ABSTRACT


Observations from aircraft, an island station, and two research vessels are used to investigate the development of an elevated mixed layer or land plume over the Arabian sea during the Indian Ocean Experiment Intensive Field Phase 1999 (INDOEX) through air mass modification. Much of the transport of aerosols and gases occur in this plume located above a well-mixed convective marine boundary layer with a depth of 800 - 1000 m. The depth of the land plume is approximately 2000 m with the peak ozone concentrations occurring near the center of this land plume. Significant latitudinal variations in the concentration of ozone occur in the marine boundary layer and in the plume. Mean ozone concentrations in the land plume decreased with distance from the Indian coastline.

The horizontal extent of the sea breeze circulation over the Arabian Sea during the Indian Ocean Experiment (1999) is investigated. Profiler data from Bombay, Goa, and Trivandrum, India show a diurnal variation in wind direction caused by land and sea breeze circulations along the west coast of India. Wind profiles taken 130 km from the west coast of India from R/V Sagar Kanya show a change in wind direction particularly at 200 to 300 m caused by the sea and land breeze circulations. Infrared satellite images show the furthest extent of the sea breeze circulation over the Arabian Sea to be around 200 km. Constant level balloons also showed the extent of the sea breeze over the ocean to be 200 km. A mesoscale numerical model was used to further investigate the horizontal extent of the sea breeze over the ocean. Simulated cross sections along the
west coast of India show the horizontal extent of the afternoon sea breeze over the ocean to vary from around 130 to 200 km. Vertical velocities of around 0.20 ms\(^{-1}\) were produced inland as the sea breeze interacted with the mountains along India’s west coast.

The development and propagation of a “pollution gradient” over the Arabian Sea during the Intensive Field Phase of the Indian Ocean Experiment (1999) is investigated. A hypothesis for the generation of the pollution gradient is presented. Infrared satellite images show the formation of the pollution gradient as the leading edge of a polluted air mass in the marine boundary layer and also its propagation over the Arabian Sea and the northern Indian Ocean. Aerosol data measured from two research vessels over the Arabian Sea show a diurnal variation in the concentrations caused by the passage of this pollution gradient. Depth of the pollution gradient was found to be about 800 m. A mesoscale numerical model was used to simulate the development of this gradient and its propagation over the ocean. Results show that its formation and structure are significantly influenced by the diurnal cycle of coastal sea-land breeze circulations along India’s west coast. Transport of aerosols and gases over the Arabian Sea in the lower troposphere from land sources appears to be through this mechanism with the other being the elevated land plume.

By

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Matthew Simpson was born on 20 September 1979 in Charlotte, North Carolina. At the age of 10, he witnessed the wrath of Hurricane Hugo over Charlotte and his interest in meteorology was born. A later encounter with a hailstorm while bike riding solidified his interest in meteorology as a career. After graduating from First Assembly Christian School in Concord, NC, he enrolled at North Carolina State University to pursue a degree in Meteorology. In May of 2001, he received his bachelor’s degree in Meteorology. Work on a Master’s degree in Meteorology began after graduation and he received his degree in June of 2003.
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CHAPTER 1. INTRODUCTION

1.1 INDIAN OCEAN EXPERIMENT (INDOEX)

Influence of anthropogenic aerosols and gases on the global radiation balance has long been a subject of debate and concern of the scientific community. To study this relationship, the Indian Ocean Experiment (INDOEX) was conducted over the Arabian Sea and tropical Indian Ocean from 14 January to 31 March 1999 during the northeast monsoon. The central hypothesis of the Indian Ocean Experiment (INDOEX) was that the transport of an aerosol-laden air mass from the Indian subcontinent and Asian landmass over the Indian Ocean could alter the global radiation balance (Ramanathan et al, 1995). The core objective of INDOEX (1999) was to study the possible variation in the magnitude of solar absorption occurring near the surface and in the troposphere where there are high concentrations of sulfates and aerosols of continental origin.

Ships, aircraft, balloons, satellites, and weather stations were used to obtain observations over the Arabian Sea and equatorial Indian Ocean from January 21 to March 31, 1999 during the Intensive Field Phase (IFP) of INDOEX. Location of the INDOEX research domain is shown in Figure 1.1. Large portions of the tropical Indian Ocean and the Arabian Sea as well as the Indian subcontinent are included in the INDOEX research domain.

A pre-INDOEX research study observed a spatial gradient in aerosol optical thickness that suggested long-range transport of aerosols from India to the North Indian Ocean (Satheesh 1998). Northeast winds transport aerosols and gases from the Indian subcontinent over the ocean during the northeast monsoon as shown in Figure 1.2. High concentrations of non-sea salt aerosols in the Arabian Sea appear to result due to
Figure 1.1 Research domain for the Indian Ocean Experiment, INDOEX 1999.)
Figure 1.2 Schematic diagram showing the general transport direction of pollution from the Indian subcontinent over the ocean by the northeast monsoon.
transport from the Indian subcontinent and Arabian peninsula (Rajeev et. al., 2000). The high concentrations of absorbing haze/aerosols tend to decrease the surface solar radiation by an amount comparable to 50% of the total ocean heat flux (Ramanathan et al., 2001). Observational analysis of sea surface temperatures has shown that the absorbing aerosols have led to a statistically significant cooling of about 0.3°C since the 1970’s (Krishnan and Ramanathan 2002). Anthropogenic influences on the radiation balance over the Indian Ocean are caused by agricultural burning and bio-fuel use that have greatly increased carbon monoxide concentrations over the Arabian Sea (Lelieveld et. al., 2001). Thus, there is a need to investigate the mechanism of transport of aerosols and gases over the ocean.

Latitudinal gradients in aerosol concentrations were observed over the tropical Indian Ocean by ship borne measurements prior to INDOEX (1999) (Satheesh et al 1998). Higher marine boundary layer ozone concentrations were observed over the Indian Ocean in the northern hemisphere during the northeast monsoon season (Johnson et al, 1990). Direct transport of anthropogenic emissions resulting in sharp increases in CO, CO₂, O₃, and NOₓ have been detected at distances of 1500 km from southern India (Rhoads et al 1997). Sudden increases in O₃, CO, and aerosol mass concentrations of sizes less than 0.6 µm have been observed with back trajectories showing air mass transport from the Indian subcontinent (Lal et al, 1998).

One interesting phenomenon observed by the various data platforms during INDOEX (1999) was the sea and land breeze circulations along the west coast of India. In particular, the horizontal extent of the sea breeze over the ocean was investigated. Previous research has shown that offshore ambient flow substantially increases the
offshore influence of the sea breeze over the ocean (Estoque 1962; Arritt 1989). Offshore winds can increase the convergence associated with the sea breeze and enhances frontogenesis (Reible 1993). Sea breeze fronts have been observed using SODAR as large updrafts over a depth of 30 to 350 m along the west coast of India (Prakash 1992).

The horizontal extent of the sea breeze over the Arabian Sea near Bombay was found to be around 120 to 150 km while the inland penetration of the circulation is greater than 80 km (Dixit 1964). Observations from a 10 m tower aboard R/V Sagar Kanya showed the influence of the sea-land breeze over the ocean at a distance of 80 km from the west coast of India but not at a distance of 130 km (Subrahamanyam et al 2001).

Aerosols and gases can be transported from India over the ocean in the marine boundary layer. Westward propagating cloud bands originating near the west coast of India were observed with a geo-stationary satellite during INDOEX 1999 (Desmaland 2002). The presence of cloud bands was found to depend largely on the magnitude of the sea / land breeze circulation. Peaks in aerosol and CO concentration were observed as the cloud bands passed research vessel (R/V) Ron Brown (Simpson and Raman 2003).

1.2 INDIAN MONSOON

The Indian monsoon refers to the seasonally shifting winds over the Indian Ocean, Arabian Sea, and surrounding region. Southwest winds blow during the summer and bring moisture and rain to the Indian subcontinent. Winds shift to northeast in the winter and cut off the moisture flow inland and result in the dry season.

The InterTropical Convergence Zone (ITCZ) separates the wind flow of the northern and southern hemispheres. The ITCZ is defined as the region where the
northeast and southeast trade winds converge. Movement of the ITCZ varies seasonally with the changes in the sun’s declinations angle. The change in the location of the summer and winter ITCZ over the India Ocean is shown in Figure 1.3. During the winter months, the ITCZ is located around 5°S to 10°S and results in northeast flow over the Indian subcontinent. The ITCZ moves northward during the summer to around 25°N and results in southwest flow over India. Strong vertical motion and rainfall along the ITCZ result from the low level convergence of the wind.

The primary differences in the Indian monsoon seasons are sea-land temperatures, location of the ITCZ, and intense convective storms. Surface temperatures over the Indian subcontinent are extremely warm by May and result in a large contrast between land surface temperatures and sea surface temperatures. The contrast in temperatures causes a shift in the wind flow from easterly (offshore) to westerly (onshore).

A strong low pressure cell develops over Western India and Pakistan during the Southwest monsoon period. Southwest winds are caused by the low pressure cell and the Coriolis force. A magnification of the winds coincides with the northward movement of the ITCZ. Moisture is transported from the Indian Ocean and released (beginning around June) over the subcontinent. Mountains along the west coast of India cause amplification of convection and produce heavy rainfall.

A reverse process is observed during the winter months. Surface temperatures over India during the winter are cold relative to the sea surface temperatures. Due to the contrast in temperatures, winds become easterly and blow offshore. The advected air mass contains little moisture and results in dry winters over the India subcontinent. INDOEX was conducted during the Northeast monsoon because the offshore flow
FIGURE 1.3 Diagram showing the location of the Inter Tropical Convergence Zone (ITCZ) during the summer (solid) and winter (dashed) months in the INDOEX research domain.
transports aerosols and anthropogenic gases over the ocean.

The population of India currently exceeds one billion people and a failure of the monsoon to bring rain to the Indian subcontinent can have terrible effects. Crop failure from lack of rain affects people locally but can also have an effect on the global economy. Too much rain from the monsoon can have negative effects such as crop damage, flooding, and the displacement of many people.

1.3 DATA PLATFORMS

1.3.1 Aircraft

All of the high-resolution airborne measurements used in this study were obtained by the EC-130Q Hercules and the French research aircraft Mystere. The meteorological data taken from the C-130 aircraft were sampled 20 times per second. Some of the instrumentation on the C-130 included a gust probe to measure turbulence, cloud physics instrumentation, radiometers, and in-situ trace gas samplers (CO, CO₂ and O₃). The parameters used in this study from the C-130 include pressure, potential temperature, altitude, latitude, longitude, wind speed, and turbulence.

Aerosol distributions are presented from measurements made by a downward looking lidar aboard the French aircraft Mystere. Lidar measurements are included to show the presence of an elevated land plume over the Arabian Sea. The goal of Mystere’s participation in INDOEX was to observe latitudinal and longitudinal distributions of aerosols.

1.3.2 Research Vessels

The ship data used in this research was collected by the research vessels (R/V) Ron Brown and Sagar Kanya during INDOEX (1999). R/V Ron Brown is operated by
the U.S. National Oceanic and Atmospheric Administration (NOAA). Some of the important atmospheric instrumentation on R/V *Ron Brown* during INDOEX (1999) included a C- Band Doppler Radar, wind profiler, and rawinsondes. Data from the three to four daily rawinsonde releases consisted of vertical measurements of pressure, temperature, humidity, latitude and longitude, and wind speed and direction every 10 seconds.

*R/V Sagar Kanya* is operated by the Indian Department of Ocean Development. Rawinsondes were released twice a day from *R/V Sagar Kanya* during the INDOEX (1999) and they obtained the same meteorological variables as from *R/V Ron Brown*. During the period, 6-9 March 1999, additional radiosondes were released as *R/V Sagar Kanya* was closer to the west coast of India for the parallel track experiment. The major observation systems used by *R/V Sagar Kanya* during INDOEX included an Eppley Total Solar Pyranometer, handheld sunphotometer, high volume bulk aerosol filter sampler, multi wavelength radiometer, pyrheliometer, surface CO and CH4 analyzer, surface ozone sampler and surface meteorological instruments.

Ship tracks of R/Vs *Ron Brown* and *Sagar Kanya* during INDOEX (1999) are shown in Figure 1.4. Both ships began at Port Louis (20°S, 57°E) in the southern hemisphere and moved northward. The ship tracks were designed to measure the latitudinal difference in pollution concentrations between the southern and northern hemisphere. *R/V Sagar Kanya* concluded its track at Goa (15.25°N, 73.43°E) on 12 March 1999.
Figure 1.4 Ship tracks for research vessels Ron Brown (solid) and Sagar Kanya (dashed) during INDOEX 1999.
1.3.3 Satellites

The Meteosat – 5 satellite was launched on 2 March 1991 under the authority of the European Space Agency (ESA). Meteosat - 5 is a meteorological satellite with a geostationary orbit operating within the worldwide network of the World Weather Watch of the World Meteorological Organization (WMO). The general mission of Meteosat - 5 was imaging in the visible, infrared, and water vapor region of the spectrum. Other satellites used during INDOEX (1999) include EOS, FY-2, INSAT, NOAA-14, NOAA-15, ScaRab, and the Tropical Rainfall Measuring Mission (TRMM) satellite.

1.3.4 Constant Level Balloons

Constant level balloons were released from Goa, India (location shown earlier in Figure 1.4.) to visualize the wind flow in the boundary layer near the west coast of India and the eventual transport towards the Inter Tropical Convergence Zone (Appu 2001). Balloons were launched around 04:30 LT just before the peak of the land breeze so that the balloon would drift towards the ocean. The balloons were filled with helium and maintained a nominal flight pressure of around 925 hPa. Balloons were equipped with a GPS receiver to measure 3D position, a pressure sensor, a thermistor mounted on the pressure sensor to control its temperature and correct for possible thermal pressure drifts, a 100um thermistor for measuring air temperature, and a commercial hygrometer for relative humidity. Data was sampled and stored on board every 30 minutes. Stored data was transmitted daily to two satellites.

1.3.5 Surface Stations

Kaaishidoo Meteorology Station (KCO) is located in the Republic of Maldives at 4.97°N, 73.47°E. KCO was chosen to be the observation site for the measurements of
most of the radiometric trace gas and aerosols so that they could be carried out in a relatively pollution-free environment. KCO also has a large locally clean air sector in the northeast that is important to pollution measurements made during the NE monsoon season.

Chemistry of trace gases and meteorological parameters were the primary measurements made at KCO during INDOEX. Ten minute averages of carbon monoxide mixing ratios were made near the surface using a CO analyzer. A gas chromatograph was used to determine 40-minute atmospheric mixing ratios for CFC’s, chlorinated gases, nitrous oxide, and sulfur hexafluoride. Ten second averages of atmospheric ozone mixing ratios were measured with an ozone analyzer. Rawinsondes were released twice a day and ozonesondes were released once daily from KCO and provided vertical profiles of pressure, temperature, humidity, wind speed and direction, and ozone concentration. Meteorological parameters such as 10 second averages of wind speed and direction, air temperature, relative humidity, atmospheric pressure, and rain amounts were measured near the surface. Radiation measurements were made with broad and narrowband radiometric sensors. A continuous scattering coefficient for aerosols and for particle/soot absorption was obtained using a three-stage, high volume impactor.

Wind data was collected at Bombay (18.55°N, 72.50°E), Goa (15.25°N, 73.43°E), Trivandrum (8.5°N, 77°E), India during INDOEX (1999). The winds were measured twice daily at 00Z (0500 LT) and 12Z (1700 LT). The location of the three stations is shown in Figure 1.5. Data from these stations was used for this paper because their locations will exhibit any latitudinal differences in the magnitude of the sea-land breeze along the west coast of India. Other stations that recorded atmospheric data include Mt.
Figure 1.5. Surface observation stations during INDOEX (1999).
Abu and Pune, India.

1.4 RESEARCH OBJECTIVES

The primary objectives of this research are as follows:

- Investigate the transport mechanisms of aerosols and gases over the Indian Ocean during the northeast monsoon.
- Study the role of the land-air-sea interaction process in the lower troposphere.
- Study the development and structure of the land plume offshore and its role in the transport of anthropogenic aerosols and gases over the ocean.

Research objectives will be achieved using observations made during INDOEX (1999) by using numerical mesoscale simulations.
CHAPTER 2. MODEL DESCRIPTION

2.1 OVERVIEW OF THE MM5 MODELING SYSTEM

The fifth-generation NCAR/ Penn State Mesoscale Model (MM5) is the latest version of a mesoscale model first used and developed at Penn State in the early 1970’s. MM5 is a primitive equation model that uses a non-dimensional $\sigma$-vertical coordinate system. The model has been changed so that it now includes multiple-nests, nonhydrostatic dynamics, and a four dimensional data assimilation (FDDA) capability. Model performance has also been enhanced with the development of more physics options and the ability to run the model on several computer platforms.

