Atmospheric Dispersion of PM$_{2.5}$ Precursor Gases from Two Major Thermal Power Plants in Andhra Pradesh, India

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ABSTRACT

Fine particulate matter (PM$_{2.5}$) predominantly comprises sulphates and nitrates, which results from sulphur dioxide (SO$_2$) and nitrogen oxide (NO$_x$) gases that are emanated from excessive industrial activities and transport systems. PM$_{2.5}$ is known to affect respiratory health in humans. Coal-fired thermal power plants are a major source of SO$_2$ and NO$_x$ gases. Evaluation of the dispersion characteristics of these precursor gases from the power plants would help understand the vulnerability. Meteorological conditions that prevail over the region would influence the dispersion characteristics. In this study, dispersion of SO$_2$ and NO from two major coal-fired thermal power plants in Andhra Pradesh, India have been studied using an integrated modeling approach of the Advanced Research Weather Research & Forecasting (ARW) model and Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Meteorological conditions are obtained at 3-km resolution using the ARW model and dispersions of SO$_2$ and NO is computed using the HYSPLIT model for the four seasons of winter, summer, monsoon and post-monsoon. Forward trajectories produced by the HYSPLIT model show diurnal variations and dispersion patterns show seasonal variations indicating the influence of meteorological conditions. Dispersion characteristics show high dispersion in winter due to calm and stable atmospheric conditions to insignificant in summer season due to stronger winds and higher atmospheric instability. The study establishes the usefulness of integrated meteorological and dispersion models for the evaluation of pollutant dispersion.

Keywords: Particulate matter; Dispersion; Power plants; ARW model; HYSPLIT.

INTRODUCTION

Air pollution is perceived when harmful substances (chemicals) are added to the atmosphere, in adequate concentrations and for a requisite time that would affect human health and/or cause environmental deterioration. Particulate matter (PM) is a blend of solid particles and liquid droplets present in the atmosphere, some of them released from a distinct source and others resulting from chemical reactions in the atmosphere. PM$_{2.5}$ is a particulate matter with a diameter less than 2.5 micrometres (µm). The primary sources of PM$_{2.5}$ originate from transport vehicles and industrial emissions. Apart from the primary sources, PM$_{2.5}$ is also produced through the chemical reactions of gases like sulphur dioxide (SO$_2$) and nitrogen oxides (NO$_x$), which are called secondary sources. For this reason, curtailment of the precursor gas emissions is considered important for reducing PM$_{2.5}$ levels. As of the physical process formation, PM$_{2.5}$ are chiefly produced through condensation of precursor gases such as SO$_2$, NO$_x$, and volatile organic compounds (VOCs), which comprise a larger quantum of total PM$_{2.5}$ in surrounding atmosphere (Parkhurst et al., 1999; Weber et al., 2003). Exposure to PM$_{2.5}$ pollution can cause detrimental health, and inhalation of high concentrations can exacerbate lung and heart conditions, sometimes leading to hospitalization and deaths (WHO, 2006; Xing et al., 2016). In addition, PM$_{2.5}$ particles can be transported over long distances by wind and cause contamination of the ground. This leads to the reduction of soil nutrients, crop damage and pollution of water sources, which degrades the nutrient balance in coastal waters and river basins.

The present study is confined to the assessment of dispersion of SO$_2$ and NO gases, which are precursors for PM$_{2.5}$ as they contribute to the formation of sulphates and nitrates in the atmosphere. Since coal fired thermal power plants are a major source for the release of the SO$_2$ and NO gases, the present study is an effort to determine the spatial dispersion of the concentrations of SO$_2$ and NO emanating from two major coal fired thermal power plants located in the study region (i.e.) Andhra Pradesh state of India.

