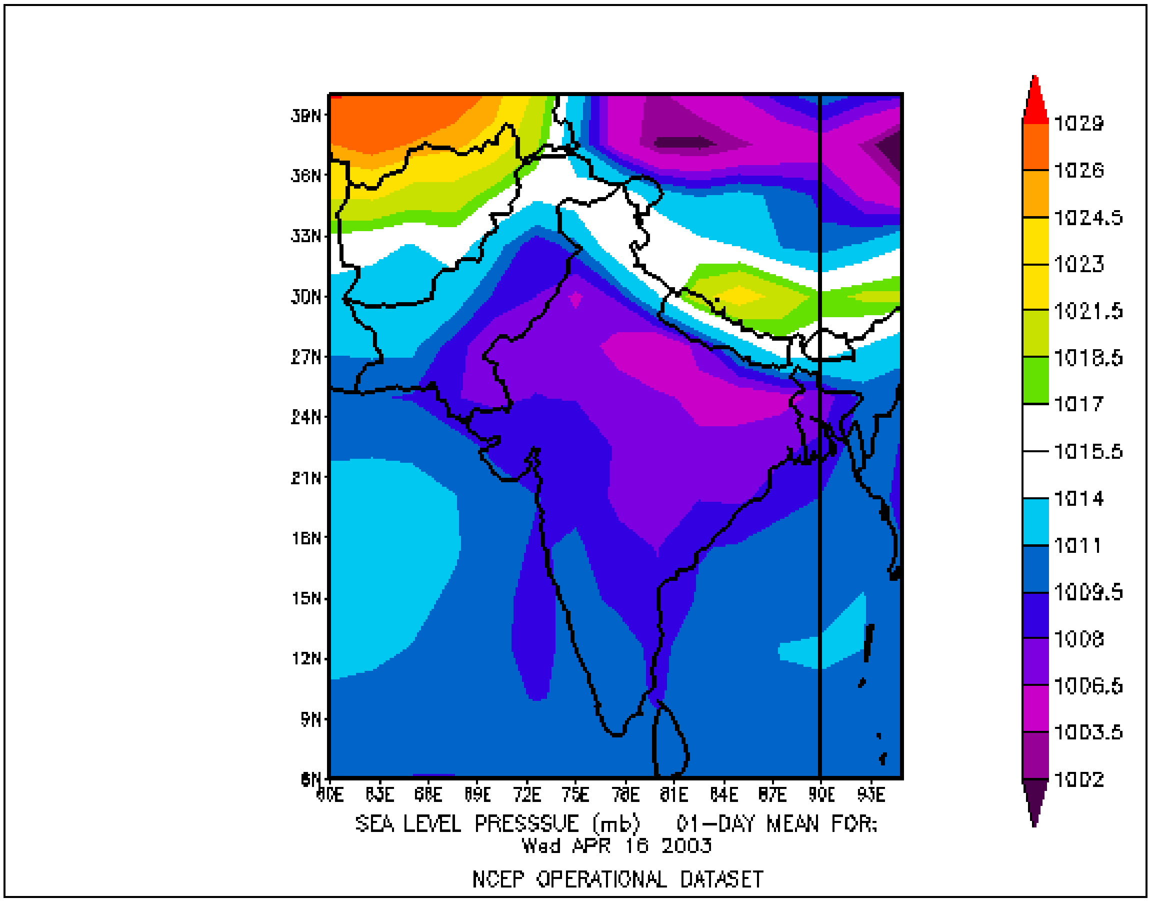


Figure 5.7: Sea Level Pressure calculated from the NCEP/NCAR Reanalysis Dataset.

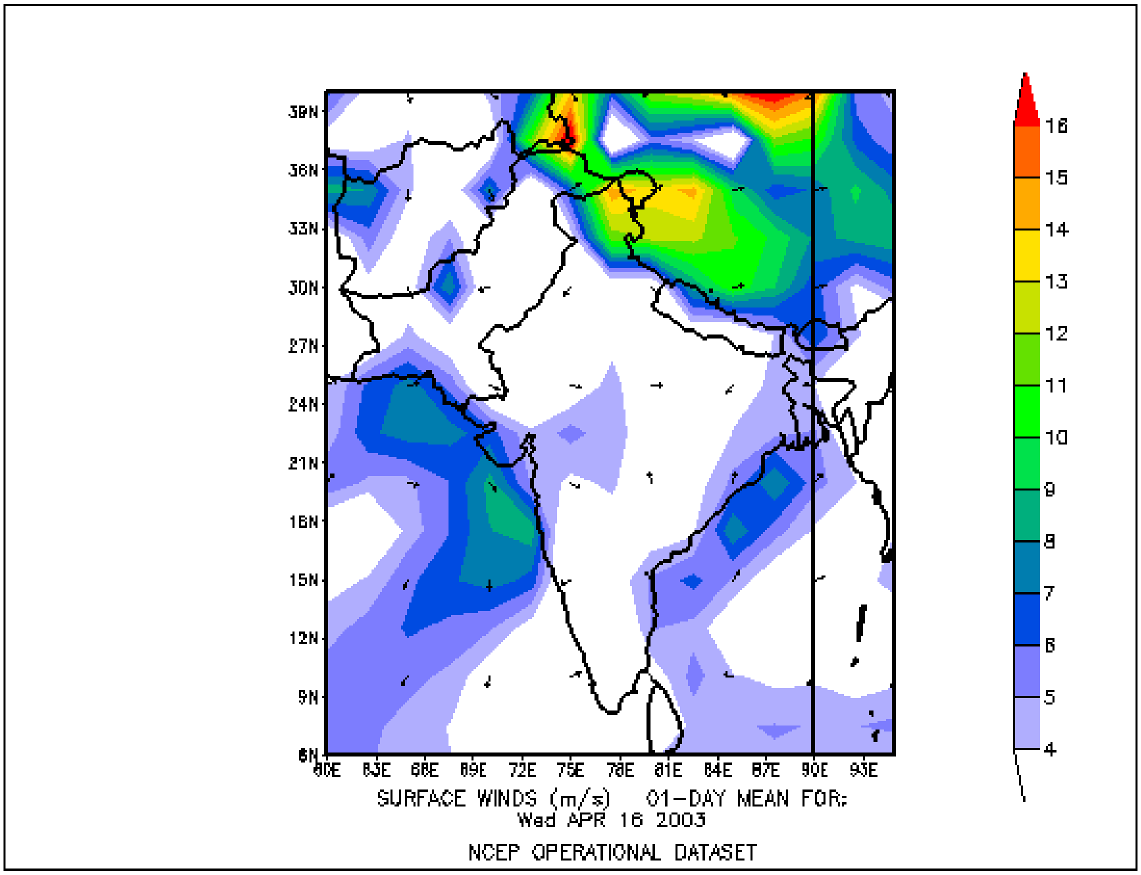


Figure 5.8: Vector winds at the surface calculated from the NCEP/NCAR Reanalysis Dataset.

