CHAPTER - IV

Numerical Study of Atmospheric Dispersion over Coastal and Non Coastal Mega cities – Model Validation using observed data
4.1 Introduction

About half of the world's population now lives in urban areas because of the opportunity for a better quality of life. Many of these urban areas are expanding rapidly, leading to the growth of megacities, which are defined as metropolitan areas with populations exceeding 10 million inhabitants. In the present chapter, two megacities—one is coastal megacity i.e., Kalpakkan area which is 80 km from south of Chennai and a non-coastal area i.e., Delhi mega city—are taken to understand the behavior of meteorological parameters which are responsible for atmospheric dispersion. For understanding coastal atmospheric dispersion studies, a non-hydrostatic mesoscale model i.e., Advanced Regional Prediction System (ARPS) is used, and for understanding the urban heat island characteristics for a non-coastal mega city i.e., Delhi, an Advanced Research Weather Research Forecast (ARW) model is used. Validation of the above model is described in this chapter.

4.2 Atmospheric Dispersion over Kalpakkam during south west and north east monsoon seasons

Meteorological parameters and turbulent fluxes near coastal areas have much influence on the atmospheric boundary layer due to their significant spatial and temporal changes. Understanding the coastal atmosphere is useful for various applications of the boundary layer process such as daily weather forecasts, pollution trapping, aviation, shipping, thunderstorm and hurricane activities, land and sea breezes, Thermal Internal Boundary Layer (TIBL) structure etc.

On the application side, most of their experimental sites were complex coastal cities; hence these studies were on the analysis of the effect of the local topography and urban terrain on the sea breeze. Borne et al. (1998a, 1998b) analysed the sea breeze observations along the western coast of Sweden and evolved a method to find sea breeze days from routine surface and upper air measurements. Further, small-scale sea breeze circulations were often noticed ahead of the main, regional sea breeze circulation. Similar circulations have been reported at Kalpakkam, the site under present study, by analysing instantaneous echoes of mini sodar (Thara et al, 2002). Effect of the upper air geostrophic flow on the characteristics of the sea breeze was studied using a numerical model by Arritt (1993).

Most of the sea breeze studies are pertaining to the mid-latitude environment where the temperature contrast between the land and sea surfaces during summer is quite significant ($\geq 10^0$ C) but the absolute values of them are lesser than their respective values at a tropical environment such as Indian coast. Here, the SST varies from $25^0$C to
28°C annually over Bay of Bengal and the daily maximum LST reaches as great as 42°C near the eastern coast. Consequently, the sea breeze circulation develops in an ambience of a very warm and relatively turbulent atmospheric boundary layer environment, the later reaching a mixing layer height of 2.5 to 4.0 km. A few studies have been made in India to understand the mechanisms of the sea breeze based on surface synoptic weather stations data (Y.E.A Raj and Nageshwari P., 2000, Krishnamoorthy et. al. 1992, Winston Jeeva Prakash et. al. 1992, among others). Very limited modelling studies have been made in India (R.Venkatesan, 1994, Bhat et. al. 2000, Satyanarayana et. al. 2000) to understand the characteristics of the coastal atmospheric boundary layer. The present study analyses the observed characteristics over an eastern coastal site of India using a mesoscale model ARPS.

### 4.2.1 Objective

Kalpakkam site on the eastern coast of Indian Peninsula (Fig 4.1) experiences frequent sea breeze events almost 80% days of the year. The sea breeze events can be grouped in to two classes occurring under two different climatic conditions namely, during the summer South West monsoon season and during the winter North East monsoon season. The conditions of synoptic profiles of wind and temperature for a typical day in each of these seasons are shown in Fig 4.2. The data is taken from RS/RW observations from a national weather station located at Chennai coastal city, at 60km north of Kalpakkam. Winds are strong and westerly during SW monsoon times. Despite strong offshore synoptic winds, intense heating of the surface often initiates a sea breeze
convective circulation for duration of about 6 to 8 hours. In contrast, the weak alongshore or onshore synoptic winds during winter season, overshadows the sea breeze circulation although its presence is sometimes felt later in the form of early morning land breezes.

