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Scenarios downscaling: qualitative comparison between RAINS-Europe and RAINS-Italy

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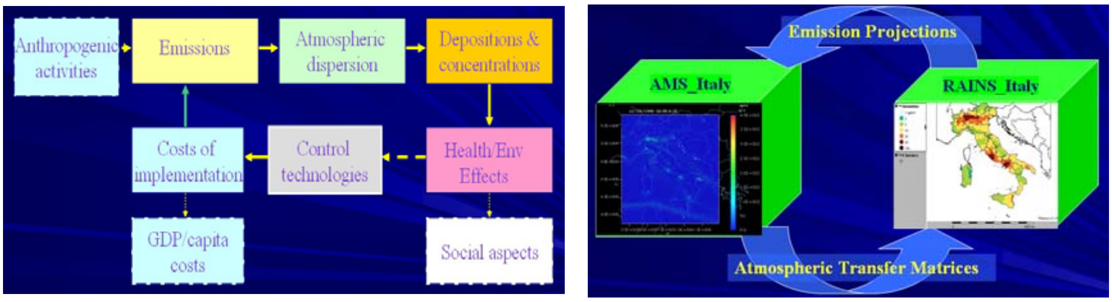
Abstract: At international level, in the frame of the UN-ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), as well as, in the context of the Community Environmental policies of the EU Commission, the RAINS-Europe model provides one of the most relevant examples of successful application of Integrated Assessment Modelling (IAM). Some European countries like Italy, among others, have tackled the issue of downscaling, introducing higher spatial resolution in similar models, pursuing the ultimate objective of a more adequate response to the need of evaluating, at national level, cost-effective policy measures to reduce air pollutant emissions, and, consequently, the pressure on environment and human health. As a result, the issue of adequate scaling in IAM becomes of the utmost importance to achieve the desired objective of a comprehensive representativeness of all the peculiar aspects, at each of the several stages of the modelling process: emissions estimates, application of abatement technologies, atmospheric pollutant dispersion, effects on ecosystems and human health. A number of issues which need to be carefully evaluated to finally establish to what extent downscaling has to be carried out, due to the difficulties in gathering detailed and accurate input data, and their consistency at the different scales. In this study, advantages and disadvantages of downscaling are explored, through a comparative analysis between impact scenarios over Italy, generated by the RAINS_Europe and RAINS_Italy models. The effects of the different resolution, 50 x 50 (km) vs. 20 x 20 (km) are highlighted, compared and discussed, in terms of impact on environment and human health, on the basis scenarios developed for the revision of the National Emission Ceiling Directive (NECD) of the European Union.

Keywords: *air pollution, spatial resolution, emissions scenarios, integrated assessment modelling (IAM), RAINS, environmental policies, impact scenarios, effects on human health.*

