Issues of Scale in *Nested* Integrated Assessment Models

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Abstract: Integrated assessment models have been used to explore cost effective abatement strategies in connection with negotiations on the Gothenburg protocol under the UN/ECE Convention on Long Range Transboundary Air Pollution (CLRTAP). A variety of spatial and temporal issues must be addressed in order to model the multi-scalar processes involved and develop nested Integrated Assessment Models (*n*-IAM) useful both for further protocol negotiations and to address inter-relationships between local air quality, transboundary air pollution and climate change. We summarise the generic framework, highlighting the spatial characteristics of its' application to UK and European contexts, and identify the specific variations of the constituent models and data at each resolution. Encompassing NH_3, SO_2, NO_X, particulates, O_3 and VOCs, it is clear a *n*-IAM must capture dynamics both beyond and through the current scales implemented by the UKIAM and ASAM. Ammonia abatement becomes significant at the micro scale using non-technical measures and buffer zones, roadside NO_2 is important at the urban scale, and the dynamics of O_3 stretch from the urban scale to the hemispheric level, affecting the fates of VOCs and NO_X. Timescales implicit in dispersion models and empirical data, together with multi-scalar effects and policy scenarios must be mapped, and methodological approaches to critical loads and ecosystem recovery must be captured. At the UK National Focal Centre for Integrated Assessment Modelling work is ongoing linking the European scale ASAM and the national scale UKIAM, and progress is being made in linking these to global and urban scale integrated assessment models.

Keywords: UKIAM; ASAM; Nested Integrated Assessment Models; CLRTAP

1. INTRODUCTION

The integrated assessment models ASAM and UKIAM bring together information on emissions, atmospheric transport between sources and exposed areas or populations, criteria for environmental protection, and potential emission control measures and costs, in order to explore effective abatement strategies in connection with negotiations on the Gothenburg protocol under the UN/ECE Convention on Long Range Transboundary Air Pollution (CLRTAP) [UNECE 1979, 1999].

The flexible architecture employed by the UKIAM and by ASAM is described in detail by Oxley and others (2004). This architecture facilitates the assessment of abatement strategies for a number of pollutants (NH_3, SO_2, NO_X, and primary and secondary particulates) at different spatial scales. Additional pollutants can also be incorporated providing that data is available and consistent at the specified scale. However, pollutants such as NO_X, VOCs, O_3 and others affecting climate in complex ways introduces a number of multi-scalar issues to integrated assessment modelling. This paper identifies some of these issues and how to address them in a nested integrated assessment model (*n*-IAM).

ASAM [ApSimon *et al.*, 1994] has been applied using the same datasets as the RAINS model [Amann *et al.*, 1999], thus providing comparable results at the European scale for negotiations under the CLRTAP. The data utilised by ASAM includes atmospheric dispersion maps generated by the EMEP (50km) model [Simpson *et al.*, 2003], emissions data and costcurves through IIASA [eg, Cofala *et al.*, 1998], and critical loads data from across Europe verified by the Coordinating Centre for Effects at RIVM [Posch *et al.*, 2003].

The UKIAM utilises comparable data for pollutant dispersion generated by the FRAME (5km) and PPM models [Fournier *et al.* 2002; Gonzales del Campo, 2003], emissions from the NAEI [Dore *et al.*, 2003], costcurves from Entec (2003), and critical loads exceedance data from CEH (2003).

Table 1 summarises the use of these data by the UKIAM and ASAM, together with details about compatible global and urban scale models STOCHEM [Collins *et al.*, 1997] and USIAM [Mediavilla-Sahagun & ApSimon, 2003].

	STOCHEM	ASAM	UKIAM	USIAM
Scale	Global	150km (50km)	5km	1km
Atmospheric Dispersion	STOCHEM	EMEP	FRAME	ADMS
Emissions	Continental, N. Hemisphere	EMEP (50km), IIASA (county)	NAEI (1km,county,MPS)	NAEI (1km)
Abatement	NO_X, VOC, CO	IIASA (Sector/pollutant)	Entec (Sector/pollutant)	Vehicles
Effects	Tropospheric O_3	CCE (50km CL) MAGIC/VSD	CEH (1km CL, 5km Exc.) MAGIC	Air Quality, Exposure
Policy Use	Ozone/Climate	CLRTAP/Götburg	CLRTAP/NECD	Urban AQ

Table 1: Overview of data sources and policy use of model spanning urban to global scales

2. INTER-RELATIONSHIPS

When the integration of models spanning multiple spatial and temporal scales is considered, it is important first to identify some of the key linkages between both scales and the processes being modelled. This is necessary both for dealing with data flows between similar processes which have been defined at different scales, and for capturing the effects at the macro-scale of processes modelled at the micro-scale, and vice-versa.

