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Radiological dose Assessment by Means of a Coupled WRF-HYSPLIT Model under Normal Operation of Bushehr Nuclear Power Plant

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ABSTRACT: The current paper uses WRF Model to generate meteorological fields for HYSPLIT dispersion model. Sensitivity and validation of the WRF model has been conducted via different combinations of physical parameterization schemes. For this purpose, eight different configurations have been examined, with the predictions of WRF, assessed by computing statistical parameters, such as Correlation Coefficient (CC) and Root Mean Square Error (RMSE). For instance, WRF results show that utilization of proper physical configuration in Bushehr syoptic station on 03/01/2005 leads to CC=0.82007 and RMSE=1.91783 for wind speed parameter. Once WRF model has been properly configurated, dispersion simulations and annual effective dose for adult age group are carried out by WRF-HYSPLIT coupled model under normal conditions for Bushehr power plant. According to the coupled model, simulated annual effective dose for adult age group has been 5.8E-08 Sv/yr, 6.7E-08 Sv/yr, and 1.1E-07 Sv/yr for the years 2014, 2015, and 2016, respectively. Results show that simulation and prediction of effective dose with coupled WRF-HYSPLIT model have been in good agreement with observations, indicating the validity of the simulations. The ratio of predicted annual effective dose to dose limit (1E-04 Sv/yr) for normal operation is below 0.2%, showing that annual exposure dose for normal operation of Bushehr power plant has been negligible, compared to the legal limit.

Keywords: dose calculations, atmospheric dispersion, simulation

INTRODUCTION

Atmospheric transport and diffusion models are frequently used at power plants in order to study the dispersion of different types of pollutants (e.g. chemical, radioactive, etc.) in both normal operating conditions and accidental ones. Meso-scale numerical weather prediction models such as the Weather Research and Forecasting (WRF) model can serve as a tool to provide meteorological input data for atmospheric dispersion models (e.g. Wu et al., 2012) to simulate and forecast the impact of the released pollutants.

Shrivastava et al. (2015) evaluated WRF model parameterization schemes for Kaiga nuclear power plant region. They used several different parameterization schemes for boundary layer, surface, and land surface models in their study of surface

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wind, temperature, and humidity in the study area. Borge et al. (2008) carried out a comprehensive sensitivity analysis of WRF Model for air quality applications over the Iberian Peninsula.

Furthermore, some works have been conducted in Iran for sensitivity analysis of WRF model, e.g. Ghader et al. (2016) studied the sensitivity of WRF model surface wind prediction over the Persian gulf to different choices of physical parametrization schemes; Malakooti and Alimohammadi (2014) studied WRF sensitivity analysis and path of Gonu storm to surface fluxes parameterizations; and Layeghi et al. (2017) dealt with sensitivity of WRF model simulations to physical parameterization over the Persian Gulf and Oman Sea during summer monsoon. In addition, results from these works suggested that conducting a sensitivity analysis to find the proper configuration of WRF model, based on different physical parametrizations, was necessary.

Based on Gaussian models, atmospheric dispersion modeling was introduced by Sutton (1947), and got developed by Pasquill (1974) and Pasquill & Smith (1983). The Gaussian dispersion models were the simplest models for atmospheric dispersion simulations and dose assessment of public members for nuclear facilities such as power plants IAEA (1980, 2001). Due to the simplicity of required input data for Gaussian model (minimum data, wind speed, and the source term), in comparison with numerical dispersion models (Schnelle & Dey, 1999), they can be used for short range distances with some modifications like steady state, homogeneous wind field, and no wind shear. Assessing the accuracy and sensitivity to input parameters of Gaussian model can be found in Vauquelin & Levy (2000), Miller & Craig (1986), and Carrascal et al. (1993).

The present work aims at atmospheric dispersion simulations of Bushehr power plant, using a Lagrangian dispersion model, an approach to fluid motion which follows a fluid parcel as it moves with the flow. To this end, it employs the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, a widely applied Lagrangian dispersion model. A complete system to compute simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations (Draxler & Hess, 1998), HYSPLIT model is enable to use numerical weather prediction models (e.g. WRF Model) output data in its calculations.

The first part here is to find proper configuration of WRF model, based on physical parametrizations, enabling us to provide more realistic meteorological data for HYSPLIT dispersion model.

Then, as its second main part, the present work uses the coupled WRF-HYSPLIT model for dispersion simulations and exposure dose assessment of Bushehr power plant.

The remaining parts of the paper are as follows: setup and configuration, used for WRF model simulations, HYSPLIT model description, and its validation for Bushehr power plant and giving details of dispersion simulations, via coupled WRF-HYSPLIT model. The concluding remarks are finally presented.

MATERIALS AND METHODS

In the present work, the WRF model is coupled with the HYSPLIT dispersion one for atmospheric dispersion simulation as well as dose calculation of Bushehr power plant under normal operation. Almost 18 km southeast of the city of Bushehr in Bushehr Province at the coast of Persian gulf, south of Iran (Fig. 1), Bushehr nuclear power plant is a VVER type NPP with 1000 MWe power.

Several studies in the past dealt with atmospheric dispersion and exposure dose assessment of Bushehr power plant, e.g. Feyzinezhad and Khamooshy (2004) developed a Gaussian dispersion model for Bushehr power plant, while Raisali et al.

(2006) evaluated collective and individual dose equivalent, using Gaussian model for normal operation and accidental conditions; furthermore, Sohrabi et al. (2013) studied collective and individual exposure dose calculations under normal operation conditions with Zali et al. (2017) calculating individual and collective effective dose equivalent under normal operation, using HYSPLIT model.

This paper, however, employed WRF model to provide meteorological fields. The computational domain of the WRF model was configured with three nests with horizontal grid resolutions of 27 km, 9 km, and 3 km, respectively, with the inner fine domain covering the Persian gulf, itself. Fig. 2 gives an overview of the computational domain, wherein outer coarse domain with horizontal resolution of 27 km is marked with a black box, while the inner finer domains with horizontal resolution of 9 km and 3 km can be seen with white and red boxes, respectively. FNL data used providing the initial and boundary data of WRF model simulations.

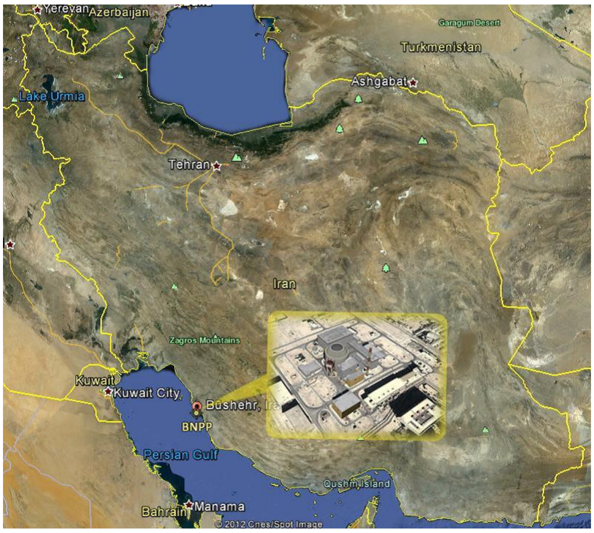


Fig. 1. Geographical position of Bushehr power plant (background image taken from Google Earth)

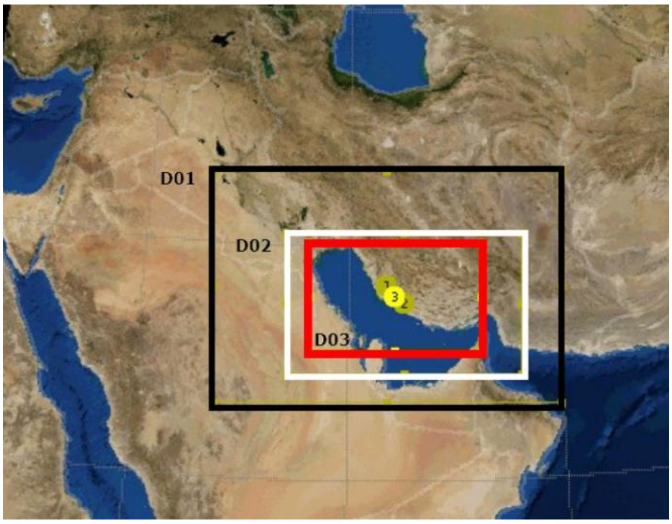


Fig. 2. Computational domains of WRF model, used in this research

To find the most suitable configuration of WRF, based on physical parametrization, it was worthwhile to carry out some sensitivity analyses, using different choices available for physical parametrization so that eight WRF model configurations could be created, presented in Table 1. These different configurations were given different names, as indicated in the second column of Table 1.