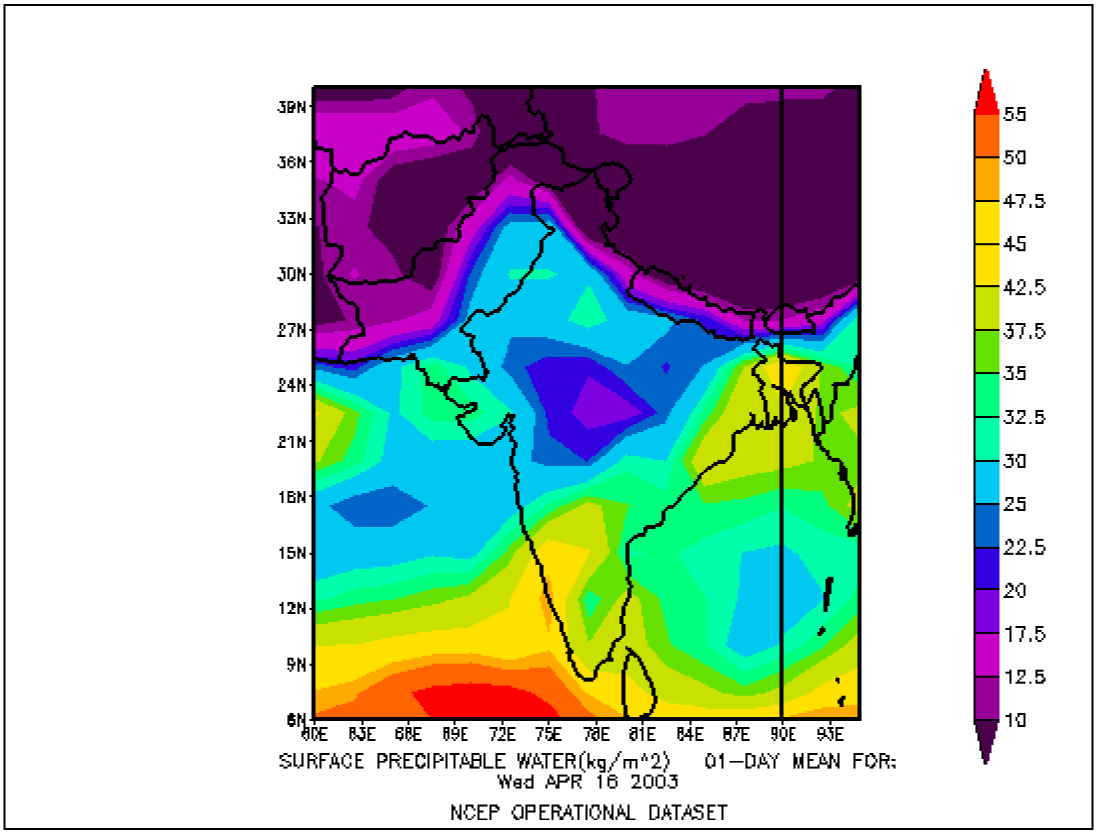


Figure 5.9: Total surface precipitable water calculated from the NCEP/NCAR Reanalysis Dataset.

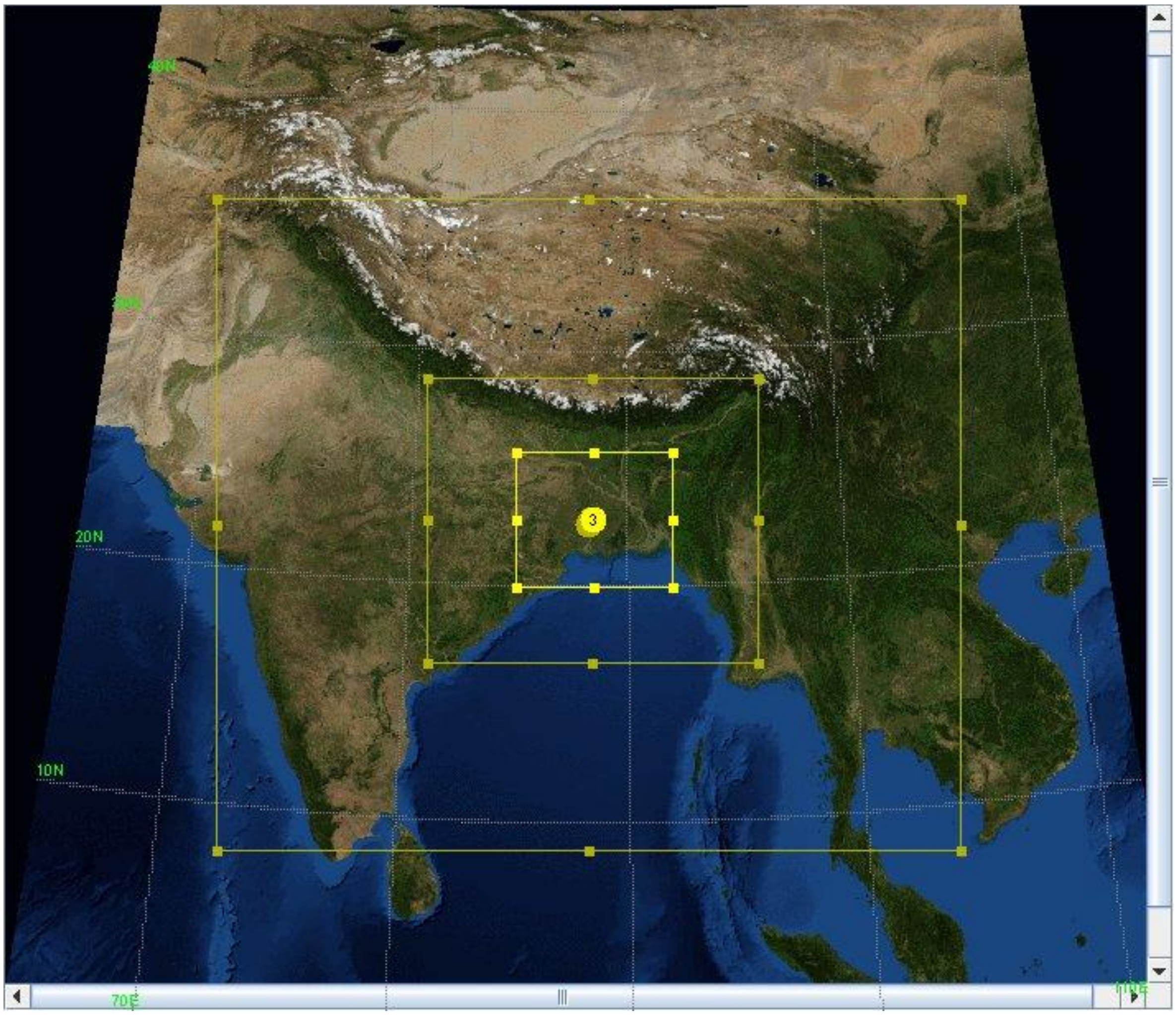


Figure 5.10: The four nest domains applied in the simulations. The domains are centered on Kolkata.