Some of these linkages between scales have been examined in depth at the UN/ECE Workshop on linkages and synergies of regional and global emissions control [CLRTAP, 2003]. It is clear, for example, that acid (SO_2) abatement strategies at the local and regional scales affect climate dynamics at the global scale through the radiative forcing effects of sulphate and other aerosols [Dentener 2003; Johnson & Derwent 1996; Warren & ApSimon 2000a]. The complex responses to acid and GHG abatement measures are less clear and models describing scenarios of the resultant influences on climate and global temperatures appear to diverge beyond 50 years [Kram, 2003].

This divergence of scenarios may be the result of different methodologies or modelling techniques but it may also be suggesting possible non-linearities in the effects of combined abatement strategies through feedback processes involving land cover and soil and water quality. It is crucial, therefore, to ensure that the mapping of nested IAM's captures not only the spatial and temporal differences but also the methodological and modelling techniques used at each scale.

Linkages also exist between acid emissions and abatement and human exposure to secondary aerosols, which become more apparent as we move to national and urban scales [Warren & ApSimon, 2000b]. Such synergies may also be found with multi-objective strategies and multi-pollutant abatement measures, where comparable prioritisation of abatements may emerge for strategies aimed at reducing acidification or exposure to aerosols.

The multi-scalar effects of O_3 influence dynamics from the urban through to the global scales, responding to complex feedbacks in the atmospheric chemistry affected by emissions of NO_X, VOC's, CO and other precursor pollutants [Collins *et al.*, 2000]. The implication of this for IAM is the possible need for multi-scalar, multi-pollutant source-receptor matrices to be implemented in order that mapping of the effects of abatements can occur simultaneously at different spatial scales.

The crucial final component within IAM's is the deposition of acidic or eutrophic pollutants and the consequent effects on vegetation (important for both soil health and CO_2 sequestration), land cover and soil and water quality. See Füssel & van Minnen (2001) for examples of climate impact response functions for terrestrial ecosystems, and Mayerhofer and others (1999) for details of air pollution dynamics in response to climate change.

Nested IAM's must therefore be able to capture the multi-scalar dynamics and make the connection between the direct effects of abatement (emissions and atmospheric pollution), the second order effects (CL exceedances, soil acidity), and third order effects (water quality) which subsequently drive abatement policies.

3. SPATIAL SCALES

The spatial scales addressed by this paper range from the urban (1km), through national (5km), European (150km/50km) and global scales. We concentrate primarily upon the UK-European scales although reference is also made to the global scale STOCHEM model and urban scale USIAM.

3.1 European (50km) & UK (5km)

Table 1 provides an overview of the four models. Note that emissions are defined at both 50km and totals by country. The EMEP dispersion model is driven by the gridded emissions, whereas ASAM (and RAINS) assess abatement strategies based upon country emissions, thus precluding them from dictating to national governments where to abate emissions in order to comply with the Gothenburg protocol.

Equity between states during negotiations for Gothenburg protocol was also important and was easier to address if IAMs were driven by total emissions levels and the transboundary pollution levels. Thus, abatement strategies and emissions levels were assessed in relation to nation states, allowing each state to develop appropriate strategies to meet their negotiated commitments.

The UKIAM was developed for this purpose within the UK, requiring increased resolution to implement abatement strategies spatially; it is significant if a measure is implemented in the south or north of the UK [Oxley *et al*, 2004]. The same methodology has been used in UKIAM, substituting counties and a 5km grid for countries and a 50km grid, again allowing equity between regions to be maintained for policy purposes.

3.2 Sub-UKIAM (5km) & Urban (1km)

At the national scale some issues have already been identified which require an even finer model resolution. One relates to NH_3 dispersion which is localised and often *within* the same cell as the emissions source. Another involves urban scale exposure studies and the ability to handle urban 'hotspots' and population movement.