Thermal power plants, using coal as fuel, are the primary source for electricity generation in India. With the escalating requirement for electricity due to growing industrial and social development, coal usage for power generation has
also been increasing. In India, coal has been mostly used due to abounding availability and competing price as opposed to importing natural gas. In India, coal based power plants are estimated to generate about 65% of the total generated power (http://indianpowersector.com/home/about/). It is widely known that the power plants in India use distinct combustion technologies under varying operating conditions and the characteristics of coal in India are unique with lower sulphur content and higher toxic elements such as “Mercury” and “Lead”. Mittal et al. (2012) estimated the SO2 emissions and reported an increase from 2519.93 Gg in 2001–02 to 3840.44 Gg in 2009–10, and the NO emissions to have increased from 1502.07 Gg to 2314.95 Gg during the decade period. The major effluents from coal fired thermal power plants are CO2, NOx, SOx, suspended particulate matter and other airborne inorganic particles. In India, coal-fired thermal power plants are to be considered as the large point sources with dominant contributions of SO2 and NOx (Garg et al., 2002). The release of SO2 is dependent on the sulphur content of the coal, whereas the concentration of oxygen and the flame temperature control the formation of NO. In the present study, emission concentrations of SO2 and NO as available from the two power plants are considered for deriving the pollutant dispersion and deposition.

Modeling methodology for the atmospheric dispersion of air pollutants is being used for the assessment of the spatial and temporal distributions of pollutants as required for air quality risk assessment and regulating the emissions. Since dispersion of the pollutants is dependent on the meteorological conditions which are highly variable and subject to variations of the land use patterns, topography and land-ocean contrast, the pollutant dispersion is subject to the influence of the local flow variations (Pielke et al., 1991; Lu and Turco, 1995). Mesoscale atmospheric models with high horizontal resolution are currently used to derive the meteorological variables associated with the mesoscale atmospheric flows over complex terrains in dispersion studies (Physick and Abbs, 1991; Kotroni et al., 1999; Wang and Ostoga-Starzewski, 2004). Segal et al. (1988) reported that the observed high concentrations of sulphur dioxide (SO2) in South Florida were due to emissions from elevated industrial sources and identified that the coastal sea breeze circulation chiefly influenced pollutant concentrations through the use of a coupled dispersion model. Similarly Moran and Pielke (1996) used a coupled atmospheric and dispersion model for examining dispersion characteristics over complex terrains. Jin and Raman (1996) used a mesoscale dispersion model to assess the influence of local topography, wind variations such as land and sea breeze and atmospheric stability on pollutant dispersion from elevated sources. Draxler (2006) had enumerated the transport and dispersion of tracer plumes over Washington, D.C., using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Myles et al. (2009) postulated that sulphur and nitrogen oxide gases in the atmosphere will form corresponding compounds that are carried to long distances and consequently deposited as particulate matter. Atmospheric dispersion over the complex terrain of the Mississippi Gulf Coast region was studied using an offline integration of a mesoscale atmospheric model for generating atmospheric variables and HYSPLIT model for dispersion (Anjaneeyulu et al., 2008; Chall et al., 2008; Anjaneeyulu et al., 2009; Chall et al., 2009). Srinivas et al. (2015) used WRF for weather prediction and FLEXPART and HYSPLIT dispersion models for the assessment of atmospheric dispersion of pollutants over Kalpakkam located on the Indian southeast coast. Modeling studies of atmospheric dispersion over India are few and the fact that atmospheric dispersion is dependent on local circulations, studies for any selected location is to be thoroughly investigated under different meteorological conditions to understand the pollutant dispersion characteristics over the region. In this context, this study presents preliminary results from the modeling of atmospheric dispersion of SO2 and NO over two important urban regions of Andhra Pradesh, India.

