Canadian Nuclear Society
Waste Management, Decommissioning and Environmental Restoration
for Canada's Nuclear Activities: Current Practices and Future Needs
Ottawa, Ontario Canada May 8-11 2005

APPLICATION OF A MESOSCALE FORECASTING MODEL (NMM) COUPLED TO THE CALMET TO DEVELOP FORECAST METEOROLOGY TO USE WITH THE CALPUFF AIR DISPERSION MODEL.

Prepared by Zivorad Radonjic[1], Bosko Telenta[1], Jennifer Kirkaldy[1], Dr. Doug Chambers[1], and Heather Kleb[2]
[1)]SENES Consultants Limited, 121 Granton Drive, Unit 12, Richmond Hill, Ontario L4B 3N4
email: dchambers@senes.ca
[2)]Atomic Energy of Canada Limited, Low Level Radioactive Waste Management Office 1900 City Park Dr., Suite 200, Ottawa ON, K1A 1A3

SUMMARY

An air quality assessment was undertaken as part of the Environmental Assessment for the Port Hope Area Initiative. The assessment predicted potential effects associated with the remediation efforts for historic low-level radioactive wastes and construction of Long-Term Waste Management Facilities (LTWMFs) for both the Port Hope and Port Granby Projects. A necessary element of air dispersion modelling is the development of suitable meteorological data. For the Port Hope and Port Granby Projects, a meteorological station was installed in close proximity to the location of the recommended LTWMF in Port Hope. The recommended location for the Port Granby LTWMF is approximately 10 km west of the Port Hope LTWMF.

Concerns were raised regarding the applicability of data collected for the Port Hope meteorological station to the Port Granby Site. To address this concern, a new method for processing meteorological data, which coupled mesoscale meteorological forecasting data the U.S. EPA CALMET meteorological data processor, was applied. This methodology is possible because a new and advanced mesoscale forecasting modelling system enables extensive numerical calculations on personal computers. As a result of this advancement, mesoscale forecasting systems can now be coupled with the CALMET meteorological data processor and the CALPUFF air dispersion modelling system to facilitate wind field estimations and air dispersion analysis.

1. INTRODUCTION

The SENES FReSH (Forecast Refinement System Host) system is a framework for running the Nonhydrostatic Mesoscale Model (NMM)[1, 2, 3]. The FReSH system was developed by and continues to be tested at SENES Consultants Ltd. (www.senes.ca). The NMM model was originally developed in 1995 by the National Weather Service/National Center for Environmental Prediction (NCEP) and has been, and continues to be, intensely tested under operational conditions. It was selected in 2004 by NCEP to replace the current operational forecast model Eta (NOAA/NCEP mesoscale model). The FReSH system incorporates efficient pre-processors and post-processors designed for a robust and automatic use of the NMM model including initialization from Eta analyses and surface data, simulation management and graphical/web interfacing. The system is very flexible and can be implemented for operational applications on a single-processor personal computer. FReSH has already been validated and produces daily weather forecasts for Southern Ontario, British Columbia and other areas. FReSH is run on a Linux PC desktop station and has been applied in many studies including weather forecasting, meteorological modelling, air dispersion modelling, and evaluation of wind power generation potential.

Coupling FReSH with regulatory air dispersion models such as CALMET[4]/CALPUFF[5] and ISC[6] has been one of SENES' priorities in the past two years due to the increasing number of applications that necessitate flexible and reliable coupled models. One interesting feature in NMM is the fact that it is nonhydrostatic, which allows simulations with fine resolution grids down to 100 metres in the non-operational mode.

This paper is intended to:

- demonstrate the improved performance of the NMM mesoscale model over the Eta model on fine resolution applications;
- describe the coupling of the NMM/CALMET models and to illustrate the application by comparing predicted meteorology to that observed at the Port Hope station; and
- illustrate how forecast meteorology can be used with air dispersion models such as CALPUFF.

2. PERFORMANCE Of FReSH 4 (BASED ON NMM) AND OPERATIONAL ETA (12 BY 12 KM)

Predictions were carried out for 2003 to demonstrate the improved performance of the FReSH (NMM-based) over Eta on a fine horizontal resolution. Wind speed, wind direction and temperature predictions were compared against observed data at 3 hour intervals over a 48 hour period of the forecast. In each season one month (30 days) were analyzed for a total of 1488 observations each season, over five (Windsor, Goderich, Toronto International Airport, Collingwood and Peterborough) Environment Canada meteorological stations. As a demonstration, the following detailed validation statistics of FReSH are presented based on a comparison of predicted hourly values of wind speed, wind direction and temperature and corresponding measured hourly values at meteorological stations. The horizontal resolution for Eta model is 12 by 12 km and for FReSH is 4 by 4 km.

