Why model wind inside coal mines?

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Open-cut coal mines are among the most contested sources of fugitive methane. Emission estimates for an individual mine can vary widely. Scientists hypothesize that measurements are affected by the somewhat unique airflow within these basin-like features. To measure emissions from open-cut coal mines accurately, we need to understand how methane moves through a mine enroute to our sensors.

The problem with treating a pit like flat ground

Most standard dispersion models assume that air is flowing over open, level terrain and that ventilation is continuous. Air moves across the surface, a plume spreads predictably downwind, and a measurement taken some distance away can be traced back to a source strength. This logic underpins inverse dispersion modeling, one of the methods used to quantify emissions at scale.

A mine pit breaks these assumptions. Steep, benched walls; depths of 100–200 metres or more; and irregular topography and emission profiles generate microclimates within mine pits. These conditions cause methane plumes to behave differently from plumes originating from a single point source on flat terrain. The pit may retain methane or, at times, release accumulated methane in spontaneous "burps." Simple models do not resolve any of this complexity. Similar issues, at a vastly different scale and dimension, are evident within cities with the so-called road canyon effect.

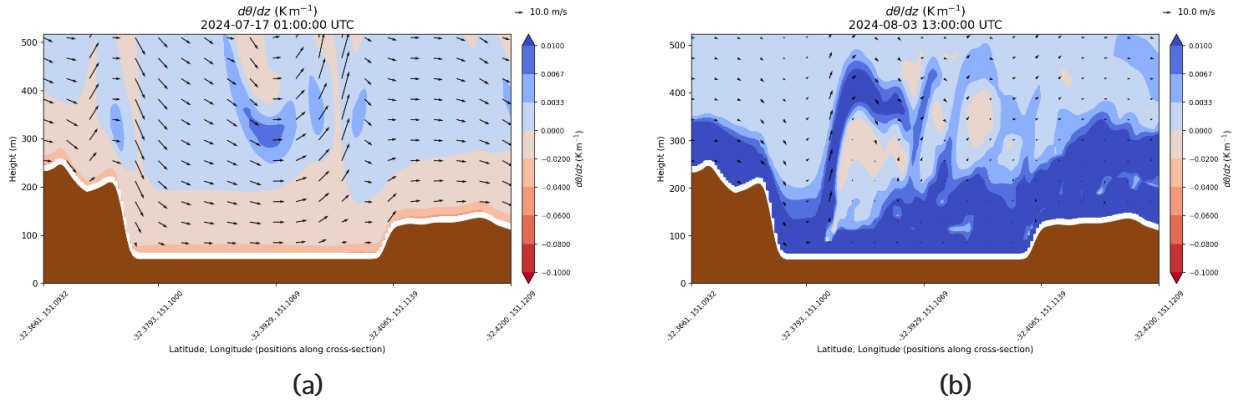
In addition to pit geometry, thermal stability is an important factor in plume behaviour. Depending on the vertical profile of atmospheric temperature and air movement, a pit can be well ventilated at one time of day, and at another methane may be trapped inside. If we sample during the wrong window, we might measure nothing, or we might observe methane that accumulated hours earlier.

How high-fidelity simulation can help

Large-eddy simulation (LES) is an atmospheric modeling technique that helps us resolve the turbulent structures governing air exchanges within a pit. This allows us to ask questions that cannot be answered using standard emissions-modeling methods, such as: How much gas is stored inside the pit versus transported out of it? How does the balance between storage and ventilation shift with pit depth, wall slope, atmospheric stability, and environmental conditions? When are emissions from a mine measurable, and when are they not?

Typically, we begin our simulation work with idealized pits, for example, inverted trapezoids of varying depths and slopes (Figure 1), so that geometry, stability, and wind forcing can be varied one

at a time. Only once these basic controls are well understood do we move to real terrain using high-resolution elevation data.



(a) (b)

Figure 1. Vertical cross-sections of temperature gradient and wind vectors for an idealized pit. (a) Daytime during a high turbulence event, suggesting strong ventilation. (b) Nighttime during a low-turbulence event, indicating high potential for methane pooling.

What we're seeing so far

The idealized simulations point to a strongly diurnal ventilation regime. During the day, convective mixing does most of the work of moving methane out of the pit. Unstable stratification actively ventilates the pit, and the stronger the turbulence, the more methane escapes.

