Integrated Assessment
2003, Vol. 4, No. 4, pp. 236–249

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The UK Integrated Assessment Model, UKIAM: A National Scale Approach to the Analysis of Strategies for Abatement of Atmospheric Pollutants Under the Convention on Long-Range Transboundary Air Pollution

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ABSTRACT

Integrated assessment modelling aims to bring together information on emissions, atmospheric transport between sources and exposed areas or populations, criteria for environmental protection, and potential emission control measures and their costs, in order to explore effective abatement strategies. We describe the development of a new UK scale *Integrated Assessment Model* which can be used to investigate strategies for the attainment of national emission ceilings. The model optimises abatement strategies in relation to acidification, eutrophication, and/or human-exposure to particulate PM_{10}, with reference to the deposition of sulphur and nitrogen (oxidised and reduced), and concentrations of primary and secondary particles. The model combines sector specific emissions, atmospheric transport and deposition, ecosystem specific critical load exceedances, and pollution abatement costs to determine optimised abatement strategies using benefit and, where applicable, recovery functions.

Keywords: Integrated Assessment, Air Pollution, Critical Loads, Abatement Strategies, National Emissions Ceilings, CLRTAP.

1. INTRODUCTION

Integrated assessment modelling aims to bring together information on emissions, atmospheric transport between sources and exposed areas or populations, criteria for environmental protection, and potential emission control measures and their costs, in order to explore effective abatement strategies. Based on experience at Imperial College from development and application of the ASAM model [1] at the European scale, working in parallel with the RAINS model of IIASA [2, 3] to support negotiations on the Gothenburg protocol under the Convention on Long Range Transboundary Air Pollution (CLRTAP), a new UK scale integrated assessment model, UKIAM, has been developed to investigate strategies for the attainment of national emission ceilings. Initially this is focused on reducing acidification, eutrophication, and exposure to particulate PM_{10} in the UK, with reference to deposition of sulphur and nitrogen (oxidised and reduced), and concentrations of both secondary SO_4, NO_3, and NH_4 particles, and primary particles.

Although not addressed under the Gothenburg protocol, PM_{10} is of concern for impacts on human health. Consequently, ASAM was adapted to consider population exposure to secondary inorganic particulates, and it was found that cost-effective scenarios to reduce this exposure were similar to those derived for acidification [4]. Interrelationships between acid abatement strategies and climate change have also been identified – with particulates affecting radiative forcing – suggesting benefits in combined abatement strategies for acid abatement and greenhouse gas emissions [5, 6].

This development continues at the national scale, and the UKIAM thus combines sector specific emissions, atmospheric transport, deposition and particulate concentrations, ecosystem specific critical load exceedances, and pollution

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10.1080/13895170490051538$16.00

abatement costs to determine optimised abatement strategies using "benefit" and, where applicable, "recovery" functions as described below. These optimised strategies complement the European scale models since UKIAM measures are implemented spatially within the domain of a single country emitter in ASAM and RAINS; it is clearly significant, especially for the country concerned, where a measure is applied within a country.

This paper discusses firstly the conceptual framework that provides the basis for the UKIAM, through a description of the architecture and linkages between the different components. It then summarises the atmospheric modelling component, the treatment of critical load exceedances – which differs from the approach taken by ASAM and the RAINS model, and the development of cost-curves. Finally, it details the process of abatement optimisation and presents some example model outputs.

It should be noted that data presented in this paper is preliminary and used only for model development. Verified data for 2000 is currently being incorporated to provide a basis for assessing abatement strategies to meet the UK's commitments to the Gothenburg protocol in 2010.

This work has been undertaken by the *UK National Focal Centre for Integrated Assessment Modelling* at Imperial College London, in collaboration with associated activities within the UK on emission inventories, atmospheric modelling, and mapping of critical loads.

2. UKIAM ARCHITECTURE AND LINKAGES

Figure 1 provides a schematic representation of the key linkages and data flows within the UKIAM, highlighting the four main driving mechanisms: emissions, atmospheric

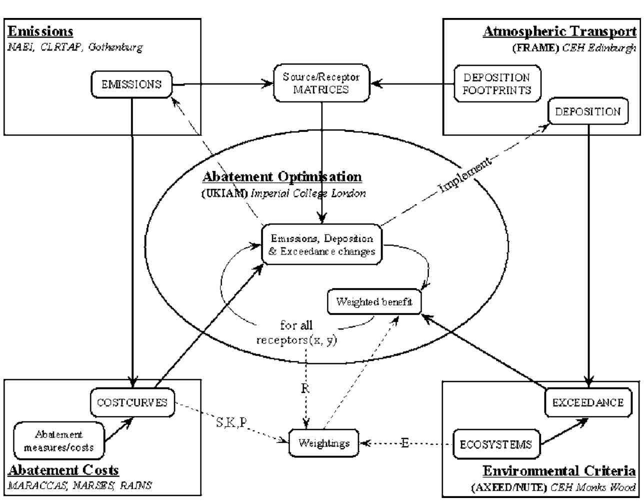


Fig. 1. Schematic representation of the key linkages and data flows within the UKIAM, highlighting the relationships between emissions, atmospheric transport, ecosystems and abatement costs as elements of the optimisation process.

transport, environmental criteria (critical loads), and abatement options (cost curves). The process of optimisation using gap closure techniques, which has been described by Warren and ApSimon [7], is extended in this paper to describe 'benefit' and 'recovery' functions in relation to ecosystem specific critical load exceedances and population exposure to airborne particulates.

The model derives a prioritised sequence of abatement measures applied to specific sources. At each step in the sequence it cycles through the sources choosing successive abatement measures still available, and examines the "benefit" of implementation in terms of reducing exceedance of environmental targets or exposure to particulates, and the cost of implementation. The measure that gives the highest ratio of "benefit" to "cost" is selected for implementation; and the process repeated. Benefit functions can be defined in alternative ways, either straightforwardly in terms of reduced exceedance, or in some more complex way to reflect reduced damage or harm – for example a reduced risk of health effects through reduction of population exposure to PM_{10}. These 'benefit' functions can also be biased towards specific policy objectives by applying a higher weighting to particular components included in the optimisation calculations; In this way contrasting scenarios can be assessed where emphasis can be placed on the abatement of specific sources or sectors (e.g., transport or power generation), the protection of a certain ecosystem type (e.g., moorland), or to mask out 'binding' cells where it is not possible to eliminate exceedances and provide protection for ecosystems within them.

The model has been designed so that it can treat several different types of sources and a selection of pollutants (currently NH_3, SO_X, NO_X and PM_{10}). The physical sources themselves are subdivided into different industrial, domestic and natural sectors. For the purposes of emissions abatement optimisation each physical source is currently treated as a separate source for each different sector and pollutant; for example, a source emitting SO_2 is treated as though independent from the same source emitting NO_X. The treatment of abatement measures addressing more than one pollutant is planned as a future improvement, as in some cases it may be important in establishing priorities. The following source types are recognised:

- *Major Point Sources (MPS)*, which are geo-located and tend to be sector specific;
- *Area Sources*, (individual UK counties) which are derived from 1 km gridded sectoral emissions data within the UKIAM;
- *National Sources* for sources which cannot be disaggregated geographically for the purposes of abatement (e.g., transport); and
- *Other Sources*, which do not fall into any of these categories and are treated in specific ways (e.g., marine/shipping emissions).

