CHAPTER - III

Climatic Conditions of megacities and Brief Description of Numerical Models Used for the Study
3.1 Geographical Description of Mega City – Delhi

Delhi is the semi-arid region geographically located between 76° 50´ and 77° 23´ E and 28° 12´ and 28° 53´ N at 216m above MSL. The map of Delhi mega city is shown in Fig 3.1. According to the census of 2011, 16.7 million inhabitants are living in the city. As the city is the capital of India, it has become the center for commerce, industries and education. The main sources of pollutants are vehicular traffic; coal based thermal power plants and industries. Delhi has three thermal power stations namely Badarpur, Indraprastha and Rajghat, which contribute nearly 13% of the air pollutants in Delhi.

3.1.1 Climatic Conditions of Delhi

Delhi features an atypical version of the humid subtropical climate. Summers are long and extremely hot, from early April to mid-October, with the monsoon season in between. Early March sees a reversal in the direction of wind, from the north-western direction, to the south-western. The months of March to May see time of hot climate. Monsoon arrives at the end of June, along with increase in humidity. The brief, mild winter starts in late November and peaks in January and is notorious for its heavy fog.
Extreme temperatures are observed from -0.6°C to 46.7 °C. The annual mean temperature is 25°C monthly mean temperatures range from 13°C to 32 °C. The highest temperature recorded
in July was 45 degrees Celsius almost a century ago, in 1931. The average annual rainfall is approximately 714 mm, most of which is during the monsoons in July and August. The average date of the advent of monsoon winds in Delhi is in the last week of June.

3.2 Geographical Description of Mega City - Kolkata

Kolkata is centered on latitude 22°34.1 North and longitude 88°24.1 east. It is about 30 kms from the Bay of Bengal and the river tides at Kolkata range over 4m as shown in Fig 3.2. Its population is about 15 million making it India's third largest metropolitan and world's 8th largest agglomeration. It is therefore very crucial to measure the ambient concentration of VOCs in Kolkata and get an idea about their impact on such a large susceptible population.

3.2.1 Climatic Conditions of Kolkata

Kolkata has a Tropical wet-and-dry climate. The annual mean temperature is 26.8°C monthly mean temperatures range from 19°C to 30°C. Summers are hot and humid with temperatures in the low 30's and during dry spells the maximum temperatures often exceed 40°C during May and June. Winter tends to last for only about two and a
half months, with seasonal lows dipping to 12°C – 14°C between December and January. The highest recorded temperature is 43.9°C and the lowest is -1°C. Often during early summer, dusty
squalls followed by spells of thunderstorm and heavy rains lash the city, bringing relief from the humid heat. These thunders are convective in nature and are locally known as Kal baisakhi, Nor'westers.

Rains brought by the Bay of Bengal branch of South-West monsoon lash the city between June and September and supplies the city with most of its annual rainfall of 1,582 mm. The highest rainfall occurs during the monsoon in August, 306 mm. Pollution is a major concern in Kolkata, and the Suspended Particulate Matter (SPM) level is high when compared to other major cities of India, leading to regular smog and haze. Severe air pollution in the city has caused rise in pollution-related respiratory ailments such as lung cancer, asthma and so on.

3.3 Geographical Description of Mega City - Mumbai

Mumbai, previously known as Bombay, is the capital of the Indian state of Maharashtra. It is the most populous city in India, and the fourth most populous city in the world, with a total metropolitan area population of approximately 20.5 million according to the census 2011. The map of Mumbai is shown in Fig 3.3. Along with the neighboring urban areas, including the cities of Navi Mumbai and Thane, it is one of the most populous urban regions in the world. Mumbai lies on the west coast of India and has
a deep natural harbor. In 2009, Mumbai was named an Alpha world city. Mumbai is also the richest city in India, and has the highest GDP of any city in South, West or Central Asia.
3.3.1 Climatic Conditions of Mumbai

Mumbai has a tropical climate, specifically a tropical wet and dry climate under the Köppen climate classification, with seven months of dryness and peak of rains in July. The cooler season from December to February is followed by the summer season from March to June. The period from June to about the end of September constitutes the south-west monsoon season, and October and November form the post-monsoon season.

Between June and September, the south west monsoon rains lash the city. Pre-monsoon showers are received in May. Occasionally, north-east monsoon showers occur in October and November. The average annual temperature is 27.2 °C, and the average annual precipitation is 2,167 mm. In the Island City, the average maximum temperature is 31.2 °C, while the average minimum temperature is 23.7 °C. In the suburbs, the daily mean maximum temperature range from 29.1 °C to 33.3 °C, while the daily mean minimum temperature ranges from 16.3 °C to 26.2 °C.

