COORDINATED EFFECTS MONITORING AND MODELLING FOR DEVELOPING AND SUPPORTING INTERNATIONAL AIR POLLUTION CONTROL AGREEMENTS

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Abstract. For 20 years the Convention on Long-range Transboundary Air Pollution has worked to control air pollutant emissions in Europe and North America. Its Working Group on Effects (WGE) has been responsible for much of the underpinning science. The WGE's six International Cooperative Programmes (ICPs) on Waters, Natural Vegetation and Crops, Forests, Materials and Cultural Heritage, Integrated Monitoring, and Modelling and Mapping, together with a Joint Task Force on Human Health with WHO, quantify air pollution effects on the environment through monitoring, modelling and scientific review. Early work found evidence to support the need for decreases in emissions of sulphur and nitrogen pollutants. More recently, monitoring results and models have provided the scientific basis, e.g. critical loads and levels, for effects-based Protocols and for evaluating their effectiveness. ICP studies on trends show recovery from acidification effects in keeping with the fall in sulphur emissions. Steady-state models provide an indication of long-term improvements. Recent increased emphasis on developing dynamic models will enable better links between recovery rates and abatement strategies. The scientific network of the ICPs and the monitoring and modelling results have been key to the development of the Convention and are an essential component for its success in the future.

Key words: air pollution effects, international cooperative programme, transboundary air pollution, critical loads.

1. Introduction

Science has always played an important role in the developing air pollution control policies, for example, scientific measurements showed the transboundary nature of air pollution emissions and their widespread effects on the environment. Now monitoring and modelling activities by scientific groups, working together internationally, provide useful answers and direction for policy development and agreed actions in Europe and North America. While major pollutant emissions in these regions continued to increase to about 1980, many have now fallen (Figure 1). Sulphur emissions have decreased considerably, while nitrogen emissions, less important in 1980, have fallen much less and are now almost equal to those for sulphur. The decreases are mainly a result of governments' efforts to control emissions, both nationally and through international agreements. To see what further measures are needed in this changing "pollution climate" we need to measure and understand the effects on

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the environment not only for the present but also for predicting the future when pollution emissions may change.

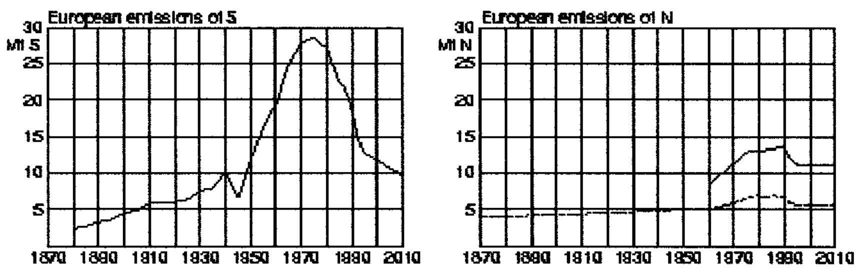

Figure 1. Temporal development of European emissions of sulfur (left) and total nitrogen (right, top line). From 1995 the emissions changes are linear predictions. The lower line in the right figure shows the emissions of ammonia (re-drawn after WGE, 1999).

This paper considers the scientific issues of the effects of air pollution in relation to the development, the activities and the results of the International Cooperative Programmes (ICPs) of the United Nations Economic Commission for Europe (UN/ECE) Convention on Long-range Transboundary Air Pollution (CLRTAP). It focuses on the support that the Programmes provide for air pollution control strategies in Europe and North America, and highlights important aspects of their activities in monitoring and modelling. It is intended to demonstrate that first class science in itself is not enough, the framework for scientific collaboration, consensus and presentation of results is essential for effective development and implementation of international science-based policies.

2. The Convention on Long-range Transboundary Air Pollution

CLRTAP (UN/ECE, 2000a) has been one of the main ways of protecting the environment in Europe and North America from air pollution. It has successfully bridged different political systems even through times of political change, and is a prime example of what can be achieved through intergovernmental cooperation. It has done this through creating an effective framework for controlling and reducing the damage to human health and the environment from transboundary air pollution.

International activity to develop the Convention dates back to the late 1960s, when scientists showed a link between sulphur emissions in Europe and the acidification of Scandinavian lakes. International cooperation on the issue began at the 1972 United Nations Conference on Human Environment in Stockholm. While it was agreed that air pollutants could travel great distances before deposition and damage occurred, solving the problem required international cooperation.