The study region of Andhra Pradesh (Fig. 1), is one of the 29 states of India, situated on the southeast coast of the Indian subcontinent. The state of Andhra Pradesh (AP) is the eighth largest state in India with an area of 160,205 km², and a population of about 50 million and has the second longest coastline of 974 km. The state has two major coal fired thermal power plants: (i) Simhadri Super Thermal Power Station (STPS), a modern coal-fired power plant located at 17.5938°N 83.0897°E near Visakhapatnam city that generates 2000 MW of power through a combination of four independent generation units and (ii) Vijayawada Thermal Power Station (VTPS), a coal-fired power plant located at 16.5907°N 80.5332°E near Vijayawada that generates 1760 MW. Both these power plants are located in densely populated regions, as Visakhapatnam has a population of 2 million and Vijayawada has 1 million. The population of Visakhapatnam district is continually growing due to increases of industrial activity. As this region harbors many major industries, the communities are vulnerable to pollution from STPS. Similarly, Vijayawada is an old commercial city that is currently experiencing an influx of population and growth with the new capital of AP established at about around 30 km, from the location of VTPS. As such, the new capital region, with exponential population growth in the next 5–10 years, will become much more vulnerable to the pollution from VTPS. The present study has been taken up with a view to assess the vulnerability of the Visakhapatnam and Vijayawada regions from the respective pollutant source power plants and the results may form a base to evaluate the annual increase of vulnerability.

These two thermal power plants are known to be sources of pollution that are emitting PM2.5 precursor gases. In this work, a numerical modeling approach is adopted to assess the atmospheric dispersion of SO2 and NO (secondary species of PM2.5) from two thermal power plants. The dispersions of SO2 and NO are calculated separately as they are precursors of PM2.5 contributing to the formation of sulphate and HNO3 in the atmosphere. This study is an effort to determine the spatial dispersion of SO2 and NO from the two identified sources under different meteorological conditions of four seasons. The details of the models, data and methodology are presented in the next section on methods. The results and conclusions are given in separate sections.
Methods

ARW Model
Advanced Research Weather Research and Forecasting (ARW) model is used to derive meteorological variables at a high spatial resolution of 3 km and temporal resolution of 1 hour. High-resolution meteorological fields required for the trajectory and dispersion calculations are obtained using ARW model. The ARW model uses nonhydrostatic dynamics and is designed for research and application of weather prediction at scales spanning from a few meters to thousands of kilometers. This model system has dexterity with options to designate the domain region; horizontal resolution; interactive nesting domains and with various other choices to adopt preferred parameterization schemes for convection, planetary boundary layer (PBL), explicit moisture, radiation and soil processes (Skamarock et al., 2008). In order to generate high-resolution meteorological data sets as required for pollutant dispersion, the ARW model was designed to have 3-km resolution covering the AP region. The ARW model was designed to have three nested grids with horizontal resolutions as 27, 9 and 3 km and 43 vertical levels (Fig. 2). As a part of the model set up, all the three domains are nested and two-way interactive in which the outer domain provides lateral boundary conditions for the inner domain and the inner domain values will blend with the outer domain using a smoother-desmoother filter and with the process applied from the inner domain to outer domain. The details of model configuration are given in Table 1. All the model physics parameterisation schemes follow nonhydrostatic dynamics. The USGS topography and vegetation data (24 categories) and FAO Soils data (16 categories) with resolutions 5' (9.25 km), 2' (3.7 km) and 30" (0.925 km) were used to derive the values for the three model domains respectively. The initial and time varying lateral boundary conditions for the model integrations were derived from the National...
Table 1. Configuration of ARW model.

<table>
<thead>
<tr>
<th>Model</th>
<th>WRF (ARW Core), WRFDA</th>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Radiation</td>
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<tr>
<td>Initial and boundary conditions</td>
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<td>Mellor-Yamada-Janjic TKE scheme</td>
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<tr>
<td>Explicit moisture</td>
<td>WSM3 scheme</td>
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<tr>
<td>Surface layer physics</td>
<td>Monin-Obukhov (Janjic) scheme</td>
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<tr>
<td>Land Surface</td>
<td>Noah LSM</td>
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Center of Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis data at 1 degree spatial resolution at 6-hour time intervals. For the present study, the boundary conditions were updated at 6-hour intervals (i.e.) at 0000, 0600, 1200 and 1800 UTC during the 36 hour period of model integration. The output during the first 12 hours was discarded as associated with model “spin up” and the output of the subsequent 24-hour period was stored at 1-hour intervals for use with the HYSPLIT model.