A flow chart showing the MM5 modeling system is shown in Figure 2.1. The flow chart breaks the MM5 modeling system into three components: 1. main programs, 2. Data Sets, and 3. Additional Capabilities. TERRAIN, REGRID, RAWINS, INTERP, and MM5 and the main programs included in the MM5 model. Programs TERRAIN and REGRID interpolate terrestrial and isobaric atmospheric data in a latitude-longitude mesh to a variable high-resolution model domain. Projection options for the model domain include Mercator, Lambert Conformal, or Polar Stereographic. Mesoscale detail is added to the REGRID data with surface and upper air observations from the standard global network of surface and rawinsonde stations in the RAWINS program. Atmospheric data is then interpolated using the INTERP program from pressure levels to the vertical sigma coordinate system employed by MM5. MM5 is the final main program and is the numerical weather prediction component of the model. The MM5 program includes the various physics options and the governing equations.
FIGURE 2.1 Flow chart showing the MM5 V.3.4 modeling system.
A double nested model domain is created in the TERRAIN program and used for the model run. The outer domain covers an area of (38.31°N-10.61°S; 44.17°E-96.10°E) and the inner domain an area of (21.82°N-4.36°N; 61.08°E-79.01°E) as shown in Figure 2.2. The horizontal resolutions for the outer and inner domains are 30 km and 10 km, respectively. The outer domain consists of (186 x 186) grid points while the inner domain has (178 by 178) grid points. The inner domain is arranged to include the mountains along India’s west coast and a large portion of the Arabian Sea.

Atmospheric data interpolated in the REGRID and RAWINS programs must be converted from pressure levels to the sigma terrain following coordinate system. The formula for the dimensionless sigma level is given by:

\[
\sigma = \frac{(p - p_t)}{(p_s - p_t)}
\]  

(2.1)

where \( p \) is the pressure, \( p_t \) is a specified constant top pressure, \( p_s \) is the surface pressure. Vertical sigma levels used for this study are shown in Table 2.1. Both model domains have 37 vertical \( \sigma \) levels between 1000 mb and 100 mb with 18 of the levels below 850 or 1.5 km. Numerous sigma levels are located in the lowest 1.5 km of the atmospheric because fluxes of heat, moisture, and momentum occur in the planetary boundary layer.

2.2 INITIALIZATION AND BOUNDARY CONDITIONS

Operational analysis from NMC, produced by the National Center for Environmental Prediction (NCEP) and archived by the National Center for Atmospheric
FIGURE 2.2  Schematic of the double nested model domain.
**TABLE 2.1** Vertical sigma levels used in model run.

<table>
<thead>
<tr>
<th>Levels</th>
<th>Pressure(mb)</th>
<th>Sigma</th>
<th>Levels</th>
<th>Pressure(mb)</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>1.000</td>
<td>20</td>
<td>820</td>
<td>0.800</td>
</tr>
<tr>
<td>2</td>
<td>995</td>
<td>0.994</td>
<td>21</td>
<td>800</td>
<td>0.778</td>
</tr>
<tr>
<td>3</td>
<td>990</td>
<td>0.989</td>
<td>22</td>
<td>780</td>
<td>0.756</td>
</tr>
<tr>
<td>4</td>
<td>985</td>
<td>0.983</td>
<td>23</td>
<td>760</td>
<td>0.733</td>
</tr>
<tr>
<td>5</td>
<td>980</td>
<td>0.978</td>
<td>24</td>
<td>740</td>
<td>0.711</td>
</tr>
<tr>
<td>6</td>
<td>975</td>
<td>0.972</td>
<td>25</td>
<td>700</td>
<td>0.667</td>
</tr>
<tr>
<td>7</td>
<td>970</td>
<td>0.967</td>
<td>26</td>
<td>650</td>
<td>0.611</td>
</tr>
<tr>
<td>8</td>
<td>965</td>
<td>0.961</td>
<td>27</td>
<td>600</td>
<td>0.556</td>
</tr>
<tr>
<td>9</td>
<td>955</td>
<td>0.950</td>
<td>28</td>
<td>550</td>
<td>0.500</td>
</tr>
<tr>
<td>10</td>
<td>945</td>
<td>0.939</td>
<td>29</td>
<td>500</td>
<td>0.444</td>
</tr>
<tr>
<td>11</td>
<td>935</td>
<td>0.928</td>
<td>30</td>
<td>450</td>
<td>0.389</td>
</tr>
<tr>
<td>12</td>
<td>925</td>
<td>0.917</td>
<td>31</td>
<td>400</td>
<td>0.333</td>
</tr>
<tr>
<td>13</td>
<td>915</td>
<td>0.906</td>
<td>32</td>
<td>350</td>
<td>0.278</td>
</tr>
<tr>
<td>14</td>
<td>905</td>
<td>0.894</td>
<td>33</td>
<td>300</td>
<td>0.222</td>
</tr>
<tr>
<td>15</td>
<td>895</td>
<td>0.883</td>
<td>34</td>
<td>250</td>
<td>0.167</td>
</tr>
<tr>
<td>16</td>
<td>880</td>
<td>0.867</td>
<td>35</td>
<td>200</td>
<td>0.111</td>
</tr>
<tr>
<td>17</td>
<td>865</td>
<td>0.850</td>
<td>36</td>
<td>150</td>
<td>0.056</td>
</tr>
<tr>
<td>18</td>
<td>850</td>
<td>0.833</td>
<td>37</td>
<td>100</td>
<td>0.000</td>
</tr>
<tr>
<td>19</td>
<td>835</td>
<td>0.817</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Research (NCAR) was used to prescribe initial conditions. The resolution of the archived data is $2.5^\circ \times 2.5^\circ$ latitude-longitude with 15 standard pressure layers. The above data are interpolated onto the model grid to serve as initial values and to provide lateral boundary conditions for the model. The model was run from 00Z (0500 LT) on 27 February to 00Z (0500 LT) on 11 March 1999. Analysis corresponding to 00Z (0500 LT) on 27 February, 00Z (0500 LT) on 2 March, 00Z (0500 LT) on 5 March 1999, and 00Z (0500 LT) on 8 March 1999 was used to initialize the non-continuous model run. This time period was chosen because of the presence of the pollution gradient in infrared satellite imagery and availability of aerosol data from R/Vs *Ron Brown* and *Sagar Kanya* during the parallel track experiment.

MM5 uses data from the United States Geological Survey (USGS) database for terrain and landuse initialization. 5 minute (9km) global terrain and landuse files were used for the outer domain. The inner domain was initialized with higher resolution 30 second (.9km) terrain and landuse files. Initialized topography for the model outer domain is shown in Figure 2.3. Complex terrain is present throughout the model region with the most interesting features being the Tibetan Plateau in the northeast region of the domain and the mountains along India’s west coast. A great deal of water is also observed in the domain because of the Arabian Sea and Indian Ocean. The complex topography and land-ocean interface will test the model's ability to perform in a diverse landscape.

Initialized terrain files include landuse files with 24 categories as shown in Table 2.2. The landuse categories are given values for albedo, moisture availability, emissivity, roughness length, and thermal inertia. Variables for landuse are given different values.
FIGURE 2.3  Model terrain initialization from USGS topography database.
<table>
<thead>
<tr>
<th>Category</th>
<th>Vegetation Type / Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Urban and built-up land</td>
</tr>
<tr>
<td>2</td>
<td>Dry Cropland and Pasture</td>
</tr>
<tr>
<td>3</td>
<td>Irrigated Cropland and Pasture</td>
</tr>
<tr>
<td>4</td>
<td>Mixed Dryland / Irrigated Cropland and Pasture</td>
</tr>
<tr>
<td>5</td>
<td>Cropland / Grassland Mosaic</td>
</tr>
<tr>
<td>6</td>
<td>Cropland / Woodland Mosaic</td>
</tr>
<tr>
<td>7</td>
<td>Grassland</td>
</tr>
<tr>
<td>8</td>
<td>Shrubland</td>
</tr>
<tr>
<td>9</td>
<td>Mixed Shrubland / Grassland</td>
</tr>
<tr>
<td>10</td>
<td>Savanna</td>
</tr>
<tr>
<td>11</td>
<td>Deciduous Broadleaf Forest</td>
</tr>
<tr>
<td>12</td>
<td>Deciduous Needleleaf Forest</td>
</tr>
<tr>
<td>13</td>
<td>Evergreen Broadleaf Forest</td>
</tr>
<tr>
<td>14</td>
<td>Evergreen Needleleaf Forest</td>
</tr>
<tr>
<td>15</td>
<td>Mixed Forest</td>
</tr>
<tr>
<td>16</td>
<td>Water Bodies</td>
</tr>
<tr>
<td>17</td>
<td>Herbaceous Wetland</td>
</tr>
<tr>
<td>18</td>
<td>Wooded Wetland</td>
</tr>
<tr>
<td>19</td>
<td>Barren or Sparsely Vegetated</td>
</tr>
<tr>
<td>20</td>
<td>Herbaceous Tundra</td>
</tr>
<tr>
<td>21</td>
<td>Wooded Tundra</td>
</tr>
<tr>
<td>22</td>
<td>Mixed Tundra</td>
</tr>
<tr>
<td>23</td>
<td>Bare Ground Tundra</td>
</tr>
<tr>
<td>24</td>
<td>Snow or Ice</td>
</tr>
</tbody>
</table>
for summer and winter to account for changes in the landuse characteristics.

The landuse file used for initializing the model outer domain is shown in Figure 2.4. Some of the predominant landuse types observed in the model outer domain include water (category 16), dry land drop or pasture (2), grassland/shrubland (7,8), and bare ground/sparse vegetable (19). As with topography, landuse is diverse in the model domain and presents a challenge for the model to perform in such a complex environment.

2.3 MODEL GOVERNING EQUATIONS

The model’s governing equations are found in the MM5 program, which is the numerical weather prediction part of the mesoscale modeling system. MM5’s equations and physics options allow for research on large and small scales. Large-scale atmospheric phenomenon such as monsoons and tropical systems and small-scale events such as fronts, land-sea breezes, and urban heat islands can all be simulated using MM5.

The equations for the nonhydrostatic model's basic variables excluding moisture in terms of terrain following coordinates (x, y, s) are as follows:

Pressure

\[
\frac{\partial p'}{\partial t} - \rho_0 g_w + \gamma p \nabla \cdot \mathbf{v} = -\mathbf{v} \cdot \nabla p' + \frac{\gamma p}{T} \left( \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta \right)
\]

(2.2)
FIGURE 2.4  Landuse file used in the model initialization.
Momentum x-component (2.3)

\[ \frac{\partial u}{\partial t} + \frac{m}{\rho} \left( \frac{\partial p'}{\partial x} - \frac{\sigma}{p*} \frac{\partial p'}{\partial \sigma} \right) = - \mathbf{V} \cdot \nabla u + u \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) - w \cos \alpha - \frac{uw}{r_{\text{earth}}} + D_u \]

Momentum y-component (2.4)

\[ \frac{\partial v}{\partial t} + \frac{m}{\rho} \left( \frac{\partial p'}{\partial y} - \frac{\sigma}{p*} \frac{\partial p'}{\partial \sigma} \right) = - \mathbf{V} \cdot \nabla v - v \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) + w \sin \alpha - \frac{vw}{r_{\text{earth}}} + D_v \]

Momentum z-component (2.5)

\[ \frac{\partial w}{\partial t} - \frac{\rho_0 g}{\rho p*} \frac{\partial p'}{\partial \sigma} + g' = - \mathbf{V} \cdot \nabla w + g \frac{p_0 T}{p T_0} - \frac{g_{R_d}}{c_p} \frac{p'}{p} + e(u \cos \alpha - v \sin \alpha) + \frac{u^2 + v^2}{r_{\text{earth}}} + D_w \]

Thermodynamics

\[ \frac{\partial T}{\partial t} = - \mathbf{V} \cdot \nabla T + \frac{1}{\rho c_p} \left( \frac{\partial p'}{\partial t} + \mathbf{V} \cdot \nabla p' - \rho_0 g \mathbf{w} \right) + \frac{Q}{c_p} + T_0 \frac{\dot{D}_\theta}{\theta_0} \]  
(2.6)

Advection terms can be expanded as

\[ \mathbf{V} \cdot \nabla A \equiv m u \frac{\partial A}{\partial x} + m v \frac{\partial A}{\partial y} + \sigma \frac{\partial A}{\partial \sigma} \]  
(2.7)

where

\[ \dot{\sigma} = - \frac{\rho_0 g}{p*} \frac{w}{p*} \frac{\partial p*}{\partial x} u - \frac{m \sigma \partial p*}{p*} \frac{\partial v}{\partial y} \]  
(2.8)
Divergence term can be expanded as

$$\nabla \cdot \mathbf{v} = \frac{2}{m} \frac{\partial}{\partial x} \left( \frac{u}{m} \right) - \frac{m \sigma}{p^*} \frac{\partial}{\partial x} \frac{\partial u}{\partial \sigma} + \frac{2}{m} \frac{\partial}{\partial y} \left( \frac{v}{m} \right) - \frac{m \sigma}{p^*} \frac{\partial}{\partial y} \frac{\partial v}{\partial \sigma} - \frac{\rho_0 g}{p^*} \frac{\partial w}{\partial \sigma}$$

(2.9)

### 2.4 MODEL PHYSICAL SCHEMES

Model physics are included in the MM5 program in the modeling system and can be changed according to the user’s desire. The model simulation for this research uses surface layer similarity for the constant flux layer and MRF planetary boundary layer (PBL) parameterization scheme for the mixed layer (Hong and Pan 1996). MRF PBL is based on Troen-Mahrt representation of the countergradient term and K profile in the mixed layer. This type of representation is also used in the NCEP MRF model. The scheme also requires a soil model that calculates ground temperature at multiple levels.

The model uses explicit equations for cloud water, rainwater, ice and water vapor. The Simple Ice scheme was used to account for the ice phase processes. There is no supercooled water and immediate melting of snow below the freezing level.

Kain-Fritsch cumulus parameterization scheme was used account for sub-grid scale convection (Kain et al., 1993). The Kain-Fritsch parameterization is complex sloud-mixing scheme that is capable of solving for entrainment or detrainment. The scheme also removes the available buoyant energy in the relaxation time. Updraft and downdraft properties are also predicted. The influence of shear effects on the precipitation efficiency is also considered by the Kain-Fritsch scheme.

A cloud-radiation scheme was used to account for the interaction of shortwave and longwave radiation with clouds and the clear air. The scheme is useful in simulating...
the atmospheric temperature tendencies. Surface radiation fluxes are also providing by using the cloud-radiation scheme.

A five-layer soil model was use to predict the ground temperature at 1,2,4,8,16 cm with fixed substrate below using the vertical diffusion equation (Dudhia et al., 1996). The scheme is capable of resolving diurnal temperature variations that result in a more rapid response from the surface temperature.

3.1. Introduction

Thermodynamic profiles obtained during Pre-INDOEX ship cruises have shown the presence of an elevated mixed layer or land plume over the Arabian Sea and tropical Indian Ocean (Manghanani et al., 2000). A hypothesis for the development of the land plume was suggested based on the air mass modification process by Raman et al (2002). The objective of this chapter is to further investigate the mechanism of formation of the land plume and its structure and also study the growth of the marine boundary layer (MBL) offshore based on a comprehensive set of observations during the field phase of INDOEX in 1999. In addition, latitudinal variation of the concentrations of gases such as ozone in these two distinct layers in the lower troposphere will be presented. Understanding the transport processes of pollution in the land plume and the marine boundary layer over the Arabian Sea will contribute to the main goal of INDOEX (1999), which is assessing the magnitude of radiative forcing caused by aerosols and gases.

3.2. Data Platforms

Various observation platforms were used during the intensive field phase of INDOEX (1999) to obtain a comprehensive data set. The research vessels (R/V) used during the IFP were Ron Brown and Sagar Kanya. The research aircraft that participated in INDOEX (1999) are EC-130Q Hercules, Citation II, Geophysica, Falcon, and Mystere. Constant level balloons were deployed from Goa, India to study low-level air trajectories. Radiosondes were released at various locations to obtain vertical profiles of
winds, temperatures, moisture, and ozone concentrations in the troposphere. Surface observations were made at the Kaashidhoo Climate Observatory located in Maldives, in Mauritius, and in Mt. Abu, Pune, and Trivandrum, India and Tromelin Island, Reunion. Remotely sensed data were obtained using the following satellites: EOS, FY-2, ScaRaB (RESURS), Meteosat 5, NOAA 14 and 15, and the Tropical Rainfall Measuring Mission (TRMM) satellite.

