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Determination of the Greenhouse Gas Emissions from Spontaneous Combustion. ACARP Project C13073

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Executive Summary

Spontaneous combustion is a potentially large source of greenhouse gas emissions from open cut coal mines. ACARP has previously supported a number of projects designed to develop a methodology to estimate the scale of these emissions, and while these have advanced the understanding of the problem, there have been practical problems which have limited their general applicability. In the current project, a novel approach was trialled where stationary monitors were placed at sites in the Hunter Valley in NSW and the Bowen Basin in Queensland and inverse modelling applied to estimate area-wide fluxes of CO_2 from mines affected by spontaneous combustion. In the Hunter Valley, flux estimates were also made by traversing CO_2 plumes from spontaneous combustion in an instrumented vehicle and the results compared to those from the stationary monitors.

Inverse modelling was used to successfully estimate area-wide CO_2 emissions fluxes from both sites. In the Hunter Valley, the technique provided an estimate for the affected mines that ranged from about 1040 to 1600 kt CO_2 y^{-1}. This compared well with the estimates obtained from direct plume measurements using traverse-based techniques of around 820 to 1600 kt CO_2 y^{-1}.

These estimates are substantially less than those found in Project C9062 which where based on infrared thermography. This may have been a result of the large uncertainty in the ground temperature-emission relationship used for the thermal thermography calculations but also the infrared data were taken more than five years previously to the data used in the inverse model.

The model requires a detailed seeding map, which in the Hunter, was provided by the airborne thermal imagery obtained as part of Project C9062. No thermal images were available for the Bowen Basin mine and the inverse modelling was based upon rudimentary seeding values provided by mine site staff. The model was able to identify regions noted by staff as prone to self heating as well as regions not originally identified, such as coal stock piles. Estimated emissions from the Bowen Basin mine ranged from 200 to 320 kt CO_2 y^{-1}, a range considerably smaller than found for the area within the Hunter Valley.

Experience gained in this study suggests a number of recommendations to enhance estimates. These include:

- Using a detailed seeding value for initialising the inverse model. Thermal imagery was found to be a suitable methodology.
- Where possible, direct plume measurements provide a reasonable method for estimating area wide fluxes. For an accurate estimate the method requires an understanding of the mixing processes at the point of measure. Numerical models such as TAPM can provide an estimate of the mixing processes. A more accurate approach would involve simultaneous measurement of vertical profiles at a fixed location using, for example, a tethered balloon.
- Simultaneous measurement of other species (eg CO, SO_2, NO_X) may provide a mechanism, through ratios, to distinguish emissions from self-heating from other sources such as diesel machinery.
- Stationary monitors require installation for long periods of time to ensure sufficient data sets are collected for modelling purposes. Six months of data were sufficient in the Hunter Valley region where a monitor was placed in a location directly downwind of the source in the predominant valley flows. In the Bowen Basin mine site however, a longer sampling period would have been more appropriate due to smaller regions of self-heating and a predominance of very light winds associated with elevated concentrations which cannot be modelled.

All three methods used in this study showed significant overlap in the emissions estimated. However, all three methods require specialist knowledge and expertise for their implementation.

Introduction

Spontaneous combustion in spoil piles in open cut coal mines has been recognised by the Inter-Governmental Panel for Climate Change (IPCC) as a potential source of greenhouse gas emissions. However, it has been excluded from greenhouse gas inventories as it is considered that there is no acceptable routine method for estimating the emissions from spontaneous combustion. In recognition of this, ACARP has carried out three previous projects to explore methods for establishing greenhouse gas emissions from spontaneous combustion.

In ACARP project C8059 (Carras et al., 2000), emissions from spontaneous combustion in open cut coal mines were determined through the use of flux chamber measurements. Measurements of emissions from spoil piles, coal rejects and tailings were conducted at 11 mines in the Hunter Valley in NSW and the Bowen Basin in Queensland using a chamber technique. While the project provided the first direct measurement of greenhouse gas emissions from spontaneous combustion and low temperature oxidation the methodology was found to be extremely labour intensive and limited in its spatial and temporal resolution.

A second project funded by ACARP, C9062 (Carras et al, 2002) used airborne infrared thermography to investigate whether more accurate and cost-effective monitoring of the extent of spontaneous combustion in spoil piles and the associated greenhouse gas emissions could be achieved. The measurements performed for ACARP C8059 found a correlation between ground temperature and greenhouse emission rates and, when combined with ground temperature measurements from the airborne infrared images, provided the first area-wide emission estimates. Although infrared thermography provided an effective method for determining surface temperatures, the complexity of the processes involved in producing heating and its surface manifestation resulted in significant uncertainty.

In 2003, Lilley and Carras reported through ACARP project C11073 on a theoretical examination of inverse modelling techniques to improve the estimate of emissions from self-heating. The basis of this technique is to measure ground level concentrations of CO_2 with fixed monitors and local meteorological data around areas affected by spontaneous combustion. These data are combined in an appropriate model to "back calculate" the flux of the CO_2 from the source. The approach taken in Project C11073 used a computer based air quality model (TAPM) which has been widely used in air pollution studies in Australia. An investigation of CO_2 sources in the Upper Hunter Valley found that spontaneous combustion and power station emissions can give rise to significant concentrations at ground level. However the impact of the power stations emissions were most pronounced during day-time hours while the impact of the spontaneous combustion emissions were most pronounced during the night. This is because the former are elevated while the latter are ground level sources. Consideration of results of the air quality modelling suggested that monitoring sites for inverse modelling should be sited such that:

• The location should be sufficiently close to the spontaneous combustion sources to enable a large measurable signal.

