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Science Features

GLOBAL IGBP CHANGE
A Core Project of the Internations Geosphere-Biosphere Programme

iCACGP
In Cooperation with IAMAS Commission on Atmospheric Chemistry and Global Pollution

A Note from the IGAC Co-chairs: Kathy Law and Tong Zhu

This issue of *IGACtivities* contains three articles relating to the IGAC/SPARC Atmospheric Chemistry and Climate Initiative ("AC&C"), first introduced in IGACtivities Issue No. 36 (see http://www.igac.noaa.gov/newsletter/index.php). In the first phase of AC&C, the goal is to understand and improve on the representation of chemistry-climate interactions in earth system models. This is being accomplished through a series of AC&C activities, two of which are described in part herein, and through parallel cross-cutting efforts, such as through emissions harmonization described here by Lamarque et al. Model runs for the activities described here are planned for completion in late 2009 (hindcast runs) or early 2010 (ACC-MIP runs). All AC&C activities are open to participation; interested parties should review the planning documents referenced in the articles and are free to contact us (igac.seattle@noaa.gov) for more information.

Under the AC&C "Hindcast" activity, chemistry-climate models will be used to generate time-series of inert tracers (CFCs, N_2O), ozone, methane and aerosols for the period 1980-2007 and for the year 1850 (pre-industrial). These past distributions will be compared to observations as a way of testing the models and will be used for model-model comparisons in order to better understand controlling processes. The aerosol portion of the Hindcasts are being organized and carried out under the auspices of the AeroCom (aerosol model intercomparison) project. Schulz et al. herein review AeroCom's past accomplishments and findings and described plans for the project's next phase, including those for AC&C.

Another activity under AC&C will be to simulate future distributions of chemically active species and to accompany these with diagnostics (e.g. deposition rates, chemical reaction rates, tracer distributions), for a range of future emissions scenarios. These are being designed to be consistent with the climate runs that will be done for the next Intergovernmental Panel on Climate Change Assessment, IPCC AR5. Effectively this will be an expansion of the climate Model Intercomparison Project (MIP) to include an Atmospheric Chemistry and Climate MIP (ACC-MIP). This activity is described by Shindell et al.

To facilitate the comparability of both the "Hindcast" and "Scenarios" runs it is necessary that the models employ a uniform set of emission scenarios in at least one set of runs. In addition, to be of utility in understanding future climate, the emissions for short-lived species should be consistent with those for the long-lived greenhouse gases. Past IPCC assessments have suffered from a lack of consistency in the emissions used to determine the distributions of long-lived greenhouse gases vs. those used to determine the distributions of other radiatively active species (e.g. aerosol); from a lack of consistency in the emissions used in different models that generate aerosol distributions; and from inconsistency in the transition from past emissions to future emissions for short-lived species. The article by Lamarque et al. describes recent efforts to produce a new set of emissions which address these issues and which will be used in the AC&C "Hindcast" and "Scenarios" model runs.

As always, we hope you find these articles useful in your own research endeavors, and we welcome your feedback on these and other IGAC activities.

The Aerosol Model Comparison Project, AeroCom, Phase II: Clearing Up Diversity

Contributed by **Michael Schulz** (michael.schulz@cea.fr), *Laboratoire des Sciences du Climat et de l'Environnement, Saclay, France*, **Mian Chin**, *NASA Goddard Space Flight Center, Maryland, USA*, & **Stefan Kinne**, *Max-Planck-Institute for Meteorology, Hamburg, Germany*