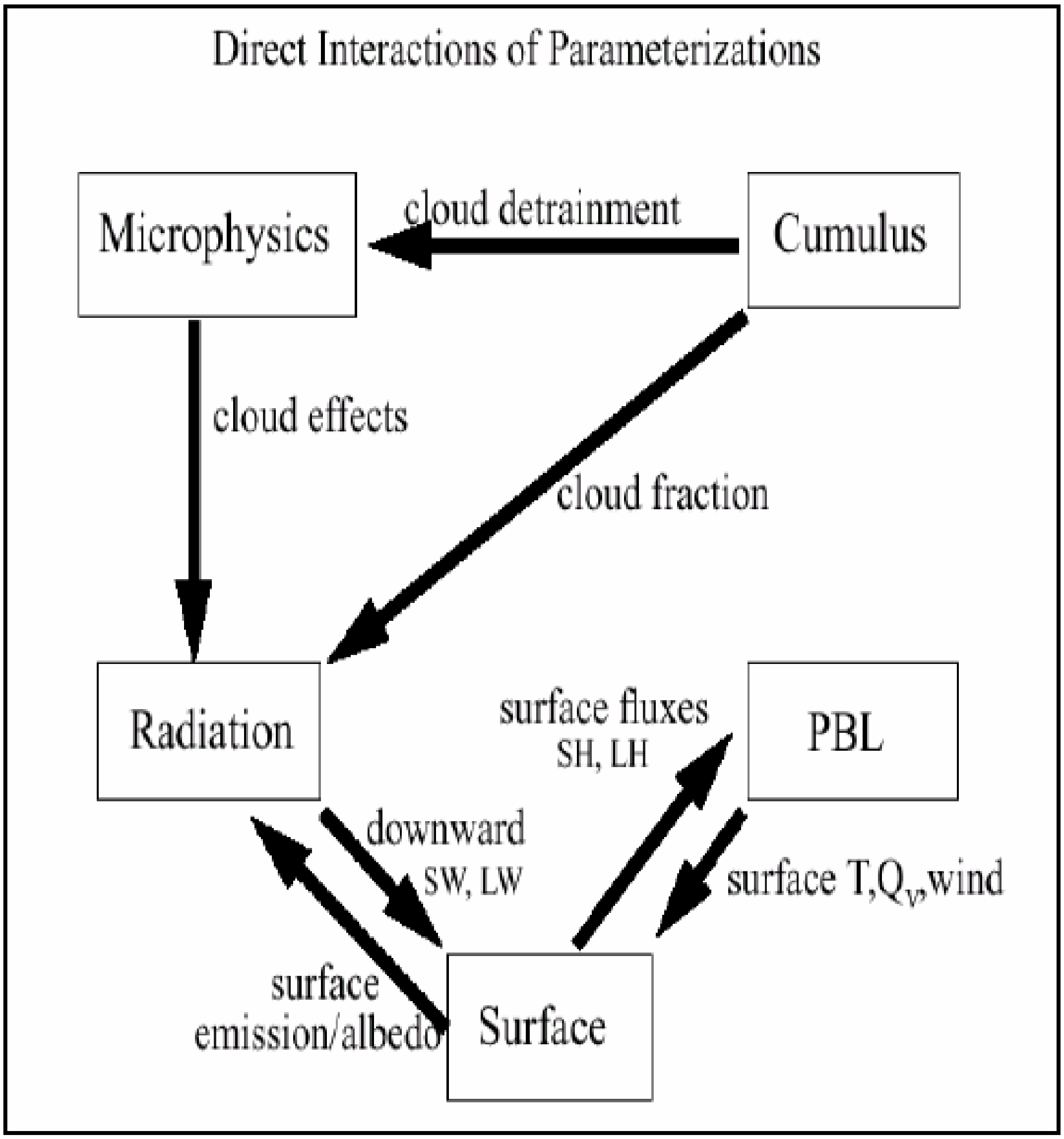


Figure 5.11: Direct interactions of parameters in WRF-NOAH model
Source:http://www.dtcenter.org/events/wrf-nmm_tutorial06_summer/Presentations/NMM_Physics_Dudhia.pdf

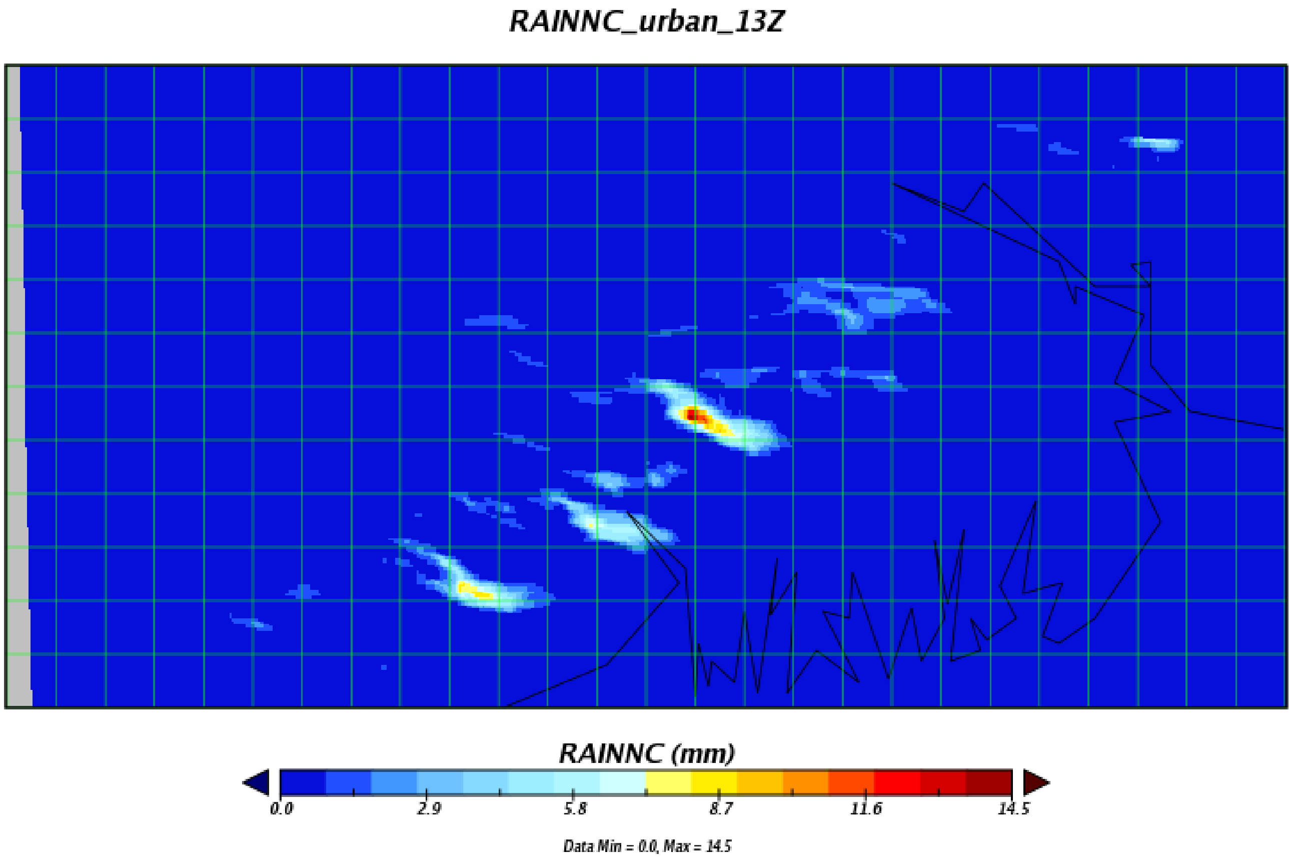


Figure 5.12: Urban Scenario: Total accumulated rainfall (mm) on 16th April 2003 at18.30 LST

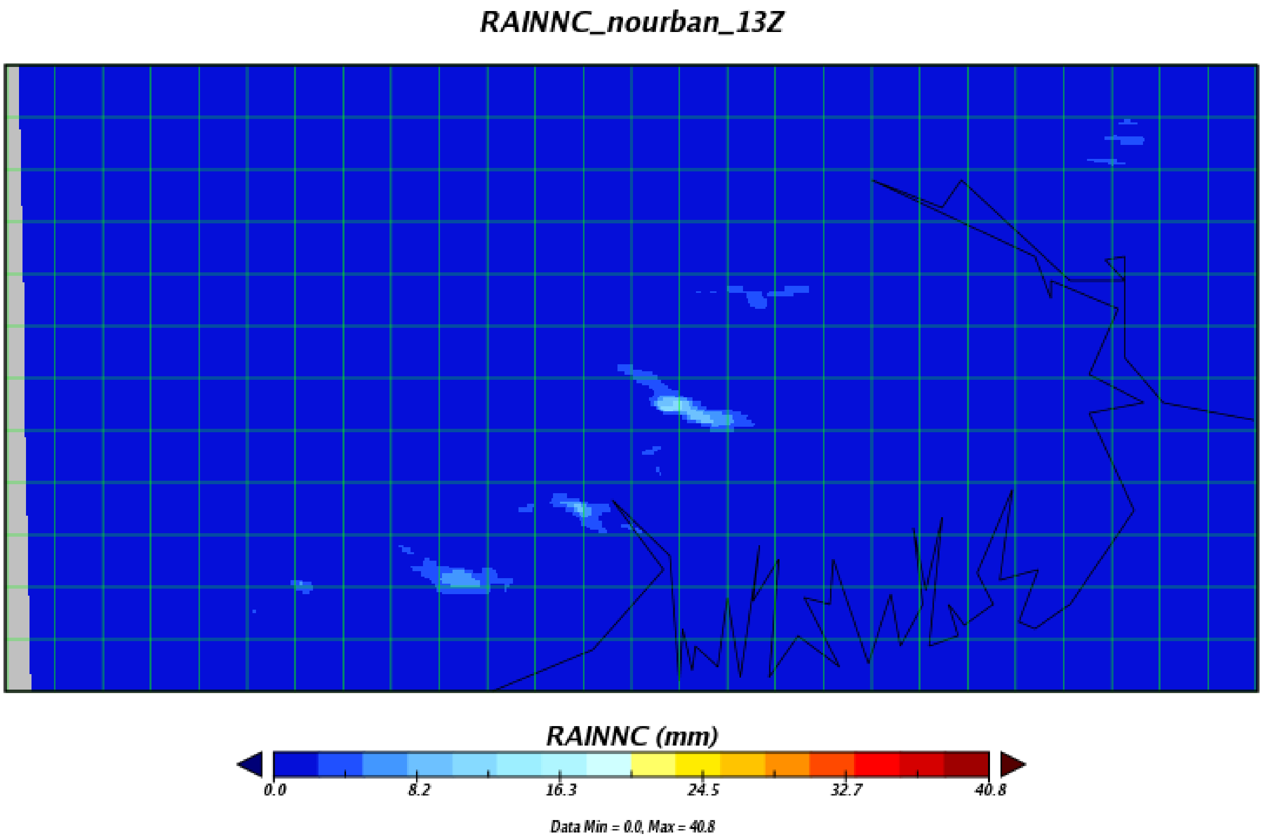


Figure 5.13: No-urban Scenario: Total accumulated rainfall (mm) on 16 April 2003 at18.30 LST

