

REPRESENTATION OF SOURCE AND RECEPTOR HEIGHTS IN STEEP TERRAIN DISPERSION MODELLING

Hector Machado and Andrew Martin

Trinity Consultants Australia, PO Box 3901 South Brisbane, 4101 Qld, Australia

Abstract

Meteorological and dispersion models use input data that samples reality. To simulate airflow and dispersion, the meteorological models use gridded terrain heights to fit wind vectors (and other parameters) to grid cells. However, due to limitations on the resolution of grid size, terrain heights will often vary substantially within each grid, so the model is producing wind fields based on smoothed terrain. In addition, the dispersion model will also use terrain heights as one determinant of plume centreline height.

Source and receptor heights can be defined as ground height plus height above ground. By default, some model interfaces will use the modelled terrain grid to assign ground height. Some modellers prefer to correct these for the actual terrain heights, so that the model accurately represents the heights of sources and receptors relative to each other. However, the modelled airflow and plume centreline, or puff centre, do not follow the actual terrain: they follow the modelled terrain. Hence, in some circumstances, it may be more appropriate to model heights accurately relative to ground level. For screening, a range of heights can be modelled to provide a conservative worst case.

This paper uses different hypothetical scenarios and the CALPUFF, AERMOD and GRAL models to compare how the models react to steep isolated hills and steep ridges. High resolution, vertical cross-section contours are used to illustrate predictions. Recommendations are provided on the importance of grid resolution and on how to treat source and receptor heights.

Keywords: complex terrain, receptor height, dispersion modelling, GRAL

1. Introduction

Air dispersion modelling in complex terrain presents challenges for air quality consultants, particularly where steep gradients occur over relatively small spatial extents. Models such as AERMOD, CALPUFF and GRAL each handle terrain differently. CALPUFF relies on gridded terrain through its CALMET meteorological pre-processor, which inherently smooths terrain features at the grid resolution. AERMOD assigns actual terrain elevations to individual receptors through AERMAP but does not use a three-dimensional wind field. GRAL resolves terrain at high spatial resolution through its GRAMM wind field model.

Plume behaviour will be partially dependent on the wind flow over and around terrain features that may not be resolved in the model.

This introduces a key question: whether source and receptor heights should be defined relative to modelled terrain or corrected to represent actual relative height difference between source and receptors. This choice can materially influence predicted concentrations, particularly in steep terrain where elevations differences between real and modelled topography may be substantial.

This paper uses two real locations in south-east Queensland to examine how AERMOD, CALPUFF and GRAL respond to steep terrain that is not resolved by the meteorological model grid. Vertical cross-section contours are used to visualise plume behaviour.

2. Background

2.1. Terrain representation in dispersion models

CALPUFF and AERMOD handle terrain in fundamentally different ways. CALPUFF transports puffs through a three-dimensional wind field produced by CALMET, which represents terrain as a grid with each cell assigned a single elevation value. In steep terrain, coarse grids can substantially underestimate peak elevations and reduce slope gradients, resulting in a smoothed terrain surface that the wind field is fitted to. Terrain features that fall below the grid resolution are effectively absent from the simulation.

AERMOD does not use a gridded wind field for terrain treatment. Instead, AERMAP assigns actual terrain elevations from the DEM to each source and

receptor individually, and calculates a hill height scale for each receptor to determine the dividing streamline height. This means AERMOD works with actual terrain elevations rather than smoothed grid values. However, AERMOD is a steady-state Gaussian plume model and is generally not recommended for complex terrain applications. Most regulatory guidance, including Australian state guidelines consistent with US EPA Appendix W, identifies AERMOD as suitable for simple and intermediate terrain but recommends alternative models for situations where terrain effects dominate dispersion

GRAL, coupled with GRAMM, resolves terrain effects through direct particle tracking in a three-dimensional wind field computed at high spatial resolution over the actual terrain. While GRAMM is also constrained by the resolution of its terrain input, its grid resolution is typically much finer than CALMET, allowing it to capture terrain features that coarser grids cannot.