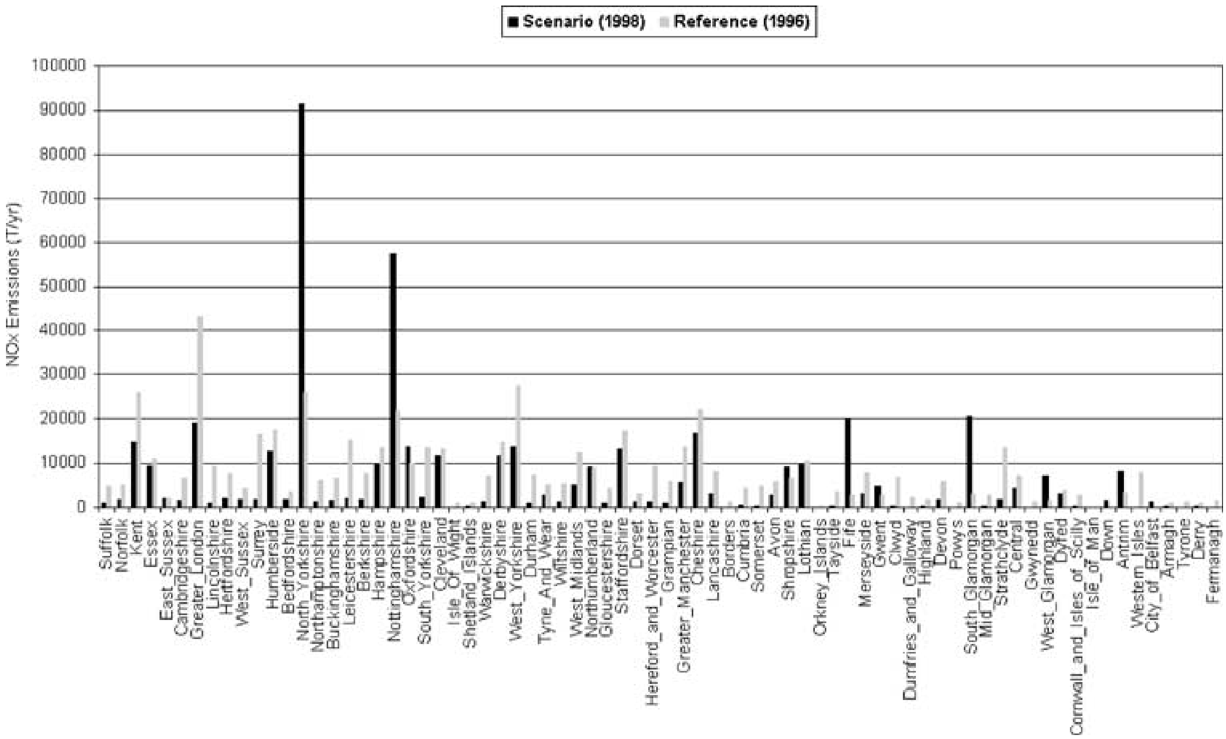


Fig. 2. Emissions by county (NO_X) for both the reference (1996) and baseline (1998) scenarios.

Figure 2 describes both the 'reference' (1996) and 'baseline' (1998) emissions of NO_X from counties used for model development. Note the potentially large differences in emissions between years depending, for example, upon which power stations are operational or on standby. This highlights the need to check the assumptions about future levels of activity and energy generation, because these will strongly influence the corresponding geographical distribution of emissions. Figure 3 describes the area sources (counties), and the major point sources (MPS) described by the National Atmospheric Emissions Inventory (NAEI) [8], of which a subset are included within the UKIAM.

Given the scope of the individual components of the UKIAM (emissions, atmospheric transport, costs, critical loads etc.) there is a variety of combinations of sources, pollutants, ecosystems and optimisation mechanisms which could potentially be included in assessments of abatement strategies, the model can be initialised with combinations of the options described in Table 1.

Scenario mode can be utilised to adjust all necessary 'reference' datasets to generate a new 'baseline' dataset, for example for a projected "business as usual" scenario, with simulation halting before optimisation procedures. This mode facilitates easy analysis of alternative emissions scenarios prior to assessment of additional abatement strategies to reduce emissions in order to achieve new targets. Source-receptor matrices, cost curves, exceedances and emissions/depositions are output after scenario adjustment to record the specific starting conditions and datasets for each simulation. The model has been coded in ANSI-C to ensure portability of the UKIAM between PC and Unix environments.

Due to both the rescaling of ASAM – which operates with country emissions sources and deposition onto the EMEP spatial grid of Europe – to develop the UKIAM (counties/5 km grid), and the incorporation of additional datasets, a number of potential uncertainties and issues of scale have emerged. For example:

- it was found that as the spatial resolution of the UKIAM increased, the resolution of wind-roses utilised by the atmospheric model, FRAME, also had to be increased accordingly [9];
- some localised spatial issues have emerged in relation to 'in-cell' deposition of NH_3, which becomes significant at 5 km model resolution [10]; and
- the more detailed UK data allows the UKIAM optimisation to include critical loads, deposition and exceedance in relation to specific ecosystems [11, 12], whereas ASAM was dependent upon *average* deposition over grid squares and total accumulated exceedance [13].

Further issues arising from the (dis)aggregation of data required for cost-curve generation are discussed below.

3. ATMOSPHERIC DISPERSION

The FRAME (Fine Resolution Atmospheric Multi-species Exchange) model is an atmospheric transport model used to

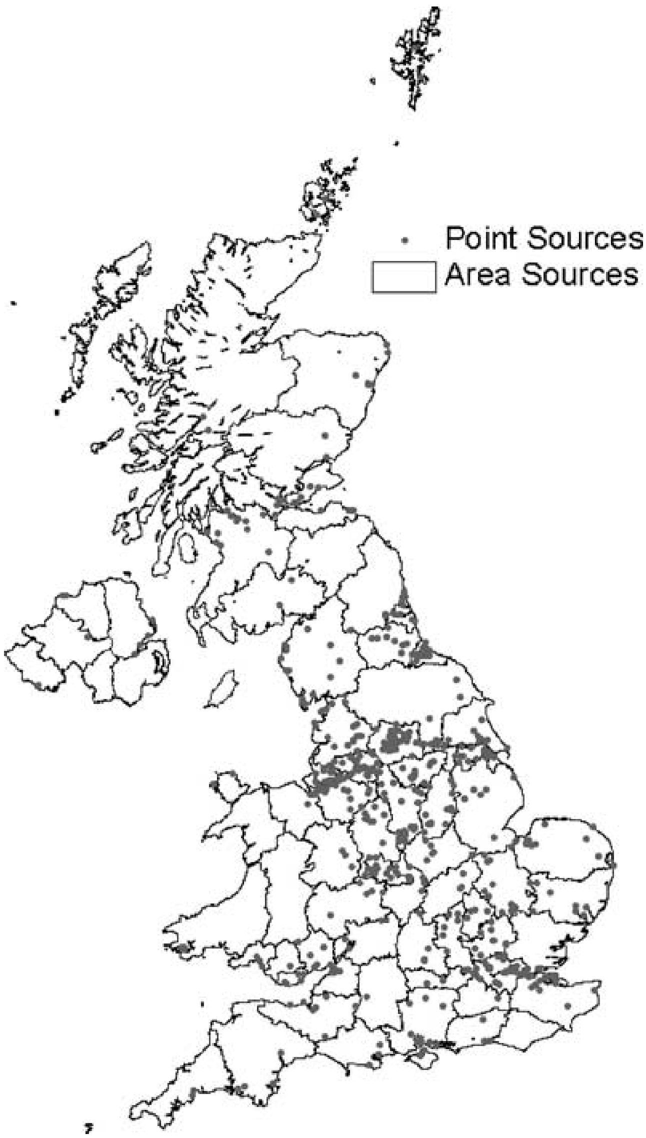


Fig. 3. Area sources (counties) and point sources. Only a selection of the most significant major point sources is treated explicitly by the UKIAM, the remainder being incorporated into the appropriate area source. (Point source data provided by NAEI).

assess the long-term annual mean deposition of sulphur and both oxidised and reduced nitrogen over the United Kingdom. It has also been adapted to produce SO_4, NO_3 and NH_4 concentrations. A detailed description of the FRAME model is provided by Singles and others [14]. Fournier and others [15] describe the development of a parallelised version of the model with an extended domain that includes Northern Ireland and the Republic of Ireland.