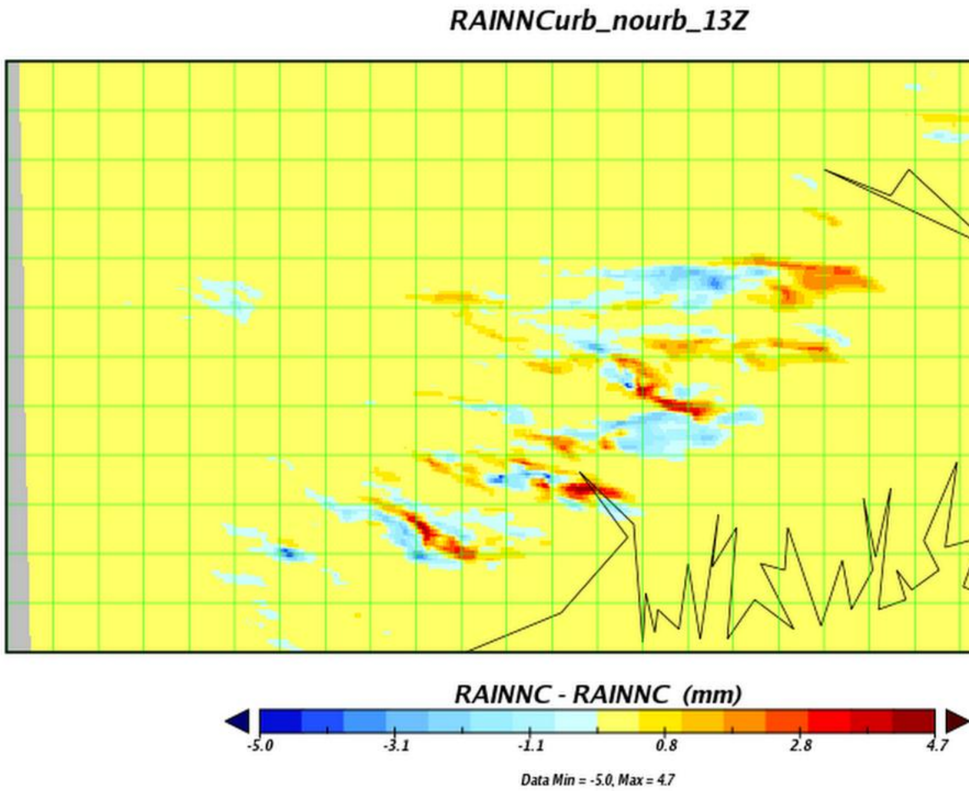


Figure 5.14: Difference plot of urban minus no-urban scenario: Total accumulated rainfall (mm) on 16th April 2003 at18.30 LST (Figure shows orientation of cross section for time series plot)

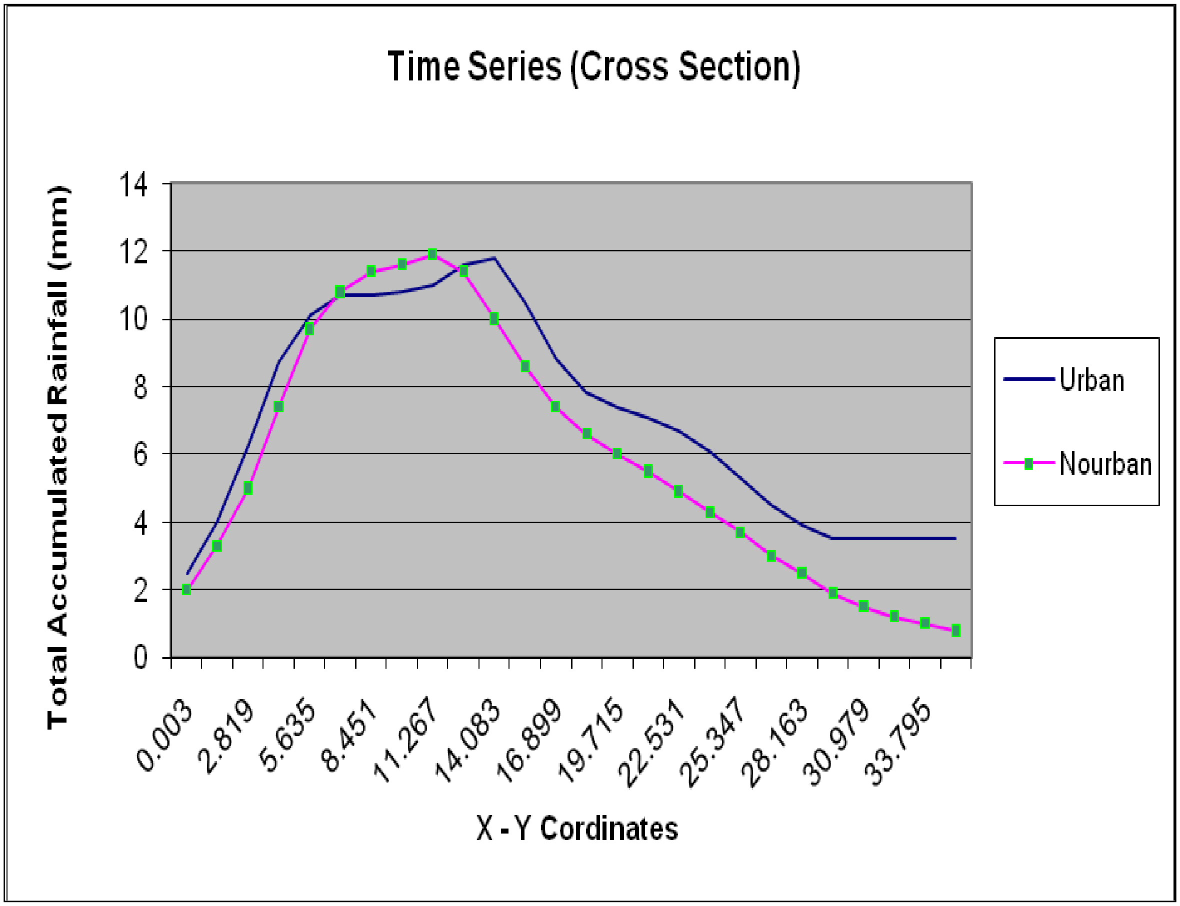


Figure 5.15: Time series showing total accumulated rainfall (mm) of urban and no-urban along the cross section. Time: 13Z or 18.30 LST