HYSPLIT Model

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is used for several applications, such as computation of parcel trajectories, simulation of pollutant dispersion and deposition (Draxler and Hess, 1998; Draxler and Rolph, 2010). HYSPLIT has the capability to generate the Lagrangian path of a particle as the trajectory and facilitates computation of the pollutant dispersion considering the pollutant particles either as a particle-ensemble or a puff. In the particle model, a consigned number of emitted particles will be advected within the model domain conforming to mean and turbulent wind components. In the puff model, the puff will expand and split as several puffs as and when the puff size exceeds the grid cube size with a share of puff mass. HYSPLIT configuration has several options for the choice of dispersion and the default is fixed as particle dispersion in the vertical and puff distribution in the horizontal directions to optimize and effectively reduce the computations of puff modeling. The vertical turbulent diffusion was treated using the Kantha and Clayson (2000) approach where the boundary layer velocity variances were defined as a function of the surface layer parameters and the mixing height. The horizontal turbulence was assumed to be proportional to the vertical turbulence. The boundary layer stability functions were derived from heat and momentum fluxes using the meteorological model fields. In the present study, we have chosen the option of varying vertical mixing with height in PBL instead of using an average value for the PBL due to its advantages in the computation of concentrations in HYSPLIT model.

In the current version of the HYSPLIT model (Draxler 2014), the sulphur module includes both the dry and wet removal of sulphur dioxide and sulphate particles considering the gas and aqueous phase oxidation of sulphur dioxide. The wet removable of gas is applied at all levels from the ground to the top of the cloud. The wet deposition can happen if the pollutant is within or below the cloud layer (as determined from humidity) with different washout coefficients which are dependent on its solubility and is governed by Henry's Law constant.

Dry deposition is assumed to occur when the pollutant is close enough to the ground. For the 3D particle method used in this study, the particle within the surface layer are only deposited. The mass from dry deposition is computed by assuming a uniform vertical concentration distribution in the layer of deposition.

If the pollutant is near the surface, there is dry deposition and the remaining part of the pollutant after deposition continue to be transported by the mean wind field at that height. In the 3D particle method adopted in this study, the dispersion carries the pollutant into the ground at given point and the pollutant with lesser mass after the deposition is reflected back and continues to transport and dispersion.

Data

Different data sets were used. They are

(i) NCEP FNL Operational Global Analysis data at 1 degree spatial resolution at 6-hour time intervals were used to produce the initial conditions and the time varying boundary conditions to make weather prediction experiments using the ARW model (http://rda.ucar.edu/datasets/ds083.2/#!access).

(ii) Average annual emission values of SO2 and NO from the two power plants in AP, from direct measurement (Central Pollution Control Board, 2010) and computation using Mittal et al. (2012) are given in Table 2.

Methodology

In the present study, an integrated modeling approach of the ARW mesoscale atmospheric model for generating meteorological fields and the HYSPLIT model for dispersion was used to identify the paths of particles from the sources using forward trajectories and then simulate the dispersion
of pollutants from the identified pollutant sources. As the first step, the ARW model was used to derive the atmospheric flow fields at 3-km resolution for the study region covering AP and its neighbourhood areas to run the HYSPLIT model. ARW model was integrated starting from 1200 UTC on each day for the period 1–7 of the months of February, May, August and November of 2014. Four of these months were identified to represent four distinct atmospheric regimes namely the winter, summer, monsoon and post monsoon. As the 2nd step, the HYSPLIT model was run, bound by the simulated 3-km atmospheric flow fields, to produce forward trajectories of parcels originating from each of the two pollutant source locations, of 24-hour duration at 1-hour intervals. These forward trajectories provide the Lagrangian path of the centroid of air parcels from the source location. As the 3rd step, the HYSPLIT model was run with estimated emission strengths, to evaluate the spatial dispersion of the pollutant from each of the sources. In these forward dispersion simulations with HYSPLIT, we used the 3-D particle mode in which the dispersion is treated with full 3-D particles in horizontal and vertical directions.