1. INTRODUCTION

In the last decade, at international level, particularly in Europe, in the frame of the UN-ECE Convention on Long Range Transboundary Air Pollution (LRTAP) and within the European Union, the Integrated Approach (Pignatelli et al., 2007), has been successfully applied for development of cost-effective policy measures, concerning air pollution and, more recently, also Climate Change. Consequently, a number of Integrated Assessment Modelling (IAM) tools have been created, continuously updated and underpinned by the work of the scientific community. Both the EU Commission and LRTAP have adopted the RAINS Methodology (Amann *et al*. 2004), to quantitatively develop policy measures, achieving air pollution reductions in a cost-effective way (Hordijk, *et al.,* 2007). A number of countries (The Netherlands, Sweden, Italy, etc.) have adopted the same (or similar in the case of UK, Oxley et al., 2007) methodology for policy development, at national level. Quite soon, the issue of scaling became one of the highest priority issues. Among national model developers the question : "*Which is the most appropriate scale in addressing air quality and impact issues, in IAM models, when moving from continental to national and local scale?*" has been one of key items under discussion. Different IAM Projects have given different answers according to their specific needs. This study aims at analyzing the pros and cons of the scaling down process, in the case of the Italian IAM Project, named MINNI (Zanini *et al*. 2005), in which the RAINS Methodology has been applied to create a national/sub-national scale model. The general flow-chart of the Integrated Approach applied to Air Pollution is reported in Figure 1a, showing the linkages among emissions, effects on the environment and human health, costs, technology etc. The pros and cons of scaling are discussed, in this paper, going through the main steps of the methodology. The effects of scaling are analysed for what concerns the emission calculation, the atmospheric dispersion, the effects on human health, in relation with the ultimate objective of the analysis, that is, to provide the policy makers with the most adequate elements to take policy decisions, in the most cost-effective way, although the cost analysis is not discussed in this study. The technical basis for the discussion is provided by the comparison between, impact scenarios developed by IIASA's RAINS-EU Model, in the frame of the revision of the National Emission Ceiling (NEC) EU Directive, and equivalent scenarios developed in Italy, by the RAINS-IT Model. The 2 sets of scenarios are considered equivalent since they are based upon the same methodology and input data sets, but at different geographical scale, continental/national/sub-national (e.g. different spatial resolution, on calculus domain, 50 x 50 (km) cells and 20 x 20 (km) cells, respectively, in RAINS-EU and RAINS-IT).



(a) (b)

Figure 1 - (a) Flow-chart of Integrated Approach to Air Pollution, (b) RAINS-IT and Atmospheric Modelling System in the MINNI Project

2. DESCRIPTION OF THE MODELS

Both RAINS-EU and RAINS-IT are widely and comprehensively described in literature, therefore a quite summary description is given here for completeness and to facilitate a better understanding of this study. RAINS (Regional Acidification INformation and Simulation), in its continental version RAINS-EU, has been recently extended to the greenhouse gases (GHGs), renamed as GAINS (Greenhouse Gases Air Pollution Interactions and Synergies, Klaassen, G., et al 2004), while preserving full consistency with RAINS for what concerns the analysis of the air pollutants. RAINS comprises analysis of SO_2, NO_x, NH_3, VOC, PM_{10}, $PM_{2.5}$ and ozone. Starting from anthropogenic activity levels (industrial production, transport, agriculture, livestock, electricity production, solvent use, etc.), emissions of the above air pollutants are calculated. Then (Figure 1a), dispersion of pollutants in the atmosphere, including chemistry of the atmosphere, is evaluated through the Atmospheric Transfer Matrices (ATMs), discussed later (§ 4.1). linking emission sources to concentrations/deposition, on the calculus domain. In RAINS-EU, ATMs follow a country-to-cell logic, while in RAINS-IT the linkage is region-to-cell. Estimated concentrations and deposition are then related to impact indicators, addressing acidification, eutrophication, statistical effects of $PM_{2.5}$ and ozone on human health, these latter based upon epidemiological studies and recommendations by WHO (WHO, 2003). If, for a given baseline emission scenario, the impact indicators are not satisfying the requirements of the existing legislations (CLE) or they are not consistent with the desired targets, then, additional abatement measures need to be implemented; further emission reductions are then calculated and recursively propagated through the system loop (Figure 1a), untill the policy objectives are finally achieved. Any further abatement measure includes the evaluation of the related abatement costs, also in relation with GDP and/or cost per capita, and social aspects like, for instance, the most exposed parts of the population (e.g. people living in urban areas). The recent extension to GHGs has introduced higher potential in the analyses, since cross-effects evaluations, in terms of synergies and trade offs, between Air Pollution and Climate Change, are now allowed in the new model GAINS.

In the following paragraphs the consequences of down-scaling from 50 x 50 (km), in RAINS-EU to 20 x 20 (km) in RAINS-IT are discussed in details.