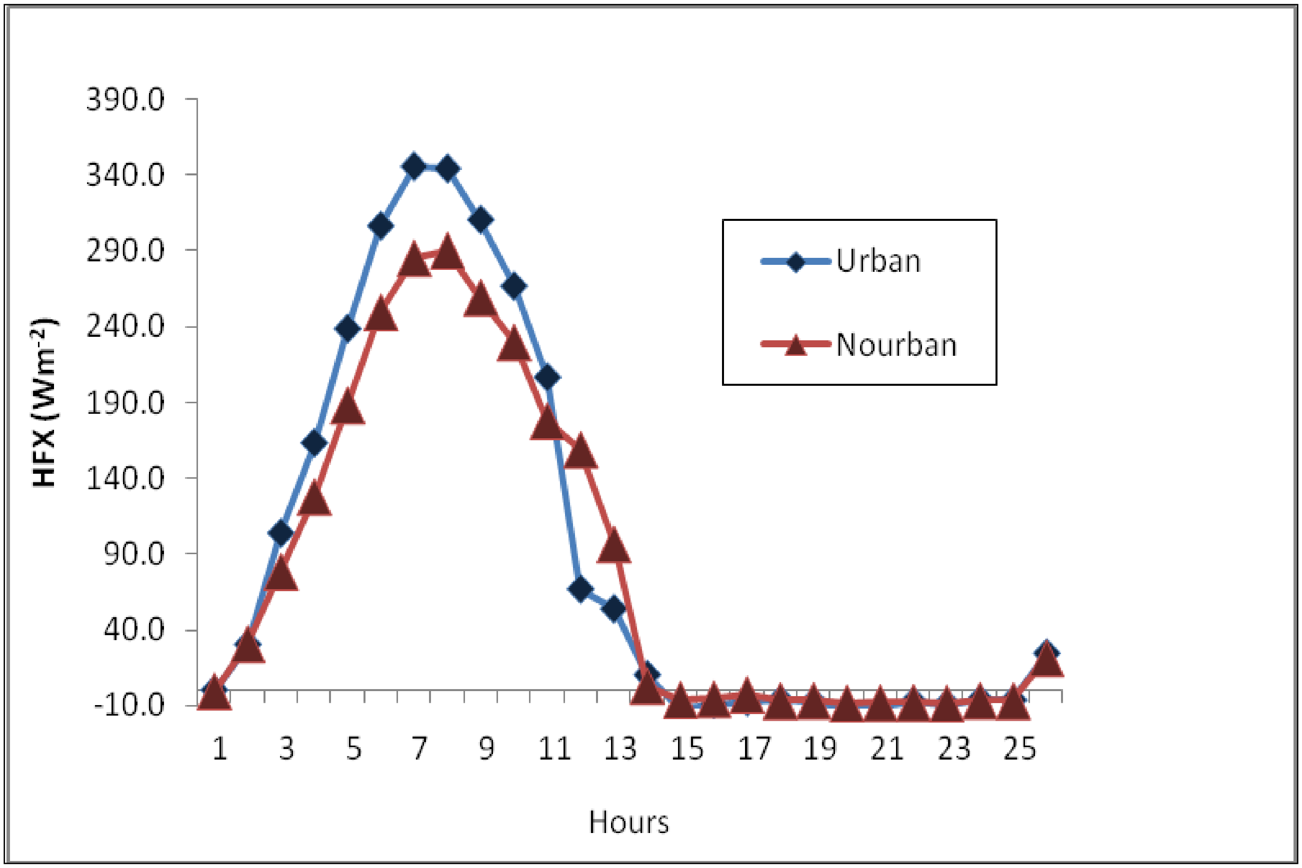


Figure 5.16: Time series showing sensible heat flux (Watts per square meter) for a particular point (X axis – 22.531 and Y axis – 16.903; location: south central part of Kolkata city) in urban and no-urban scenario