• The site should be chosen on the basis of meteorology to best capture the likely CO_2 spontaneous combustion signal.

• The sites should be chosen to minimise the influence of other sources.

As a result of that study, the current project C13073 was developed to test the inverse methodology using data collected over extended periods from mines in both the Hunter Valley in NSW and the Bowen Basin in Queensland.

Methodology

Inverse modelling technique

As described in project C11073 (Lilley and Carras, 2003), Lehning et al. (1994) developed an inverse technique for use in determining area source emissions from measured downwind concentrations. The model determines an emission flux using measurements at two receptor arrays positioned downwind of the source (see Figure 1). Using two arrays enabled the model to reconstruct the spatial pattern of the emission source. The model was found to accurately predict emissions from a small experimental source 20m x 20 m in size by taking measurements at 11 locations in each array. The experiments in this case were of limited duration, and as such subtleties in the meteorology were less influential.

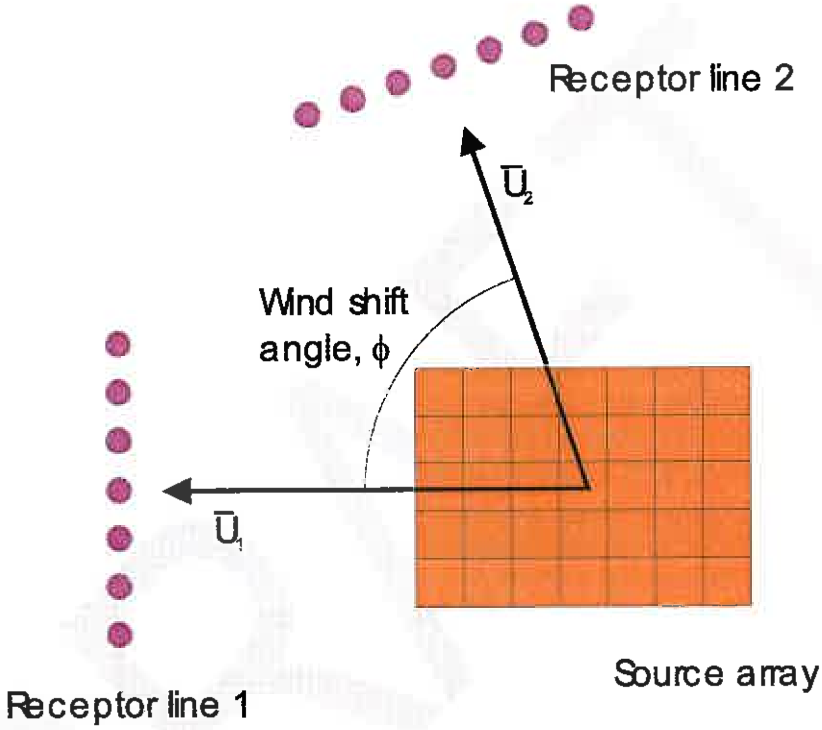

Figure 1. Source-receptor arrangement for the inverse model of Lehning et al. (1994)

The model of Lehning et al. (1994) was developed to treat dispersive processes with a Gaussian assumption for horizontal diffusion and either a Gaussian or Huang similarity solution for dispersion in the vertical direction. The degree of dispersion from an area source at the receptor is provided by the kernel, *K*:

$$c(x,y,z)=\int_{-x_s}^{+x_s}\int_{-y_s}^{+y_s}Q'(x',y')K(x,y,z,x',y')dx'dy' \qquad 1)$$

where, *Q* is the source flux, *c* is the concentration at position *x,y,z* (where *z* represents the height above ground), x_s and y_s are the locations of the along wind and cross wind boundaries of the source area, *x'* and *y'* are the coordinates of the source area.

By discretising the source into a number of unit cells (see Figure 1), Equation 1 can be described by a summation equation (Equation 2) where the indices *i* and *j* represent the source and receptor locations respectively.

$$c(x_j,y_j,z_j)=\sum_{x_i}\sum_{y_i}Q'(x_i,y_i)K(x_j,y_j,z_j,x_i,y_i)\Delta x_i\Delta y_i \qquad 2)$$

The formulation used for the kernel (*K*) in the current study is based upon the Gaussian equation, and for a ground level source is given by Equation 3, below

$$K(x_j, y_j, z_j, x_i, y_i) = \frac{1}{\pi \sigma_y \sigma_z u} \exp\left(-\frac{|y_j - y_i|^2}{2\sigma_y^2} \right) \quad 3)$$

where, *u* is the wind speed, σ_y and σ_z are the horizontal and vertical dispersion coefficients derived from a Pasquill Gifford scheme determined from the distance of the source to the receptor, x_j, y_j, z_j represents the receptor location and x_i, y_i represents the location of the source.

Lehning et al. (1994) also provide an alternative vertical dispersion routine using a similarity solution developed by Huang (1979).

The iterative process developed by Lehning et al. (1994) to determine the source flux from the receptor measurements is described below.

1) begin with an initial estimate (seed) of the source,
2) solve the convolution summation (Equation 2),
3) calculate scaled residuals from the deviation between the calculated receptor concentration c_{calc} at each iteration with the measured data set c_{obs},

$$res(x_j, y_j, z_j) = res_j = \frac{c_{obs}(x_j, y_j, z_j) - c_{calc}(x_j, y_j, z_j)}{c_{obs}(x_j, y_j, z_j) + c_{calc}(x_j, y_j, z_j)} \quad 4)$$

4) adjust the emission flux (Equation 6) with a correction factor (Equation 5) and repeat until the residual becomes sufficiently small, for instance $1e^{-03}$.

$$f_i = \prod_j \left(1 + \frac{F res_j K_{ij}}{\sum_j K_{ij}} \right) \quad 5)$$

$$Q_i^{new} = f_i Q_i^{old} \quad 6)$$

where, *F* is an over-relaxation factor used to decrease the number of iterations

While the example above displays the model operating with two linear receptor arrays, the model is not bound to this geometrical arrangement. This example is provided for simplicity. An equally valid alternative, for instance, could be a single series of receptors spread in two arcs surrounding the source.