3. EMISSION CALCULATION

The calculation of emissions is carried out by formula (1):

$$E_i = \sum_{j,k,m} A_{i,j,k} ef_{i,j,k,m} * (1-\eta_m) * R_m \quad (1)$$

where: *Ei* = Emissions in country or Region *i*

i,j,k,m = Country or Region, sector, activity, abatement technology

A = activity in a given sector (e,g, fuel consumption)

e*f* = unabated emission factor

η_m = removal efficiency of abatement technology *m*

R_m = Application rate of technology *m*

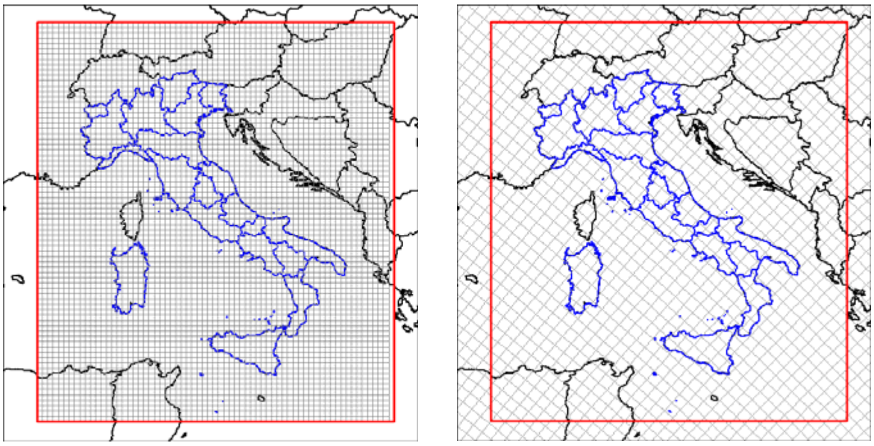
In particular, *ef* is the unabated emission factor which is combined with the *removal efficiency η* of the abatement technology and its *application rate R,* as specified by the user in the *Control Technology*, per sector/activity/technology combination, to provide emission *E. A* is the activity level, per sector per activity type, representing the intensity of the anthropogenic activity (e.g. fuel consumption, fertilizer use, solvent use, number of animals in livestocks etc.) entered by the user for all the Countries in RAINS-EU and all the Regions in RAINS-IT. In down-scaling from continental to country level, formula (1) is applied to smaller geographical areas. In RAINS-IT, these areas correspond to the administrative regions, with surfaces ranging between 3264 km^2 (Val d'Aosta) and 25710 km^2 (Sicily, about 8,5% of the total surface of Italy 301338 km^2). At lower scale, the number and type of emission sources, the allocation of the sources, the information on the abatement technologies are generally different than at national scale and often of better quality. In a number of cases, in fact, regional authorities have developed independent emission inventories, at a fine geographic scale (e.g. municipalities), based on detailed data available, at local level. Bottom-up emission inventories involve significant efforts for data collection and validation, but when available, these results, aggregated in space, can then be compared with the emissions calculated through RAINS-IT. In this respect, an extensive work has been recently carried out in cooperation with the local experts, to harmonize emission inventories and model emission calculations, at the reference year. Although being complex and in some cases still in progress, the process allowed to identify and solve mismatches and mistakes on both sides, ultimately improving the overall quality of inventories and the robustness of the model. Furthermore, the national modeling framework provided energy and industrial projections, often not available at regional level (e.g. two regions only had developed regional energy scenarios), allowing consistent emission projection calculation.

4. POLLUTANT DISPERSION IN THE ATMOSPHERE

Within the national modeling tools for integrated assessment in Italy, the atmospheric processes can be represented in two complementary ways: through Atmospheric Transfer Matrices (ATMs) and through direct 3D simulation (Figure 1b).

4.1. Atmospheric Transfer Matrices

As mentioned above, dispersion and chemistry of pollutants in the atmosphere are included in RAINS framework through ATMs., These matrices are obtained through off-line computationally intensive runs of an atmospheric modelling system, based on a 3D Eulerian model, the EMEP Unified Model (Simpson et al. 2003) in case of RAINS-EU and the FARM model (EEA MDS, 2005), in turn derived from STEM model (Carmichael *et al.*, 1998), in case of RAINS-IT. The FARM model is the core of the Atmospheric Modeling System (AMS-Italy). Figure 2 shows the calculus domains, in RAINS_IT (a) and EMEP (Italy, only) (b).



