Simulation of Atmospheric Pollution Dispersion over Complex Terrain Region of Jharkhand with FLEXPART-WRF with incorporation of improved Turbulence Intensity relationships

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Highlights

❖Boundary layer turbulence intensity relationships developed for Ranchi

❖ Incorporated the new turbulence intensity relationships in Hanna scheme of FLEXPART-WRF

❖Ground level concentrations of nitrogen oxides (NO_x) and suspended particulate matter (SPM) over Patratu Jharkhand in southern Chota Nagpur of eastern India simulated using FLEXPART-WRF

❖Modified Hanna scheme considerably improved NO_x and SPM concentrations over default Hanna scheme

❖Study demonstrate utility of turbulent observation in air quality modeling

Abstract

The complex terrain region of Patratu, Jharkhand in southern Chota Nagpur of eastern India has high air pollution problems besides complex mesoscale flow and meteorology. The FLEXPART-WRF mesoscale Lagrangian Particle dispersion model is used to simulate the dispersion of elevated effluent releases of nitrogen oxides (NO_x) and suspended particulate matter (SPM) from Patratu thermal power plant over Patratu at a high resolution of 1 km. The WRF is integrated with nested domains (27, 9, 3 km resolutions, 51 vertical levels). The relationships for turbulent intensities in the default diffusion parameterization of the Hanna scheme of FLEXPART is modified with new empirical relationships derived as a function of atmospheric stability from one year fast response turbulence measurements from a nearby observational site at Ranchi. The pollutant dispersion simulated by FLEXPART is evaluated with modified version of the model and using the WRF simulated atmospheric flow field and thermodynamical structure with three alternative PBL schemes [Yonsei University (YSU), Asymmetric Convective Model version 2 (ACM2) and Mellor-Yamada Nakanishi and Niino Level 2.5 PBL (MYNN2]. Results indicate that the new turbulence intensity relationships in FLEXPART provide better comparisons for concentrations of NO_X and SPM with available observations relative to the default relationships. Further, the meteorological parameters simulated using YSU significantly reduces the bias in modelled pollutant concentrations in terms of lesser mean absolute error (MAE), root mean square error (RMSE), normalized mean square error (NMSE), fractional bias (FB) and FAC2 (Factor of 2). These parametric tests enabled to fine tune and validate the FLEXPART-WRF dispersion model with YSU PBL physics and improved Hanna relationships to realistically simulate pollution dispersion over complex terrain of the study region. The study demonstrates the utility of high quality turbulence measurements in pollution dispersion model for better diffusion parameterization needed in air quality modeling.

Study region, data and quality checks

Study Region

The study region, Patratu (23° 40' N, 85° 16' E), is located in southern part of the Chota Nagpur plateau which forms the eastern edge of the Deccan plateau system. It has a hilly topography with an average altitude of 405 meters above the sea level and undulating land features.

Surface Layer Turbulence Data

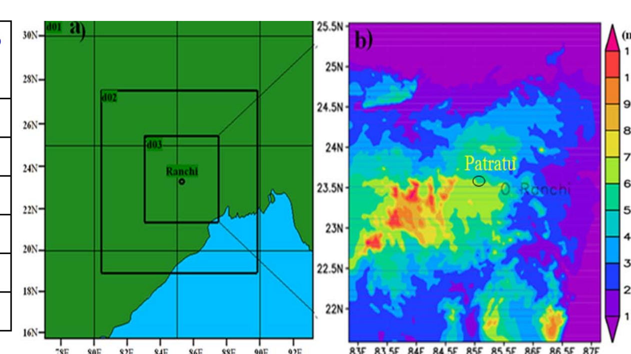
The turbulence intensity relationships needed in FLEXPART model for the Ranchi region are developed from one year fast response (10 Hz) measurements of wind and temperature at 10 m height acquired using an Ultra Sonic Anemometer from an observational site at Ranchi.

Air Pollution emission data

The present study sources of emissions i.e., elevated effluent releases of NO_x and suspended particulate matter (SPM) from Patratu thermal power plant. Air concentration data from the monitoring location located at DM Plant is considered for FLEXPART model validation.