Introduction

Aerosols are now such an established part of the conversation about climate that it is easy to forget how recently the scientific community recognized their role and how recently we started to be able to assess their radiative impact through both measurements and models. The international activity AeroCom was initiated in 2002, in light of many new observations from satellite, ground-based networks, and coordinated field campaigns that had become available after earlier model intercomparisons efforts in 1997 (Comparison of large scale Atmospheric Sulfate Aerosol Models, COSAM[1] *Barrie et al., 2001*) and 1999 (for the IPCC Third Assessment Report, *Penner et al., 2001*). A major goal of AeroCom was to establish data test-beds against which the performance of individual aerosol modules could be tested. Hereby, the focus was not so much on overall performance but on performance at sub-process levels. The ultimate motivation was to better address the large uncertainty attributed to aerosols when exploring anthropogenic climate change. Since 2003, seven AeroCom workshops have been hosted by participating groups at Paris, Ispra, New York, Oslo, Virginia Beach, Lille and Reykjavik. These workshops provided a platform for exchange among modeling groups and for interactions between modelers and data-providers and lead to fruitful discussions on model representation of atmospheric aerosols and the satellite and ground-based aerosol observations now available to test the model output. To date, twenty modeling groups have participated in coordinated model experiments and have submitted their model output to a common database, held at the LSCE, Saclay, France. The compilation and analysis of AeroCom results, which were also summarized in the published literature, contributed the 4th IPCC assessment, resulting in new total aerosol radiative forcing estimates which clarified the picture in the IPCC radiative forcing bar chart: The main, though largely uncertain, counter-balance to greenhouse gas warming in current top-of-atmosphere radiative forcing is provided by atmospheric aerosol. Further, the uncertainty in total anthropogenic climate forcing is dominated by the uncertainties in aerosol forcing.

AeroCom is mostly a volunteer-based coordination effort which has never benefited from a source of overarching funding. However, groups contributing to the AeroCom database have received research support from several EU projects (CREATE, PHOENICS, EUCAARI, GEOMON) and from the space agencies NASA (US) and CNES (France). Since 2007 AeroCom has also been a part of the IGAC Atmospheric Chemistry and Climate (AC&C) initiative. Since the initial round of AeroCom analyses, models have evolved and modelers are now preparing new simulations for the next IPCC report (AR5). Some of this is being coordinated under the AC&C initiative with the goal of providing past and future aerosol distributions that can be more readily assessed for a "best-guess" and uncertainty bounds on global aerosol distributions and properties (see accompanying article by *Shindell and Lamarque*). Further, the AC&C aerosol runs will employ emissions scenarios which are consistent with those used for short- and long-lived gas-phase species (see accompanying article by *Lamarque, Granier et al.*). It is thus timely at this juncture to summarize the lessons learned in the first phase of AeroCom assessments and to discuss the needs and planning for a second phase of AeroCom, and we do so herein.

AeroCom phase I: AeroCom A, B and PRE experiments and model documentation needs

The initial work in the AeroCom model intercomparison provided a fair documentation of the state of the art of global aerosol modeling (*Textor et al., 2006, Kinne et al., 2006, Schulz et al., 2006 and Penner et al., 2006*). Almost all major international model groups participated and results from ca. 50 model simulations can now be found on the AeroCom data server. These correspond to AeroCom experiments A ("models as they are"), B and PRE ("models using prescribed AeroCom emissions" for present, B, and pre-industrial, PRE, conditions; see *Dentener et al., 2006*). For the first time a set of multi-component aerosol models, often resolving aerosol size, had been analyzed. Based on this analysis, it appears that significant diversity exists among models for a large set of diagnostics parameters, due to different assumptions about emissions, transport, humidity growth, removal pathways and optical properties (*Textor et al., 2006*). An attempt to eliminate some of the diversity by prescribing

[1] The WCRP/IGAC sponsored Comparison of Large Scale Sulphate Aerosol Models study (COSAM) compared the performance of atmospheric models with each other and with observations. It involved design of a standard model test for the world wide web, broad international participation in model simulations conforming to that design, the assembly of a new global set of $SO_4^{=}$, SO_2, MSA observations and a workshop in Halifax Canada to analyze model performance and future model development needs. The global sulphur and ^{222}Rn/ ^{210}Pb cycles were simulated.

emissions within experiment B showed that differences in emissions are not the main cause for model diversity (*Textor et al., 2007*).

From further analysis of the AeroCom results, shown below as examples, we concluded that the actual process coupling in each model is difficult to understand without additional joint experiments and diagnostics. This raised the question of whether sensitivity experiments with reasonable bounding assumptions performed within one model could reproduce the span of diversity across the AeroCom contributing models. Such work has since been started. *Bian et al.* (*2008*), for example, investigated the spatio-temporal variability of relative humidity and its impact on aerosol optical depth, showing that this factor alone might explain part of the differences among AeroCom models.