Table 1 summarizes the performance of FReSH (4 km resolution) versus operational Eta (12 km resolution) for the meteorological station model above. The comparison is based on the Root Mean Square Error (RMSE) between predicted and observed values and is a common measure of overall accuracy and reliability of the forecast.

Table 1. Performance of FReSH (NMM-based) and ETA Against Real Observational Data Over 2003 Year (Percentage of the Time that NMM Outperforms Eta).

	SEASON				
PARAMETER	**Winter**	**Spring**	**Summer**	**Fall**	**Year**
Wind Speed (10m)	**75%**	**86%**	**100%**	**100%**	**90%**
Wind Direction (10m)	**71%**	**57%**	**75%**	**61%**	**65%**
Relative Humidity (2m)	**88%**	**81%**	**77%**	**69%**	**79%**
Temperature (2m)	**64%**	**73%**	**62%**	**63%**	**66%**

Notes:
based on Root Mean Square Error which is a measure of overall accuracy
based on 31 days / 1488 observations per season
based on a 48 hour forecast

NMM outperforms Eta	75%
Eta outperforms NMM	25%

Boxed area represent updates with 2003 data
91 days/2190 observations/season

Figures 1 through 3 show three statistical measures of performance, namely, RMSE, mean absolute error and bias (mean algebraic error which allows both positive and negative differences between the forecast and observed values). Figures 1 to 3 are for a forty-eight hour forecast of temperature, wind speed and wind direction for the same period and same number of stations as in Table 1.

Figure 1. Statistics for Temperature
NMM Summer 2003 validation on 1488 observations in Southern Ontario
Temperature at 2 meters

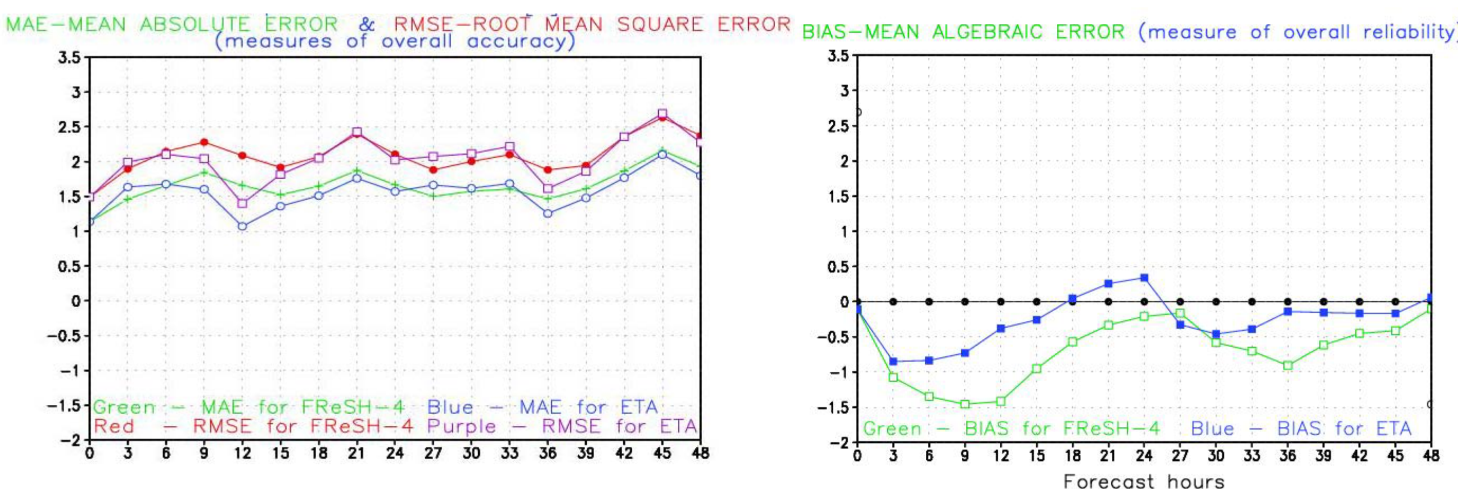

Figure 2. Statistics for Wind Speed
NMM Summer 2003 validation on 1488 observations in Southern Ontario
Wind Speed at 10 meters [m/s]

