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 at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia. Predicting radiological dispersion for emergency response at this site proves challenging due to complex topographical conditions including a steep-sided river valley located between the reactor and the nearest residents. A large number of ^{41}Ar measurements from a network of environmental gamma detectors are used to evaluate the model under a range of atmospheric stability conditions. Topographic and meteorological influences that potentially affect a released plume, such as channelling, wind shear, local terrain slope flows and strong inversions are explored. A sensitivity analysis using various combinations of meteorological station data for model input, including vertical wind and temperature profiles, also identifies model strengths and weaknesses within the complex terrain. Various model evaluation tools, such as relevant statistical indices and gamma dose contour plots, are used to evaluate this new version of RIMPUFF for emergency response purposes at ANSTO and for inclusion in the ARGOS Decision Support System.

Key words: *model evaluation, dispersion modelling, radiological, complex terrain, emergency response*

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 5km from its former HIFAR research reactor, 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 (RIso Mesoscale PUFF) with 2 different diagnostic wind models (Williams, A. *et al*., 2005). More recently the observations were used to evaluate RIMPUFF with the Local Scale Model Chain (Dyer, L., 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 weakness of the Carruthers (Dop, H van, 1992) puff growth parameterisation scheme (based on similarity scaling). Consequently, RIMPUFF was updated so the puff growth rate otherwise following the parameterisation of Carruthers has been limited to not exceed 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.

The main objective of this model evaluation is to a) determine whether the model can provide emergency personnel with a high-resolution radiological plume in complex terrain, and b) predict the timing and location of the maximum dose rate in order to direct the deployment of hand-held detectors for further measurements. Areas of interest here include the sensitivity of the wind field to varying input of measured meteorological data during these times of complex conditions. Other important aspects are the spatial variation of land-use characteristics and surface roughness to achieve an accurate simulation of the surface wind flows. The evaluation of the models performance is displayed qualitatively using concentration 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, J. C. and S. R. Hanna, 2004). Statistical performance measures recommended by Hanna, S. R. (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.

DATA AND METHODOLOGY

Site description and dataset

Meteorological data is available at the ANSTO site from a 49m 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 100m steep-sided river valley (Figure 1). All 3 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 50-60% of observations (Clark, G., 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 is 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.

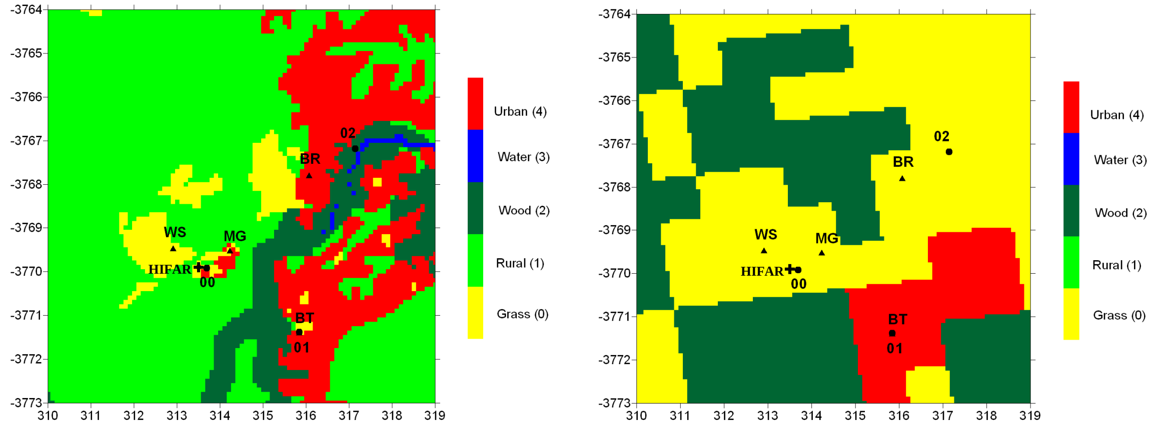

Figure 1: Left: 25m resolution land use map (Map 1 is shown and Map 2 is the same except rural is replaced with wood). Right: USGS 1km resolution land use map

Four GR-150 gamma detectors, developed by Exploranium Canada (Grasty, R.L. *et al.*, 2001) were deployed as a perimeter up to 5km from the HIFAR reactor, covering most directions, especially the predominant southerly winds and the nearest residents to the reactor. The detectors were located < 1km away at Main Gate (MG) and Waste Services (WS) and up to 4km at Boys Town (BT) and Barden Ridge (BR) (see Figure 1). The detectors were situated 2m above the ground except for Boys Town which was 2m above a 10m flat roof. The number of cases used in this analysis is 16, chosen to include at least 2 cases at each receptor station under stable and unstable conditions. It should be noted that some cases have multiple peaks.