Selection of the most suitable WRF model physical configuration among the 8 configurations, given in Table 1, to regenerate meteorological fields (such as wind field for dispersion simulation), was carried out by evaluating WRF model simulation against the observational data such as wind, temperature, and surface pressure, observed at synoptic stations around Bushehr power plant, and on-site meteorological tower and SODAR system. Table 2 shows the observational stations, used in this work (with their locations demonstrated in Fig. 3). In addition, a number of points across the Persian Gulf were used to evaluate WRF model simulations against ASCAT and QuikSCAT satellite observations (Fig. 4).

Several dates got selected for WRF model runs. They were chosen, based on occurrence of annual maximum and minimum temperature and wind speed, observed in the nearby synoptic stations (Table 2). Extreme observational values were used as they were likely to have a significant impact on atmospheric dispersion of pollutants with WRF model being verified by the model evaluation tools (MET), developed in the test bed center (DTC) at NCAR (Bullock et al., 2017).

Table 1. Different WRF model configurations Long wave radiation scheme for all configurations is RRTM

No.	Configuration name	land surface	Cumulus	Short wave	Surface layer	PBL	Microphysics
1	Phys01	Pleim-Xiu	KF	Goddard	Pleim-Xiu	ACM2	Lin
2	Phys02	Noah	KF	Goddard	Revised MM5	MRF	Lin
3	Phys03	Noah	KF	Goddard	Eta	MYJ	Lin
4	Phys04	Noah	KF	Goddard	MYNN	MYNN2	Lin
5	Phys05	Noah	KF	Goddard	QNSE	QNSE	Lin
6	Phys06	5 layer thermal diffusion	Grell	Dudhia	MM5	YSU	Thompson
7	Phys07	Noah	GD	RRTM	Eta	MYJ	Goddard
8	Phys08	Noah	BMJ	Dudhia	MM5	YSU	Ferrier

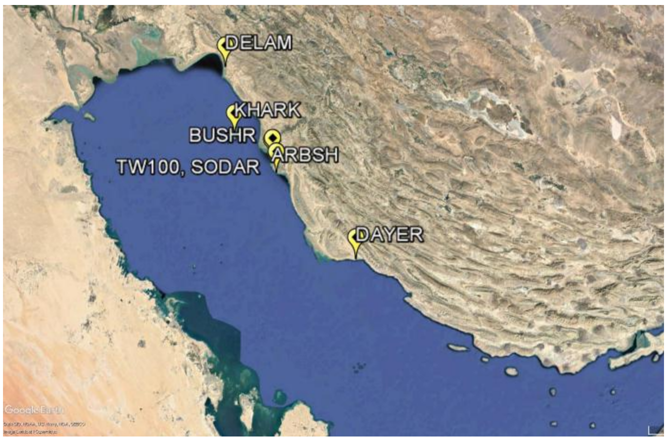


Fig. 3. Geographical position of synoptic observational stations, used in this work (background image taken from Google Earth)

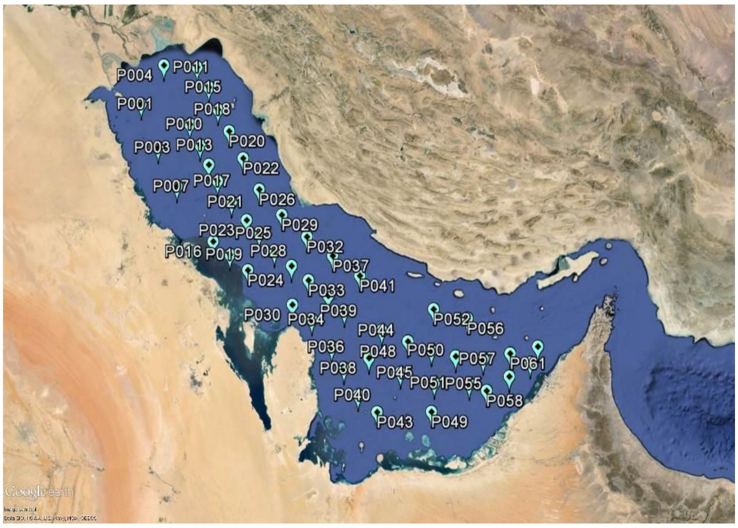


Fig. 4. Observational points of satellite (ASCAT, QuikSCAT), used in this work (background image taken from the Google Earth)

Table 2. Observational stations, used to evaluate WRF simulations

No.	Station name	Latitude	Longitude	Data period
1	BUSHR	28.9800 N	50.8300 E	2005-2015
2	ARBSH	28.9631 N	50.8192 E	2005-2015
3	DELAM	30.0503 N	50.1667 E	2005-2015
4	DAYER	27.8459 N	51.9421 E	2005-2015
5	TW100	28.8253 N	50.8831 E	2000-2010

To find the proper configuration of WRF, it was necessary to evaluate the model's results against the observation data (synoptic station and satellite points). As such, using MET, the root mean squared error (RMSE) and correlation coefficient (CC) between observations and simulations were calculated (e.g., Wilks, 2011), the two values being the main statistical quantities employed to select the proper model configuration. The RMSE parameter was obtained as follows:

$$\mathrm{R}MSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2}$$

where,

N = number of points

e = the error, or the difference between the predicted (P_i) and observed (O_i) data.

Also, the correlation coefficient was computed as below:

$$CC = \frac{\sum_{i=1}^{N}(P_i - \bar{P})(r_i - \bar{r})}{\sqrt{\sum_{i=1}^{N}(P_i - \bar{P})^2 (r_i - \bar{r})^2}}$$

In which,

r = the reference data (observations)

P = the predicted values by the model

In addition, $\bar{r}$ and $\bar{P}$ represent the average observation and prediction data, respectively.

Table 3 presents a sample CC and RMSE of the evaluation process for the 10 m surface wind field and its components for different stations and different dates.

Summary of statistical analysis (which was not presented here for all available observational data, used in this work) led to the suitable configuration of WRF with Table 4 showing the final configuration and setup of the model.

Table 3. A sample CC and RMSE of 10 m wind vector, including speed (SPD) and its components (U,V)

Station	Model setup	Date	SPD CC	SPD RMSE	U CC	V CC
OEDF	Phys03	03/01/2005	0.78380	0.97173	0.71173	0.98823
OKBK	Phys03	03/01/2005	0.89814	1.84251	0.91226	0.92523
BUSHR	Phys03	03/01/2005	0.82007	1.91783	0.89739	0.88888
TW100	Phys02	09/05/2015	0.83400	1.55964	0.86204	0.69624
OEDF	Phys04	08/29/2015	0.88935	1.68631	0.74387	0.88121
ARBSH	Phys06	08/26/2014	0.73515	1.76236	0.72695	0.49598
DAYER	Phys01	07/12/2006	0.88463	3.19075	0.75234	0.87109
DELAM	Phys05	08/29/2015	0.92092	3.32288	0.65936	0.61105

Table 4. Final WRF model configuration, used in this work

Dynamics	ARW
Horizontal resolution	Domain 1, 27 km Domain 2, 9 km Domain 3, 3 km
Vertical levels	39
Domain center	28.8251 N; 50.8831 E
Model physics	Phys03 of Table 1 i.e., Microphysics: Lin scheme Planetary boundary layer (PBL): MYJ Surface layer: Eta Shortwave radiation: Goddard scheme Longwave radiation: RRTM scheme Land surface model: NOAH LSM Cumulus convection: Kain-Fritsch
Initial/boundary conditions	NCEP/FNL, every 6 h

HYSPLIT model is a complete system to compute simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations. It uses a hybrid method between Eulerian and Lagrangian approaches. Advection and diffusion calculations are made in a Lagrangian framework while concentrations are calculated on a fixed grid (Draxler & Hess, 1998; Draxler et al., 2017). The model is capable of converting concentration outputs to radiological dose equivalent for members of public. The fourth version of HYSPLIT model (Draxler et al., 2017) considered three exposure pathways for dose calculations, namely cloud shine (direct exposure of plume), ground shine, and inhalation. More information regarding relations used for dose calculations was given by Slaper et al. (1994), IAEA (2001), and Smith & Simmonds (2009).

The present study, however, validated HYSPLIT model for dispersion simulation and exposure dose assessment of Bushehr power plant under normal operation. To do so, it compared simulation results with dispersion patterns and dose calculation in environmental report, hereafter ER, AEOI (2003, 2013) and final safety analysis report, hereafter FSAR, AEOI (2015) of Bushehr power plant, as well as works done by others. To this end, on-site meteorological data and activity releases of Bushehr power plant was used, as well.

The HYSPLIT model, in addition to using numerical weather prediction models output data, is capable of using measured on-site meteorological data, including wind velocity (m/s), mixed layer depth (m), and Pasquill stability category (A to G). To this end, the study used a file with hourly-recorded meteorological variables for 2010 from on-site meteorological tower measurements at a height of 100 m at the level of power plant stack. As many as 7547 records were employed, a sample of which can be seen in Table 5.

Other required HYSPLIT input data, i.e., activity releases, being a list of radionuclides released under normal operation of Bushehr power plant, has been given by FSAR (AEOI, 2015). Table 6presents the list. Dose conversion coefficients, used for pathways considered in this work, were obtained from ICRP 72 (ICRP, 1995) and FGR 12 (US EPA, 1993). In order to have a proper public representation at the considered area, the doses got calculated for the representatives of this work's adult age group, in accordance with ICRP 101 (ICRP, 2006).

