Comparison of Two Prognostic Models WRF and TAPM for Short Ranged Forecasts for Kaiga, India

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Abstract

This study compares the performance of two widely used prognostics models Weather Research and Forecasting (WRF) and The Air Pollution Model (TAPM) for short ranged forecasts for Kaiga site. Several cases during the past few years (2004-2006) were formulated and executed using the two models. The variables compared were near surface temperature, humidity and wind components. The cases selected for simulation correspond to occurrences of annual maximum, minimum temperature and maximum wind speed in the years (2004-2006). This choice of cases has enabled us to cover selected days in almost all the twelve months. Results suggest that, for specific humidity, in most of the cases simulated, the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) values in the WRF model are < 0.002 kg kg\(^{-1}\) which indicates a good performance and the errors in the TAPM model are greater than that in the WRF model. The Index of Agreement (IOA) for both the models is ~ 0.4. In case of temperature, the MAE of the WRF model is ~ 2 \(^0\)C in almost all the simulations, the RMSE is < 3 \(^0\)C and the IOA is > 0.9. These values indicate a good model performance. Corresponding figures for the TAPM model are ~ 2.5 \(^0\)C for MAE, and ~3.5 \(^0\)C for RMSE which are on the higher side with respect to the reference values and the WRF model. The results indicate that for temperature and humidity, the WRF model performs better than TAPM in all the case studies conducted. In case of wind components, the statistical indices like MAE, RMSE, IOA show little variation among the two models; however, differences with the observation were seen.

Keywords: WRF model, TAPM model, Short ranged forecast, Prognostic modeling, Kaiga.

1. Introduction

Prognostic atmospheric models are used for operational weather forecasting in the aviation sector, agricultural sector, for emergency preparedness in the nuclear industry and for routine weather updates. Models differ from each other in terms of built in assumptions, degree of complexity of equations and methods of solution. The models intended for use in emergency preparedness are generally those which can provide a reasonable answer within short time and less computational resources as opposed to the models generally used in research where computational time and resources used are less important. The different modeling approaches, however, need to be compared with each other, before selecting a particular approach for the intended application. The study on the comparison of models deals with the performance of models under similar but not identical input conditions.

A number of model inter comparison studies have been carried out by several other investigators. For example Lu et al. (2011) evaluated three models namely Mesoscale Meteorological version 5 (MM5), Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) and Weather Research and Forecasting (WRF) over south east United States for the warm season in 2003 and cold season in 2003-2004. This study compared model generated values of surface wind, sea level pressure, surface temperature and rainfall at 129 locations in the domain with the corresponding observed values. The results of the three
models for surface wind, sea level pressure and surface temperature showed seasonal dependence. For precipitation it was seen that MM5 under predicted the seasonal precipitation where as COAMPS and WRF over predicted it. An evaluation of surface variables using WRF and Eta models was carried out by Cheng and Steenburgh (2005) for the warm season in 2003. They found that the WRF model had larger 2 – m temperature and dew point mean absolute and bias errors as compared to Eta. In case of 10 m wind speed, WRF over predicted it while Eta under predicted it. Tang et al. (2009) evaluated the performance of The Air Pollution Model (TAPM) against MM5 at urban scale during GOTE2001 field campaign in Gothenburg (Sweden) and showed that TAPM performs better than MM5 in simulating near surface air temperature and wind in urban area, both models reproduce night time vertical temperature gradient well and under estimate the day time temperature gradient and both of them significantly under estimate the occurrences of low wind speed conditions at night. The performance evaluation of the WRF model using different parameterization schemes during winter season for a semi arid region was carried out by Soni et al. (2014).

The present study focuses on the comparison of the WRF and TAPM models for Kaiga site. Kaiga is one of the sites where nuclear power plants are operated for generation of electricity by Nuclear Power Corporation of India Ltd (NPCIL). For model performance evaluation as well as for the inter comparison of model results, the simulation periods are selected based on the occurrences of annual maximum, minimum temperature and maximum wind speed in the years 2004-2006. The extreme cases provide an opportunity to select days from different months of the year. A brief description of the two models used in this study namely WRF and TAPM are presented in the next section. The methodology followed and results are presented in the subsequent sections.