The present study focuses on the properties of the sea breeze and the internal boundary layer structure during these two different seasons. An advanced numerical model ARPS is chosen to simulate these properties. A set of observations made over a coastal site Kalpakkam using tether balloons and tower based flux and profile measurements are used to compare the simulations. From this study,

- Characteristics of sea breeze like onset, duration and strength,
- Changes in coastal surface layer parameters and
- Developments of IBL under the two different contrasting seasons and during these two seasons are examined.
Fig. 4.1 A sketch (not to scale) showing the field site and Kalpakkam. The study area is shown as a box on the eastern coast of India.
Fig 4.2 Radiosonde and Rawinsonde observations of wind speed, wind direction and potential temperature for a) Case I (south west) and b) Case II (north east)
4.2.2 Outline of the coastal site modeled and meteorological data set used for comparison.

A plain rural land with a fairly linear coastline is chosen for the model study. The site Kalpakkam is located at 80°10'E and 12°35'N and elevated to about 2m MSL. A sketch of the area is shown in Fig 4.1. The site has sparsely vegetated areas. A series of field measurements, (CABLE – 2001, Sivaramakrishnan and Venkatesan 2002 Report) were conducted during a few days in summer south-west and winter north-east monsoons at an inland site, 5.5 km away from the coast. The experimental facilities include meteorological tower, sonic anemometer, tethered balloon and radiation sensors. Synoptic data was taken during the experimental period from a national weather station at Chennai coastal city, 60km north of Kalpakkam.

4.2.3 Initialization

ARPS was run for two cases i.e. case I (south west monsoon) and case II (north east monsoon). Since the nature of the coastline is approximately linear, the model was run in its 2D form. The lower levels were initialized using field experiment data collected from kytoon and meteorological tower. The number of grid points or nodes in x and z directions are 100 and 20 respectively and spacing between the grid (dx) is given as 2000m. Horizontally 100km from the coast is initialized as land and 100km after the
coastline as sea. The horizontal and vertical grid positions of $x$ and $z$ co-ordinates used in the model are given below:

Horizontal grids: $X(0) = 0$

$$X(I) = [X(I-1) + 2] \text{ km}$$

$$I = 1 \ldots \text{LAND (100km)} \quad I = 51 \ldots \text{SEA (100km)} \quad I = 100$$

Vertical Grids:

<table>
<thead>
<tr>
<th>Grid No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z (m)$</td>
<td>2</td>
<td>10</td>
<td>18</td>
<td>26</td>
<td>34</td>
<td>42</td>
<td>50</td>
<td>60</td>
<td>75</td>
<td>100</td>
<td>170</td>
<td>345</td>
<td>650</td>
<td>1000</td>
<td>2000</td>
<td>3000</td>
<td>4000</td>
</tr>
</tbody>
</table>

In an earlier parametric study, the two layer soil-vegetation model (Noilhan and Planton; 1989) which is incorporated in ARPS was tested for Kalpakkam soil conditions (Jamima et al., 2001). Site specific soil properties obtained from experiments and fine tuned using the parametric study have been used for the current study. Various options chosen in the ARPS model for the present study are shown in Table 4.1 grids:
<table>
<thead>
<tr>
<th>Options</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialization</td>
<td>External sounding</td>
</tr>
<tr>
<td>Model run</td>
<td>2D x-z plane</td>
</tr>
<tr>
<td>Vertical grid stretching</td>
<td>Hyperbolic tangent function</td>
</tr>
<tr>
<td>Buoyancy terms</td>
<td>Second order</td>
</tr>
<tr>
<td>Momentum and Scalar</td>
<td>Fourth order</td>
</tr>
<tr>
<td>Advection</td>
<td></td>
</tr>
<tr>
<td>Computational mixing</td>
<td>Second order</td>
</tr>
<tr>
<td>Divergence damping</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Rayleigh damping</td>
<td>Yes</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>Radiation</td>
</tr>
<tr>
<td>west &amp; east</td>
<td>Periodic</td>
</tr>
<tr>
<td>north &amp; south</td>
<td>Rigid</td>
</tr>
<tr>
<td>top &amp; bottom</td>
<td></td>
</tr>
<tr>
<td>Coriolis force</td>
<td>Yes</td>
</tr>
<tr>
<td>Turbulence</td>
<td>1.5 TKE mixing (Sun and Chang 1986)</td>
</tr>
<tr>
<td>Micro physics</td>
<td>Kessler warm rain with Kain &amp; Fritsch convective</td>
</tr>
<tr>
<td></td>
<td>cumulus parameterization</td>
</tr>
<tr>
<td>Atmospheric Radiation</td>
<td>Yes</td>
</tr>
<tr>
<td>Surface physics</td>
<td>Yes</td>
</tr>
<tr>
<td>Two layer soil model</td>
<td>Yes</td>
</tr>
</tbody>
</table>
4.2.4 Boundary layer conditions for CASE I