(a) (b)

Figure 2a, 2b – Calculus domain in RAINS-IT (a), 20 x 20 km cells, and in EMEP Unified Model (b) 50 x 50 km cells (Italy shown, only).

In both cases, atmospheric transfer coefficients are associated to each cell of the calculus domain, establishing a functional relationship between the emission sources and the values of the concentration/deposition indicators, in the cell. In RAINS-EU ATM coefficients are calculated as contributions to the cell from each country, while in RAINS-IT the logic is region to cell. For each cell and country or region, the coefficients approximate the response of the atmospheric system to variations of emissions respect to a reference case, considering one source area at the time, and keeping constant the contribution from the other source areas. ATMs provide annual average values of the indicators, in the cell area, and refer to a reference meteorological year (1996 in RAINS-EU, 1999 in RAINS-IT). In RAINS-IT a new set of ATMs is currently being developed, based on multiple meteorological years and calculated around a specific projected year (e.g. at 2015) of a future scenario to reduce the uncertainties, closer to the target years usually considered in policy development. This is because of the non-linear relationships between emissions and concentration changes, hence a linear relationship can be assumed with small emissions changes (EMEP considers +/- 15% interval). Non-linear response to Secondary Inorganic Aerosols (SIA) concentrations also results from cross-pollutant effects.

4.2. Coupled modeling systems

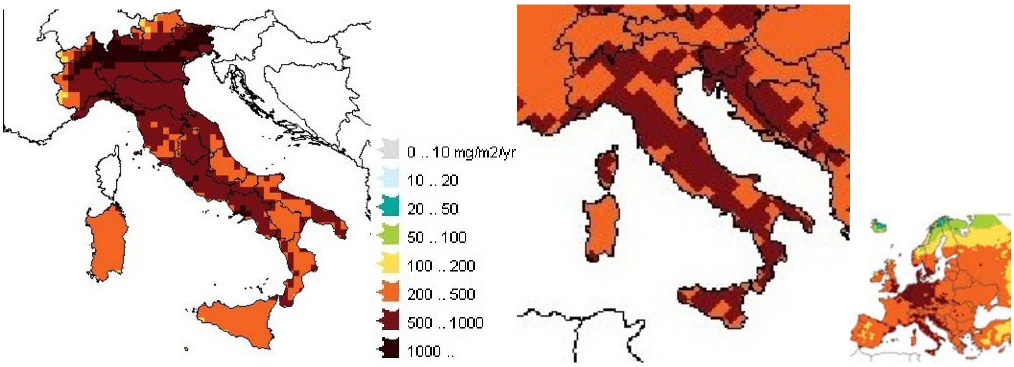
The direct use of 3D atmospheric transport-chemistry model is a different option for simulating the atmospheric processes, related to specific scenarios. In consideration of the above discussion on ATMs and the need, at local/policy level, of having forecasts on local areas where the EU legislation air quality limits could be exceeded, a different approach has been considered, in Italy. As said above, ATMs are calculated by AMS-Italy. Such modeling system takes emission inventories as input, with a high level of details in activities, space, time and chemical speciation. AMS-Italy simulates dispersion and chemical transformation of pollutants, taking into account the meteorology of a reference year (1999), and provides pollutant concentrations, at high spatial and temporal resolution, as output. The new approach comprises the combination of the projection of RAINS_IT with the high level of details provided by AMS_Italy. In practice, the emission trends of the RAINS_IT scenarios are used to derive projections, over years, of the inventory emissions. Such "projected emission inventory" is suitable to be used as input for AMS_Italy, or other local models, so taking advantage of the higher resolution of the atmospheric models, respect to RAINS_IT. This coupling of models has been successfully adopted for air quality assessment in some Italian Regions, where emission trends, calculated by RAINS-IT, have been used derive projections of national or regional emission inventories, in turn used as input to AMS-Italy or equivalent modeling systems, at 20 km or higher resolution, down to 4 km (Vialetto *et al*, 2009).