The Convention on Long-range Transboundary Air Pollution was signed in Geneva in November 1979 by 34 governments and the European Community (EC). It was the first internationally legally binding instrument to deal with air pollution problems on a broad regional basis, laying down general principles for international cooperation on air pollution abatement and a framework for linking research and policy (ECE, 1996).

Forty-seven parties have now ratified the Convention. Since its entry into force in 1983, it has been extended by seven protocols that define national targets for emission reductions. Early protocols were "flat rate", defining "equal" (e.g. percentage) reductions for all Parties. Recent "effects-based" protocols define emission targets using integrated assessment (IA) modelling supported by atmospheric transport models, quantitative effects estimates (critical loads and levels) and costs of abatement technologies, all areas of knowledge developed under the Convention (UN/ECE, 2000a).

The most recent protocol to the Convention, adopted in Gothenburg in December 1999, is the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. This multi-pollutant, multi-effect protocol marks a new era for pollution control and a recognition of the need to consider the overall pollution climate if we are to address environmental effects effectively. In its development the protocol has relied greatly upon scientific underpinning, and will require continued scientific support to evaluate benefits in the future.

CLRTAP's supervising and implementing Executive Body gives responsibility for effects-related activities to its Working Group on Effects (WGE) (UN/ECE, 2000b). Other subsidiary bodies, and their roles, are:

- The Implementation Committee, considers how countries comply with the Convention and its protocols;
- The Working Group on Strategies and Review, deliberates on the need for policies, protocols and specific measures, and prepares the necessary draft agreements and obligations; and,
- The Steering Body of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), responsible for atmospheric monitoring and modelling of pollutants in Europe (EMEP, 2000).

3. Activities of the International Cooperative Programmes

WGE is responsible under CLRTAP for issues of Research and Development (Article 7 of the Convention) on "the effects of sulphur compounds and other major air pollutants on human health and the environment, including agriculture, forestry, materials, aquatic and other natural ecosystems and visibility, with a view to establishing a scientific basis for dose/effect relationships designed to protect the environment". Also Parties agree to share information on "physico-chemical and biological data relating to the effects of long-range transboundary air pollution" and the extent of damage attributed to it.

The six ICPs operating WGE are each coordinated by a Task Force with a centre that is responsible for collating data, developing models, providing information and for reporting results (UN/ECE, 2000b). The Programmes are:

- *International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests)* collects data and determines cause-effect relationships on changes in forests due to air pollution and other stresses through both large-scale assessment and monitoring on permanent sample plots;
- *International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters)* assesses, on a regional basis, the degree and geographical extent of acidification of surface waters. The data collected provides information for dose/response relationships and on the physical, chemical and biological status of lakes and streams;
- *International Cooperative Programme on Effects of Air Pollution on Materials, Including Historic and Cultural Monuments (ICP Materials)* evaluates the effects of major pollutants, and factors such as climate, on the atmospheric corrosion of important materials to determine dose/response relationships for assessing critical and/or target levels and calculating costs of material damage;
- *International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation)* considers the underlying science for quantifying vegetation damage, in particular crops. It evaluates the effects of pollutants, especially ozone, by developing dose-response relationships and through the development of critical levels maps;
- *International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP IM)* determines and predicts the state of ecosystems (or catchments) and their changes from a long-term perspective with respect to the regional variation and impact of air pollutants, especially nitrogen, sulphur, ozone, and heavy metals;
- *International Cooperative Programme on Modelling and Mapping (ICP M & M)* models critical levels and loads, maps geographical areas to determine the scope and extent of pollutant depositions/concentrations which exceed critical levels/loads and establishes appropriate methods for assessing potential damage.

In addition, the *Joint Task Force on Health Effects,* run in collaboration with the World Health Organization, reviews existing evidence to determine the effects and risks of transboundary air pollution (e.g. fine particulates) to human health, and to identify information needed for sound assessment of present impacts and public health benefits gained from the implementation of CLRTAP protocols.

4. Observed trends in air pollution effects

ICP monitoring activities have been extremely important for showing the degree and extent of effects throughout the ECE region. Many have operated for 15 years or more, so they can identify changes and trends that may result from decreased emissions throughout the ECE region (WGE, 1999). We know that decreases in emissions of sulphur over the last 20 years have resulted in less acidity falling on Europe and North America. The results from the ICPs show these decreases are, for example, linked to observed improvements in chemistry (Figure 2) and recovery of biology in freshwaters.