However, a clear understanding of the diversity found in the initial AeroCom comparison has not yet been reached, and this problem deserves to be resolved. Previous to the AeroCom analysis, the large inter-model diversity was not recognized, and we note that it may have developed through the isolation of the different modeling groups. Global aerosol models, imbedded in transport or climate models, have become too complex to be documented by traditional publication means only, such as peer reviewed papers. A lot of spatial and temporal detail on the simulated aerosol budget, aerosol size, optical properties and speciation details are not worth being published in a single-model paper and so it was easy for large differences to go unrecognized. We hope that through efforts such as AeroCom these differences can be brought to the fore and be used to understand how they affect derived aerosol distributions and properties.

Evaluation with observation data

The AeroCom models have also been compared to different observational datasets, the most prominent being the datasets from the ground-based sun photometer network, Aerosol Robotic Network (AERONET) (*Kinne et al., 2006*). Surface concentrations of dust, sulfate, black carbon, particulate organic matter, aerosol optical depth and aerosol extinction and extinction vertical profiles stem from global and regional networks of GAW, AERONET, IMPROVE, EMEP, Aeroce and Earlinet. Satellite observations have been assembled primarily from POLDER/Parasol and MODIS, but also MISR, TOMS and AVHRR. Simple statistics have been established to give a first idea on modeling skill. Results can be viewed via the AeroCom web interface, described below. Ranking of models based on such model-data comparisons is tempting but is probably not as powerful as one would hope it to be. *Gleckler et al.* (*2008*) provide a good discussion of the similar problem of scoring climate models against observations. The scores for the AeroCom models established against different data sets did not unveil a unique ranking of model quality. Although some models are found more often in the group of the “better” models, they fail with respect to reproducing all properties equally well. Such inhomogeneous performance of the models may be interpreted in different ways: It may indicate that the different modelers have specialized in order to reproduce aerosol observations in certain regions and thereby biased the model with respect to other parameters. Notably, it may simply indicate that the applied observational data are not sufficiently representative and that the scores themselves bear uncertainty and do not allow for a clear ranking. The models with better performance for a parameter, however, do suggest that there is room for further model improvement.

An important added value of the AeroCom database compilation is the conclusion that there may be gains by using the model ensemble. A median model constructed from all AeroCom models has been compared to two reference datasets of aerosol optical depth observations from MODIS and AERONET. The median model is shown to be a stable model with the lowest RMS error and correlation coefficients matching that of the best individual model. Other satellite-derived AOD datasets have also been compared to MODIS and AERONET and do not outperform the median AeroCom model. These findings indicate that a combined aerosol model offers a chance to derive a better estimate of aerosol properties. This applies in particular to parameters which are difficult to observe but nevertheless highly relevant, such as the aerosol radiative forcing.

Aerosol microphysics and number budget

The simulation of aerosol size is crucial for understanding the aerosol number budget and, through this, the availability of cloud condensation nuclei. Aerosol size also determines the efficiency of the aerosol at scattering light, its ability to act as long-range carrier of matter and its integrated radiative impact: Coarse particles sediment quickly and they are more efficiently scavenged by settling hydrometeors. The simulation of size is done differently in different models, depending on the chosen degree of complexity. Different numbers of modes for a modal distribution and varying sets of size classes for a bin scheme interplay with assumptions on chemical composition. The initial AeroCom protocol only asked for a fine and coarse mode classification of mass and optical depth, with the idea that these can be verified with information from sun photometers or with MODIS, MISR or POLDER retrievals. In retrospect, this clearly was not sufficient information to evaluate the different approaches to treating size in different models. The divergence of the size distributions of “natural” species among the AeroCom models is partly caused by the sizes of the emitted particles, and partly by the simulated removal processes. However, *Textor et al.* (*2006*) showed that it was not possible to differentiate between these two options using the information available from the AeroCom datasets, because a large fine mass fraction can either be the reason for slow dry removal rate coefficients for fine particles (calculated from the burdens and the fluxes) or – in contrast – be the result of a fast dry removal rate for large particles.

