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Integrated Modelling for Health and Environmental Impact Assessment of Air Pollution and Climate Change

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Abstract
Modelling the impacts of air pollution and climate change on human health and ecosystems in integrated assessment models (IAMs) has emerged as a key tool to inform policy decision making, where simplistic solutions are unlikely to deliver efficient and sustainable pathways for future development.

Model integration is facing a complex set of challenges in different dimensions, as integrated models have to be:

- Spatially explicit and of sufficiently high spatial resolution for their respective domain, with nesting approaches providing the integration across different spatial scales.
- Temporally dynamic to model system responses and recovery e.g. pollutant accumulation, time-lag (e.g. of measure implementation) and time-bomb effects. Due to different temporal horizons for different processes (e.g. days-years for air pollution, decades-centuries for climate change, centuries-millennia for accumulation of heavy metals/POPs in soils), integrated models also need to nest models with different temporal resolution.
- Sectorally detailed to model trade-offs and synergies and to allow for the representation of paradigm-shifts (e.g. in energy systems) and behavioural changes (e.g. non-technical measures).
- Accessible, providing clear illustrations of inter-sectoral synergies and tradeoffs (e.g. ammonia emission reduction vs. nitrate leaching in agriculture) using visualisations and multi-media.

In addition to the aforementioned requirements, integrated models need to be flexible and scalable to be able to provide answers to varying problems. This paper discusses current challenges faced by IAMs and emerging developments based on a literature review.

***Keywords**:* integrated modelling; integrated assessment; air quality; climate change; human health; ecosystems.

1. INTRODUCTION

1.1 The situation of integrated assessment modelling in Europe today

In recent years, a number of anniversaries and milestones could be observed in relation to European air pollution control activities. To begin with, the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP) celebrated its 30 year anniversary, having spawned 8 protocols since it was established in 1979 (Sliggers and Kakebeeke, 2004). And while the CLRTAP was initially conceived and driven by a single purpose, to combat transboundary air pollution identified as the main cause for the *Waldsterben* (forest dieback) in the 1970s, it had soon evolved into a comprehensive hub for monitoring and modelling of air quality and action to reduce the burden of air pollution for human health and ecosystems in the UNECE region.

Within the CLRTAP, especially the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (known as the Gothenburg Protocol), the target year 2010 was selected as an intermediate step towards closing the gap between critical levels and loads and observed exceedances of for the protection of health and ecosystems. Having now reached this target year, it is timely to reflect upon the development so far and the challenges ahead. This is of particular importance, as the Gothenburg Protocol – as well as the EC National Emissions Ceilings Directive – are currently under revision and aim at setting new targets for the year 2020 and beyond, with aspirational targets are discussed for 2050 (see http://ec.europa.eu/environment/air/pollutants/rev_nec_dir.htm).

As another relevant anniversary, it has been 20 years since the publication of Alcamo et al. (1990), which marks a starting point for many years of continuous development and application of the RAINS (Regional Air Pollution INformation and Simulation). The RAINS model has been an essential tool for the analysis of alternative strategies to reduce acidification, eutrophication and ground-level ozone in Europe, underpinning evidence-based policy decision making. In the past 20 years, its focus has evolved as well towards integrating air pollution control and climate change aspects into the latest version of the GAINS (Greenhouse Gas and Air Pollution INteractions and Synergies) model.

Finally, the past decades have been marked by a strong trend towards appreciating the complex relationships and connections between different drivers of global environmental change. The year 2010 has been declared by the United Nations as the International Year of Biodiversity, and current research into the influence of the human perturbation of the nitrogen cycle has identified many areas where air pollution control, climate change and the protection of vulnerable ecosystems cannot be separated (Erisman et al., 2008). It is thus timely to conduct a review of the current understanding of, the state-of-the-art in science and the availability of tools for the integrated assessment of air quality and climate change.

1.2 What is Integrated Assessment (Modelling)?

The term Integrated Assessment (Modelling), in short, IA(M), is widely used, however, in different contexts and within a variety of scientific disciplines and policy applications. For the purpose of this paper, we will briefly discuss two definitions, firstly that of CIESIN (1995):

"An assessment is integrated when it presents a broader set of information than is normally derived from a standard research activity. Because integrated assessments bring together and summarise information from diverse fields of study, they are often used as tools to help decision makers understand very complex environmental problems."

With regard to the modelling aspect, CIESIN (1995) further defines:

"Integrated assessment modelling is a tool for conducting an integrated assessment."