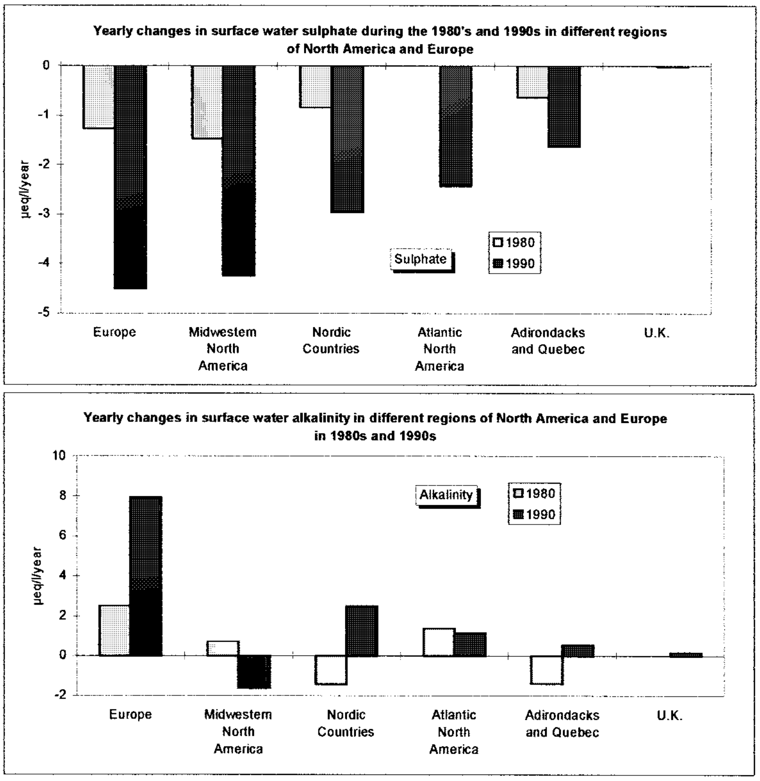

Figure 2. Average yearly changes in surface water sulphate and alkalinity in the 1980s and 1990s in different regions of Europe and North America

Regional trend analyses of surface water chemistry for ICP Waters monitoring sites show that sulphate concentrations are decreasing almost everywhere (Stoddard et al, 1999, Skjelkvåle et al, 2000). In most cases the decreases in the 1990s are greater than those in the 1980s. In Finland, Sweden and Norway, alkalinity falls in the 1980s (acidification), but increases in the 1990s (recovery). At many European sites (Italy, Germany, Netherlands, Denmark) alkalinity also increases in the 1980s, but the rate accelerates in the 1990s. The remaining regions monitored (Adirondacks and Quebec, mid-western North America, British Isles) show either no recovery or further acidification. ICP Waters also report improvements in aquatic invertebrate fauna at many Norwegian and German sites. Some indications of improvement are seen in data from Canada and Sweden.

Observations by ICP Materials show that the decreasing trends in the concentration of acidifying air pollutants have resulted in decreasing corrosion rates of exposed materials (SVUOM, 1997). Both carbon steel and zinc show decreased corrosion in unsheltered as well as in sheltered positions. These changes occurred first in Scandinavia and later in western and central Europe. Sulphur dioxide is the largest single contributing factor to trends of decreased corrosion. The decreasing acidity in precipitation is a contributing factor, but its effect is much smaller than that of dry deposition of sulphur dioxide.

Acidity critical loads exceedances (Posch et al, 1999) as predicted from results of the ICP M & M and EMEP, are falling and are predicted to fall further in the future (Figure 3). Nitrogen emissions, especially in the form of ammonia, will remain high, causing widespread and continuing eutrophication of natural ecosystems as well as acidification. As a consequence, improvements in exceedances of nutrient nitrogen critical loads are small.