Regarding NH_3, local deposition (<5km) is often below the resolution of the UKIAM. Ongoing studies at the farm level suggest additional abatement measures such as buffer strips between intensive farming and sensitive ecosystems may provide a useful means of abatement [ApSimon *et al.*, 2003], with other investigations assessing how to represent 'in-square' dynamics statistically [Dragositis *et al.*, 2002].

Similar problems are found with urban scale exposure, where 'hotspots' along major roads and the dynamics of pollutant dispersion amongst street canyons cannot be addressed adequately at 5km resolution [Mediavilla-Sahagun & ApSimon, 2003, Colvile *et al.*, 2003]. Combined with the need to model and evaluate the effects of mobile populations for epidemiological studies of human exposure to aerosols, it is clear that further complications arise if urban scale assessments are to be incorporated into a nested IAM.

4. MAPPING

The architecture used by the UKIAM [Oxley *et al.*, 2004] captures emissions, dispersion of pollutants, deposition, environmental responses and pollutant abatement measures for multiple sources. The architecture is designed to be flexible and generic so that alternative spatial grids, pollutants and source-receptor matrices can be introduced.

With ASAM now using this architecture, mapping between ASAM and the UKIAM is simple, assuming of course that methodologies, models and data are compatible. Complications can still arise owing to differences such as orientation and geo-referencing of spatial grids or incompatibilities between the methodologies or data.

4.1 Technical

With this generic architecture the model can be implemented on any spatial grid, assuming that data and source-receptor relationships can be defined. However, the existing models may not be defined upon compatible grids with the result that mapping between grids becomes non-trivial. The UKIAM and UK urban scale models (eg. USIAM) are already defined using Ordnance Survey grids and can thus be directly mapped.

The mapping between the UKIAM 5km grid and

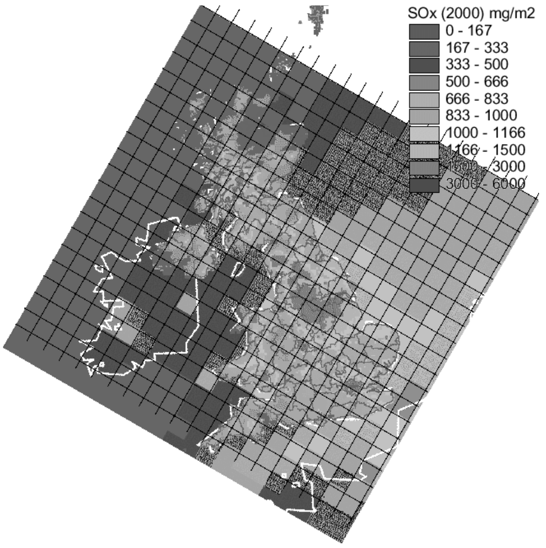

Figure 1 : Visual representation (SO_X deposition) of the mapping between the UK Ordnance Survey 5km grid and the EMEP polar stereographic 50km grid

ASAM is more complex since ASAM uses the EMEP 50km grid which is based upon a polar stereographic projection which does not preserve areas; ie. a 50x50 km^2 grid cell is $2500km^2$ only on the projection plane, but never on the globe except at 60º Latitude [Posch *et al.*, 2003]. Thus both the orientation of the ASAM and UKIAM grids and the area of cells must be mapped in order to communicate data between the scales. Figure 1 highlights this mapping visually over the UK. Mapping between ASAM and global scale grids may also require a re-projection of grids in order to nest the models, but equally important is that the method followed at each scale be mapped for data flows between scales to have any meaning.

4.2 Methodology

With model architectures and spatial definitions mapped, it is important also to verify the mapping of methodologies; in the case of ASAM and the UKIAM, this includes critical loads, modelling methods and emissions and abatement projections.

ASAM was developed to handle critical loads by using aggregated isolines specifying the *average* accumulated exceedance for each EMEP grid cell [Posch *et al.*, 2003]. These aggregated isolines capture the type and extent of ecosystems in a grid cell but cannot explicitly distinguish ecosystems or the differential rates of deposition upon them. The critical loads methods used by the UN/ECE 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 (5km), enabling the UKIAM to explicitly optimise abatement strategies towards protecting different types of ecosystem [CEH, 2003].