2. WRF Model

The WRF (Skamarock et al. 2008; Wei et al., 2009) is an advanced weather forecast model developed by National Oceanic and Atmospheric Administration (NOAA), National Centre for Atmospheric Research (NCAR), University Corporation for Atmospheric Research (UCAR) etc. under collaboration with many universities and institutions. This model is suitable for applications across scales ranging from few kilometer to thousands of kilometers like real time numerical weather prediction (NWP), coupled model applications, data assimilation research etc. It is a fully compressible, non hydrostatic model using a terrain following coordinate system. It solves the full Navier Stokes equations including the curvature terms. Various physical processes not resolved by the model are represented by parameterization schemes. On an average there are 6–7 parameterization schemes (as of version 3.1.1) for each process such as shortwave and long wave radiation, cumulus convection, cloud microphysics, and physical processes in the planetary boundary layer and surface layer. WRF also has advanced data assimilation options where in radiance data from satellites as well as wind, temperature and humidity measurements from various instruments can be assimilated into it.

3. TAPM Model

TAPM is a coupled meteorological and air pollution model. The meteorological component of TAPM is an incompressible, non–hydrostatic, primitive equation model with terrain following vertical coordinate for three dimensional simulations. It solves momentum equations for horizontal wind velocities, the incompressible continuity equation for vertical velocity and scalar equations for virtual potential temperature and specific humidity of water vapor, cloud water and rain water, turbulent kinetic energy and eddy dissipation rate. Meteorological -

Table 1: Description of case studies

<table>
<thead>
<tr>
<th>Simulation Period</th>
<th>Case study</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>00Z 26 December 2004 – 00Z 29 December 2004</td>
<td>Minimum Temperature</td>
<td>TMN1</td>
</tr>
<tr>
<td>00Z 17 January 2005 – 00Z 20 January 2005</td>
<td>Minimum Temperature</td>
<td>TMN2</td>
</tr>
<tr>
<td>00Z 26 January 2006 – 00Z 29 January 06</td>
<td>Minimum Temperature</td>
<td>TMN3</td>
</tr>
<tr>
<td>00Z 13 March 2004 – 00Z 16 March 2004</td>
<td>Maximum Temperature</td>
<td>TMX1</td>
</tr>
<tr>
<td>00Z 04 April 2005 – 00Z 07 April 2005</td>
<td>Maximum Temperature</td>
<td>TMX2</td>
</tr>
<tr>
<td>00Z 23 February 2006 – 00Z 26 February 2006</td>
<td>Maximum Temperature</td>
<td>TMX3</td>
</tr>
<tr>
<td>00Z 03 May 2004 – 00Z 06 May 2004</td>
<td>Maximum Wind Speed</td>
<td>WX1</td>
</tr>
<tr>
<td>00Z 16 June 2005 – 00Z 19 June 2005</td>
<td>Maximum Wind Speed</td>
<td>WX2</td>
</tr>
<tr>
<td>00Z 02 July 2006 – 00Z 05 July 2006</td>
<td>Maximum Wind Speed</td>
<td>WX3</td>
</tr>
</tbody>
</table>
parameterizations include explicit cloud microphysics, a vegetative canopy and soil scheme as well as radiation at the surface. The air pollution model uses predicted meteorology and turbulence at each time step and represents pollutant dispersion through a combined Eulerian and Lagrangian approach. It also includes plume rise, gas and aqueous phase chemical reactions, wet and dry deposition. Detailed technical discussions on TAPM can be found in (Hurley, 2005). This model is not suitable for horizontal domain sizes greater than 1500 km by 1500 km since curvature effects are neglected in this model.