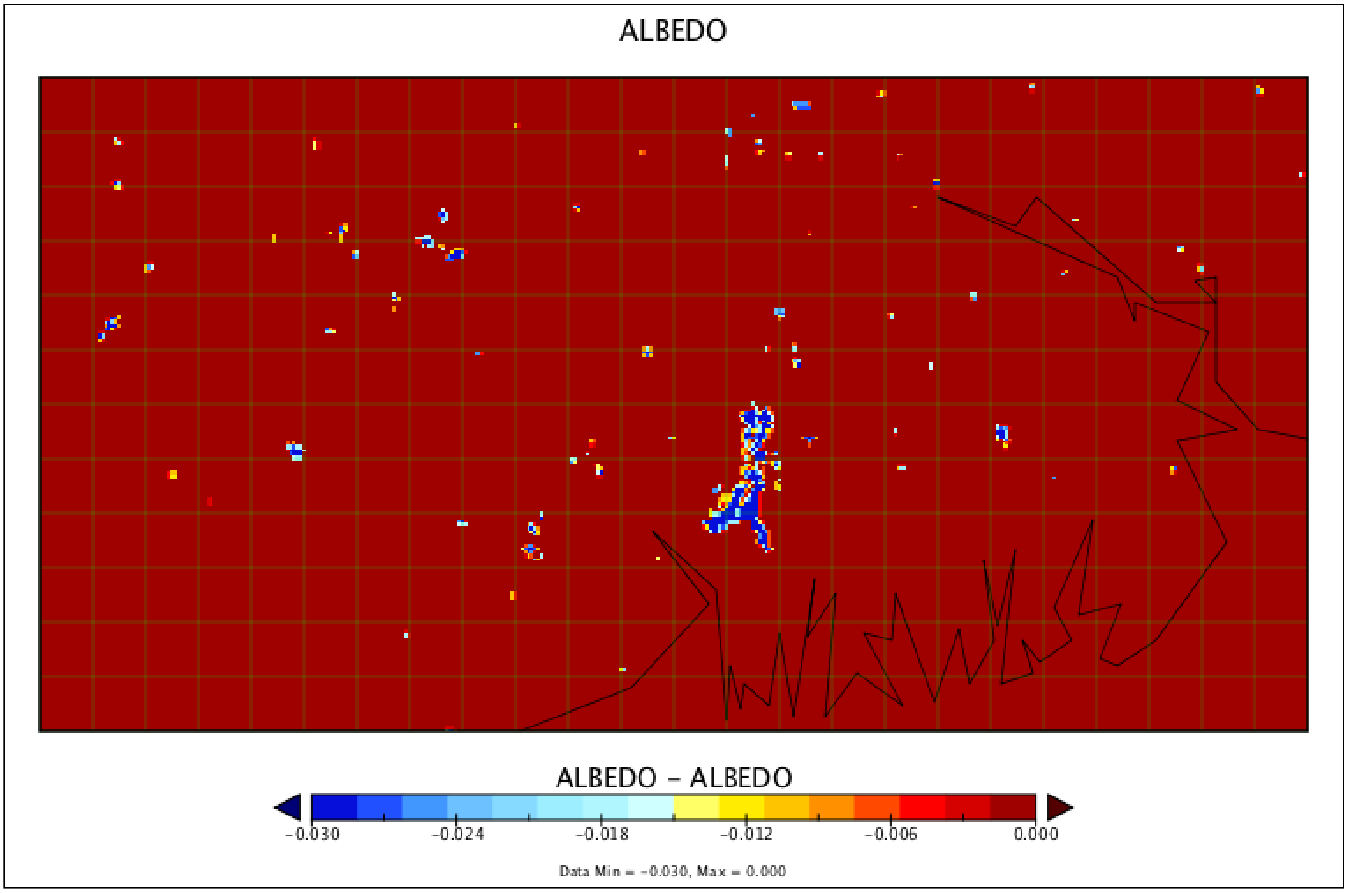


Figure 5.17: Difference plot showing albedo between urban and no-urban scenarios

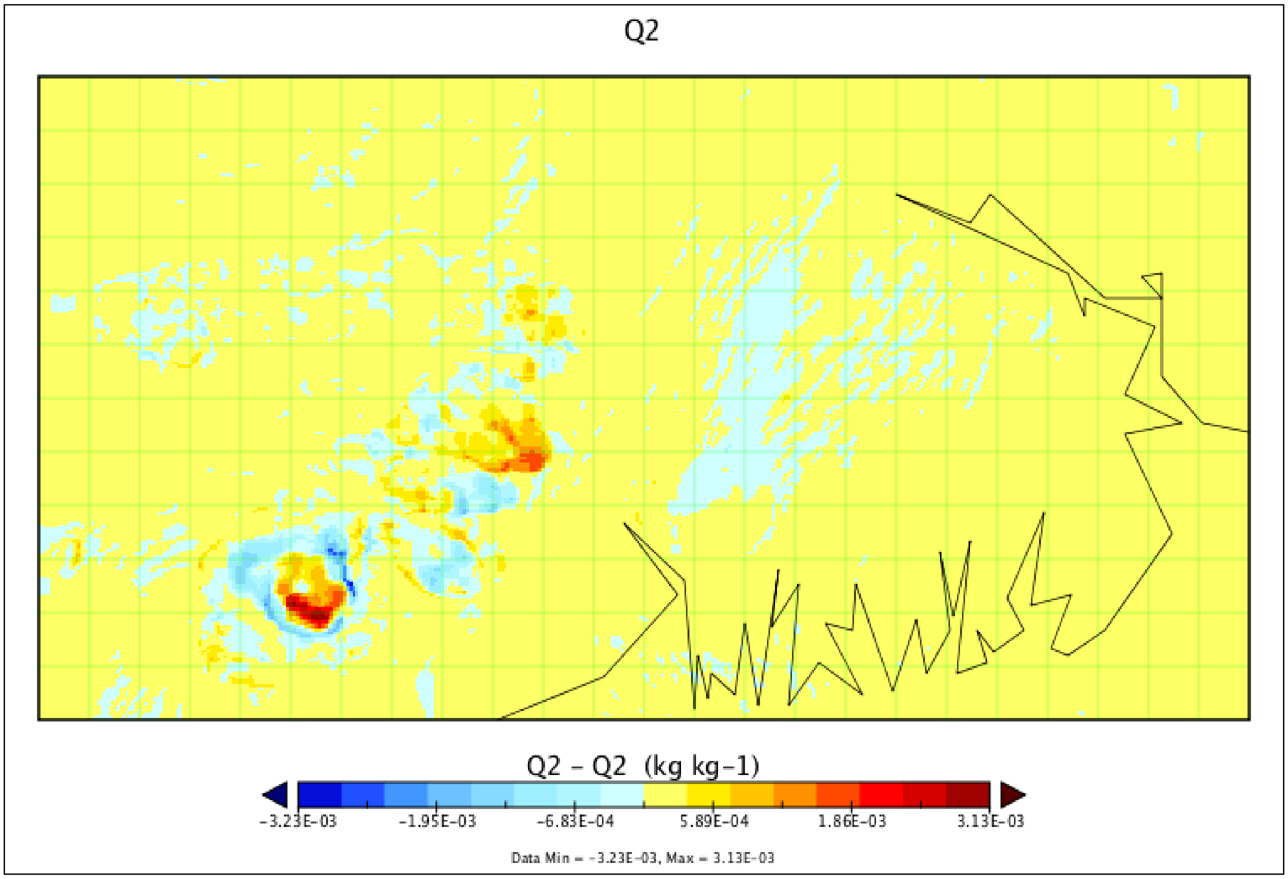


Figure 5.18: Difference plot showin Q2 (water vapor at 2 meters, kg/kg) between urban and no-urban scenarios

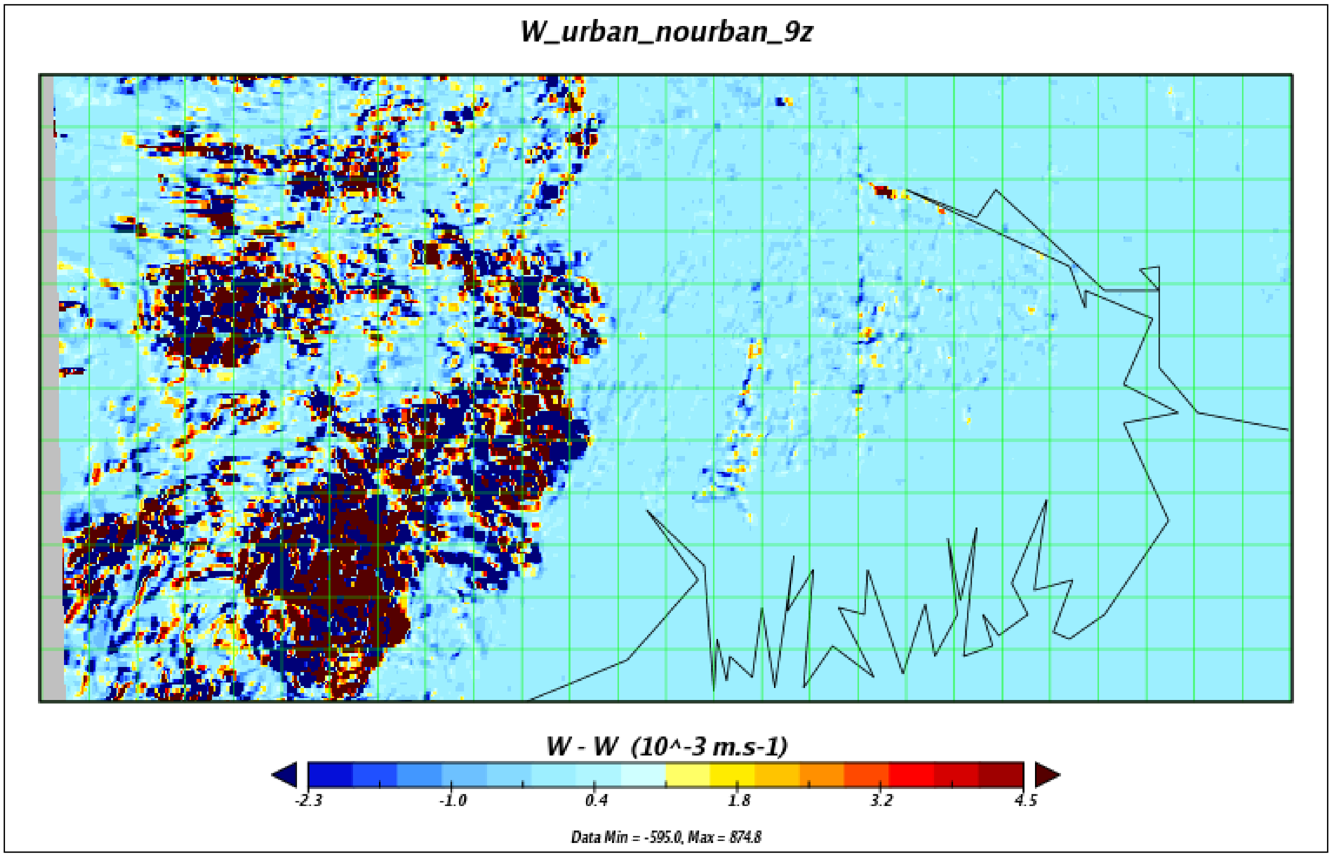


Figure 5.19: Difference plot of vertical velocity (m/s) between urban and no-urban scenario

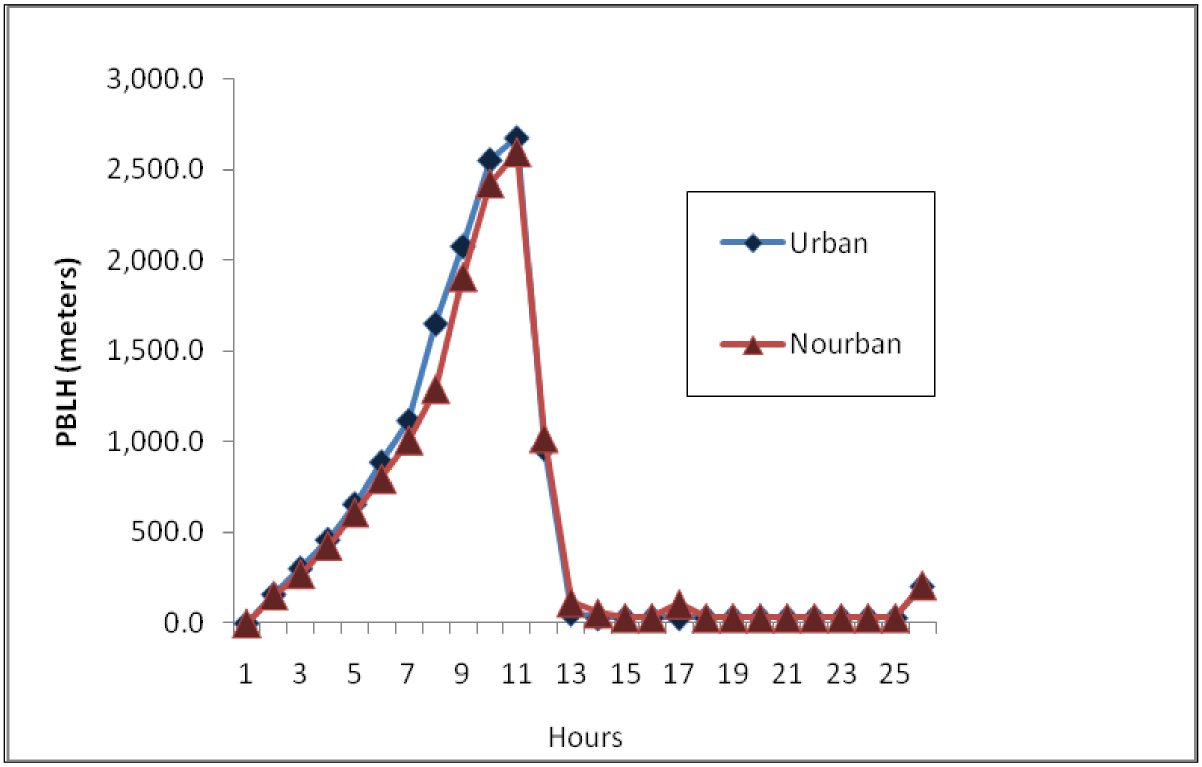


Figure 5.20: Time series showing planetary boundary height (m) for a particular point (X axis – 22.531 and Y axis – 16.903; location: south central part of Kolkata city) in urban and no-urban scenario