3.3. Discussion of Results

A distinct elevated thermal layer over the ocean was observed in thermodynamic profiles obtained during pre-INDOEX cruises by research vessel (R/V) Sagar Kanya. This layer suggested the presence of an elevated land plume during the northeast monsoon (Warrior 1999). R/V Sagar Kanya, along with R/V Ron Brown, also collected data during INDOEX (1999). Cruise tracks of R/Vs Ron Brown and Sagar Kanya during INDOEX (1999) are shown in Figure 3.1. R/V Ron Brown started from Port Louis, Mauritius at 20°S, and moved north to near 20°N. The atmosphere is generally more pristine south of the equator due to less pollution from land masses. However, as R/V Ron Brown moved further north along the west coast of India, ozone concentrations are expected to increase due to the presence of the continental air mass. R/V Sagar Kanya started from Goa, India located at a latitude of 14.2°N. The two research vessels had tracks that enabled measurements to determine latitudinal and longitudinal variations in aerosol and anthropogenic gas concentrations over the Indian Ocean.

Locations of the various data platforms used in this study for the period March 7-9, 1999 are shown in Figure 3.2. It includes the flight tracks of the C-130 aircraft on 7
Figure 3.1. Cruise tracks of research vessels *Ron Brown* and *Sagar Kanya* during INDOEX - IFP (1999).
Figure 3.2. Location of R/Vs Ron Brown and Sagar Kanya and the flight track of the C-130 aircraft on 7 March 1999. The flight track of Mystere on 9 March 1999 is also shown.
March 1999 and the French aircraft *Mystere* on 9 March 1999. At 08 Z (13:00 LT) on 7 March 1999 the C-130 research aircraft was 1100 km off the west coast of India. The locations of the R/Vs *Ron Brown* and *Sagar Kanya* on 7 March 1999 are also indicated in Figure 2. They had a parallel track to observe offshore variations of different parameters. At 12 Z (17:00 LT), R/V *Ron Brown* was 800 km from India’s west coast while R/V *Sagar Kanya* was only 140 km from the shore. The location of the Kaaishidoo Meteorology Station is also indicated in Figure 2 to show its relative location to the west coast of India.

Daytime see breeze circulations along the west coast of India are a common feature during northeasterly monsoon because of the contrast between sea (about 30°C) and land temperatures (about 40°C). This contrast in surface temperatures induces a strong sea breeze circulation that can extend up to a distance of 100-200 km off shore as observed by R/V *Sagar Kanya* wind data and inferred from the infrared satellite imagery (shown later).

### 3.3.1 Land Plume Structure

Vertical ozone concentration profiles provide a reliable way of characterizing the land plume over the ocean. Over the Arabian Sea, ozone concentrations depend on wind direction and trajectories from land account for maximum values. Observations made at the Kaaishidoo Climate Observatory (KCO) provide a good source of data for establishing any relationship between wind direction and ozone concentrations and also the structure of the land plume. Ozone soundings were taken at KCO during INDOEX (1999) once a day. The ozonesondes were released at 09 Z (14:00 LT) to coincide with
the NOAA-14 satellite overpasses. A complete description of the ozone experiment at KCO can be found in Lobert et al. (1999).

A wind speed profile taken from KCO on 9 March 1999 at 11:00 LT is shown in Figure 3.3(a). The wind speed is constant within the 800 m depth of the marine boundary layer (MBL) with a mean value of 2 m s\(^{-1}\). A strong elevated jet with a maximum value of 13 m s\(^{-1}\) is seen above the MBL at a height of 1400 m. The winds decrease above the jet to a value of 4 m s\(^{-1}\) at 2000 m.

A wind direction profile taken from KCO on 9 March 1999 at 11:00 LT is shown in Figure 3.3(b). The wind direction in the MBL varies from northwesterly near the surface to northeasterly in most of the MBL (800 m) and in the land plume (800 to 2000 m). Northwesterly winds near the surface are believed to be due to local effects. Northwesterly to northerly wind directions are seen above 2000 m. The core of the elevated jet at 1400 m is in the layer of northeasterly winds occurring between 800 m and 2000 m.

The ozone concentration profile observed on 9 March at 09 Z (14:00 LT) is shown in Figure 3.3(c) as a solid line. High concentrations of ozone were observed in the land plume between the altitudes of 800 m and 2000 m. A maximum concentration of 90 ppb occurred at an altitude of 1600 m, the location of the jet maximum. In the 700 m depth of the MBL, the ozone concentration is approximately 30 ppb, appreciably lower as compared to the concentrations in the land plume.

Ozone concentrations depend very much on the trajectories of air masses (and hence the wind direction). The concentration profile (dashed) for 5 February 1999 at 09 Z (14:00 LT) is shown in Figure 3.3(c). Winds at this time varied from southerly to
Figure 3.3.  (a) Wind speed profile at Kaashidhoo Climate Observatory (KCO) on 9 March 1999 at 06Z.  (b) Wind direction profile at KCO at same time as (a).  (c) Ozone concentration profiles taken at KCO on 5 February 1999 for southwesterly wind direction (dashed line) and on 9 March 1999 for northeasterly wind direction (solid line).
westerly in the lower troposphere. Ozone concentrations are constant with values less than 20 ppb in the lowest 5000 m of the atmosphere as compared to values between 30 ppb to 90 ppb observed on 9 March with northeasterly air trajectories from the Indian subcontinent. The ozone concentrations on 5 February are low and show no variation with height because the southerly and westerly winds transport an unpolluted marine air mass.

In summary, ozone concentrations in the lower troposphere at KCO were much higher on 9 March than that on 5 February because of northeasterly winds and KCO’s location relative to the Indian peninsula (shown in Figure 3.2). Northeasterly winds advect the polluted air mass from the Indian subcontinent and increase the ozone concentrations at KCO. The shift in wind direction from S-SW to NE increased the ozone concentrations at the surface by 100% and in the 1000-2000 m layer (land plume) by 400%. It appears that the bulk of the anthropogenic gases such as ozone are transported in the elevated land plume. Enhancement of ozone concentration in the land plume may also occur as a result of photochemical reactions involving NO and NO₂ being transported in the plume.

Vertical profiles of potential temperature and ozone from R/V Ron Brown also show variations consistent with the presence of the land plume as a mixed layer above the MBL separated by a shallow inversion. A typical virtual potential temperature (θv) profile from R/V Ron Brown (11°N, 68°E) on 7 March 1999, 12 UTC is shown in Figure 3.4(a). Thermodynamic structure in the lower troposphere exhibits two distinct layers over the ocean for northeasterly winds. One is a convective MBL capped by a strong inversion and the other is another well-mixed layer above this inversion again capped by another
Figure 3.4. (a) Virtual potential temperature profile taken from R/V Ron Brown on 7 March 1999 at 12Z. (b) Ozone concentration profile taken from R/V Ron Brown (11.3°N, 68.3°E) on 7 March at 13:35Z.
strong inversion. The air is fairly well mixed with a virtual potential temperature, $\theta_v$, of 303 K up to 1000 m within the MBL capped by a shallow inversion labeled A. An elevated mixed layer or land plume is present between 1600 and 3000 m. Virtual potential temperature, $\theta_v$, has a magnitude of 311 K in the elevated mixed layer. This layer represents the land plume where much of the transport of aerosols and gases from the continent occurs. Above the elevated mixed layer is a strong capping inversion labeled B. Above the second strong inversion, a stable layer exists.

An ozone concentration profile taken 800 km off the west coast of India aboard R/V *Ron Brown* (11.3°N, 68.3°E) on 7 March 1999, 13:35 UTC (18:35 LT) is shown in Figure 3.4(b). Ozone is fairly well mixed in the lower portion (500 m) of the MBL with a value of about 30 ppb. However, the concentration begins to increase towards the top of the MBL because of a change in wind direction from northerly in the first 700 m to northeasterly from 700 m to 3000 m (not shown). Immediately above the MBL, ozone concentrations increase sharply with maximum values in the 1400 – 3200 m depth of the land plume. The layer-averaged concentration of ozone for the land plume is about 70 ppb. At the top of the land plume, concentrations drop sharply to 50 ppb because of mixing with the free atmosphere through entrainment and then remain constant at 60 ppb up to 5000 m. These values are larger than those observed in the MBL by a factor of about two. Large concentrations even above the land plume (with east-south easterly wind direction) may be associated with upwind land based sources.

A potential temperature ($\theta$) profile taken from the C – 130 aircraft during Research Flight # 09 on 7 March 1999 at 13:00 LT at the location (12.3°N, 63°E), about 1100 km off the Indian coast over the Arabian sea is shown in Figure 3.5(a). The
Figure 3.5. Profiles taken from C-130 aircraft on 7 March 1999 at 14:00LT. (a) potential temperature profile, (b) wind direction profile, (c) profile of $\sigma_w$, standard deviation of vertical velocity fluctuations, and (d) ozone concentration profile.
characteristic elevated mixed layer associated with the land plume can be seen in this profile. Within the MBL, the potential temperature is well mixed up to 700 m with a value of 289 K. A strong capping inversion exists above the MBL. From 1000 to 3000 m, an elevated mixed layer is again present where a potential temperature of 308 K was observed. Another capping inversion is present just above the land plume at 3000 m.

A wind direction profile taken from the aircraft at 13:00 LT on 7 March 1999 is shown in Figure 3.5(b). Within the MBL up to an altitude of 700 m, the wind direction is from the NE. Above the MBL, the winds are easterly up to a height of 3000 m. Presence of easterly winds in the 1000 to 3000 m altitudes agrees with the conclusion that the land plume is an air mass with a trajectory from the Indian subcontinent. Above the land plume, the wind direction shifts to northerly.

The location and magnitude of the entrainment zones associated with the land plume can be determined by profiles of turbulence. Vertical variation of the standard deviation of vertical velocity fluctuations, $s_w$, taken from the C-130 aircraft on 7 March 1999 at 13:00 LT is shown in Figure 3.5(c). The $s_w$ profile gives a good estimate of the degree of turbulence present at any particular level. Values of $s_w$ were averaged over layers of 100 m up to 5000 m. At the surface, $s_w$ has a value of 0.4 m s$^{-1}$ increasing to a maximum value of 0.47 m s$^{-1}$ at an altitude of 200 m, and then decreases to 0.2 m s$^{-1}$ near the top of the MBL (700 m). Turbulence decreases above the MBL to 0.11 m s$^{-1}$ at an altitude of 2000 m. Within the land plume, the turbulence varies only slightly until the top of the land plume where $s_w$ increases to 0.22 m s$^{-1}$. This region represents the entrainment zone between the land plume and the free atmosphere. The location of the entrainment zones at 1000 m and 3000 m altitudes determined by the turbulence profile.
agrees well with the R/V *Ron Brown* ozone profile shown in Figure 3.3(c). Above the land plume, turbulence decreases to a value of 0.05 ms\(^{-1}\) and remains constant to 5000 m.

Ozone profile using the C-130 aircraft on 7 March 1999 at 13:00 LT is shown in Figure 3.5(d). Maximum ozone concentrations of 80 ppb are seen within the MBL up to a height of 500 m. Above the MBL, ozone concentrations decrease to 35 ppb at 1000 m. A layer of high ozone concentrations is seen above the MBL from 1000 to 3000 m representing the depth of the land plume. The maximum concentration in the land plume is 60 ppb and occurs at an altitude of 2000 m. Above the land plume, the concentrations remain well mixed at a value of about 20 ppb. Ozone concentrations are lower in the land plume than in the MBL because the wind direction shifted to easterly-southeasterly (Figure 3.5b) in the land plume as compared to northeasterly winds in the MBL.

A direct way of observing the dynamic structure of the land plume is to use downward looking lidar to observe the aerosol distribution over the Arabian Sea. Scattering distributions measured by a downward looking lidar on the French aircraft *Mystere* is shown in Figure 3.6. The data was collected on 9 March 1999 at 09 Z (14:00 LT) from 4.5°N to 7.0°N at 70°E. The flight track of Mystere is shown in Figure 3.2. A relatively low concentration of aerosols is indicated within the MBL by minimal backscattering up to 800 m, the height of the MBL. The small amount of backscattering observed in the MBL is caused by entrainment with the aerosol rich land plume. A layer of large backscattering indicating high aerosol concentrations is seen above the MBL from 800 to 2400 m. This layer of high aerosol concentration corresponds to the general location of the land plume. Above the land plume, low values of backscattering are observed indicating that the land plume is entraining air from the free atmosphere.
Figure 3.6. Aerosol distribution measured by airborne lidar aboard Mystere on 9 March 1999 at 1500 LT over the Arabian Sea.
Figure 3.7. Schematic diagram showing the typical daytime processes involved in the development of the land plume through air mass modification caused by land-ocean interface.
A schematic of the process of development of the land plume near the coast during a typical daytime condition is shown in Figure 3.7(a). Sea breeze circulations form near the coast during daytime when opposing large-scale easterly flow is not too strong. Narrower land breezes occur during the night. An air mass modification results with offshore flow in this region as the warmer air flows over cooler ocean surface.

Static stability of this modified layer tends to be stable with a surface-based inversion close to the coast as shown in Figure 3.7(b). With increasing distance the MBL becomes convective as the air closer to the surface adjusts to the warmer ocean temperatures and the land air mass gets modified. Height of the MBL grows with distance from the coastline through entrainment and this layer close to the ocean surface represents the air mass modified by the ocean and is capped by a shallow, but strong inversion. Growth of the MBL offshore will be discussed further in the next section. This modified air mass tends to be moister and well mixed. The convective boundary layer over land in India frequently grows to a depth of 2000 m (Raman et al, 1990) and the aerosols and gases within the boundary layer become well mixed. This air mass of about 2000 m depth above the MBL remains distinct from the modified air mass closer to the ocean surface even at large distances over the Indian ocean because of minimal large scale forcing. The second inversion above the land plume is the remnants of the inversion over the convective boundary layer over land as the air mass gets advected over the ocean.

3.3.2 Air Mass Modification and the Land Plume Development

A parallel track experiment was conducted with R/V *Ron Brown* and R/V *Sagar Kanya* on 7 March 1999 to compare their observations and to study offshore variations of
Figure 3.8. Potential temperature profiles taken from R/Vs Ron Brown (9.2°N, 69°E) and Sagar Kanya (10.6°N, 74.5°E) at 00Z on 7 March 1999.
various parameters such as winds, and ozone concentration. North-south track of R/V Sagar Kanya was 140 km from the west coast of India, while R/V Ron Brown had a near-parallel track at 800 km from the west coast of India as shown in Figure 3.2. The parallel tracks of the two research vessels provided a unique opportunity to investigate the air mass modification, MBL growth offshore, and the development of the land plume over the Arabian Sea.

Potential temperature profiles from R/V Ron Brown (9.2°N, 69°E) and R/V Sagar Kanya (10.6°N, 74.5°E) are shown in Figure 3.8. Both profiles were taken at 00Z (05:00 LT) on 7 March 1999. The solid line is the R/V Ron Brown profile and the dashed line is the R/V Sagar Kanya profile. Height of the marine boundary layer measured by R/V Sagar Kanya is 600 m while the MBL height measured by R/V Ron Brown is 1000 m. A strong inversion exists between the marine boundary layer and the land plume in both the profiles as the MBL grows offshore through air mass modification. Land plume between 1400 m and 3400 m altitudes is better developed at the location of R/V Ron Brown (800 km offshore) as compared to that of R/V Sagar Kanya (140 km). The reason for this difference is not known; however, one can speculate two possibilities. Assuming a wind speed of 10 ms\(^{-1}\), air mass arriving at R/V Ron Brown 800 km offshore would have originated from India around 09:00 LT. Therefore, the air aloft arriving at R/V Ron Brown could be the remnants of the previous daytime well mixed boundary layer thus showing the characteristic land plume uniform temperature profile. However, the air arriving at R/V Sagar Kanya, 200 km offshore, would have originated from India at 01:00 LT. This air mass will therefore be characteristic of the nighttime stable boundary layer and the residual layer aloft. Land – breeze circulations can also influence the
Figure 3.9. Potential temperature profiles taken from Ron Brown and Sagar Kanya at 12Z, 7 March 1999 over the Arabian Sea.
advection of the nighttime air mass. These circulations would affect the profiles observed from R/V *Sagar Kanya* because of its proximity to coast.