4. Materials and Methods

The study domain covers south west India centered at the Kaiga Generating Station (KGS) (14° 51’ 48” N, 74° 26’ 31” E) as shown in the Fig 1. Kaiga is situated in the valley of the Kali river on the southern bank of the man made Kadra reservoir. There are minor forests and patches of agricultural land on both the banks of the river. The ghats are covered by major evergreen and semi evergreen forests with the average height of the trees being above 15 metres. A small fraction of land is used for agricultural purposes. The average height of the Western Ghats in the region is around 600 metres. The Environmental Survey Laboratory (ESL, Kaiga) carries out meteorological measurements at Kaiga site. The meteorological instrumentation at the site includes a Stevenson screen for measurement of temperature and relative humidity at 1.2 m, a 60 m tower for wind measurements at multiple levels (10 m, 40 m and 60 m), a rain gauge and a solarimeter. Based on the analysis of these data during 2004-2007, it is seen that on an annual basis, the predominant wind sectors are West southwest (WSW), West (W), ENE (East northeast) and NE (Northeast) with the average wind speed being of the order of 1 m s\(^{-1}\). In summer, temperatures reach around 40 °C whereas in winter temperatures of 14 °C are observed at this site. This region receives very good rainfall with the cumulative rainfall from June to September being about 3700 mm.

The WRF model version 3.1.1 is integrated using three nested domains with grid spacing varying from 27 km, 9 km, and 3 km. The grid points in the three domains are 180 x 180; 220 x 220 and 244 x 244 respectively. The WRF model uses 28 vertical sigma levels. The model sigma levels (height in km) are: 1.000 (0.035), 0.990 (0.106), 0.978 (0.204), 0.964 (0.329), 0.946 (0.486), 0.922 (0.687), 0.894 (0.934), 0.860 (1.309), 0.817 (1.802), 0.766 (2.317), 0.707 (2.858), 0.644 (3.651), 0.576 (4.687), 0.507 (5.726), 0.444 (6.769), 0.380 (7.817), 0.324 (8.865), 0.273 (9.914), 0.228 (10.962), 0.188 (12.000), 0.152 (13.060), 0.121 (14.104), 0.093 (15.163), 0.069 (16.241), 0.048 (17.353), 0.029 (18.521), 0.014 (19.9735) and 0.000 (20.000). The terrain and land use data for the innermost domain are taken from the 30” resolution data, for intermediate domain it is obtained from 5’ data, and for the outermost domain it is obtained from 10’ data supplied by the United States Geological Survey (USGS). For the WRF model, the parameterization schemes used in this study were chosen based on the studies carried out by the authors.
for the site (Shrivastava et al., 2014). The physics options consist of the Mellor Yamada Janjic Eta (MYJ, Janjic 1990, 2002) as the PBL scheme, Monin Obhukhov Janjic Eta (MYJ, Monin et al., 1954; Janjic, 1996) as the Surface Layer scheme, Noah land surface model (Chen and Dudhia, 2001) as the land surface scheme, Rapid Radiation Transfer Model for long-wave radiation (RRTM, Mlawer et al., 1997), Dudhia (Dudhia, 1989) for short-wave radiation, Kain Fritsch scheme for cumulus parameterization (Kain and Fritsch, 1990; Kain, 2004) and Ferrier new Eta (Ferrier et al., 2002) scheme for representing microphysical processes in the clouds. The National Centers for Environmental Prediction (NCEP) Final Analysis data available at 6 hourly interval on a 1° x 1° resolution are used to supply initial and boundary conditions.

