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EXTENDED ABSTRACT

Assessing the impact of thermally driven flows on regulatory air dispersion modelling

David Carruthers, Cambridge Environmental Research Consultants

david.carruthers@cerc.co.uk

Martin Seaton[1], Rose Jackson[1], Kate Johnson[1], Victoria Hamilton[1], Sarah Strickland[1], Jenny Stocker[1], John Moncrieff[2], Ben Marner[3], Roger Timmis[4], Rob Kinnersley[4] and Philippa Douglas[4]

[1]Cambridge Environmental Research Consultants, [2]University of Edinburgh, [3]Air Quality Consultants, [4]Environment Agency

Introduction

Air quality assessments for environmental permits do not typically consider how variations in air temperature near the ground can cause local thermal air flows, which incorporate and transport air pollutants. Flows can occur in areas of sloping terrain, varying land cover, or at the coast. Many sites regulated by the Environment Agency in England are in such areas, and recent experience of thermal air flows at a high-profile site prompted this study into their potential impacts. The emphasis was on katabatic flows, and sea and land breezes; urban heat island flows were considered, but were not readily detectable. The study covered the following components: defining characteristics of thermal flow types and determining metrics for estimating their occurrence; identification of case study locations and characterisation of thermal flows occurring there; exploring modelling options for determining the impacts of thermal flows in these locations; and generalisation to allow the metrics and results of case studies to be applied more broadly. Key aspects of these components are presented below.

Metrics for Thermal Flows

Katabatic winds are cold air downslope flows which may occur in valleys or on slopes in stable conditions, typically at night, when the air at the surface is colder and therefore denser than the air above. Wind speeds vary from ~ 1 m/s or less, on shallow slopes or in small valleys, to a few m/s in the most conducive conditions in large valleys with high rates of surface cooling, e.g. over snow or ice. The cold air layer depth (d) ranges from 1 or 2 m up to tens of metres, and may increase with distance down the slope (Mahrt 1982, Whiteman 1990, Princevac *et al.* 2008). Key parameters are d, the density difference between the cold air layer and the overlying air, the terrain slope angle, surface roughness and the synoptic wind.

Sea breezes are onshore winds which occur when air over land becomes warmer and therefore less dense than air over the sea. Sea breezes occur during the day when there is strong solar heating of the land surface. The strength of the sea breeze may be over 5 m/s with d up to a few hundred metres (Oke 1987, Stull 1988). Land breezes are offshore night-time winds which occur when air over land becomes denser than air over the sea; they are generally weaker than sea breezes, ~ 2 m/s (Oke,1987), with d up to a few tens of metres. The key parameters for sea and land breezes are the sea surface temperature, near surface temperature over land, d and the synoptic wind.

The different terms in the momentum equation determining the time evolution of katabatic winds are discussed in Mahrt (1982). For the purposes of determining simple metrics for the occurrence and strength of thermal flows, they are assumed to be in steady state with an approximate balance between buoyancy forces that accelerate the flow and drag forces that retard it. This is one of the cases considered by Mahrt (1982) and results in the following approximate expression for the katabatic flow speed, U_T:

$$U_T = \begin{cases} \left(\frac{dg\Delta\theta \sin\alpha}{2C_d\theta} - \frac{1}{2}{U_S}^2\right)^{\frac{1}{2}} & \text{if } \frac{dg\Delta\theta \sin\alpha}{2C_d\theta} > \frac{1}{2}{U_S}^2 \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

where θ is the mean potential temperature of the near-surface cold air layer, $\Delta\theta$ is the difference in θ between this layer and the air above, α is the hill slope angle, U_S is the synoptic (non-thermal) wind at a representative height $z = {}^{d}/_{2}$, C_d is a drag coefficient and g is the acceleration due to gravity. For sea and land breezes the same equilibrium formula is assumed, where in these cases sin α = 1 and $\Delta\theta$ represents the difference between the sea surface temperature and the near surface air temperature over the land.

To determine the occurrence and strength of the thermal flows, equation (1) is applied to successive hours of meteorological data of the appropriate stability, then the flows are categorized according to Table 1. Applications of this approach using meteorological data for case study sites and other locations suggest that the frequencies and strengths of flows vary with the local wind and temperature climate and, for katabatic flows, with the slope. In UK conditions, they typically dominate the local flow for up to several hundred hours per year in coastal situations, and for up to several tens of hours in katabatic situations.

Table 1 Wind speed criteria used to categorise likelihood of thermal flows in conducive stability conditions

Wind criterion	Category	Description
$\boldsymbol{U_s > 2U_T}$	Synoptic dominates thermal	Synoptic flow suppresses development of thermal flows
$\boldsymbol{2U_T > U_s > 0.5U_T}$	Some thermal influence	Thermal flows will have an impact on the overall flow
$\boldsymbol{U_s < 0.5U_T}$	Thermal flow dominates	Thermal flows dominate the flow

Case Study locations

The Environment Agency examined 30 years of mobile monitoring facility (MMF) data to derive a list of potential case study areas across England. The final selection comprised: katabatic flows of landfills at Walleys Quarry near Newcastle-under-Lyme and at Peckfield near Leeds; and sea and land breezes at Immingham in North Lincolnshire and Grangetown near Teesside. This paper presents modelling results from Walleys Quarry, although the generalisations draw from the whole study. A contour map of Walleys Quarry and the locations of four monitoring sites is shown in Figure 1. This shows elevated terrain to the west and a small valley orientated east and southeast of the site.