The dispersion calculations were done for all radionuclides of Bushehr power plant's routine operation, as presented in Table 6. A total of 1,000,000 particles or puffs were released during the simulation. The time step was chosen in such a way that a particle could transit 0.75 grid cell distance in one advection step. The ground level concentrations got computed as averages for the lowest 100 m within each horizontal grid cell. Table 7 shows a summary of the used parameters .

Table 5. A sample of on-site meteorological data at 100 m height level

Year	Month	Day	Hour	Speed (m/s)	Dir. (deg)	Mix. height (m)	Stab. class
2010	1	1	0	7.3	333	59	D
2010	1	1	1	7.9	327	110	D
2010	1	1	2	7.9	316	116	D
2010	1	1	3	7.9	301	99	D
2010	1	1	4	6.3	311	100	E
2010	1	1	5	5	359	60	D
2010	1	1	6	6.1	5	73	D
2010	1	1	7	3.5	346	164	C
2010	1	1	8	3.5	284	475	B
2010	1	1	9	5.2	289	761	B
2010	1	1	10	6	307	883	C
2010	1	1	11	5.7	306	939	C

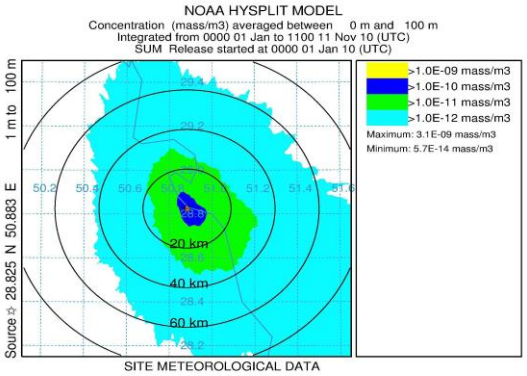
Table 6. Radioactive elements, released from Bushehr power plant for normal operation taken from FSAR 2015

Radionuclides	Release (Bq/hr)
^{85}Kr(m), ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{135}Xe, ^{85}Kr, ^{138}Xe	2.02E+09
^{133}I, ^{135}I, ^{131}I, ^{132}I, ^{134}I	4.29E+06
^{134}Cs, ^{137}Cs, ^{138}Cs, ^{139}Ba, ^{42}K, ^{24}Na, ^{88}Rb, ^{91}Sr, ^{92}Sr	2.38E+05
^{84}Br, ^{97}Nb, ^{89}Rb, ^{131}Te, ^{132}Te, ^{133}Te, ^{97}Zr	2.50E+04
^{140}Ba, ^{141}Ce, ^{60}Co, ^{99}Mo, ^{89}Sr, ^{95}Zr	1.68E+03
^{144}Ce, ^{58}Co, ^{51}Cr, ^{140}La, ^{54}Mn, ^{103}Ru, ^{59}Fe, ^{95}Nb, ^{144}Pr, ^{90}Sr	< 410

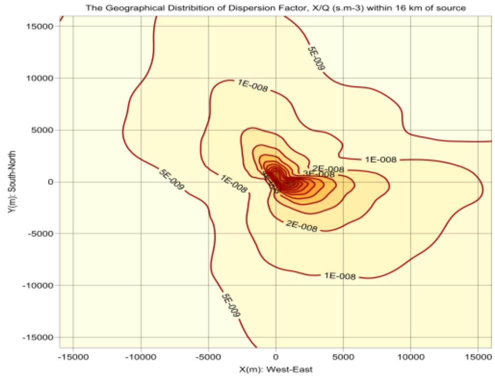
Table 7. Grid-configuration and options, used in HYSPLIT model validation

Start of simulation:	2010/01/01, 00 UTC
End of simulation:	2010/11/11, 10 UTC
Lat. & Lon. of release point:	28.8251 N; 50.8831 E
Height of release point:	100 m
Pollutant:	All radionuclides given in Table 6
Release rate:	Bq/hr
Horizontal resolution:	0.01 deg (~1 km)
Meteorology:	On-site hourly meteorological data
Number of release particles:	1000000
Averaging rate:	3600 s
Averaging time:	7547 h

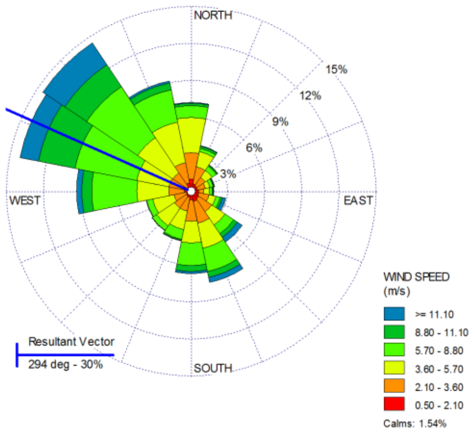
Here, the first step of HYSPLIT validation involved a qualitative comparison of dispersion simulation with annual atmospheric dispersion patterns, presented in ER for 2010. As shown in Fig. 5(a), simulation of HYSPLIT model had a good agreement with the dispersion pattern for 2010, as illustrated in Fig. 5(b) (results presented in ER). In addition, Fig. 5(c) shows annual wind rose diagram.



(a)



(b)



(c)

Fig. 5. The annual atmospheric dispersion pattern, (a) the present work, (b) 2010 given in ER, and (c) wind rose for 2010

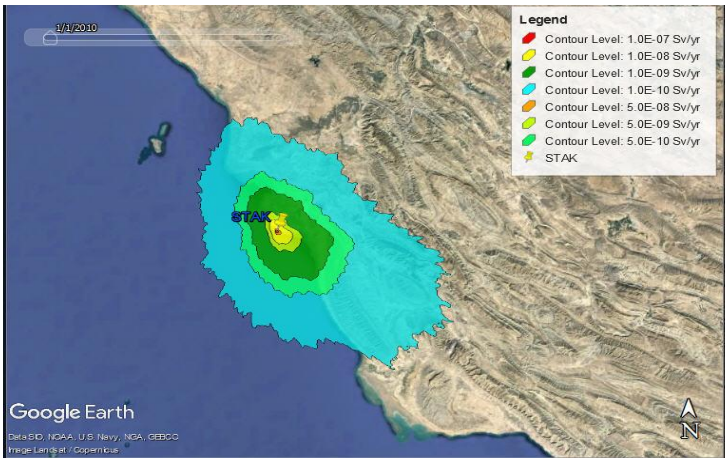


Fig. 6. Geographical distribution of annual total effective dose equivalent (Sv/yr) by HYSPLIT for 2010 (background image taken from Google Earth)

Qualitative comparison made the second step of validation, with calculated maximum annual effective dose of adult age group being compared to those, reported in ER and FASR. In addition, the results were compared with the dose limit (1E-04 Sv/yr) for normal operation conditions, set by INRA (Iranian Nuclear Regulatory Authority). Fig. 6 shows the annual effective dose distribution pattern around Bushehr power plant, simulated by HYSPLIT model with Table 8 presenting the results of maximum annual total effective dose equivalent of adult age group for the present work along with the reports referred to.

As it can be seen, the maximum calculated dose was 2.1E-07 Sv/yr in SE direction (Fig. 6), about 1km away from the source point, according to the HYSPLIT grid resolution (Table 8). This value was lower than INRA dose limit and the maximum annual effective dose, reported in FSAR 2015, was 7.7E-08 Sv/yr in the S direction, 0.6 km off the source point. Table 8 gives the values, presented in ER reports, which indicate that dose simulation, performed by HYSPLIT model, were valid, having an acceptable accuracy.

Moreover, the HYSPLIT simulation results were compared with those, reported by Sohrabi et al. (2013) and Zali et al. (2017). In addition, Zali et al. (2017) performed dose calculations, using HYSPLIT model for Bushehr power plant normal operation conditions. These results can also be seen in Table 8.

The third step in this research work to validate the HYSPLIT model was to compare the environmental (ambient) doses, simulated by the model with the ambient gamma dose rates, recorded via monitoring stations' network around Bushehr power plant, which included 17 measuring stations to cover an area, up to 60 km in radius, of the power plant. They also measured natural terrestrial gamma radiation dose which had a mean value of 60 ± 8 nSv/hr (Pashazadeh et al., 2014). In this work, the environmental dose rate (nSv/hr) got calculated, using the HYSPLIT results and the background dose. Table 9 gives these results and Figure 7 illustrates them graphically. Observational data and results of Sohrabi et al. (2013) are also presented. These results reveal that Bushehr power plant did not have any significant impact on background gamma radiation level during normal operation. Results from Table 8, Table 9, and Figure 7 show that the HYSPLIT dispersion model can be used as a tool for dispersion simulation and dose calculations.

