USING PLUME RISE SCHEMES TO MODEL HIGHLY BUOYANT PLUMES FROM LARGE FIRES

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INTRODUCTION

The explosion at the Buncefield oil depot in Hemel Hempstead, UK on Sunday 11th December 2005 resulted in the largest peacetime fire in Europe to date. The main fire burned for four days and, at the height of the blaze, 20 large fuel tanks were on fire, each reported to hold up to 3 million gallons of unleaded and super-unleaded petrol, motor-spirit, gas oil, ultra low sulphur diesel and jet fuel. The thick black smoke plume was visible on satellite imagery (see Figure 1).
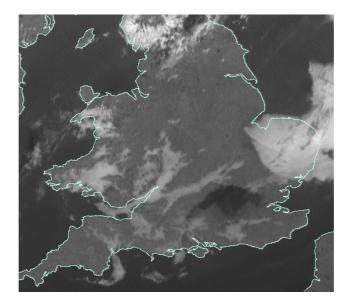

Fig. 1; Visible satellite imagery for 11Z on Sunday 11th December 2005 showing the plume from the Buncefield oil depot explosion

EMERGENCY RESPONSE

As part of the emergency response to the incident, the transport and spread of the plume was predicted by the Met Office, UK, using the atmospheric dispersion model, NAME *(Jones, A. et al.*, 2007). NAME has a wide range of applications including simulating releases of hazardous materials (chemical, biological, radiological and nuclear), modelling the transport of ash clouds from volcanic eruptions, disease spread, air quality forecasting, episode analysis and identifying sources and source strengths.

The heat of the fires at the Buncefield oil depot resulted in a highly buoyant plume which rose vertically upwards to a significant height within the atmosphere. At the time of the incident, the initial plume rise was included in the source release details rather than use a sophisticated plume rise scheme. This decision was based on the fact that important source properties were unknown and on the need to ensure a rapid response.

The meteorological conditions at the time of the event were favourable for a number of reasons. The stable atmosphere and light winds resulted in most of the elevated plume remaining at a high level within the atmosphere with very little mixing of material down to ground level. There was also significant wind shear on Sunday 11th December which spread the plume out over a wide area and gave it a fan-like appearance (see Figure 1). At lower levels, winds were from a north-westerly direction transporting the plume south-eastwards from the depot. At higher levels, winds were from a north-easterly direction transporting the plume south-westwards. This fact, coupled with the availability of satellite imagery in near real-time, provided vital information to the atmospheric dispersion modellers and enabled the height to which the plume was rising within the atmosphere to be estimated. By comparing NAME model predictions of the plume with satellite imagery, it was determined that the plume was reaching a range of heights within the atmosphere, with a plume top of about 3000 m and a plume base of a few hundred metres. This was supported by eye witness observations of an elevated plume and by a report from a commercial airline that the plume was rising to a height of 9000 ft. The NAME predicted plume at 11Z on Sunday 11th December with a release of material from 500 m to 3000 m above ground (thereby including the observed plume rise) is shown in Figure 2. It can be seen that there is good agreement with the satellite imagery for the same time shown in Figure 1.
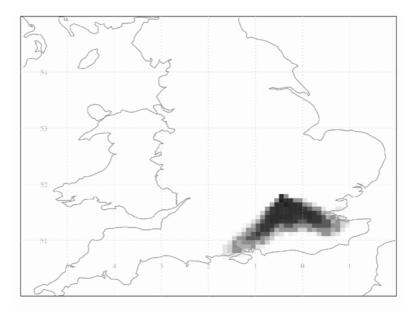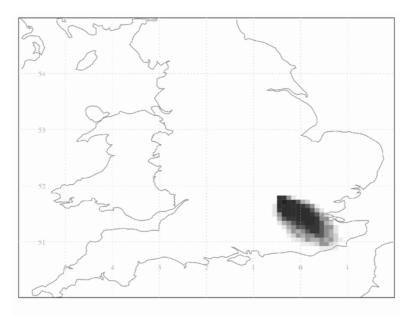

Fig. 2; Hourly averaged NAME predicted plume at 11Z on Sunday 12th December 2005

PLUME RISE MODELLING
Following the event, the decision was made to try and model the initial rise of the plume due to buoyancy using the plume rise scheme within NAME. The plume rise scheme solves integral conservation equations of mass, momentum and heat and was designed to be used to model plumes from power station stacks (*Webster, H.N. and D.J. Thomson*, 2002). The scheme has never been used to model a source as buoyant and as large as the Buncefield plume before. In addition there is a vast degree of uncertainty in the input source term, in particular, the amount of fuel that was on-site at the time of the explosion, the amount of fuel that was burnt during the incident, the emissions and heat released from the uncontrolled burning of refined fuel and the variation of these quantities over time, particularly due to fire fighting activities.

Assuming that fuel was initially burnt at a rate of 381.3 kg s^{-1} (obtained by assuming that 42 million litres was burnt during the first 24 hours at a constant rate) and that the heat is released at a rate of 43.3 GJ t^{-1} for gas oil and DERV, 43.9 GJ t^{-1} for kerosene and jet fuel and 44.8 GJ t^{-1} for petrol, gives an estimated heat flux of 16.8 GJ s^{-1}. This figure is broadly within the range expected from comparisons with other heat sources – a large power station stack emits about 0.6 GJ s^{-1} and the heat flux estimate from the large Chisholm forest fire in Alberta, Canada is 3585 GJ s^{-1} (*Luderer, G. et al.*, 2006).