Statistical metrics of BIAS, RMSE (Root Mean Square error) and IOA (Index of agreement) used for model evaluation are computed using the formulae as:

\[ \text{BIAS} = \frac{1}{n} \sum_{i=1}^{n} (f_i - o_i) \]

\[ \text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (f_i - o_i)^2} \]

\[ \text{IOA} = 1.0 - \frac{\sum_{i=1}^{n} (f_i - o_i)^2}{\sum_{i=1}^{n} (f_i - \bar{f} + o_i - \bar{o})^2} \]

\( f_i \) is model forecast values, \( o_i \) is observation values

**Forward Dispersion Simulations**

The meteorological fields needed for input to the HYSPLIT dispersion model are the 3-dimensional wind speeds, temperature, moisture, pressure, and the 2-dimensional surface pressure, and fluxes. The HYSPLIT model linearly interpolates the meteorological profiles from this gridded input at each horizontal grid point to its terrain-following vertical grid. The dispersion simulation for 24-hour period was done over a range of about 300 km around the emission sources. In this study, the emission sources are the coal-fired power plants. Simulations of transport and dispersion were carried out for the two major coal-fired power plants situated within AP region. The hourly emission strengths of SO\(_2\) and NO are computed from the annual emission amounts with the assumption of uniform distribution throughout the year.

**Experiments**

To generate meteorological conditions, ARW model was used to make 36-hour integrations. Model outputs for the first 12-hours were discarded to avoid model spin up errors and the subsequent 24-hour period was used to drive the HYSPLIT model. Meteorological parameters of 3-dimensional fields of temperature, humidity, geopotential height, wind speed and wind direction along with 2-dimensional fields of surface pressure, 2-m temperature, 10-m wind and precipitation are derived and stored at 1-hour interval. Model integrations were performed to derive 24-hour output for 7-consecutive days of each of the four months of February, May, August and November of 2014. Meteorological variables, thus generated are used as input to HYSPLIT model. HYSPLIT model was used to generate 24-hour forward trajectories from the pollutant source. Forward trajectories are drawn at 1-hour intervals each with 24-hour duration. These trajectories indicate the Lagrangian trajectory of the pollutant in a 3-D environment. HYSPLIT model was also used to produce the pollutant dispersion. The 24-hour dispersions of the pollutant have been assessed for a 24-hour period for each of the 7 days and each of the four seasons. For all the pollutant dispersion computations with the HYSPLIT model, the height of the emission source was taken as 300 m considering the real stack height of 275 m at both the power plants. The concentration estimation was made below 10 m level considering the effective influence on humans. Sensitivity experiments with respect to the level of concentration estimation have indicated an enhancement of pollutant concentration by 15% with the level of concentration up to 100m as compared to 10m height.

**RESULTS AND DISCUSSION**

This study pertains to the assessment of the dispersion of air pollutants from two identified coal fired thermal power plants in AP. As described in the previous section, 3-D spatial distribution of the meteorological variables and 2-D surface fields were generated at 1-hour intervals, to be used for the computation of pollutant dispersion. The dispersion of a pollutant is dependent on the meteorological conditions that are known to vary continuously and have diurnal and seasonal variability. In the present study, an assessment of the characteristics of the pollutant dispersion within a 24-hour period and during each of the 4 seasons.
was made. A 7-day period (i.e.) from 1 to 7 of the months of February, May, August and November were chosen to be representative of the winter, summer, southwest monsoon and northeast monsoon seasonal regimes.