The domain of the model covers the British Isles with a grid resolution of 5 km and grid dimensions of 172×244. Input gas and aerosol concentrations at the edge of the model domain are calculated from a larger scale European simulation using the model of Transport over Europe of Reduced Nitrogen (TERN) [16], which, as a predecessor of FRAME, has a very similar structure, and has been modified to run as a Lagrangian model over the entirety of Europe with a 150 km scale resolution. FRAME is a Lagrangian model that considers an air column moving along straight-line trajectories. The atmosphere is divided into 33 separate layers with variable thickness, varying from 1 m at the surface to 200 m at the top of domain. Separate trajectories are run at a 15° resolution for all grid edge points. A climatological wind rose is used to give the appropriate weighting to directional deposition and concentration for calculation of total deposition and average concentration.

Table 1. User selectable options for the UK Integrated Assessment Model.

Model setting	Options
Simulation mode	➢ Scenario mode ➢ Optimisation mode (incl. scenario)
Optimisation mode	➢ Acidification, eutrophication, or both ➢ Acid Neutralising Capacity (freshwater only) ➢ Exposure (PM_{10})
Optimisation mechanism	➢ $\Sigma\delta$ *Deposition* ➢ $\Sigma\delta$ *Exceedance* (lookup tables or ANC) ➢ $\Sigma\delta$ *Exposure* (particulates)
Pollutant	➢ NH_3, NO_X, SO_X and/or PM_{10}
Sources	➢ Area sources (counties) ➢ Major point sources (MPS)
Ecosystems	➢ Woodland (coniferous/deciduous) ➢ Grass (acid/calcareous) ➢ Heathland ➢ Freshwater ➢ ALL
Emissions Sectors	➢ ALL

Emissions of ammonia are estimated for each 5 km grid square using national data of farm animal numbers (cattle, poultry, pigs and sheep) as well as fertiliser application, crops and non-agricultural emissions (including traffic and contributions from human sources, wild animals etc). Emissions of SO_2 and NO_X are taken from the National Atmospheric Emissions Inventory, NAEI [17].

NH_3 is emitted into the lowest layer, with SO_2 emissions being mixed into the lowest 300 m and NO_X emissions into the lowest 100 m, or at a pre-calculated height for major point sources. Diffusion of gaseous and particulate species in the vertical is calculated using K-theory eddy diffusivity and solved with a Finite Volume Method. The chemical scheme in the model includes gas phase and aqueous phase reactions of oxidised sulphur and oxidised nitrogen and conversion of NH_3 gas to ammonium sulphate and ammonium nitrate aerosol. The model employs a constant drizzle approach using precipitation rates calculated from a climatological map of average annual precipitation for the British Isles. Wet deposition of chemical species is calculated using scavenging coefficients taken from the literature, with account taken for the orographic increase in wet deposition due to the seeder-feeder effect. This is a very important factor for sensitive upland areas of the UK.

Dry deposition of NH_3 is calculated individually to five different land categories (arable, forest, moorland, grassland and urban) using a canopy resistance model. The deposition velocity is generated from the sums of the aerodynamic resistance, the laminar boundary layer resistance and the surface resistance. Dry deposition of SO_2 and NO_2 is calculated using maps of deposition velocity derived by the CEH dry deposition model [18]. Other species are assigned constant values of deposition velocity. The model code is written in High Performance Fortran 90 and executed in parallel on a 4-processor workstation. The overall budgets for, and spatial distribution of dry and wet deposition of each pollutant compares favourably with monitoring data from the UK and with EMEP model results [19].

Aerosol concentrations of sulphur and nitrogen (SO_4, NO_3 and NH_4) are calculated simultaneously, providing the UKIAM with maps of secondary particulate matter, directly linking acid emissions abatement measures with effects upon population exposure to PM_{10}. However, the FRAME model does not address primary PM_{10}, so the PPM model [20] – developed for integration with ASAM, but adapted to the UK – has been used to generate source-receptor matrices for primary particles. This model is simpler than FRAME as it does not include chemistry, and assumes uniform mixing in the vertical. It can distinguish between $PM_{2.5}$ and PM_{10}, with greater gravitational settling of the latter, and maintains transitions between dry and wet periods along trajectories, but there is no allowance for orographic enhancement.

These output data from FRAME and PPM (spatialised across a 5 km UK grid) represent the key datasets required by the UKIAM in order to maintain the linkages between pollutant abatement strategies and their effects upon acidification, eutrophication and particulate concentrations. These data fall into the following categories:

- *Deposition maps* describing the total deposition (SO_X, NO_X, NH_3) from all sources (see Fig. 4, for example).
- *Deposition footprints*, describing the *change* in deposition due to emissions reductions of 70%, 50% & 30% (SO_X, NO_X, NH_3, respectively) from the 1996 reference scenario for each area source. These footprints are utilised by the UKIAM to generate *source-receptor matrices* (SRM) for each source and pollutant combination describing the deposition & concentration reductions due to a 'unit' change in emissions, thus, for example:

$$SRM_{x,y}^{S,P} = \frac{Deposition_{footprint}^{S,P}}{Reduction^{P} * Emission^{S,P}},$$

where P is the pollutant & S is the source

Using $SRM_{x,y}^{S,P}$, the deposition resulting from the abatement from any given source can be calculated by:

$$Deposition_{x,y}^{P}(t) = Deposition_{x,y}^{P}(t-1) - (SRM_{x,y}^{S,P} * \delta Emission^{S,P})$$