The two activities, however, are not identical even though the terms are often confused and used interchangeably. Integrated assessment models (IAMs) are mathematical computer models based on explicit assumptions about how the modelled system behaves. The strength of an IAM is its ability to calculate the consequences of different assumptions and to interrelate may factors simultaneously, but an IAM is constrained by the quality and character of the assumptions and data that underlie the model.

A similar definition is available from The Integrated Assessment Society (TIAS, 2010) and states:

"Integrated assessment (IA) can be defined as the scientific "meta-discipline" that integrates knowledge about a problem domain and makes it available for societal learning and decision making processes. Public policy issues involving long-range and long-term environmental management are where the roots of integrated assessment can be found. However, today, IA is used to frame, study and solve issues at other scales. IA has been developed for acid rain, climate change, land degradation, water and air quality management, forest and fisheries management and public health. The field of Integrated Assessment engages stakeholders and scientists, often drawing these from many disciplines."

Both definitions highlight the interdisciplinary nature of IA(M) and its role to provide evidence for policy making, as a tool to inform and support policy decisions. It is interesting to note that while the CIESIN (1995) definition has emerged from a climate change background, the work of TIAS has strong roots in water management and sustainable development.

1.3 Aims and scope

A global review of all aspects of IA(M) would by far exceed the limits of a single paper; hence this review will focus on the following key aspects:

- Integrated assessment modelling of air quality and climate change in general and
- Specifically, how IA(M) has informed policy making in the context of the UNECE CLRTAP and the EC NECD.

In addition to that, the following discussion will highlight:

- Major achievements in the evolution of IA(M)s in the past 20 years, as well as
- Key future challenges for IA(Ms) with regard to their development, application and policy support role.

2. HISTORIC DEVELOPMENT OF IAM – EUROPE AND BEYOND

2.1 Existing models and their evolution

A wide range of IA(M)s has been developed over time and has been, respectively is currently, applied in scientific research projects and for direct policy support. These can, for instance, be distinguished by their spatial coverage, by environmental compartment, by topic, their degree of integration and so on:

- Global climate change modelling (e.g. IMAGE, ICAM , MERGE , IGSM)
- European air pollution control and greenhouse gas reduction strategies (e.g. RAINS/GAINS, see Höglund-Isaksson L. and Mechler R., 2005; Klaassen et al., 2005; Tohka et al., 2005; Winiwarter et al., 2005; Hordijk, L. and Amann, M., 2007)
- National modelling of air pollution control and greenhouse gas emission reductions (e.g. UKIAM for the UK, MINNI for Italy)
- Models for integrated assessment of water resource allocation and contamination (e.g. Letcher et al., 2007)

Furthermore, we can distinguish between models developed primarily for policy decision support (applied, operational) and models for scientific research (often process based, technical). While the latter are often more closely linked to new scientific developments, the former reflect the demands of policymakers. Transforming a model suite from its scientific development stage into an operational, applied stage is not straightforward, and funding for such work is often elusive since the effort is unlikely to be rewarded in the conventional scientific "currency" of peer-reviewed publications.

As indicated above, the abundance of different models does not allow making general statements for the whole domain of IAM, yet, a few common trends can be observed:

1) Many models have evolved to extend their scope, e.g. incorporating additional topics (air quality based models extending to climate change, multimedia models covering air, water, soils and working across environmental compartments)

2) Spatial integration, both up- and downscaling and/or nesting is frequently being conducted (e.g. regional models downscaling to national/local applications)

3) Addition of further process detail to existing stand-alone models and extended coupling/linking of specialised models takes place (e.g. the integration of process-based agricultural models into RAINS/GAINS)

4) Development of object-orientated and semantic frameworks to wrap and link component models (e.g. the OpenMI framework, http://www.openmi.org)

These developments reflect the growing understanding of the complex connections between a variety of environmental problems on local to global scale and represent a trend towards a systems approach to problem solving, in contrast to the single-problem, one-purpose strategies that had marked the initial stage of (environmental) research and policy development.

2.2 Emerging challenges

As indicated in the previous section, the development and application of IAMs face quite a few challenges. In the field of extending models to include additional topics - for instance when integrating impact assessment of air pollution and climate change - different time scales and time steps need to be taken into account. While air pollution effects typically occur in a matter of hours or days where human health is concerned, or within days to years for ecosystem effects, climate change effects are likely to occur in decades and centuries. This is of particular relevance when trying to assess the ration between the costs of action and the benefits, as arriving at a monetary evaluation of effects that may occur over a period of decades or centuries to compare on equal terms is not a trivial task.