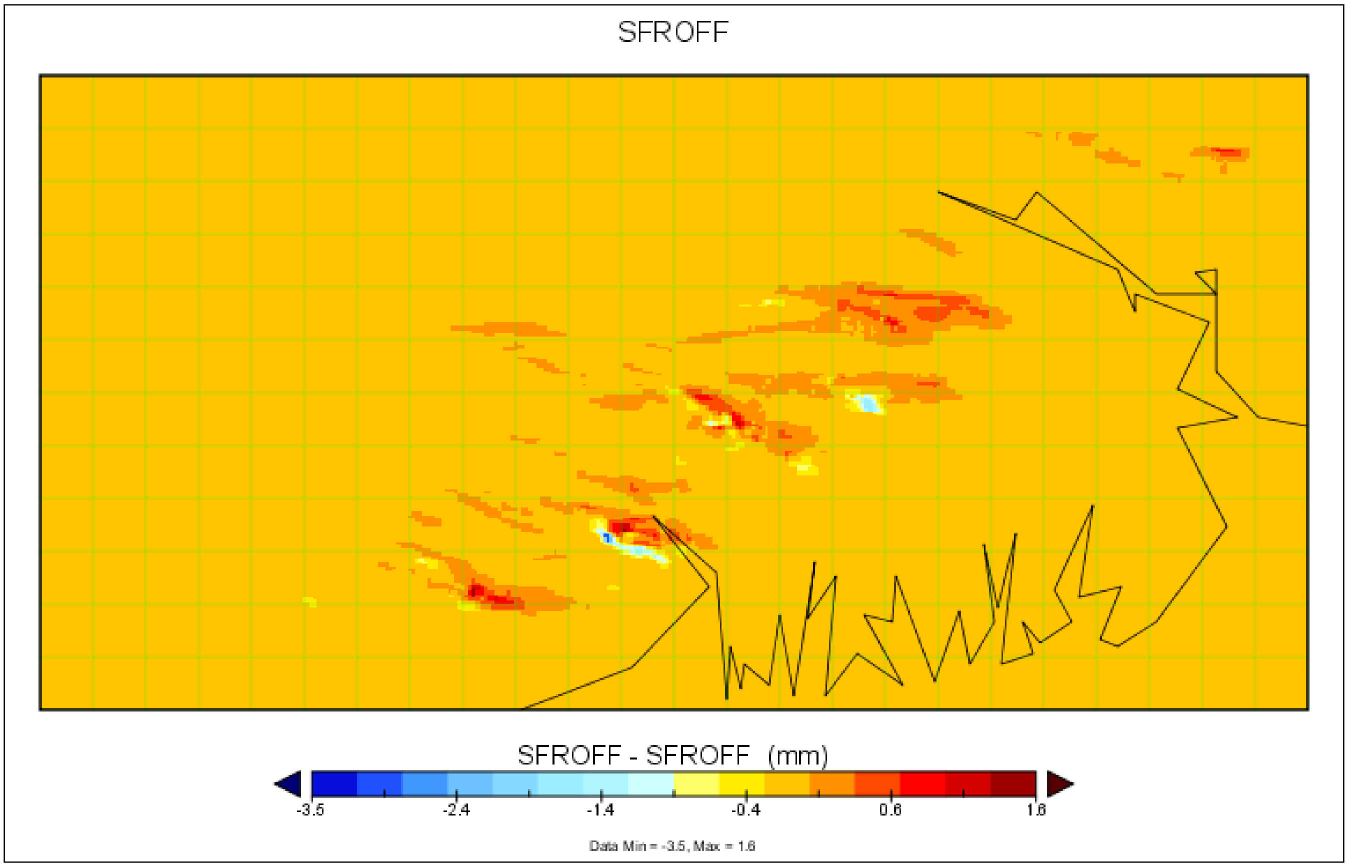


Figure 5.21: Difference plot of surface runoff (mm) for urban and no-urban scenario

Chapter 6

SUMMARY AND CONCLUSION

6.1 Overview:

The urban dynamics of Kolkata city was driven and molded by historical factors like the influx of four million refugees before and after independence in 1947 and its status as the most important city in eastern India (Chatterjee, 1990, Roy, 2003). Kolkata has being aggressively multiplying itself in the last three decades. In 2007 Kolkata had a population of 14.787 million. It has been estimated that Kolkata will have a population of over 20 million by 2025 (UN 2007b).

The example of Kolkata city holds true for most of the cities in the developing part of the world, where the maximum urban growth will take place. From 1750 to 1950, Europe and the New World experienced the most rapid population growth of any region, while the populations of most of Asia and Africa grew very slowly. Since 1950, rapid population growth shifted from Western countries to Africa, the Middle East, and Asia (Cohen 2003). The world population is expected to be on the order of 70 percent urban by 2050 (UN 2007a).

The footprint of a large urban concentration has multiple dimensions. It encompasses not only the area physically occupied by the city, but also the area that contributes resources to the city and the area that is affected by the outflows from the city (e.g., waste, air and water pollution). This extended footprint of affluent, populous cities is typically most associated with environmental influences and feedbacks (Bugliarello 2003).

It is important to investigate linkages between urban growth and environmental factors like temperature and precipitation, which directly can impact humans. Most of the early urban climate related research (Kratzer 1956, Landsberg 1970, Lee 19884, Goldreich 1996) was conducted on air quality, radiation, temperature and wind. To a much lesser extent, studies have examined moisture-related elements including humidity, clouds, precipitation, and hydrometeorological processes. The principal differences are based on the fact that temperature is continuous in both time and space, whereas precipitation is continuous in neither. Lowry maintains that because of these differences, urban climatologists have had much greater success in specifying and explaining urban effects on temperature than on precipitation amount (Lowry 1998). But it is important to understand how urban land cover affects precipitation, a key component of Earth's climate and water cycle system. Numerous investigations on urban effects of precipitation variability have been conducted (Landsberg 1956; Atkinson 1968; Changnon 1968; Landsberg 1970; Huff and Changnon 1972, Dai et al. 1997; Bornstein and Lin 2000; Inoue and Kimura 2004; Shepherd et al. 2002, Hand and Shepherd 2009; Lacke et al. 2009, Shepherd et al. 2007; Shem and Shepherd 2009; Trusilova et al. 2008; Shepherd et al. 2010 and many others).

Kolkata, with its estimated population of 20 million people by 2025 (UN 2007a) and an area of 2653 sq. km (Mitra et al. 2011), will have a significant impact on the physical and environmental condition of the region. Herein, an attempt has been made to quantify the extent of urban growth in the city of Kolkata, over 300 years, project how the city will grow in the next 25 years and investigate, theoretically, how physical processes related to urban and non-urban landscapes might impact the premonsoonal precipitation climatology. Though broadly the Kolkata area falls under the tropical monsoon rainfall regime, in this study the premonsoon rainfall season (March, April and May) was chosen. During the premonsoonal period, the primary source of rainfall for Kolkata is the Nor'westers (Lohar 1996; Sadhukhan et al. 2000a;

Sadhukhan et al. 2000b; Mukhopadhyay et al. 2005), which is well-known, though poorly studied, mesoscale-dryline convective system. Because the premonsoon is generally devoid of large-scale atmospheric forcing, it was ideal setting for studying urban-mesoscale precipitation interactions.