In this report the method is adopted to use data measured at only two locations. In this case, the method works by using observations from multiple wind directions resulting in a series to which the iteration method can be applied. This series can be considered analogous to a version in which observations for two wind directions are taken at points distributed in two arcs surrounding the source.

To enable this method the model was operated by sorting the observations at the CO_2 monitors into 5° wind increments in which an average concentration and wind speed is determined for each stability class. Averaging of concentrations and wind speed into these well defined divisions results in a smoothing of small differences in dispersive processes for similar atmospheric conditions and for temporal changes in emission rates.

When using the Gaussian formulation it is possible for the method to give rise to artefacts due to small kernel values. To minimise this effect, the model was operated by capping the maximum emission flux in each cell. An iterative procedure was adopted by setting the maximum flux at a low value and operating the model with incremental increases in the capped value. The model was repeatedly run until the solution converged and little change was apparent with increasing the maximum cell flux.

Flux methods in the Hunter Valley

Figure 2a shows an aerial infrared image detailing an area in which emissions from spontaneous combustion occur in the Hunter Valley. This image was taken during 2000 for Project C9062. The image is formed from a composite of images recorded at a height of around 1 km. The orange lines marked on the image correspond to two roads running adjacent to conveyors transporting coal to a nearby power station. These roads were used to traverse CO_2 plumes during favourable meteorological conditions.

Figure 2a. Aerial infrared image of a region in the Hunter Valley containing spontaneous combustion

A single fixed CO_2 monitor (Ecotech Model ML9820) was placed in a building in the south-east corner of the region shown in Figure 2a. The monitor logged data continuously over approximately a six-month period. It was not possible to secure a suitable site for a second monitor and therefore, only one monitor was used in the Hunter Valley. Meteorological data, including wind speed and direction, measured at 15-minute intervals at a site approximately 2 km from the monitor, were provided by staff from the nearby power station.

Figure 2b shows the Hunter Valley domain with the grid used to calculate the emission fluxes superimposed. Each grid cell was set at 50 m x 50 m covering a total area of 5 km x 5 km.

The grid was initialised by dividing the emissions calculated with the thermal imagery used in Project C9062 by one hundred. All other areas were assigned zero emissions. Although only one monitor was available, the methodology was able to resolve the area-wide emission fluxes due to the quality of the initial grid based on thermal imagery (see Results section).

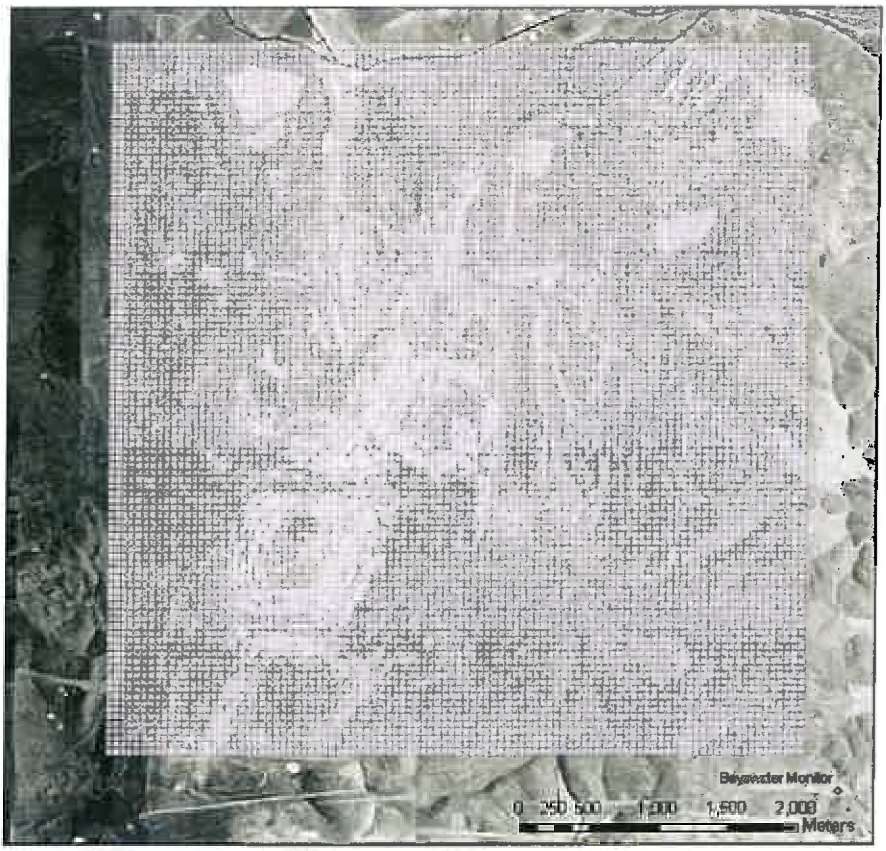

Figure 2b. Modelling domain for the Hunter Valley sub-region

A second method of estimation was also used in the Hunter Valley as only one fixed monitoring site was available. The second method involved the use of direct plume measurements taken by traversing an instrumented vehicle through the plume downwind of the source. These measurements where taken by driving the vehicle along the roadways displayed in orange in Figure 2a. The average concentration of a plume traverse was used to estimate the area wide flux using Equation 7.

$$Q = u \iint C(x,y,z) dy dz \qquad 7)$$

Where, C is the cross wind concentration and u is the average wind speed.