A similar challenge occurs when trying to integrate across different environmental media, e.g. air pollution control and effects of the deposition of air pollutants on water and soil quality. Last, but not least, research into ecosystem effects has been moving towards more dynamic approaches (see for instance Joint Expert Group on Dynamic Modelling under the Working Group on Effects, http://nora.nerc.ac.uk/8658/). As current IAMs typically operate on an annual scale and deliver annual average values as output, integrating dynamic modelling results on the effects side will likely require multi-year assessment runs and more detailed temporal profiles within annual assessments.

The issue of integrated assessments across different time scales is closely related to that of dealing with varying spatial scales. Climate change is a global phenomenon, whereas air pollution effects typically occur on regional to local scale, with distinct hotspots due to differential deposition onto and damage to different landscape components. But not only effects are spatially explicit; the sources of pollutants and precursors are highly spatially variable, and the location of observed effects does not always coincide with source locations. With regard to the spatial representation in models, again two trends can be observed: on the one hand, applying dedicated models at different scales, with the potential of nesting or linking model input and output across scales and on the other hand, integrating for instance local indicators into regional models, using derived functional relationships. The latter approach has been taken e.g. to include an urban increment to air pollution exposure of the urban population in the European-scale RAINS model (Cuvelier et al., 2007). Examples for a nested/scaled approach can be found in the national implementations of IAMs, as they have been developed in Italy (RAINS-ITALY, Zanini et al., 2005) or the UK (UKIAM, Oxley et al., 2004). The accuracy of the spatial results of IAMs is of particular importance for the development and implementation of national policies.

2.3 Different trends in integration and towards complexity

The previous section has highlighted two main trends emerging with the development of European IAMs, increasing levels of integration and complexity on the one hand, and a modularisation or disaggregation into individual models for specific tasks/scales on the other hand. Both developments have advantages and caveats.

Any increased complexity of models may render the interpretation of results and the assessment of uncertainties substantially more difficult (Warren, 1999; ApSimon, 2002; Krysanova, 2007). In addition to that, the relationships between changes in parameters and the response observed in model results are often not straightforward to predict. In contrast, applying different models for different purposes often provides robust, individual results, yet faces the difficulty of combining or integrating results based upon very different model formulations into policy relevant scientific evidence.

3. CURRENT STATE AND FUTURE DEVELOPMENTS

3.1 What next?

As it has been discussed in the previous sections, IAMs are widely applied in providing policy decision support in particular in the development of integrated air pollution control strategies. There is a trend towards extending models that were primarily developed for air pollution control into the realm of climate change, both with regard to greenhouse gas emission reductions and the quantification of changes in radiative forcing (e.g. Dentener et al., 2005). Further to that, a growing community of national scale IAM developments in Europe is fertilising the ground for a drive towards a larger knowledge base both regarding model development and application for policy decision support on different levels.

The extension of European IAM to further include climate change aspects is reflected by an increasing interest in longer time scales, for instance regarding energy and emission scenarios and aspirational targets for the year 2050 and beyond. Such long time scales have typically not been relevant for the assessment of air pollution alone.

Interactions between air pollution and climate change have primarily focused on CO_2, but the global nitrogen (N) cycle also strongly interacts with global climate processes, via effects on primary production and on trace greenhouse gas production. Recent developments involve the more complex perturbation of the global nitrogen cycle and feature biochemical process models that allow for a quantification of nitrogen input and losses at different stages of the cycle. Nitrogen species are closely linked to air pollution effects as well as contribute to climate change, yet the nitrogen cascade spans not only air pathways, but affects soils, freshwater and marine ecosystems through biochemical transformation and physical transport processes. The key difference between modelling carbon and nitrogen in IAMs, however, is the relevance of spatiotemporal aspects for the representation of N effects compared to a more simplistic mechanism that is sufficient to quantify the effect of CO_2 equivalents on e.g. global temperature increases.

IA(M) in Europe has covered both health impacts and ecosystem effects from an early stage. However, it has to be stated that due to the comparatively more advanced knowledge on the monetary evaluation of health effects (and the lack of a comprehensive approach for a similar valuation of ecosystem effects to date), health impact costs have been the main driver for assessment results in recent years. Particulate Matter (PM) has thus had a strong influence on the priority setting for air pollution control, while acidification, eutrophication and ground level ozone have been of less importance until recently. The revision of the Gothenburg Protocol and the EC National Emissions Ceilings Directive will lead to an inclusion of PM for instance. Emerging evidence on the relevance of ecosystems for carbon sequestration, as well as the concept of ecosystem services as a means of quantifying the benefits from natural ecosystems have somewhat changed this again recently.

