The Climate-Air Quality Scale Continuum and the Global Emission Inventory Activity

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ABSTRACT

The Global Emissions Inventory Activity (GEIA), a core program activity of the International Global Atmospheric Chemistry (IGAC) Project of the International Geosphere-Biosphere Program, develops data and other related information on key chemical emissions to the atmosphere and communicates through its virtual center at www.geiacenter.org. GEIA inventories are developed by international teams and are quality assured through peer review publications. GEIA inventories are traditionally provided on a one degree latitude by one degree longitude grid, as annual and/or seasonal averages, and are aggregated over emission category sectors for individual chemical inventories. As researchers and decision makers world wide become more concerned about the relationship of global climate change and regional air quality, additional flexibility in tools, more highly resolved spatial scales of inventory development, and enhanced coordination among inventory developers will be needed. To address these growing needs, GEIA plans to distribute other important and quality assured emission information through its web site. New information will include underlying data sets from which the emission data were derived (e.g., activity data), global and regional emission inventory data at finer spatial resolutions and/or more refined temporal resolutions and expanded time periods, algorithms for modeling processes selected natural emissions, references to promising new approaches to emission estimates, such as satellite imagery and inverse modeling, and brief summaries of the state of knowledge regarding emissions of individual chemicals and source categories. Through planning and discussions with its network of over 500 emission data developers and collaborators, GEIA will seek to increase the awareness, development, and exchange of versatile data management systems and plans. With sincere and coordinated global community effort that facilitates modifications and quality assurance of databases, inventories that are more useful for examining the relationship between global climate change and regional air quality can be developed.

INTRODUCTION

The Global Emission Inventory Activity (GEIA), a program of the International Global Atmospheric Chemistry (IGAC) Project was established in 1990 as a result of the need of the international global climate and air quality community for methodologically uniform and reasonably current spatially-gridded emission inventories for modeling purposes.[1] GEIA is a consortium of volunteers, relying on the contribution of peer-reviewed global emission inventories by cooperating

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scientists. IGAC does not fund development and distribution of data. Inventory development is sponsored by a variety of organizations throughout the world, and depends on collaborating groups to develop the databases. The GEIA data management and coordination activity is funded by the United States National Science Foundation and National Aeronautics and Space Administration. Although regional and national emission inventories (principally of criteria pollutants) were and are available, they vary substantially in terms of contents, spatial and temporal representation, and emission estimation methodology. GEIA approached the problem of producing emission inventories for global modeling by means of extensive volunteer efforts following agreed formats and documentation procedures under five-year plans. It was agreed at the beginning of the process that the new inventories would be in a one degree by one degree longitude and latitude form, would be made available freely on the Internet, and would be documented by means of peer-reviewed journal articles.

GEIA is nearing the end of the current five year plan for 1998-2003, which has science and data objectives that began to address data needs related to broader assessments of regional air quality. GEIA's key scientific objectives during this five year period have included the following: enhanced uncertainty estimates, completion of biomass burning emission inventories, methane and carbon monoxide inventories, addition of natural emissions for key chemical compounds, source sector breakdowns, seasonal/monthly emission variations, updating inventories from 1990 to 1995, addition of finer grid resolutions and country emission totals, and references to predictive models where possible. There has been a recognition that the spatial and temporal resolution of current GEIA inventories does not meet increasing needs for fine resolution in climate and air quality modeling. In addition, the current GEIA data base is missing inventories for some of the chemical compounds that are key to climate and air quality modeling, including primary aerosols. Consequently, during the last GEIA international workshop, held in Paris in June 2001, new plans aimed at enhancing GEIA's role in helping to address regional-global spatial modeling continuum needs were initiated.

MODELING SPATIAL CONTINUUM, DATA NEEDS AND NEW TECHNIQUES

Historically, air quality modeling and climate modeling developed separately. Air quality modeling was treated as a relatively local short-term phenomena, and climate modeling was addressed globally or hemispherically on longer time scales. Increased understanding of the chemical and physical components of atmospheric circulation and chemistry, and increased computational capacity, made it clear that atmospheric dynamics and chemistry could not realistically be compartmentalized by spatial scale and chemical constituents if modeling accuracy was to improve. This problem is recognized in regional climate modeling by the need to post-process global climate model data to obtain realistic "down-scaled" data to drive regional climate models.[2] Improvement of the performance of global scale models is focusing on the need to include the chemistry of shorter-lived chemical species such as nitrogen oxides.[3] Recognition of the need for more detailed data has driven the establishment of improved emission data bases, such as GEIA, and efforts to improve the chemical completeness and spatial resolution of both climate and air quality models. There is now a partial convergence in research since, as a part of examining the effects of climate change, there are renewed efforts toward linking climate change with effects on air quality. For example, the U.S. Environmental Protection Agency's Office of Air and Radiation and Office of Research and Development have begun work to link the outputs of climate change models to the input conditions of the regional Community Multiscale Air Quality (CMAQ) model. The CMAQ and documentation is available on the Internet at http://www.epa.gov/asmdner/models3/ .

