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Model evaluation of RIMPUFF within complex terrain using an ^{41}Ar radiological dataset

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Abstract: The newly updated atmospheric dispersion model RIMPUFF is evaluated using routine releases of ^{41}Ar from the former HIFAR research reactor located in Sydney, Australia. A large number of 41Ar measurements from a network of environmental gamma detectors are used to evaluate the model under a range of atmospheric stability conditions within the complex terrain area. Model sensitivity of input data is analysed including meteorological station data, land use maps, surface roughness and wind interpolation schemes. Various model evaluation tools are used such as gamma dose rate plots, exploratory data analyses and relevant statistical performance measures.

Keywords: model evaluation; dispersion modelling; radiological; complex terrain; emergency response; detector; environmental pollution.

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recently, evaluating atmospheric dispersion models in complex terrain. She is responsible for the Meteorological and Environmental Gamma Monitoring Networks at ANSTO, as well as for maintaining the emergency response computer system.

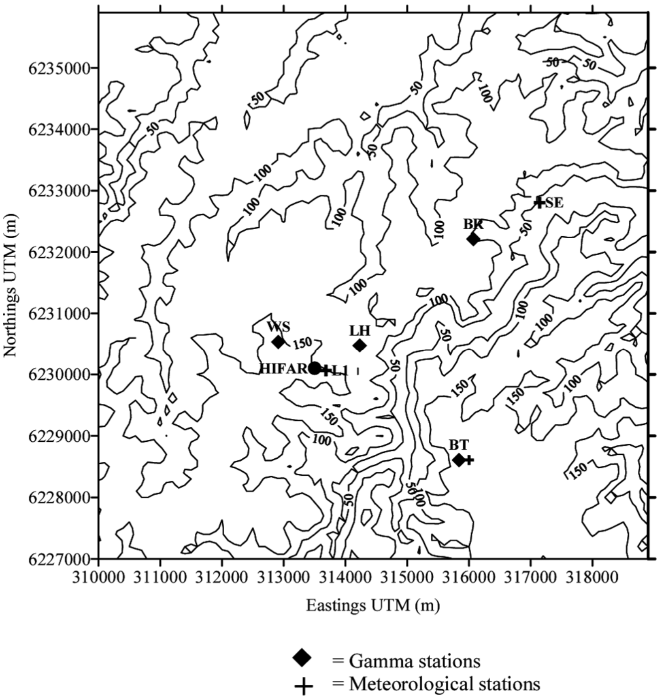
Poul Astrup received his MSc in Mechanical Engineering from the Technical University of Denmark in 1974, and was first employed by a diesel engine factory. Since 1976, he has been employed at the Risø National Laboratory for Sustainable Energy, which since 2007 has been a part of the Technical University of Denmark. Flow modelling has been his main theme of research: two phase steam-water flow for nuclear reactor cooling and boiler internal flows for coal combustion, leading up to receiving a PhD Degree in 1992 in turbulent suspension flows, again from the Technical University of Denmark. Since 1996, modelling of atmospheric dispersion and wind field disturbances caused by land surface have been his main topics.

1 Introduction

Modelling emission plumes for emergency response purposes requires a fast and relatively simple system to assist emergency personnel to respond quickly. Generally, diagnostic wind models are preferred if there is sufficient observational data available for input; however, in areas of complex terrain, it can often be difficult to place the meteorological stations in the ideal location for models. The terrain surrounding the HIFAR research reactor at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia, is characterised by dissected plateaus and valleys, and this has a significant influence on the movement of airborne particles. Around the ANSTO site, the complex topography causes challenging meteorological conditions for models in terms of predicting dispersion where wind shear, local terrain slope flows and strong inversions frequently occur. Having a radiological dataset within this complex environment for evaluating atmospheric dispersion models is very important, especially one of high frequency and covering a variety of atmospheric conditions.