The plume traverses carried out in this study provide the *ground level concentration*. In order to use Equation 7, knowledge of the vertical extent of the plume is also required. In the current study the vertical extent and structure of the plume was obtained from modelling using the air quality model TAPM (Hurley, 2005).

Flux methods in the Bowen Basin

In Figure 3a, an aerial photograph is displayed of the mine site and the positions of two long term monitors located to the SE and to the NW sections of the mine. In Figure 3b the domain used to estimate the mine site emission fluxes is displayed. Each grid cell was set at 50 m x 50 m and in total, all cells covered a region 5 km x 4 km in size. No thermal imagery data were available for this mine to initialise the model domain. Instead the model was operated with simple seed values estimated in consultation with mine site personnel.

The regions shaded in red (Figure 3b) show areas identified by mine site staff as prone to self heating. The areas shaded in yellow represent general mine site regions while the areas shaded green signify rehabilitated vegetation. The model was simply initialised with a seed value which was largest for the known emission areas and smallest for the rehabilitated zones. All other areas were assigned zero emissions.

Figure 3a. Aerial photograph of the Bowen Basin mine.

Figure 3b. Modelling domain and initial grid for Bowen Basin

Results

Hunter Valley emissions

a) Inverse calculations

Results are presented in Figure 4 for the estimated emission flux using the inverse model. Data used by the model were filtered for stable meteorological conditions and for wind speeds greater than 0.5 ms^{-1}. The model was operated by assuming that the stable conditions were represented by either D (Figure 4A) or E (Figure 4B) class stability parameters. Figure 4C provides the emissions estimated from thermal imagery.

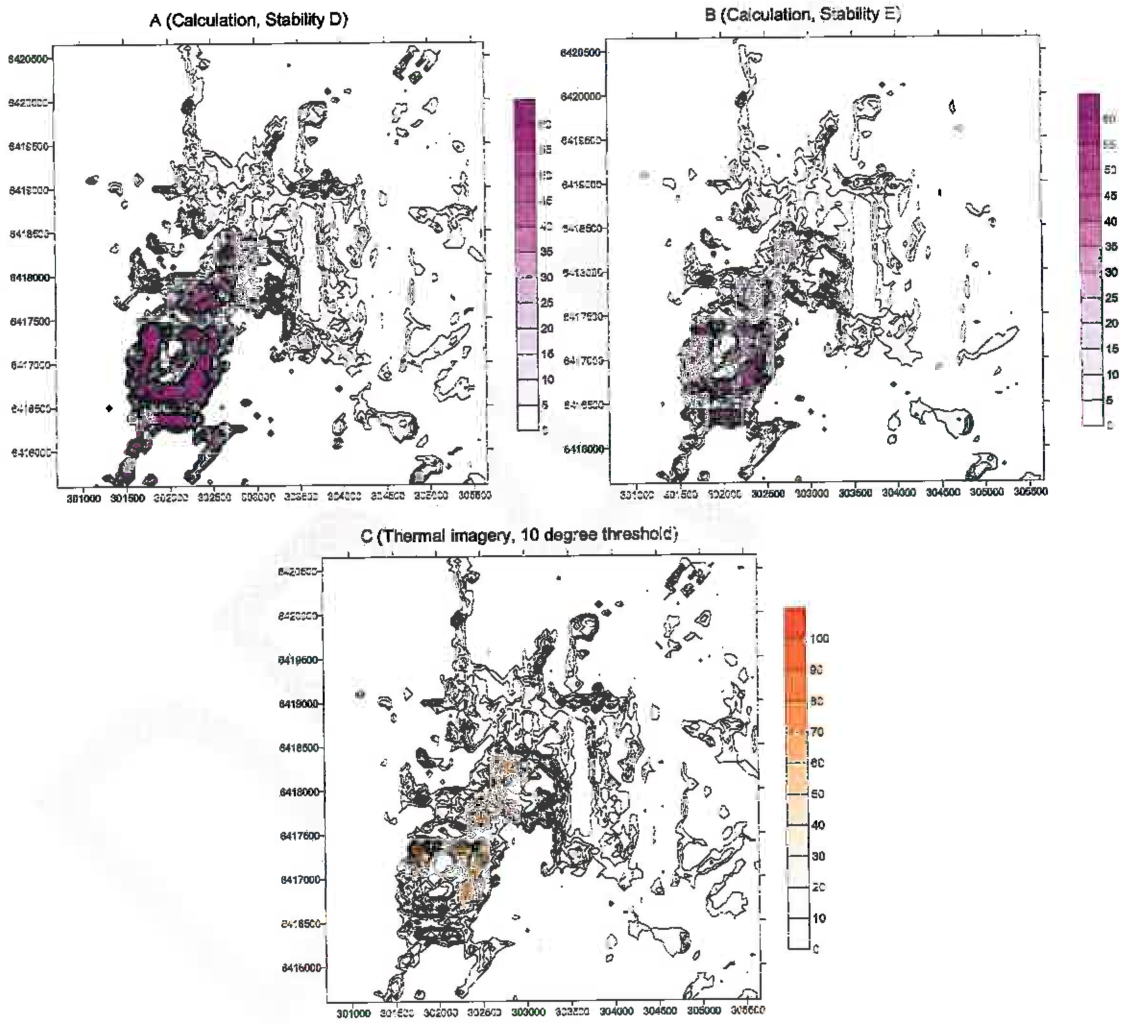

Figure 4: Flux estimates from inverse modelling (purple) and thermal imagery (orange)

The estimated total CO_2 emission flux for the region from the inverse model ranged from 1040 to 1600 kt CO_2 y^{-1}.

b) Emission estimates from thermal imagery

The estimates based on thermal imagery rely upon the temperature-emissions relationship developed in project C9062 (see Figure 5, below).