For regulatory purposes, air quality is normally evaluated relative to ambient concentration standards, violations of which are usually triggered by a combination of emitted pollutants and relatively extreme episodic meteorological events. The pollutants and meteorology are applied to three-dimensional gridded chemical transport models (CTMs) that use input emission data and meteorology data at spatial and temporal scales finer than for global climate models (e.g., 4 km to 50 km horizontal resolution with equations solved every few minutes vs. approximately 2 to 6 degree grid cell size horizontal resolution with half hourly equation solutions).[4] Within the U.S. Environmental Protection Agency, regional air quality modeling and the implementation of a unified "one-atmosphere" approach has led to regional high-resolution multi-pollutant air quality modeling as manifested in the Community Multiscale Air Quality (CMAQ) model.[5] Climate change research has demonstrated that data and processes needed for global modeling require relatively high resolution (sub-grid scale to a global climate model) in order resolve important processes such as urban pollution and biomass burning. Consequently, it is important to bridge between the global spatial and temporal scales of climate modeling to regional climate, and related regional and local air quality episodes.

Regional climate modelers are working to increase the spatial and temporal resolution of their models. Three general approaches have been used to date.[2] First, atmosphere-ocean general circulation models (AOGCMs) are used in conjunction with higher resolution atmospheric general circulation models run at 50 km to 100 km horizontal resolution for periods of interest. Second, regional climate models are nested from AOGCMs by using the meteorological, surface boundary and initial conditions from the global climate model to initialize the regional climate model. Regional climate models are run in horizontal resolutions of approximately 20 km to 125 km.[3] Third, statistical downscaling relationships may be derived between AOGCM variables and local variables reflecting physiographic features, land-sea distribution and land use. Continental to regional scale chemical transport air quality models are increasingly sophisticated, and now operate at spatial resolutions which range at the upper bound from the finer resolutions of regional climate models (approximately 50 to 100 km) down to 4 km resolution or less, such as CMAQ. The increased role of these chemical transport models is recognized in the Global Integration and Modeling (GIM) work, which, like GEIA, is a cross-cutting activity of IGAC, and seeks to improve coordination and inter-comparison of chemical transport models.[6]

Data Needs

Emission inventories are an increasingly crucial component in the modeling efforts. Examination of climate change effects on air quality at regional or local scales requires knowledge of a wider range of chemical emissions (e.g., traditional criteria chemical pollutants, toxic emissions, naturally occurring emissions) and related atmospheric chemistry than do traditional global climate change studies. In addition, there is a need for multi-pollutant emission data synonymous in time, current (e.g., year 2000) inventories, better identification of point sources (emission from stacks), and more highly resolved data either in terms of finer spatial resolution and/or by political unit and by emission source sector. It is also important to specify source-category-specific temporal patterns and species profiles of emissions, location information, surrogate data where necessary to allow spatial allocation of emission sources, emission modeling/estimation methods, and related activity data such as population, biomass burning, and land cover. To the extent possible, it is important to retain and report the greatest resolution of available information, to allow inventory developers and modelers to take advantage of resolution where it exits. Increased spatial and temporal resolution places greater demands on the accuracy of emission inventory data. Where coarse resolution might to some degree average or blur uncertainties in the emission data, finer resolution demands better information.

Finally, it is important to develop information on temporal emission trends and projections at a level useful for meeting the needs of both air quality and climate modeling. More spatially and temporally resolved data for the present will improve baseline accuracy for both higher resolution air quality and climate models, and could provide a common detailed "starting point". Air quality modeling is generally projected approximately 5 to 20 years into the future based on local and regional annual economic projection scenarios,[7] while climate modeling scenarios may be projected hundreds of years or more, based on a range of more generalized economic and physical possibilities (scenarios) for the world, such as those used by the Intergovernmental Panel on Climate Change.[8] Trend and projection scenarios of emission and activity data need to be developed on common spatial scales, and with compatible (not identical) methodologies for the 20 to 50 year range in order to be useful for examining the relationships between air quality and climate change in that time frame. Beyond 50 years, uncertainties are likely to mask any differences in air quality and climate modeling scenarios.