In the HYSPLIT model, the 3-D particle method was selected for computing the dispersion of the precursor gases. The HYSPLIT model has several options to choose from, and sensitivity to important parameters is required. General perception is to use the default values as is done by many of the earlier researchers who used HYSPLIT model. As a part of the present study, sensitivity experiments pertaining to the choice of the number of particles were carried out to optimize the number of particles for simulating stable and smoother dispersion. In the 3-D particle method, two important parameters (i.e.) “NUMPAR”, the total number of particles released per emission cycle and “MAXPAR”, the maximum number of particles that are permitted in the simulation are to be prescribed. In the present study, sensitivity studies have been done with NUMPAR to be 1000, 2500, 5000, 10000, 20000 and 50000 per hour; and MAXPAR is set to 24*NUMPAR respectively so that the particle release is not spuriously restrained. The dispersion patterns of the different sensitivity experiments are presented in Fig. 3. Sensitivity analysis has shown that the spatial distributions are irregular for values of NUMPAR value of 5000, and the distribution of concentration stabilized with higher NUMPAR values. Based on these sensitivity experiments, a NUMPAR value of 10000 has been chosen for all the dispersion simulations from each of the emission sources.

HYSPLIT model, bound by meteorological conditions derived using ARW model was used to produce the foreword trajectories to assess the variations of pollutant dispersion diurnally. This study is confined to the dispersion of SO2 and NO which are the precursors of secondary PM2.5. These two gases are chosen as of the availability of emission data. In the study region, there are two major coal fired thermal power plants which are located at approximately 350 km apart as shown in Fig. 1. These two power plants are situated within the vicinity of densely populated regions and are considered as major sources of air pollution. HYSPLIT model has the option to choose the options of gas or particle and contributions to dry and wet deposition. In the present study, both SO2 and NO are gases and computations have been performed with possibilities of dry and wet deposition. Computations without any deposition indicate an increase of concentration by about 6–7% only. Although computations have been performed for all the seven days of each season, results are presented only for one day (i.e.), the middle day which corresponds to the pollutant concentration within the 24-hour period from 0000 UTC of 4th to 0000 UTC of 5th. Although not presented, the concentrations show minor variations and the general pattern of the pollutant concentration remained the same.

The emission strengths of SO2 and NO are available as annual emissions and so for the purpose of computation, these values are used to obtain representative hourly emissions. In the absence of hourly emission values, the authors thought it appropriate to use the derived hourly emissions with the implied assumption of uniform emissions. Considering the study to be concerned only with the spatial extent of pollutant concentrations from the identified emission sources, the

Fig. 3. Dispersion patterns from the sensitivity experiments with respect to number of particles in HYSPLIT model. Numbers at the top left hand corner denote the prescribed number of particles for the simulation.
results have value to understand how each of the emission sources affects the surrounding regions under different meteorological regimes. The results, in terms of the wind flow patterns at 0000 UTC and 1200 UTC, forward trajectories and the spatial concentration of the PM$_{2.5}$ precursor gas (SO$_2$) are described for each of the seasons. Since the emission rate of NO is about one order smaller than SO$_2$, the significantly polluted region in terms of health standards are noted to confine to a very small region of less than 5 km near the source. Hence the results of dispersion of NO are not presented. In the dispersion diagrams, concentration ≥ 20 µg m$^{-3}$ are only contoured following the threshold of health standard for 24-hour mean of SO$_2$ (WHO, 2014).

**February**

The wind flow shows an increase of wind speed from February, with wind speeds at 2–5 m s$^{-1}$ over ocean region. The wind direction also manifests strong differences between 0000 UTC and 1200 UTC with wind flow from the southeast at 1200 UTC (Figs. 5(a) and 5(b)). At VTPS, most of the trajectories had paths towards the north and a few of them towards the west and north (Fig. 5(c)). The path of the trajectories had higher elevation, some of them reaching 3 km and a few of them 5 km also. During the summer season, the pollutant concentration is highly dispersive both horizontally and vertically indicating a minimal polluting effect both at VTPS and STPS (Figs. 5(d) and 5(f)). This indicates the effect of the strong summer winds and strong vertical mixing in the planetary boundary layer.