Radiosonde observations on a day typical of South-West monsoon season and used to initialize the model are shown in Fig 4.2a. The wind profile shows that winds are westerly and south westerly at lower levels at 05:30 hrs and 17:30 hrs respectively and easterly above 10 km. The Low Level Jet (LLJ) at 05:30 hrs is seen around 1 km (~13 m/sec). At 17:30 hrs, since sea breeze opposing the ambient wind set in, the wind speed was small in the lower levels and remained strong aloft. The potential temperature profile shows a weak stable boundary layer (3K/km) in the boundary layer and strong stable stratification in troposphere up to 10 km. The surface temperature of the land and ocean used for model initialization were taken as 297°K and 300°K respectively with 25% surface soil moisture and 70% relative humidity. These data were obtained from field measurements over land (CABLE – 2001 - Report; Sivaramakrishnan and Venkatesan 2002).

4.2.5 Boundary layer conditions for CASE II

Fig 4.2b shows the wind and potential temperature profiles used to initialize the model for North-East monsoon season. Mostly winds are North Easterly and Easterly upto 10km and south westerly above 10km at 5:30 hrs and 17:30 hrs. Winds were weak and Jet is not observed in the boundary layer in this season. Strong stable stratification is observed within the boundary layer (5 K/km) from the potential temperature profile during north-east monsoon. The troposphere has almost similar stratification like case I. In case II, the surface temperature of
land and ocean are 294°K and 297°K respectively. The relative humidity and moisture content are initialized as 85% and 25% respectively at the surface level as per the observed data.

4.2.6 Model results and Discussion

The general pattern of meteorological parameters, sea breeze characteristics, TIBL height and surface layer parameters near the coastal are simulated and compared with the experimental data. Major aspects are discussed as follows.

4.2.6.1 CASE I (south west season)

a. Wind pattern comparison with observations

On the day chosen for simulation during South-West monsoon, the winds are south westerly (<5m/sec) at lower levels and westerly (above 10m/sec) at the higher levels in the morning 6:00hrs. Wind profile simulated at 6:00hrs is compared with the radiosonde observation which is predicted well by the model. Due to the passage of monsoon through a Low Level Jet (LLJ) is also simulated as per the observations.

At around 14:00hrs, the difference between the measured land and sea surface temperatures (ΔT) reached 9°C. Sea breeze set sharply at 14:45 hrs. To see the vertical and horizontal extent of the simulated sea breeze, spatial variation of wind field at 15:00hrs and 18:00hrs are shown in the Fig 4.3a. South-Easterly wind gradually penetrated towards the inland
with increase in wind speed (~7m/sec). Maximum strength and depth of the sea breeze is simulated at 18:00hrs. The vertical extent of sea breeze is about 100 m at 15.00hrs and 350 m at 18.00hrs. After 20:00hrs, simulation showed offshore wind indicating on set of land breeze. The temporal variation of the simulated wind speed and wind direction at 10m level is compared with the observed data as shown in Fig 4.3b. At the early hours of the day a small increase in the simulated wind speed with respect to time is seen and winds are South-Easterly. At around 15:00hrs a sudden increase of wind speed from ~3.5m/sec to ~7m/sec and strong wind backing of about 140° are simulated indicating the sharp onset of sea breeze. The onset is simulated one hour before actual onset. Wind speed during night and morning hours were over estimated by about 2m/s.

b. Potential temperature variation and comparison with observations

The nocturnal atmospheric boundary layer was strongly stable over land. The potential temperature profiles after the onset of sea breeze are shown in Fig 4.4a.
Fig 4.4 During Case I, a) Spatial variation of potential temperature at 15:00 and 18:00 hrs. b) Temporal variation of potential temperature over land and sea and comparison with observations. c) Profiles of potential temperature before and after onset of sea breeze. d) Comparison of potential temperature profiles before and after onset of sea breeze.
ulated mixing height over land was about 650m and the sea breeze had just set in. An internal boundary layer was formed over inland after the sea breeze circulation matured to its full form, and this can be clearly seen at 18:00 hrs, with a height of about 60m. Variation of potential temperature at 10m throughout the day at grid points on either side of the coast is plotted along with the land surface observations in Fig 4.4b. In morning hours, the difference in temperature between land and sea (Δt) is <1°K and temperature of the land is increased due to solar radiation. Sea breeze set when Δt reached ~9°K and a sudden fall in the temperature by 2°K is noticed. Temperature sharply fell from ~307°K to ~302°K over land due to the advection of cold air followed by declining solar radiation. Simulated potential temperature is comparable with the observations in non sea breeze hours where as a major difference is seen at the sea breeze time. A small increase (3°C) in the temperature over sea near the shore is simulated until noon which remained constant for the rest of the day.