To investigate any diurnal variation in the land plume structure, thermodynamic profiles obtained at different times of the day were analyzed. Potential temperature profiles taken from R/V *Ron Brown* (11°N, 68°E) and R/V *Sagar Kanya* (11°N, 74.5°E) at 12 Z (17:00 LT) on 7 March 1999 are shown in Figure 3.9. The height of the MBL measured by R/V *Sagar Kanya* is now about 500 m as compared to 600 m at 00 Z (05:00 LT) shown in Figure 3.8. However, the MBL height obtained by R/V *Ron Brown* profile is still about 1000 m and the mixed layer is more uniform. In both the profiles, the characteristic elevated mixed layers are present. Again assuming a mean transport wind of 10 ms\(^{-1}\), the air arriving at R/V *Ron Brown* would have originated from India the previous day at 19:00 local time and deeper inversion above the MBL corresponds to the stable land boundary layer. Unlike, the 00 Z (05:00 LT) sounding, the elevated mixed layer associated with the land plume is better defined in the R/V *Sagar Kanya* profile. The air mass at R/V *Sagar Kanya* probably originated at 14 LT and is representative of the daytime convective boundary layer over land.

Moisture profiles are good indicators of air mass modification. One would expect the air to get moister with distance from the coastline. Specific humidity profiles taken aboard R/V *Ron Brown* (11°N, 68°E) and R/V *Sagar Kanya* (11°N, 74.5°E) at 12 Z (17:00 LT) on 7 March 1999 are shown in Figure 3.10. Comparing the moisture profiles from R/Vs *Ron Brown* and *Sagar Kanya*, it is apparent that the MBL is moister at the farther location. It is interesting to note that the land plume in the moisture profiles are
Figure 3.10. Specific humidity profiles taken from RVs *Ron Brown* and *Sagar Kanya* at 12Z on 7 March 1999.
Figure 3.11. (a) Wind speed profile taken from RV Sagar Kanya at 12Z on 7 March 1999 showing an elevated jet of about 11 ms−1 at a height of 2000 m. (b) Wind direction profile showing the winds at the height of the jet to be northeasterly.
characterized by a deep layer of near constant humidity corresponding to the land plume location indicating the remnants of the land based mixed layer.

Wind speed and direction profiles taken from R/V *Sagar Kanya* (11°N, 74.5°E) at 12 Z (17:00 LT) on 7 March 1999 are shown in Figures 3.11(a) and 3.11(b) respectively. The winds within the MBL are much weaker with a value of about 2 ms\(^{-1}\) at this location. Above the MBL, the wind speed profile has a well-defined jet-like structure with a maximum speed of 11 ms\(^{-1}\) at 1400 m. The altitude of this jet corresponds to the typical land plume layer discussed before. It appears the jet formation is related to entrainment of air at both the edges of the land plume and associated increase in turbulence (Figure 3.5 c). Typical offshore ozone distributions also have the same vertical structure with maximum values near the middle of the plume (Figure 3.5 d). The wind direction profile shown in Figure 3.11(b) indicates a northeasterly wind in the MBL and in the land plume between 800 m and 3000 m and corresponds well with the wind speed vertical profile in Figure 3.11(a).

### 3.3.3 Latitudinal Variation of Ozone

Analysis of latitudinal variations in ozone concentrations over the Arabian Sea will determine the magnitude of air mass modification by the land plume. Latitudinal variations of ozone concentrations measured at a height of 18 m over R/V *Ron Brown* for the period February 24 – March 19, 1999 is shown in Figure 3.12. The track of R/V *Ron Brown* during INDOEX (1999) is shown in Figure 3.1. A TECO 49 ozone instrument was used and the data averaged into 30-minute time bins. A complete description of the R/V *Ron Brown* ozone experiment is provided by Stehr et al (2002). Ozone concentrations decreased from 45 ppb at 18°N where R/V *Ron Brown* was close to the
Figure 3.12. Latitudinal variation in ozone concentration measured at a height of 18 m from R/V Ron Brown.

Figure 3.13. Latitudinal variation of mean ozone concentrations in the MBL (square) and the land plume (circle) from R/V Ron Brown observations.
source region to 10 ppb at 10°S. A regression line with a correlation coefficient of 0.95 indicates a high correlation of ozone concentration with latitude. The slope of the regression line is 1.49 ppb/ deg. latitude showing a gradual decrease in ozone concentrations towards the equator essentially by entrainment and dispersion.

To get a better idea of the transport of ozone in the two layers, MBL and the land plume, integrated layer averages of ozone concentrations were calculated for each layer. Latitudinal variation of average ozone concentration in the MBL and the land plume (defined as the layer between 2000 and 3000 m) is shown in Figure 3.13. Layer averages were calculated from ozone soundings made from R/V *Ron Brown* during its track across the tropical Indian Ocean and the Arabian Sea. Square data points represent MBL ozone concentration averages and circles represent the land plume average ozone concentrations. Regression lines were plotted for both layers with the solid line representing the land plume and dotted line representing the MBL. Ozone concentrations in the MBL decrease by a factor of two from 40 ppb at 18°N to 20 ppb at the equator. There is a more dramatic decrease in the ozone concentrations in the land plume. Concentrations decrease from 80 ppb at 16°N to 30 ppb at the equator. The slope of the regression line is 3.84 ppb/ deg., which is almost 3 times the variation of ozone in the MBL. As with the mixed layer, this regression line is well correlated with the data with R = 0.86. It is clear that the majority of ozone transport over the Arabian Sea is occurring in the land plume and the same would be true for aerosols.

### 3.4. Summary

An elevated land plume transports gases (and aerosols) from the Indian subcontinent over the Arabian Sea and the Indian Ocean. This well mixed layer has a
typical depth of 2000 m. Vertical wind distribution through this layer has a jet-like structure with the maximum winds occurring in the middle of the land plume. Marine boundary layer grows in height with offshore distance reaching a maximum depth of about 1000 m at a distance of 800 km. The MBL and the land plume are separated vertically by a strong inversion. This strong inversion is a general feature associated with the air mass modification and the formation of the land plume. The structure of the land plume appears to depend on the trajectory of the air mass and the time of origin at the coast. Analysis of high frequency aircraft turbulence observations indicate the jet-like structure of the plume to depend on the entrainments at the bottom and the top of the plume at altitudes of about 1000 m and 3000 m respectively.

The wind direction is an important factor in the variation of ozone concentration measured at the Kaaishidoo Observatory, Maldives. Ozone concentrations at the surface are 100% more when the winds are from the NE as compared to other directions. In the land plume the ozone concentrations increase by about 400% for a northeasterly wind direction.

Ozone concentrations are consistently higher in the land plume than in the MBL. The ozone concentration in both layers (land plume and the MBL) decrease towards the equator with distance from the source region. However, the ozone concentrations in the land plume decrease faster. Entrainment processes with the free atmosphere and the MBL are believed to be the reason for the sharp decrease in concentration in the land plume. Even near the equator, several hundred kilometers away from the source region, the ozone concentration in the land plume is around 30 ppb, larger than the ambient concentration of 15 ppb observed for marine air mass.
CHAPTER 4. OBSERVATIONS AND NUMERICAL SIMULATION
OF THE SEA AND LAND BREEZE CIRCULATIONS ALONG THE
WEST COAST OF INDIA.

4.1. Introduction

One interesting phenomenon observed by the various data platforms during
INDOEX (1999) was the sea and land breeze circulation along the west coast of India.
In particular, the horizontal extent of the sea breeze over the ocean was investigated.
Synoptic flow substantially influences the offshore extent of the sea breeze over the
ocean (Estoque 1962; Arritt 1989). Opposing winds can increase the convergence
associated with the sea breeze and enhance frontogenesis (Reible 1993). Large updrafts
over a depth of 30 to 350 m along the west coast of India have been observed with
SODAR during the passage of sea breeze fronts (Prakash 1992).

The horizontal extent of the sea breeze over the Arabian Sea near Bombay was
found to be around 120 to 150 km while the inland penetration of the circulation is
greater than 80 km (Dixit 1964). Horizontal extent of the sea breeze over the ocean in the
tropics has been quoted at distances up to 300 km (Wexler 1946, Clarke 1955)
Observations from a 10 m tower aboard R/V Sagar Kanya showed the existence of the
sea breeze over the ocean at a distance of 80 km from the west coast of India
(Subrahramam et al 2001).

Aerosols and gases can be transported from India over the ocean in the marine
boundary layer. Westward propagating cloud bands originating near the west coast of
India were observed with a geo-stationary satellite during INDOEX 1999 (Desmaland
2002). The presence of cloud bands appears to depend largely on the magnitude of the
sea and land breeze circulation. Peaks in aerosol and CO concentration were observed as the cloud bands passed research vessel (R/V) *Ron Brown* (Simpson and Raman 2003).

Transport of pollutants in the MBL depends on the extent and intensity of coastal sea-land breeze circulations. The objective of this paper is to investigate the sea and land breezes along the west coast of India using a set of multiplatform observations during the field phase of INDOEX (1999). Numerical modeling of the coastal circulation will also be used to provide further insight into the timing and magnitude of the coastal circulations. Understanding the horizontal extent of the sea breeze and its role in pollution transport over the Arabian Sea will contribute to the core objective of INDOEX (1999), which is assessing the magnitude of radiative forcing caused by aerosols and gases.

During March, the daytime land surface temperature over India approaches 38°C while the sea surface temperature is around 28°C. The contrast in surface temperature sets up the thermally based sea breeze circulation as shown in Figure 4.1(a). Vertical depth of the sea breeze circulation is generally around 1km. The onshore flow is observed to penetrate inland around 80 km. Onshore winds interact with the mountainous topography along India’s west coast to produce deep convection and heavy rainfall. The offshore extent of the sea breeze varies depending on the synoptic flow but is usually between 150 to 200 km.

The land breeze circulation develops during the night when the land surface temperatures drops to around 20-25°C while the sea surface temperature remains the same. Offshore flow at the surface results from the temperature gradient as shown in Figure 4.1(b). Contrast in surface temperatures between ocean and land are not as great
Figure 4.1. (a) Schematic diagram showing the sea breeze circulation along the west coast of India. (b) same as (a) but showing the land breeze.
during the night as during the day. As a result, the depth of the land breeze is generally lower than the sea breeze and does not have a large horizontal extent over the ocean.

4.2. Data Platforms

Several different data platforms were used during INDOEX (1999) to measure parameters relevant to the magnitude and horizontal extent of the sea and land breezes along India’s west coast. These platforms include the research vessel (R/V) Sagar Kanya, Meteosat-5 infrared satellite, constant level balloons, and observations from coastal stations at Bombay, Goa, and Trivandrum, India. A detailed description of the various platforms is presented below.

4.2.1 Coastal Stations

Wind data were collected using pilot balloons at Bombay (18.55°N, 72.50°E), Goa (15.25°N, 73.43°E), Trivandrum (8.5°N, 77°E), India during INDOEX (1999). The winds were measured twice daily at 00 Z (0500 LT) and 12 Z (1700 LT). The location of the three stations is shown in Figure 4.2. Data from these stations was used for this paper because their locations will exhibit any latitudinal differences in the magnitude of the sea and land breeze along the west coast of India.

4.2.2 R/V Sagar Kanya

R/V Sagar Kanya is operated by the Indian Department of Ocean Development. The track of R/V Sagar Kanya and its location denoted by Julian day during the parallel track experiment portion of INDOEX (1999) is shown in Figure 4.2. The parallel track experiment was from March 3 -11, 1999. On 7 March 1999, R/V Sagar Kanya was within 130 km of the west coast of India. Such close proximity to the west coast of India provided an unique opportunity to study the horizontal extent of the diurnal coastal
Figure 4.2. Location of coastal stations and the ship track for research vessel Sagar Kanya during the parallel track experiment during INDOEX (1999).
circulation over the Arabian Sea. Soundings were made several times a day during the parallel track experiment to observe the wind profiles. R/V Sagar Kanya was also equipped with a sun photometer to measure aerosol optical depth.

4.2.3 IR Satellite Data

The Meteosat – 5 satellite was launched on 2 March 1991 under the authority of the European Space Agency (ESA). Meteosat - 5 is a meteorological satellite with a geostationary orbit operating within the worldwide network of the World Weather Watch of the World Meteorological Organization (WMO). The general mission of Meteosat - 5 is imaging in the visible, infrared, and water vapor regions of the spectrum. Meteosat –5 was moved over the Indian Ocean in 1998 to measure data during INDOEX.

4.2.4 Constant Level Balloons

Constant level balloons were released from Goa, India (location shown earlier in Figure 4.2.) to visualize the wind flow in the boundary layer near the west coast of India and the eventual transport towards the Inter Tropical Convergence Zone (Appu 2001). Balloons were launched around 04:30 LT just before the peak of the land breeze so that the balloon would drift towards the ocean. The balloons were filled with helium and maintained a nominal flight pressure of around 925 hPa. Balloons were equipped with a GPS receiver to measure 3D position, a pressure sensor, a thermistor mounted on the pressure sensor to control its temperature and correct for possible thermal pressure drifts, a thermistor for measuring air temperature, and a commercial hygrometer for relative humidity. Data were sampled and stored on board every 30 minutes. Stored data were transmitted daily to two satellites.
4.3. Observations

4.3.1 Coastal Stations

Land breezes during the night are a common occurrence along the west coast of India. The u-component of the horizontal wind at Bombay at 00 Z (0500 LT) on 2 March 1999 is shown in Figure 4.3(a). Winds are easterly (offshore) at the surface with a magnitude of about 4 ms$^{-1}$. The easterly winds increase to a maximum of about 9 ms$^{-1}$ at a height of 100 m. Winds remain easterly up to a height of 1200 m where they shift to westerly. Westerly values of around 5 ms$^{-1}$ are observed up to 3000 m.

Easterly winds near the surface are also observed further to the south at Goa at 00 Z (0500 LT) on 2 March 1999 as shown in Figure 4.3(b). The winds near the surface are around 1 to 2 ms$^{-1}$. Winds remain weak and easterly up to 3000 m with a maximum value of 5 ms$^{-1}$. Westerly winds aloft were observed at Bombay and not at Goa located further south because of the strong northeast monsoon winds present in much of the troposphere.

Weak offshore flow at the surface is also observed at Trivandrum, south of Goa, at 00 Z (05:00 LT) of 2 March 1999 as shown in Figure 4.3(c). The easterly winds at the surface are around 0.5 ms$^{-1}$ and increase to a maximum of 8.5 ms$^{-1}$ at 1700 m. Easterly winds are observed from the surface up to 3000 m. No westerly winds aloft are observed at Trivandrum because of the strong northeast monsoon flow in the troposphere observed in southern India.

Winds at the surface shift from easterly to westerly during the transition from land to sea breeze along the west coast of India. Westerly (onshore) winds at the surface are observed at Bombay at 12 Z (17:00 LT) on 2 March 1999 as shown in Figure 4.4(a).
Figure 4.3. (a) The u-component of the horizontal wind at Bombay, India at 00Z on 2 March 1999. (b) Same as 2(a) but at Goa, India. (c) Same as 2(a) but at Trivandrum, India.
Winds at surface are around 2 ms\(^{-1}\) and reach a maximum of 4 ms\(^{-1}\) at 300 m. Above 1000 m, the winds shift to easterly but remain light with values around 2 to 3 ms\(^{-1}\).

Onshore flow is also observed further to the south at Goa at 12 Z (17:00 LT) on 2 March 1999 as shown in Figure 4.4(b). The westerly winds at the surface are around 3 ms\(^{-1}\) and reach a maximum of 4 ms\(^{-1}\) at 300 m. Above 1000 m, winds shift to easterly and reach a maximum of 10 ms\(^{-1}\) at a height of 3000 m. The easterly winds aloft were much stronger at Goa than at Bombay because of the increasing northeast monsoon winds towards the equator.

The winds at the surface at Trivandrum at 12 Z (17:00 LT) on 2 March 1999 are also westerly as shown in Figure 4.4(c). Westerly winds of around 3 ms\(^{-1}\) at the surface increase to 4 ms\(^{-1}\) at a height of 300 m. Above 700 m, the westerly winds shift to easterly and reach a maximum of 13 ms\(^{-1}\) at 2100 m. As was the case in Goa, the easterly winds aloft are strong because of the return flow aloft associated with the sea breeze and the northeast monsoon winds.

Observations along the west coast of India show that the daytime sea breeze is stronger than the nighttime land breeze. Winds at the surface during the land breeze at Goa and Trivandrum were around 1 ms\(^{-1}\) while the winds during the sea breeze were around 3 to 4 ms\(^{-1}\).

### 4.3.2 R/V Sagar Kanya

Wind profiles from R/V Sagar Kanya during the Parallel Track Experiment provided an opportunity to research the horizontal extent of the sea breeze circulation over the Arabian Sea. R/V Sagar Kanya was approximately 130 km from the west coast of India on 7 March 1999. The observed u-component of the horizontal wind measured
Figure 4.4. (a) The u-component of the horizontal wind at Bombay, India at 12Z on 2 March 1999. (b) Same as 4.3(a) but at Goa, India. (c) Same as 4.3(a) but at Trivandrum, India.
Winds at the surface are light but increase to 2.5 ms$^{-1}$ at 200m. Above 200 m, the winds shift to a easterly direction and remain so up to 3000 m with values ranging from 0 to 7 ms$^{-1}$.

