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A Better Nuclear Tomorrow

Special Case Comparison of Gaussian and Non-Gaussian Atmospheric Transport of Radionuclides

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INTRODUCTION

The Gaussian transport calculation is a well-understood and proven technique for calculating atmospheric dispersion of pollutants. This is especially true in the field of nuclear safety and analysis. Developed well before the advent of electronic calculation (let alone personal computers), the Gaussian or *Pasquill-Gifford* technique was devised to quickly and easily determine airborne concentrations of pollutants downwind of a release using a minimum amount of data (wind speed, turbulence estimate, release quantity, release height and measurement height).

Results from using the SAIC-designed DoseWin (SAIC, 1998) software, which uses the CSA N288.2-M91 (CSA, 1991) calculation for dispersion of radionuclides, was compared to results obtained from using HPAC (USDTRA, 1999), which uses SCIPUFF as the air transport calculation engine. The N288.2 calculation is a typical P-G calculation while SCIPUFF (Second-Order Closure Integrated PUFF) is a mass-conserving wind transport model used extensively in risk assessment for many types of accidental releases, including radiological and non-radiological events.

Without significant modification to the typical form of the calculation, the P-G technique is not well-suited for speed wind shear, katabatic winds or sea/lake breezes. This paper will attempt to demonstrate the strengths and weaknesses of the P-G technique and how that technique can be applied to duplicate or match unusual meteorological situations that are otherwise too specialised for the unmodified calculation. In circumstances where such modifications cannot be performed, we will point out deficiencies in the technique and potential errors in calculation and assumption.

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METHODOLOGY

The following was performed to compare the behaviour of different dispersion simulation techniques under unusual but not uncommon weather scenarios:

- Pollutant: Kr-85 was chosen for the tests;
- Scenarios: the scenarios that were chosen for the tests were speed wind shear, katabatic or *nocturnal drainage* winds and land/sea breezes;
- Atmospheric conditions: wind and temperature profiles were compiled or computed using references or "textbook" case data for the chosen scenarios. Reasonable effort was made to properly simulate the scenarios given the inherent limitations of each simulation tool;
- Results: tests were performed and the results were compared; and
- Conclusions: conclusions were drawn on the adequacy of each model, its strengths and its weaknesses.

POLLUTANT

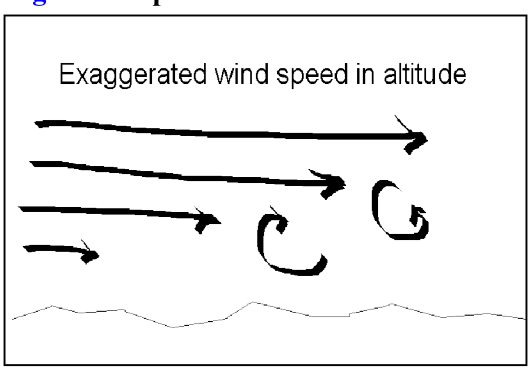
Krypton-85 is a noble gas with a half-life of more than 10 years. As a noble gas, its deposition behaviour can be neglected. Its treatment in health physics applications, along with other noble gases, is that it does not depose onto the ground, nor is it absorbed in the lungs of animals.

For all of the above reasons, Kr-85 was chosen for the tests discussed in this report.

SCENARIOS

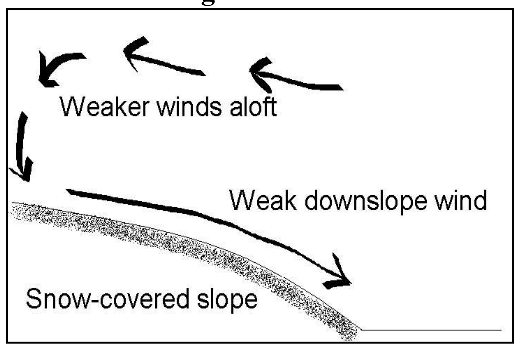
A set of test cases were established and representative data was compiled. Each test was set to simulate different types of unusual weather phenomena.