Simulated temperature profiles before and after onset of sea breeze is shown in Fig 4.4c. Before onset, the entire boundary layer was unstable with a mixing height of about 650m. After the onset, air cooled by about 3°K with a strong lapse rate near the surface. The profile was compared with the Kytoon data observed in the field experiment as shown in Fig 4.4d. Kytoon was operated at 14:15 hrs just before the sea breeze on set. The wind became relatively calm for about 10 minutes and enabled the Kytoon operation. The ascend profile represented the condition before the breeze (as noted from directional measurement) and the descend profile was immediately after the onset. Simulated potential temperature profile showed the changing of the boundary layer from a slightly unstable to a weakly stable condition, where the measurements showed a strong stable layer. Some differences seen close to the surface and at other levels are
probably because of the local nature of the data and grid average property of the simulated values. If the inversion height is to be considered as the internal boundary layer height, it is shown as about 50m by the Kytoon and 100m by the model at this time and location (5.5km from coast).

c. Relative humidity

Fig 4.5a shows that relative humidity is gradually decreasing with time but after the onset of sea breeze there is sudden increase from 40% to 70%. The simulated relative humidity variations with height before and after onset of sea breeze are shown in Fig 4.5b. From the profiles it is seen that there is an increase of 13% (simulated) and 17% (observed) in relative humidity after the onset of sea breeze. The simulated values before and after onset of sea breeze are agreeing to some extent with the observations. The differences are noticed particularly at higher levels.

4.2.6.2 CASE II (north east season)

a. Wind pattern comparison with observations

During north-east monsoon, simulation showed morning north-westerly winds at lower levels with a speed of <5m/sec and north-easterly at higher levels (~15 m/sec) as
After the onset, the strength of the sea breeze is gradually increased and reached maximum at 15:00hrs. Wind speed and direction are compared with the tower data in Fig 4.6b at 10m. Good agreement is seen at the early hours of the day and night time and a small difference in wind speed is seen at daytime sea breeze hours and also time of onset simulated an hour before it is observed. It is quite difficult to determine the sea breeze as a distinct event when the ambient flow is towards the land. The front is not sharp and changes in surface parameters are not rapid as in the case of off-shore ambient wind. Such difficulties have been expressed in many observations (Arritt, 1993 etc.). Most often a gradual increase in wind speed and a slight change in direction are observed. In order to delineate the effect of land-sea terrain on the observed data, ARPS was run with land alone as the terrain keeping all other conditions alike for case II. The difference due to the terrain heterogeneity is shown in Fig 4.7.
While there is no change in the meridional component of the wind, the zonal component across the shore line has a clear gradual increase toward the land by about 3 ms⁻¹. The associated
updraft is also simulated. Cooling of the land near the coast is noticed to take place gradually but with a definite rate during the entire period of sea breeze. Thus though gradual, a shift in observed wind direction of about $50^\circ$ is due to the sea breeze on set during the on-shore ambient wind condition.

b. Potential temperature variation and comparison with observation

From the contours of spatial distribution of potential temperature shown in Fig 4.8a stable atmosphere in the early morning 6.00hrs is noticed as in the case of south-west monsoon. During this time the surface wind was NWly and since the coastline is along the NNE to SSW direction, a component of wind towards the sea (land breeze) was present.

![Fig 4.7 Temporal variation of zonal and meridional wind components at different terrain inhomogenity](image)

![Potential temperature at 6:00 hrs](image)
In the afternoon, the wind was East-North-Easternly with a component perpendicular to the coast. At this hour, the mixing height was ~350 m. It is quite difficult to find out the inversion that develops due to the marine air inflow. A layer of inversion between 100m and 200m is however noticeable which corresponds to the height of the thermal internal boundary layer.