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, P. 2001). Two different wind interpolation schemes can be used within RIMPUFF: firstly, the local scale flow model LINCOM (LINearised COMputation) which takes the orography and surface roughness pattern 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. Secondly, 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 the dispersion over hilly terrain, which involves channelling, slope winds and inversion layer effects (Mikkelsen, T. *et al*., 1998).

Based on the meteorological input data RIMPUFF uses different methods for calculating stability. The preferred option is to use the temperature gradient (between 10 and 50m) and surface wind speed (Thykier-Nielsen, S. P. *et al.*, 2004). If temperature profiles are not available one surface temperature with net radiation can be used or alternatively cloud cover. The various stability calculations are explored and how they affect the wind field. Surface roughness for a met-station is defined by the user and RIMPUFF then determines the wind speed profile at that station. For all other purposes roughness is based on the local land use. In this study surface roughness is varied for all cases and two land-use schemes are used: the U.S. Geological Survey (USGS) 1km spatial resolution dataset (USGS, 2008); and a locally-derived 25m spatial resolution dataset (see Figure 1). The USGS has 24 land-use categories but these were reduced to 5 as required by RIMPUFF (here called Map USGS). Two variations of the 25m resolution land use dataset were also run to see the effect on the results: one includes rural (with roughness length 0.1m) as a category (Map 1) and the other where rural is replaced with wood (1.0m) (Map 2).

The latest version of RIMPUFF was run with a modified puff growth parameterisation scheme using the similarity scaling method as mentioned above. The model runs involve 91 x 91 grid points, grid size of 100m x 100m with inputs of 15-minute average source data from the 23m tall HIFAR reactor stack emissions and 15-minute average met-data from stations 00 and 01.

RESULTS AND DISCUSSION

The different methods in the RIMPUFF code for calculating stability have been explored with varying meteorological input. 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 2m may be affected by the ground surface or nearby buildings or trees. These measurements were withheld from the model runs and stability calculated using the 10 and 49m data with the temperature gradient method.

In order to evaluate the model results, a certain number of graphical representations and statistical methods have been used. Firstly concentration contour plots including calculated wind vectors and 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 input. Using a diagnostic wind model requires a dense 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, 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 is found to be most suitable for the meteorological network at ANSTO. Wind shear between stations 00 and 01 occurs in Case 2 and although the inverse method over-predicts the dose rate, 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 2). Case 2 is a very stable night case during winter where the surface and upper wind speeds drop to 1-2 ms^{-2} at 2200 EST when the plume passes over station BT. Concentration plots in Figure 2 show how important the wind field and dispersion calculations are when complex topography causes valley entrainment and plume splitting in the model predictions.