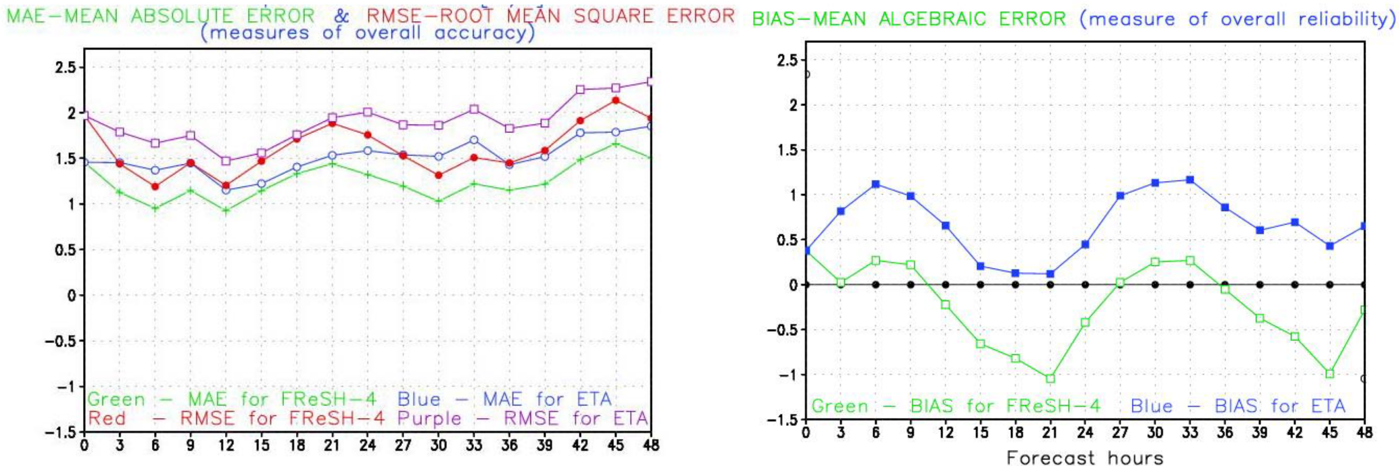

Figure 3. Statistics for Wind Direction
NMM Summer 2003 validation on 1488 observations in Southern Ontario
Wind Direction at 10 meters

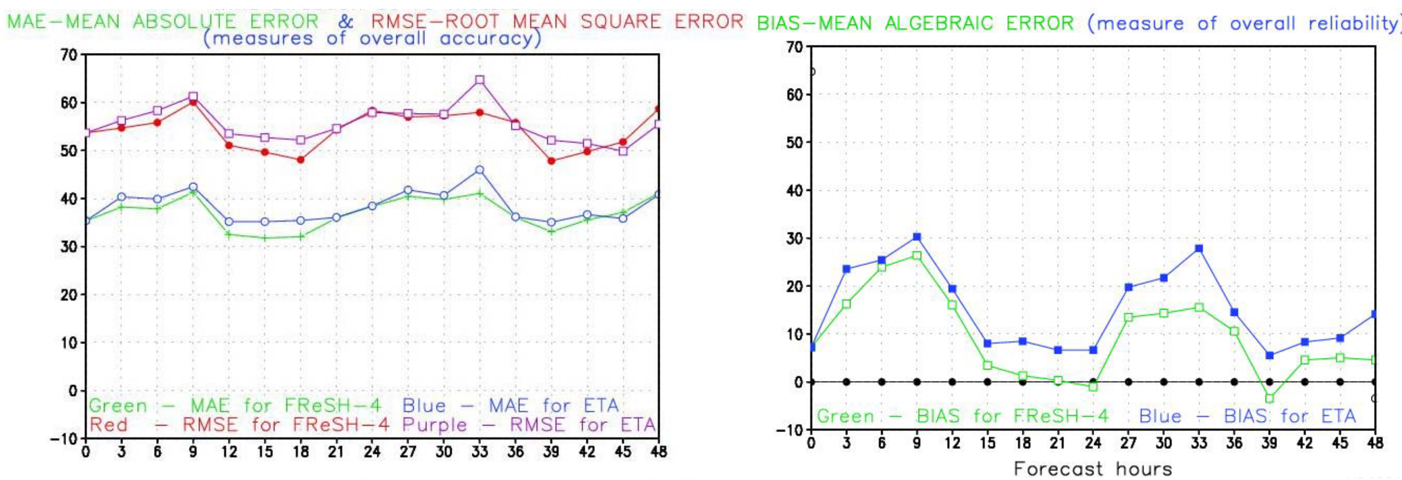

Table 2 shows the summary of the bias, mean absolute error and RMSE for the forecast at hour 3 after the forecasting model was initialized. The reference height for comparison was 10 m for wind and 2 m for temperature. Based on RMSE the temperature range is 2 K, wind speed in the range of 1.5 m/s and wind direction of 55 degrees, approximately two and a half wind sectors (the first hour of the forecast for which statistics were available to compare to observations).