3.4 Geographical Description of Mega City - Chennai

Chennai is the capital city of the Indian state of Tamil Nadu. Located on the Coromandel Coast off the Bay of Bengal, it is a major commercial, cultural, and educational centre in South
India, while the port of Chennai is the second largest port in India. The outline map of Chennai is shown in Fig 3.4.

As of the 2011 census, the city had 4.68 million residents making it the sixth most populous city in India; the urban agglomeration, which comprises the city and its suburbs, was home to approximately 8.9 million, making it the fourth most populous metropolitan area in the country.

Although the area has been part of successive South Indian kingdoms through centuries, the recorded history of the city began in the colonial times, specifically with the arrival of British East India Company and the establishment in 1644 of Fort St George, an English settlement. The British defended several attacks from the French colonial forces, and from the kingdom of Mysore, on Chennai’s way to become a major naval port and presidency city by late eighteenth century. Following the independence of India, Chennai became the capital of Tamil Nadu and a hotbed of regional politics that tended to bank on Dravidian identity of the populace. Chennai had become a bustling metropolis with beautiful classical and colonial European styled buildings, lining the city’s thoroughfares.
3.4.1 Climatic Conditions of Chennai

Fig 3.4 Map of Chennai Mega City
Chennai has a tropical climate, specifically a tropical wet and dry climate. The city lies on the thermal equator and is also on the coast, which prevents extreme variation in seasonal temperature. The weather is hot and humid for most of the year. The hottest part of the year is late May to early June, known locally as Agni Nakshatram ("fire star") or as Kathiri Veyvil, with maximum temperatures around 35–40 °C. The coolest part of the year is January, with minimum temperatures around 15–22 °C. The lowest temperature recorded is 13.8 °C and the highest recorded temperature is 45°C. The average annual rainfall is about 140 cm. The city gets most of its seasonal rainfall from the north–east monsoon winds, from mid–October to mid–December. Cyclones in the Bay of Bengal sometimes hit the city. The highest annual rainfall recorded is 257 cm in 2005. Prevailing winds in Chennai are usually southwesterly between April and October and northeasterly during the rest of the year.

3.5. Brief Description of Numerical Models used for the Study

The following two numerical models are used for the study.

- Advanced Regional Prediction System (ARPS)
- Weather Research Forecast (WRF)

3.5.1 Advanced Regional Prediction System

Advanced Regional Prediction System (ARPS) is a storm and mesoscale model developed by (Xue et., al. 1995, 2000, 2001 and 2003) Center for Analysis and Prediction of
Storms (CAPS), Oklahoma University. ARPS model is a non-hydrostatic, compressible atmospheric prediction mesoscale model in a terrain following coordinate with equal spacing in x and y directions and grid stretching in the vertical and is used for scales ranging from a few meters to hundreds of kilometers. The model can be run in 1D, 2D and 3D modes. ARPS solves prognostic equations for $u$, $v$, $w$ the $x$, $y$, and $z$ components of velocity, the perturbation potential temperature $\theta'$, and perturbation pressure $P'$, sub-grid scale turbulent kinetic energy and the six categories of water variables such as water vapor, cloud water, rain water, cloud ice, snow and hail. The governing equations for fluid motion in a fully 3-D curvilinear system can be found in the literature (e.g., Thompson et al., 1985). Sharm an et al. (1988) and Shyy and Vu (1991) discuss the choice of velocity vectors (covariant, contra variant and Cartesian velocity, etc.) that allow a conservative formulation of the momentum equations.

The model can be initialized using horizontally homogeneous single sounding data or three-dimensional horizontally inhomogeneous data. Different options for initializing base state fields such as external sounding, isentropic atmosphere, isothermal atmosphere, constant static stability atmosphere etc can be used. Many options for including terrain characteristics, vertical grid stretching, Coriolis Effect, boundary condition, turbulent mixing, cloud microphysics, surface physics, atmospheric radiation with detailed physics are included. The model also contains two-layer soil model with surface energy budget equations. The current features and capabilities of the ARPS model is shown in Fig 3.5.

3.5.1.1 Subgrid Scale Turbulence Closure
Turbulence parameterization, the closure linking the resolved scales and the unresolved subgrid-scale (SGS), is critical to the successful simulation of many flows. This section discusses three available options in ARPS for parameterizing the subgrid scale turbulence - the Smagorinsky, 1.5 order turbulent kinetic energy (TKE) and Germano dynamic subgrid-scale (SGS) closure schemes.

The Smagorinsky scheme is a special case of the TKE equation. The Germano dynamic SGS closure converts previously prescribed SGS model coefficients to self-determined parameters that vary with time and space.

### 3.5.1.2 PBL Depth Calculation

The planetary boundary layer (PBL) processes and the dispersion of atmospheric pollutants are limited by the PBL depth. Therefore, the prediction of the PBL depth is of great practical concern. In addition, the development of certain convective systems (e.g., dry line-forced thunderstorms) is sensitive to the PBL depth.
3.5 Current Features and Capabilities of ARPS

ARPS predicts the time evolution of PBL depth in response to the surface heat fluxes. ARPS will make use of the computed PBL depth to model certain physical processes in future versions of ARPS.