Emission Inventory

Date	Species	Stack_A (gs^{-1})	Stack_B (gs^{-1})
26 February 2007	No_x	15.43	13.35
	SPM	127.02	138.75
22 March 2007	No_x	20.23	20.75
	SPM	143.42	201.22
20 April 2007	No_x	25.40	20.60
	SPM	144.35	111.38



Domains used in the ARW model

Description of Models

The off-line air quality modeling system FLEXPART-WRF (Fast and Easter, 2006) used in the present study consists of two components , a) meteorology and b) dispersion.

Atmospheric model

The atmospheric model to simulate the meteorological fields over Ranchi in the present study is ARW (version 3.2).

Dispersion model

The FLEXPART Lagrangian Particle Dispersion model (LPDM) computes the mesoscale transport, diffusion, dry and wet deposition of emissions released from point, line, area or volume sources by computing trajectories of fluid particles (Stohl et al., 2005).

Overview of ARW model configuration

Dynamics	Non hydrostatic
Initial and boundary data	NCEP FNL
Temporal interval of boundary data	6 hrs
Grid size	Domain1: (60 ×61)×51 Domain2: (109×109)×51 Domain3: (151×151)×51
Resolution	Domain1: 27 km × 27 km Domain2: 9 km × 9 km Domain3: 3 km × 3 km
Covered area of outermost domain	15.7º- 30.5º N and 77.1º- 92.9º E
Map Projection	Mercator
Horizontal grid system	Arakawa-C grid
Integration time step for outermost domain	90 sec
Vertical coordinates	Terrain-following hydrostatic pressure vertical co-ordinate with 51 vertical levels
Time integration scheme	3rd order Runga-Kutta Scheme
Spatial differencing scheme	6th order center differencing
PBL Schemes	YSU, MYNN2 and ACM2
Cumulus Parameterization	Kain-Fritsch scheme
Surface layer Parameterization	Noah land Surface Scheme
Microphysics	WSM6
Short wave radiation	Dudhia scheme
Long wave radiation	RRTM scheme
Terrain and Land Use Data	USGS

Results and discussion

❖The dispersion model FLEXPART-WRF uses the gridded meteorological fields form ARW model given in a latitude/longitude coordinate system.

❖In our earlier study (Srikanth et al., 2014) the impact of horizontal resolution in ARW for simulating the mesoscale flow over Ranchi region in Chota Nagpur plateau region was examined. simulations using 3 km grid spacing provided better results for PBL vertical structure and surface meteorological variables.

❖Srikanth et al., (2015) studied sensitivity of ARW simulated flow-field and PBL parameters over Ranchi region to different PBL schemes and have shown that the non-local ACM2 followed by the TKE closure MYNN2 and non-local YSU PBL turbulent diffusion parameterizations in ARW performed better in simulating surface meteorological variables.

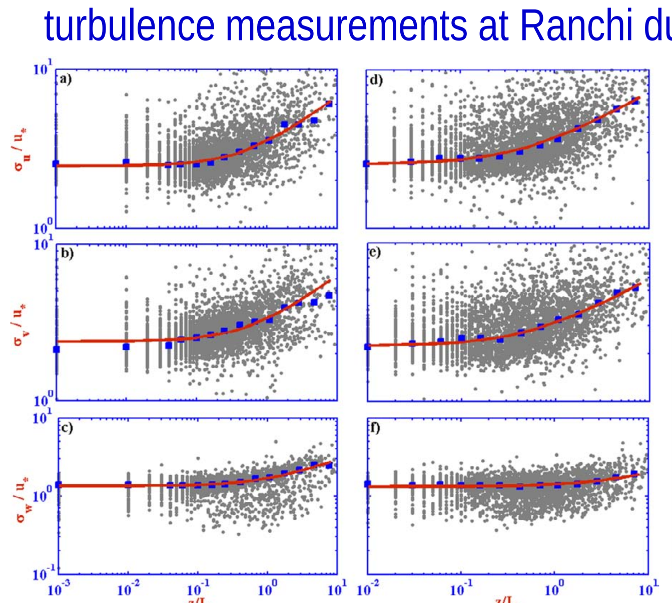
❖In the present study we have adopted these tested model grid and physics configurations in ARW model and we are not showing any ARW model analysis.

Non-dimensionalised standard deviation of wind components

❖The exchange of momentum, heat and moisture between Earth's surface and atmosphere happens in atmospheric surface layer (ASL) where the frictional drag force of the Earth and turbulent forces are predominant.

❖These relationships are being fitted by considering 50% bin quartile values. Horizontal fluctuations of winds are following 1/3 power law, in both unstable and stable stratification (Tyagi and Satyanarayana et al., 2013).