The meteorological fields, required to perform the coupled WRF-HYSPLIT simulations, were provided by the WRF model with Table 4 presenting the set-up for this model, providing the details of horizontal and vertical resolutions, physical parameterization schemes, etc. Output of WRF model for the innermost domain (D03 domain in Fig. 2) were stored at one-hour intervals to provide the required meteorological data for HYSPLIT model.

Table 10 shows the HYSPLIT model set-up and configuration, used in the current work. A total number of 10,000 particles were released during one release cycle with a maximum of 300,000 particles, permitted to be carried at any time during the simulation. By dumping particle information at the end of each day (24-hour simulation), dispersion simulations were conducted for a given date, with each simulation, performed by means of hourly routine release rates of Table 6 pollutants, driven by hourly WRF output. The sampling rate was 3 min (180s) and the sampling average used, one hour (3600s). Several dates were used for WRF-HYSPLIT simulations; however, results of HYSPLIT model simulations for four cases were presented here.

Table 8. Maximum annual total individual dose (Sv/yr) for adults, calculated using HYSPLIT and values reported in ER, FSAR, Sohrabi et al. (2013), Zali et al. (2017), and INRA dose limit

	HYSPLIT This work	FSAR 2015	ER 2013	ER 2003	Sohrabi et al. 2013	Zali et al. 2017	INRA[1]
Max. Dose	2.1E-07	7.7E-08	5.1E-08	1.6E-07	1.3E-07	3.8E-08	
Direction	SE	S	SE	SE	ESE	SE	1E-04
Distance to source	1 km	0.6 km	2 km	3 km	0.6 km	0.6 km	

1. annual dose limit for routine operation is 0.1 mSv/yr

Table 9. Environmental gamma dose rates (nSv/hr) calculated by HYSPLIT model (The table features both records of the power plant monitoring stations and results of Sohrabi et al. (2013))

No.	Station name	Present work Obs.[1] ± STD[2] (incl. BG[3]) 2014	2015	2016	Env.[4] dose (Calc.[5]+BG)	Sohrabi et al. (2013) Obs. ± STD (incl. BG)	Env. dose (Calc.+BG)
1	CAMP	61± 2	60± 2	61 ± 5	100.7	65 ± 1	72
2	BAND	53± 3	52± 2	52 ± 2	109.4	53 ± 0	90
3	R5KM	61± 5	60± 2	60 ± 2	71.6	*	*
4	REYS	56± 7	55± 2	56 ± 2	65.6	58 ± 1	64.2
5	ELAB	60± 3	60± 3	61 ± 3	63.9	59 ± 1	66.0
6	OSTN	67± 2	67± 2	68 ± 2	62.9	57 ± 1	63.5
7	CHAT	61± 3	60± 2	60 ± 2	62.1	55 ± 1	63.2
8	SHIL	58± 2	58± 2	58 ± 2	62.2	59 ± 1	63.6
9	DELV	61± 3	61± 3	60 ± 3	62.0	57 ± 2	63.4
10	CHOQ	60± 2	58± 2	59 ± 3	60.6	66 ± 1	61.7
11	BSHI	64± 2	64± 2	64 ± 2	61.4	66 ± 1	60.9
12	SHIF	62± 6	60± 2	61 ± 2	60.5	62 ± 1	61.7
13	BOOL	57± 2	56± 2	56 ± 2	60.6	*	*
14	AHRM	60± 3	60± 2	60 ± 2	60.2	61 ± 1	60.5
15	KHOR	69± 4	63± 2	64 ± 2	60.3	*	*
16	ZIAR	68± 3	69± 4	70 ± 4	60.1	68 ± 1	60.9
17	HEDK	52± 6	51± 2	51 ± 2	60.2	*	*

1. Obs. (observation), 2STD (standard deviation), 3BG (background)=60 nSv/h, 4Env. (environmental), 5Calc. (calculated),

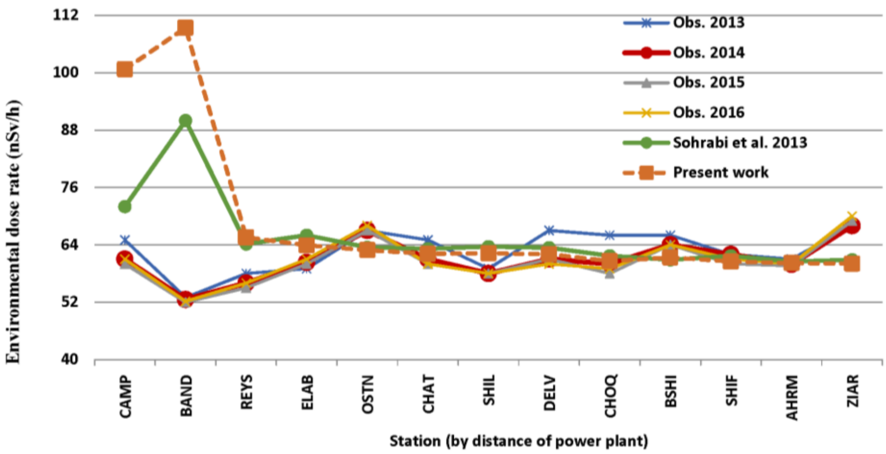


Fig. 7. Environmental gamma dose rates (nSv/hr)
(The power plant monitoring network observational data and results of Sohrabi et al. (2013) are present)

Table 10. Grid configuration and options used in WRF-HYSPLIT simulations

Lat. & Lon. of release point:	28.825 N; 50.8831 E
Height of release point:	100 m
Pollutant:	All radionuclides given in Table 6
Release rate:	Bq/hr
Horizontal grid:	10 × 10 degree
Horizontal resolution:	0.01 × 0.01 degree (≈ 1 km × 1 km)
Meteorology:	WRF simulated hourly meteorological fields
Number of release particles per cycle:	10,000
Maximum number of particles:	300,000
Sampling rate:	180 s
Averaging time:	3600 s (1 hr)

RESULTS AND DISCUSSION

Fig. 8 demonstrates the simulated wind field by WRF model and daily wind rose (adopted from NOAA) on January 6, 2014. Wind direction changed from ESE at start of simulation to NW at its end. Fig. 9 shows the particle plume dispersion after 9, 18, and 24 hours following the release. During the early hours, the plume had NW direction, then to change to SE at the end of the simulation period. In addition, to better understand the plume's behaviour, Fig. 9 also shows vertical particles profile along the longitude and latitude. It can be seen that particle density in altitudes below 2500 m had the highest value.

Results from such a simulation is important, both in emergency conditions and accident analysis for the sake of predicting plume movement direction as well as assessing the exposure dose.

Fig. 10 shows the hourly wind rose and surface wind field for December 2, 2014. An obvious feature in this figure is the fixed wind direction, i.e., NNW, for the entire 24-hour simulation, which resulted in the dispersion pattern in SE direction (Fig. 11). Figures 12-15 show the same results for November 7, 2015 and November 22, 2016, respectively. As for the former, the dominant wind direction for the majority of time was NE, its speed, below 4 m/s. Fig. 13 illustrates plume dispersion and vertical profiles, while Fig. 14 demonstrates the hourly wind rose and surface wind field on November 22, 2016. On this date, wind direction fluctuated between N and WNW and the wind speed was about 4 m/s, most of the times. Fig. 15 shows plume dispersion and vertical cross sections on this date.

In addition, the climatological dispersion evaluation for Bushehr power plant region can also be used as an approach for dispersion studies. To this end, it is necessary to identify climatological characteristics of study area like synoptic systems, local wind regimes (such as Shamal wind), and local phenomena such as the sea and land breeze circulation. There have been several climatological studies, carried out in southern Iran, such as the works by Malakooti et al. (2016), Komijani et al. (2014), and Bidokhti & Moradi (2004). However, such studies go beyond the scope of the present work.