To better accommodate the examination of the effects of climate change on air quality, the products required from GEIA and other sources must become much more specific and accurate than the currently available information. Of course, this is a challenge because of the limitations of available data in general, and in some areas of the world in particular. The problem can approached by applying a combination of more highly resolved traditional emission inventories and new observational and modeling techniques.

Supplemental Emission Estimation Techniques

Establishment of a current high resolution emission inventory remains a significant problem in many areas of the world. Even where the data are relatively good, many uncertainties remain with respect to sources and some compounds, for example ammonia. Improving inventories by traditional reporting methods is constrained by cost and time limitations. Consequently, there is a definite need for supplemental inventory methods. The application of satellite sensors and inverse modeling of emissions are two techniques that may help improve accuracy as well as spatial and temporal allocation of emission inventory data sets.

The application of higher-resolution satellite sensors to near-surface tropospheric chemical constituents holds promise for significant improvement in verification of chemical transport models and emission inventories in the next ten years. The limited spatial resolution of satellite sensors, the interference of water vapor and carbon dioxide spectral bands, and the inability to penetrate the troposphere and distinguish the near-surface chemical constituents are long-standing problems with satellite-based techniques. New satellite sensors, such as the Tropospheric Emission Spectrometer (TES) (proposed for launch in 2004) should provide substantially increased chemical, spatial and temporal resolution in the longer term.[9] For example, TES proposes to use both nadir and limb (horizon) spectral sounding to detect ozone, water vapor, carbon monoxide, methane, nitric acid, nitrogen dioxide, nitric acid, nitrous oxide, and perhaps other chemical compounds, with a horizontal resolution of 5 km. The chemical concentration fields may then be compared with model simulated concentration fields, with differences having implication for improvements in emission input data.

Inverse modeling is not conceptually new to emission budgets and inventories, particularly at a global scale.[10,11,12] This technique is also being applied at regional modeling scales.[13] Basically, a chemical transport model is used to simulate the concentrations of chemical compounds using emission inventory input data; and the results are compared to measured concentrations. Using a statistical reverse modeling technique, emission adjustments are estimated that would normalize (e.g.; minimum least squares error) the difference between the observations and the model results. This generally provides information on the “closeness” of emission concentrations between monitored and modeled results and clues to where the inventory might most benefit from increased attention to sources and spatial and temporal allocation information. Inverse modeling has traditionally used data from surface air quality monitoring stations for comparison. As data from satellite sensors improve, inverse modeling capabilities will be advanced because more spatially representative chemical concentration data can be considered.

Inventory Uncertainty

Although compilation of detailed, consistent, regional and global emission inventories is difficult, it is crucial and often more difficult, to document their uncertainty. For this reason, GEIA has emphasized peer reviewed documentation of its emission data sets. Although any inventory has limitations, at least the user is alerted to the strengths and weaknesses. However, it has generally been infeasible to quantify uncertainty, especially after compilation of an inventory, because of loss of information about assumptions, and the need for more detailed information to describe uncertainty. An understanding of the uncertainty of emission inventories at any scale of resolution becomes increasingly important since emissions drive much of the change depicted by climate and air quality models. Improvements in quantifying uncertainty are consequently an essential goal. Quantification of emission inventory uncertainty have been attempted, but are not widely applied in practice. The EPA has devised a semi-quantitative descriptor, the Data Attribute Rating Systems (DARS), that assigns a relative weight to each component of an emission estimate.[14] The weights are then aggregated to an overall score. There has also been some research on quantifying uncertainty of specific emission components (as opposed to the overall inventory).[15,16,17] The challenges are to further develop quantifying techniques, and most importantly, to routinely apply them to emission inventories as the inventories are developed.

GEIA DIRECTIONS

To respond to the growing needs associated with the climate-air quality continuum analysis, GEIA plans to build on its existing data and emission information bases and principals, and provide the highest quality information possible for application to the spatial continuum of global-regional air quality modeling. This effort relies on the established infrastructure and network of involved researchers.

GEIA Foundations

The GEIA inventories provide a scientific foundation for policy initiatives designed to address urgent environmental issues such as global warming, stratospheric ozone depletion, acid precipitation and biological damage.[18] As these issues continue to become more pressing, GEIA has entered a new phase of revitalization, growth, and enhanced responsiveness to an expanding user community.[19]

GEIA is composed of a core of dedicated, international participants, many of whom have been active for over a decade. There are 28 projects, plus the data management and coordination activity which is responsible for the GEIA communication hub at http://www.geiacenter.org. Since 1990, GEIA has hosted 12 international planning workshops, and the GEIA e-mail network now includes almost 500 members. Data base quality assurance and protocol updating are ongoing activities.