5. COMPARATIVE ANALYSIS OF SCENARIOS

The consequences of the different spatial resolutions are illustrated through the examples descripted in the following paragraphs, where results generated by RAINS-EU and RAINS-IT, for equivalent scenarios, are compared.

5.1. Nitrogen deposition

Nitrogen deposition is still causing serious effects of eutrophication in some parts of Europe and in Italy. An accurate analysis of such effects implies an accurate knowledge of the source distributions and related deposition levels on the territory and a detailed localization and definition of the eco-system properties. Down-scaling in RAINS-IT has allowed to allocate emission sources on the calculus domain, at a higher level of detail, for each of the 20 Administrative Regions, as well as, a more accurate technology penetration data have been introduced, region by region. Otherwise, some accumulation effects, due to local sources can not be fully represented by the average values in the 50 x 50 (km) cells of RAINS-EU. This is clear in Figure 3, where the nitrogen deposition maps for the Current Legislation Scenario (CLE), at year 2010, are reported, for the national and continental cases (in Figure 3b Italy is zoomed out from the EU map in the low right corner).



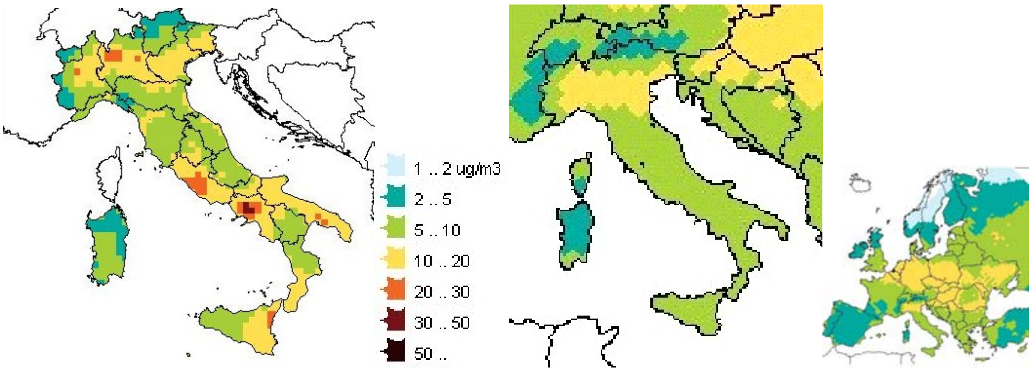
(a) (b)

Figure 3 – Nitrogen Oxides deposition (mg/m2/yr), at 2010, calculated by RAINS-IT (a) and RAINS-EU (b), CLE scenario

While the average levels over the country are consistent between the two models, the RAINS_IT calculation reveals some critical areas in Northern Italy, in the pre-Alpine region north of the Po Valley, as well as, hot spots in the most populated urban areas (Rome and Naples, notably). On the other side, in Sicily, the average deposition results lower in RAINS-IT than in RAINS-EU.

5.2. PM$_{2.5}$ concentrations and effects of PM$_{2.5}$ on human health

Figure 4 shows maps of annual average PM$_{2.5}$ rural background concentrations (primary and secondary inorganic aerosols, only), as calculated by RAINS-IT (a) and RAINS-EU (b, zoom out of Italy)