TAPM is used to generate 3 dimensional flow fields for Kaiga site using a domain of 40 x 40 grid points in the horizontal direction and 50 grid points in the vertical direction. With the same grid configuration, three nested domains were used starting with a horizontal resolution of 27 km, 9 km, 3 km and the model generated data from the domain with 3 km resolution (domain extent of 120 km x 120 km) are used for comparison with observations. The vertical levels in the TAPM model are: 10 m, 25 m, 50 m, 75 m, 100 m, 150 m, 200 m, 250 m, 300 m, 350 m, 400 m, 450 m, 500 m, 550 m, 600 m, 650 m, 700 m, 750 m, 800 m, 850 m, 900 m, 950 m, 1000 m, 1050 m, 1100 m, 1150 m, 1200 m, 1250 m, 1300 m, 1350 m, 1400 m, 1450 m, 1500 m, 1600 m, 1750 m, 2000 m, 2250 m, 2500 m, 2750 m, 3000 m, 3250 m, 3500 m, 3750 m, 4000 m, 4500 m, 5000 m, 5500 m, 6000 m, 6500 m, 7000 m and 8000 m. The terrain height, land use and soil type data are obtained from the United States Geological Survey (USGS) data base for all the domains. Unlike the WRF model, the parameterization schemes used here cannot be changed by the user and their details are available in Hurley (2005). The initial and boundary conditions are obtained from the Australian Global Analysis and Prediction (GASP) data set available at 6 hourly interval on a 1° x 1° resolution. For both the models the simulation is for three days period, one on the day of occurrence, one day prior and one day later.
Fig 3: Time series of (a) specific humidity (kg kg\(^{-1}\)), (b) temperature (°C), (c) zonal wind (m s\(^{-1}\)) and (d) meridional wind (m s\(^{-1}\)) during 00Z 04 April 2005 – 00Z 07 April 2005. (Model data for temperature and specific humidity at screen level i.e. 2 m from the surface, whereas the observations are at 1.2 m from the surface. The observed wind data are at 40 m, WRF model results at 36 m and TAPM model results at 25 m).

The process of integrating the WRF and TAPM models can be described by a simple flowchart as shown in Fig 2. It may be noted that the domain sizes for both the models are not the same. However, results for both the domains are extracted at the location of the plant, which is at the centre of the domain in both the models and sufficiently away from the model boundary.

Near surface observations taken by the Environmental Survey Laboratory at the Kaiga Generating Station (KGS) on an hourly basis are used for comparison. Various statistical parameters like MAE, RMSE and IOA, (Hurley, 2000) defined below
Fig 4: MAE, RMSE and IOA for humidity (top row), temperature (upper central row), zonal wind (lower central row) and meridional wind (bottom row) are evaluated to interpret the performance of the two models. The MAE represents the average difference between the model and observation, the RMSE represents the effect of large errors (due to the square term in the definition) and the IOA represents the percentage of agreement between the model and observed data (0 < IOA < 1).

Mean Absolute Error

\[
\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |P_i - O_i|
\]  

Root Mean Square Error

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2}
\]

Index of Agreement

\[
\text{IOA} = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (P_i - O_{\text{mean}})^2 + (O_i - O_{\text{mean}})^2}
\]

In the above equations, N denotes the number of hours in the time series which is generally 72 for a three day simulation but could be less in case the -
Fig 5: Time series of zonal wind for the case studies (a) WX1, (b) WX2 and (c) WX3

observation is missing for a particular hour. In such cases, the corresponding hours were excluded from the model data as well so that the two time series compared are equal in length.