Another challenge can be identified regarding the use of IAMs for ex-ante or ex-post cost-benefit assessment (CBA) of environmental policy, as it has for instance been conducted by Kelly et al. (2010). The quantification of health impacts in monetary terms is – even acknowledging the substantial uncertainties in this field – more advanced as it is the case for ecosystem impacts. Thus, a full scale comparison of all costs and benefits of a policy measure is – at this time – not feasible. Instead, most often policies designed to achieve compliance with individual directives or protocols are evaluated, lacking a full and meaningful integration and the quantification of co-benefits and spill-over effects of potentially conflicting (environmental) policy targets. A full-scale integrated assessment in this area requires further advances in evaluation methodologies and a consistent framework for a monetarisation of ecosystem effects in a similar fashion as it is being done for human health effects. For both areas, health and ecosystems, however, the underlying scientific evidence for the quantification is currently scarce and larger scale empirical studies in a European realm are needed.

Apart from these specific topical aspects, a potentially greater challenge is the lack of a common framework or concept for the development of integrated assessment models. The following two sections will briefly discuss two key issues arising from this.

3.2 Degree of integration

The first question to tackle is how to achieve integration, and what measure or indicator can serve to distinguish integrated from partial models. This is not just of academic relevance, as IAMs, as alluded to previously, are widely used in support of policy development and as it is unlikely that one single model will satisfy all policy needs, a way of determining and describing the level of integration a model represents can serve as a core selection criterion.

It is difficult to find a comprehensive indicator for the degree of integration that current models are reflecting. One angle that could be taken is to measure the components of IAMs to in how far they cover a full-chain impact assessment, as for instance represented by the DPSIR framework (EEA, 2010), an extension to the OECD Pressure-State-Response (PSR) model (OECD, 1993). The DPSIR framework describes the causal chain from the origin of an environmental problem to its outcome, covering the following stages:

- Driving forces
- Pressures
- States
- Impacts
- Responses

While the DPSIR model has been modified and applied in different research areas (e.g. Morris et al., 2006). However, for the purpose of analysing levels of integration, the original DPSIR framework is well suited. A similar approach has been developed and applied in the frame of the ExternE (http://www.externe.info) project series developing a framework for impact assessment and external costs of energy, transport etc. and was termed the “impact pathway methodology” (see Mensink et al., 2007).

However, any indicator or concept of “integration” on its own account is not sufficient or suitable to assess the quality of an IAM. Specialist models representing only selected parts of the DPSIR chain can equally be marked by a high coverage of all aspects relevant for a specific problem or task. There remains a need for methods to evaluate the quality and suitability of an IAM for answering a given set of questions.

Current applications of integrated assessment models have most often emerged from a specific area of research or with a well-defined policy question to answer. With an increasing understanding of the complex relationships of these specific issues integration has then occurred by extending the system boundary of the models and including additional parameters, datasets and modules. This approach requires either the scalability of a modelling concept from the start; alternatively, substantial conceptual rethinking and redesign of existing models are needed.

In the field of Earth System Modelling (ESM) approaches exist to design and apply common frameworks to support the development of integrated models. An example of this approach can be found with the Earth System Modelling Framework (ESMF, http://en.wikipedia.org/wiki/ESMF).

3.3 Methodological challenges

With regard to the assessment methods implemented in current IAMs, one could easily classify or categorize along a vast number of different concepts or topics, for instance by

- the timing of the assessment *(ex-ante or ex-post)*
- design *(simple one-dimensional vs. complex multi-dimensional)*
- application *(decision support system or optimisation tool)*
- spatio-temporal resolution *(short term to long term, local to global)*
- topic *(air quality, water quality, catchment modelling, climate change, ...),* etc.

What needs to be kept in mind, however, is that most IAMs that are currently applied for policy decision support have not (or not entirely) been designed and implemented strategically for this purpose, but have often evolved over extended periods of time, reacting to emerging policy needs. In this process, models have at times begun their life cycle as a specialist, scientific tool and matured to more easily accessible tools that may be operated by non-expert users. However, the gradual evolution of models often results in legacies which can seriously affect the performance and flexibility of their application, e.g. due to programming or hardware restrictions imposed on previous versions that have been long overcome by current technological progress.