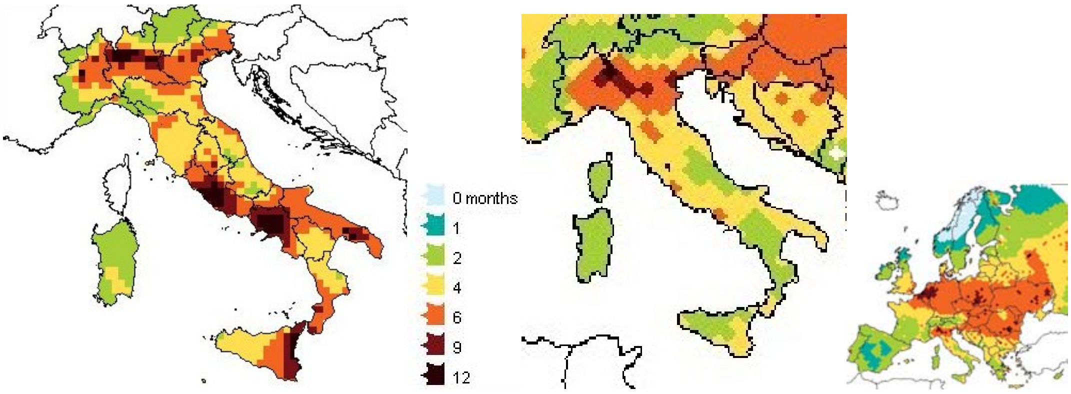


(a) (b)

Figure 4 – PM$_{2.5}$ rural background concentrations (μg/m^2/yr) (primary and secondary inorganic aerosols, only), annual average values, at 2010, calculated by RAINS-IT (a) and RAINS-EU (b), CLE scenario

In this case also, general consistency between two cases is visible, although obtained by underlying different atmospheric models and input datasets with different level of details. The higher resolution map (Figure 4a) shows a better definition of the hot spots occurring in the urban areas of Turin, Milan, Rome and Naples, as well as in the industrial sites of eastern Sicily and Taranto, in Puglie region. The higher concentrations are mainly related with traffic and domestic heating (extensive use of biomass). The effect of these sources does not appear clear due to the different resolution in RAINS-EU.

The differences highlighted in the previous maps have direct and significant consequences on the impact of anthropogenic $PM_{2.5}$ on the human health, considering the higher population density in the urban areas.



(a) (b)

Figure 5 – Impact on human health from anthropogenic $PM_{2,5}$, expressed as Life Expectancy Reduction (months), at 2010, calculated by RAINS-IT (a) and RAINS-EU (b), CLE scenario

Figure 5 shows how the Life Expectancy Reduction calculated by RAINS-EU, for CLE scenario at 2010, is significantly underestimated in and around the urban areas of Rome and Naples, as well as near Taranto and eastern Sicily (Italy zoom out in Figure 5b). This can be attributed to the combination of the different resolution of the underlying atmospheric models and differences in population distribution. In fact, the differences are less pronounced in the Po Valley in Northern Italy, where the lower populated areas give rise to emissions and impact patterns which are shown also in the RAINS_EU map.

6. DISCUSSION AND CONCLUSIONS

The comparative analysis discussed above has clearly shown that significant differences may arise from modelling at different scales, even when the same methodological approach is used.

In terms of impact on the environment, in this case nitrogen deposition, the down-scaling allows a more accurate identification of critical areas, otherwise hardly detectable, at continental scale.

For what concerns the impact on human health, in this case from exposure to $PM_{2.5}$, the down-scaling has highlighted areas, mainly urban and industrial sites, where the exposure of the population is higher and, as a consequence, the risk for human health is higher. Considering that the European Union has based its Thematic Strategy on Air pollution (EU COMM, 2005), on significant reductions of impact on human health from $PM_{2,5}$, it stems from that the higher accuracy of analysis is of the utmost importance for the correct cost-effective analysis of the effects on the population health.

In order to take into account the local peculiarities, the down-scaling is necessarily associated with a different modeling of the meteorological conditions and emissions distribution. In terms of emissions, a more accurate allocation by the sector and space, allows the policy makers, at national level, to focus the attention on those sectors where the potential of reduction is higher and / or the costs of reduction are relatively lower.

This can be also pushed further at level of the administrative regions of Italy, where local policy makers may have an better picture of the emission distribution. The scenarios developed by national modeling tools provide the basis to develop consistent ex-ante analysis of Regional Air Quality Plans, so eventually identifying the most effective sets of measures.