5. Results and Discussion

To generate the time series of observation, hourly screen level observations (at 1.2 m from the earth’s surface) of temperature and relative humidity are used where as for wind, data collected at 40 m level from the tower measurements are used. These observations are taken at the Environmental Survey Laboratory (ESL) of the Kaiga Generating Station (KGS). In case of WRF model, 2 m temperature and relative humidity are used where as the wind data are extracted at first sigma level (~ 36 m) are used for comparison. For TAPM, the 2 m temperature and relative humidity are used and the wind data are extracted at the second vertical level (25 m) for comparison. For both the models, the comparison with observations is carried out by choosing the model grid point coincident with the observation location. Fig 3 shows the time series of specific humidity, temperature, zonal and meridional wind speed components during 00Z 04 April 2005 – 00Z 07 April 2005. This plot is used for a representative comparison whereas the statistical analysis for all the cases simulated is presented in Fig 4. The Fig 3a shows the time series of specific humidity as given by the two models and the observation. It is seen that the TAPM model has a large bias with respect to the observation as compared to the WRF model. To quantify the performance of the two models, statistical parameters like MAE, RMSE and IOA for both the models are estimated and presented in Fig 4a-c. These values are compared with the international reference values defined in (Borge et al., 2008; Carbonell et al., 2013). For humidity a MAE, RMSE of $< 0.002$ kg kg$^{-1}$ and IOA > 0.6 are representative of a good simulation. For most of the case studies carried out, the MAE and RMSE values in the WRF model are $< 0.002$ kg kg$^{-1}$.
which indicates a good performance and the errors in the TAPM model are greater than that in the WRF model. The IOA values for both the models is ~ 0.4 which on the basis of reference values indicates an average performance. Similarly figure 3b shows the time series of screen level temperature. Here it is evident that both the models predict a warmer night time temperature as compared to the observation. The reference values for a good simulation of temperature are MAE, RMSE < 2 °C and IOA > 0.8. The MAE of the WRF model is ~ 2 °C in almost all the simulations, the RMSE is < 3 °C and the IOA is > 0.9 (Fig 4d-f). These values indicate a good model performance. Corresponding figures for the TAPM model are 2.5 °C for MAE, 3.5 °C for RMSE which are on the higher side with respect to the reference values and the WRF model. The IOA for the TAPM model is > 0.8 (Fig 4d-f). The vegetation type and soil type defined in the models influence the surface energy balance and exchange of momentum, heat and moisture across the air soil interface and thereby the transport of these quantities in the entire atmospheric column. In TAPM model, the only soil type used is sandy clay loam in the entire modeling domain and this could be one of the reasons for poor simulation of 2 m temperature and humidity as compared to the WRF model. The time series of zonal and meridional wind components for the case study TMX2 is presented in Fig 3c-d respectively. Here it is evident that for both the zonal and meridional component of wind speed, significant differences with respect to the observation are seen. Both the models have generally indicated a positive bias for wind speed which has been noted by other investigators also (Cheng and Steenburgh, 2005). The MAE, RMSE and IOA values for both the models are shown in Fig 4g-l give an idea of their performance for all the case studies. In case of wind speed a MAE, RMSE of < 2 m s^{-1} and IOA > 0.6 and MAE < 30° for wind direction is a measure of a good model performance. Since no separate criteria are defined for wind speed
components, the reference values available for wind speed are used. The difference in the performance of the two models in predicting zonal and meridional wind components is less as compared to humidity and temperature. The average MAE for zonal wind for all the simulations performed with the WRF model is 2.32 m s\(^{-1}\) and that for TAPM model is 2.53 m s\(^{-1}\). Similar figures for RMSE are 3.04 m s\(^{-1}\) and 3.25 m s\(^{-1}\) respectively. The IOA is 0.62 for WRF model and 0.56 for TAPM model. The MAE values for the two models are marginally higher as compared to the reference values where as the RMSE values are higher by 50 %. The IOA values compare well with the reference values defined. For meridional wind the average MAE, RMSE and IOA for the WRF model are 1.8 m s\(^{-1}\), 2.34 m s\(^{-1}\) and 0.43 whereas the same for TAPM model is 2.12 m s\(^{-1}\), 2.54 m s\(^{-1}\) and 0.38 respectively. These figures suggest that performance of both the models is marginally good in reproducing the observed wind speed components. It should be noted that the models are run with analyzed meteorological data at 1\(^{\circ}\) resolution which may be insufficient to capture the local flow features for a complex site like Kaiga. Assimilation of measured data from a tower or Automatic Weather Station (AWS) into this model may help to improve this.