ANSTO deployed a network of meteorological stations and gamma radiation detectors on a local scale up to 5 km from its former HIFAR research reactor (see Figure 1), with data collected every 15 minutes. Observations of ^{41}Ar by the gamma detector network from HIFAR's routine releases during 2002-03 have previously been used to evaluate the dispersion model RIMPUFF (RIsø Mesoscale PUFF) (Mikkelsen et al., 1984) with 2 different diagnostic wind models (Williams et al., 2005). More recently, the observations were used to evaluate RIMPUFF with the Local Scale Model Chain (Dyer and Pascoe, 2008), which incorporates modern micrometeorological scaling approaches. As a result of tests against two cases of the ^{41}Ar dataset comparing observed and predicted dose rates, RIMPUFF has recently had one of its puff growth models modified. Cases characterised by very light winds identified the weakness of the puff growth parameterisation scheme of Carruthers et al. (1992) based on similarity scaling. Consequently, RIMPUFF was updated so that the puff growth rate, otherwise following the parameterisation of Carruthers, has been limited to not exceeding the growth rate given by the Karlsruhe-Julich (IAEA, 1982) parameterisation (based on Pasquill-Gifford stability classes). This updated puff growth scheme is used in the model evaluation presented here.

Figure 1 The Lucas Heights region in southern Sydney, Australia showing locations of meteorological and environmental gamma monitoring stations, the HIFAR reactor release point and topographic features



The main objective of this model evaluation is to

1 determine whether the model can provide emergency personnel with a high-resolution radiological plume in complex terrain

2 predict the timing and location of the maximum dose rate to direct the deployment of hand-held detectors for further measurements.

Areas of interest here include the sensitivity of the wind field model to varying input of measured meteorological data, particularly when the meteorological stations are located within complex terrain. Other important aspects are the spatial variation of land-use characteristics and surface roughness to achieve an accurate simulation of surface wind flows. The evaluation of the model's performance is displayed qualitatively, using dose rate contour plots, dose rate graphs, scatter and quantile-quantile plots, as well as quantitatively, by comparing observed and predicted dose rates in time and space, known to be the most stringent test (Chang and Hanna, 2004). Statistical performance measures recommended by Hanna (1989) for evaluating air dispersion models are also relevant to this application, and thus, the BOOT software from the Model Validation Kit was used to produce these indices. The number of cases used in this analysis is 16, chosen to include at least 2 cases at each receptor station and covering stable and unstable conditions. A case represents the event of a plume of ^{41}Ar passing over one of the detectors and causing a peak in the time series. The time length of a case varies between 2 and 12 hours, and some of the longer cases have multiple peaks where the wind changes direction and the plume passes over the detector a number of times.

2 Data and methodology

2.1 Site description and dataset

Meteorological data is available at the ANSTO site from a 49 m tower, met station 00, close to the HIFAR reactor, as well as from two stations offsite: met station 01 to the south-east, where the closest residents are located, and 02 to the north-east of the reactor, located at the bottom of a 100 m steep-sided river valley (Figure 1). All three met stations have different meteorological conditions due to their location in the complex terrain. At the ANSTO site at station 00, predominant winds are from the south, and the general area on the plateau experiences sea breezes from the east-north-east during late morning and afternoon through most seasons of the year. The valley station 02 conditions are dominated by local terrain features with strong east-north-east to north-east sea breezes during most of the year except winter, when south to south-west winds account for 5060% of observations (Clark, 2003). In summer, autumn and spring, the nocturnal winds at station 02 are due to drainage of cold air into the valley from the south-west to west directions and in winter, there are near-calm conditions. Station 01 is also influenced by the valley, especially during nocturnal hours, with south to south-west winds along the ridge, whereas at station 00, there is a stronger influence from southerly winds. Different combinations of meteorological stations were used to determine the appropriateness of their location.

Four GR-150 gamma detectors, developed by Exploranium Canada (Grasty et al., 2001) were deployed as a perimeter up to 5 km from the HIFAR reactor, covering the areas affected by the predominant winds from the WSW – SE sector and also where the nearest residents live. The detectors were located < 1 km away at Main Gate (MG) and Waste Services (WS) and up to 4 km away at Boys Town (BT) and Barden Ridge (BR) (see Figure 1). The detectors were situated 2 m above the ground except for Boys Town, which was 2 m above a 10 m flat roof. The 16 cases in this analysis have been chosen to include all receptor stations, where Cases 1–5 are for receptor BT, Cases 6–9 are for WS, Cases 10–11 are for BR and Cases 12–16 are for MG.