2.2. Source and receptor height

Source and receptor heights are defined as ground elevation plus height above ground. For models that use gridded terrain, such as CALPUFF, many model interfaces assign ground elevation automatically from the terrain grid. In steep terrain, the difference between this grid-assigned elevation and the true ground elevation at a specific location can be tens of metres.

Some modellers correct for this by specifying actual terrain elevations derived from high-resolution DEMs. This improves geometric accuracy between source and receptor. However, for CALPUFF it introduces an inconsistency: the corrected heights are referenced to a different terrain surface than the one governing the wind field and puff centreline. The plume follows the modelled terrain, not the real one, so a geometrically accurate height may not produce a physically consistent result.

2.3. Implications for plume behaviour in steep terrain

For models using gridded terrain, the plume centreline follows the modelled terrain surface. There are circumstances where geometric height corrections move a receptor to the wrong side of the plume that is simulated in the model. On a steep windward slope where the model underestimates elevation, a corrected receptor may appear to be above the plume centreline when the model's own physics would place it below, or vice versa.

Similarly, height corrections can move a receptor in or out of the modelled plume.

3. Methodology

3.1. Hypothetical scenarios

Two real locations in south-east Queensland were used as the basis for the terrain scenarios. Both sites were assumed to have urban land use. The first site was a long, steep ridge located within Whites Hill Reserve in Holland Park (Figure 1), while the second was a short, sharp hill at Eildon Hill Reservoir in Windsor (Figure 2). These locations were selected specifically because their terrain features are not resolved at the grid resolution used by CALMET, making them representative of the practical challenge this paper addresses.

Terrain data were obtained from the Geoscience Australia Digital Elevation Model (DEM) of Australia, derived from LiDAR surveys and provided at 5 m spatial resolution. A single point source was modelled at each location as a 5 m stack. A raincap was applied in CALPUFF and AERMOD to prevent plume rise. GRAL does not have a raincap option, so a minimal exit velocity of 0.1 m/s was used instead to approximate the same condition.

Receptors were placed uphill and downhill of the source along a 100 m transect at 1 m horizontal resolution and 1 m vertical resolution up to 30 m above ground. This high-resolution receptor configuration allowed the vertical concentration structure near the terrain surface to be examined in detail.

3.2. Meteorological inputs

Two wind direction scenarios were examined at each site, covering upslope and downslope flow. Each scenario was run across three stability classes (Pasquill-Gifford A/B, D and F/G) with two wind speed variants per class, one low and one high, giving 12 meteorological conditions in total.

A prognostic meteorological dataset was first generated using The Air Pollution Model (TAPM). The TAPM output was then processed through CALMET in no-observations mode to produce a three-dimensional gridded wind field. Specific hours corresponding to the desired wind speed, wind direction and stability conditions were identified and extracted for each of the 12 scenarios.

For CALPUFF, the extracted CALMET wind fields were used directly as meteorological input for each selected scenario.

For AERMOD, the TAPM and CALMET outputs were processed using PRTMET to generate the surface and upper air profile files required by AERMOD.

For GRAL, the GRAMM meteorological pre-processor was run independently for each scenario, configured with the corresponding wind speed, wind direction and stability class. The resulting wind fields

were then used by GRAL for particle dispersion modelling.