6.2 Summary:

a) On the relationship between the premonsoonal rainfall (PMR) climatology and urban land cover dynamics in Kolkata city, India

The purpose of the first manuscript (Chapter 2) was to understand the relationship between premonsoon rainfall (PMR) and the urban growth of Kolkata city. The study represents a contemporary climatology of a poorly studied regime, premonsoonal precipitation and its related trends in the past 50 to 100 years. The study is a unique blend of traditional in-situ based climatological and statistical analysis coupled with advanced satellite-based precipitation estimation and land cover dynamics analysis.

Kolkata has been growing significantly since its independence. The real population explosion took place between 1940 and 1950 during the Indian independence phase, and is still continuing (Chakraborty, 1990). Under such growth scenarios, it is vital to understand how aspects of the natural system are responding to the urbanization. Herein, we have focused on the precipitation component of the hydroclimate system to frame the study. To quantify the coupled human-natural system interactions of the unprecedented growth of the city, PMR was chosen as a parameter for assessment. Fifty years of rainfall data were analyzed to investigate the associations between land cover change and rainfall variability during a period of time, premonsoon months, when mesoscale and urban forcing are more likely to explain the majority of the variance associated with rainfall. A Mann-Kendall analysis (Mann 1945; Kendall 1955) was performed on mean PMR for (1) the entire country of India, (2) the East Gangetic region, and (3) six stations within the East Gangetic region, including two stations within the city. The analysis does not show any significant trend for the entire country or the east Gangetic region. This suggests that no trends that are observed at local stations are governed by any regional or larger scale trends. The results from the analysis of individual stations are quite intriguing. The Mann-Kendall analysis results show three station time series with statistically-significant trends, two within the city Kolkata and one Midnapore, which is a fairly sizeable city, slightly south-west of the Kolkata Metropolitan region. In all the three cases the p-value is less than 0.05, which establishes that it is significant at the 95% level. The Mann– Kendall analysis appears to support the hypothesis that large urban areas like Kolkata have influenced cumulative rainfall in the premonsoonal season. The non-urban stations did not show any significant increasing trend. We can hypothesize that Midnapore is in a downwind anomaly region of the Kolkata urban area and thus may experience some of the urban enhancement though this is not a conclusive statement and thus, further research is required. Spatial analyses of TRMM, infrared and gauge-derived precipitation data also reveal the enhanced rainfall in the Kolkata region. This finding portends the fact that if Kolkata grew more, its impact on the overall environment would be profound. This motivated to the second part of the research, which deals with the factors governing Kolkata's past, present and future growth.

b) Growth of Kolkata, India– past, present and future

The second manuscript is a synergistic analysis using cartographic, GIS, remote sensing, and cellular automata modeling. These methods are used to conduct a thorough spatio-temporal assessment of urban growth in Kolkata. It provides possibly the longest assessment of Kolkata's land cover growth (~ 300 years) of any study of record. Kolkata has experienced unprecedented growth before and after its independence from the British. The city expanded in all directions to accommodate the approximately four million refugees (Chatterjee, 1990; Roy, 2003). Up to 1947 the rate of urban land cover growth per year was 2.50 sq. km, and it increased to 23.20 sq. km per year by 1990. Between 1990 and 2000, the rate of growth per year was 29.50 sq. km.

To examine, how such land cover growth trends would continue into the future, a series of urban growth projection simulations were conducted using a Cellular Automata (CA)-Markov model. CA Markov model results suggest that the city will expand towards the south, south-east and along the river Ganges by 2025 at a rate of 39.80 sq. km. This expansion will be mainly along lines of communication, primarily the river Ganges and the railway lines. The analysis also revealed that growth rates over the period 2000 to 2025 might exceed the growth rates in the most recent 20 year period.

Contemporary assessment of past, present and future growth of cities in developing countries is critical to future analysis of planning strategies, environmental impacts, and land management amongst others. It is very important to comprehend what the impact of urbanization will be on the overall environment, regionally and globally. Keeping this view, it is necessary to understand the dynamical mechanisms which play and modify the intensity and spatial coverage of a mesoscale convection system when they pass over the urban area. So the third section of this dissertation analysed different parameters and the physical mechanisms that modify a convective system.

c) The Role of Urban-Mesoscale Interactions on Premonsoonal Precipitation in Kolkata, India

The third manuscript investigates how urban land cover physically influences mesocale forced precipitation during the premonsoonal period in Kolkata, India. The coupled WRF NOAH atmosphere–land surface modelwas employed to assess whether premonsoonal precipitation trends in Kolkata can be explained by the presence of urban land cover. The goal is to investigate whether precipitation associated with typical Nor'wester might be influenced under two scenarios a) current urban and b) no urban (pre-Kolkata). A case study for 16 April 2003, a typical PMS "Nor'wester" case day (Mukhopadhyay et al. 2005), is chosen during the premonsoon rainfall regime, which is characterized by weaker large scale forcing.

The results from the urban and no-urban scenario experiments through the WRF-NOAH model showed that up to 4 mm of additional rainfall is produced in some places around Kolkata in the urban experiment as compared to the no urban experiment. To explain the causes behind such a difference in cumulative rainfall, several physical parameters (e.g., sensible heat flux, vertical motion (via low level convergence), moisture, and other thermodynamic variables) were analyzed. Shem and Shepherd (2009) states that the parameters that are uniquely modified by urbanization include land use, surface roughness, green vegetation fraction, albedo, volumetric heat capacity and soil thermal characteristics among others (Shem and Shepherd 2009). The results show that in case of the urban scenario, there are increases in the surface fluxes and the depth of the planetary boundary. The urban case had approximately 60 W/m^2 more sensible heat flux than the no-urban scenario and this likely related to the higher albedo (less reflective) surfaces in the urban experiment. This is expected as the altered urban surfaces can significantly modify the energy balance in and around the cities (Shepherd et al. 2010a). Similarly the planetary boundary was also deeper than the no-urban case.

Our results also indicated that near-surface water vapor was less in an urban environment likely due to a reduction in vegetation and associated evapotranspiration. In this study near-surface vertical velocity was used as a proxy for divergence and convergence. Results showed the presence of pockets of enhanced positive vertical velocity over the city of Kolkata, which could serve as convective trigger or enhancement mechanisms for the propagating Nor'wester.

Thus the combined physical mechanisms in the urban region, namely increased sensible fluxes, and vertical velocity, enhances the lift of warm unstable air required to increase convection enough to produce slightly more rainfall in the Nor'wester system.

6.3 Conclusions:

In conclusion, we would like to highlight the significance of this dissertation and how much it would be a benefit to society and pave way for further research.

Significance of Research

1. The study represents possibly the most thorough spatio-temporal evaluation of Kolkata's urban dynamics, spanning several centuries.
2. This study paves the way for further research in other similar cities, especially the coastal cities, which have similar terrain. The local government can also benefit from this study as policies and decentralization techniques can be molded depending on the study.
3. The study represents one of the first attempts to use the urban growth model, CA Markov model, on any city in India. The use of this model will help others to conduct similar application on cities around the world, which are as flat as Kolkata (<10 meters).
4. The knowledge of the future growth of city will benefit the government, the real estate industry and even the general public immensely as all development decisions can be taken keeping the direction of future growth in mind.
5. This study provides a much-needed assessment of trends in premonsoonal rainfall in the study area, particularly using historical ground data and more recent satellite-datasets.

6. Further, this provides one of first studies investigating effects of Kolkata on premonsoonal rainfall and the well-known Nor'wester.
7. It is likely the first modeling study to focus on Kolkata precipitation-urban interactions.
8. The results also have implications for future societal issues related to flooding, reservoir construction to store water for agricultural use, rainwater harvesting in the city, and future urban planning strategies. Transportation lines, business centers and an overall developmental plan can be framed based on the results of the study.

The need to study the extent to which cities, in future will influence the ecosystem and environment is very important. The overall interest in cities lies in the fact that they modify weather and climate, and global-scale forcings are superimposed on the effects of the built environment through local transfers of heat and moisture. Conversely, the impacts of cities on weather and climate may extend to regional scales too (Shepherd et al 2010). It is important to gauge how cities produce their own microclimate yet link with regional and global climates radiation processes and greenhouse gas emissions (Roth 2007). This research gains its importance as it takes a step forward in trying to understand the background of urban growth, its impact on local weather conditions and see how much the change in the natural system will influence regional weather conditions over the urban areas now and in the future.

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