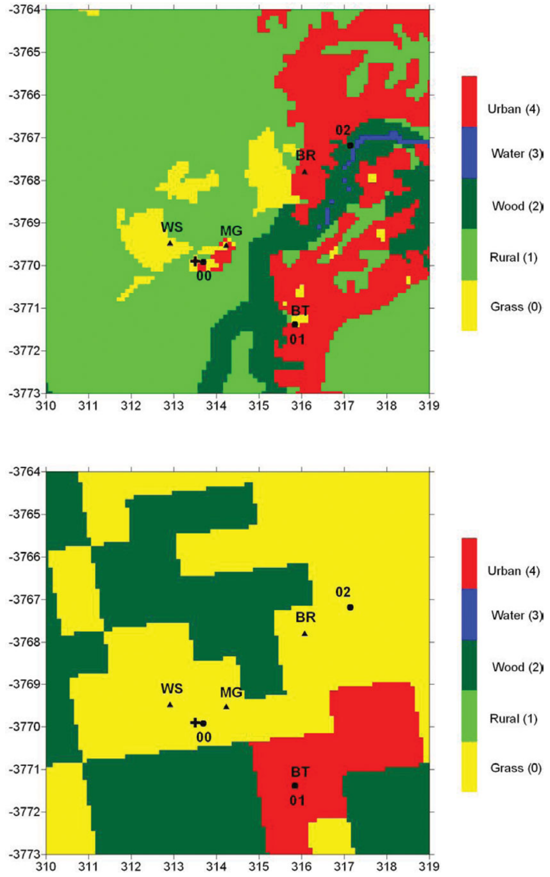
2.2 Dispersion model

RIMPUFF is a rapid operational puff diffusion code, developed for real-time simulation of atmospheric dispersion during nuclear accidents. RIMPUFF uses the Local Scale Preprocessor for Atmospheric Dispersion (LSPAD) to obtain finely gridded met-data fields over the area of interest and calculates stability and similarity parameters based on meteorological tower data (Astrup et al., 2001). Two different wind interpolation schemes can be used within RIMPUFF: the first is the local scale flow model LINCOM (LINearised COMputation) which takes orography and surface roughness patterns into account, but not thermal stratification. It creates a wind field that matches a weight of the measured winds, the weights falling exponentially with distance from the release point. Second, the inverse square distance interpolation method on the measured wind speed components can be specified. The dispersion model has a puff splitting feature for modelling dispersion over hilly terrain, which involves channelling, slope winds and inversion layer effects (Mikkelsen et al., 1997).

Based on meteorological input data, LSPAD uses different methods for calculating stability. The preferred option is to use the temperature gradient (between 10 and 50 m) and surface wind speed. If temperature profiles are not available, one surface temperature with net radiation, or alternatively cloud cover, can be used. The study here explores various stability calculation methods and how they consequently affect the wind field. Surface roughness for a met station is defined by the user, and RIMPUFF uses this for the determination of the wind speed profile at that station. For all other purposes, roughness is based on the local land use. In the model runs here, the met station surface roughness is varied for all cases, and three land-use schemes are used: the US Geological Survey (USGS) 1 km spatial resolution dataset (USGS, 2008) and two locally-derived 25 m spatial resolution datasets. The USGS has 24 land-use categories, here reduced to 5 as required by RIMPUFF (called USGS Map). The two 25 m resolution datasets, derived at ANSTO are equal, except that the one called ANSTO Map (a) includes a rural area (with roughness length 0.1 m), see Figure 2, while the other called ANSTO Map (b), specifies wood (roughness 1.0 m) where ANSTO Map (a) specifies rural.

RIMPUFF was run on a 9 × 9 km area using 91 × 91 grid points, i.e., with grid size of 100 m × 100 m, with inputs of 15-minute average source data from the 23 m tall HIFAR reactor stack emissions and 15-minute average met-data from stations 00 and 01.