The combined use of the RAINS-IT policy model and the atmospheric dispersion models, provides a very efficient and flexible tool to further deepen the analysis. The characterization of the main indicators (e.g. concentrations) is so carried out at higher level of details and the non-linearities in the response of the atmospheric system is better taken into account.

On the contrary, the lower the scale the higher the level of resources engaged in the analysis, in terms of human resources, computational capacity, collection and validation of data, coordination among different institutions involved (e.g. statistics, economy, technology etc.), ultimately increasing costs and time requirements. Nevertheless, although taking in due account the scientific constraints, many countries in Europe have developed modeling tools, at national and sub-national scale, having recognized the importance and the need of developing integrated assessment analysis on air pollution and climate change, autonomously. In this way, national and local policy makers receive support in developing, scientifically underpinned and cost effective policies for the protection of the environment and the human health.

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REFERENCES

Amann, M., Cofala, J., Heyes, C., Klimont, Z., Mechler, R., Posch, M., Schöpp, W. (2004) The RAINS model. Documentation of the model approach prepared for the RAINS peer review 2004

Carmichael, G.R., Uno I., Padnis M.J., Zhang Y., Sunwoo, Y., (1998), Tropospheric ozone production and transport in the springtime in east Asia, J. Geophys. Res., 103, 10649-10671.

Commission of the European Communities (2005), Thematic Strategy on air pollution COM(2005) 446 final

EEA MDS (2005) Model Documentation System. European Environment Agency, European Topic Centre on Air and Climate Change, http://pandora.meng.auth.gr/mds/mds.php.

Hordijk, L. & Amann, M., (2007), How science and policy combined to combat air pollution problems, Environmental Policy & Law, 37(4), pp 336-340

Oxley, T., ApSimon, H. (2007), Space, time and nesting Integrated Assessment Models, Environmental Modelling & Software, 22, pp 1732-1749

Pignatelli, T., Monforti, F. Amann, M. (2007), Concept of Integrated Approach to Air Pollution and its potential applicability on a wide scale, presentation at the United Nations Commission on Sustainable Development (CSD), 15th Session, Side Event, May 2007 ialetto, G. *et al* (2009) Regional Air Quality Plans: assessment of plan efficacy through integrated assessment modelling and other local models, International Conference on Air Quality - Science and Application, Istanbul, 24-27 March 2009, Special session Air Quality Policy

Zanini G., Pignatelli T., Monforti F., Vialetto G., Vitali L., Brusasca G., Calori G., Finardi S., Radice P., Silibello C. The MINNI Project: An Integrated Assessment Modelling System For Policy Making (2005). MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, ISBN: 0-9758400-2-9, pp 2005-2011.

WHO (2003) Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide Report on a WHO Working Group

Pignatelli, T., Monforti, F. Amann, M. (2007), Concept of Integrated Approach to Air Pollution and its potential applicability on a wide scale, presentation at the Commission on Sustainable Development (CSD), 15th Session, Side Event, May 2007
http://www.un.org/esa/sustdev/csd/csd15/sideEvents/air_pollution_presentation.pdf

Klaassen, G., Amann, M., Berglund, C., Cofala, J., Höglund-Isaksson, L., Heyes, C., Mechler, R., Tohka, A., Schöpp, W., Winiwarter, W. (2004) The Extension of the RAINS Model to Greenhouse Gases. An interim report describing the state of work as of April 2004. IIASA IR-04-015

Simpson, D., Fagerli, H., Jonson, J., Tsyro, S., Wind, P., Tuovinen, J., 2003. Unified EMEP Model Description EMEP Status Report Part I,. http://www.emep.int/UniDoc

Vialetto, G. *et al* (2009) Regional Air Quality Plans: assessment of plan efficacy through integrated assessment modelling and other local models, International Conference on Air Quality - Science and Application, Istanbul, 24-27 March 2009, Special session Air Quality Policy.