Table 2. Summary of FreSH-4 statistics for the forecasted hour 3.

	Hour 3 at 10 m		
Element	BIAS	MAE	RMSE
Temperature (K)	-1.00	1.50	2.00
Wind Speed (m/s)	0.00	1.20	1.50
Wind Direction (^{0})	18.00	38.00	55.00

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3. NMM COUPLED TO CALMET

The coupled model, FReSH(NMM)-CALMET, was applied to the Port Hope, Ontario region for 2003. The "experiment" compares observed and simulated winds at a specific location in Port Hope (South of Highway 401, west of Toronto Rd.), where a well-exposed automatic Campbell Scientific meteorological station had been installed following U.S. EPA Guidance.

In this application, NMM was initialized on the 00Z Eta 12 km by 12 km analyses, and was run using 6-hour Eta analyses boundary conditions. In turn, NMM was run for 2003 on a 2.2 km grid spacing over a domain approximately a 60 km by 60 km. Finally, CALMET was run over a domain of 27 km by 16 km with a horizontal grid spacing of 100 m x 100 m (Figure 4). Several case studies were designed to investigate the CALMET initialization and the impact of the CALMET results on the CALPUFF dispersion results. The modelling period for case studies illustrated below was July, 2003, the month with the greatest variance from observations. The cases are:

- **CASE A (Reference case): CALMET in observation mode with one surface and one upper air station**

  This is the reference run. Data from one surface meteorological station and one upper-air station.

- **CASE B: CALMET coupled with FReSH (no-observation mode)**

  CALMET gets input data from the FReSH (M3D) and interpolates the data from the first level above ground down to the surface. The wind field at 10-metres above ground calculated by the FReSH is not used in the interpolation. Also, the "initial-guess" wind field is not modified according to terrain and surface characteristics as in CASE A.

- **CASE C: Modified CALMET interpolation algorithm in no-observation mode**

  CALMET was modified to take 10-metre winds from FreSH and use them to interpolate down to the ground.

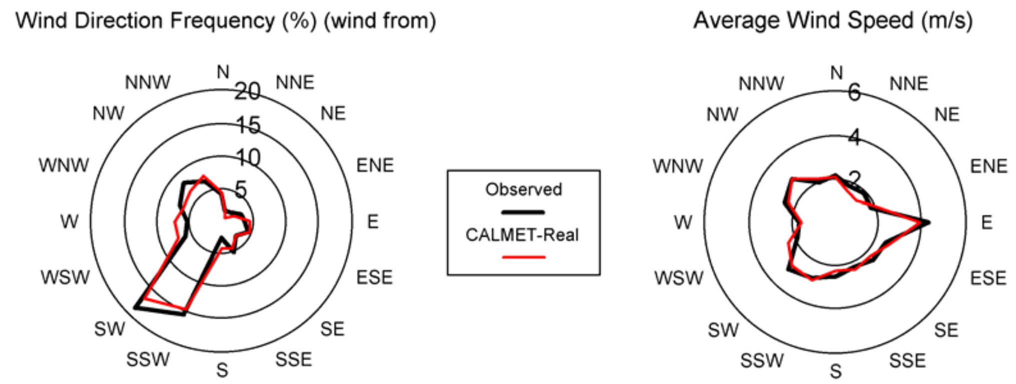
- **CASE D: Pseudo-Observation Mode**

  10-metre wind fields from FReSH are reformatted as surface and upper air observations at a limited number of discrete points and used to run CALMET in observation mode. Five surface stations are considered, one station at each corner of the modelling domain and a fifth station at the meteorological monitoring station inside the domain. At these locations, upper air profiles are created in CALMET's READ62 output format.

CASE A: CALMET Observation Mode – Reference Case

In the CALMET observation mode one surface station and one upper-air station located at Buffalo about 100 km south-west from Port Hope were used. As for the other simulations, CALMET grid spacing in this mode was 100 by 100 meters. The wind rose comparison is presented in Figure 5. As would be expected, excellent agreement is achieved.