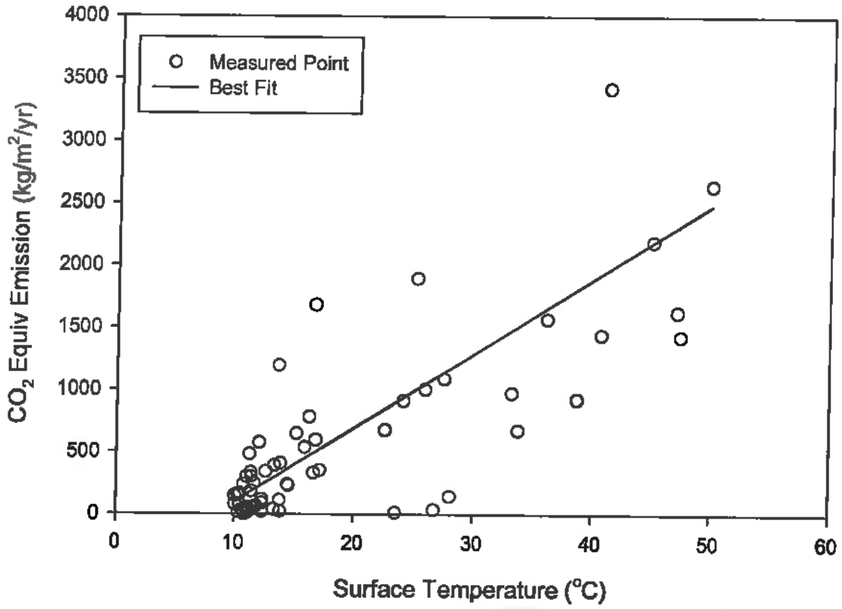

Figure 5: Measured average emission rates (as CO_2 equivalent) as a function of average surface temperature. The solid black line is the line of best fit used to estimate the total emission flux (Carras et al., 2002).

The data in the figure were obtained by measuring the emission of greenhouse gases simultaneously with measurements of surface temperature. The data show a clear relationship between emission rate and temperature although there is a large degree of inherent scatter around the line of best fit to the data. The scatter arises principally from two sources;

(i) The *surface temperature* is a function of the intensity of heating beneath the surface, the nature of the surface, the location of the heating relative to the surface and the intervening thermal properties and the meteorology at the time the measurements were made

(ii) The *emission rate* depends on the intensity of the heating as well as on the structure of the ground between the surface and the location of the heating ie cracks and channels will provide higher permeability pathways for gas flow than will compacted uniform soil or clay

Applying the data in Figure 5 to the thermography, results in area wide flux estimates ranging from 1270 to 2400 kt CO_2 y^{-1}. Note, however, that the infrared thermography data were collected more than five years prior to the measurements made for the inverse modelling estimates and changes in the extent of heating in the spoils piles are likely to have occurred (through better management, for example).

c) Plume traverses

A number of direct plume measurements were made in the sample area by traversing a vehicle along the two roadways shown in Figure 2a. In total eight successful traverses were made. In Figure 6 an example is displayed of ground level CO_2 concentration (above background) measured during two consecutive successful plume traverses. The example shows two traverses taken along the southern roadway indicated in Figure 2a. The traverses show the large horizontal extent of the plume (~5 km) and the repeatability of the measurements. TAPM was used to estimate the height and vertical distribution of emissions for each event. It was also used to calculate atmospheric stability.

In Figure 7 an example of a plume calculated by TAPM for the Hunter based mines is displayed.

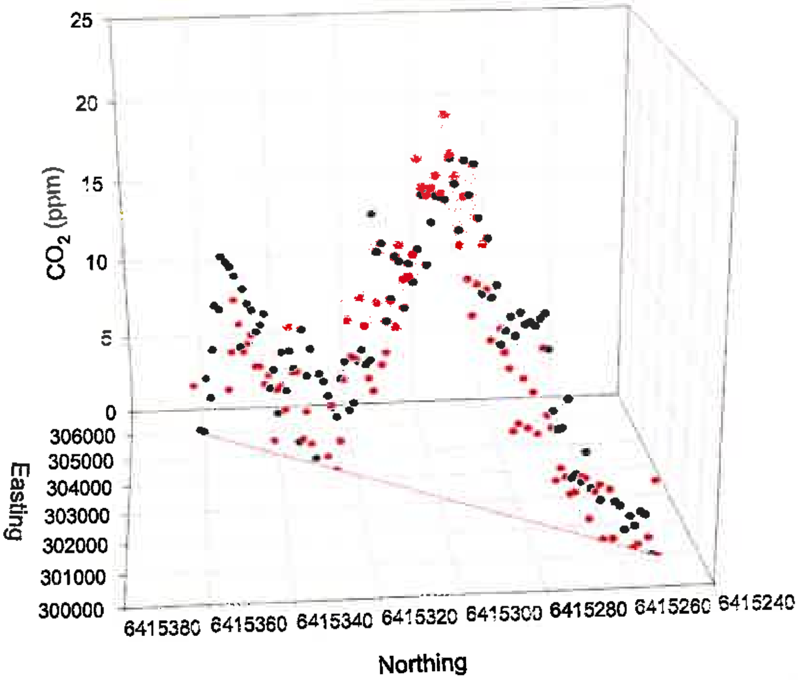

Figure 6: Example of traverse based measurement in the Hunter Valley. Black markers represent the first traverse; red markers correspond to the second traverse. The red line shows the route taken, which is approximately 5 km in length.