To complicate such methodological differences, it is important to ensure that the underlying data is also comparable (eg. ecosystem types) so that it is possible to aggregate and transfer data meaningfully. Compatibility between modelling approaches and empirical data is necessary, with studies ongoing to verify the operation and representation of models used at the UK and EMEP scales [ApSimon *et al.*, 2004]. If IAMs are to be nested with the ability to assess abatement strategies at a finer scale, emissions projections, abatement measures and timeframes, the treatment of different sectors, and definitions of 'business-as-usual' scenarios must be consistent [Entec 2003].

4.3 Data

Underlying everything is, of course, empirical and modelled data and the flow of these data between scales. It is important, therefore, that there is consistency between landuse definitions, the definition of ecosystem types, and the pollutants and source-receptor relationships. With the need to maintain a consistent baseline year for model data, both ASAM and UKIAM datasets are being continually reviewed in line with CLRTAP and national policy timescales.

5. TIMESCALES

The effects of air pollution have primarily been addressed using critical loads at both ASAM and UKIAM resolutions. Exceedance of critical loads is only a crude indicator of ecosystem protection and does not capture ecosystem recovery times, although these can be addressed using the concept of Target Load Functions (TLF) [Ferrier *et al.*, 2003]. In the context of nested IAMs, additional effects become significant, particularly where there are combined or conflicting responses of terrestrial ecosystems to acidification or climate change [eg. Beier et al. 2003], and where the effects of soil acidification upon biota influence other dynamics within terrestrial ecosystems [eg. Sverdrup & Warfvinge, 1993].

The UN/ECE Joint Expert Group on Dynamic Modelling discussed the utility of TLF's generated using the MAGIC model for integrated assessment models [Ferrier *et al*,. 2003]. The VSD model

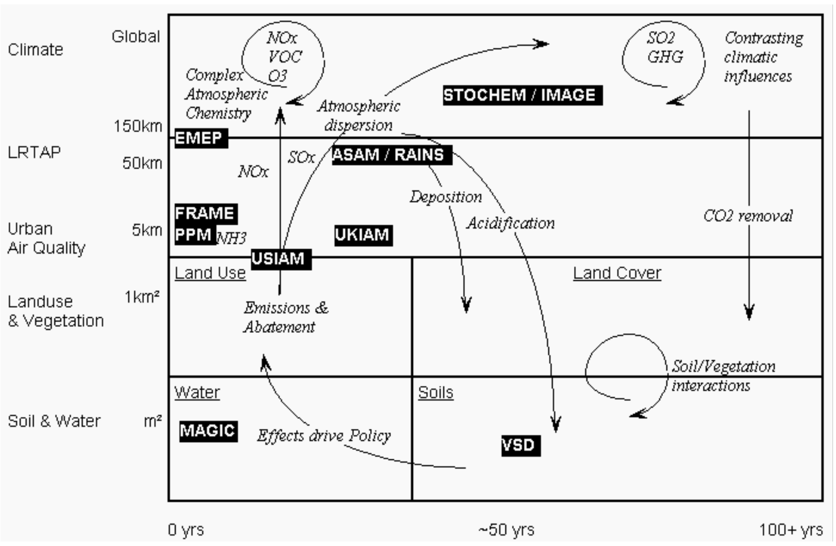

Figure 2 : Multi-scalar linkages to be captured by a nested integrated assessment model (*n*-IAM), together with the models discussed herein.

[Posch & Reinds, 2003] – oriented towards soils, with longer timeframes and trans-national effects – may be able to provide 'proxy' TLF's for integrated assessment modelling where MAGIC has not or cannot be applied. Preliminary studies have found that TLF's enable IAM's to include recovery timescales in the assessment of abatement strategies [Oxley *et al.*, 2003].

Policy regarding air pollution tends to be implemented at the local level (urban air quality, ammonia abatement) and to address issues such as national emissions ceilings (NEC). These issues tend to be of significance to short and medium-term policy objectives. Climate policy, however, transcends national boundaries and inherently involves medium to long-term timescales.

Recovery of freshwater from acidification can be captured within the timeframe of short-term policy, and is thus of interest to policy makers, with the effects of abatement being seen to be protecting ecosystems. On the other hand, soil recovery occurs over the medium to long-term, exceeding the timeframes even of international policy (eg. Gothenburg protocol). The influence of soil quality upon both freshwater and land cover is important with respect to recovery timescales and the effects of climate change.

A *nested*-IAM must therefore be able to capture policy timescales, their spatial applicability, and their relationships with acid or GHG abatement strategies and ecosystem recovery timescales. Given the inter-relationships between air pollution and climate change [CLRTAP, 2003], it is important to capture these multi-scalar dynamics within a *nested* IAM.