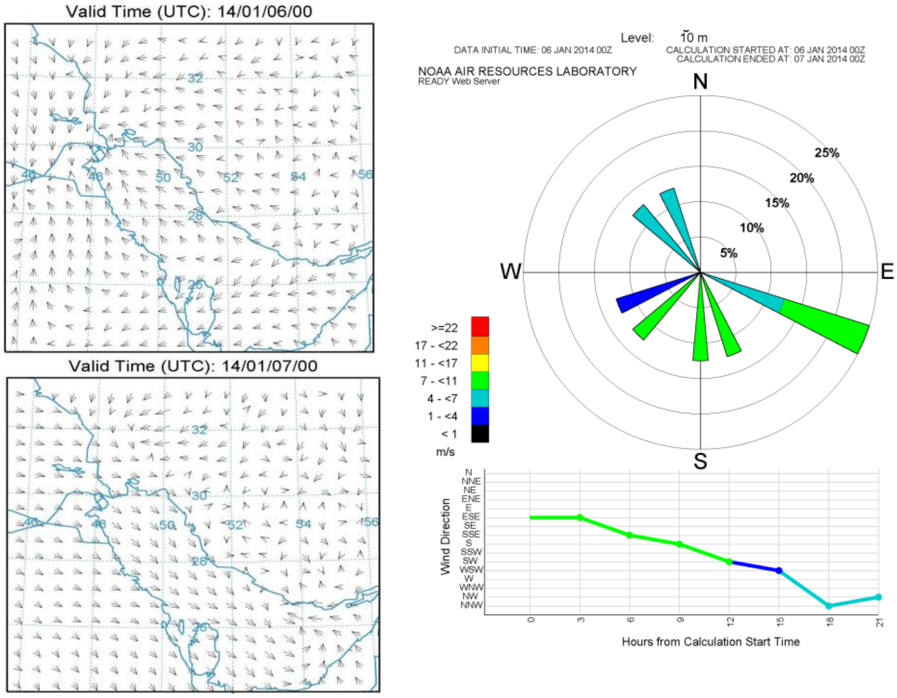


Fig. 8. Wind field, simulated by WRF model, and wind rose diagram (right), on January 6, 2014

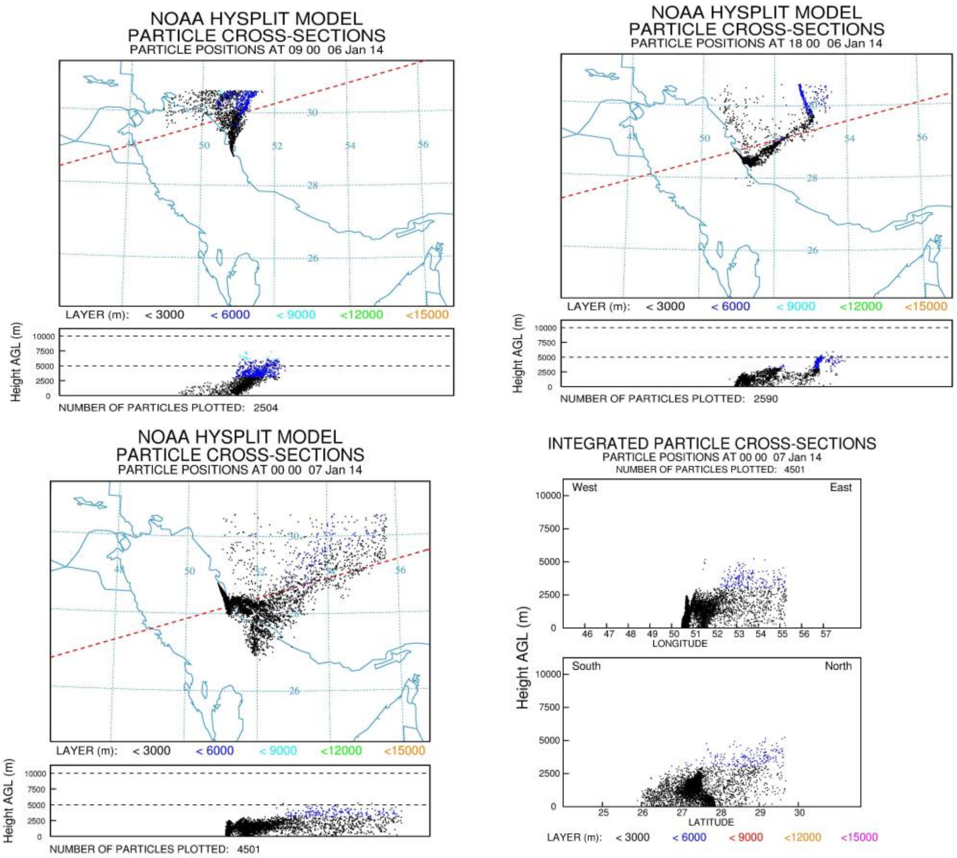


Fig. 9. Time evolution of simulated particles plume by WRF-HYSPLIT, on Jabuary 6, 2014

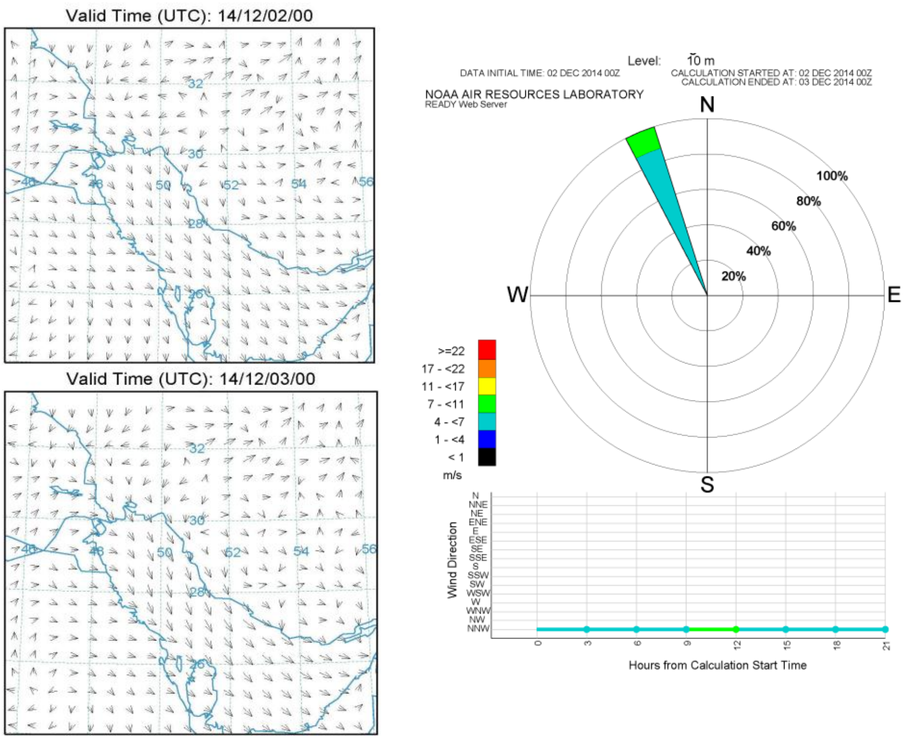


Fig. 10. Wind field, simulated by WRF model, and wind rose diagram (right), on December 2, 2014

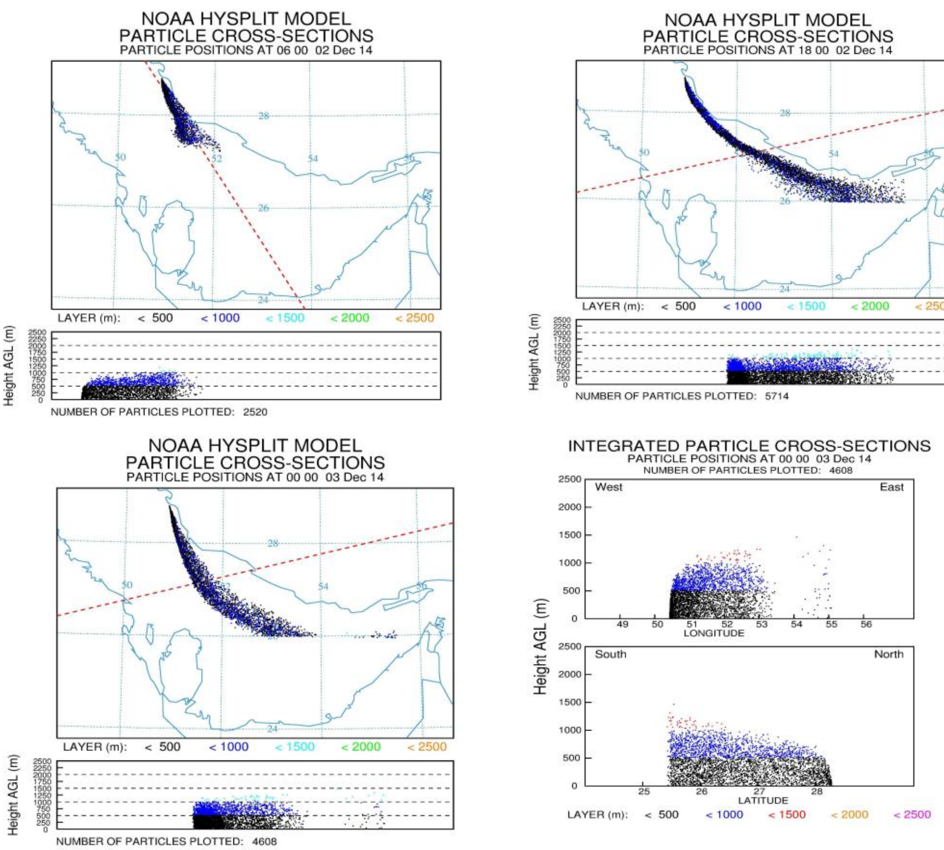


Fig. 11. Time evolution of simulated particles plume by WRF-HYSPLIT, on December 2, 2014