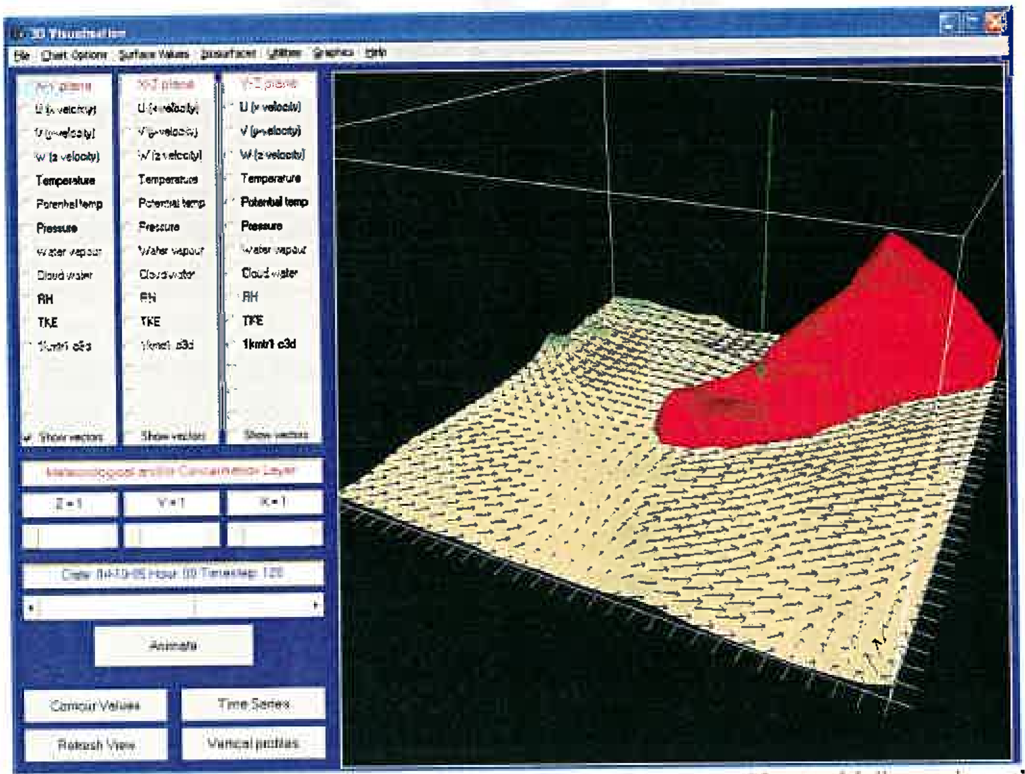

Figure 7: Example of a plume calculated by TAPM in the Hunter Valley sub region

In Figure 7 the vertical line in green shows a location at which the height and vertical concentration profile was determined. The range of flux estimates yielded from the traverses varied between 820 to 1620 kt CO_2 y^{-1} with the exception of measurements taken on one very hot windy day. Very high emission fluxes were estimated on this day and these two values are shown in Figure 8. At the time of the traverses, the region was characterised by very hot, strong winds (40°C and ~7 ms^{-1}). It is suggested that the emissions measured on this day were probably enhanced by the high temperature and the wind may have been fanning the fire leading to increased emission rates well in excess of those on average.

d) Comparison of the three methods employed in the Hunter Valley and their uncertainties

A comparison of the three methods employed in the Hunter Valley is shown in Figure 8.

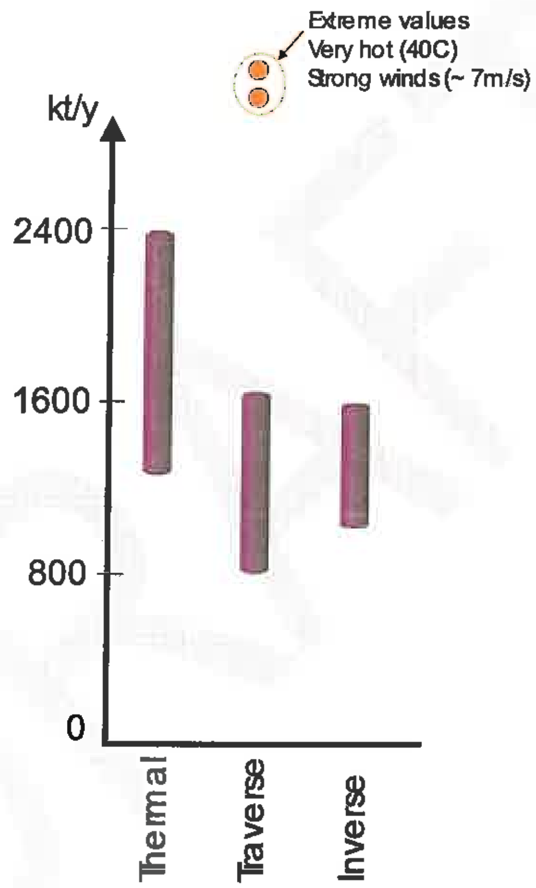

Figure 8: Estimated fluxes for a sub region of the Hunter Valley

All three methods provide a reasonably coherent estimate of emissions from the selected region. Other sources such as diesel emissions from mine site machinery are likely to be present and will have influenced the inverse and traverse based measurements, however, a simple estimation based on NPI data suggests this contribution is around 45 kt CO_2 y^{-1}. This is considerably smaller than the spontaneous combustion estimates and is therefore unlikely to be a major source of error.