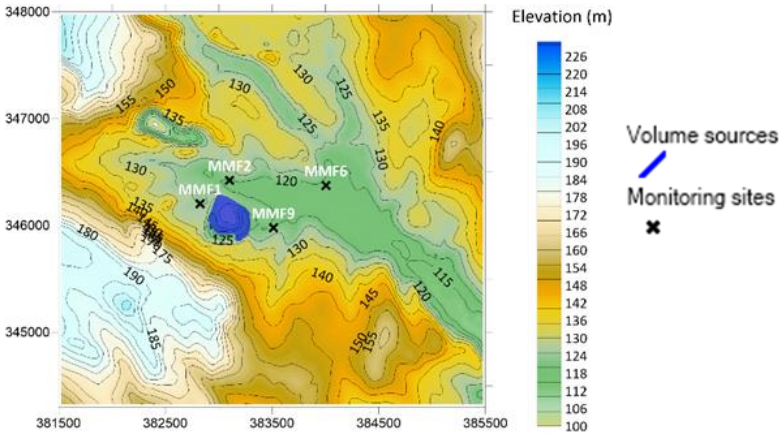

Figure 1 Walleys Quarry. Terrain elevation (m) showing volume sources modelled by ADMS and the monitoring sites MMF1, MMF2, MMF6 and MMF9.

Modelling and Validation

Three modelling approaches were used for Walleys Quarry. Firstly, using the standard version of the quasi-Gaussian dispersion model, ADMS (Carruthers et al 1994), unconfigured for katabatic flows but using the ADMS 'calms module' which is based on a simple radial plume. Secondly, using a modified version of ADMS, configured for katabatic flows by combining: (i) vertical profiles for mean synoptic wind flow and turbulence, and (ii) katabatic profiles from equation (1). Thirdly using, KLAM_21 (Sievers and Kossman, 2016), a two-dimensional cold-air-drainage model that predicts the development of a density-driven flow due topographic routine and nocturnal cooling using a specified surface heat flux which is constant in time, but varies with land-surface type.

Figure 2 compares period average (~two year) concentrations of H_2S for the four monitoring locations using the standard ADMS approach. Measured and modelled concentrations range from 1.6 to 5.2 µg/m³ and 0.4 to 2.8 µg/m³ respectively. The model performs relatively well at MMF1 and MMF2, but underpredicts at MMF6 and MMF9 where the highest measured values occur. The difference in performance suggests the standard approach does not fully account for local dispersion, specifically katabatic flows occurring downslope from the landfill.

For MMF1 and MMF9, Figure 3 shows that the relationship between observed concentrations and concentrations predicted by the standard ADMS model varies significantly between: (i) hours without thermal influence (blue and orange), and (ii) hours with thermal influence (yellow and green). This suggests that the metrics distinguish successfully between subsets of data corresponding to different amounts of thermal influence. At both sites, the model significantly underpredicts the measured values for categories with thermal influence.

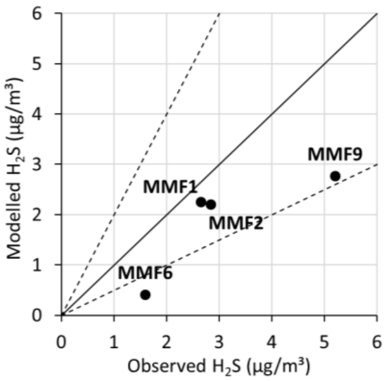

Figure 2 Period average H_2S concentrations: comparison of the standard ADMS modelling with observations

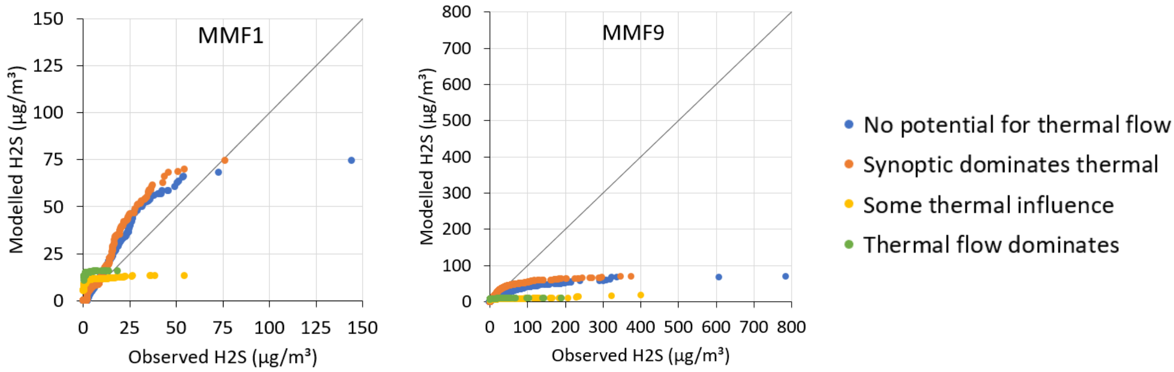

Figure 3 Quantile-quantile plots of hourly H_2S concentrations at MMF1 and MMF9: comparisons of standard ADMS modelling against observations, for 4 metric categories. Note the different concentration scales.