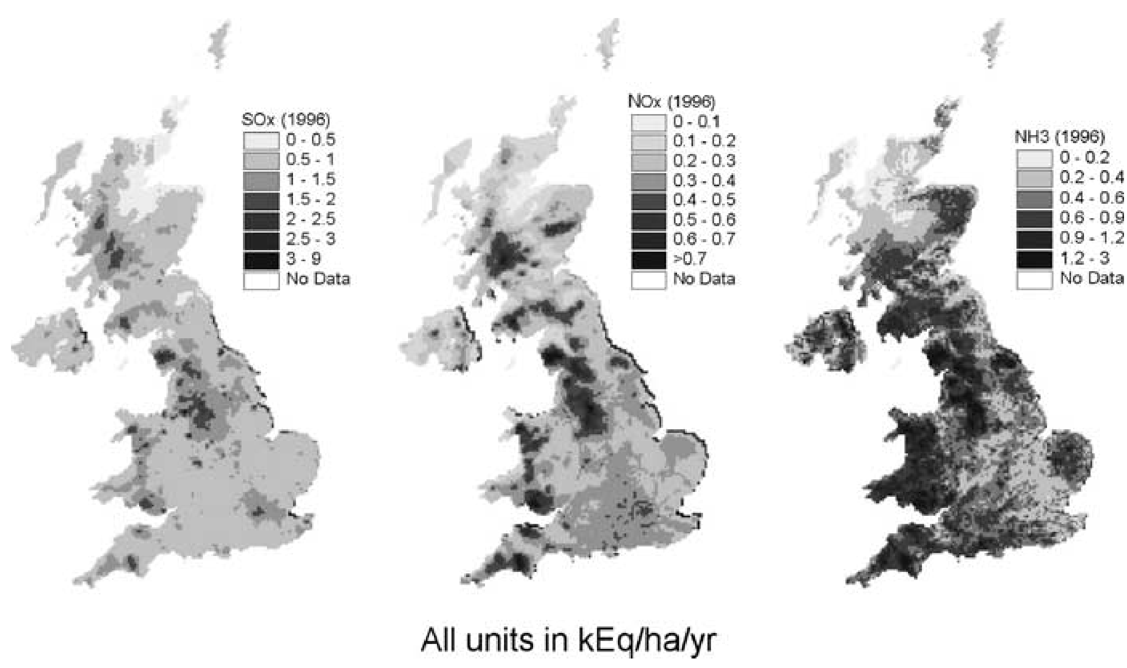
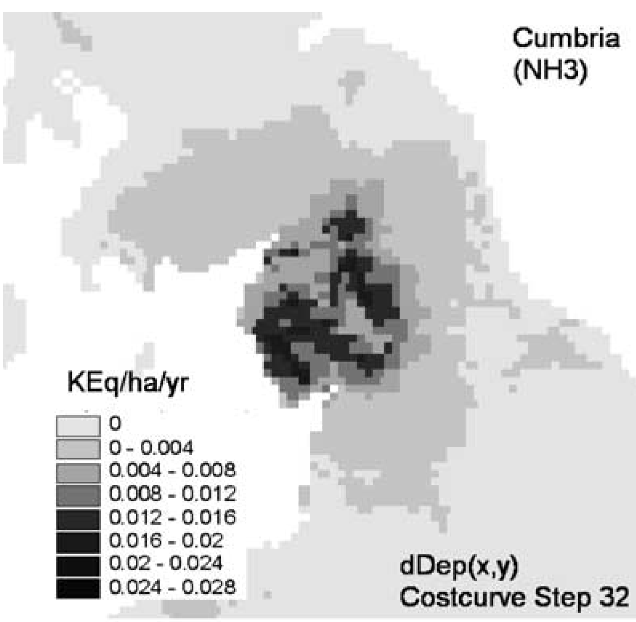


Fig. 4. Total deposition maps generated by FRAME, from all sources for SO_X, NO_X and NH_3; based upon the 1996 'reference' emissions data.

- Equivalent *concentration maps* of secondary particulates (SO_4^{--}, NO_3^-, NH_4^+), and primary particulates with source-receptor matrices calculated in a similar manner to deposition using FRAME and PPM.
- Vegetation specific deposition maps (woodland & moorland etc).

These datasets provide the mechanism for translating a specific abatement measure from a given source (either area or point) into a spatialised deposition pattern which can be used to adjust the overall deposition (or concentration) pattern following implementation of that measure. For any given reduction of emissions a reduction in deposition can thus be calculated using the SRM, with corresponding changes in exceedance of critical loads for each individual ecosystem, or in population exposure. The direct effect of an abatement measure can be described (see Fig. 5, for example, which describes the direct effect of an NH_3 abatement measure, and the change in emissions and cost if implemented), and used to derive the corresponding "benefit" ascribed to such a reduction in exceedance, reflecting for example the relative importance attached to specific sites or ecosystems.



County#:	*44 (Cumbria)*
Costcurve step:	*32*
Total emissions (Cumbria):	*6028.33 T/yr*
δEmissions:	*256.56 T/yr*
Total Cost (Cumbria):	*£3,585,054*
δCost:	*£1,385,429*
Agricultural sector:	*Dairy_Cattle*
Process:	*Slurry_Application_on_Grass*
Action:	*Closed_Slot_Injection*

Fig. 5. Deposition footprint and associated data for NH_3 abatement measure 32 for Cumbria.

4. ECOSYSTEM CRITICAL LOAD EXCEEDANCES (*AXEED/NUTE*)

A critical load is defined as: '*A quantitative estimate of the exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge*' [21].

The amount of deposited pollutant in excess of the critical load is termed the exceedance. Reducing the exceedance of critical loads is one of the main aims of international agreements to curb transboundary air pollution, such as the UNECE Protocol to Abate Acidification, Eutrophication and Ground-level ozone (1999), and the EC National Emission Ceilings Directive (2001). The effect of the same magnitude of exceedance on a sensitive ecosystem with low critical load, and on a less sensitive one with higher critical load, is likely to be far greater on the former. Hence in work with ASAM we explored the use of benefit functions that assumed that damage was proportional to the ratio of the exceedance to the critical load, hence putting more emphasis on reduction of deposition in sensitive areas [22]. These ideas are being explored further with UKIAM, including extension to the use of dynamic modelling of critical loads and recovery times for fresh-waters.

The critical loads for UK habitats are calculated and mapped by the National Focal Centre (NFC) for Critical Loads, at CEH Monks Wood, producing maps at a 1 km resolution, consistent with the resolution of national-scale soils data. Based upon these data, exceedances (both acidification and eutrophication) can be calculated which are dependent upon the levels of deposition of sulphur and nitrogen.

As noted above, ASAM handled critical loads by using aggregated isolines specifying the *average* accumulated exceedance for each 150 km EMEP grid cell [23]. These aggregated isolines capture the type and extent of ecosystems in the grid cell but are unable to explicitly distinguish between ecosystems, or the differential rates of deposition upon them. The critical loads methods used by the UNECE continue to provide the basis of the exceedance calculations within the UKIAM, but the representation of critical load exceedances has been extended to take advantage of the increased model resolution (5 km), enabling the UKIAM to explicitly optimise abatement strategies towards protecting different types of ecosystem.