Figure 2 Top: ANSTO Map (a) – 25 m resolution land use map. Bottom: USGS Map – 1 km resolution land use map. Meteorological stations (00, 01, 02) and environmental gamma stations (WS, MG, BT, BR) are shown as well as the HIFAR reactor release point at the cross, next to met station 00 (see online version for colours)



3 Results and discussion

The different methods in the RIMPUFF code for calculating stability have been explored with varying meteorological inputs. Important variables such as surface roughness, frictional velocity and the Monin-Obukhov length were compared, as well as the final stability categories for a number of cases which identified limitations in some of the measured meteorological data for the period of data concerned. The net radiation data was found to have limited variability, and the station 00 temperature data at 2 m may be affected by the ground surface or nearby buildings or trees. These measurements were subsequently withheld from the model runs, and stability calculated using the 10 and 49 m data with the temperature gradient method.

To evaluate the model results, a number of graphical representations and statistical methods have been used. First, gamma dose rate contour plots including calculated wind vectors combined with time series of dose rates are used to analyse the results of different wind model parameterisation schemes, and to explore the sensitivity of results to varying inputs. It should be noted that all data presented here are 15-minute averages. Using a diagnostic wind model requires a network of spatially diverse meteorological observations; therefore, various parameterisation schemes were tested to determine whether the met stations were appropriately sited and to identify the most accurate wind field generated. The observations collected at station 02 located on the valley floor are controlled by local terrain features where katabatic winds are observed due to drainage of cooler air into the sloping terrain. These observations are only useful as input to wind models if the model can reproduce thermal flows. The LINCOM code for wind over terrain extrapolates a given wind at a given place, or a weighted sum of winds at different places to a greater area, taking orography and changing roughness into account, but not atmospheric stability. It was found that including a met station, such as 02, that is not representative of the general area in the weighted sum leads to poor calculations, and that it should not be included in the calculations. The inverse square distance parameterisation scheme with station 02 excluded is found to be most suitable for the meteorological network at ANSTO. An example of this is Case 2, where wind shear is present between stations 00 and 01. Although the inverse square distance method over-predicts the dose rate in Case 2, it produces a more accurate wind field following the met station data, rather than the weighted sum method of LINCOM that causes the plume to follow a different direction and under-predict (see Figure 3). Case 2 is a very stable night case during winter, when the surface and upper wind speeds drop to 1–2 ms^{-1} at 2200 EST, when the plume passes over station BT. Contour plots in Figure 3 show how important the wind field and dispersion calculations are when complex topography causes valley entrainment and plume splitting in the model predictions.

The met station input for RIMPUFF includes a surface roughness parameter which is used in the determination of the wind profile at the met station, and thereby, of the overall flow field. Variations in this roughness value were found to produce large differences in the dose rate calculation, particularly in the timing and the magnitude of the maximum dose rate (Figure 4). Case 4 shows that a variation from 0.005 m to 1.0 m in specified met station 00 roughness can result in a 30-minute difference in peak arrival time and more than double the dose rate. The sensitivity of dose rate calculations to model inputs such as land use and topography was explored using the USGS 1 km resolution global data and ANSTO-derived 25 m resolution data. In most cases, the model prediction was closer to the observations when the higher resolution land-use data was used; however, the better results vary between use of ANSTO Map (a) and ANSTO Map (b), depending on the location of the receptor station. This indicates that inclusion of more land use categories than the present 5, and thereby, a better resolved surface roughness pattern might improve the code. Figure 4 shows a case for which the use of ANSTO Map (a) gives slightly better results at MG than does ANSTO Map (b). The results using the USGS Map are also shown, but in relation to this particular site, which has had new developments built in the last 10 years, the USGS land use data created in 1993 is found to be out of date, and not at a suitable resolution for such short range dispersion.