Fig 4.8 During Case II, a) Spatial variation of potential temperature at 6:00 and 15:00 hrs b) Temporal variation of potential temperature over land and sea and comparison with observations c) Profiles of potential temperature before and after onset of sea breeze d) comparison of potential temperature profiles before and after onset with observations.
From Fig 4.8b variation of surface temperature over land and sea is plotted and compared with the observed data. It is seen from the figure that temperature is increasing with respect to time and decreased gradually around 13:00hrs after onset of sea breeze. The temperature over sea is also shown which remains unchanged throughout the day.

Simulated profiles of potential temperature before (9:00 hrs) and after (13:00 hrs) onset of sea breeze are shown in Fig 4.8c and are compared with observations (Fig 4.8d). Before onset, a neutral profile is seen at the lower levels whereas the simulated potential temperature shows a stable profile with a temperature difference of $2^\circ$K. Whereas after the onset of sea breeze around 13:00hrs simulated profile is coinciding well with the observations and an unstable layer at the surface is noticed.

c. Relative humidity

From the plots of Fig 4.9a it is seen that the relative humidity is decreasing with time and after 15:00hrs it started increasing. This is in contrast to case I where a rapid increase to 80% was seen after the onset of sea breeze.

Fig 4.9 Simulated relative humidity (a) Variation throughout the day (b) Profiles before and after onset of sea breeze and comparison with field data.
Relative humidity profile is seen in Fig 4.9b compared with the observations (in presence of weak onshore wind) before and after the onset of sea breeze. Values are comparable at lower levels and some differences as in case I are noticed aloft.

4.2.7 Thermal internal boundary Layer

The formation and growth of Thermal Internal Boundary Layer (TIBL) due to spatial change in roughness and temperature of the surface, plays an important role in understanding the diffusion properties of air pollutants. The TIBL acts as a lid suppressing the vertical mixing of air pollutants. Growth of the TIBL is controlled by both convective and mechanical turbulence (Gryning and Batchvarova; 1990). Melas and Kambezidis (1992) showed that TIBL depth is a function of downwind distance from the coastline, wind speed and land and sea surface roughness. Many semi empirical and numerical models for estimating TIBL height profile is found in literature and a review of empirical formulations are given by Stunder and Sethu Raman (1985) and Garratt (1990). In this study, the heights of TIBL for these two cases are discussed based on ARPS simulations and observation at the coastal site.

4.2.7.1 CASE I (south west season)

The height of the TIBL is identified in the potential temperature profiles where inversion is seen near the surface level. In Fig 4.4a, it is observed as 60 m above ground level with a
downwind distance of 5.5 km from the coastline. The simulated temperature profile does not show a very sharp inversion as observed. The change from unstable to slightly stable layer is simulated at the level of 100m. Fig 4.10a shows simulated temperature profiles at different downwind distances over land. There is an increase of TIBL depth with respect to distance from the coast. The height of the mixed layer above the TIBL is simulated as 650 m, where constant temperature is observed above the land.

4.2.7.2 CASE II (north east season)

In this case it was quite difficult to delineate the inversion of TIBL. The sea breeze sets well in advance, ahead of the maximum heating of the surface due to radiation. However, from observation and simulations, though not a distinct inversion,
Fig 4.10 Profiles of potential temperature from grid 45 to grid 52 (Grid 51 is coast line)
TIBL height a) case I and b) Case II is shown.
a weak inversion layer between 100m and 200m is seen which must be due to the formation of TIBL Fig 4.10b shows simulated profiles for case II are drawn and the pattern of TIBL can be seen with downwind distance.

4.2.8. Conclusion

Comparisons of sea breeze parameters under the two contrasting synoptic situations are summarized in the following. The synoptic parameters taken from observation are shown in Table 4.2. The strength of the sea breeze is shown as the change in the horizontal component of the wind. Table 4.3 lists out the simulated and observed parameters for both the cases. It gives an idea of the overall performance of ARPS in simulating onset time, duration, increase in the wind speed, change in the wind direction, decrease in potential temperature and increase in relative humidity due to the onset of sea breeze. During the offshore ambient winds, the observed characteristics like the sudden increase in speed and swift in direction of wind and cooling of the surface temperature were simulated but these changes are slightly over estimated.