4 CONCLUSIONS AND OUTLOOK

4.1 Conclusions

The previous sections have highlighted a few of the many issues marking the complexity of the field of integrated (assessment) modelling in its current state. This complexity exists in two different, but closely related, dimensions: the complex design and structure of IAMs as a challenge to the methodological and conceptual development of models on the one hand, and the difficulty to represent complex biochemical, physical or economical/social processes in assessment models on the other hand.

With regard to the latter, we can observe a substantial improvement in the understanding of the interactions between different environmental problems and a strong drive towards a more integrated approach in solving them. This is for instance the case in tackling air quality and climate change in combination, taking full account of the co-benefits and potential spill-over effects of individual measures in a common framework (see for instance Pleijl et el., 2009).

While understanding the need for integration helps to focus research into the interactions and dependencies of the underlying processes, the modelling community has been actively discussing concepts, model linkages and interactions. In this context, Harris (2002) sees IA(M) as an essential and systematic way forward, in connection with Earth System Modelling (ESM), Natural Resource Management (NRM) and Ecological Sustainable Development (ESD). Around the same time, Jakeman and Letcher (2003) derive common features of IA starting from an example in catchment management. This list of features contains, among others, the *"Connection of complexities between natural and human environment; recognition of spatial dependencies, feedbacks, and impediments; an iterative, adaptive approach."* (Jakeman and Letcher, 2003, p. 492). More recently, Jakeman et al. (2006) propose "Ten iterative steps in development and evaluation of environmental models", which could form a basis for a comprehensive framework for IAM development that is currently lacking (see Section 3.2). A more systematic and formalised approach towards the development and implementation of IAMs could not only be beneficial for knowledge transfer and collaboration between modellers, but as well help to inform the users of IAM output with regard to uncertainties (quantified) and a *"better qualitative understanding of the system"* (Jakeman et al., 2006). The aspect of the usability of tools for policy-relevant research is highlighted as well by McIntosh (2007).

From the general trend of discussions in literature, a development to a more systematic, methodological approach towards IAM design and application has consolidated in the last five to ten years.

Looking forward, there is no lack of emerging topics and some of these have been the subject of recent publications. D'Elia et al. (2009) focus on the integration of non-technical measures (NTM) into IAM, which has been discussed vividly in the European IAM community for some time. This reflects a growing concern that more ambitious environmental targets are likely not achievable using technological control measures alone. At the same time, the integration of behavioural and structural change (which marks most of those non-technical measures) is a non-trivial task as most models have been built with a focus on end-of-pipe control options and established energy systems, which cannot be easily overcome. Closely related is the conceptual integration of external costs into the IAM process, which has been extensively done for human health effects (see Section 3.2), but has gaps when it comes to ecosystems or climate change effects. Kosugi et al. (2009) describe an approach linking an IAM with a model for life cycle assessment (LCA) to fully internalise external costs of air pollution and climate change, as well as land-use and land cover change.

Another trend could be the modularisation of IAMs, as described by Hinkel (2009) for a specific model. Making IAMs modular does not yield improved models per se, but could enable their linkage using concepts such as OpenMI and increase the interoperability and flexibility of the IAM by allowing to select different modules for specific tasks. Yet, for this to work, models and modules need to be described and documented in a consistent way that is accessible across disciplines and scientific domains. Janssen et al. (2009) elaborate on the use of a common ontology to achieve such a level of integration in a large-scale European research project (SEAMLESS IP, http://www.seamless-ip.org).

4.2 Outlook

The development of IAMs faces a lot of challenges, but at the same time has the potential to mature into an essential and indispensable tool to provide underpinning scientific evidence for informed policy decisions to address the critical issues of today's global environmental change.

Among the various challenges highlighted in this paper, the authors see two emerging areas as key to achieve progress in integrated assessment modelling: on the one hand, a conceptual framework and advances for a better spatio-temporal representation of cause and effects in both health and ecosystem impact assessment is required, while on the other hand a more comprehensive integration across different environmental media and environmental pressures has to be realised. Both are not trivial and the necessary complexity of models may be a limiting factor. For this purpose, an overarching concept of modularisation and linking of models and modules may be seen as the best way forward.

This would as well further aid the application of methods for in-depth, quantitative uncertainty assessment, which will be vital to provide robust scientific results to underpin evidence-based policy development.

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