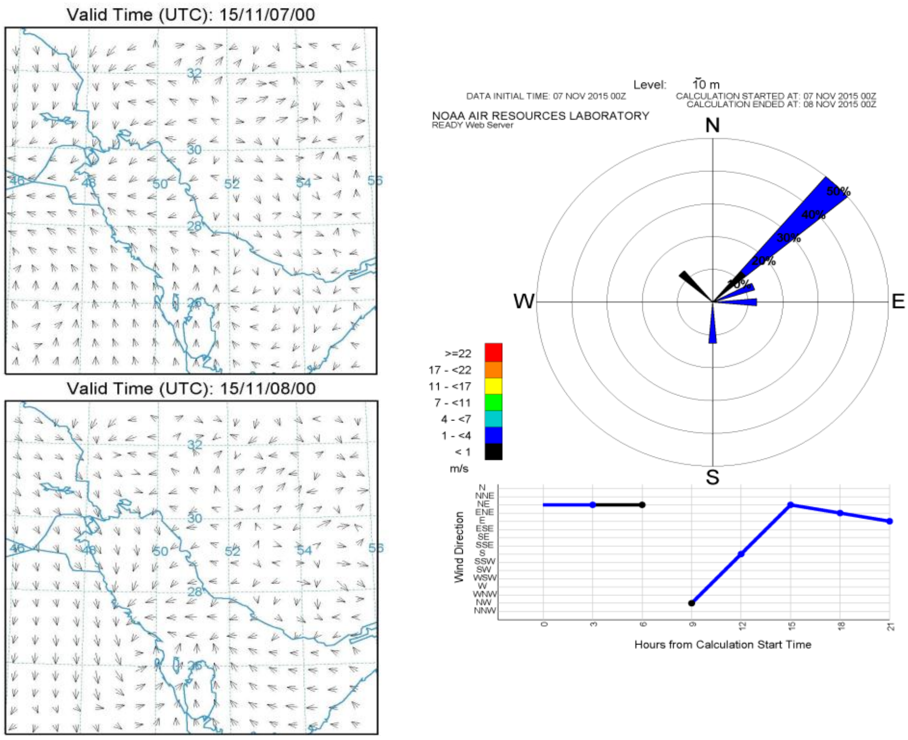


Fig. 12. Wind field, simulated by WRF model, and wind rose diagram (right), on November 7, 2015

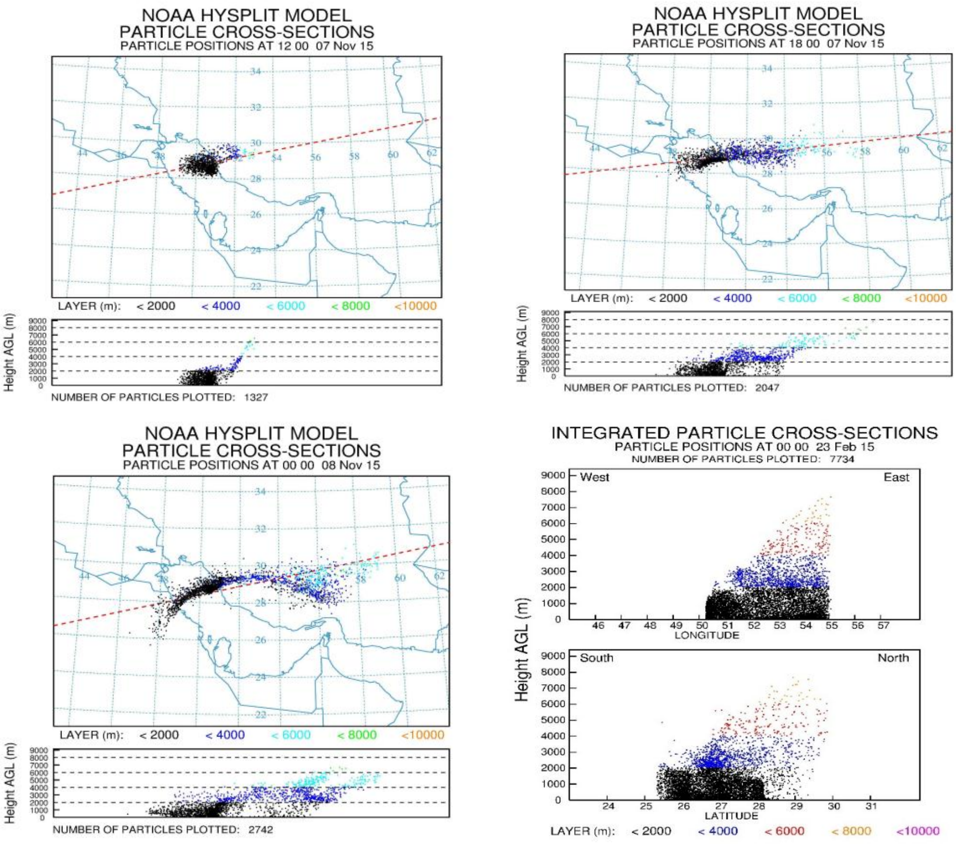


Fig.13. Time evolution of simulated particles plume by WRF-HYSPLIT, on November 7, 2015

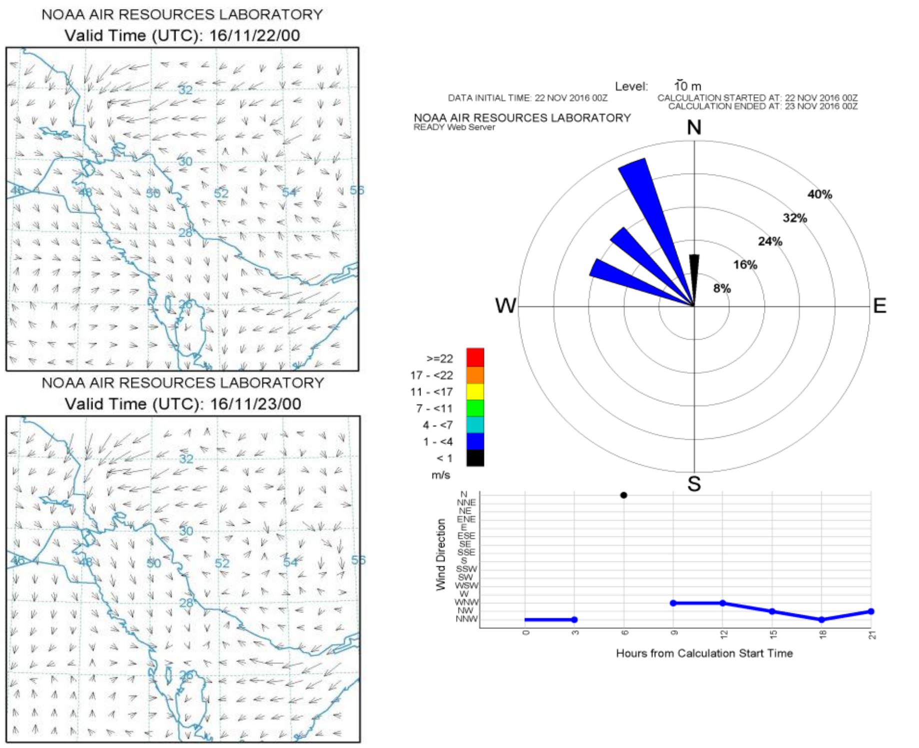


Fig. 14. Wind field, simulated by WRF model, and wind rose diagram (right), on November 22, 2016

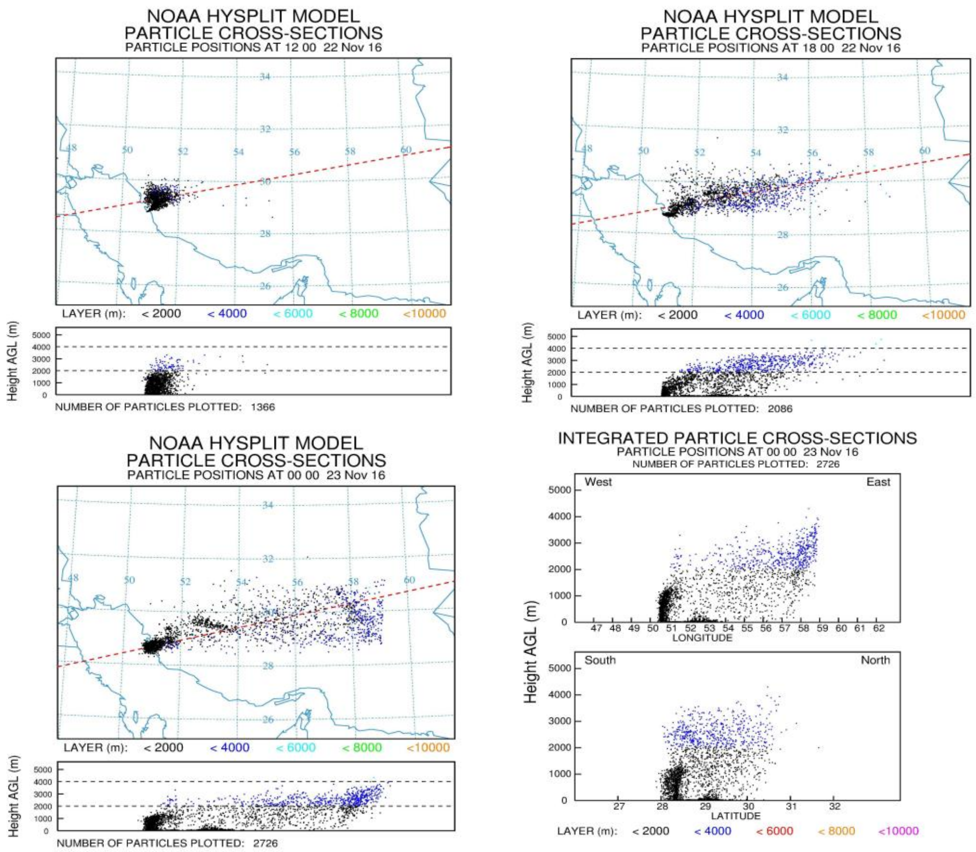
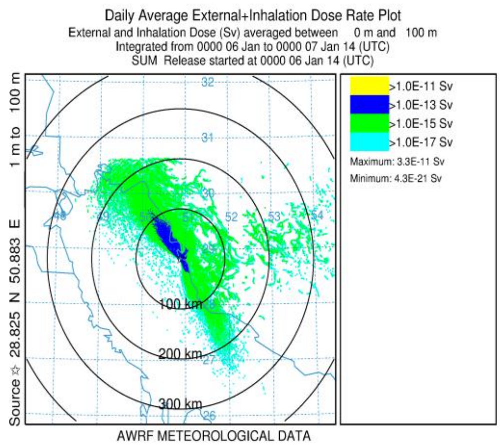