At night, the picture inverts. Atmospheric inversions, with colder air near the ground, cause air to pool on the pit floor, reinforced by cold air flowing down the pit walls. The steeper and deeper the pit, the stronger the effect.

How quickly does the transition between these states occur? In other words, how quickly does methane that has accumulated overnight escape from the pit in the morning? Early results suggest that this stability transition is relatively fast. Understanding it will be key in designing controlled-release experiments and evaluating measurement systems.

How can wind modeling help us carry out a better controlled release study?

First, we are looking to establish experimental "go/no-go" criteria. We need to identify a defensible and representative set of meteorological and operational conditions under which measurements can be trusted.

Second, we need guidance for the experimental design: Where should we place release nodes and receptors? When should we release methane? How long will it take to achieve a steady state, where

the methane added to the pit equals the methane lost? The modeling already suggests two complementary experiments.

Of course, the field study can also help us improve our models. During the study, we will collect data to validate these simulation techniques. To our knowledge, this will be the first direct comparison of simulated methane transport with measured concentrations in a controlled-release setting inside an open-cut mine.

The takeaway

Everything above comes down to one practical point: the same emission can look very different depending on when you measure it. Figure 2 shows this in a real mine. We simulated a single methane source twice under the same wind, changing only the atmospheric stability. In stable air, the plume stays concentrated near the source. In convective air, it breaks up and spreads out. A sensor downwind would see two very different signals from exactly the same emission. To measure mine emissions accurately, we need to know which of these situations we are in.

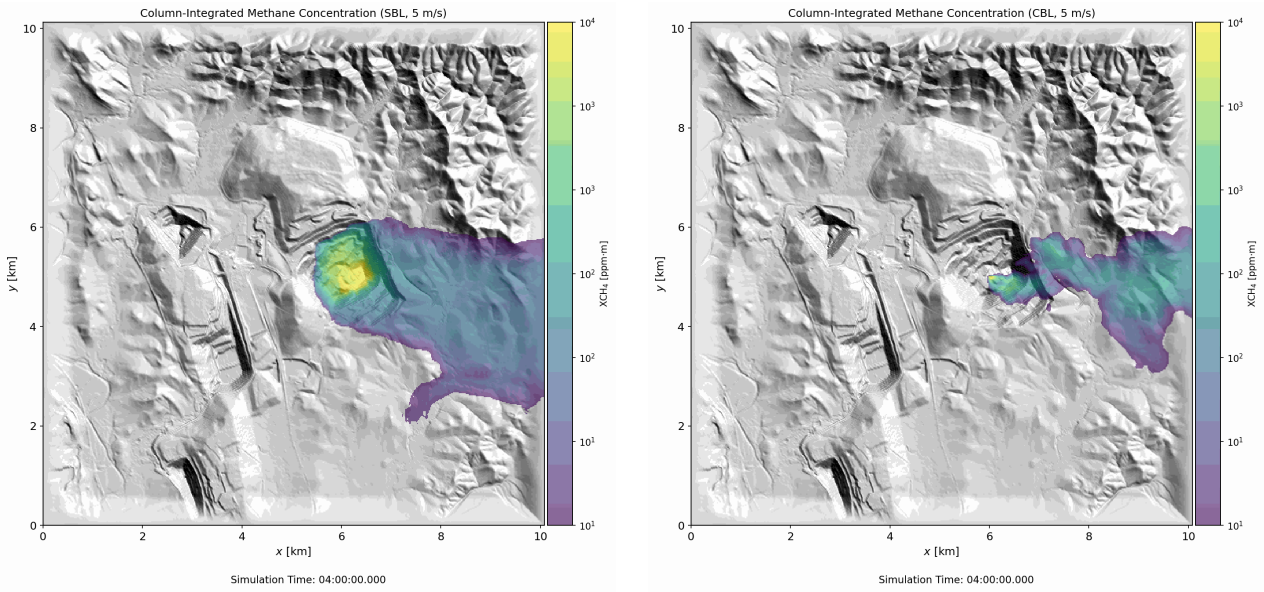


Figure 2. Column-integrated methane emissions from a single point source within an open-cut mine. (a) Methane accumulation under stable atmospheric conditions. (b) Convective atmospheric conditions are effective at transporting methane out of the pit. Static frames shown at 4 hours of simulation time.

Ultimately, wind modeling informs how we design a trustworthy controlled-release experiment at a coal mine. It also helps determine how we can apply the results of the experiment to methane measurements at open-cut coal mines globally.