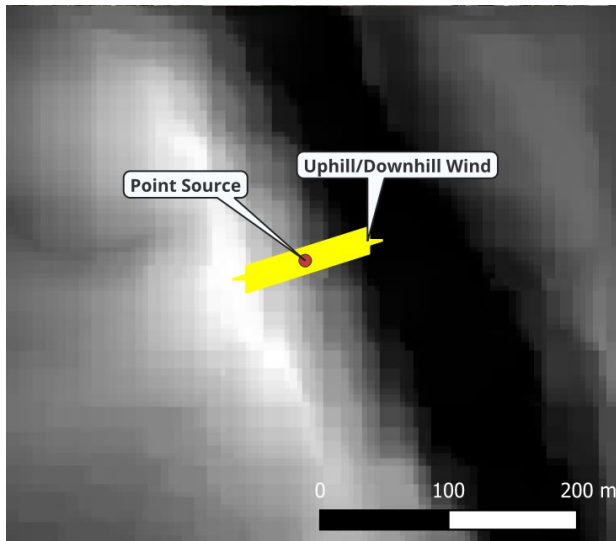


Figure 1. Modelled Ridge Scenario

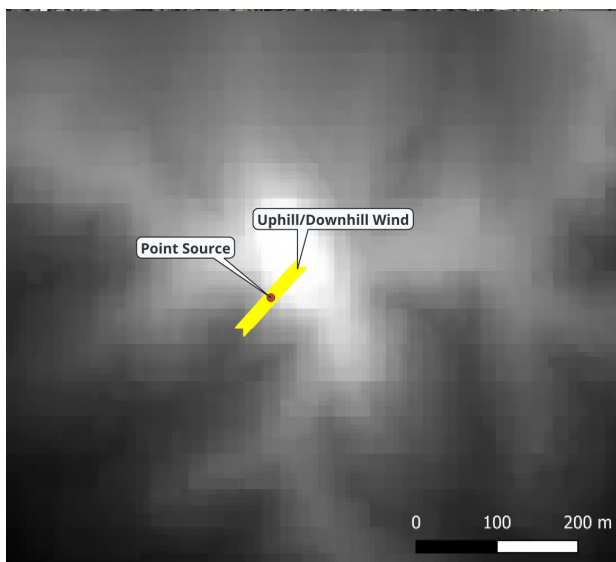


Figure 2. Modelled Hill Scenario

3.3. Model terrain treatment

CALPUFF transports puffs through the three-dimensional CALMET wind field. The puff centreline follows the wind vectors on the CALMET grid, so terrain effects on plume transport are limited to terrain the grid resolves. Where terrain features fall below the grid resolution, the puff travels as though the terrain is not there. CALPUFF's Partial Plume Path Adjustment modifies puff height based on stability class, local terrain elevation above the stack base, and the original puff height above ground. An adjustment coefficient of 0.5 is applied to the original puff height in non-stable conditions, allowing the puff to rise following the terrain but only to half its original height when terrain above stack height is encountered. Under stable conditions, a smaller path coefficient is used, allowing puffs to approach nearer the surface. Coefficients can be modified by the user.

AERMOD calculates concentration at each receptor as a weighted combination of two plume states: a terrain-following plume that follows the ground surface, and a horizontal plume that remains at a constant absolute elevation.

GRAL tracks individual particles through a three-dimensional wind field generated by GRAMM at high spatial resolution over the actual terrain. The plume behaviour is therefore a direct result of the resolved flow patterns, including slope flows, flow separation and drainage. There is no parameterised terrain adjustment; terrain effects on the plume arise from the physics of the wind field itself.

4. Results

4.1. Modelled receptor height and CALPUFF results

Figure 3 presents vertical cross-section concentration contours for CALPUFF at the hill and ridge sites under unstable and stable conditions. Each plot shows the actual terrain profile (black line), the modelled terrain used by CALMET (red line), the point source location, and two receptor positions: one at ground level relative to the modelled terrain (blue dot) and one corrected to the actual terrain elevation (dark red dot).

At both sites, the modelled terrain did not resolve the terrain feature. The difference between the two terrain surfaces created a large vertical gap between the two receptor height treatments. In all four cases, the receptor at relative height sat within the plume, while the corrected receptor sat above the main plume body with low or negligible predicted concentrations.

Stability class also influenced the outcome. Under unstable conditions, the plume spread more vertically over a shorter horizontal distance, partially bridging the gap between the plume and the corrected receptor. Under stable conditions, the Partial Plume Path Adjustment applied a smaller path coefficient, compressing the plume vertically and extending it further along the terrain. The tighter vertical spread meant the corrected receptor sat further above the plume centreline, making the height correction effect more pronounced. This trend is reflected in the concentration ratios between receptors referenced to modelled and actual terrain elevations. Ratios were 5 and 30 for the hill and ridge scenarios under unstable conditions, as shown in Table 1, increasing to 34 and 25,487 respectively under stable conditions.