Figure 3 shows the NAME predicted mean plume from 06Z to 12Z on Sunday 11th December using the NAME plume rise scheme with a heat flux of 16.8 GJ s^{-1}. Comparing Figure 3 with the satellite imagery in Figure 1 we see that NAME does not spread the plume enough. In particular, the plume rise achieved using the NAME plume rise scheme only transports the plume to a height of approximately 1750 m above ground level and therefore does not capture the transport of the plume south and south-westwards at higher levels.
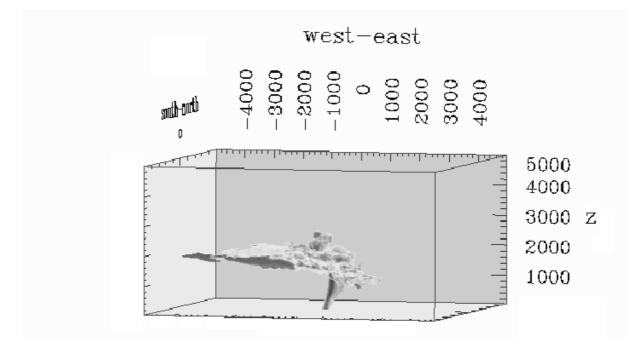

Fig. 3; NAME predicted mean plume from 06Z to 12Z on Sunday 11th December calculated using the plume rise scheme with a heat flux of 16.8 GJ s^{-1}

Given the uncertainties involved, namely the amount and rate of fuel burnt and the heat released per unit mass / volume of fuel, an increase in the estimated heat release rate required to achieve the plume rise observed, is plausible. However, modelling studies show that whilst a higher heat release rate estimate increases the plume rise in NAME, the vertical spread of the plume is still too small resulting in too little horizontal spread and poor agreement with satellite imagery. This suggests that there may be other factors, which have not been taken into account, for the poor vertical spread of the predicted plume.

Luderer, G. et al. (2006) studied the large Chisholm forest fire in Alberta, Canada and found that the energy budget was dominated by the release of latent heat from condensing water vapour from entrained water from the ambient air. The atmospheric conditions on Sunday 11th December had high levels of relative humidity with reports of thick fog in places and hence latent heat released from entrained moisture may have had a significant contribution to the energy budget. NAME does not take into account the release of latent heat from condensing water vapour. The effect of latent heat release on the plume rise is being studied using a large eddy model (LEM). Initially, LEM simulations of the Buncefield plume were conducted in a

dry atmosphere (i.e. not taking into account the effects of latent heat release). Figure 4 shows a LEM simulation in a dry atmosphere using fixed atmospheric wind and temperature profiles obtained from the Met Office's numerical weather prediction model (the Unified Model) at 06Z on Sunday 11th December. The plume rise obtained is a maximum of approximately 2000 m and agrees well with the NAME predictions. Work is ongoing to extend the LEM simulations to include the effect of latent heat release from condensing water vapour. In addition, the contribution to the energy budget due to the release of latent heat from condensing water vapour from water produced by the combustion of fuel was estimated. The latent heat of vaporisation of water released by the combustion process was found to make a very small contribution to the energy budget (approximately 7% of the heat released due to combustion).

Fig. 4; LEM simulation of the Buncefield plume in a dry atmosphere using fixed wind and temperature profiles from the Met Office's numerical weather prediction model at 06Z on Sunday 11th December

Herring, J.A. and P.V. Hobbs (1994) studied a smoke plume from the 1991 Kuwait oil files and suggested that absorption of solar radiation could lead to additional heating within the plume causing radiatively driven lofting. The top of the plume experiences the strongest radiatively driven lofting thus absorption of solar radiation could potentially stretch the vertical extent of the plume. Irradiance measurements taken by the FAAM (Facility for Airborne Atmospheric Measurements) research aircraft on Tuesday 13th December showed that 100 W m^{-2} of the solar radiation flux was absorbed by the plume at a distance of approximately 78 km downwind of the source. The total solar radiation observed was 280 W m^{-2}. Radiative transfer calculations enabled heating profiles within the plume to be estimated. These calculations, under cloud-free conditions using appropriate atmospheric profiles of temperature, humidity and other gaseous constituents and appropriate solar insolation and solar zenith angles, indicated that the top of the Buncefield plume was subject to an additional radiatively driven heating rate of 0.34 K hr^{-1}, resulting in a relatively modest increase in the plume top by 60 m during the first hour after release. The effect of lofting was also incorporated into the NAME plume rise scheme and simulations agreed with a modest predicted rise of a few tens of metres per hour due to absorption of solar radiation.

The Buncefield plume was characterised by a number of smaller plumes from individual tank fires which combined, due to their close proximity. NAME, however, models the Buncefield plume as a single plume from a uniform source. It is possible that the spatial variation in the plume's properties as the smaller plumes from the individual fires combine and reinforce each other may result in a larger vertical spread than is predicted with NAME.

Other potential explanations as to why NAME does not show the observed plume rise and vertical spread of the plume include the possibility that the input meteorological data, from the Met Office's numerical weather prediction model (the Unified Model), does not accurately capture the atmospheric meteorological situation. The plume rise will be particularly sensitive to the atmospheric temperature profile. However, comparisons of profiles of Unified Model meteorological data with radiosonde ascents and surface observations, suggest that the Unified Model had a good representation of the meteorology during the event.

CONCLUSIONS

Good agreement was obtained between NAME modelling of the Buncefield plume using a simple elevated release and satellite imagery. NAME modelling of the Buncefield plume using the complex plume rise scheme resulting in an underprediction of the vertical spread. Potential reasons for this have been investigated and discussed here. In light of this study and the fact that, during an emergency situation, key source information is not available or at best highly uncertain, it seems advisable to choose simple modelling options which make use of all available information and observations over complicated plume rise schemes.

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