GEIA collaborators have produced several emission inventories gridded by one degree of latitude and longitude for the Earth. These inventories, their documentation and GEIA projects are available on the Internet from the GEIA center. The list below includes more than a dozen available global data bases. Inventories are available or in progress for many specific chemicals or groups of chemicals and for several source categories such as biomass burning. Chemical-compound specific data bases are classified by emissions associated with human activities (A) and by natural processes (N). Additional emission data bases are organized by emission source, and a beginning has been made on spatial allocation surrogate data sets with the gridded population and land use data.

Available Inventories	**Inventories in Progress**
Ammonia (A and N)[20]	Dimethylsulfide (N)
Black Carbon (A)[21,22]	Organochlorines (A)
Carbon Dioxide (A)[23]	Radionucleides (N)
Carbon Monoxide (A)[24]	Methane (A)
Chlorofluorocarbons (A)[25]	Primary Particles (A and N)
Nitrous Oxide (A and N)[26]	HCFC (alternative chlorofluorocarbons)
Lead	HFC/FPG/SF6
Mercury	CFC (chlorofluorocarbons)
Methane (N)[27,28]	International Shipping
Sulfur and Nitrogen Oxides (A)[29]	Biomass Burning
Reactive Chlorine Emissions (A and N)[30]	
Volatile Organic Compounds (A and N)[31]	
Aircraft Emissions	
Lightning[32]	
Nitrogen Oxides from Soils (A)[33]	
Sulfur from Volcanos (N)[34]	
Population (activity data)[35]	
Cropland (activity data)[36]	

The GEIA data sets complement other information sources, particularly the Emission Database for Global Atmospheric Research (EDGAR) inventories compiled by the Netherlands Health and Environment Agency (RIVM) for greenhouse gases. The latter are available at http://www.rivm.nl/env/int/coredata/edgar/. In addition, collaborative global emission inventory compilations are available from the CGEIC on the Internet at http://www.ortech.ca/cgeic/ . GEIA and related web sites also contain maps of emission and support information data bases.

Plans

The 2001 GEIA workshop, held in Paris, was made more successful in that it followed a joint Precursors of Ozone and their Effects in the Troposphere (POET)/IGAC workshop entitled “Emissions of Chemical Species and Aerosols into the Atmosphere”. The combination of meetings provided topical reviews on the status of emission inventories, much interaction with the Global Integration and Modeling (GIM) community, and considerable discussion regarding future directions for GEIA.

Two new GEIA initiatives resulted from the workshop:

- to interact more closely with modelers and
- to broaden the kinds of emission information provided through GEIA

To encourage interaction with modelers, GIM and GEIA plan to hold workshops focused on common themes such as “Constraints on emission data based on satellite and in situ observations”. This direction agrees with the need for expanded use of non-traditional methods of composing emission inventories discussed previously. For example, modelers are increasingly estimating and refining emissions with the help of field measurements (e.g, the Biomass Burning Experiment), inverse modeling and, more recently, satellite data. These techniques can be used in conjunction with traditional emission data, both to expand and verify existing inventories. Therefore, joint modeling and emission workshops on emission constraints are an appropriate and productive next step for GEIA and the modelers.

Model evaluation is another important role for global emission work. GIM studies global distributions, global budgets and evaluations of trends over time. This is done by development and implementation of chemical transport models and by intercomparison of modeled concentration fields, e.g., of ozone, CO, NOx, SO_2 and precursors; and dynamic aerosol modeling. In particular, inventories of radon or SF_6 are very important because these chemicals can be used as tracers to help evaluate the transport features of the models.

Some official GEIA inventories are considered "out-of-date" by modelers and other data developers because they are typically compiled for 1990 or 1995. There is less need for a number of updates since the more recent peer-reviewed EDGAR data sets are available and widely used, and in many cases are cited by GEIA as reasonable "non-GEIA" data. Substantial time and resources of the volunteer community are required to address the publication and the related formal peer review pre-requisites needed for a data base to become a formal GEIA data base. In view of this resource constraint, a more feasible and valuable contribution for the GEIA community at this time is to address the growing need for a determination of which emission information is now available at global and regional scales, and provide critiques of its quality.