Figure 1 - Speed Wind Shear



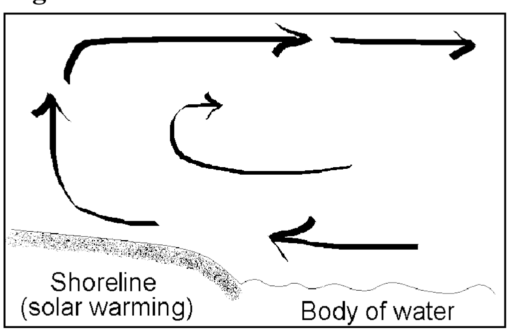
Speed wind shear: Typical wind profiles along the vertical indicate higher wind speeds aloft due to drag effect (surface roughness). However, under very high wind conditions, this effect increases as the gradient of wind speed rises. Speed wind shear occurs under these conditions, often exhibiting highly turbulent episodes for aircraft. The dramatic friction forces that are not normally present at lower wind speeds reveal strong mixing. Due to Bernouilli and vorticity effects, this case exhibits enhanced turbulent mixing, perhaps with one of the effects prevailing (Figure 1). A prevailing effect would create net lift or downward motion of the pollutant. In aviation, the quantity of "speed shear" that is considered dangerous is 1 m/s change for a 10 m change in altitude (0.1 s^{-1}) or greater (Gera, 1991). Direction shear - where the horizontal direction of the wind changes with altitude - is also an important atmospheric effect that is expected to affect the dispersion of pollutants. It is expected that such shear would enhance the mixing in the horizontal direction. Direction shear is not studied in this report.

Figure 2 - Katabatic Wind



Katabatic wind: Other names include *nocturnal drainage winds* or *valley winds*. This effect can occur when the lines of atmospheric pressure lie parallel to a cool (perhaps snow-covered) plateau or slope with light winds initially (Figure 2). The lines of atmospheric pressure lying in such a way can lead to a mis-prediction of the wind direction by incorrectly assuming that the wind will flow in the direction of the geostrophic wind (along lines of equal pressure). The result can be a gravitational and pressure effect which brings the cool dense air down the slope with a light prevailing wind aloft, sometimes in a different direction.

Figure 3 - Land/Sea Breeze



Land/sea breeze: This type of situation occurs when there is warming on land near a large body of water, typically with a temperature difference greater than 2°C (Pasquill, 1983, p. 366). The convection of the air creates a circulation cell with cool air rushing from the body of water and returning to the water aloft after lifting over the land (Figure 3). The full horizontal depth of a typical circulation cell is on the order of 40 km inland (Koo, 1995). A temperature inversion is also exhibited on the inland portion of the cell (Sills, 1998). The circulation pattern is similar to a katabatic wind with the main difference being a deeper surface flow in the land/sea breeze case (~1000 m vs ~600 m) (Horst, 1986) (Sills, 1998).

Test cases were chosen to reveal atmospheric transport issues as opposed to ground/water deposition or effects that impact on the dose calculation; these can include receptor residence time, choice of dose conversion factors or corrections for gamma exposure to a cloud of finite size. Therefore, this study will deal specifically with air concentrations of pollutants only and pollutants with no chemical or settling properties, as these will differ from isotope to isotope and can be a function of aerosol size. This constraint puts further restrictions on the conclusions that will be drawn from the results, though the results remain useful and assist in determining directions for future work.

ATMOSPHERIC CONDITIONS

SCIPUFF DATA

The following temperature and wind profiles were used in performing the SCIPUFF calculations (Tables 1 through 3). In each case, the effluent was assumed to be at thermal equilibrium with the atmosphere (i.e. no thermal buoyancy). Cross-flows have been neglected in order to concentrate attention on local and cell circulations:

Table 1 - Speed Wind Shear Atmospheric Profile

Altitude (m)	u (m/s)	T (°C)
20	20.0	20
100	28.0	19.48
200	38.0	18.83
300	48.0	18.18
400	58.0	17.53

Table 2 – Katabatic Wind Atmospheric Profile

Altitude (m)	T (°C)	u (m/s)
0	7	0
10	13	1.1
20	15	1.5
30	16.5	0.6
40	16.7	0.2
50	16.7	0
60	16.5	-0.2
100	16	-1

Table 3 – Land/Sea Breeze Atmospheric Profile

Horiz. (m)	Altitude (m)	T (K)	u (m/s)	w (m/s)
-30000	0	288	0	-2
-15000	0	288	2	-2
0	0	289	2	-2
15000	0	291	2	-2
30000	0	293	0	-2
-30000	200	289	0	-2
-15000	200	289	4	-2
0	200	289	4	-2
15000	200	292	4	-2
30000	200	293	0	-2
-30000	700	292	0	-2
-15000	700	293	7	-2
0	700	293	7	-2
15000	700	294	7	-2
50000	700	294	0	-2
-30000	1000	292	0	-2
-15000	1000	293	4	-2
0	1000	293	4	-2
15000	1000	294	4	-2
30000	1000	294	0	-2

P-G CALCULATION

To best replicate calculations using a P-G technique, data was required to represent the more detailed atmospheric profiles that can be used by the SCIPUFF program.

The following data was used in performing the P-G calculations (Table 4). Common data include no nearby buildings, no deposition, and physical stack height used with no effluent velocity or buoyancy (effective release height equal to the physical release height). To simulate a pure P-G calculation, wind speed and direction are those that would have been measured at 10 m from the ground surface.