The AXEED (acidification) and NUTE (eutrophication) programs calculate exceedances at 5 km resolution – for compatibility with the UKIAM – based upon 1 km critical loads and ecosystem data. The UKIAM uses these accumulated exceedances to assess the 'benefit' of an

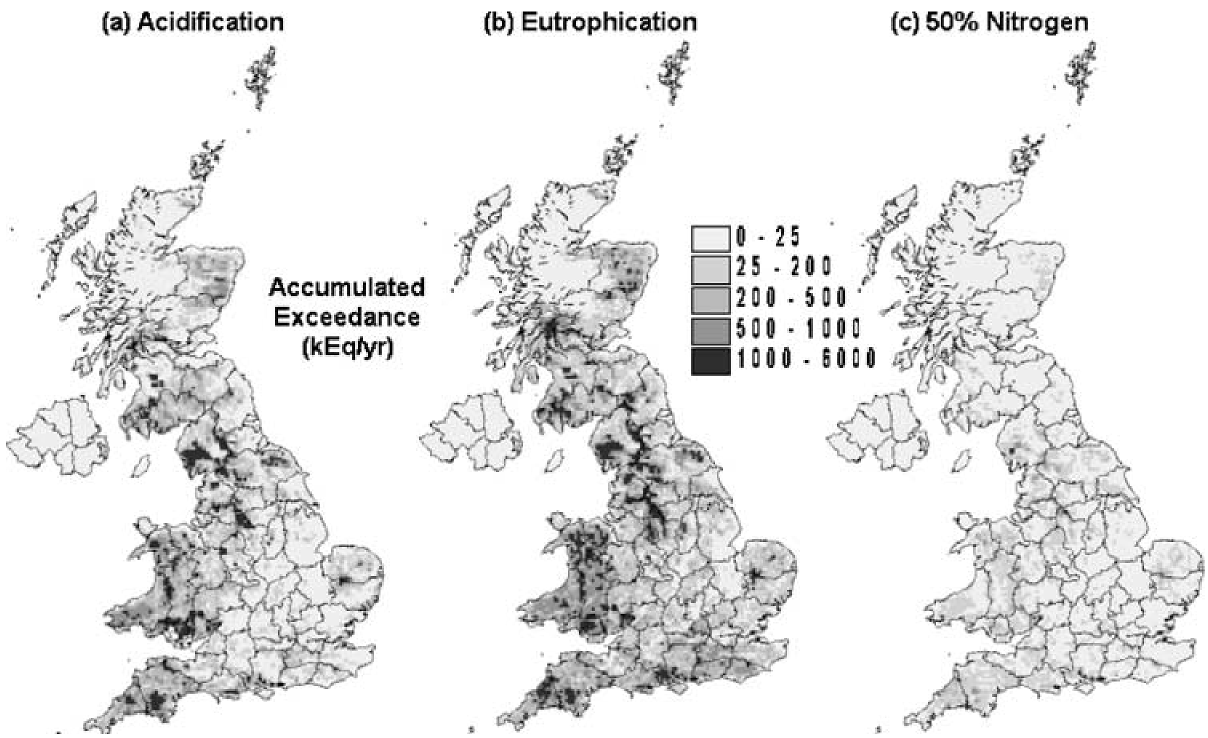


Fig. 6. Accumulated exceedances generated by AXEED/NUTE (based upon the reference (1996) scenario) for (a) acidification, (b) eutrophication, and (c) eutrophication after a reduction of N deposition by 50%.

abatement measure. *Accumulated Exceedances* (AE) are a measure of exceedance that takes into account both the magnitude of exceedance and the ecosystem area exceeded, calculated as:

$$AE\ (\text{kEq/yr}) = Exceedance\ (\text{kEq/ha/yr}) * Area\ Exceeded\ (\text{ha})$$

Based upon accumulated exceedance and marginal costs of emission abatement measures, benefit functions have been defined to prioritise the implementation of individual abatement measures (see below). Environmental benefits of emission abatement are based on reductions in exceedances with respect to acidification and eutrophication integrated over the UK.

Within these data there is information relating to:

- 7 ecosystem types (acid & calcareous grassland, heathland, coniferous & deciduous woodland, freshwaters, and 'all' ecosystems)
- Ecosystem area, exceeded area, %exceeded area, and accumulated exceedance

In order to avoid the excessive computational overheads involved in recalculating exceedances for each *potential* abatement step, some pre-processing of exceedance data is carried out prior to optimisation. This involves the generation of lookup tables giving exceedances for incremental percentage reductions in both sulphur and nitrogen deposition in each grid cell, which are then used to calculate the benefit functions during optimisation. Exceedances can be recalculated upon implementation of the next abatement measure.

Some example outputs showing the effects of the 'reference' (1996) emissions upon accumulated exceedances for both acidification and eutrophication are presented in Figure 6. The accumulated exceedances shown relate to all ecosystems; the UKIAM generates equivalent outputs for each ecosystem selected for optimisation.

5. ABATEMENT MEASURES AND COST-CURVES

Information on abatement measures and costs are assembled in the form of cost curves for each pollutant in each county and for each major point source (MPS). Cost curves, instead of using a random list of measures, reduce computing time in optimisation mode by automatically ordering measures according to increasing marginal cost of abatement. Transport emissions are treated separately and reduced nationally (rather than in counties). Other sectors can be separated out in a similar manner for regional or national abatement. Annualised costs and efficiencies are used, partly based on those used in the RAINS model and partly on more specific data for the UK [24], especially for primary PM_{10} [25].

Major point sources were selected from a complete list of UK point sources in the NAEI [26] as the major contributors to emissions of SO_X, NO_X and PM_{10}. Point sources are geo-located in their respective counties, so that emissions from the county can be adjusted accordingly to distinguish the point source. The different origins of the data forced the creation of different cost curves for SO_X, NO_X and PM_{10} and for power stations and process plants.

For *power station point sources* enough data on the details and characteristics of the power stations was available through the NAEI. Therefore, the unit costs for power stations were created individually following the methodology described in the IIASA interim reports [27]. For PM_{10}, the methodology followed is described by Lükewille and others [28].

For *process plant point sources* (iron and steels plants, cement plants etc.) and area sources cost-curves were based on national cost-curves compiled by AEA Technology [29]. Disaggregation to derive county cost curves for area sources was performed on a sectoral basis, using the geographical distribution of emissions within each sector in the NAEI national database [30].

5.1. Ammonia Cost Curves

Cost curves for ammonia were treated separately from NO_X, SO_X and PM_{10} since ammonia emissions come predominately from agricultural sources (see, for example, Cowell and ApSimon [31]).

The MARACCAS (*Model for the Assessment of Regional Cost Curves for Abatement Strategies*) model was developed to derive UK costs for successive levels of abatement of ammonia emissions from agriculture during development of the Gothenburg protocol [32]. The efficiencies and applicability of abatement measures were specified based on European and UK experience, taking account of typical UK agricultural practice but without regional variations. Current work on the NARSES (*National Ammonia Reduction Strategy Evaluation System*) project is providing detailed information across the UK from which the variability in efficiency and applicability can be derived more accurately for different locations [33].

In order to generate geographically disaggregated data MARACCAS has been adapted to calculate separate cost curves for each county of England and Wales, as well as for the whole of the UK. It should be noted that there are differences between the MARACCAS emissions and those of the NAEI, although the totals agree within a few kilotons; MARACCAS neither includes the emissions from hard standings, nor the efficiencies and costs for reducing these – for example, by washing off into storage. There have also been some systematic changes in agricultural practices which are not reflected yet in MARACCAS, such as an increased proportion of pigs kept outside, and the increased burning of poultry wastes, together with uncertainties about future caged poultry systems under new legislation, the effects of BSE and Foot-and-Mouth, and other extraneous influences. These uncertainties are being addressed as part of the NARSES project.

6. ABATEMENT OPTIMISATION

Abatement optimisation and the evaluation of weighted benefit functions represent the integration of the various models and datasets (Fig. 1) to suggest optimal abatement strategies using various options.

A *least marginal cost* ordering of abatement measures is already implicit in the ordering of the cost curves prior to optimisation. One mode of operation therefore is to derive the least cost way of reaching specified emissions targets for the different pollutants, and examine the corresponding change in environmental protection without taking this into account in selecting the abatement measures. By comparison, the more usual mode of operation selects abatement steps sequentially as described above according to benefit to cost ratios. In its simplest form the benefit is equated to the direct effect of abatement in terms of overall reduction in deposition or exceedance for ecosystems, or concentrations or exposure for human health. Alternatively more complex benefit functions are used bearing a closer relationship to damage avoided, and relative values ascribed to different effects, or reflecting other preferences.