As a first step towards realizing the broadened role for GEIA as an informational data center for emissions, GEIA is organizing expert groups qualified to provide information for the web site, and to quality assure information to be placed on the site. The objectives will be to provide references to alternative emission inventories or (for national sources) scenarios with comments regarding the strengths or limitations of each; and to incorporate data sets and algorithms (e.g., emission factors) from which emission data can be derived.

Other steps being considered include allowing different data sets for one source category or compound, just as there are different models used by GIM, provided that the origins of the differences are clearly documented. Different versions of an inventory through time (e.g., different years) also ought to be documented. It is important to highlight emission trends through time. As part of this activity, it also will be important to periodically prepare review papers inviting the scientific community to contribute additional or updated information and propose priorities for modifications.

Addition of emission-related data sets contributed by others, e.g., activity data or information on seasonality, is also being considered for the GEIA web site. GEIA is also considering providing references to both inventories judged scientifically by the GEIA community, as well as official government inventories. To capture this valuable information, activities may be initiated to expand the present GEIA web site to include a web page for each compound with information about the data available. GIM could be used as an evaluation tool for different emission data sets.

Overall, the GEIA, GIM and other communities recognize the need for dynamic rather than static inventories, through which variations on all time scales (diurnal to inter-annual to future years) might be simulated. In order to make GEIA more responsive to informational needs, the contents of the GEIA site might be broadened further to include, for example, dry deposition information and information on combinations of feedbacks that might affect future emissions.

In summary, GEIA is embarking on the following new initiatives:

- provide web site references to non-GEIA emission data sets with descriptive comments (this requires collaboration with other (non-GEIA) groups and a review of proposed additions);

- provide, through its web site, underlying data sets and algorithms from which the emission data were derived (viz. activity data, calculation algorithms for nationally-provided emission sources, and seasonal temporal profiles of emissions);

- interact more closely with air quality modelers, hold joint meetings with GIM and similar other modeling efforts, and seek joint modeling/emission activities;

- provide clear definitions of the contents of emission data sets and the starting point of modeling with respect to the data sets (e.g.; primary emissions, extent of (natural) sinks included; and dry deposition calculated by atmospheric models);

- provide long-term historical and future trends of emissions;

- provide information on the seasonality of emissions;

- provide information on short-term inter-annual changes of emissions in subsequent years;

- provide (references to) key scenarios for future emissions available on a gridded basis, e.g., the IPCC scenarios; and

- provide more precise labeling of the reference year of the emission inventories.

CONCLUSIONS

The growing need to better understand the relationships between regional air quality and climate change is placing new demands on models and emission data bases. Most currently available global data bases are provided on spatial and temporal scales that are much too coarse for application across the global-regional modeling continuum. Meeting these data base challenges will require an increased international and coordinated response since there must be greater consistency and quality for this new class of emission inventories.

GEIA, as an established and recognized global emission data base coordinating body, is moving forward to better address these enhanced data needs. The GEIA foundation provides a suite of quality assured data for many of the key chemicals of concern with respect to climate change and air quality. However, many of these data need to be updated and expanded, or replaced, by more current information.

The primary role of GEIA in addressing the now pressing need for new information more relevant to studies of regional and global issues goes beyond providing the data bases themselves. A more immediately useful role for GEIA is to be an international coordinating body. In this capacity, GEIA will provide a formal and internationally accepted organizational structure for identifying the state of knowledge of available data and progress on development of new techniques and management systems. GEIA, through its network of experts, will also help provide quality assurance of information to be distributed.

For development of the necessary new information and data bases needed for regional and global studies, it will be essential for GEIA and other groups to come together in a collaborative mode for the greater good of the overall assessment community.

DISCLAIMER

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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The Global Emissions Inventory Inventory Activity (GEIA), a core program activity of the International Global Atmospheric Chemistry (IGAC) Project of the International Geosphere-Biosphere Program, develops data and other related information on key chemical emissions to the atmosphere and communicates through its virtual center at www.geiacenter.org . GEIA inventories are developed by international teams and are quality assured through peer review publications. GEIA inventories are traditionally provided on a one degree latitude by one degree longitude grid, as annual and/or seasonal averages, and are aggregated over emission category sectors for individual chemical inventories. As researchers and decision makers world wide become more concerned about the relationship of global climate change and regional air quality, additional flexibility in tools, more highly resolved spatial scales of inventory development, and enhanced coordination among inventory developers will be needed. To address these growing needs, GEIA plans to distribute other important and qality assured emission through its web site.

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