Table 4 – P-G Data Used for Calculations

Speed Wind Shear
Wind Speed (10 m): 20 m/s
Inversion Layer Depth: 400 m
Pasquill Stability Class: A
Katabatic Wind
Wind Speed (10 m): 1.1 m/s
Inversion Layer Depth: 60 m
Pasquill Stability Class: F
Land/Sea Breeze
Wind Speed (10 m): 2 m/s
Inversion Layer Depth: 200 m
Pasquill Stability Class: E

To obtain better results for comparison, release rate, release time and residence time differ from case to case. However, for each atmospheric scenario, the same release rate, release time and residence time are used from SCIPUFF and the CSA Standard calculations.

RESULTS

The following integrated concentration results were obtained in the calculations performed (Tables 5, 6 and 7). The time period whereby the data were obtained are the same. Sample graphical illustrations are offered to show the instantaneous dispersion result from SCIPUFF (Figures 4, 5 and 6). Note the shape of the plumes as they are evidence of the flow regimes in altitude and their direct effect on the net flow direction of the cloud.

The data is presented to convey the difference in empirical mixing of the pollutant (rather than raw concentrations). Each code's data is compared to data calculated at a different distance from the source for that code. This way, we can obtain a mixing profile in the horizontal that allows us to understand the mixing capacity for each atmospheric case.

SPEED WIND SHEAR

Figure 4 - Instantaneous Vertical Slice (SCIPUFF)

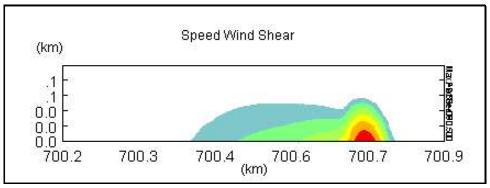


Table 5 – Normalised Surface Results (time-integrated concentration)

Distance from source, centreline	SCIPUFF	CSA Standard
(km)	(Normalised)	
5	1	1
10	.05	.18

The normalised time-integrated concentrations indicate that at 10 km downwind from the source, the SCIPUFF code indicated that the time-integrated concentration is reduced to 5% of that measured at 5 km. Conversely, the CSA Standard calculation shows that the reduction is only to 18% of that measured at 5 km.

KATABATIC WIND

Figure 5 - Instantaneous Vertical Slice (SCIPUFF)

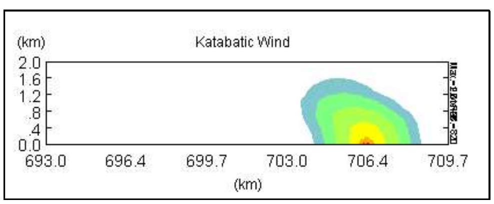


Table 6 - Normalised Surface Results (time-integrated concentration)

Distance from source, centreline	SCIPUFF	CSA Standard
(km)	(Normalised)	
10	1	1
15	0.72	0.09
20	0.57	0.00

The SCIPUFF calculation resulted in some of the pollutant being dispersed in the <u>opposite</u> direction to those of the CSA calculation, as illustrated above. The low dispersion (high concentration) SCIPUFF results are evidence of the strong re-circulation effect that is neglected in the CSA Standard calculations.

LAND/SEA BREEZE

Figure 6 - Instantaneous Vertical Slice (SCIPUFF)

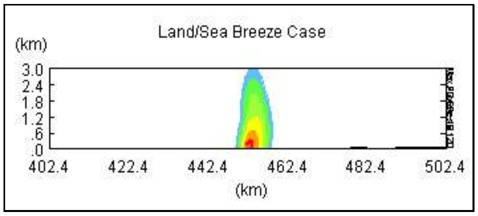


Table 7 – Normalised Surface Results (time-integrated concentration)

Distance from source, centreline	SCIPUFF	CSA Standard
(km)	(Normalised)	
10	1	1
20	0.18	0.17

There were non-trivial surface concentrations in the opposite direction to the mean flow at low altitude when using SCIPUFF. Therefore, the dose associated with those concentrations is ignored when using the CSA Standard. These are not shown above since the doses calculated with the CSA Standard are zero. The data shown above is in the direction of the low-level flow.

DISCUSSION

SPEED WIND SHEAR

This case exhibited enhanced low-level mixing in the SCIPUFF calculations. It becomes evident that speed wind shear will inhibit a rising plume from dispersing in altitude. However, even with using the greatest Pasquill mixing condition, A, the CSA Standard does not show the mixing results obtained in the SCIPUFF calculations. It has been discussed that vertical and horizontal dispersion conditions can and should be calculated independently (Lord, 2000). The CSA Standard guidance currently only suggests the use of temperature lapse rate as the measure of turbulence in the atmosphere. In accordance with that guidance, this case could have resulted in less turbulent mixing parameters (B through F) and even more exaggerated differences between the codes. Instead, the limiting case of A was used.