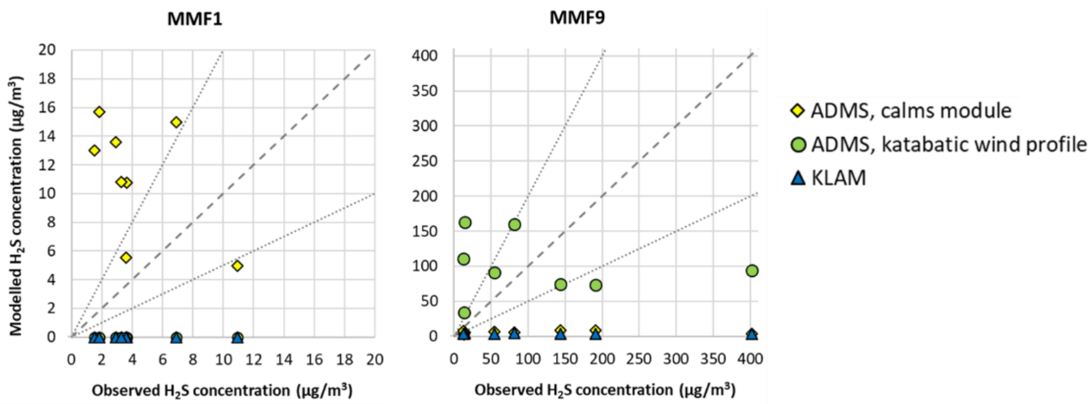

Figure 4 Scatter plots of hourly measured and modelled H_2S concentrations at MMF1 and MMF9 for the three modelling approaches. Note the different concentration scales.

Figure 4 presents hourly scatter plots at MMF1 and MMF9, for selected hours in the 'dominant katabatic' category (i.e. Us< 0.5 <Ut). At the downslope monitor MMF9, both the standard ADMS and the KLAM_21 models predict near-zero concentrations. For

standard ADMS, this suggests that, when katabatic flows are absent, terrain effects do not disperse pollutants downslope to MMF9. For the KLAM_21 model, the near-zero concentrations occur because it receives only the southern edge of the plume (Figure 5(B)). Figure 4 shows that when katabatic conditions are accounted for by using the modified ADMS, concentrations of similar magnitude to those measured are predicted at MMF9 (see also Figure 5(A)). At the upslope monitor MMF1, Figure 4 shows that modified ADMS and KLAM_21 models both predict near-zero concentrations because the plume does not disperse upslope. However, it also shows that the calms module of standard ADMS predicts concentrations of similar magnitude to the measurements.

(A)

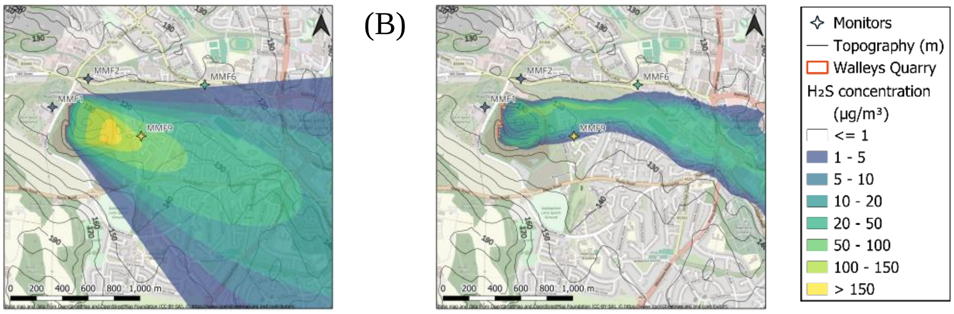

Figure 5 Contour plots of modelled H_2S concentrations using katabatic modelling based on (A) modified ADMS and (B) KLAM_21; light WNW synoptic wind, low cloud cover.

Generalisation

The metrics and case study findings have been generalised in checklists which enable practitioners to determine if: (i) thermal flows are likely, and (ii) they will significantly affect dispersion and pollutant concentrations so should be considered further, for example with modelling. For katabatic flows, dispersion models which include explicit representation of the airflow can be modified in a simplified way to account for the effect of katabatic flows on the overall airflow. This results in improvements in model predictions of pollutant concentrations at downslope locations, when katabatic flows are significant. For sea and land breezes, no modifications are required; these can be used with observed or NWP meteorological data representative of the source location.

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