❖Atmospheric stability classification based on high frequency turbulence measurements at Ranchi during 2009.



Normalized standard deviation of zonal wind (u), meridional wind (v) and vertical wind (w) as a function of z/L at Ranchi during unstable (a, b and c) and stable (d, e and f) atmospheric conditions.

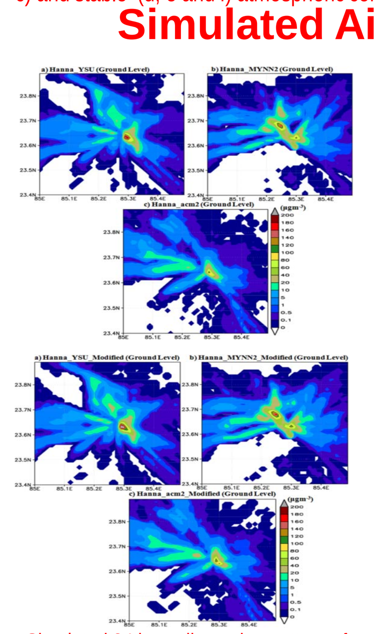
Stability classification over Ranchi

Stability	Stability Range (Z/L)	Mean Stability	Number of hours
unstable	≤ 0	-0.45	3883
stable	> 0	0.79	3607

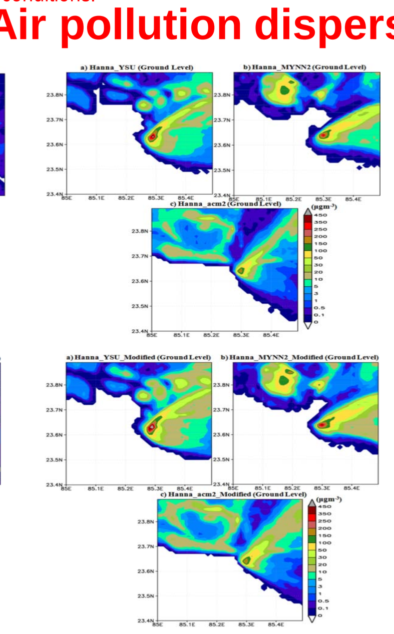
Stability dependent turbulence intensity relationships for Ranchi.

Unstable stratification	Stable stratification
$\frac{\sigma_u}{u_*} = 2.47\left(1-1.95\frac{z}{L}\right)^{1/3} \quad -10<\frac{z}{L}\le 0$	$\frac{\sigma_u}{u_*} = 2.55\left(1+2.15\frac{z}{L}\right)^{1/3} \quad 0<\frac{z}{L}\le 10$
$\frac{\sigma_v}{u_*} = 2.4\left(1-1.75\frac{z}{L}\right)^{1/3} \quad -10<\frac{z}{L}\le 0$	$\frac{\sigma_v}{u_*} = 2.25\left(1+1.75\frac{z}{L}\right)^{1/3} \quad 0<\frac{z}{L}\le 10$
$\frac{\sigma_w}{u_*} = 1.37\left(1-0.93\frac{z}{L}\right)^{1/3} \quad -10<\frac{z}{L}\le 0$	$\frac{\sigma_w}{u_*} = 1.34\left(1+0.23\frac{z}{L}\right)^{1/3} \quad 0<\frac{z}{L}\le 10$

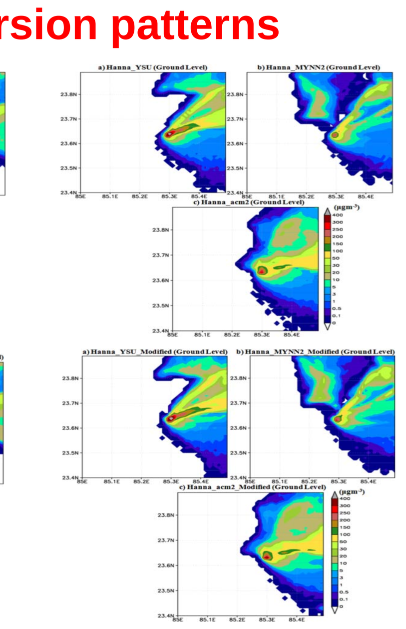
Simulated Air pollution dispersion patterns



Simulated 24 hour dispersion pattern of NO_x for both default and modified Hanna Schemes for 26 February 2007