3.5.1.3 Grid Structure and Boundary Conditions

In a regional atmospheric model, only the lower boundary is physical. The boundaries at the top and sides are usually artificial. ARPS permits the user to choose different types of boundary conditions for the lateral, top and bottom boundaries. Five types of lateral boundary conditions are available in ARPS: rigid wall, periodic, zero normal gradient, wave-radiating open boundary, and externally specified boundary conditions. All five options can be specified independently for each lateral boundary. Three types of boundary conditions are available at the top and bottom boundaries rigid top lid (impermeable ground), periodic, and zero-normal gradient. Wave reflection from the rigid top boundary can be suppressed by use of a Rayleigh damping layer near the top boundary. To implement the boundary conditions, extra grid points are defined
outside the physical boundary of the model domain. These extra points are often referred to as the “fake” points or zones.

3.5.2 Weather Research and Forecast (WRF) Model

The Advanced Research WRF (ARW) modeling system has been in development for the past few years. The current release is Version 2. The ARW is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting a subset of the overall WRF code (Version 2) that includes:

- WRF Software Framework (WSF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nest.
- The WRF Preprocessing System (WPS)
- WRF Variational Data Assimilation (WRF-Var) system which currently supports 3DVAR capability
- Numerous physics packages contributed by WRF partners and the research community and several graphics programs and conversion programs for other graphics tools

3.5.2.1 Features of WRF Model

The key features of the WRF model include:
• Fully compressible non hydrostatic equations with hydrostatic option
• Regional and global applications
• Complete coriolis and curvature terms
• Two-way nesting with multiple nests and nest levels
• One-way nesting
• Moving nests
• Mass-based terrain-following coordinate
• Vertical grid-spacing can vary with height
• Map-scale factors for conformal projections:
  • polar stereographic (conformal)
  • Lambert-conformal
  • Mercator (conformal)
• Latitude and longitude, which can be rotated
• Arakawa C-grid staggering
• Runge-Kutta 2nd and 3rd order time integration options
• Scalar-conserving flux form for prognostic variables
• 2nd to 6th order advection options (horizontal and vertical)
• Monotonic transport and positive-definite advection option for moisture, scalar tracer, and TKE
• Time-split small step for acoustic and gravity-wave modes:
  • small step horizontally explicit, vertically implicit
  • divergence damping option and vertical time off-centering
• external-mode filtering option
• Upper boundary absorption and Rayleigh damping
• Lateral boundary conditions
• idealized cases: periodic, symmetric, and open radiative
• real cases: specified with relaxation zone
• Full physics options for land-surface, planetary boundary layer, atmospheric and surface radiation, microphysics and cumulus convection
• Grid analysis nudging using separate upper-air and surface data, and observation nudging
• Spectral nudging
• Digital filter initialization
• Adaptive time stepping
• Gravity wave drag
• A number of idealized examples

3.5.2.2 The WRF Modeling System Program Components

The flow chart of the WRF Modeling System Version 2 is shown in the Fig 3.6. As per the diagram, the WRF Modeling System consists of these major programs:

• The WRF Preprocessing System (WPS)
• WRF-Var
• ARW solver
a. WPS

This program is used primarily for real-data simulations. Its functions include 1) defining simulation domains; 2) interpolating terrestrial data (such as terrain, landuse, and soil types) to the simulation domain; and 3) degribbing and interpolating meteorological data from another model to this simulation domain. Its main features include:

- GRIB 1/2 meteorological data from various centers around the world
- Map projections for
  1) polar stereographic, 2) Lambert-Conformal, 3) Mercator, and 4) latitude-longitude
- Nesting and User-interfaces to input other static data as well as met data
b. **WRF-Var**

This program is optional, but can be used to ingest observations into the interpolated analysis created by WPS. It can also be used to update the WRF model's initial conditions when the WRF model is run in cycling mode.

c. **ARW Solver**
This is the key component of the modeling system, which is composed of several initialization programs for idealized and real-data simulations, and the numerical integration program. It also includes a program to do one-way nesting. Fig 3.7 describes the flow chart of WRF modeling system

### 3.5.2.3 WRF Initialization

The WRF model has two large classes of simulations that it is able to generate: those with an *ideal* initialization and those utilizing *real* data. The ideal versus real cases are divided as follows:

**Ideal cases**

3d
- em_b_wave - barclinic wave
- em_quarter_ss - super cell

2d
- em_grav2d_x
- em_hill2d_x
- em_squall2d_x
- em_squall2d_y

**Real data cases**
- em_real
The WRF model itself is not altered by choosing one initialization over another, but the WRF pre-processors are specifically built based upon a user's selection.