Figure 5. Wind Rose for Comparison CALMET (observation mode) vs. Observation – July, 2003

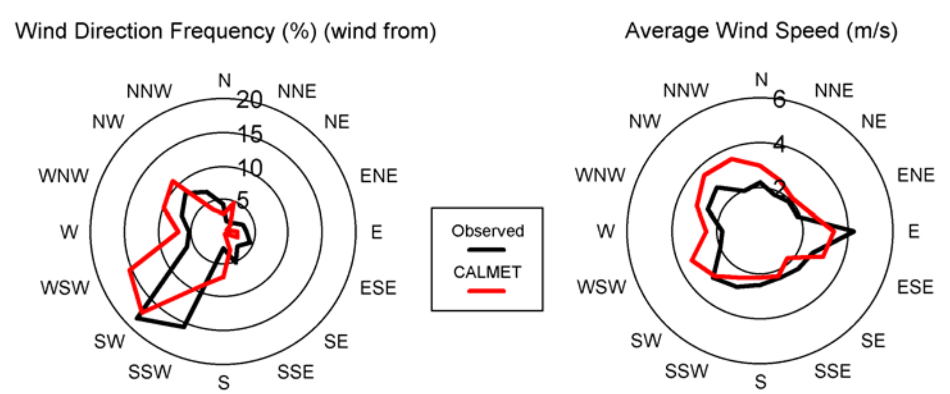


CASE B: CALMET coupled with FReSH (no-observation mode) - 2.2 km Mesoscale Horizontal Resolution and 100m CALMET Resolution

The July 2003 wind rose is presented in Figure 6 comparing observations vs. CALMET CASE B. In this scenario, 10 m winds from the mesoscale model are not taken for the vertical interpolation routine. It is important to note that on an annual basis, agreement is much better, but for illustrative purposes, the month with the greatest variance from observations is presented. The overall observation pattern is achieved, even in no-obs mode, however, certain directions show deviation in both wind speed and wind direction.

The initial wind fields for CALMET were taken from NMM output (91 mesoscale grid points were used), and run in no-observation mode (NOOBS = 2) for CASES B, C and D. For CASE A (reference case), on-site surface observations and data from one upper air station (Buffalo, U.S.) approximate 100 km South-west of the site were used. Hourly wind observation data from automatic stations were used only for model comparison to the closest CALMET grid point. Blue lines in Figure 4 represent terrain elevations. Red dots are the two studied locations.

Figure 6. Wind Rose Comparison Observation vs. CALMET (no-obs) Simulation – July, 2003

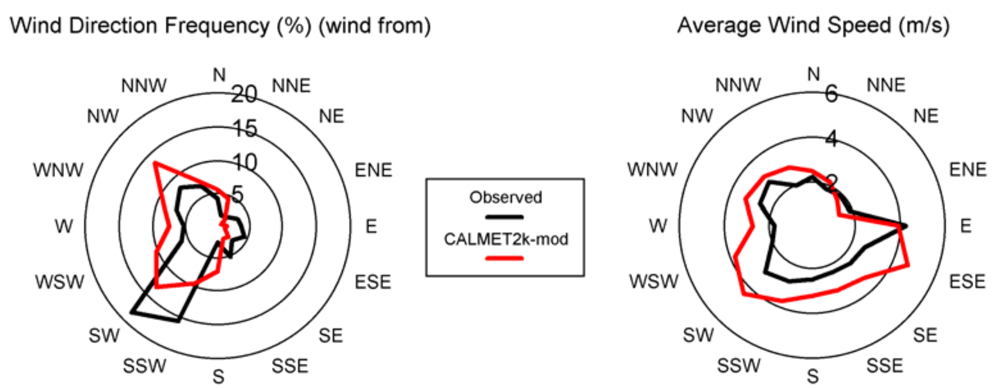


Note: CALMET represents initialization of CALMET by NMM at 2.2 km resolution

CASE C: Modified CALMET interpolation algorithm in no-observation mode - 2.2 km Mesoscale Horizontal Resolution and 100m CALMET Resolution

A modified CAL-Eta and CALMET Algorithm were applied to the month with the greatest variance from observations (July 2003). This scenario is similar to CASE B except that the mesoscale 10 m winds were taken for the vertical interpolation routine.

Figure 7. Wind Rose comparison – July, 2003



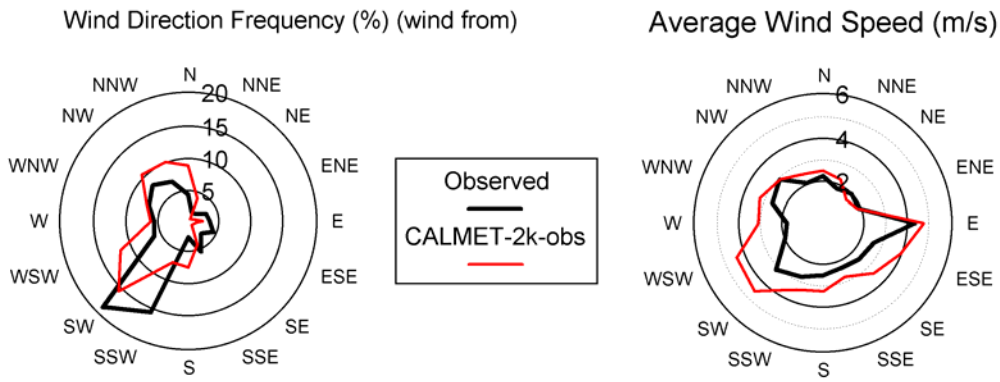
Note: CALMET2k-mod represents initialization of CALMET by NMM at 2.2 km resolution