Thus weightings are incorporated into the benefit function during optimisation. Weightings can be specified for all sources, emissions sectors, pollutants, ecosystems and receptors (x, y) included for a given optimisation, in a manner which provides maximum flexibility for setting up the model for specific policy scenarios. For example, in the outputs presented below, one scenario has been run where *all* sources were abated whereas in the other a zero weighting was applied to major point sources, effectively excluding them from abatement. Similarly, investigations may require a lesser or greater emphasis on reducing emissions from specific SNAP1 sectors (e.g., transport or power generation), or on reducing NO_X emissions in preference to SO_X (e.g., in conjunction with possible reductions of non-UK sources such as shipping). Simultaneously, weightings can be applied to receptors and effects; more importance may be placed on reducing acidification than eutrophication, or on protecting one ecosystem in preference to another, or protecting particular sites such as SSSI's.

The ability to optimise with respect to exposure to particulates allows parallel scenarios to be run to assess similarities or differences between abatement strategies aimed towards reducing exposure and those for reducing acidification; similarities can be expected due to linkages through secondary aerosol concentrations (SO_4, NO_3 & NH_3).

Although possible, it is unlikely at this stage that a scenario would involve attempts to weight reductions in human exposure against protecting ecosystems since the units of the benefit function would be incomparable. Assessments would more usefully be directed at comparing the impacts of the strategies arising from alternative optimisation scenarios.

Figure 7 describes the operation of the UKIAM optimiser. In order to select the next measure to be implemented, all cost-curves are scanned to evaluate the benefit of implementation of the next abatement measure. Using the predetermined source-receptor matrices the direct effect of the measure is calculated (*δDeposition*) and then the indirect effect (*δExceedance* etc.) depending upon the optimisation mode. A weighted benefit is calculated simultaneously, and the benefit to cost ratio compared with that of the 'best' measure identified so far. When all cost-curves have been assessed in this way, the 'best' measure is implemented and the cycle repeated. Optimisation continues until either a pre-specified target has been achieved or all measures have been implemented.

As indicated above optimisation can be carried out in several different ways. The *deposition* mode responds to the direct changes in pollutant deposition, equivalent to minimising anthopogenic pressures irrespective of the environmental capacity reflected in critical loads. This mode provides a useful benchmark against which the other optimisation modes can be assessed. All units are in

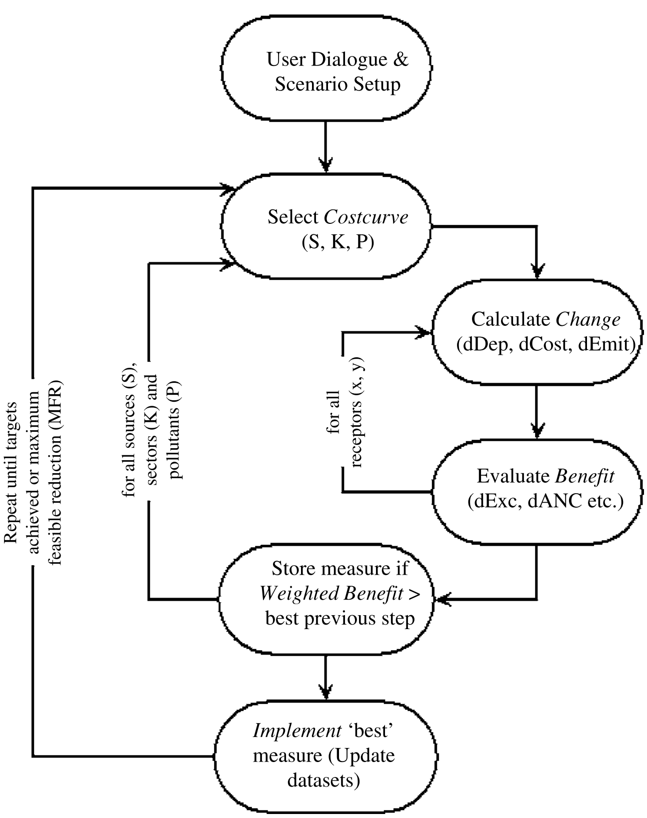


Fig. 7. Flowchart describing the optimisation processing loops at the core of the UKIAM.

kEq/ha/yr in order to ensure compatibility between the effects of the different pollutants, except particulates, which are in units of $\mu g/m^3/yr$. The optimisation modes available are:

- *Deposition*
  This is the benchmark optimisation mechanism, based upon the cost of an individual abatement step and its' deposition footprint. Representing the *direct* effect of a measure, this mode can, for example, be utilised with weightings for SSSI's or other receptors where critical loads are not applicable. The benefit function is given by:

$$fBenefit^{\Sigma\delta Dep}(AbateStep_{S,K,P}) = \frac{\sum_{(E=1)}^{n}\left[W_E * \sum_{(R=0,0)}^{x,y}(W_R * \delta Dep_{P,R,[E]})\right]}{\delta Cost(AbateStep_{S,K,P})} * W_{S,K,P}$$

  where: S = source, K = sector, P = pollutant, E = ecosystem, R = receptor(x,y), and W_n = weightings

- *Accumulated Exceedance*
  CEH Monks Wood have provided two programs (AXEED & NUTE) which will calculate acidification and eutrophication exceedances from deposition data output by the UKIAM. These programs are used to generate exceedance lookup tables for changes in deposition, thus overriding the need to re-calculate the exceedances every time for every potential abatement step. The benefit function is given by:

$$fBenefit^{\Sigma\delta Exc}(AbateStep_{S,K,P}) = \frac{\sum_{(E=1)}^{n}\left[W_E * \sum_{(R=0,0)}^{x,y}(W_R * \delta Exceed_{P,R,E}^{Acid|Eut})\right]}{\delta Cost(AbateStep_{S,K,P})} * W_{S,K,P}$$

- *Exposure (Ecosystem independent)*
  For the optimisation of the abatement of particulates (PM_{10}), the aerosol concentrations are required. If secondary particulates are to be included then SO_X, NO_X and NH_4 concentrations are also required. In addition, population densities are used to assess the *exposure* to particulates, thus defining the benefit function to be used for PM_{10}. The benefit function is given by:

$$fBenefit^{\Sigma\delta Conc}(AbateStep_{S,K,P}) = \frac{\sum_{(R=0,0)}^{x,y}(W_R * \delta Conc_{P,R} * Pop\delta ensity_R)}{\delta Cost(AbateStep_{S,K,P})} * W_{S,K,P}$$

- *Acid Neutralizing Capacity (Freshwater only)*
  An additional optimisation mechanism has been implemented for fresh water bodies, namely the utilization of Acid Neutralizing Capacity (ANC). Similar in approach to the use of critical loads, this mechanism provides a way of assessing the (dis)benefit to fresh water, and, where the ANC passes the zero threshold, we can begin to address recovery times rather than purely the damage caused. For further information see Jenkins and others [34]. Figure 8