Table 1. Ratio of concentrations predicted using modelled receptor heights compared with actual receptor heights

Scenario	Figure	Terrain Height Difference (m)	Concentration Ratio (Relative Height / Actual Height)
Hill - Unstable	3(a)	10	5
Hill - Stable	3(b)	10	34
Ridge - Unstable	3(c)	11	30
Ridge - Stable	3(d)	11	25,487

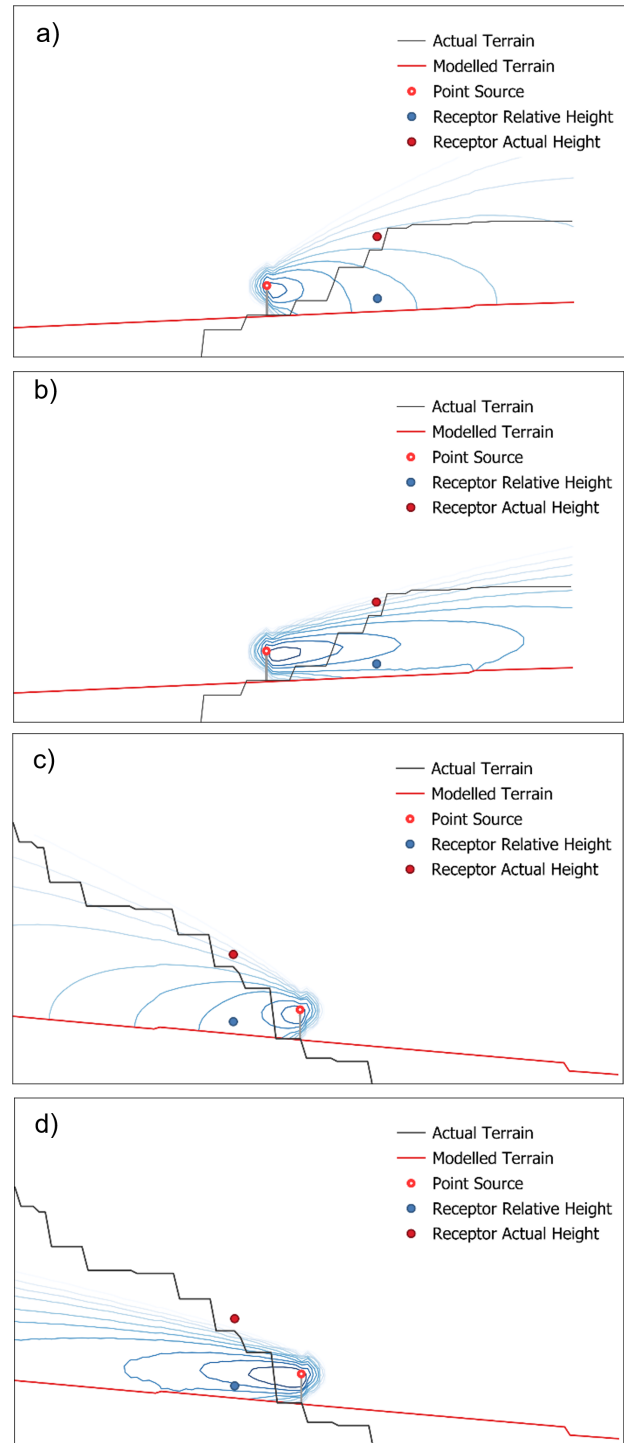


Figure 3. CALPUFF vertical cross-section concentration contours at the hill site under (a) unstable and (b) stable conditions, and at the ridge site under (c) unstable and (d) stable conditions.

4.2. GRAL results

Figure 4 presents vertical cross-section concentration contours for GRAL at the hill site under unstable upslope, unstable calm and stable downslope conditions. Results for the ridge site are provided in Appendix A.

Unlike CALPUFF, GRAL resolves the actual terrain through its GRAMM wind field at high spatial resolution and further refinement with the GRAL model. The plume therefore responds directly to the terrain features, and the concentration contours follow the ground surface.