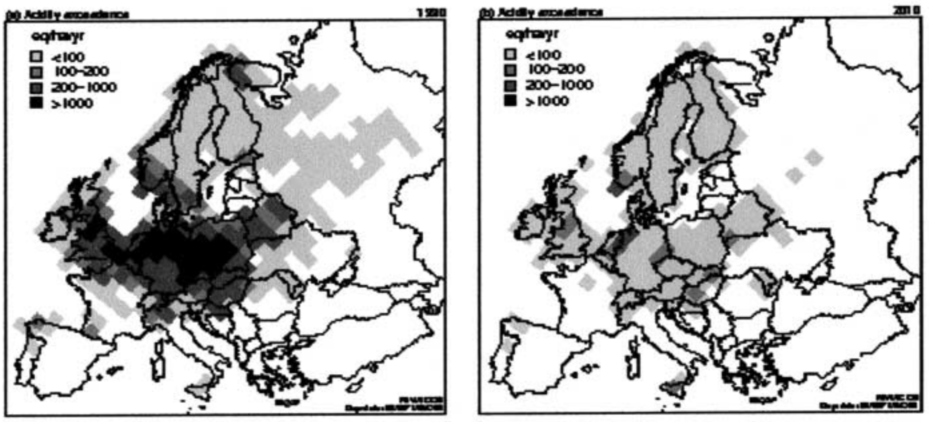

Figure 3. Acidity critical loads exceedance maps for 1990 and 2010 showing the improvements predicted from implementing the 1999 Gothenburg Protocol (white areas indicate non-exceedance or lack of data)

ICP Forest observations of forest tree condition show continued signs of deterioration in some parts of Europe (Lorenz et al, 2000, Muller-Edzards et al, 1997). The results are confounded by stress factors other than air pollution. Climatic (e.g. drought), site quality (including soil properties and nutrients), and biotic (e.g. insects, fungi) factors may contribute to leaf or needle deficit. Pollution effects (e.g. acidification, ozone) are seen as a predisposing or triggering factor for damage to tree crown condition, but trends related to pollution have not been identified. However, monitoring results do show relationships between pollution and particular compartments of forest ecosystems (e.g. soil condition, nutrient status).

Measurements of ozone concentrations in the monitoring programmes reflect the marked yearly variation and geographical differences reported by EMEP. Effects of ozone on crops are widespread (Benton et al, 2000) and follow the yearly changes of pollutant concentrations, but there are no overall trends in time. Ozone critical levels are exceeded at most monitoring sites for ICP Forests so ozone is expected to contribute to forest damage.

ICP results show that recovery from the effects of some pollutants, e.g. sulphur, has started while for others, e.g. nitrogen and ozone, there remain problems for the future. They also demonstrate the importance of the scientific monitoring ICP networks that have enabled the necessary data to be collected and analysed to indicate trends where they exist. The data are also important for the development and validation of models of chemical and biological change.

5. Models of air pollution effects

Air pollution effects models come in a wide range of complexities with differing applications. Detailed models for specific situations and small geographic areas are not considered here. Models with wide applicability and high policy relevance are the focus for this paper. Dynamic models with predictive capacity are considered later in section 6.

Very simple models, based on empirical relationships, have featured highly in policy linked studies. Not surprisingly monitoring programmes with their wealth of measured data are well placed to develop such models.

ICP Vegetation, using Artificial Neural Network analysis, have developed numerical models for acute visible damage and chronic growth effects by ozone on clover plants grown experimentally in ambient air across Europe (Mills et al, 2000). The chronic damage analysis identified a similar AOT40[1] model to that derived experimentally elswhere. An analogous model is available for forests. The ozone AOT40 "critical level" model was included in the IA calculations for the Gothenburg Protocol. Current work is refining the empirical model to include important climatic factors (e.g. soil moisture deficit which decreases ozone effects in dry periods when plant stomata close). In the longer term, more sophisticated flux models, based upon ozone exposure and uptake by plants, are planned for use in developing pollution abatement strategies.

Health effects of ozone were also included in the Gothenburg Protocol IA modelling obligations. A similar, simple AOT model was used as a surrogate for less easily included exposure-response relationships.

Effects of nitrogen (N) on aquatic and terrestrial ecosystems have also been well studied. The monitoring sites of ICP Waters have provided good evidence for the changes in the seasonal patterns of N concentrations in freshwaters that occur when catchments become N saturated. Leakage of N to

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[1] AOT40 (Accumulated dose over a threshold of 40 parts per billion concentration in the air) is the sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each hour when the concentration exceeds 40 ppb, accumulated during daylight hours.

streamwater throughout the year indicates a saturated system. This is likely to occur above a deposition threshold of about 8-10 kg N ha^{-1} $year^{-1}$. In remote upland catchments saturation is generally due to excess N deposition, i.e. the exceedance of critical loads.