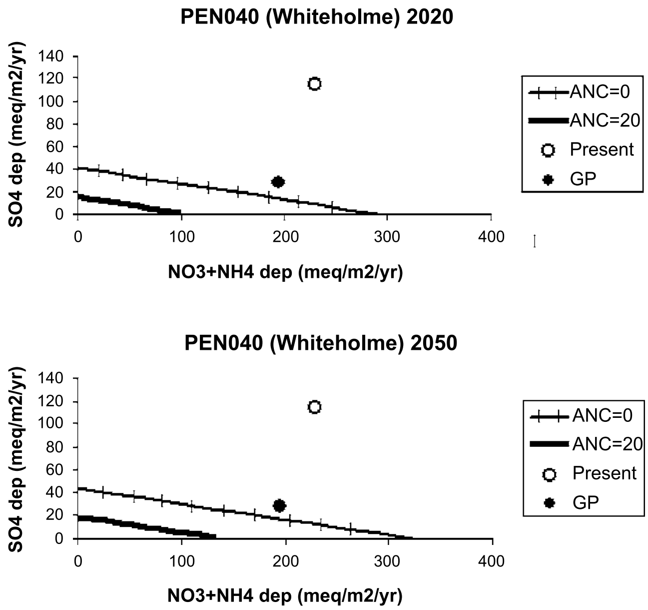


Fig. 8. Example of the ANC Isolines to be utilised as an optimisation mechanism to assess the potential recovery of fresh waters.

presents examples of the ANC isolines to be used for optimisation. The benefit function for mode 4 is given by:

$$fBenefit^{\Sigma\delta ANC}(AbateStep_{S,K,P}) = \frac{\sum_{(R=0,0)}^{x,y}(W_R * \delta Exceed^{ANC}_{P,R,WATER})}{\delta Cost(AbateStep_{S,K,P})} * W_{S,K,P}$$

There are several issues in relation to these optimisation modes that must be addressed:

- The use of source-receptor matrices for calculating the change in deposition ($\delta Dep_{R,P}$) assumes a degree of linearity between the emissions reduction and the deposition; tests are currently ongoing to assess the validity of such linearity assumptions by regenerating the final deposition levels produced by the UKIAM using FRAME.
- Similar linearity assumptions are made with aerosol concentrations ($\delta Conc_{R,P}$). In addition, the UKIAM currently assumes that population densities are static. Additional complications emerge if populations are assumed to be mobile, and located particularly in urban areas where urban air quality is of importance; ongoing work on the DAPPLE and TiGrESS projects [35, 36] will address some of the spatio-temporal issues associated with these complexities to determine the feasibility of incorporation into later versions of the UKIAM.
- Calculation of changes in exceedance ($\delta Exceed_{R,P,E}$) make use of lookup tables generated for incremental reductions in sulphur and nitrogen deposition thus overcoming the need to recalculate for every potential abatement measure in every optimisation cycle. Thus, changes in exceedance can be calculated by interpolating the lookup table from the current exceedance. Linear interpolation is currently assumed to be adequate (see, for example, Heywood and others [37]), with tests ongoing to validate this assumption.
- Finally, mode 4 (Acid Neutralising Capacity) is only applicable to bodies of freshwater, and exceedances are calculated in relation to isolines calculated using the MAGIC model [38]. Work is ongoing involving the development of recovery functions which become significant when the deposition levels fall below $ANC = 0$, but have yet to achieve $ANC = 20$ [39].

Encompassing all of these issues are problems of spatial resolution. These include the aggregation of emissions/costs for area sources and of 1 km resolution critical loads to 5 km resolution accumulated exceedances, the effects of localised NH_3 deposition *within* individual 5 km grid cells [40], and the effects of urban exposure and demographic changes within the timeframe of the specified scenario.

It should be noted that there are additional uncertainties involved in using the critical loads data, such as the fact that terrestrial critical loads are based upon the dominant soil type in each 1 km square; other soils may be present that may have higher or lower critical loads [41].

7. SIMULATION OUTPUT

The results presented here are illustrative only to highlight the type of information generated by the UKIAM, as they are based on very preliminary data. Verification of the 2000 baseline data is ongoing, and will be used for more specific scenario analysis during review of the Gothenburg protocol in 2004/2005.

A variety of test simulations have been carried out for various combinations of sources, pollutants and ecosystems. These preliminary simulations have been documented elsewhere [42]. The UKIAM will produce outputs in a number of formats, such as:

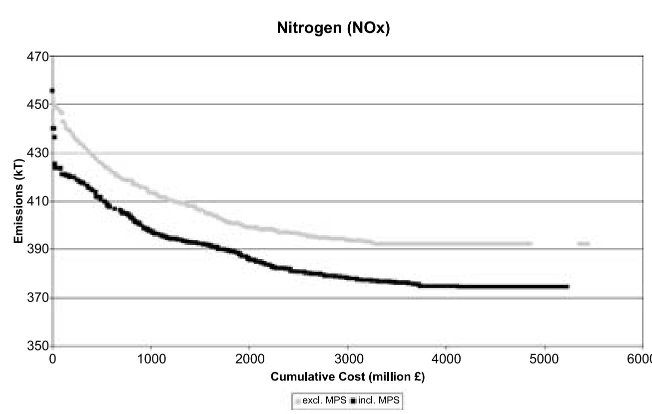


Fig. 9. An example of the emissions/cost graphs output by the UKIAM. The graphs shown correspond with the outputs shown in Figure 10.

- Maps of deposition, concentration, exceedance etc. (see, for example, Fig. 4 & 6), which can be output at user specified intervals;
- Cost/emission graphs, such as shown in Figure 9, highlighting the cost effectiveness of abatement throughout the optimisation;
- Details of individual abatement measures (if required) in order to examine specific details of any given abatement step (e.g., Fig. 5); and
- various other formats which highlight particular characteristics of interest to the user (see Fig. 10).