The observed u-component of the horizontal wind measured from R/V Sagar Kanya at 08 Z (13:00 LT) on 7 March 1999 is shown in Figure 4.5(b). Winds are observed to be easterly (offshore) from the ocean surface up to 3000m. Wind speed values range from 0 to 8 ms$^{-1}$. The easterly winds throughout the depth of the lower troposphere at this time may be a result of the northeast monsoon winds.

By 12 Z (17:00 LT) on 7 March, the winds near the surface measured from R/V Sagar Kanya have shifted to westerly (onshore) as shown in Figure 4.5(c). Wind values range from 1 to 3.5 ms$^{-1}$ up to 700m. Above 700m, the winds shift to easterly and remain so up to 3000 m. The maximum easterly wind observed at this time is around 10 ms$^{-1}$. The wind shift observed in the lowest 700 m of the atmosphere is believed to be due to the developing sea breeze circulation.

Winds at the surface are still easterly at 18 Z (01:00 LT) on 7 March as shown in Figure 4.5(d). The values range from 0 to 4.5 ms$^{-1}$ up to 800 m. Above 800 m, the winds shift to easterly and remain so up to 3000m. Maximum easterly values are still around 10 ms$^{-1}$. The westerly winds in the lower portion of the atmosphere still suggest the influence of the sea breeze.

The wind shift in the lowest 700 m of the atmosphere measured by R/V Sagar Kanya while it was 130 km from the west coast of India suggests the influence of the sea
Figure 4.5. (a) The u-component of the horizontal wind measured 130 km from the west coast of India from R/V Sagar Kanya at 00Z on 7 March 1999. (b) Same as 4.4(a) but at 08Z. (c) Same as 4.4(a) but at 12Z. (d) Same at 4.4(a) but at 18Z.
breeze circulation. Wind speeds at the surface changed little but a more dramatic wind shift is observed at a height of 200 to 300 m.

Anthropogenic aerosols and gases from the Indian subcontinent are transported by the land breeze over the ocean. Aerosol optical depth (AOD) measured by a sun photometer (Jayaraman 2001) aboard R/V Sagar Kanya from 6 to 9 March 1999 is shown in Figure 4.6. R/V Sagar Kanya was located at approximately 130 km from the west coast of India during this time period as shown earlier in Figure 4.2. The AOD measured at 1700 LT on 6 March 1999 was 0.75 AOD units. AOD values increase as the sea breeze weakens and the northeast flow in the lower troposphere dominates and transports a continental air mass off shore. A peak of 1.8 AOD units is measured at 0800 LT on 7 March. AOD values then decrease as the daytime sea breeze develops and transports a less polluted marine air mass towards R/V Sagar Kanya. By 1700 LT on 7 March 1999, the AOD value had decreased to 0.5. An increase in AOD is again observed as the sea breeze weakens and by 0800 LT on 8 March the observed AOD is around 1.6. The AOD then decreases as the sea breeze develops and AOD values have dropped to around 0.6 by 1700 LT on 8 March 1999. Weakening of the sea breeze circulation and strong northeast flow in the lower troposphere along the west coast of India results in the sudden increase of anthropogenic aerosols and gases over the Arabian Sea.

4.3.3 IR Satellite Data

Infrared satellite images provide an opportunity to research the horizontal extent of the daytime sea breeze circulation over the ocean. An infrared satellite image taken by Meteosat 5 on 7 March 1999 at 14:30 LT over the Arabian Sea is shown in Figure 4.7. A region of warm temperatures (red) is seen along the west coast of India. This region of
Figure 4.6. Aerosol optical depths measured from R/V Sagar Kanya during the parallel track experiment showing peaks at 0800 LT on 7 March and at 0800 LT on 8 March 1999.
Figure 4.7. Meteosat 5 infrared satellite image at 14:30 LT on 7 March 1999 showing the horizontal extent of the sea breeze over the Arabian Sea to be around 200 km.
warm temperatures represents the unpolluted marine air mass being advected onshore by the daytime sea breeze. Cooler temperatures observed far from the coast are caused by attenuation of the infrared signal by aerosols and represent an air mass of continental origin. The region of warm temperatures is seen extending for about 200 km offshore and represents the horizontal extent of the sea breeze over the ocean. The cooler temperatures observed further offshore represent a polluted continental air mass that originated from the Indian subcontinent.

**4.3.4 Constant Level Balloons**

Horizontal extent of the sea breeze over the ocean can also be investigated using data obtained from constant level balloons released along the west coast of India during INDOEX (1999). The track of balloon # 10 from 13 to 16 February 1999 is shown in Figure 4.8. The balloon was released during the night and was transported over the ocean by the offshore winds near the surface associated with the land breeze. Once the balloon reached its constant height of 800 m, offshore winds associated with sea breeze circulation transport the balloon to a maximum distance of 140 km from the shore. The balloon then moves back towards the coast as a result of westerly winds aloft associated with the land breeze. After briefly moving towards the coast, the balloon escapes the influence of the coastal circulation and is transported by the northeast monsoon flow towards the ITCZ.

Larger offshore extent of the sea breeze over the ocean was observed by balloon # 11. The track of balloon # 11 from 14 to 16 February 1999 is shown in Figure 4.9. The balloon was released during the night and transported over the ocean because of the easterly winds at the surface associated with the land breeze. As the balloon rose to
Figure 4.8. Track of constant level balloon # 10 at an altitude of 925 hPa from 13 to 16 February 1999 during INDOEX.
Figure 4.9. Track of constant level balloon # 11 at an altitude of 925 hPa from 14 to 16 February 1999 during INDOEX.
around 800 m, the influence of the easterly winds aloft associated with the sea breeze pushed the balloon further over the ocean. A maximum distance of 200 km from the west coast of India was observed before the balloon began to move back towards the coast. Onshore winds aloft associated with the land breeze transported the balloon back towards the coast. As the winds shifted to offshore aloft because of the sea breeze, the balloon became nearly stationary during the day of 15 February 1999. The balloon was then transported by strong northeast winds away from the coast and the influence of the sea and land breeze.

Not all of the balloons released got caught up in the sea and land breeze circulation. The track of balloon # 16 from 24 to 26 February 1999 is shown in Figure 4.10. Easterly winds at the surface associated with the nighttime land breeze push the balloon over the ocean. As the balloon rises to 800 m, the easterly winds aloft associated with the sea breeze transport the balloon further over the ocean. Once the balloon is around 200 km from the coast, the balloon slows down and is then eventually transported by the northeast monsoon winds toward the ITCZ. Since the land breeze circulation is generally weaker than the sea breeze, perhaps the northeast winds were much greater than any return circulation and prevented the balloon from moving back towards the coast.

4.4. Numerical Simulation

A numerical mesoscale model is used along with observations to better understand the horizontal extent of the sea and land breeze over the Arabian Sea and the magnitude of inland vertical motion caused by the sea breeze along India’s west coast.

4.4.1 Model Description

A three-dimensional, non-hydrostatic version of the fifth generation of the PSU-
Figure 4.10. Track of constant level balloon # 16 at an altitude of 925 hPa from 24 to 26 February 1999 during INDOEX.
NCAR Mesoscale Model (MM5) (Grell et al., 1995) was used in this study. MM5 is a primitive equation model that uses a non-dimensional $\sigma$-vertical coordinate system. The model uses surface layer similarity for the constant flux layer and MRF planetary boundary layer (PBL) parameterization scheme for the mixed layer (Hong et al., 1996). The Kain-Fritsch cumulus parameterization scheme is used for sub-grid scale convection (Kain et al., 1993). The ground temperature is calculated using a five-layer soil model scheme (Dudhia et al., 1996).

Initial conditions were prescribed using the operational analysis from NMC, produced by the National Center for Environmental Prediction (NCEP) and archived by the National Center for Atmospheric Research (NCAR). Resolution of the archived data is 2.5° x 2.5° latitude-longitude with 15 standard pressure layers. The model was run from 00Z on 27 February to 00Z on 11 March 1999. The simulation was not continuous but rather initialized at 00Z on 27 Feb., 00Z on 2 March, 00Z on 5 March, and 00Z on 8 March 1999. This particular time period was chosen to study the horizontal extent of the sea breeze over the Arabian Sea because of the availability of wind profiler data from several stations along the west coast of India and wind profiles taken from R/V Sagar Kanya during the parallel track experiment (March 3-11).

A single nest model domain is used for the simulation. The outer domain covers an area of (38.31°N-10.61°S; 44.17°E-96.10°E) and the inner domain an area of (21.82°N-4.36°N; 61.08°E-79.01°E) as shown in Figure 4.11. The horizontal resolutions for the outer and inner domains are 30 km and 10 km, respectively. The outer domain consists of (186 x 186) grid points while the inner domain has (178 by 178) grid points. Both domains have
Figure 4.11. Map of the region showing the outer coarse (30 km resolution) and inner fine (10 km resolution) model domains.
The inner domain is arranged to include the mountains along India’s west coast.

4.4.2 Diurnal Variation of Sea and Land Breeze

Comparisons between the model output and observations need to be made to insure the model was able to simulate the timing and magnitude of the sea and land breeze. The model output is compared to observations of the land and sea breezes on 2 March 1999. A latitudinal difference in northeast winds aloft was also observed on 2 March.

Model output (dashed line) and observations (solid line) from Bombay at 00Z (05:00 LT) on 2 March 1999 is shown in Figure 4.12(a). Winds are easterly (offshore) in the lowest 1 km of the atmosphere indicating a land breeze is occurring. Above 1km, the winds shift to westerly (onshore) with a maximum value of 5 ms\(^{-1}\). The model simulated the easterly winds in the lowest 1km and the shift to westerly winds.

At Goa on 2 March 1999 at 00Z (05:00 LT), there is weak easterly flow throughout the lowest 3 km of the atmosphere as shown in Figure 4.12(b). Observed wind values range from 1 to 5 ms\(^{-1}\). The model simulates the weak wind at Goa with values ranging from 0 to 5 ms\(^{-1}\). Winds are much lighter at Goa than Bombay at this time.

Winds are stronger at Trivandrum at 00Z (05:00 LT) on 2 March 1999 as shown in Figure 4.12(c). Observed winds are easterly throughout the lowest 3 km of the atmosphere with values ranging from 0 to 8 ms\(^{-1}\). Simulated winds are also easterly in the lowest 3 km with a maximum value of 11 ms\(^{-1}\).
Figure 4.12. (a) Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at Bombay, India at 00Z on 2 March 1999. (b) Same as 4.2(a) but at Goa, India. (c) Same as 4.12(a) but at Trivandrum, India.
The model was able to simulate the latitudinal difference in winds. Strong onshore winds aloft were observed in Bombay indicating little synoptic influence on the land breeze circulation. There was no onshore flow observed to the south at Goa and Trivandrum because of the possible influence of synoptic flow.

Looking at the winds at 12 Z (17:00 LT) on 2 March 1999 will test the models ability to simulate the diurnal change in flow as well as the latitudinal difference in northeast winds aloft. The model as shown in Figure 4.13(a) simulates the observed onshore winds at the surface at Bombay at 12 Z (17:00 LT) on 2 March 1999. Westerly winds of around 2 ms\(^{-1}\) are simulated at the surface. The simulated winds then turn easterly by 300 m while the observed winds do not shift to easterly until about 1300 m. The model was unable to simulate the depth of the onshore flow but did simulate the diurnal wind shift at the surface from 00Z (05:00 LT).

Onshore flow is also simulated at Goa at 12 Z (17:00 LT) on 2 March 1999 as shown in Figure 4.13(b). Westerly winds are simulated to increase to 5 ms\(^{-1}\) at 600 m and then begin to shift to easterly. The simulated winds are within 2 to 3 ms\(^{-1}\) of the observed winds for most part of the lower atmosphere. Again the model was able to simulate the diurnal wind shift near the surface caused by the transition from a land to sea breeze.

Westerly winds at the surface are also simulated at Trivandrum at 12 Z (17:00 LT) on 2 March 1999 as shown in Figure 4.13(c). Winds of around 2 to 3 ms\(^{-1}\) are simulated at the surface and agree with observations. The simulated winds shift to easterly at around 800 m and reach a maximum value of 12 ms\(^{-1}\) at 2100 m. The model was able to simulate the increasing northeast winds towards the equator.
Figure 4.13. (a) Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at Bombay, India at 12Z on 2 March 1999. (b) Same as 4.13(a) but at Goa, India. (c) Same as 4.13(a) but at Trivandrum, India.
Cross sections are plotted to test the models ability to simulate the diurnal shift in wind direction caused by the sea and land breeze circulations. A cross section is taken from $10^\circ$N, $72^\circ$E (labeled A) to $10^\circ$N, $76^\circ$E (B) as shown in Figure 4.14(a). The cross section covers a portion of the Arabian Sea and the mountains along the west coast of India.

Weak westerly (onshore) winds are simulated along the coast at 06 Z (11:00 LT) on 6 March 1999 as shown in Figure 4.14(b). The onshore winds extend only 50 km over the ocean and represent the developing sea breeze circulation. Winds are light around 1 ms$^{-1}$ and are in the lowest 1.5 km of the atmosphere. Positive vertical motion of around 0.21 ms$^{-1}$ is produced as the onshore winds converge with the mountains. Easterly flow of around 5 ms$^{-1}$ is simulated above 1.5 km.

By 12 Z (17:00 LT) the westerly winds have extended to 150 km over the ocean as shown in Figure 4.14(c). Winds are simulated to increase towards the coast and reach a maximum of 5 ms$^{-1}$ along the coast. The depth of the onshore flow is about 700 m over the ocean. Vertical velocities of around 0.19 ms$^{-1}$ are simulated along the west coast of India as the onshore flow converges with the mountains.

Westerly winds at the surface have shifted to easterly by 18 Z (01:00 LT 7 March) on 6 March as shown in Figure 4.14(d). The shift in the winds at the surface represents the developing nighttime land breeze. Easterly winds at the surface are light around 2 to 3 ms$^{-1}$. Westerly winds are observed at a height of 500 to 1200 m and represent the return flow aloft associated with the land breeze. The return flow is around 1 ms$^{-1}$. Since the atmospheric flow at the surface has shifted to offshore, it is not surprising that the simulated vertical velocity along the coast has decreased to 0.07 ms$^{-1}$.
Figure 4.14. (a) Location of cross section taken along the west coast of India. (b) Model simulated u-component of horizontal wind in contours at 06Z (11:00 LT) on 6 March 1999. (c) same as (b) but at 12 Z on 6 March. (d) same as (b) but at 18Z on 6 March. (e) same as (b) but at 00Z on 7 March. (f) same as (b) but at 06Z on 7 March.
Easterly winds are simulated to increase with distance from the coast at 00 Z (05:00 LT) on 7 March as shown in Figure 4.14(e). The easterly flow reaches a maximum of 5 ms\(^{-1}\) around 150 km from the coast. Increasing winds over the ocean could be a result of katabatic flow caused by air cooling and rushing down the mountains along the west coast of India. No return flow is simulated with the land breeze at this time. Vertical velocities are minimal since the flow is offshore.

Westerly (onshore) winds are again observed in the lower atmosphere along the coast at 06 Z (11:00 LT) on 7 March as shown in Figure 4.14(f). The daytime sea breeze is again developing and the corresponding onshore flow is simulated to extend around 40 km over the ocean. Depth of the onshore flow over the ocean is around 200 m and reaches a maximum value of 2 ms\(^{-1}\) inland. The onshore flow results in the return of convection along India’s west coast. Vertical velocities around 0.16 ms\(^{-1}\) are simulated as the onshore flow interacts with the mountainous terrain. Easterly winds of around 6 ms\(^{-1}\) are simulated above the onshore flow.

A comparison of model output and observations has shown that the model is capable of simulating the atmospheric flow along the west coast of India. Simulated cross sections along the west coast of India will provide further insight into the horizontal extent of the sea breeze. Inland vertical motion caused by the interaction of onshore flow and the mountains along the west coast of India will also be discussed.

The location of a cross section taken along the west coast of India at Goa is shown in Figure 4.15 (a). The cross section is designed to look at the horizontal extent of the sea breeze and the influence of the coastal circulation on vertical velocity along the west coast of India.
Figure 4.15. (a) Location of cross section taken along the west coast of India at Goa. (b) Cross section of simulated circulation vectors and vertical velocity at 12Z on 5 March 1999. (c) Same as 4.15(b) but at 12Z on 7 March 1999.
Circulation vectors at 17:00 LT on 5 March 1999 along the west coast of India at Goa are shown in Figure 4.15(b). Westerly flow at the surface is simulated to a distance of 150 km from the coastline of India. Depth of the sea breeze circulation is simulated to be around 900 to 1000 m. Positive vertical velocities are produced by the onshore flow along the west coast of India. The maximum value simulated at this time is around .22 ms\(^{-1}\).