Under calm conditions, the plume disperses more symmetrically around the source, with concentration contours spreading in all directions along the terrain surface. Under stable downslope, the plume is compressed vertically and hugs the terrain surface, with concentration contours following the descending slope closely. This is consistent with expectations for drainage flow that GRAMM/GRAL is able to simulate well because it resolves the slope at sufficient resolution. CALPUFF cannot reproduce either of these behaviours when the terrain feature is not captured by the CALMET grid.

4.3. AERMOD results

Figure 5 presents vertical cross-section concentration contours for AERMOD at the hill and ridge sites under stable upslope and stable downslope conditions.

AERMOD differs from CALPUFF in how it handles terrain. AERMAP assigns actual terrain elevations to each receptor individually from the DEM, so there is no smoothed terrain surface of the kind seen in the CALPUFF results. AERMOD calculates concentration at each receptor as a weighted combination of two plume states: a terrain-following plume that follows the ground surface, and a horizontal plume that remains at a constant absolute elevation.

Compared to GRAL under the same conditions, AERMOD does not produce the terrain-hugging drainage flow visible in the GRAL results. The concentration distribution near the surface is a product of the mathematical weighting between the two states, not a simulation of the actual flow pattern. These results illustrate why AERMOD is generally not recommended for complex terrain applications. While the receptor heights are correct, the plume does not physically respond to steep terrain features, and the dual-state parameterisation becomes less representative as terrain steepness increases. Ground level concentrations at many locations upslope are substantially under-estimated compared to GRAL modelling and our expectations of reality.

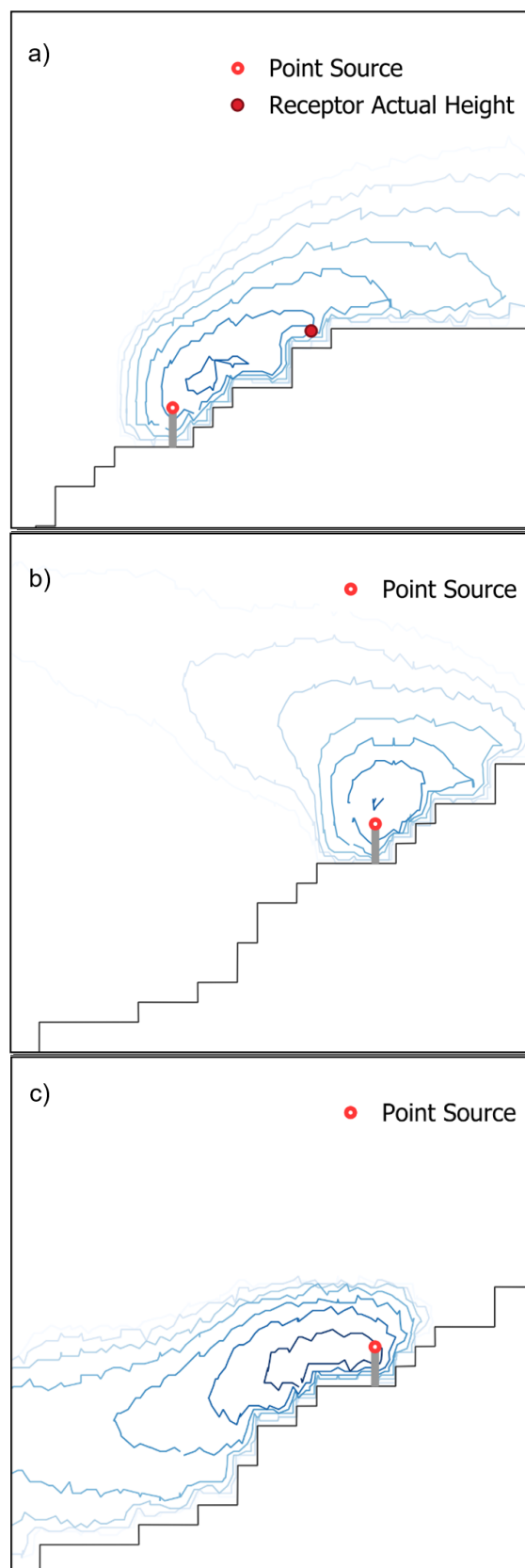


Figure 4. GRAL vertical cross-section concentration contours at the hill site under (a) unstable upslope, (b) calm conditions and (c) stable downslope conditions.