The TIBL height for these two different synoptic conditions seem to be misleading because, for the summer case I, it is expected to be deeper than the winter case II. The measurement and model show the converse of it. The shallow TIBL during case I must be because of the strong sea breeze compared to the case II. The TIBL height is generally proportional to the heat flux and inversely proportional to the mean wind speed of the incoming column of marine air. TIBL height can be calculated using the empirical formulation suggested
by Luhar (1998) as $h = A_o x^{1/2}$, where $x$ is the downwind distance from the coastline. The empirical coefficient $A_o = \left[2.7H_0 / (\rho c_p \gamma U)\right]^{0.5}$ where $H_0$ is the surface sensible heat flux, $\rho$ is the density and $c_p$ is specific heat capacity of dry air at constant pressure. $\gamma$ is the potential temperature gradient and $U$, the mean wind of the incoming marine air. Using the values shown in Table 4.2 & 4.3, $h$ for case I and II are calculated as 380m and 250m respectively at a distance of 5.5km. Tether balloon data did not show inversion at this height, particularly for case I. The data collected by tether balloon was just after the onset of sea breeze and it was not possible to launch the balloon again, to get the profile data after stabilization of the breeze, due to high wind speed. ARPS also did not simulate the height given by the empirical model. But ARPS simulations were better comparable with measurements than the one estimated with empirical formulation. It is to be noted that $h$ is very sensitive to the proportionality constant value (2.7) used in the formulation and if this is changed to 1.0, then $h$ would be 220m and 150m respectively for case I and II.

Some discrepancies in simulated wind speed, temperature and TIBL structure are of course there as it is noticed in many studies based on field measurements. They are mainly due to local nature of the measurements and sub-grid averaging of the model. To investigate the differences, more extensive spatially covered measurements are required and the model horizontal and vertical resolutions have to be increased.

Table 4.2 Difference in the simulated parameters before and after onset of sea breeze for both seasons
Table 4.3 Comparison of simulated parameters with the observed values for both seasons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day-Max. ($T_{\text{Land}} - T_{\text{Sea}}$)</td>
<td>9°C</td>
<td>4°C</td>
</tr>
<tr>
<td>Night-Min. ($T_{\text{Land}} - T_{\text{Sea}}$)</td>
<td>-1°C</td>
<td>-5°C</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>3.5 K/km</td>
<td>5.5 K/km</td>
</tr>
<tr>
<td>$V_g$</td>
<td>10 ms$^{-1}$</td>
<td>4 ms$^{-1}$</td>
</tr>
<tr>
<td>Direction</td>
<td>W</td>
<td>NNE</td>
</tr>
<tr>
<td>Change in cross wind comp. $[u_{\text{sea breeze}} - u_{\text{ambient}}]$</td>
<td>-9 ms$^{-1}$</td>
<td>-3 ms$^{-1}$</td>
</tr>
</tbody>
</table>

The present study, nevertheless, has revealed the general coastal atmospheric features during on-shore and off-shore / along shore wind conditions typical of two different seasons over
a plain land on the Indian peninsular region. The coastal land use being similar, the changes in sea breeze characteristics would be majorly due to the latitude variation along the eastern coast running from $7^\circ$N to $17^\circ$N. The difference between mid-latitude conditions and tropical Indian coast lies in the relatively warm boundary layer. An area of further investigation could be to see how the sea breeze circulation evolves under this different ambience while the land-sea surface temperature contrast and the ambient wind velocity remain same.

### 4.3 Study of Atmospheric Dispersion around Urban - Heat island, Delhi

Urban air pollution is aggravated because of mainly growing cities, rapid economic development and industrialization. It can cause health problems and can also damage the environment and property. The main pollutants affecting the urban areas are CO, NOX, SOX etc. emitted from vehicular traffics, thermal power plants, burning of fossil fuels etc. Hence it is necessary to study the pollution dispersion in and around urban areas through experimental and numerical modeling. It is a difficult task to study the pollution dispersion over large areas experimentally due to high cost and experimental difficulties. Hence some mathematical models developed for studying the dispersion of pollutants can solve these problems.

#### 4.3.1 Review Studies

Many Studies have been made to understand dispersion of pollutants in and around Delhi experimentally and numerically. Meteorology plays an important role in understanding the
dispersion of pollutants. Dispersion of pollutants (Wark and Warner, 1981) is mainly due to the mean airflow, which transports the pollutants down wind and turbulent velocity fluctuations that disperse the pollutants in all directions. GPM models are generally applicable when the pollutants are chemically inert, the terrain is not steep or complex, meteorology is homogeneous spatially and when there are calm or light winds. In most of the studies Gaussian plume models (GPMs) are used to understand the dispersion of pollutants. Studies of Goyal et. al., 1994; Arya, 1995; Sharan and Yadav reveal that standard steady-state GPMs generally over predict ground level concentrations at low wind conditions.