Looking at a cross section along the coast at Goa at another time will provide further insight to the variation of the horizontal extent of the sea breeze circulation. Simulated circulation vectors at 17:00 LT on 7 March 1999 are shown in Figure 4.15(c). The horizontal extent of the onshore flow is simulated to be around 150 km over the ocean, which has changed little since 5 March. Depth of the sea breeze circulation over the ocean is around 600 to 700 m. Maximum positive velocity resulting from the sea breeze at this time is around 0.17 ms\(^{-1}\). There was little change in the simulated horizontal extent of the sea breeze and inland vertical velocities from 5 March to 7 March.

To investigate any possible latitudinal variation in the horizontal extent of the sea breeze, a cross section was also taken along the west coast of India at Trivandrum. The location of the cross section is shown in Figure 4.16(a).

Circulation vectors at 17:00 LT on 5 March 1999 are shown in Figure 4.16(b). The simulated horizontal extent of the onshore flow is around 200 km from the west coast of India. This is around 50 km further offshore than was simulated at Goa for the same time. Depth of the sea breeze circulation is simulated to around 1.5 km above the
Figure 4.16. (a) Location of cross section taken along the west coast of India at Trivandrum. (b) Cross section of simulated circulation vectors and vertical velocity at 12Z on 5 March 1999. (c) Same as 4.16(b) but at 12Z on 7 March 1999.
ocean surface. Maximum inland vertical velocity resulting from the onshore flow is around 0.19 m\(^{-1}\).

Again it will be useful to look at another time for the cross section to explore any possible changes in the atmospheric flow. Circulation vectors at 17:00 LT on 7 March 1999 are shown in Figure 4.16(c). Simulated horizontal extent of the onshore flow is now around 130 km, considerably less than what is simulated for 5 March at the same location. Simulated depth of the sea breeze circulation is around 800 m. The maximum positive vertical velocity inland is around 0.24 m\(^{-1}\).

### 4.3 Simulated Trajectories

An analysis of model simulated trajectories should show the influence of the coastal circulations on air parcels along the west coast of India. Model trajectories released at a height of 10 m and simulated from 15 Z (20:00 LT) on 5 March to 00 Z (05:00 LT) on 6 March 1999 are shown in Figure 17. Trajectory 1 is released from 15.8°N, 73.5°E and is observed to move along the coast for several hours. The parcel eventually moves over the ocean and is transported by northerly winds. At 00 Z (05:00 LT), the trajectory is 200 km off the west coast of India and did not get caught up in the coastal circulations.

Further to the south at 14.2°N, 74.5°E, trajectory 2 was released and did not move much initially because of the weak winds associated with the land breeze. As the sea breeze develops, the parcel moves inland around 50 km. The parcel is lifted to around 1.5 km by interaction with the mountains and is transported out to sea by the northeast winds aloft.
Figure 4.17. Model simulated forward trajectories released at a height of 10 m and simulated from 15Z on 5 March to 00Z on 8 March 1999.
Trajectory 3 (11.5°N, 75.7°E) does not move much until the sea breeze develops. Onshore flow associated with the sea breeze transports the parcel around 50 km inland. Positive vertical motion along the mountains raises the parcel to around 2 km. Northeast winds then transport the parcel over the ocean. By 00 Z (05:00 LT) on 8 March, the parcel is around 500 km from the west coast of India.

As with the other trajectories, parcel 4 does not move much initially because of the weak winds associated with the land breeze. As the sea breeze develops, onshore flow transports parcel 4 approximately 100 km inland. The parcel is raised to about 1 km height by the vertical motion associated with the mountainous terrain. Strong northeast winds aloft transport parcel 4 over the ocean. By 00 Z (05:00 LT) on 8 March, the parcel is around 75 km from the west coast of India.

A great deal of variance is observed in the simulated trajectories. Air parcels released at 10 m in the northern region of India’s west coast did not get caught up in the coastal circulations. Parcels further to the south were brought inland by the daytime sea breeze. Interaction with the mountains lifted the parcels to 1-1.5 km. Northeast winds at the higher altitude transported the parcels over the ocean and away from the west coast.

Simulated trajectories released at a height of 1 km at 15 Z (20:00 LT) on 5 March and ending at 00 Z (05:00 LT) on 8 March 1999 are shown in Figure 4.18. Trajectory 1 moves along the coast for about 15 hours at a constant height of 1 km. Once offshore, the trajectory is seen to rise to a height of 2.5 km. The strong northeast winds at this height transport the parcel over the Arabian Sea and by 00 Z (05:00 LT) 8 March the trajectory is around 900 km from the west coast of India.
Figure 4.18. Model simulated forward trajectories released at a height of 1 km and simulated from 15Z on 5 March to 00Z on 8 March 1999.
Trajectory 2 also does not get influenced by a coastal circulation. The trajectory is observed to move offshore at a height of around 1 to 1.5 km. Strong northeast winds transport the parcel over the Arabian Sea. The parcel is around 400 km from the west coast of India by 00 Z (05:00 LT) on 8 March.

Further to the south, coastal circulations begin to influence the model simulated trajectories. Trajectory 3 is seen to move very little during the night because of the weak winds associated with the land breeze as shown in Figure 4.18. The parcel begins to move offshore at a height of 1 km because of the return flow associated with the sea breeze. The trajectory is observed to travel around 150 km over the Arabia Sea before it starts to return to the coast. Return flow aloft associated with the land breeze transports the parcel back towards the shore and comes within 50 km of the coast before the influence of the sea breeze transports the parcel back over the ocean. By 00 Z (05:00 LT) on 8 March, the parcel is around 250 km from the west coast of India.

Coastal circulations also influence the track of trajectory 4 as shown in Figure 4.18. The parcel is released from 9.3°N, 76.2°E and travels parallel with the coast during the night when the winds are light. As the daytime sea breeze develops, the trajectory is observed to move offshore because of the return flow aloft. The trajectory is around 100 km from the coast when it begins to move back towards the shore because of the land breeze. Onshore flow aloft associated with the land breeze transports the parcel inland where it interacts with the mountains along India’s west coast. The trajectory is raised to a height of around 2.5 km by convection near the mountains. Strong northeast winds at 2.5 km transport the parcel offshore and by 00 Z (05:00 LT) on 8 March the trajectory is observed around 200 km from the coast.
4.4.4 Horizontal Extent of Sea Breeze Over the Ocean

One feature of the sea breeze that is of particular interest is the horizontal extent of the circulation over the ocean. The track of R/V *Sagar Kanya* (as shown in Figure 4.2) brought the vessel close to the west coast of India during the parallel track experiment portion of INDOEX (1999). On 7 March 1999, R/V *Sagar Kanya* was at approximately 130 km from India’s west coast and launched soundings every 6 hours. The data collected provides an excellent opportunity to research the model’s ability to simulate the timing and the horizontal extent of the sea and land breeze circulations along the west coast of India.

The observed (solid) u-component of the horizontal wind measured from R/V *Sagar Kanya* and model simulated (dashed) at 00 Z (05:00 LT) on 7 March 1999 is shown in Figure 4.19(a). The model simulates the easterly flow throughout most of the lowest 3000 m of the atmosphere reasonably well. Light westerly winds were present at 200 m that the model does not simulate but for the rest of the lower troposphere the model is within 1 to 3 ms$^{-1}$ of the observed winds.

A comparison of observed winds and simulated winds at 08 Z (13:00 LT) on 7 March is shown in Figure 4.19(b). Again, the model simulates the easterly flow throughout the lowest portion of the atmosphere. The model is again within 1 to 3 ms$^{-1}$ of the observed wind speeds at all heights.

Winds at the surface shift to westerly at 12 Z (17:00 LT) because of the developing sea breeze circulation. The model is able to simulate the wind shift in the lower atmosphere at 12 Z (17:00 LT) on 7 March as shown in Figure 4.19(c). Winds
Figure 4.19. (a) Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at 00Z on 7 March 1999 from R/V Sagar Kanya. (b) Same as 4.19(a) but at 08Z. (c) Same as 4.19(a) but at 12Z. (d) Same as 4.19(d) but at 18Z.
have shifted from easterly in the lowest 700 m of the atmosphere at 08 Z (13:00 LT) to westerly at 12 Z (17:00 LT) on 7 March. The model simulated the timing of the wind shift and the magnitude of winds in the lowest atmosphere. Above 700 m, the model simulated the observed change to easterly winds aloft.

By 18 Z (01:00 LT) on 7 March, the model has simulated the weakening of the westerly winds in the lower atmosphere as shown in Figure 4.19(d). The observed winds in the lowest 500 m of the atmosphere have begun to weaken but there is still moderate westerly flow at 200 to 300 m that the model does not resolve. However, above 700 m, the model simulates the shift to easterly winds and is within 1 to 3 ms$^{-1}$ of the observed winds up to 3000 m.

A comparison of wind profiles taken from R/V Sagar Kanya and simulated wind profiles shows that the model was able to simulate the wind shift near the ocean surface caused by the developing sea breeze along India’s west coast. Observed winds in the lowest 700 m of the atmosphere shifted from easterly at 08 Z (13:00 LT) on 7 March to westerly at 12 Z (17:00 LT) on 7 March. The model was able to simulate the timing and magnitude of the wind shift in the lower atmosphere.

Now that a comparison of model and observed vertical wind profiles has been made, a regional comparison is needed as well. An infrared satellite image taken on 7 March 1999 at 11:30 LT over the Arabian Sea is shown in Figure 4.20(a). A region of warm temperatures (red) around 26°C is seen along the west coast of India extending up to around 100 km offshore. This region represents the horizontal extent of the sea breeze at this time.
Figure 4.20. (a) Meteosat 5 IR satellite image at 11:30 LT on 7 March 1999 showing the horizontal extent of the sea breeze over the ocean to be around 100 km. (b) Model simulated u-component of the horizontal wind at 12:00 LT on 7 March 1999 showing onshore flow extending for 100 km over the ocean. (c) Meteosat 5 IR satellite image at 14:30 LT on 7 March 1999 showing the horizontal extent of the sea breeze over the ocean to be around 200 km. (d) Model simulated u-component of the horizontal wind at 15:00 LT on 7 March 1999 showing onshore flow extending for around 200 km over the ocean.
Model simulated u-component of the horizontal wind at 10 m at 11:00 LT on 7 March 1999 is shown in Figure 4.20(b). Westerly (onshore) flow is observed along the west coast of India at this time representing the sea breeze. The simulated horizontal extent of the onshore flow over the ocean is around 100 km, which agrees with the observations shown in Figure 14(a).

An infrared satellite image taken on 7 March 1999 at 14:30 LT is shown in Figure 4.20(c). The region of warm temperatures along the west coast of India has extended further offshore due to the developing sea breeze circulation. Horizontal extent of the sea breeze over the ocean is now observed to be around 150 to 200 km.

The model should be able to simulate the strengthening of the sea breeze circulation. Model simulated u-component of the horizontal wind at 10 m at 14:00 LT on 7 March 1999 is shown in Figure 4.20(d). The region of westerly (onshore) flow along the west coast of India has extended further offshore since 11:00 LT and is now around 200 km over the ocean. This simulation agrees with the infrared satellite images showing the increase in horizontal extent of the sea breeze.

Maximum horizontal extent of the sea breeze over the ocean appears to occur along the southern portion of India’s west coast because of weaker synoptic influence. Increasing land surface temperatures towards the equator also cause larger sea breeze circulations in southern India. A cross section is taken from 11°N, 73°E (Labeled A) to 11°N, 77°E (B) and the location is shown in Figure 4.21(a). The cross section extends for 450 km from the Arabian Sea to the mountains along the west coast of India.

Westerly (onshore) winds are simulated to extend 260 km over the ocean on 6 March 1999 at 12Z (1700 LT) as shown in Figure 4.21(b). The westerly component of
FIGURE 4.21. (a) Location of cross section taken along the west coast of India (b) u-component of horizontal winds (ms⁻¹) in contours showing the horizontal extent of the sea breeze over the ocean to be around 260 km at 12Z (1700 LT) on 6 March 1999.
the horizontal wind is in contours and the winds are simulated to increase towards the coast. A maximum value of 6.0 ms\(^{-1}\) is simulated around 30 km inland. Positive vertical motion is produced as the onshore flow interacts with the mountains along India’s west coast. Maximum vertical velocities of around 0.25 ms\(^{-1}\) are simulated at a height of 1.5 km. The positive vertical velocity produced by the sea breeze is responsible for deep convection and heavy rainfall along India’s west coast.

### 4.5. Summary

Land and sea breeze circulations are shown to occur along the west coast of India during INDOEX (1999). Weak offshore winds are observed during the night while a strong onshore flow is observed during the day. Northeast winds in the 1 to 3 km layer above ground level are observed to increase towards the equator.

Wind profiles taken 130 km from the west coast of India from R/V *Sagar Kanya* reveal a wind shift due to the land and sea breeze circulations. The greatest wind shift of around 7 ms\(^{-1}\) took place in the 200 to 400 m layer above the ocean surface. Winds at the surface only changed by around 1 to 2 ms\(^{-1}\). Diurnal peaks in aerosol optical depth were measure from R/V *Sagar Kanya* during the parallel track experiment. The peaks were a result of aerosol transport from India during the land breeze and a less polluted marine air mass observed during the sea breeze.

Constant level balloons released from Goa, India during INDOEX reveal that the horizontal extent of the sea breeze over the ocean along the west coast of India varies from day to day. The sea breeze extent was shown to vary from 140 to 200 km over the ocean and varied due to synoptic flow.
A mesoscale model was used to investigate the horizontal extent of the sea breeze over the Arabian Sea. The numerical model was able to simulate the land and sea breeze circulations observed along the west coast of India. Simulated forward trajectories released at heights of 10 and 1000 m show the influence of the coastal circulations increases towards the equator. The model was also able to simulate the wind shift recorded from R/V Sagar Kanya while it was located around 130 km from the west coast of India. Simulated cross sections show the horizontal extent of the afternoon sea breeze to vary from around 130 to 260 km. Maximum vertical velocities of about 0.25 ms\(^{-1}\) were simulated inland as the onshore winds associated with the sea breeze interacted with the mountains along the west coast of India.
CHAPTER 5. DEVELOPMENT AND PROPAGATION OF A “POLLUTION GRADIENT” IN THE MARINE BOUNDARY LAYER.

5.1. Introduction

Westward propagating cloud bands were observed using a geo-stationary satellite during INDOEX (1999) (Desalmand et al 2002). Infrared temperatures recorded by the Meteosat-5 satellite showed cloud tops to be about 5°C colder than the sea surface temperature over the Arabian Sea, which corresponds to a cloud height of 600 -1000 m. In all, sixteen transient cloud bands were observed in satellite imagery from 1 January to 15 April 1999 with the most frequent observations occurring in early March.

In this chapter, observations and numerical modeling results to show that these cloud bands were in fact “pollution gradients”, leading edges of a polluted air mass from the Indian subcontinent with relatively high aerosol and anthropogenic gas concentrations. Infrared satellite data is used to show the development of this “pollution gradient” along the west coast of India and its propagation over the Arabian Sea. A hypothesis is presented for the development and propagation of this “pollution gradient” and tested using a high-resolution mesoscale numerical model. Results from this numerical simulation are compared with observations to achieve a better understanding of the characteristics of the “pollution gradient”.

5.2. Observations

Several different data platforms were used during INDOEX (1999) that measured data relevant to the formation and propagation of the pollution gradient. These platforms include R/Vs Ron Brown and Sagar Kanya, the Meteosat-5 infrared satellite, and coastal
soundings from Mangalore, India (12.9°N; 74.9°E). Detailed descriptions of the various platforms are presented below.

R/V Ron Brown was equipped with instrumentation to measure aerosol concentrations and various anthropogenic pollutants during INDOEX (1999). R/V Ron Brown is operated by NOAA’s Office of Marine and Aviation Operations (OMAO). R/V Sagar Kanya is operated by the Indian Department of Ocean Development. Aerosol data used in this paper were measured from R/V Ron Brown from the equator to 20°N over the Northern Indian Ocean and the Arabian Sea. The R/V Ron Brown aerosol concentration data used in this paper was obtained from the INDOEX (1999) data base maintained by Joss Data Management Center (http://www.joss.ucar.edu/cgi-bin/codiac/ds_proj?INDOEX) called CODIAC that supplies public domain data from INDOEX to researchers.