Simulated 24 hour dispersion pattern of NO_x for both default and modified Hanna Schemes for 22 March 2007



Simulated 24 hour dispersion pattern of NO_x for both default and modified Hanna Schemes for 20 April 2007

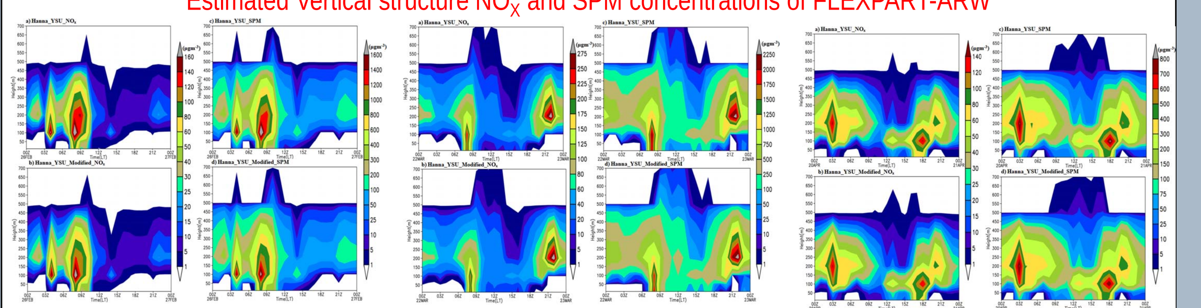
Model simulated and observation of 24-hour average NO_x and SPM over DM plant location over Patratu

Date	Species	YSU_ Hanna	MYNN2_ Hanna	ACM2_ Hanna	YSU_ Hanna_ Modified	MYNN2_ Hanna_ Modified	ACM2_ Hanna_ Modified	OBS (μgm^{-3})
26 Feb 2007	No_x	6.60	1.06	5.33	7.58	1.42	5.94	15.70
	SPM	69.11	10.91	55.95	75.33	14.97	57.83	117.0
22 Mar 2007	No_x	15.43	9.58	6.55	17.78	11.45	6.52	18.00
	SPM	138.21	83.97	61.97	149.71	97.59	56.85	204.00
20 Apr 2007	No_x	10.59	7.70	6.35	12.40	9.09	6.82	19.00
	SPM	60.84	43.35	36.30	69.50	51.68	40.68	149.00

Error Statistics

Species	Errors	YSU_ Hanna	MYNN2_ Hanna	ACM2_ Hanna	YSU_ Hanna_ Modified	MYNN2_ Hanna_ Modified	ACM2_ Hanna_ Modified
No_x (μgm^{-3})	MB	-6.69	-11.45	-11.49	-4.98	-10.25	-11.14
	RMSE	7.31	11.73	11.53	6.04	10.72	11.19
	NMSE	0.82	3.69	3.71	0.49	2.58	3.31
	FB	0.47	0.97	0.97	0.33	0.82	0.93
	FAC2	0.62	0.35	0.35	0.72	0.42	0.37
SPM (μgm^{-3})	MB	-67.28	-110.59	-105.26	-58.49	-101.92	-104.88
	RMSE	69.27	110.79	110.45	60.56	101.99	110.89
	NMSE	0.95	4.44	4.46	0.66	3.19	4.53
	FB	0.55	1.09	1.01	0.46	0.96	1.01
	FAC2	0.57	0.29	0.33	0.63	0.35	0.33

Estimated Vertical structure NO_X and SPM concentrations of FLEXPART-ARW



Conclusions

❖In this study long-term surface layer turbulence data gathered using a fast response Sonic Anemometer are used to derive semi-empirical relationships of turbulence intensity (σ_u/u_*, σ_v/u_* σ_w/u_*) as a function of surface layer scaling and local stability at Ranchi, a complex terrain in Jharkhand, Eastern India.

❖As an application the derived relationships are introduced in the Hanna diffusion scheme in FLEXPART-WRF model.

❖ Negative bias of the model is reduced with the modified Hanna scheme using new turbulence intensity empirical relationships and using ARW simulated atmospheric parameters with all PBL physics schemes.

❖Significant improvement in the modelled pollutant concentrations are noticed with the combination of YSU derived PBL parameters with modified Henna Schemes over the study region.

❖The useful outcome of the present study is formulation of empirical diffusivity relationships for Ranchi region for their application in atmospheric dispersion model.

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