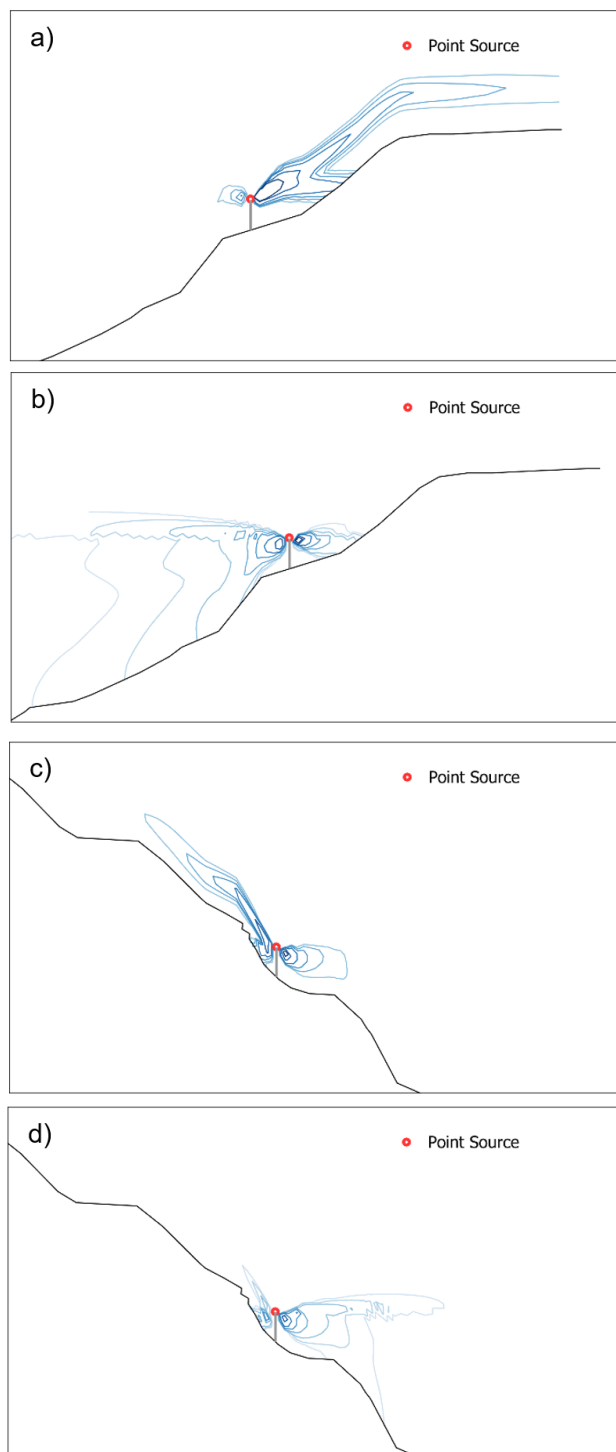


Figure 5. AERMOD vertical cross-section concentration contours at the hill site under (a) stable upslope and (b) stable downslope conditions, and at the ridge site under (c) stable upslope and (d) stable downslope conditions.

5. Conclusions

CALPUFF's plume followed the smoothed CALMET terrain. At both sites, the terrain features were not resolved by the grid. Receptors at modelled ground level sat within the plume and received high concentrations. Receptors corrected to actual elevation sat above the plume with low or negligible concentrations.

AERMOD used actual terrain elevations through AERMAP, avoiding the smoothed terrain problem. Both horizontal and terrain-following plume states were visible in the cross-sections. However many ground level concentrations appear substantially under-estimated.

GRAL resolved the terrain through GRAMM and produced a more realistic plume behaviour that followed the actual terrain.

6. Recommendations

In steep and poorly resolved terrain, internal model consistency is more important than geometric accuracy. Source and receptor heights should generally be referenced to the terrain representation used by the model's wind field. Alternative scenarios with adjusted heights should be applied only as sensitivity analyses and clearly identified as such.