Figure 3 Above: Contour plots of ^{41}Ar dose rate (Gy/h) for Case 2 at BT (22/06/2003 1815 EST) using the inverse square distance parameterisation r^{-2} (top contour) and the weighted sum method in LINCOM (bottom contour). Below: Plots of ^{41}Ar dose rate and Met station 00 wind direction for Case 2 (see online version for colours)

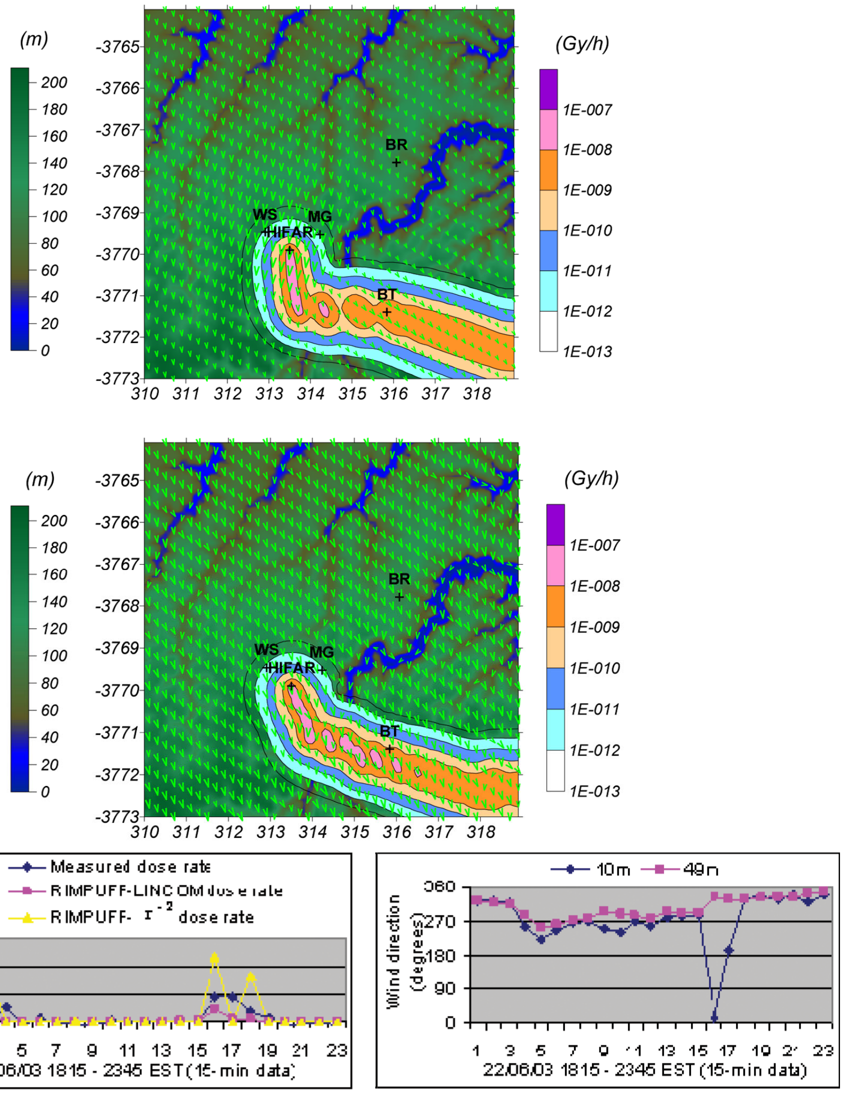
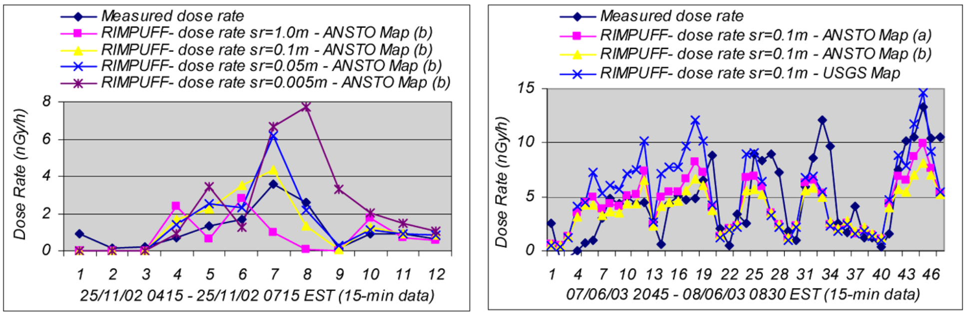