CASE C demonstrated improvement in the wind speed over CASE B from the northern sectors, but over-estimated speed from southern sectors. This is directly related to the interpolation routine. The surface winds from the mesoscale model play a role in the interpolation indicating that the mesoscale model predicts higher speeds over the Lake Ontario than over land. This is consistent with expectations since surface roughness is lower over water than over land. However, further horizontal scale refinements (i.e. resolution <2.2 km) may improve the simulation.

CASE D: CALMET in Pseudo Observation Mode - 2.2 km Mesoscale Horizontal Resolution and 100 m CALMET Resolution

Results from this simulation are presented in Figure 11. Conclusions are similar to CASE C for wind direction and wind speed, however, the magnitude of the overestimated speeds is higher in the southern sector. This approach effectively develops surface data at several different locations across the domain (in this case 5 locations). The overestimation of wind speeds in the southern sector is likely caused by the pseudo-surface data being developed overtop of a large water body (Lake Ontario). It is believed that because of the close proximity to the lake, that wind speeds are being skewed high. Selection of different locations (i.e. not over the lake) may result in an improved simulation. In addition, at the 2.2 km resolution, the model may not fully capture the lake-breeze effect which may contribute to the wind direction shift in July 2003. Further testing at a finer resolution (e.g. 1 by 1 km) may provide some improvement.

Figure 8.Wind Rose comparison – July, 2003



Note: CALMET-2k-pobs represents initialization of CALMET by NMM at 2.2 km resolution

A bias analysis for all scenarios for July 2003 is presented in Table 3. Bias analysis for July are in the order of the NMM model statistics performed over seven locations in Ontario and for summer season on 4 km resolution summarized in Table 2.

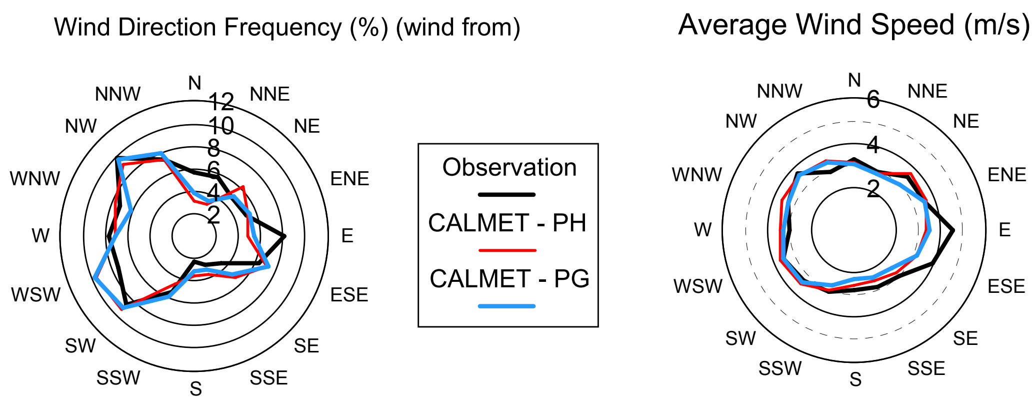
Table 3. Bias, Mean Absolute Error and Root Mean Square Error – July 2003

	Wind Speed			Wind Direction			Temperature		
MODE	BIAS	MAE	RMSE	BIAS	MAE	RMSE	BIAS	MAE	RMSE
CASE A - CALMET-OBS	0.00	0.12	0.14	0.77	3.08	13.67	0.02	0.14	0.16
CASE B - CALMET-ORIG	0.39	1.23	1.51	18.29	42.98	66.03	0.80	2.06	2.65
CASE C - CALMET-MOD	0.75	1.16	1.46	25.00	47.17	82.28	0.83	2.07	2.67
CASE D - CALMET-PSEUDO	0.79	1.39	1.84	21.16	63.45	95.44	-0.42	3.15	4.00

Wind speed is an important consideration for air dispersion modeling. Overall, the modified CAL-Eta and CALMET performed better based on the MAE and RMSE. For wind direction, the original CAL-Eta and CALMET were better than the modified mode. The pseudo-observation mode did not work well. These differences result from different interpolation routines in the CALMET algorithm in the CAL-Eta interface. Our experience suggests that many of these approaches could be improved to reflect mesoscale horizontal and vertical resolution. For situations with a lack of nearby monitoring, our experience suggests that the mesoscale model validation should be done at least at one point in the larger modelling domain incorporating the site of interest.