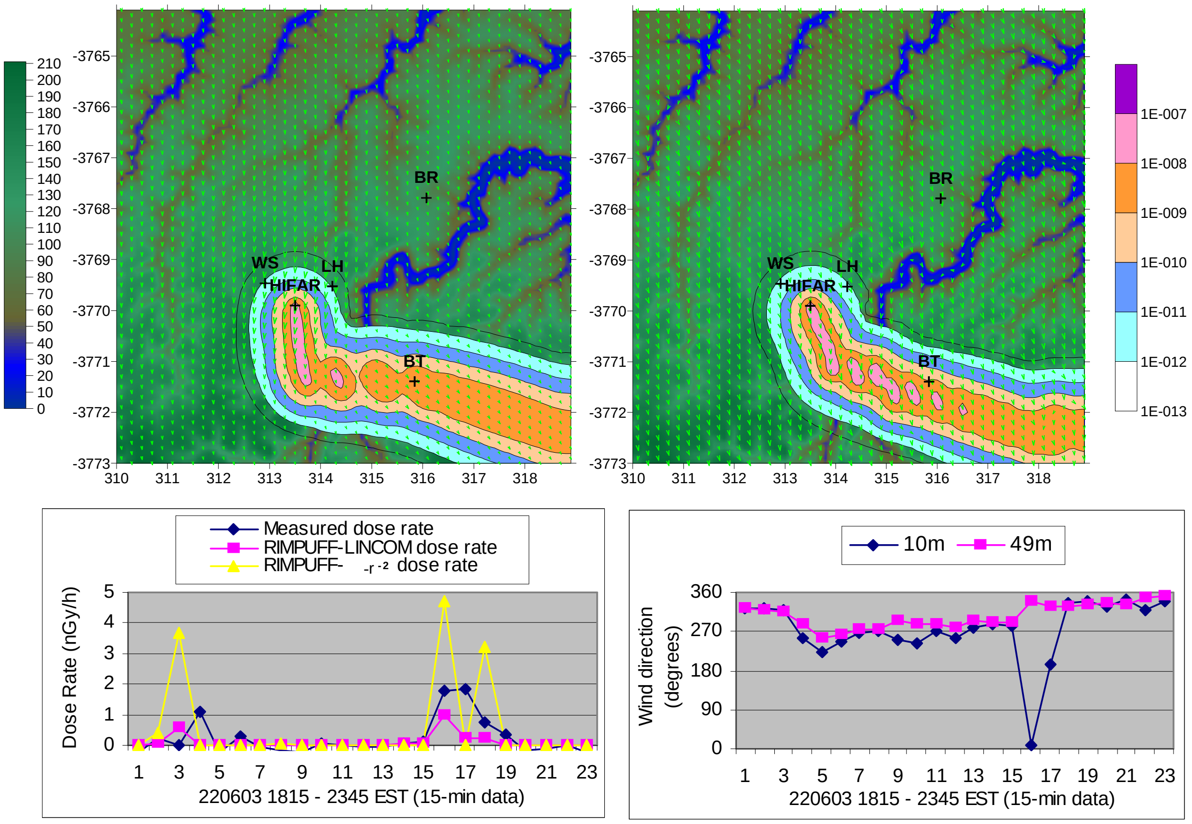

Figure 2: Above: Concentration contour plots for Case 2 at BT (22/06/2003 2200 EST) using r^{-2} (Left) and the wind flow model LINCOM (Right). Below: Dose rate and wind direction plots for Case 2.

The meteorological input for RIMPUFF includes a user defined surface roughness parameter used in the puff growth parameterisation at the source. Variations in this roughness value were found to produce large differences in the dose rate calculation, particularly in the timing and the concentration of the maximum dose rate (Figure 3). Case 4 shows that a variation of 0.005m to 1.0m in surface 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 were explored using the USGS 1km resolution global data and ANSTO derived 25m resolution data. In most cases the model prediction was closer to the observations when the higher resolution land-use data was used however the results vary between Map 1 and Map 2 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 3 shows a case for which the use of Map 1 gives slightly better results at MG than does Map 2. Also the results using the USGS map is shown, but in relation to this particular site which have 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.

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 Map 2 and met-station 00 surface roughness set to 0.1m. The 16 cases produced 242 pairs of 15-minute observations to predictions when paired in space and time. Receptor BT appears to have the best performance from the two scatter plots (Figure 4) with ratios falling mostly within a factor of 2. Further analysis reveal that these good results are generally cases with neutral conditions or slightly unstable with constant wind direction. Results for receptor BT have a slight tendency to over-predict and these are during stable conditions with low wind speeds. The closest receptors WS and MG under-predict during neutral conditions however they both have a few large over and under-predictions in the scatter plots and common in those cases is a large vertical wind shear with low wind speeds of 1-3ms^{-1} at 10 and 49m at the time of the peak. The smaller sample size for receptor BR meant all cases under-predicted for neutral conditions and constant wind direction. The quantile-quantile plot shows good correlation up to 5 nGy/h and slightly under-predicting but then over-predicting for all large doses.

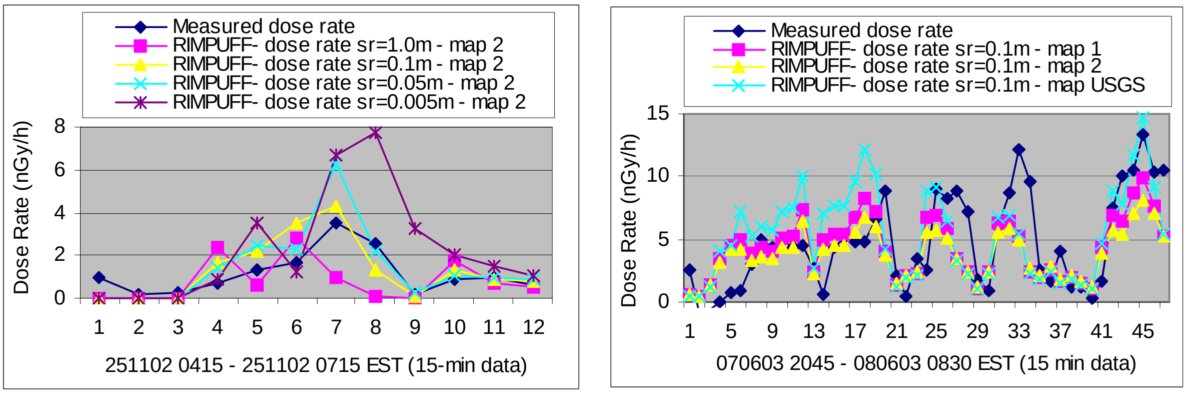

Figure 3: Dose rates for Case 4 at BT with specified surface roughness varied for met-station 00 (Left), and for Case 15 at MG where land use maps are varied (Right)