Figure 4 Left: ^{41}Ar dose rates for Case 4 at BT (25/11/02 0415 EST) with specified model surface roughness varied at met station 00 and ANSTO Map (b) used. Right: ^{41}Ar dose rates for Case 15 at MG (07/06/03 2045 EST) where specified model surface roughness is defined as 0.1 m and 3 different land use maps are used for comparison (see online version for colours)



Further exploratory analysis was carried out using scatter plots, quantile-quantile plots and residual scatter plots where pairs for the scatter plots are grouped by the receptor station. RIMPUFF results displayed here are from runs using ANSTO Map (b) and met station 00 surface roughness set to 0.1 m. The 16 cases produced 233 pairs of 15-minute observations to predictions when only including positive values and paired in space and time. The instrument limit of detection (LOD) of 0.4 nGy/h was used as a threshold and measured or predicted values falling under the threshold were set to the LOD. Receptor BT appears to have the best performance from the two scatter plots (Figure 5), with ratios falling mostly within a factor of 2. Further analyses reveal that these good results are generally cases with neutral or slightly unstable conditions, and with constant wind directions. Results for receptor BT have a slight tendency to over-predict during stable conditions with low wind speeds. The receptors closest to the release point, WS and MG, are under-predicted during neutral conditions; however, they both have a few large over- and under-predictions in the scatter plots. Common in those cases is a large vertical wind direction shear with low wind speeds of 1–3 ms^{-1} at 10 and 49 m at the time of the peak. The smaller sample size for receptor BR had all cases under-predicted for neutral conditions and constant wind direction. The quantile-quantile plot shows good correlation up to 5 nGy/h, some under-prediction up to 10 nGy/h and large over-predictions for larger doses.

Quantitative statistical performance measures such as FB, MG, NMSE, VG and FAC2, recommended by Chang and Hanna (2004), were generated using the BOOT software package. A perfect model would have MG, VG, and FAC2 = 1.0 and FB and NMSE = 0.0. Once again, the LOD was used as a threshold, and there were a total of 233 pairs. The results are presented in Table 1, with cases grouped into receptor stations to analyse the results based on wind direction and distance. Chang and Hanna (2005) have summarised typical magnitudes of the above performance measures and estimates of model acceptance criteria where $FAC2 > 0.5$, $|FB| < 0.3$ or $0.7 < MG < 1.3$ and $NMSE < 1.5$ or $VG < 4$. These criteria are based on comparisons of maximum concentrations on arcs (i.e. unpaired in space), and can be used as a guide for acceptable model performance. The results for receptor station BT here satisfy Chang and Hanna's criteria, and they also have the more stringent test of pairing in space and time. Receptor station MG (with the largest sample size) satisfies FAC2, FB and MG, but not NMSE or

VG, due to large over and under-predictions. Large NMSE values at receptor station WS are due to large values of observations or predictions for that receptor, whereas large MG and VG values at receptor station BR are due to small observed or predicted values here.

Figure 5 Top Left: Scatter plot of observed to predicted ^{41}Ar dose rate pairs. Top Right: Scatter plot of observed to predicted ^{41}Ar dose rate pairs up to 10 nGy/h. Bottom Left: Residual plot of predicted/observed ^{41}Ar dose rate ratios. Bottom Right: Quantile-quantile plot of separately ranked observed and predicted ^{41}Ar dose rate pairs. Black full line is 1-1 and dotted lines represent within a factor of 2 (see online version for colours)