ICP IM also confirmed the above critical deposition thresholds for N leakage. A combined European data set showed that output flux of N was related to key ecosystem variables (Forsius et al, 1996). Data from selected ICP IM sites also contributed to studies on carbon (C) to N ratios in soil organic horizon as an indicator of nitrate leaching. The ratio seems to give a reasonable estimate of the annual export flux of N for European forest sites receiving deposition up to about 30 kg N ha^{-1} $year^{-1}$ (Dise et al, 1998). Some exploratory work on multi-variate statistical gradient analysis of the effects of pollutant deposition on natural vegetation has also been carried out (de Zwart, 1998).

Empirical models are also well established for the occurrence/disappearance of plant species in relation to excess N deposition. Experimental and field observations have been brought together in workshops organized under CLRTAP to define empirical critical loads for N deposition (UBA, 1996). In addition, models based on mass balance calculations have been developed for estimating N critical loads for some ecosystems (UBA, 1996). These critical loads, reported by countries across Europe, provide some of the maps used for IA modelling activities.

For acidification, empirical biological relationships (models) are well-established for fresh-waters. The disappearance of fish at certain chemical thresholds (e.g. acid neutralizing capacity values) has been the basis of defining acidity critical loads for freshwaters, for example using the Henriksen or the First-order Acidity Balance (FAB) model (Henriksen & Posch, 2000). Changes in diatom species distributions in freshwater lakes have provided a similar basis for modelling critical loads at the onset of biological effects (Henriksen & Posch, 2000). While invertebrate species have not lent themselves to critical load modelling, changes in invertebrate species with acidification are well-documented. ICP Waters has developed an index from observations of the species occuring at its sites; this shows the acidification status of freshwaters from biological samples.

For terrestrial systems the biological effects of acidification are less well documented. While decreased forest growth has been linked to acidification in Scandinavia, analysis of ICP Forest data has shown less significant relationships between tree condition with pollution stress. This has been attributed, as noted above, to the large number of factors that affect tree health.

Proposals for modelling terrestrial critical loads for acidity were suggested in the 1980's (Nilsson,1986) using empirically based soil weathering rates, on the assumption that if the weathering rate is exceeded soil acidification will occur with harmful effects to terrestrial ecosystems. This empirical model has been used in the past, but in recent years a Simple Mass Balance (SMB) model has been applied extensively to forest ecosystems throughout Europe. The SMB was used by many countries for calculating the critical loads for

CLRTAP maps used in IA models for recent protocol deliberations. The SMB incorporates a chemical criterion. Most have used a calcium (or base cation) to aluminium ratio, related experimentally to effects on plant roots and growth, but alternatively, hydrogen or aluminium ion concentration criteria can be used (UBA, 1996).

The ICP Materials monitoring activities not only identify trends. They have enabled the development of exposure-response relationships linking corrosion to measured pollution and environmental parameters (SCI, 1998). The multi-variate models provide the means for understanding the corrosion process and the possibility to predict future effects as abatement measures are implemented.

6. Dynamic models for predicting effects

The simple models of air pollution effects described above are useful for indicating that abatement measures are required and even provide a crude prediction for "recovery" in the very long term if critical loads or levels are not exceeded. However, they provide no information on the rate of change (e.g. recovery), and hence fail to identify:

- Slow recovery due to hysteresis effects in physical and chemical processes, particularly in soils;
- Rates of change and recovery processes in a changing (i.e. improving) pollution climate;
- The benefits of decreasing pollution below the critical load or level, i.e. attaining an enhanced rate of recovery through setting lower targets;
- The advantages of setting targets based on dynamic interpretation of effects.

It is not surprising that CLRTAP has identified dynamic modelling as a priority area for future effects oriented work.

For some years a small number of dynamic models have featured in the activities of some ICPs. The models have not achieved a very high profile in policy discussions and the work has been targeted at small areas, generally small river or lake catchments, where sufficient quantities of data are available for calibrating models. Dynamic models generally require much data before they can operate effectively. ICP Integrated Monitoring has recently reported results of such modelling work, e.g. Figure 4, through the EU/Life project (Forsius et al, 1998). It demonstrates that while there may be some differences in the results produced by individual models, they all show:

- The quicker the target level of reductions is achieved, the more rapidly surface water and soil status recover; but,
- In the long-term (>30 years), the magnitude of emission reductions is more important than the timing.