Fig. 15. Time evolution of simulated particles plume by WRF-HYSPLIT, on November 22, 2016

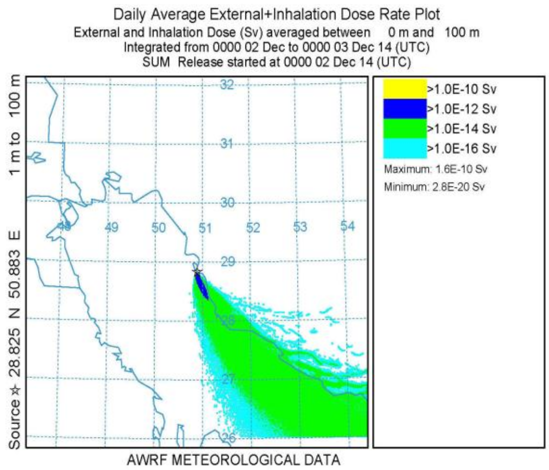
Based on WRF-HYSPLIT simulations, daily effective dose equivalent of adult age group got calculated for all dates, which can be seen in Table 11. Fig. 16 illustrates the distribution of daily effective dose. The estimated dose is a sum of all doses from three exposure pathways, namely cloud shine, ground shine, and inhalation. In addition, maximum annual effective dose can be obtained to daily effective dose. These annual effective doses were then compared with the INRA dose limit (1E-04 Sv/yr) for normal operation, their results, presented in Table 12.

Figure 17 shows the ratio of calculated dose to dose limit (percentage). In this figure, the maximum percentage of this ratio is below 0.2%, which shows that the annual exposure dose for normal operation of Bushehr power plant is negligible, being much less than the legal limit.

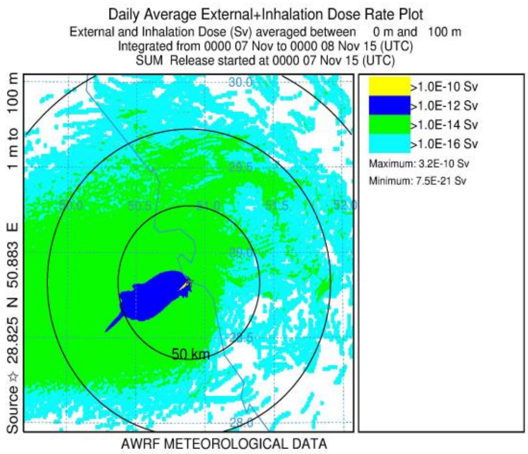
Table 12 compares simulated dose by means of WRF-HYSPLIT with works of other researches and those reported in ER and FSAR. As can be seen, simulated annual effective dose had an acceptable accuracy. For instance, simulated dose in 2014 was 5.4E-08 Sv/yr, and in 2016, 1.1E-07 Sv/yr. Also Figure 18 makes a comparison of different results of calculated annual dose.



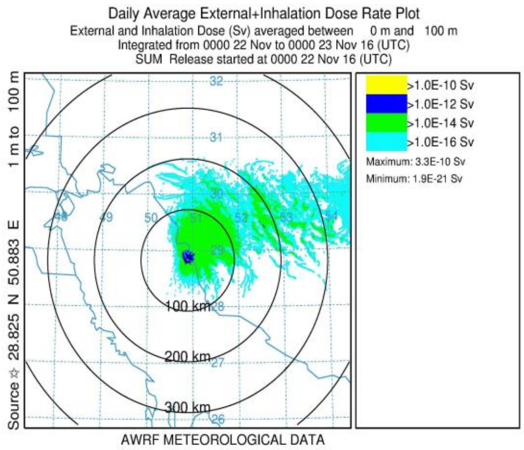
(a)



(b)



(c)



(d)

Fig. 16. Daily total effective dose simulation (Sv/day), using WRF-HYSPLIT, for different dates, (a) January 06, 2014, (b) December 2, 2014, (c) November 7, 2015, and (d) November 22, 2016

Table 11. Simulated daily and annual effective dose (Sv) via WRF-HYSPLIT

No.	Date	Daily effective dose (Sv)	Annual effective dose (Sv)	Calculated dose/dose limit (%)
1	01/06/2014	3.3E-11	1.2E-08	0.01
2	10/21/2014	2.5E-10	9.1E-08	0.09
3	12/02/2014	1.6E-10	5.8E-08	0.06
4	02/22/2015	8.2E-11	3.0E-08	0.03
5	11/07/2015	3.2E-10	1.2E-07	0.12
6	12/24/2015	1.4E-10	5.1E-08	0.05
7	02/01/2016	6.8E-11	2.5E-08	0.03
8	08/04/2016	5.1E-10	1.9E-07	0.19
9	11/22/2016	3.3E-10	1.2E-07	0.12

Table 12. Maximum annual individual dose (Sv/yr) for adults, calculated with WRF-HYSPLIT, and values reported in ER, FSAR, Sohrabi et al. (2013), and Zali et al. (2017)

This work WRF-HYSPLIT			FSAR (2015)	ER (2013)	ER (2003)	Zali et al. (2017)	Sohrabi et al. (2013)
5.4E-08	6.7E-08	1.1E-07	7.7E-08	5.1E-08	1.6E-07	3.8E-08	1.3E-07

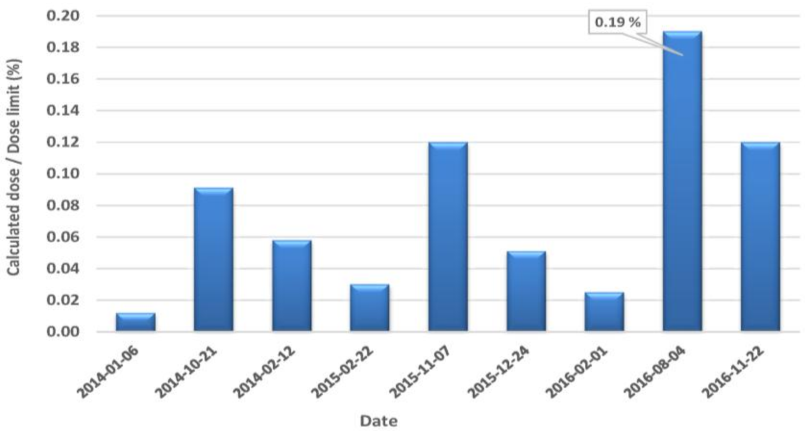


Fig. 17. Ratio of calculated dose to dose limit (%) for different simulation dates

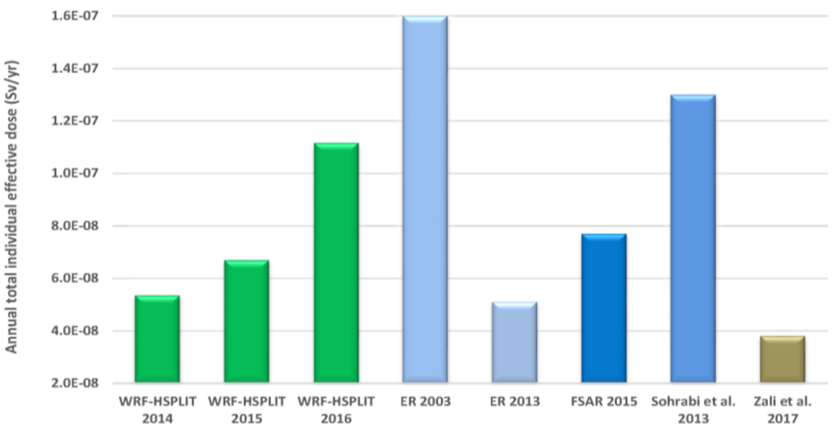


Fig. 18. Comparison of annual individual dose (Sv/yr) for adults, calculated with WRF-HYSPLIT, and values reported in ER, FSAR, Sohrabi et al. (2013), and Zali et al. (2017)

CONCLUSION

The present study examined the coupled WRF-HYSPLIT model as an applied tool to evaluate the atmospheric dispersion and dose assessment for an area, which contained Bushehr Power Plant. The WRF model predictions were used to provide the meteorological data, needed for the HYSPLIT dispersion model. As the first step to achieve this goal, some sensitivity analyses, based on different physical parametrizations, were performed to find the suitable configuration of the WRF model and set-up with HYSPLIT validations, carried out, by means of on-site meteorological tower data for the year 2010 and routine releases of power plant. Simulation results for maximum annual effective dose of the adult age group was 2.1E-07 Sv/yr, compared to 7.7E-08 Sv/yr presented in FASR report. HYSPLIT model validation showed that this model can provide valid and significant results for dispersion simulation and dose calculations. In addition, validation results were compared with works of Sohrabi et al. (2013) and Zali et al. (2017).