Quantitative statistical performance measures such as FB, MG, NMSE, VG and FAC2, recommended by Chang and Hanna (2004) were generated using the BOOT software. A perfect model would have MG, VG, and FAC2 = 1.0 and FB and NMSE = 0.0. The instrument limit of detection (LOD) of 0.4nGy/h was used as a threshold where measured or predicted values falling under the threshold were set to the LOD. The results are presented in Table 1 with cases grouped into receptor stations to analyse the results based on wind direction and distance. BT is the only receptor with all statistics satisfying the Model Acceptance Criteria (Change, J.C. and S.R. Hanna, 2005) 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) therefore model performance will deteriorated for more stringent tests such as pairing in time and space as expected. Receptor MG with the largest sample size satisfies FAC2, FB and MG but not NMSE or VG due to the large over and under-predictions. Large NMSE values at receptor station WS are due to large values of observations or predictions for that station whereas large MG and VG values at station BR are due to small values.

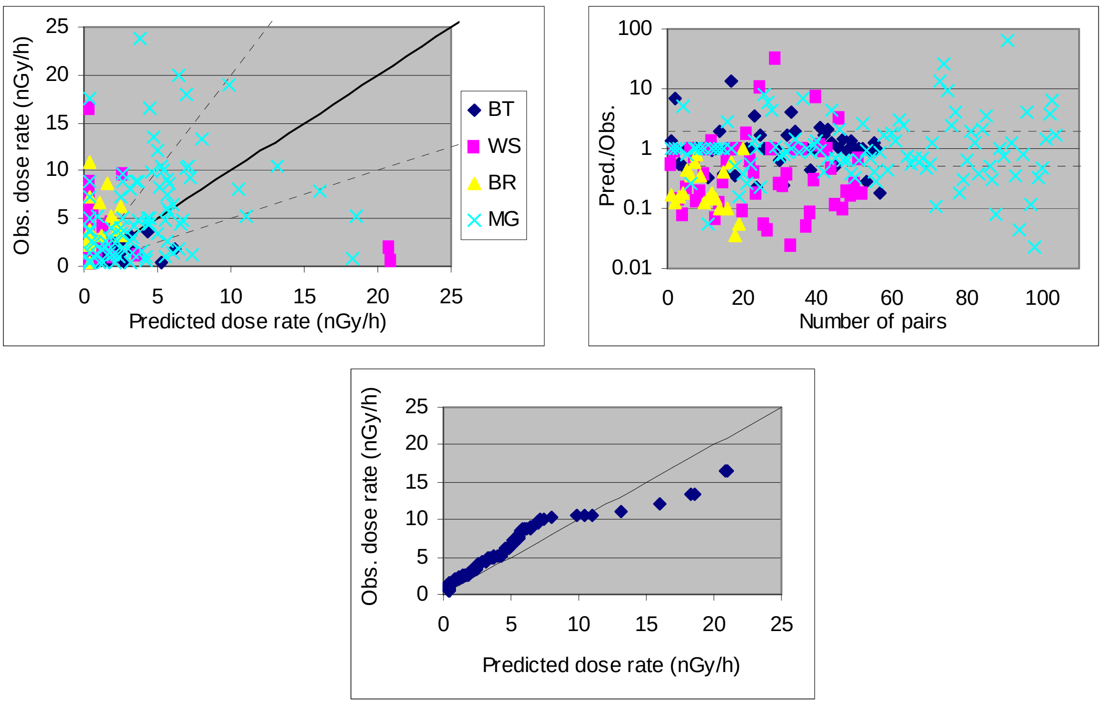

Figure 4: Top Left: Scatter plot of observed to predicted pairs. Top Right: Residual plot of predicted/observed ratios. Bottom: Quantile-quantile plot of separately ranked observed and predicted pairs. Black diagonal line is 1-1 and dotted lines represent within a factor of 2.

Table 1: Statistical measures from the BOOT software

Case	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

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 studying 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 the 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 shear near the reactor for low speed winds blowing towards the nearby receptor WS. Results were shown to improve when upper level wind data at 49m were used however observations at higher levels for input would enable the models to provide better predictions of wind shear. The evaluation has shown that in this area of complex terrain, the model is very sensitive to inputs such as surface roughness, land use and vertical profiles of meteorological data. Based on the results presented here, RIMPUFF produces the most accurate dose rate predictions at the ANSTO site when using the r^{-2} model for wind data interpolation, surface roughness at met-station 00 defined as 0.1m and a high resolution land-use and topography map is preferred when using a high resolution wind and dispersion code.

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