Sharan et al. 2002 study used an analytical model for dispersion of pollutants in low-wind conditions to explain the diffusion data, in weakly convective conditions, collected at IIT Delhi. The turbulence parameterization based on friction velocity has been tested in this study to simulate diffusion experiment. Such a parameterization is considered justifiable on prevailing meteorological and dispersion conditions have been generally of weakly unstable type as indicated by values of Monin–Obukhov length and bulk Richardson number and uncertainties associated with the application of convective velocity based similarity parameterization. Brooke et al. (2007) compared boundary layer heights estimation by AERMET (04300) and ADMS 3.3 for Yorkshire, UK and found that AERMET estimation of BLH were higher than that of ADMS-Urban. The models could perform differently in different climatic zones. The ADMSUrban meteorological module provides good estimates of boundary layer depth when the site is in mid-latitudes (CERC, 2006). However, there is no comparison of these two models for Indian (tropical/sub-tropical) conditions. Hence the study was undertaken by Mohan et al. 2009. Winter months are characterized by low boundary layer conditions, and the estimated concentrations are
very sensitive to any change in this parameter. Boundary Layer Height (BLH) estimations by AERMET and meteorological processor of ADMS-Urban for both years 2000 and 2004 shows that about 64% of estimated values of boundary layer height fall within the \( \text{ADMS/AERMET} \) ratio of 0.5 and 2. About 14% of BLH estimations by AERMET are more than twice of those estimated by ADMS-Urban. On the other hand, about 22% of BLH estimations by ADMS-Urban are more than twice those of AERMET. Thus overall, BLH estimations by ADMS-Urban are comparatively higher than those by AERMET. The study concluded could be the reason for slightly higher concentration estimations by AERMOD in comparison to ADMS-Urban and consequently lower bias.

So simulating the air quality of a region involves both the meteorological factors such as wind speed and direction, turbulence, radiation, clouds precipitation and chemical processes like emissions and depositions. So far usually meteorological and dispersion/chemical models are used separately to study the dispersion of pollutants. The output of the meteorological model obtained for every one or two hours are used as an input to the chemical model to understand the chemistry of the atmosphere. Due to this separation of meteorology and chemistry some important information will be lost about the atmospheric processes that quite often have a time scale of much less than the output time of the meteorological model example wind speed and direction, rainfall and cloud formation which is important for predicting the air quality. In this study Delhi mega city is taken to understand the urban heat-island characteristics using WRF model. Fig 4.11 shows the map of study area i.e. Delhi.

4.3.2 Results and Discussion
Urban areas are mainly comprised of large buildings, industries and many human made activities thus mostly in these areas temperature will be more compare to the surrounding rural areas. This increased heat due to raise in temperature is called urban heat island. To compensate this discomfort caused due to increase in heat more amount of energy is used for cooling purpose. Hence this is also one of the reasons for increase in pollution. Hence the WRF model was run for 36 hours on the selected domain Delhi to study the urban heat island characteristics. The model was initialized at morning 5:30 hrs Dec 1st 2004 and run for 36 hours in a 3 dimensional mode.

The number of grids in x and y direction in the model domain are 50 with constant grid spacing of 1km and 15 levels vertically in the z direction. The Delhi city has a flat terrain consisting of large buildings with loam and sandy loam soil type. The GFS $1^0$ resolution meteorological data from NCEP for every 6 hours is used as an input data to the WRFSI package. The Land Use category of Delhi from USGS data is shown in Fig 4.12.
Fig 4.11 Outline map of Delhi (map not to scale)
Table 4.4 Various options used in the WRF model
<table>
<thead>
<tr>
<th>Advection Scheme</th>
<th>Runge-Kutta 3\textsuperscript{rd} order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>Kessler scheme</td>
</tr>
<tr>
<td>Long-wave radiation</td>
<td>RRTM</td>
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<tr>
<td>Short-wave radiation</td>
<td>Dudhia</td>
</tr>
<tr>
<td>Surface layer</td>
<td>Monin-Obukhov (Janjic Eta) scheme</td>
</tr>
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<td>Land-surface model</td>
<td>Noah land-surface model</td>
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<td>Boundary layer scheme</td>
<td>YSU scheme</td>
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<tr>
<td>Eddy coefficient</td>
<td>1.5 order TKE closure scheme</td>
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<td>Cumulus parameterization</td>
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</tr>
<tr>
<td>Chemistry option</td>
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</tr>
</tbody>
</table>
Fig 4.13 Wind and temperature profiles from radiosonde data at 5:30 hrs on 01/12/2004