Some additional cases studies are considered for comparison covering selected days in the pre-monsoon season and monsoon season. This was primarily done because the cases corresponding to minimum and maximum temperature did not include this period. These case studies are designated as WX1, WX2 and WX3. Only the results of wind speed and direction are compared in these case studies. The time series plots are shown in Fig 5 and Fig 6 and model performance statistics in Fig 7 and Fig 8. From Fig 5 which shows the time series of zonal wind for the case studies WX1, WX2 and WX3 it is seen that the hourly variations in wind speed recorded at the site are better captured in the WRF model as compared to TAPM. However the model performance statistics in Fig 7 indicate a marginal difference in the performance of the two models. The average MAE of the WRF model is 2.23 m s\(^{-1}\) and that of TAPM model is 2.47 m s\(^{-1}\). Corresponding figures for RMSE are 3.04 m s\(^{-1}\) and 2.91 m s\(^{-1}\) respectively and the average IOA is 0.57 and 0.51 for the two models. As for the case studies TMN1 – TMX3, the MAE values for the two models are -
marginally higher as compared to the reference values where as the RMSE values are higher by 50 %. The IOA values compare well with the reference values defined. The time series of meridional wind is shown in Fig 6. Here too it can be seen that the hourly variations are better simulated in the WRF model than in the TAPM model with the model performance statistics in figure Fig 8 indicating a marginal difference in the performance of the two models. The average MAE of the WRF model is 1.74 m s$^{-1}$ and that of TAPM model is 2.05 m s$^{-1}$. Corresponding figures for RMSE are 2.32 m s$^{-1}$ and 2.56 m s$^{-1}$ and the IOA is 0.45 and 0.4 for the two models. Although the MAE values indicate a good simulation, the RMSE values are higher with respect to the reference value for comparison.

6. Conclusions

This study compared the performance of two prognostic models namely WRF and TAPM for Kaiga site. It should be noted that TAPM does not accept FNL data and similarly WRF does not accept GASP data set. It is partly possible to use FNL data set in TAPM through another model CCAM (Conformal Cubic Atmospheric Model), but in this case TAPM actually utilizes the forecast provided by CCAM and not the analysis available in FNL. Thus, technically it is not possible to initialize both models with the same initial conditions. Regarding parameterization schemes, TAPM has fixed set of parameterization schemes and user does not have option to select a particular scheme. However, both models (TAPM and WRF) have got several merits and are well validated by various researchers. This study inter compares the results of both the models for Kaiga site. The differences in the model performance are due to variations in the model physics and in the initial/boundary conditions. The simulations carried out in the present study are only representative of short range weather forecasts and a comprehensive model comparison is possible with extended period simulation, preferably over a period of a year with both the models. Based on the present simulations, it is seen that for temperature and relative humidity, the performance of the WRF model is better than TAPM at this site in all the cases simulated. In case of wind speed components, the model performance indices like IOA, MAE, RMSE show little variation in the performance of the two models, however differences with the observation were seen. It
is also seen that the hourly variations in wind are better simulated in the WRF model as compared to the TAPM model. It should also be noted that the WRF model has been tuned for better performance at this site by the proper choice of parameterization schemes. The main advantages of the TAPM model are the small run time, modest computational resources required for simulation and the capability of performing dispersion calculations simultaneously. It is suitable for applications like environmental impact assessment of the proposed nuclear power plants, industries as well as mining areas. For many of such facilities, important consideration is the impact of the facility on nearby areas on average basis. For example, in the nuclear industry, it is required to demonstrate that the radiological dose to the member of public in a year is only a fraction of the radiological dose limit specified by the regulatory authority. In such cases, year long simulations of meteorology and dispersion are required. For such applications, the TAPM model might prove to be more suitable as compared to the WRF model. In case of accidental conditions, the results are required in minimum period of time and probably the higher uncertainty in model prediction may be tolerated. The WRF model on the other hand has a larger run time and also requires superior computational infrastructure making it more suitable in situations where an elaborate result is required without much limitation on model run time. Based on the desired application, the choice of a particular model can be made. These studies on model evaluation assume importance because it provides insight into the performance of the models. Such studies are also useful in selecting a model for a particular application.

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