The cruise tracks of the research vessels R/Vs Ron Brown and Sagar Kanya during INDOEX (1999) are shown in Figure 5.1. R/V Ron Brown started from Port Louis, Mauritius (20°S, 57°E), and moved as far north as 20°N. The atmosphere is generally less polluted south of the equator due to fewer land sources. However, as R/V Ron Brown moved north along the west coast of India, ozone concentrations increased due to the presence of the continental air masses. R/V Sagar Kanya started from Goa, India. The two research vessels had parallel tracks that enabled measurements to delineate latitudinal and longitudinal variations over the Arabian Sea and the Indian Ocean.

The tracks of R/Vs Ron Brown and Sagar Kanya during the parallel track portion of INDOEX (1999) are shown in Figure 5.2. R/V Ron Brown’s track is from 26
Figure 5.1. Ship tracks of R/Ns Ron Brown (solid) and Sagar Kanya (dashed) during INDOEX (1999)
February to 10 March. *R/V Ron Brown* was approximately 800 km off the west coast of India and recorded high concentrations of aerosols and carbon monoxide over the Arabian Sea even at this large distance offshore. Measured concentrations of the aerosols and CO showed a diurnal variation. *R/V Sagar Kanya’s* track during 3 - 10 March brought the ship within 140 km of the west coast of India. This parallel track was designed so that the two ships could record the development of the marine boundary layer (MBL) and the offshore variation in anthropogenic aerosols and gases.

The Meteosat – 5 satellite was launched on 2 March 1991 under the authority of the European Space Agency (ESA). Meteosat - 5 is a meteorological satellite with a geostationary orbit operating within the worldwide network of the World Weather Watch of the World Meteorological Organization (WMO). The general mission of Meteosat - 5 was imaging in the visible, infrared, and water vapor region of the spectrum.

Mangalore (12.9°N; 74.9°E) is located along India’s west coast as shown in Figure 5.2. Soundings were made twice a day at 00 Z (5:00 LT) and 12 Z (17:00 LT) at Mangalore during INDOEX (1999). Soundings from Mangalore are used to show the development of the land and sea breeze along the west coast of India.

### 5.3. Pollution Gradient

The polluted air mass in the marine boundary layer has a sharp gradient of aerosols and other pollutants at the leading edge. This region with high concentrations defines the boundary between the unpolluted marine air mass over the Arabian Sea and the air mass from the Indian subcontinent high in aerosol and anthropogenic gas concentrations.
Figure 5.2. Ship tracks of R/Vs Ron Brown and Sagar Kanya during the parallel track experiment phase of INDOEX (1999). Location is denoted by Julian day.
3.1 Satellite Data

Remotely sensed data from the Meteosat - 5 infrared (IR) satellite is able to show the presence of the pollution gradient because the unpolluted marine air mass corresponds to the SSTs in infrared images and the polluted continental air mass to cooler temperatures. The polluted air mass appears cooler than the marine air mass in the IR image because of attenuation caused by the aerosols. The location of the pollution gradient is along the horizontal gradient of warm and cooler temperatures as observed by the IR sensor. Locations of the research vessels are denoted by “RB” (R/V Ron Brown) and “SK” (R/V Sagar Kanya) in the IR images in Figure 5.3.

No discernable pollution gradients are observed by IR satellite at 22:30 LT on 5 March 1999 as shown in Figure 5.3(a). However, by 4:30 LT on 6 March two front-like features are apparent at as shown Figure 5.3(b). One pollution gradient is located at 62°E. Another gradient is located along the strong temperature gradient in the IR image at 74°E near the west coast of India. The formation of the pollution gradient at 4:30 LT is believed to have been caused by the land breeze and strong NE winds (shown later). The region labeled “1” is the unpolluted marine air mass with significantly less aerosols than the continental air mass. Therefore, the IR signal is able to see the ocean surface without attenuation and records the warm sea surface temperature. The region labeled “2” is the aerosol rich continental air mass that shows up as cooler colors. This region appears cooler because the aerosols are scattering the infrared spectrum and result in a weaker signal. The location of the pollution gradient is along the gradient of polluted continental air mass (dark colors) and the unpolluted marine air mass (warm colors). The pollution gradient is oriented from north to south at a longitude of 72°E. R/V Ron Brown
Figure 5.3. (a) Infrared Satellite Image showing the location of the pollution gradient 22:30 LT on 5 March 1999. (b) same as (a) but at 04:30 LT on 6 March. (c) same as (a) but at 10:30 LT on 6 March. and (d) same as (a) but at 16:30 LT on 6 March.
was located at 6.5N 70.8E in the unpolluted marine air mass at this time as shown in Figure 5.3(b).

By 10:30 LT on 6 March 1999, the location of the pollution gradient near the coast of India has moved to the west by about 200 km and is centered at a longitude of 71°E as shown in Figure 5.3(c). The gradient is just east of R/V *Ron Brown* which is located at 7.1N, 70.2E. Again the clean marine air mass shows up as warm temperatures in the IR image and is denoted as region “1”. The aerosol rich continental air mass shows up as cooler temperatures and is denoted by region ‘2”. The gradient in infrared temperatures indicates the location of the pollution gradient. The region of warm temperatures now appearing along the coast, denoted by region “3”, represents the advection of the marine air mass onshore by the developing sea breeze circulation.

At 16:30 LT on 6 March 1999, the gradient has become tilted with the northern region of the gradient around 66°E while the southern part of the gradient is still around 70°E as shown in Figure 5.3(d). The gradient moved past R/V *Ron Brown* (8.0N, 69.3E) at approximately 13:00 LT and one would expect to see the aerosol and gas concentration increase at this time (shown later). The clean marine air mass shows up as warm temperatures and is labeled as region “1”. The aerosol rich continental air mass shows up as a region of cooler temperatures and is labeled region “2”. The near shore region labeled “3” corresponds to the marine air mass being advected on shore by the strong daytime sea breeze. Formation of the sea breeze is discussed in a later section.

### 3.2 Observations from Research Vessels

During the parallel track experiment of INDOEX (1999), R/V *Sagar Kanya* was 140 km off the west coast of India while R/V *Ron Brown* was 800 km off the coast. The
location of the two ships provides an excellent opportunity to observe the transport of aerosols from the Indian subcontinent over the Arabian Sea. Aerosol optical depth (AOD) was measured from a sun-photometer aboard R/V *Sagar Kanya* during INDOEX 1999 (Jayaraman et al 2001). AOD measurements from 6 to 9 March 1999 during the parallel track experiment are shown in Figure 5.4. Peaks in AOD of 1.6 to 1.8 optical depth units were observed at 8am LT on 7 March and at 8am LT on 8 March. These peaks result from the passage of the pollution gradients over the Arabian Sea. The continental air mass has more aerosols and thus more scattering than the pristine marine air mass and results in high optical depths as the pollution gradient passes. Since R/V *Sagar Kanya* is 140 km off the coast of India, it will take the pollution gradient about 4 hours to reach the ship for a mean transport wind of 10 m s\(^{-1}\) in the MBL.

Since near shore aerosol concentration observations by R/V *Sagar Kanya* show several peaks as a result of pollution gradient passage, one would expect to find such peaks further offshore. Aerosol concentrations measured aboard R/V *Ron Brown*, located 800 km off the west coast of India, are analyzed to investigate the presence of the pollution gradient. Specifically, peaks in the aerosol concentrations should be present as the gradient moves past R/V *Ron Brown* as shown in Figure 5.3(d).

The aerosol concentration distributions measured by R/V *Ron Brown* are 30–minute averages in 24 size bins with aerodynamic diameters ranging from 0.9 to 4.7 micrometers. Aerosol concentrations were measured at 18 m above sea level through a heated mast. Densities used to convert the diameters were calculated using a thermodynamic equilibrium model (AeRho). AeRho uses ion chromatograph data from impactor measurements and the measured RH to determine the densities for each
Figure 5.4. Aerosol optical depths from R/V Sagar Kanya during the parallel track experiment.
impactor stage (Quinn and Coffman, 1998). These calculations assume the aerosol to be internally mixed. The result is a density distribution for each impactor-sampling period.

Latitudinal gradients in aerosol size concentrations were present over the Arabian Sea. The latitudinal variation in aerosol size bin 0.072 – 0.084 µm concentration taken from R/V *Ron Brown* during INDOEX (1999) is shown in Figure 5.5. Small radius aerosol size concentrations were used since large aerosols have a short residence time and cannot be detected far from the source region. The aerosol data covers the latitudes from 15°S to 20°N. A decrease in aerosol concentration is observed with distance from the source region of India. This decrease in aerosols towards the equator is due to the air being more polluted near the source region of India while the air at the equator is relatively pollution free.

Since an increase in aerosols with latitude has been established, it will be of interest to study the concentration of aerosols and other pollutants (CO) while R/V *Ron Brown* was close to the Indian coast during the parallel track experiment and the possible influence of the pollution gradients. A TECO 48 CO instrument was used to collect the CO data and a thorough description is given by Stehr *et al* (2002). The CO data was then averaged into 30-minute time bins.

An analysis of aerosol data from R/V *Ron Brown* located at about 800 km off the west coast of India during the parallel track experiment of INDOEX (1999) reveals a diurnal variation in aerosol concentration. Latitudinal variation in aerosol number size distributions for radius 0.072 – 0.084 µm measured from R/V *Ron Brown* during INDOEX (1999) is shown Figure 5.6 (solid line). The data was taken from 4 March to 10 March 1999 with the latitudes ranging from 5°N to 18°N. Several noticeable peaks in
Figure 5.5. Latitudinal variation in aerosol number concentrations measured from R/V Ron Brown.
aerosol concentrations are seen in the data caused by the successive pollution gradients. The first peak (labeled A) occurred on 5 March 01:00 LT with a concentration of 1700 N cm\(^{-3}\) at 5°N. The aerosol distribution quickly falls to 800 N cm\(^{-3}\) after the peak. Another peak (B) is seen two days later on 7 March 01:00 LT with a concentration of 1200 N cm\(^{-3}\) at 8°N. However, this increase in aerosols measured from R/V Ron Brown resulting in the peak at 01:00 LT on 7 March begins around 08 Z or 13:00 LT on 6 March. This time corresponds to the pollution gradient passage observed in satellite imagery as shown earlier in Figure 5.3(d). After the peak, the aerosol concentration again falls to 800 N cm\(^{-3}\). Another strong peak (C) in aerosol concentration is seen 19 hours later on 7 March 20:00 LT at 12°N. Again the aerosol concentration falls to around 800 N cm\(^{-3}\) after a sharp increase. Another peak (D) in the aerosol concentration is seen on 8 March at 15:00 LT at 14°N. The magnitude of this aerosol concentration peak is 1200 N cm\(^{-3}\).

Carbon monoxide measurements from R/V Ron Brown also show the presence of a pollution gradient. Latitudinal variations in carbon monoxide concentration at a height of 18 m measured from R/V Ron Brown are shown in Figure 5.6 (dashed line). Peaks in Carbon Monoxide measured from R/V Ron Brown can be correlated with the times of peaks in the aerosol concentrations. The first peak (A) in CO concentration was observed on 5 March 01:00 LT at 5°N with a concentration of 195 ppb. Concentrations gradually decrease until the pollution gradient passage shown in Figure 5.3(d) results in a peak (B) of 210 ppb on 7 March at 01:00 LT at 8°N. Again the concentration gradually decreases and the next peak (C) is seen at 12°N on 7 March 20:00 LT with a concentration of 150 ppb. As with the aerosol data, a small peak in the CO concentration is seen on 8 March 15:00 LT at 14°N with a concentration of 135 ppb. Unlike the aerosol concentration
Figure 5.6. Aerosol number concentrations (solid) and CO (dashed) concentration measured from R/V Ron Brown during the parallel track experiment.
data, the carbon monoxide concentration did not increase significantly with latitude over the Arabian Sea possibly because of different removal mechanism and residence time. However, the presence of identical times of occurrence of carbon monoxide and aerosol concentration peaks showed the presence of the pollution gradient where all pollutants are expected to increase sharply.

5.4. Sea and Land Breezes

Sea and land breeze circulations along the west coast of India appear to play a significant role in the formation and propagation of the pollution gradient. Thus an investigation of the variations in the diurnal coastal circulations is essential to fully understand the development of the pollution gradient.

The formation and eventual propagation of the pollution gradient appears to depend largely on the strength of the land and sea breezes along the west coast of India. The greatest change in the horizontal wind speed vector during land and sea breeze development will occur in the u-component of the wind because the Indian coastline is oriented from north to south. Observations from Mangalore, India showing the u-component of the horizontal wind speed are shown in Figure 5.7. There are easterly (offshore) winds of 1 to 2 ms\(^{-1}\) from the surface up to 400 m at Mangalore on 5 March 00 Z (05:00 LT) shown in Figure 5.7(a). Westerly (onshore) winds of 1 to 2 ms\(^{-1}\) are observed from 400 to 1500 m indicating the presence of possible return flow aloft. Above 1500 m, the u-component shifts back to synoptic easterly (offshore) flow and remains so up to 3000 m. This wind profile shows that a land breeze did develop at Mangalore.
Figure 5.7. (a) u-component of horizontal wind at Mangalore, India at 00Z on 5 March 9, (b) at 12Z on 5 March, (c) at 00Z on 6 March, and (d) at 12Z on 6 March, 1999.
By 12 Z (17:00 LT) on 5 March, winds from the surface up to about 800 m are westerly (onshore) indicating the development of a sea breeze as shown in Figure 5.7(b). Winds shifts to synoptic easterly (offshore) flow and remain so up to 3000 m with a maximum value of 7 ms$^{-1}$ thus showing a well developed sea breeze circulation at 12 Z.

Easterly (offshore) winds develop again at the surface by 00 Z (05:00 LT) on 6 March as shown in Figure 5.7(c). Winds are easterly from the surface up to 3000 m with values ranging from 1 to 7 ms$^{-1}$. The presence of easterly winds throughout the lower troposphere and no defined land breeze circulation may have been influenced by a strong high pressure system (not shown) to the north of Mangalore with strong offshore winds.

A fully developed sea breeze was again observed at 12 Z (17:00pm) on 6 March at Mangalore with westerly winds of 2 - 4 ms$^{-1}$ as shown in Figure 5.7(d). The onshore westerly winds were observed from the surface up to 1000 m. Above 1000 m, winds shift to easterly and remain so up to 3000 m. A sea breeze appears to have developed despite the strong easterly winds caused by a high pressure system to the north.

Observations from Mangalore show that strong onshore flow of about 5 ms$^{-1}$ developed on 6 March 1999 as a result of the daytime sea breeze. During the night, the flow reverses and a land breeze is observed. The presence of synoptic features, such as a strong high pressure system to the north of Mangalore, can enhance the NE (offshore) flow during the night. On 6 March 1999, a high pressure system was located to the north of Mangalore and resulted in strong synoptic easterly flow observed at heights from 1 to 3 km above the surface (shown earlier in Figure 5.7).

A hypothesis to describe the development and propagation of the pollution gradient in the marine boundary layer is presented that involves the onshore sea breeze
and the offshore land breeze circulations. With the occurrence of the sea breeze
circulation in the daytime, a progressively polluted air mass develops particularly over
the land portion of the circulation. Strong convergence along the sea breeze front over
land would also have a high concentration of pollutants when there is no deep convection
and associated precipitation. By about 2 pm LT, the sea breeze circulation is well
developed and a marine air mass with low aerosol concentrations is transported onshore
as depicted schematically in Figure 5.8(a). A sea breeze front then forms inland as
discussed above with the observations from Mangalore, India. Around 6pm LT, the sea
breeze circulation begins to weaken and the prevailing winds shift to northeasterly as
illustrated in Figure 5.8(b). As the nighttime land breeze intensifies, the polluted air mass
is pushed out to sea by the land breeze and is in the same direction as the synoptic wind
(easterly) and by about 10 pm LT a pollution gradient forms offshore as the leading edge
of this polluted air mass in the marine boundary layer. A strong high pressure system to
the north of India’s west coast enhances the offshore flow during the night. Katabatic
flow down the mountains located about 100 km inland can also increase the offshore
flow. Low level convergence appears to result as the polluted air mass encounters
relatively pristine marine air mass as illustrated in Figure 5.8(c). Weak positive vertical
velocities occur at this convergence zone associated with the pollution gradient and result
in the formation of the observed low level stratocumulus clouds.