In recent work assessing the anthropogenic influences upon desertification processes it was shown how multi-scalar dynamics can influence each other, observable through differences between the temporalities of events and effects [Oxley & Lemon, 2003]; events observed on hourly or monthly timescales gave rise to effects which were only observable after days and decades, respectively. Such non-linearities between events and effects are also apparent in the context of air pollution, climate change and terrestrial ecosystem responses [Füssel & van Minnen, 2001], leading to the recognition that linkages and synergies exist between air pollution and climate related abatement strategies.

The derivation of abatement cost-curves will also have implicit implementation timescales associated with each abatement measure. Most crucial, however, is consistency in definitions of, for example, ‘business-as-usual’ scenarios, since conflicting approaches will make information flow between scales nonsensical.

Already identified here are disparate timescales of effects in both the atmospheric processes and soil and water quality. Taking into account the inter-relationships between vegetation (land cover) and climate change or acidification, these complex interactions can lead to feedbacks in the system which may subsequently give rise to counter-intuitive environmental responses. Some of these linkages and relationships are highlighted in Figure 2, showing the importance of assessing both the short-term (5-50yrs) and long-term (20-200yrs) effects of abatement strategies.

Thus we see the importance of not only capturing all spatial resolutions within a *nested* IAM, but the temporal scales of effects must also be included.

6. CONCLUSIONS

In moving towards a *nested* Integrated Assessment Model (*n*-IAM) it is clear that we must firstly understand the inter-relationships and linkages between scales. Mapping of models between spatial scales is then possible, but it is important to capture not only the spatial resolution but also any methodological or data differences. Crucially, a *n*-IAM must also address the disparate timescales of abatement, effects and policy scenarios, and a consistent baseline scenario is essential. All the issues identified in this paper should be addressed to verify the capture of all significant processes.

Finally, the basis of a *nested* IAM framework has been defined. Work to implement a *n*-IAM which can be used for exploration of alternative abatement policies in support of CLRTAP is ongoing, in collaboration with the UN/ECE Task Force on Integrated Assessment Modelling.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Amann, M., J. Cofala, Ch. Heyes, Z. Klimont & W. Schöpp, The RAINS model: a tool for assessing regional emission control strategies in Europe, *Pollution Atmospherique, December*, .41-63, 1999.

ApSimon, H., (ed.), *Comparison of the EMEP model and other models for the UK region*, Report to DEFRA, Imperial College, 2004

ApSimon, H., T. Loh, T. Oxley & A. Grossinho, Strategies to reduce deposition of N from agricultural sources on sensitive ecosystems: spatial considerations, UN/ECE TFIAM, Haarlem, 7-9 May, 2003.

ApSimon, H., R. Warren & J. Wilson, The Abatement Strategies Assessment Model: Applications to reductions of SO_2 emissions in Europe, *Atmos. Env.*, 24(4), 649-663, 1994

Beier, C., F. Moldan & R.F. Wright, Terrestrial ecosystem recovery – modelling the effects of reduced acidic inputs and increased inputs of sea-salts induced by climate change, *Ambio* 32(4), 275-282, 2003

CEH: *Status of UK critical loads: Critical loads methods, data & maps*, Centre for Ecology & Hydrology, Monks Wood, 2003.

CLRTAP, Workshop on linkages and synergies of regional and global emission control, UNECE Convention on Long-Range Trans-boundary Air Pollution, IIASA, 27-29 January 2003.

Cofala, J. & S. Syri, Sulphur emissions, abatement technologies and related costs for Europe in the RAINS model database, IIASA, Interim Report IR-98-35, 1998

Collins,W., D.Stevenson, C.Johnson & R.Derwent, The European regional ozone distribution and its links with the global scale for the years 1992 & 2015, *Atmos. Env*. 34, 255-267, 2000.

Collins, W.J., D.S. Stevenson, C.E. Johnson & R.G. Derwent, Tropospheric ozone in a global scale three-dimensional Lagrangian model and its response to NO_X emissions controls, *J. Atmos. Chem*. 26, 223-274, 1997.

Colvile, R., J. Gomez & M. Nieuwenhuijsen, Use of dispersion modelling to assess road-user exposure to $PM_{2.5}$ & its source apportionment, *Atmos. Env.* 37, 2773-2782, 2003.