After validating the HYSPLIT model, dispersion simulations were performed, using the coupled WRF-HYSPLIT model for some dates between 2014 and 2016 years. The dispersion simulations results and effective dose calculations were presented. The results of maximum simulated effective dose compared with ER and FSAR and those of others were also presented.

Results from this research showed that WRF-HYSPLIT model can be used as a promising tool for dispersion prediction and dose calculations of Bushehr power plant under normal operation. In addition, the results of this coupled model can provide the required information for emergency management, meaning that the results of the coupled WRF-HYSPLIT model simulations can be used to provide information needed for accident analysis, since it is necessary to predict radioactive plume pathway and dose calculations in the early phase of an accident in order that the intervention level (e.g., sheltering, evacuation) could be determined.

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REFERENCES

Atomic Energy Organization of Iran, AEOI (2003). Environmental Report of BNPP-1, Tehran, Iran

Atomic Energy Organization of Iran, AEOI (2013). Environmental Report-2 of BNPP-1, Tehran, Iran.

Atomic Energy Organization of Iran, AEOI (2015). Final Safety Analysis Report of BNPP-1, Moscow, Russia.

Bidokhti, A. A. and Moradi M. (2004). A study of observations on the sea breeze in the Bushehr area. Nivar 30(56-57), 7-31, (in Persian).

Borge, R., Vassil, A., Del Vas, J. J., Julio, L. and Encarnacion, R. (2008). A comprehensive sensitivity analysis of the WRF model for air quality applications over the Iberian Peninsula. Atmos. Environ., 42, 8560-8574.

Carrascal, M. D., Puigcerver, M. and Puig, P. (1993). Sensitivity of Gaussian plume model to dispersion specifications. Theor. Appl. Climatol., 48, 147-157.

Draxler, R. R. and Hess, G. D. (1998). An overview of the HYSPLIT 4 modeling system of trajectories dispersion and deposition. Aust. Meteor. Mag., 47, 295-308.

Draxler, R. R., Stunder, B., Rolph, G., Stein, A. and Taylor, A. (2017). The HYSPLIT4 user's guide. NOAA Air Resources Laboratory, Maryland, USA.

US Environmental Protection Agency, EPA (1993). External exposure to radionuclides in air, water, and soil. EPA 402-R-93-081, Federal Guidance Report No.12, Washington D.C.

Feyzinezhad, M. and Khamooshy, C. (2004). Atmospheric dispersion modeling in Bushehr nuclear power plant. J. of Nuclear Sci. and Tech., 31, 35-42, (in Persian).

Bullock, R., Fowler, T., Gotway, J. H., Newman, K., Brown, B. and Jensen T. (2017). Model Evaluation Tools Version 6.1 (METv6.1) User's Guide Boulder, Colorado, USA.

Ghader, S., Yazegi, D., Soltanpour, M. and Nemati, M. H. (2016, november). On the use of an ensemble forecasting system for prediction of surface wind over the Persian Gulf (paper presented in proceedings of the 12th International Conference on Coasts, Ports and Marine Structures, Tehran, Iran).

International Atomic Energy Agency, IAEA (1980). Atmospheric dispersion in nuclear power plant siting.Vienna, Austria.

International Atomic Energy Agency, IAEA (2001). Generic models for use in assessing the impact of discharges of radioactive substances to the environment.Vienna, Austria.

International Commission on Radiological Protection, ICRP (2006). Assessing dose of the representative person for the purpose of radiation protection of the public and the optimization of radiological protection. broadening the process, ICRP publication, 101a.Ann. ICRP 36 (3).

International Commission on Radiological Protection, ICRP (1995). Age-dependent doses to the members of the public from intake of radionuclides part 5 compilation of ingestion and inhalation coefficients. ICRP publication, 72.Ann. ICRP 26 (1).

Komijani, F., Nasrolahi, A., Nazari, N. and Shahrzad, N. (2014). Analysis of the Persian Gulf wind regime using synoptic meteorological stations data. Nivar, 38(84-85), 27-44, (in Persian).

Layeghi B., Ghader S., Bidokhti, A. A. and Azadi, M. (2017). Sensitivity of WRF model simulations to physical parameterization over the Persian Gulf and Oman Sea during summer monsoon. Iranian Journal of Geophysics, 11(1), 1-19, (in Persian).

Malakooti, H. and Alimohammadi, M. (2014). Study of the sensitivity and path of Gonu storms to the surface fluxes parameterizations of Advanced Hurricane WRF model. Geography and Environmental Hazards, 9, 97-112, (in Persian).

Malakooti, H., Pakhirehzan, M. and Hassani, V. S. (2016). Observational and synoptic behavior of Shamal wind in the north west coast of Persian Gulf: Bushehr, Iran. Physical Geography Research Quarterly, 48 (1), 22-25.

Miller, C. W. and Craig, A. (1986). Accuracy of Gaussian plume dispersion model predictions as a function of three atmospheric stability classification calculations. Health Phys., 39, 773-782.

Pashazadeh, A. M., Aghajani, M., Nabipour, I. and Assadi, M. (2014). Annual effective dose from environmental gamma radiation in Bushehr city. Iran J. Environ Healt., 12(4), 2-4.

Pasquill, F. (1974). Atmospheric Diffusion. 2nd ed. (New York: Halstead Press).

Pasquill, F. and Smith, F.B. (1983). Atmospheric diffusion. (New York: Wiley).

Raisali, G., Davilu, H., Haghighishad, A., Khodadadi, R. and Sabet, M. (2006). Calculation of total effective dose equivalent and collective dose in the event of a loca in Bushehr nuclear power plant. Radiat. Prot. Dosim., 121(4), 382-390.

Schnelle, K. B. and Dey, P. R. (1999). Atmospheric dispersion modelling compliance guide. (Europe: McGraw-Hill).

Shrivastava, R., Dash, S. K., Oza, R. B. and Hegde, M. N. (2015). Evaluation of parameterization schemes in the weather research and forecasting (WRF) model: A case study for the Kaiga nuclear power plant site. J. Annals of Nuc. Energy, 75, 693-702.

Slaper, H., Blaauboer, R. O. and Eggink, G. J. (1994). A risk assessment method for accidental releases from nuclear power plants in europe. national institute of public health and environmental protection.

Smith, J. G. and Simmonds, R. (2009). The methodology for assessing the radiological consequences of routine releases of radionuclides to the environment used in PC-CREAM 08. Health Protection Agency.

Sohrabi, M., Parsouzi, Z., Amrollahi, R., Khamooshy, C. and Ghasemi, M. (2013). Public exposure from environmental release of radioactive material under normal operation of unit-1 Bushehr nuclear power plant. Ann. Nucl. Energy, 55, 351-358.

Sutton, O. G. (1947). The theoretical distribution of airborne pollution from factory chimneys. Q. J. Royal Meteorol. Soc., 73, 426-436.

Vauquelin, O. and Levy, F. (2000). Evaluation of a Gaussian-modified dispersion model for atmospheric release from the Marcoule nuclear site. Environ. Model Assess., 5, 75-81.

Wilks, D. S. (2011). Statistical methods in the atmospheric sciences. (London: Academic Press).

Wu, Q., Wang, Z., Chen, H., Zhou, W. and Wenig, M. (2012). An evaluation of air quality modeling over the Pearl River Delta during november 2006. Meteorol. Atmos. Phys., 116, 113-132.

Zali, A., Shamsaei Zafarghandi, M., Feghhi, S. A. and Taherian, A. M. (2017). Public member dose assessment of Bushehr nuclear power plant under normal operation by modeling the fallout from stack using the HYSPLIT atmospheric dispersion model. J. Environ. Radioact., 171, 1-8.