Each of the methods employed contains uncertainties. For the thermal imagery the largest uncertainty is in the scatter shown in Figure 5 and the dependence on the actual ground temperature. As stated before the latter is a complicated function of the intensity of the heating, its location, the thermal properties of the intervening layers (including water content) and the local meteorology.

For the plume traverses the largest uncertainty resides in the exact plume geometry, the local micrometeorology including wind speed and especially the local atmospheric stability. These factors are all part of the stochastic nature of the atmospheric boundary layer and still subject to considerable uncertainty for an 'instantaneous' traverse.

For the inverse methods the uncertainties are also mainly related to the ability of the models to accurately predict downwind concentrations of pollutants for extended and, potentially, intermittent sources.

Nevertheless, the three methods employed show quite good overlap, suggesting a convergence, within the uncertainty of each method.

Bowen Basin emissions

In Figure 9 an estimate of the CO_2 flux from the Bowen Basin mine is provided. Part C displays the grid used to initialise the inverse model. As there were no available thermal images, the model was initialised with simple seed values based on estimates from mine site staff. The areas designated as prone to self heating (red) where set with the largest value while general disturbed mine site areas (yellow) and rehabilitation zones (green) where set with a small seed value.

Part A and B display the flux estimates from the inverse model. As for the Hunter Valley calculations, the model was operated with data measured during stable atmospheric conditions and for wind speeds greater than 0.5 ms^{-1}.

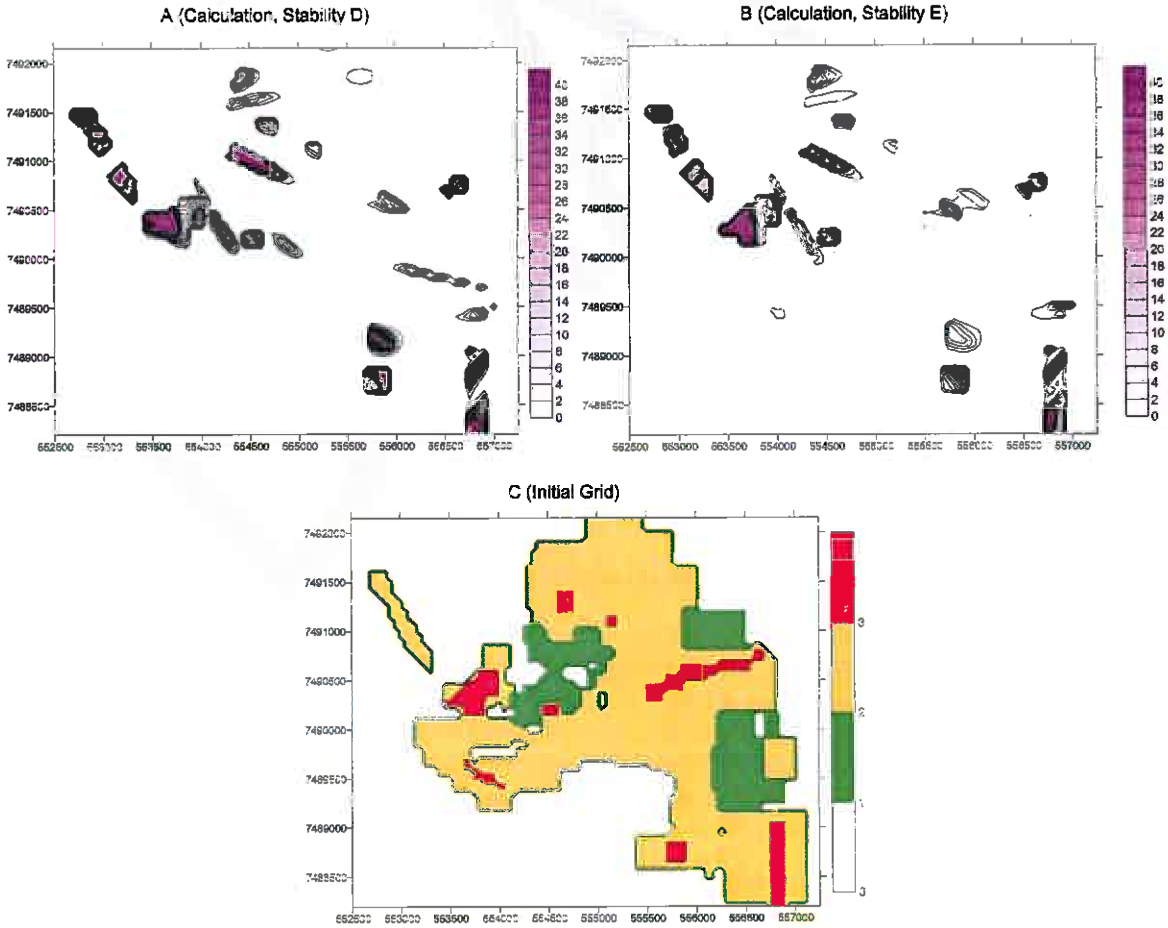

Figure 9: Flux estimates from inverse modelling

Part A provides an estimate from the model using D class stability to describe the atmosphere while Part B provides an estimate using E class stability. Although the mine site contained two monitors, only a small amount of data were available for modelling purposes. This was due to limited pockets of self-heating within the mine and the generally low wind speeds associated with elevated concentrations at this mine.