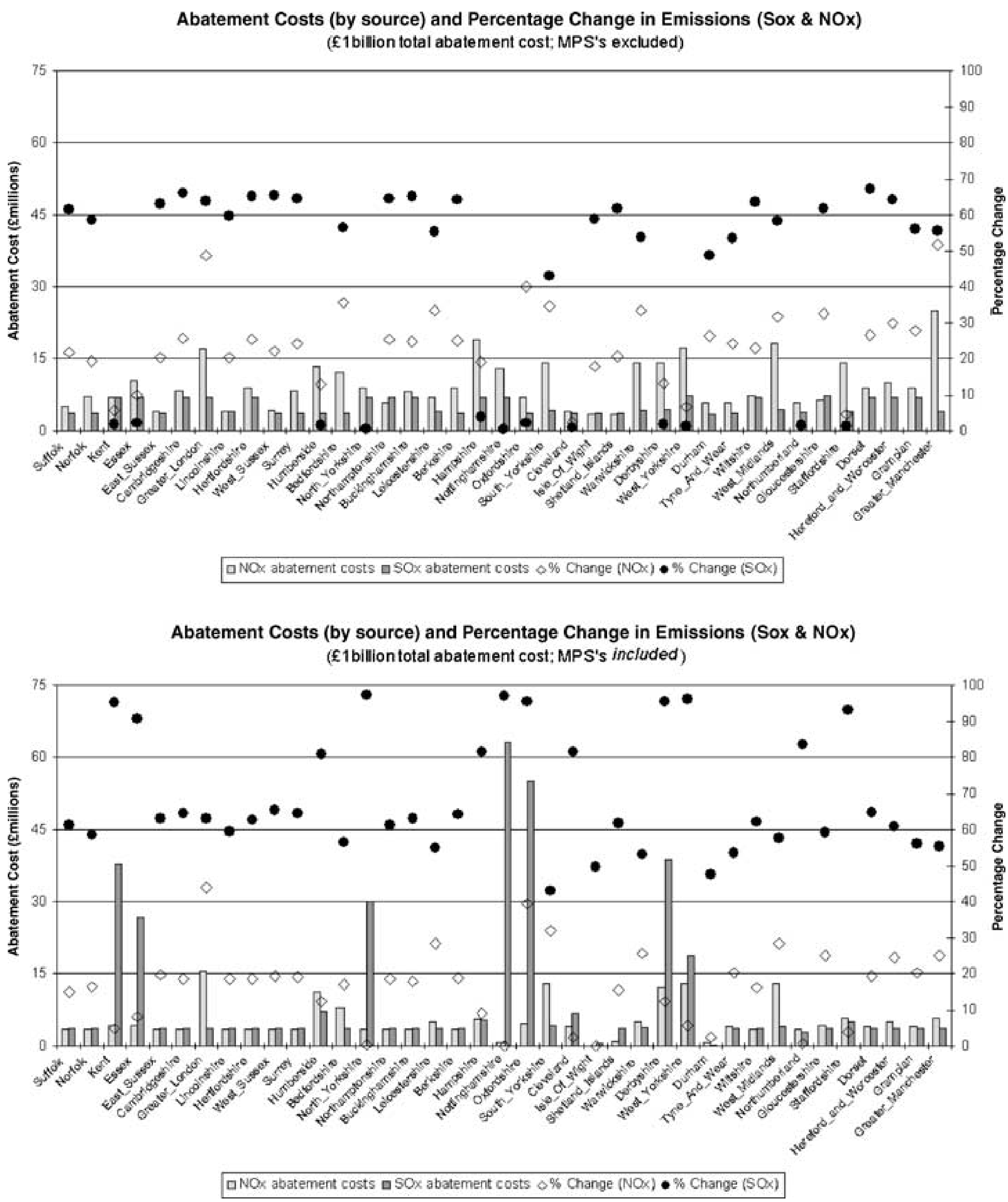


Fig. 10. An alternative representation of the SO_X and NO_X abatement costs in relation to the percentage change observed in emissions from each source (MPS's are included within the area source). Separate graphs are presented for optimisations with (a) MPS's excluded and (b) MPS's included.

The graphs shown in Figure 9 give an indication as optimisation progresses of the cumulative costs of abatement in relation to remaining total emissions. The steep part of the graph shows how the most cost-effective measures are implemented first with the flat part highlighting expensive measures in relation to the emissions reduction; beyond approximately 3–3 1/2 billion expenditure there is little further reduction in emissions. Total emissions are significantly lower when major point sources (MPS) are included in the abatement, with large reductions in MPS emissions implemented first. However, this output does not distinguish between sources, nor does it indicate the relative changes in cost or emissions in different regions.

Figure 10, however, highlights the spatial variations, showing two optimisations – based upon *accumulated exceedance* – where the only difference is the inclusion (or exclusion) of major point sources from the optimisation; since preliminary datasets are used, care should be exercised in interpreting these outputs. Both abatement costs and the percentage change in emissions are shown for both SO_X and NO_X. Ammonia is not abated in this scenario, and only a selection of the sources (counties) is presented in order to increase the clarity of the outputs for this paper.

It is clear that there is a significant difference resulting from the inclusion of MPS's. For example, whereas Nottinghamshire and Oxfordshire show a negligible change in SO_X emissions in Figure 10a, the inclusion of MPS's results in an approximate 95% emissions reduction with a corresponding marked increase in their abatement cost at the equivalent total annualised abatement cost of £1billion.

Also evident is a marked swing towards SO_X abatement when MPS's are included in the optimisation, reflecting the generally higher costs of NO_X abatement measures. If necessary, user defined pollutant weightings can be applied to the optimisation if the policy scenario being assessed requires a different emphasis – for example, when attainment of national emission ceilings is reached for one or more pollutants.

8. CONCLUSIONS & DISCUSSION

In this paper we have described the development of a new UK scale integrated assessment model that can be used to investigate strategies for the attainment of national emission ceilings. The model can optimise abatement strategies in relation to acidification, eutrophication, and human-exposure to particulate PM_{10}, with reference to deposition of sulphur and nitrogen (oxidised and reduced), and concentrations of both secondary and primary particles. The UKIAM combines sector specific emissions, atmospheric transport and deposition, ecosystem specific critical load exceedances, and pollution abatement costs (annualised) to determine optimised abatement strategies using benefit functions tailored to the optimisation mode selected.

This model development has used preliminary datasets. However, all datasets are being continually reviewed and updated, and as new datasets become available from FRAME, new critical loads are defined encompassing additional ecosystems [43], and revised abatement measures and scenarios are presented [44], these data will be integrated into the UKAIM. The importance of maintaining consistent baseline data in Integrated Assessment Modelling cannot be overstated; such baselines must reflect both the current empirical and modelled data and the emissions policies and activity projections at that time. (The significance of this baseline can be observed in Fig. 2 where emissions are noticeably different in 1996 and 1998).

The UKIAM complements European scale integrated assessment modelling by providing greatly increased spatial resolution in assessment of both abatement measures and the effects of emission reductions *within* the domain of a single country. The UKIAM extends the capabilities of ASAM since it supports a flexible and generic internal architecture providing two key characteristics:

- Different types of source (area, point, national & non-UK) and pollutants (NH_3, SO_2, NO_X, primary & secondary PM_{10}) can be distinguished, abatement strategies can be oriented towards protecting specific ecosystems, and with the ability to address exposure to particulates, provides an explicit link – through secondary aerosols – between abatement strategies designed to reduce acidification and those to reduce population exposure; and
- The flexibility of the UKIAM with regards to the use of source-receptor matrices facilitates the incorporation of additional or different sources (e.g., roads), and receptors such as urban areas, so that urban air quality issues can be integrated with the other effects already covered.

Further enhancements and development are ongoing in a number of areas. These may be summarised as follows:

- Further development of ANC optimisation to define benefit functions which can also capture recovery times in freshwaters, implementation of ASAM optimisation functionality, and the inclusion of $PM_{2.5}$ dynamics for enhanced exposure assessments;
- Evaluation of micro-scale dynamics, including 'in-square' NH_3 deposition [45], and the incorporation of SSSI definitions into the optimisation to facilitate the assessment of the effects of emitters either surrounded by or surrounding ecologically or biologically sensitive areas;
- Assessment of the multi-scalar dynamics driving O_3 and VOC concentrations and abatement measures [46], with a view towards potential nesting of the UKIAM with ASAM and/or urban scale abatement modelling; and
- Further development of cost-curves to facilitate both simultaneous abatement of different pollutants where measures affect the emissions of multiple pollutants, and new technologies and non-technical abatement measures.

ACKNOWLEDGEMENTS

This work was funded by the Department for Environment Food and Rural Affairs (DEFRA) under Contract No EPG1/3/167 (Analysis of abatement strategies – Phase III). This paper was presented at the 28th meeting of the UNECE/CLRTAP Task Force on Integrated Assessment Modelling, 7–9 May 2003, Haarlem, The Netherlands (http://www.unece.org/env/tfiam/).

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