The aim of current work is to develop simplified dynamic models for making predictions across all areas of Europe to enable results to be included in

IA modelling. The policy maker might then consider not only recovery *per se*, but also the rate and extent of recovery achieved with any proposed abatement measures. Local and broad-scale modelling together will provide such information.

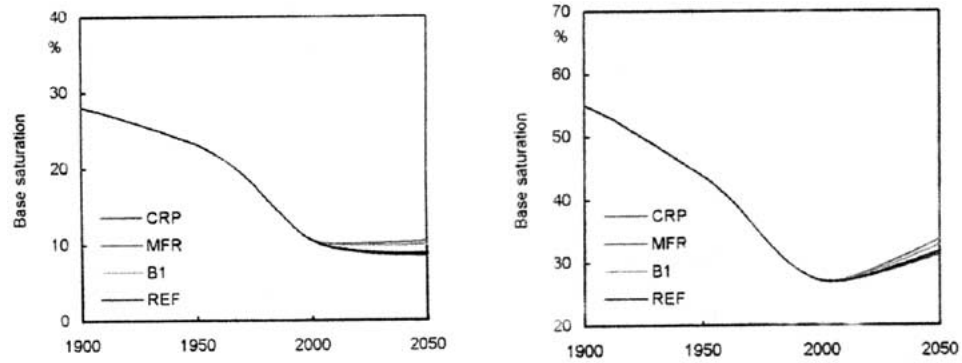

Figure 4. Dynamic models predictions for two catchments showing chemical responses in relation to four different possible future emission scenarios.

The dynamic models being developed are, as with many of the simple models, chemical models with simple links to biological effects. Relatively little work has been done on the dynamics of biological recovery processes, but those which have indicate that biological systems seldom revert to their original state when pollution loads decline. Ecosystem changes are complex, and much more work is needed in the future to enable useful predictions to be made. Furthermore, we cannot exclude the added complications of global climate change. This may influence energy scenarios, and hence emissions, as well as affecting ecosystem processes through changing climate (e.g. increasing temperature).

7. Discussion and conclusions

The monitoring and modelling activities of the ICPs have brought us a long way in the development of effective air pollution abatement strategies for the UN/ECE region. The work continues to underpin the priorities of CLRTAP. These priorities are now focused on the implementation and review of existing protocols, since recent protocols cover most of the major transboundary air pollutants so new protocols at this time are considered unnecessary. Hence the increased interest on recovery, or its absence, in the light of planned emission decreases, in addition to assessment of the magnitude and extent of damage throughout the UN/ECE region.

Now that abatement strategies are effects-based, the limitations of the scientific approaches available for decision making are becoming more apparent. For continued successful application of sound science, knowledge and models must be developed further. This is emphasized by the ever-increasing costs of abatement measures as emissions continue to fall. Decisions on decreasing emissions already cost much, and further spending must be based on confident predictions of benefits.

In the future therefore it will be of high priority to:

- Ensure biological thresholds and effects are incorporated into model predictions; for this, ecosystem changes must be simplified for policy interpretation;
- Extend the successful critical loads/IA modelling approach in an effective and transparent way;
- Incorporate dynamic elements into the predictions for the future, to provide timescales for recovery and change;
- Include more effectively the health effects of long-range transboundary air pollution in abatement strategies (these are not easy to quantify, or to disaggregate from local pollution effects);
- Include material and cultural heritage damage in the development of abatement strategies (these also need to be considered from local and transboundary pollution perspectives);
- Further develop advanced ozone response models for incorporation into IA;
- Focus increased attention on nitrogen effects, since these will become increasingly important as sulphur emissions decrease;
- Consider the importance of transboundary heavy metal pollution through an effects based approach as a means for taking further abatement measures.

Successful progress for all these will depend upon the continued development of science both at the national and international level. This in turn will require the basic information for better understanding environmental processes and for modelling – data. ICP monitoring activities are of paramount importance for this. They can provide data not only for model development now, but also for model validation in the future. Parties to the Convention recognize that monitoring, and the science associated with it, must be funded and efforts must be made to maintain the scientific networks. These have taken more than 20 years to establish, the Convention, and other national and international instruments for air pollution control, can ill afford to lose this vital asset. Other regions should take note of the benefits of establishing such scientific networks.

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