Figure 9 indicates spontaneous combustion in regions generally associated with the areas designated by the mine staff. The model did, however, find elevated emissions in other areas such as the stockpiles to the NW, an area not originally identified by staff as a prone to significant self-heating. Subsequent discussions with mine staff confirmed that the area could be prone to self-heating but was considered less significant than other areas within the mine. While a portion of these emissions may be associated with diesel vehicles, the total mine site flux from these sources is estimated at 30 kt CO_2 y^{-1} (Day et al., 2006) suggesting only a minor contribution.

The range of fluxes estimated for the Bowen Basin Mine was 200 to 320 kt CO_2 y^{-1} as shown in Figure 10. While the figure expresses an emission rate on a yearly basis, it should be remembered that the values represented in this figure are derived for a portion of a year (in this case from 4 months of reliable data). Some variations may occur particularly for sources that are subject to considerable temporal variation, such as coal stockpiles.

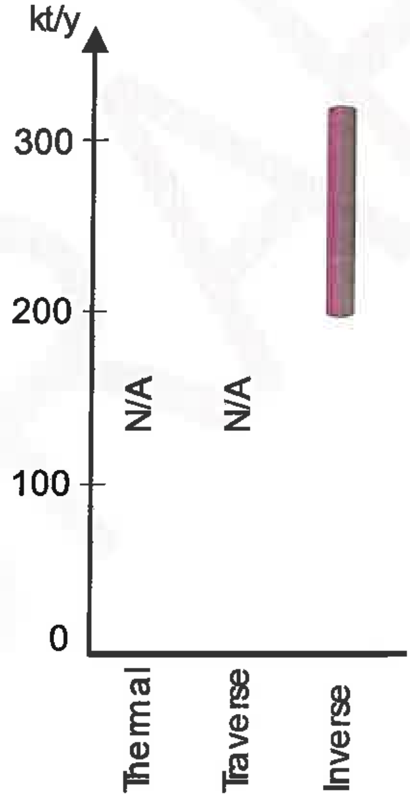

Figure 10: Estimated fluxes for Bowen Basin

This emission rate for the Bowen Basin mine is much lower than for the region studied in the Hunter Valley. While the mine studied may on occasion show strong visible signs of spontaneous combustion, the affected regions appeared to be geographically sparse. The thermal imagery taken in the Hunter Valley, on the other hand, suggests a larger area of more generalised self-heating.

Discussion of emission estimate methodologies

A number of techniques were employed in the current study to estimate spontaneous combustion emissions from mine site areas. Some comments on each technique follows.

(i) While the inverse model shows promise as a technique for evaluating mine site fluxes, the method relies to a large extent on a reasonable seed value for the emission profile. In the Hunter region the seed values were provided from airborne thermal images. The high degree of specification in this regard enabled the use of only one monitor. The choice of one monitor was not optimum and was based on limited access to areas containing electrical power. To a large extent the results from the Hunter experiment were due to detailed existing data on spontaneous combustion in the region that had resulted from a number of previous ACARP funded studies. This guided the placement of the monitor downwind of the sources within the predominately NW flow regime of the Hunter Valley. A monitor located outside the major zone of influence would have seriously compromised the project outcomes for this region.

    In the Bowen Basin a less sophisticated method was required to seed the model using only the knowledge of mine site staff. At this site the model capability was enhanced through the use of a second monitor. The model was able to identify regions not originally identified by staff as containing significant self-heating. Direct plume measurements from traverses taken in the Hunter Valley corroborated the general range of flux from the inverse technique. Traverse measurements were not undertaken in the Bowen Basin. While the traverses are a very useful measure, they are largely opportunistic in nature and require an understanding of vertical mixing at the measurement sites.

(ii) While thermal imagery played a key role seeding the inverse model, the results of this study suggest that the method alone lead to high estimates of greenhouse fluxes in the Hunter primarily as a result of the inherent variability in the temperature-emission profile developed from observations. While measurements were taken at a number of sites, the flux chamber methodology is limited to studying small regions within affected areas. Further the emission rate formed in ACARP C8059 is an aggregate from many mines and may not be representative at a local level.

(iii) Experience gained in this study suggests a number of recommendations to enhance estimates in future studies, these include:

    a. Using a detailed seeding value for initialising the inverse model. Thermal imagery was found to be a suitable methodology.

    b. Where possible, direct plume measurements provide a reasonable method for estimating area wide fluxes but require an understanding of the mixing processes at the point of measure. Numerical models such as TAPM can provide an estimate of the mixing processes. A more accurate approach would involve a simultaneous measurement of vertical profiles at a fixed location using, for example, a tethered balloon.

    c. Simultaneous measurement of other species (eg CO, SO_2, NO_X) may provide a mechanism, through ratios, to distinguish emissions from self-heating from other sources such as diesel machinery.

    d. Stationary monitors require installation for long periods of time to ensure sufficient data sets are collected for modelling purposes. Six months of data were sufficient in the Hunter Valley region where a monitor was placed in a location directly downwind of the source in the predominant valley flows. In the Bowen Basin mine site however, a longer sampling period would have been more appropriate due to smaller regions of self-heating and a predominance of very light winds associated with elevated concentrations which cannot be modelled.

Conclusions

Inverse modelling was found to be a successful technique in estimating area wide fluxes of CO_2 from mine sites. In the Hunter Valley the technique provided similar estimates to those obtained from direct plume measurements using traverse based techniques. The model requires a detailed seeding map which in the Hunter was provided by thermal imagery. Fluxes based only on thermal imagery were larger in magnitude probably due to the uncertainty introduced by estimating the surface temperature of a section of spoil pile.

No thermal images were available for the Bowen Basin mine and inverse modelling based upon rudimentary seeding values was able to identify both regions noted by staff as prone to self heating as well as regions not originally identified such as coal stock piles.

Acknowledgements

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