Local meteorological data for Port Hope was generated using CALMET (no-observation mode) coupled with FReSH (CASE B). Overall, micrometeorological effects generally appear to be well captured. (This approach may be even more suitable for complex terrain settings). Figure 9 shows annual modeled wind roses at Port Hope and Port Granby area. The observations at Port Hope (reference location) are also presented for ease of reference. This figure illustrates that the meteorological data generated with CALMET in no-observation mode coupled with FreSH generally captures the observed wind profile at Port Hope. Also, the wind profile at Port Granby, located approximately 10 km distant is virtually the same as the Port Hope wind profile.

Figure 9. 2003 - Wind Rose Differences between Port Hope (PH) and Port Granby (PG)



4. USING FReSH (COUPLED NMM/CALMET) TO DRIVE CALPUFF

Air dispersion models are commonly used to assess the consequences of chronic or accidental releases to the air. It is important to understand how the predictions from different models are affected by meteorological inputs. In this section, meteorological data from the above case-studies are used to investigate the performance of the CALPUFF air dispersion model. The exercise to illustrate the sensitivity of the predicted concentrations was carried out for the CASEs A through D. The results are illustrated below for CASE B.

The air dispersion modelling domain was set-up with the stack at the same location as the meteorological station, marked as Port Hope (Figure 4). The CALPUFF simulations were performed over a 100 by 100 m grid out to 10 km in each direction from the stack. The dispersion grid is equivalent to the meteorological grid, and maximum predictions from the entire grid were used for the summary results. For this demonstration "reference" stacks of differing characteristics were chosen to show the impact of meteorological uncertainty on air dispersion calculations.

Table 4. Summary of Reference Stack Parameters Used in Modelling

Source ID	Stack Height (m)	Stack Diameter (m)	Exit Velocity (m/s)	Exit Temperature (K)	Emissions (g/s)
Low	35.0	2.4	11.7	432.0	100.0
Medium	100.0	4.6	18.8	416.0	100.0
High	200.0	5.6	26.5	425.0	100.0

CALPUFF simulations were performed for all three reference stacks. The predicted maximum locations reported, were taken as an absolute maximum over the entire modelled grid. Summary tables present, for each reference stack (low, medium and high), the predicted maximum 1-hour, 24-hour and period average (month) concentrations. For each maximum predicted concentration, the location coordinates are recorded to demonstrate spacial variability caused by variable meteorology. The coordinates represent the distance from the stack locations in east and north directions.

Table 5 shows the results of the simulation for CASE B, CASE A as a reference. The low-stack ratios of the predicted concentrations show that the maximum predicted 1-hour average concentrations are underpredicted by ~13% compared to the reference CASE A; maximum 24-hour average concentrations are overpredicted by ~120%; and annual concentrations are overpredicted by 4%. For the medium stack, the ratios of the predicted concentrations show that the maximum predicted 1-hour average concentrations are under-predicted by ~50% compared to reference CASE A, maximum 24-hour average concentrations are overpredicted by 24% and annual concentrations are overpredicted by 1%. For the high stack, the ratios of the predicted concentrations are showing that maximum 1-hour average concentrations overpredict by ~70% (compared to reference CASE A), maximum 24-hour are overpredicted by 54% and annual concentrations by 40%.

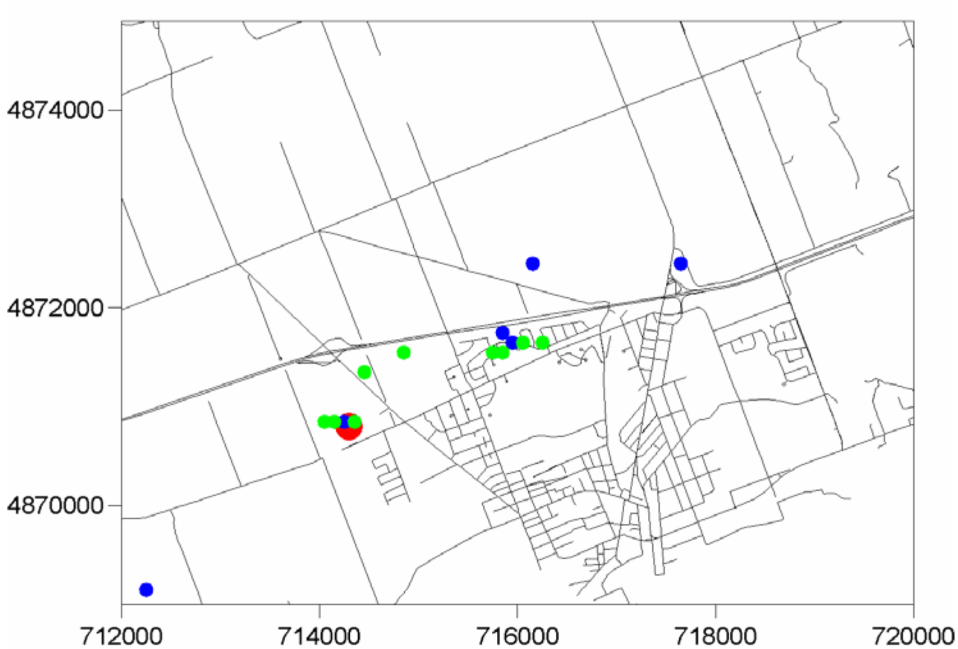
Table 5. CALPUFF Dispersion Modelling Results for CASE B