Dentener, F., *Radiative Forcing of Air Pollutants*, in [CLRTAP, 2003]

Dore, C., J. Goodwin, J. Watterson, T. Murrells, N. Passant, M. Hobson, K. Haigh, S. Baggott, S. Pye, P. Coleman & K. King, *UK Emissions of Air Pollutants 1970-2001*, AEA Tech., 2003.

Dragositis, U., J. Hill, H. ApSimon & M. Sutton, Ammonia emission, deposition and impact assessment at the field scale: a case study of sub-grid scale variability, *Environmental Pollution* 117(1), 147-158, 2002.

Entec UK Limited, *Spatially disaggregated cost-curves for air pollutants*, Final Report to DEFRA, 07230-09 CA034Ri0, October 2003

Ferrier, R.C., R.F. Wright & A. Jenkins (eds.), Predicting recovery of acidified freshwaters in Europe and Canada, *Hydrology & Earth System Sciences* 7(4), 2003

Fournier, N., V. Pais, M. Sutton, K. Weston, U. Dragosits, S. Tang & J. Aherne, Parallelisation and application of a multi-layer atmospheric transport model to quantify dispersion and deposition of ammonia over the British Isles, *Env. Pollution*, 116, 95-107, 2002.

Füssel, H-M. & J.G. van Minnen, Climate impact response functions for terrestrial ecosystems, *Integrated Assessment* 2, 183-197, 2001.

Gonzalez del Campo, T., Integrated Assessment of Abatement Strategies for Primary Particulates, PhD Thesis, Imperial College London, 2003

Johnson, C.E. & R.G. Derwent, Relative radiative forcing consequences of global emissions of HCOs, CO & NO_X from human activities estimated with a zonally averaged 2D model, *Climatic Change* 34, 439-462, 1996

Kram, T., *Modelling across scales: The IMAGE model*, in [CLRTAP, 2003]

Mayerhofer. P., J. Alcamo, J. G. van Minnen, M. Posch, J-P. Hettelingh, R. Guardans, B. S. Gimeno, *Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM)*, WZ Report A9901, CESR, 1999

Mediavilla-Sahagun, A. & H. ApSimon, Urban scale assessment of options to reduce PM_{10} in London towards attainment of air quality objectives, *Atmos. Env.* 37, 4651-4665, 2003.

Oxley, T., H. ApSimon, A. Dore, M. Sutton, J. Hall, E. Heywood, T. Gonzales del Campo & R. Warren, A national scale approach to the analysis of strategies to comply with National Emissions Ceilings under CLRTAP: The UK IAM, *Integrated Assessment* (in press), 2004

Oxley, T., H. ApSimon & A. Jenkins, Dynamic critical loads in freshwaters and the use of target load functions in integrated assessment modelling, UN/ECE TFIAM, Haarlem, 7-9 May, 2003.

Oxley, T. & M. Lemon, From social-enquiry to decision support tools, *Arid Environments* 54, 595-617, 2003.

Posch, M., J-P. Hettelingh, J. Slootweg & R.J. Downing (eds.), *Modelling and Mapping of Critical Thresholds in Europe: CCE Status Report 2003*, CLRTAP, Coordination Center for Effects, ISBN 90-6960-106-0, 2003.

Posch, M. & G.J. Reinds, VSD – User manual of the Very Simple Dynamic soil acidification model, CCE, The Netherlands, 2003

Simpson, D., H. Fagerli, J. Jonson, S. Tsyro, P. Wind & J. Tuovinen, *Unified EMEP Model Description*, EMEP Status Report Part I, 2003

Sverdrup, H. & P. Warfvinge, The effect of soil acidification on the growth of trees, grass and herbs as expressed by the (Ca+Mg+K)/Al ratio, *Rep. in Ecol. & Env. Eng.*, 2, Lund, 1993

UNECE, *The 1979 Geneva Convention on Long-range Trans-boundary Air Pollution (CLRTAP)*, UN/ECE 1979

UNECE, *The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, UN/ECE 1999

Warren, R. & H. ApSimon, Integrated assessment of SO_2 reduction schemes: robustness studies, choice of environmental targets and country roles. *J Env Management* 59, 3-20, 2000a

Warren, R. & H. ApSimon, The role of secondary particulates in European emission abatement strategies, *Int. Assessment* 1, 63-86, 2000b