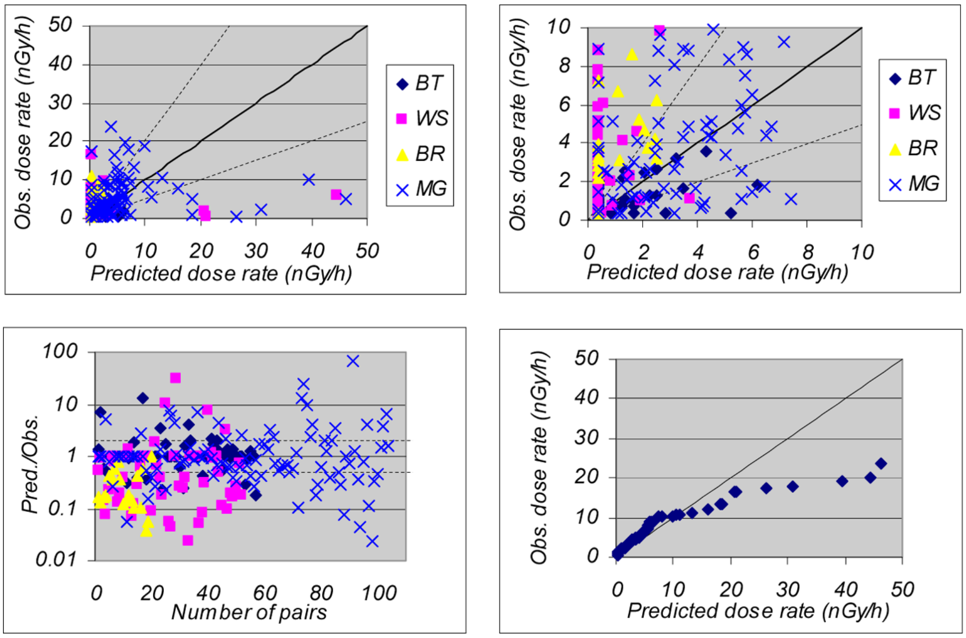


Table 1 Statistical measures generated using the BOOT software package. Cases have been grouped into stations, with the underlying data representing comparisons of predicted and observed 15 min dose rates paired in space and time. Model inputs include met station 00 surface roughness of 0.1 m, ANSTO Map (b)

Case (# of pairs)	*NMSE*	*FA2*	*FB*	*VG*	*MG*
(Median)	3.97	0.524	0.096	5.37	1.42
BT (56)	1.18	0.75	–0.187	1.67	0.96
WS (52)	9.24	0.385	0.179	15.2	2.39
BR (20)	3.48	0.15	1.225	26.5	5.12
MG (105)	2.54	0.543	–0.013	4.42	1.07

4 Conclusions

The newly updated local scale puff model RIMPUFF was evaluated using paired, observed and predicted ^{41}Ar dose rates in time and space to determine its suitability for estimating radiological consequences for a nuclear accident in complex terrain.

A sensitivity analysis was carried out where input parameters were varied to evaluate the accuracy of the combined wind field generation and atmospheric dispersion as well as to study the site-specific meteorological characteristics. The 16 cases covered a variety of atmospheric conditions, with many challenging the model with strong wind shears and complex local flows. The BOOT software from the Model Validation Kit was used to calculate statistical indices, and data was grouped into receptor stations. RIMPUFF gave the best results for the large sample size receptor station BT, followed by MG, with both satisfying Chang and Hanna's recommended Model Acceptance Criteria except NMSE and VG for station MG. RIMPUFF mostly under-predicted during neutral conditions, but was found to over-predict often during very stable conditions with low wind speeds. Particularly difficult cases were characterised by vertical wind direction shear near the reactor for low speed winds blowing towards the nearby receptor WS. Results improved when both 10 m and upper level 49 m wind data were used as input, as this enabled the model to reproduce the shear field. Results were also improved when the data from met station 02 located in the valley were not included in the simulation, since the model was unable to resolve these valley flows on such a small scale. The evaluation has shown that in this area of complex terrain, the model is very sensitive to inputs such as met station orientation, met station surface roughness, land use and vertical profiles of meteorological data. Based on the results presented here, RIMPUFF produces the most accurate dose rate predictions around the ANSTO site when using the r^{-2} model for wind data interpolation, with surface roughness at met station 00 defined as 0.1 m and with high resolution land-use and topographic maps.

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