Reference Stack	Averaging Period	Location		Concentration	Location		Concentration	Ratio
		Easting	Northing	CASE A - $\mu g/m^3$	Easting	Northing	CASE B - $\mu g/m^3$	CASE B/ CASE A
Low Stack	Max. 1 hr	-50	50	**1925.8**	-150	50	**>1681.9**	0.87
	Max. 24 hr	-250	50	**253.53**	-250	50	**<551.48**	2.18
	Max Period	50	50	**63.87**	50	50	**<66.52**	1.04
Medium Stack	Max. 1 hr	-4450	-850	**274.79**	150	550	**>140.75**	0.51
	Max. 24 hr	1650	850	**22.91**	1550	750	**<28.46**	1.24
	Max Period	1550	950	**4.4**	1450	750	**<4.43**	1.01
High Stack	Max. 1 hr	-2050	-1650	**55.46**	550	750	**<93.89**	1.69
	Max. 24 hr	3350	1650	**5.83**	1950	850	**<8.99**	1.54
	Max Period	1850	1650	**1.47**	1750	850	**<2.05**	1.39

It is important to note that in this simulation, the CALPUFF concentrations are quite sensitive to low stack heights (35m). The speed in the CALMET layers (10, 35 and 60, 88 and 150 m) are directly related to the vertical interpolation routines and the starting surface-layer speed. Thus, change in the wind speed causes a relatively greater change in the predicted concentrations. For other stack heights the ratios of predicted concentrations are not quite variable as in the case of low stacks.

In summary this variability in absolute levels is quite acceptable from the point view of model uncertainty (i.e., within a factor of 2), but the locations of predicted maximum concentrations are quite variable (see Figure 10). From a design perspective, such predictions using this approach are likely to be acceptable; however, if the location in which the maxima is predicted to occur is of interest, the predictions, e.g., for a regulatory permit that specifies a limit at a specific location, may or may not be acceptable. From a risk assessment point of view, such issues can be resolved with the help of a probabilistic modelling approach to account for such differences.

Figure 10. Predicted Maximum Locations for CASE A and CASE B – CALPUFF



Note: Blue dots are for reference CASE A and green dots are for CASE B

CONCLUSIONS

It is often necessary to carry out air quality and atmospheric dispersion studies based on "nearby" or regional meteorological data. This situation arose in the environmental assessment studies carried out under the Port Hope Area Initiative where meteorological data collected in Port Hope was the nearest station to Port Granby, approximately 10 km distant. The studies discussed in this paper demonstrate that mesoscale forcasting models can be coupled to the meteorological processor CALMET to develop meteorological data suitable for use in air dispersion analyses. Several variations of coupling the mesoscale model NMM with CALMET were performed to test the sensitivity of meteorological parameters and ultimately the sensitivity of the CALPUFF air dispersion model to these meteorological parameters. The conclusions of this study can be summarized as follows:

1. FReSH/NMM performance is excellent and demonstrates the applicability of the mesoscale models to develop data for use in air dispersion meteorology at locations where there is no on-site meteorological station;
2. Coupling of mesoscale meteorological models with CALMET is appropriate especially, the absence of on-site meteorological measurements;
3. Based on this study and the authors' observations from other coupled applications, it appears that the improved algorithm for taking surface wind speed at 10 m from the mesoscale model can produce better wind fields for air dispersion modelling; and
4. Mesoscale model simulations have to be designed for specific areas and situations (complex terrain, lake-breeze effects etc.);

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Acknowledgements

The authors wish to thank the Atomic Energy Control Limited - Low Level Radioactive Waste Management Office for their assistance in developing this paper.

Key Words

MESOSCALE MODEL
FReSH
NMM
CALMET
CALPUFF
ISCST3
Modelling
Emissions