**August**

The wind flow is largely dominated by the southwest monsoon current, with westerly winds prevailing over the land region (Figs. 6(a) and 6(b)). Wind speeds are higher at 5–10 m s$^{-1}$ over most of the region except near VTPS where the wind speeds are 2–5 m s$^{-1}$. The trajectories from VTPS source show (Fig. 6(c)) a clear and distinct direction towards east. Correspondingly, the concentration is oriented towards east and with the maximum extending up to 50 km radius (Fig. 6(d)). The trajectories from STPS show a narrow region (Fig. 6(e)) towards east-northeast and the particles’ movements are confined to lower levels below 700 m. At this time, the pollutant concentration is oriented towards east at VTPS and east-northeast at STPS. At VTPS, high concentrations of 20–40 µg m$^{-3}$ extended to about 30 km (Fig. 6(d)) as compared to about 50 km at STPS (Fig. 6(f)). The slight differences in the wind direction and speed due to local effects are manifested both in the trajectories as well as the dispersion pattern.

**November**

The wind flow shows wind from the northeast, and with a speed of 2–5 m s$^{-1}$. Wind flow is from northwest at VTPS and north at STPS at 0000 UTC which changed to northeast at 1200 UTC both at VTPS and STPS (Figs. 7(a) and 7(b)). At VTPS, the trajectories are mostly oriented towards south and the particles are confined to below 900 m (Fig. 7(c)). At STPS, the trajectories are mostly oriented towards south and about 30% had the path oriented towards the south and southwest, corresponding to the change in wind direction. The path of the trajectories is confined to below 900 m (Fig. 7(c)). The pollutant concentration extended towards south at both the VTPS and STPS sites. However the concentration is higher at VTPS (Fig. 7(d)) with the region of 20–40 µg m$^{-3}$ extending up to 40 km as compared to 30 km at STPS (Fig. 7(f)). Both at VTPS and STPS, higher concentrations of 40–80 µg m$^{-3}$ are noted within the 20–30 km distance. This pattern corresponds to post-monsoon with weaker winds and higher atmospheric stability. The above description brings out the salient features of the pollutant dispersion and the seasonal variation. The differences in the pollutant dispersion characteristics between the two sources also bring out the importance and influence of local meteorological conditions. To summarize, both VTPS and STPS had similar pollutant dispersion as insignificant in May; towards the east in August and towards
Fig. 4. Simulated wind flow near the surface (hatched regions denote wind speed and vectors represent wind direction); forward trajectories and spatial distribution of \( \text{SO}_2 \) concentration for the period 04–05 February, 2014. (a) wind flow at 0000 UTC; (b) wind flow at 1200 UTC; (c) forward trajectories at VTPS, Vijayawada; (d) concentration sourced from VTPS, Vijayawada; (e) forward trajectories at STPS, Visakhapatnam; and (f) concentration sourced from STPS, Visakhapatnam.

south in November. In February, the dispersion orientations are different, towards north at VTPS and east at STPS. The dispersion pattern also exhibits the maximum to be at 10 km extending outwards, which is due to the stack height of 300 m and the computation of concentration confined to 0–10 m. The areal extent of the concentration indicates the influence of the seasonal varying wind strength. The HYSPLIT model experiments "with" and "without" deposition have indicated a 4% rise of pollutant concentration when deposition is not included.
Model Evaluation

Since meteorological conditions play an important role in the atmospheric dispersion of pollutants, an evaluation of model predicted meteorological variables is made. The magnitudes of 10m level wind direction and speed at two locations nearest to the two power plants from model predictions are compared with corresponding observations. Statistical metrics of RMSE, BIAS and IOA are computed for each of the two locations and are presented in Table 3.