KATABATIC WIND

The striking difference in the calculations for this scenario is the direction of travel of the overall plume. The CSA Standard only allows for one wind speed and direction to be used. Therefore, even a very light re-circulation, such as a drainage wind, cannot be modelled adequately. As well, due to the very low-altitude drainage wind boundary where the affected stable air meets the prevailing wind aloft (around 60 m), the SCIPUFF plume is quickly and easily drawn aloft and is dispersed in the direction of the mean flow above this level, i.e. in the opposite direction to the mean flow near the surface (in this case). The overall result is, in the case used, a plume that is dispersed in the opposite direction to the flow measured near the surface.

It should be noted that a katabatic scenario will not necessarily result in a flow aloft in the opposite direction to that at the surface. A different scenario might result in winds aloft flowing perpendicular to the flow near the surface. This type of flow regime was not examined.

LAND/SEA BREEZE

This atmospheric case resulted in a similar result to that of the katabatic case, in that the SCIPUFF runs obtained non-zero concentrations in the opposite direction from the surface mean flow. This is due, as in the katabatic case, to a re-circulation effect aloft. In contrast to the katabatic case, this case results in a much higher altitude wind direction change zone. Therefore, the pollutant travel in the opposite direction is not immediately noted, but rather occurs as time passes (after about 4 hours in the case used). Such time is required to allow the pollutant to reach the boundary (around 1000 m). Also, the nature of the phenomenon indicates that the mean flow aloft will be in the opposite direction to flow below. This is in contrast to the katabatic case where the flow aloft can be in practically any direction.

CONCLUSIONS

Differences are noted between the SCIPUFF and the CSA Standard calculations. Some of limitations of the CSA Standard that are possible in more sophisticated models are the result of:

- Insufficient flow modelling in altitude;
- Inappropriate use of temperature profile to model turbulent mixing; and
- Inability to model non-buoyant atmospheric lift.

Scientists who study pollutant dispersion need to be familiar with the different local atmospheric effects that can influence plume flow.

FUTURE WORK

Given the differences noted qualitatively in dispersion character and quantitatively in time-integrated concentration at the surface, more study is required to better understand the local geography and diurnal effects.

This study concentrated solely on the dispersion of a noble gas. In the case of nuclear isotope dispersion from a power plant as a result of fuel failure, there will be aerosol particulates and other chemical species that will be affected by deposition and plume depletion. This effect needs to be examined further under these atmospheric scenarios.

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THE AUTHORS

Mick Lord received his Bachelor of Science degree in Physics from the University of New Brunswick in 1989. His undergraduate research was on a neutronic technique for detecting explosives in luggage. After spending some time at AECL (Chalk River) working in neutron radiography, he attended McGill University and received his Diploma in Meteorology in 1990. After a short period with Environment Canada as a weather forecasting trainee, Mr. Lord was recruited by Science Applications International Corporation (SAIC Canada) in 1991. As a physicist with SAIC, he has had the privilege of working on many types of projects, from atmospheric dispersion to radiation protection to nuclear emergency response. Mr. Lord recently co-wrote a report for the Atomic Energy Control Board in response to a requirement to update the current

CAN/CSA N288.2 standard on dispersion of radionuclides from a power plant under accident conditions. Mr. Lord has been involved with the Canadian Association of Physicists as a Councillor-At-Large and received his Professional Physicist (P.Phys.) status from the CAP in April.

Terry Jamieson is Division Manager of the Emergency and Safety Services Division of SAIC Canada where he has been a staff member since 1989. He received his Bachelor of Applied Science degree in 1979 and his Masters of Applied Sciences degree in 1981, both from the University of Toronto. His expertise extends from reactor containment behaviour and release pathways to dosimetry and shielding calculations. Prior to his career at SAIC, Mr. Jamieson was a senior engineer with ECS responsible for the initial design of a small mobile nuclear reactor for use in a research submarine. In 1995, Mr. Jamieson graduated from the Certified Advanced Technology Manager program. Most recently, Mr. Jamieson co-wrote a report for the Atomic Energy Control Board in response to a requirement to update the current CAN/CSA N288.2 standard. Mr. Jamieson received his Consulting Engineer (C.Eng.) designation from the Association of Professional Engineers of Ontario in 1996.

Kerry Marshall is a geographic information specialist with SAIC Canada. He received his Diploma in Survey and Mapping Technology from Algonquin College in 1989. He then obtained a Bachelor of Arts in Geography in 1996 from Carleton University. He followed this training with certificate programs from Algonquin College in Computing Science and Geographic Information Systems. In 1996, Mr. Marshall was a GIS technician involved in the process of redistributing Federal electoral boundaries for Elections Canada. Recruited by SAIC in 1998, Mr. Marshall has developed a wide variety of applications, including tools for the Department of National Defence, Environment Canada and Health Canada.