The following key recommendations are made:

- In steep terrain, model selection is critical. Models that resolve 3D flow over terrain (e.g. GRAL/GRAMM) provide more realistic results than Gaussian or coarse grid approaches.
- Terrain resolution should be sufficient to capture key topographic features. Where this is not achievable, the implications of terrain smoothing should be explicitly assessed.
- For models using gridded terrain (e.g. CALPUFF), source and receptor heights should generally be defined relative to the modelled terrain, ensuring consistency with the wind field and plume pathway.
- A conservative assessment approach is recommended, using model-consistent heights as the base case but doing supplementary sensitivity runs with adjusted height receptors where appropriate.

7. Future Research

Future research should include a sensitivity analysis of terrain grid resolution to quantify how terrain smoothing influences source and receptor heights, plume behaviour, and predicted concentrations in steep terrain.

References

Scire, J.S., Strimaitis, D.G. and Yamartino, R.J. (2000). *A User's Guide for the CALPUFF Dispersion Model (Version 5)*. Earth Tech, Inc.

US EPA (2024). *User's Guide for the AMS/EPA Regulatory Model (AERMOD)*, Version 24142. EPA-454/B-24-007. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Appendix A

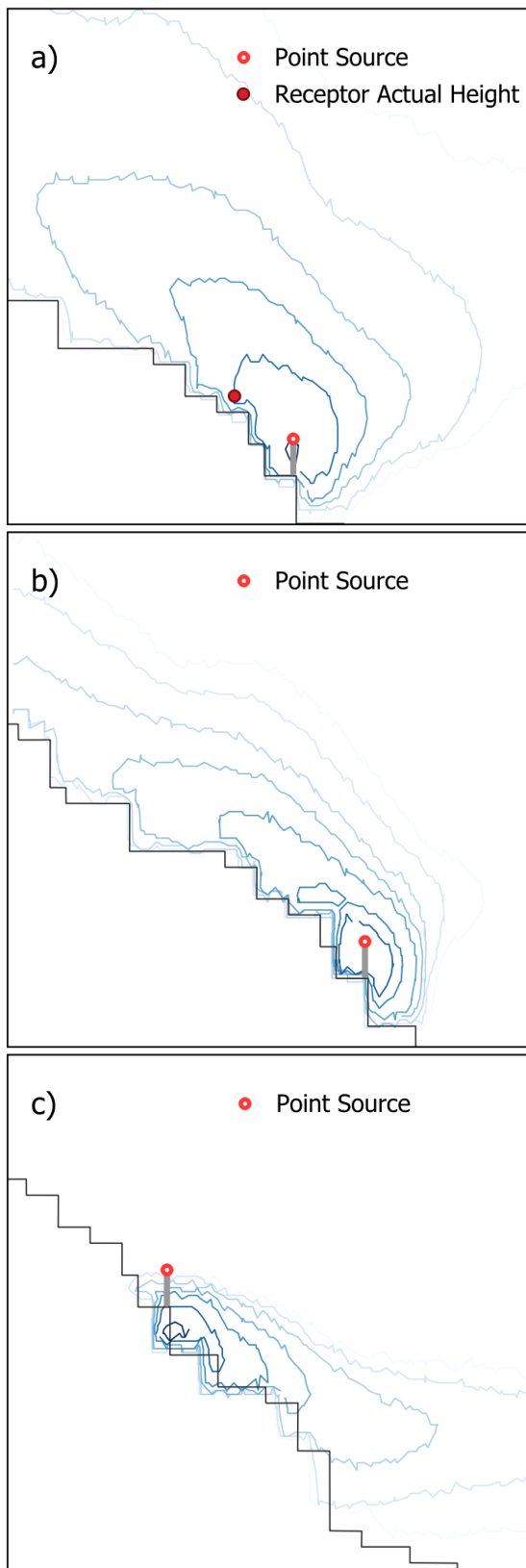


Figure A1. GRAL vertical cross-section concentration contours at the ridge site under (a) unstable upslope, (b) calm upslope conditions and (c) stable downslope conditions.