5.5. Numerical Simulation

A numerical mesoscale model is used to simulate the atmospheric flow that
includes sea / land breezes and to test our hypothesis concerning the development and
propagation of the pollution gradient.
Figure 5.8. (a) Schematic diagram showing the development of the coastal sea breeze circulation, (b) the development of the pollution gradient, (c) and the propagation of the pollution gradient over the Arabian Sea.
5.1 Sea and Land Breeze

A comparison between numerical simulations and observations is needed to insure that the model accurately simulated the atmospheric flow in general and the development of the land and sea breeze along the west coast of India in particular. The u-component of the observed horizontal wind (solid line) at Mangalore, India and the model simulated u-component (dashed line) are shown in Figure 5.9. The model simulates the observed presence of a weak land breeze at 00 Z (05:00 LT) on 5 March at Mangalore as shown in Figure 5.9(a). The simulated u-component is approximately 0.5 m/s easterly at the surface and shifts to a westerly direction at 300 m. Westerly winds are simulated above 300 m with values 1 - 2 ms\(^{-1}\) that agrees with observations. The simulated u-component shifts back to easterly at 1500 m and remains so through 3000 m. The model accurately simulated the shallow nighttime land breeze and the weak return flow aloft occurring at Mangalore.

By 12 Z (17:00pm LT) on 5 March, the daytime sea breeze circulation has developed as shown in Figure 5.9 (b). The model simulated the shift in the u-component direction at the surface to westerly winds from the nighttime easterly winds 12 hours earlier. Westerly winds are simulated up to 1000 m that then shift to easterly. The model simulated the development of the sea breeze to an altitude of 800 m.

At 00 Z (05:00 LT) on 6 March, the observed u- component is easterly from the surface to 3000 m as shown in Figure 5.9 (c). The model simulates the easterly winds up to 3000 m except for a weak westerly flow of about 0.75 ms\(^{-1}\) at the surface. However, the simulated u-component quickly shifts to easterly at 100 m.
Figure 5.9. (a) Model simulated $u$-component of horizontal wind at Mangalore, India compared with observations at 00Z on 5 March, (b) at 12Z on 5 March, (c) at 00Z on 6 March, and (d) at 12Z on 6 March 1999.
Both observations and the model simulated $u$-component show the development of the sea breeze by 1Z (17:00 LT) on 6 March as shown in Figure 5.9 (d). The simulated $u$-component is westerly at the surface and shifts to easterly at 1000 m in agreement with the observations. Again, the model simulated the development of the daytime sea breeze at Mangalore.

5.5.2 MBL Heights

A comparison of MBL heights is provided to show that the model could simulate the growth of the MBL with distance from the west coast of India. Model simulated MBL heights and corresponding observations of the MBL heights from R/Vs Ron Brown and Sagar Kanya is shown in Figure 5.10. Comparisons between MBL heights observed (solid line) from soundings taken from R/V Ron Brown, 800 km off the coast of India, and model simulated MBL heights (dashed line) are shown in Figure 5.10(a). The model simulated MBL heights agree in general with the observed heights with the maximum difference being approximately 200 m. The average MBL height is around 900 m at this distance (800 km) from the Indian coastline.

Comparisons between MBL heights observed (solid line) from soundings taken from R/V Sagar Kanya, located at about 140 km off the coast of India, and the model simulated MBL heights (dashed line) at this location are shown in Figure 5.10(b). The observed MBL heights are lower than the heights recorded by R/V Ron Brown because R/V Sagar Kanya was much closer to the India coastline. The model simulates the lower MBL heights closer to the coast reasonably well. The model-simulated values are within $\pm 75$ m of the observed MBL heights except for a few locations. The model has thus
Figure 5.10. (a) Model simulated marine boundary layer heights compared with observations from R/V Ron Brown and (b) R/V Sagar Kayna.
been able to simulate the growth of the MBL with distance from the Indian coast and the simulations are reasonable.

5.5.3 Pollution Gradient Simulation

The location of the pollution gradient can best be found by plotting modeled convergence at 10 m. A model simulation of the convergence at an altitude of 10 m for the inner domain is shown in Figure 5.11. Corresponding locations of the pollution gradients derived from satellite imagery shown previously in Figure 3 are overlaid as solid lines with the model simulated convergence for comparison. At 2300 LT on 5 March 1999 the maximum simulated convergence associated with the pollution gradient over the Arabian Sea is $-6 \times 10^{-5} \text{ s}^{-1}$ as shown in Figure 5.11(a). The land breeze is strengthening at this time so the development of a pollution gradient is expected to occur.

By 0500 LT 6 March 1999, the land breeze is at its maximum strength and a large area of convergence is simulated over the Arabian Sea about 300 km from the west coast of India as shown in Figure 5.11(b). This area of convergence represents the location of the developing pollution gradient. The maximum convergence within the pollution gradient is approximately $-8 \times 10^{-5} \text{ s}^{-1}$.

At 1100 LT 6 March 1999, the simulated convergence associated with the gradient has reached a maximum of $-10 \times 10^{-5} \text{ s}^{-1}$ and the location of the gradient is clearly discernable in Figure 5.11(c). The gradient extends for about 800 km over the Arabian Sea and since 0500 LT the gradient has moved 80 km to the west. Convergence is now seen along the west coast of India as well because of the developing on shore flow caused by the sea breeze circulation.
Figure 5.11. (a) Model simulation convergence at 10 m height at 23:00 LT on 5 March 1999, (b) at 0500 LT on 6 March, (c) at 1100 LT on 6 March, and (d) at 1700 LT on 6 March. Solid line represents the corresponding observed location of the pollution gradient.
The pollution gradient weakens by 1700 LT 6 March 1999 shown by the diminishing area of simulated convergence in Figure 5.11(d). The maximum convergence is now \(-7 \times 10^{-5} \text{ s}^{-1}\) and is only found in two small pockets within the larger areas of convergence. Weakening of the gradient has occurred because the sea breeze circulation is now at a maximum for the day and has turned the winds from NE to SE. The wind shift has resulted in less convergence over the Arabian Sea. Strong convergence extending along the west coast of India shows the impact of the sea breeze circulation. Large regions of convergence with a magnitude of greater that \(-14 \times 10^{-5} \text{ s}^{-1}\) exist along the west coast of India.

A cyclonic circulation centered around 9°N, 73°E is observed in the model simulated 10 m convergence along the southern end of the pollution gradient. This circulation may play a role in the intensity and propagation of the pollution gradient. A more detailed examination of the circulation is presented later.

Looking at a cross section of the convergence associated with the pollution gradient will show the depth of the gradient and its propagation. A convergence cross section from a location “A” over the Arabian Sea (7°N, 68°E) to a location “B” along the west coast of India (13°N, 76°E) through the pollution gradient indicated in Figure 5.12(a). The depth of the cross section is only 4 km since we are primarily concerned with the dynamics of the pollution gradient in the lower troposphere.

At 0500 LT on March 6, an area of convergence is simulated at approximately 350 km off the west coast of India as seen in Figure 5.12(b). The region of simulated convergence is the location of the pollution gradient at this time. The maximum convergence simulated is around \(-10 \times 10^{-5} \text{ s}^{-1}\). Positive vertical velocities of about 16 cm
Figure 5.12. (a) Map showing the locations of cross sections, (b) cross section of model simulated convergence across the pollution gradient over the Arabian Sea at 0500 LT on 6 March, (c) same as 5.12 b, but at 1100 LT on 6 March, and (d) same as 5.12 b, but at 1700 LT on 6 March 1999.
s$^{-1}$ are observed and extend up to 4 km. The depth of the pollution gradient is simulated to be around 700 m, in agreement with the observations presented earlier in Figure 3(a).

Maximum simulated convergence is around $-18 \times 10^{-5}$ s$^{-1}$ by 1100 LT 6 March 1999 as shown in Figure 5.12(c). The gradient has propagated towards the west and is now 420 km from the west coast of India. The depth of the convergence has grown to 900 m by this time. A maximum positive vertical velocity of 17.7 cm s$^{-1}$ results from the convergence.

By 1700 LT on 6 March 1999, the offshore flow has weakened and is resulting in less convergence over the Arabian Sea as shown in Figure 5.12(d). The gradient is now 500 km from the west coast of India. The maximum convergence has decreased to $-8 \times 10^{-5}$ s$^{-1}$ and the depth is again around 700 m. The maximum positive vertical velocity has decreased to approximately 6 cm s$^{-1}$.

As shown in Figure 5.12, positive vertical motion is one of the features associated with the pollution gradient. The vertical motion at an altitude of 1000 m caused by the pollution gradient at 11:00 LT on 6 March 1999 is shown in Figure 5.13. The simulated positive vertical velocity is present over a distance of about 600 km over the Arabian Sea. The maximum positive vertical velocity at 1000 m is around 8 cm s$^{-1}$ while the velocity in the majority of gradient is around 4 to 5 cm s$^{-1}$. Locations of positive vertical motion correspond well with the location of the pollution gradient at this time as was shown earlier in Figure 5.3(c). The maximum vertical velocity simulated was about 20 cm s$^{-1}$ and it was at an altitude of about 500 m.

Another model simulation was conducted using the same physics except for subgrid scale convective parameterization. Using no convective parameterization will
Figure 5.13. Model simulated vertical velocity (cm s$^{-1}$) at a height of 0.9 km at 11:00 LT on 6 March over the Arabian Sea.
give us a more realistic representation of the clouds forming along the aerosol gradient. Low stratocumulus clouds are simulated over the Arabian Sea because of the weak positive vertical motion associated with the pollution gradient. The total simulated cloud-mixing ratio at 12:00 LT on 6 March 1999 at 900 m over the Arabian Sea is shown in Figure 5.14. The clouds are located around 300 km off of the west coast of India and stretch from 71°E to 67°E. The maximum cloud-mixing ratio is 0.096 g kg\(^{-1}\) but the majority of the cloud-mixing ratio values are lower. The length of the clouds extends from 8°N to 13°N with the majority of the cloud cover along 13°N. The model simulated cloud liquid water agrees with the observed narrow cloud band shown in Figure 5.3(a) extending from 70°E to 67°E with the majority of the cloud coverage to the north.

A cross section of simulated convergence taken along the cyclonic circulation seen in Figure 5.11 will further explain the role of the coastal circulation on the strength of the gradient. The cross sections in Figure 5.15 are taken to a height of 4 km and extend horizontally from over the Arabian Sea (9°N, 71°E) labeled A to the west coast of India (9°N, 77°E) labeled B.

At 0500 LT 6 March 1999, the width of the simulated convergence associated with the circulation is approximately 160 km while the depth is 800 m as shown in Figure 5.15(b). Strong off shore flow caused by the land breeze has caused the area of convergence to form. The maximum convergence is around \(-16 \times 10^{-5}\) s\(^{-1}\) and the vertical velocity is about 14 cm s\(^{-1}\).

By 1100 LT 6 March 1999, the maximum convergence in the circulation has increased to \(-19 \times 10^{-5}\) s\(^{-1}\) and has produced vertical velocities of about 18 cm s\(^{-1}\) as shown
Figure 5.14. Model simulated total cloud-mixing ratio at 12:00 LT on 6 March 1999 at a height of 0.9 km over the Arabian Sea and tropical Indian Ocean.
Figure 5.15. (a) Map of cross section location across the low level circulation over the Arabian Sea, (b) cross section of model simulated convergence and circulation vectors through the circulation over the Arabian Sea at 0500 LT on 6 March, (c) same as 5.15 b, but at 1100 LT on 6 March, and (d) same as 5.15 b, but at 1700 LT on 6 March 1999.
in Figure 5.15(c). The depth and the width of the convergence caused by the circulation have changed little since 0500 LT.

The developing sea breeze circulation at 17:00 on 6 March 1999 causes the convergence in the circulation to decrease to a maximum value of $-8 \times 10^{-5}$ s$^{-1}$ as shown in Figure 5.15(d). The depth of the convergence in the pollution gradient has decreased to 600 m and the width is now only 100 km. During the 12 hours of model simulation shown here, the simulated closed circulation over the southeast Arabian Sea only moves about 50 km away from the west coast of India.

5.6. Summary

A hypothesis for the formation and propagation of a pollution gradient over the Arabian Sea is proposed. The pollution gradient is defined as a boundary between the unpolluted marine air mass over the Arabian Sea and the air mass high in aerosol and anthropogenic gas concentrations originating from the Indian subcontinent.

Sea and land breeze circulations are shown to occur along the west coast of India. Strong onshore winds were observed during the day while the flow shifts to offshore during the night. The development of the pollution gradient occurs when the easterly winds advect polluted air mass offshore creating a sharp gradient in aerosol and anthropogenic gas concentrations. Propagation of the pollution gradient over the Arabian Sea occurs with strong offshore winds during the night transporting the anthropogenic aerosols and gases.

Observations during INDOEX showed aerosol number concentrations to increase with latitude over the Arabian Sea. The data also revealed several peaks caused by the passage of pollution gradients. Carbon Monoxide data also showed several peaks in
concentrations resulting from the passage of the pollution gradients. The timing of the occurrence of concentration peaks correlated well with the timing of the pollution gradient passage observed from infrared satellite images.

A mesoscale model was employed to verify the hypothesis of the formation and propagation of the pollution gradient. The numerical model simulated the formation of the pollution gradient and its propagation over the Arabian Sea. The gradient appears to develop as a result of the diurnal coastal circulations. As the sea breeze weakened, the pollution gradient was pushed out to sea by the large-scale easterly winds. Simulated convergence agreed well with the observations. The depth of the aerosol gradient extended to a height of 800 m above the surface. Maximum vertical velocities of about 20 cm s\(^{-1}\) were simulated from the low level convergence associated with the pollution gradient. Stratocumulus clouds at 900 m were shown to develop as a result of the vertical velocity caused by the pollution gradient.

Transport of aerosols and anthropogenic gases is shown to occur in the marine boundary layer through the development and propagation of the pollution gradient. This represents one mechanism of regional transport of pollution from the Indian subcontinent over the Arabian Sea and the Indian Ocean during the northeast monsoon.
CHAPTER 6. CONCLUSIONS

Observations made during the Indian Ocean Experiment (1999) show that there are two primary mechanisms for the transport of aerosols and anthropogenic gases from the Indian subcontinent over the Arabian Sea and Indian Ocean. The first mechanism for pollution transport is the elevated land plume. An air mass that is high in aerosol and gases originates over the Indian subcontinent. Strong northeast winds associated with the monsoon transport the air mass towards the ocean. The polluted air mass is transported just above the marine boundary layer. Since the MBL height increases with the distance from the coast, the height of the land plume layer is raised as it moves further away from the Indian subcontinent. Air mass modification results in a more defined land plume and higher pollution concentrations in the MBL with distance from the coast.

Height of the land plume layer is easily obtained from pollution measurements (example ozone concentration). Ozone concentrations are well mixed in the MBL. However, a noticeable increase and sharp peak in concentration is observed in the center of the land plume. Above the land plume, pollution concentrations decrease steadily and eventually become fairly constant with height in the lowest 5 km of the atmosphere. Pollution measurements reveal that the depth of the land plume is generally 1.5 to 2 km in depth and located above the MBL.

Turbulence measurements are also an effective way to find the location of the land plume. Measurements of the variance of the vertical component of wind reveal an increase in turbulence in the land plume layer. This is observed because the land plume air mass originated over land where there is a large degree of convection and turbulence during the daytime. Turbulent mixing results in an elevated wind speed jet located within
the land plume. Entrainment is observed at the bottom and top of the land plume that creates a localized jet in the middle of the land plume.

The other mechanism for pollution transport takes place within the marine boundary layer. As the daytime sea breeze develops, onshore flow at the surface brings an unpolluted marine air mass towards the coast. The marine air mass transported inland creates a convergence zone at the sea breeze front and a gradient in pollution concentrations. Easterly (offshore) winds associated with the Northeast monsoon transport the polluted mass away from the Indian subcontinent over the ocean.

Remotely sensed data is able to observed the gradient in pollution concentrations occurring in the marine boundary layer. Infrared satellite images show the less polluted marine air mass as warm colors because the sensor is able to see all the way to the ocean surface. The polluted air mass shows up as cooler colors because the high aerosol concentrations attenuate the infrared signal and results in a colder temperature measurement. Along the contrast in measured IR temperatures is the location of the pollution gradient in the MBL.

Pollution measurements made by R/V Ron Brown, 800 km from the west coast of India, show an increase in aerosol and gas concentration as the pollution gradient in the MBL passes the ship. Aerosol optical depth measurements taken from R/V Sagar Kanya, 130 km from west coast of India, reveal a diurnal variation in the aerosol concentration caused by the daily propagation of the pollution gradient in the MBL.

Sea and land breeze circulations influence the development and eventual propagation of a pollution gradient off the west coast of India. Synoptic flow in the
direction of the land breeze enhanced the propagation of the pollution gradient over the Arabian Sea.

The horizontal extent of the sea breeze over the ocean varies from 150 to 200 km. Numerical modeling results show the horizontal extent of the sea breeze over the ocean to vary with latitude with the largest extent off southern India. Westerly winds associated with the sea breeze were simulated as far as 250 km over the ocean in southern India.
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