The output developed by the WRFSI package is given to the WRF model. The various physics and dynamic options are given to the model is shown in Table 4.4. The vertical profiles of wind speed, wind direction and temperature observed from radiosonde data on the simulation day is shown in Fig 4.13. The observed wind profiles shows that winds are calm in north-easterly and easterly direction below 1-2km and gradually increasing with respect to height moving towards westerly and north westerly side. A wind shear is observed above the 10km with a wind
speed of ~58 m/sec. From the temperature profiles it is seen that atmosphere is stable below 1km and above that it is unstable up to 18km. The spatial distribution of temperature simulated by the WRF model is shown in Fig 4.14 (a), (b), (c). At morning 6:00 IST the temperature is around 292\(^0\)K and the temperature has started increasing inside the city gradually during day time and reached to 300\(^0\) K and 301\(^0\)K at 11:30 IST and 14:30 IST respectively. The simulated temperature during nighttime indicates that temperature over urban area is more than the rural area. At 20:30 hrs temperature the city is 296.4\(^0\)K whereas surrounding the city it is 295.5\(^0\)K and the next day morning 5:30 IST we can see that there is a difference of 2\(^0\)C inside and outside the city. Thus urban heat island effect is simulated. From the previous studies it is observed that there is a difference of nearly 5-6\(^0\) C of temperature between urban and rural areas. This difference of temperature is not simulated by the model since because in the urban land use of USGS data for the selected domain there are many other land use categories like large buildings, parks etc. which was not considered by the USGS land use data. This is one of the reasons for not seeing the much difference in the temperature between urban and rural areas and also by selecting suitable PBL and surface physics schemes the simulations may be improved.
Fig 4.14 (a) Spatial distribution of temperature simulated by WRF model at 6:30 and 11:30 IST on 01/12/2004
Fig 4.14 (b) Spatial distribution of temperature simulated by WRF at 14:30 and 20:30 IST on 01/12/2004
4.14 (c) Spatial distribution of temperature simulated by WRF at 5:30 IST on 02/12/2004
The comparison between simulated and observed diurnal variations of temperatures is shown in Fig 4.15. Two observatories are located in Delhi namely Safdurjung, which is inside the city, and Palam is situated outside the city. Fig 4.15 shows that the WRF model has simulated the diurnal variation of temperature in an acceptable limit. At both observatories daytime temperatures are coinciding well than nighttime. This problem can be overcome by suitable selection of surface and land use schemes.

Fig 4.15 Simulated diurnal variation of temperature and comparisons with observations at Safdurjung and Palam
Fig 4.16 (a) Simulated wind field on the selected domain by WRF at 5:30 IST and 11:30 IST on 01/12/2004 at 10m level
Fig 4.16 (b) Simulated wind field on the selected domain by WRF at 14:30 IST and 20:30 IST on 01/12/2004 at 10m level
The wind field at 10 m level over the domain is shown in Fig 4.16(a) and 4.16(b). It is observed from the figures that winds are weak and are moving towards the urban area in the morning 5:30 hours and during daytime as temperature increases the wind speed started increasing and urban area will have more temperature thus the winds started moving towards the rural area.

4.3.3 Conclusions

In the present paper urban heat island effect is studied over a mega city Delhi using a Weather Research and Forecast model. The model was run for 36 in a 3-dimensional mode for Dec 1st 2004 by initializing the model at morning 5:30 hrs. The model has simulated the urban heat island features very clearly and it is observed that nearly 2°C difference in temperature is simulated between urban and rural areas. The temperatures inside the city are recorded higher than rural areas. It is understood that the amount of anthropogenic heat release is one of the important causes of heat island phenomenon. Simulations can be improved by incorporating the accurate data of land and surface characteristics such as large building, parks, and different soil conditions in the model. The diurnal variation of temperatures from the observed and simulated results also coincides in an acceptable limit.