The results show a very good agreement between the model prediction and the observations as evident from lower RMSE, BIAS and higher IOA values.

The model produced SO₂ concentration during the four seasons are compared with corresponding monthly averaged concentrations (Pollution Control Board, Government of Andhra Pradesh) within the vicinity of 30-km for the two thermal power plants. The results clearly denote maximum concentration during February followed by 60% reduced
concentration in May and August and the lowest during November. The very good agreement validates the integrated WRF-HYSPLIT modelling approach for the assessment of pollutants sourced from thermal power plants.

**CONCLUSIONS**

This study is an effort to assess the dispersion of SO$_2$ and NO gases sourced from two coal-fired thermal power plants in Andhra Pradesh, India. Since the dispersion patterns are influenced by mesoscale local atmospheric circulations which are strongly dependent on the local static variables such as land use and topography, there is need to ascertain the pollutant concentration dispersion under different meteorological conditions for an identified locality. The two power plants are established near thickly populated urban localities and are known to pollute the environment. One of the power plants is situated near the
coast and the other is located inland and provides the contrasting differences of pollutant dispersion between inland and coastal circulation regimes. The pollutant dispersions are estimated through an integrated modeling approach, with ARW model, providing simulations of 24-hour meteorological conditions at 3-km resolution and HYSPLIT model generating the forward trajectories and dispersion patterns from the two sources under different meteorological conditions. Since meteorological conditions show strong diurnal and seasonal variations, dispersion characteristics are produced for a 24-hour period and for representative periods of the winter, summer, monsoon and post-monsoon seasons. Emission strengths as annual values for the two sources are taken from the reports of the Central Pollution Control Board, India and hourly emissions are computed with the assumption of uniform emissions from the source. In the absence of any other data, the authors used the only data available from one official source. This
assumption may not restrict the application of these results, as the dispersion patterns would be the same for the prescribed meteorological conditions and the magnitudes may vary as per the emission strengths. The conclusions from the study are as follows;

(i) Meteorological variables simulated by the ARW model agree with the observations and analysis over a larger resolution. The model derived wind flow shows diurnal and seasonal variations as of observations.

(ii) HYSPLIT model generated forward trajectories show the paths of the particles with diurnal variation in conformity with wind variations. The trajectories show paths toward southeast, northeast, east-northeast and south at STPS, Visakhapatnam during the months of February, May, August and November respectively. Contrastingly, VTPS at Vijayawada had trajectory paths towards west, north, east and south respectively.

(iii) Sensitivity of HYSPLIT model in the selection of the number of particles to be released per hour and the compatible 24-hour value is studied. The results show that the dispersion may not be smooth and stable unless a minimum threshold number of particles are taken. This result is important for users of HYSPLIT as the default values may not always be suitable to produce stable results.

(iv) HYSPLIT model had simulated the pollutant concentration distribution within a 24-hour period, corresponding to the two sources and for the four seasons. Higher concentrations are observed during winter due to low wind speed, calm and stable atmospheric conditions. During summer, the concentrations have been insignificant attributed to stronger winds and higher atmospheric instability. Dispersion during the monsoon and post-monsoon seasons is noted to be within 30–40 km, but with different directions.

(v) The pollutant concentrations due to the power plants have been more than 20 µg m⁻³ indicating possible health issues. Although 20 µg m⁻³ may not significantly affect the health, it needs to be remembered that there are other sources of these precursor gases in urban localities such as transport vehicles which would exacerbate the pollution effects.

This research study brings out the influence of meteorological conditions on the dispersion of pollutants. The static variable data of topography and land use are seen to be prominent to produce the mesoscale atmospheric circulation features that significantly influence the dispersion of the pollutants. The integrated modeling approach of ARW model for simulating the meteorological variables and the HYSPLIT model for computing the dispersion are shown to provide good and stable estimations of pollutant dispersion. These results are encouraging and the authors would further use this methodology for more detailed investigation of pollutant dispersion over India.

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