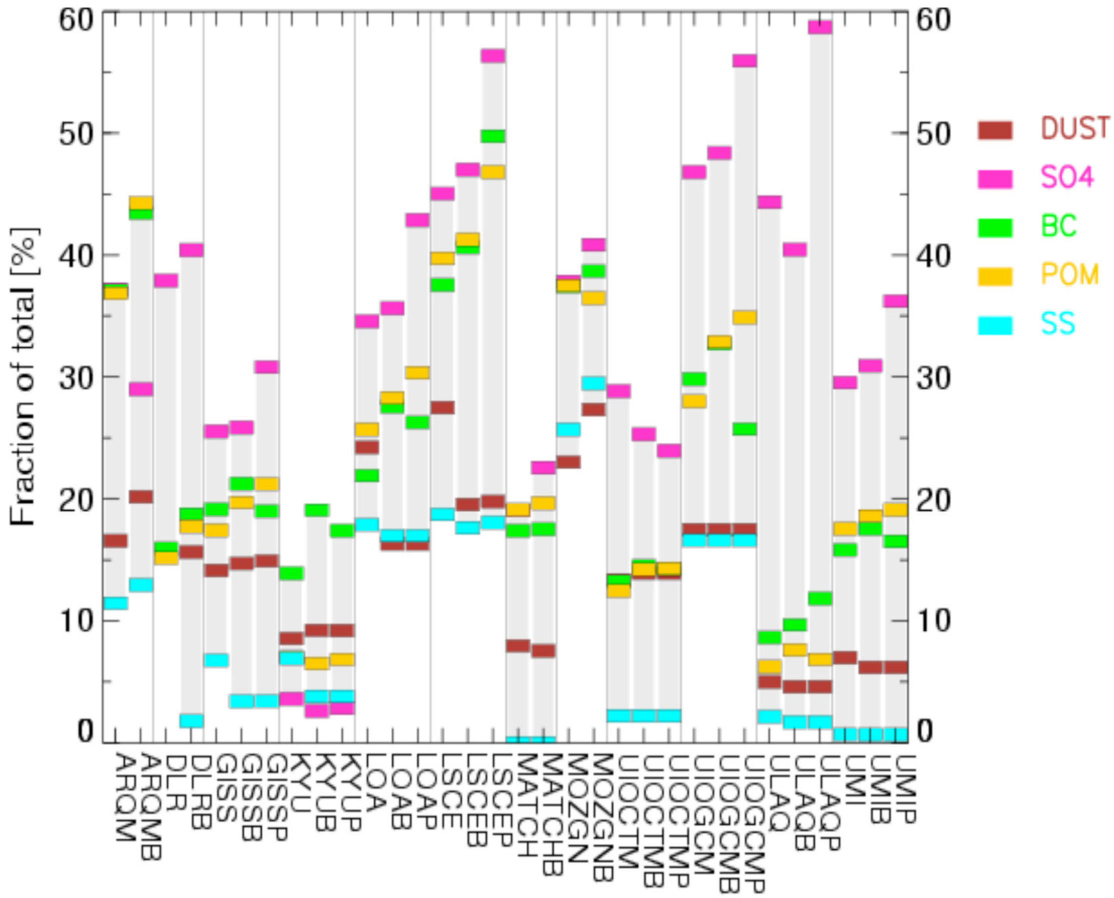

Figure 1. Simulated mass fraction of major aerosol compounds found above 5 km altitude, globally averaged. Up to three experiments per model: AeroCom A (original model state), B (present-day prescribed emissions) and PRE (preindustrial prescribed emissions). Simulations representing experiments B and PRE are identified by original model names expanded by abbreviation B and P (model versions correspond to *Textor et al., 2006* and *2007*).

Global aerosol mass budget

The aerosol mass budget is a powerful diagnostic for a global model, not only because it reveals model problems with mass conservation but also because it summarizes the overall efficiency of removal processes and the simulated spatial coincidence of wet or dry removal with high aerosol loads. Globally averaged residence times are independent of the amplitude of emissions and can be used to interpret emission scenarios without running the transport model. However, residence times may change if there are temporal changes to spatial patterns of emissions, spatial patterns of removal or to vertical mixing. For instance, it is not clear how the recent shift of declining emissions from Europe and North America and increasing emissions from East Asia translates into global aerosol loads.

Unfortunately, there is no easy observational constraint on total aerosol residence time and even less so on that of individual aerosol components. The diversity across models found in the early AeroCom experiments is impressive across a large variety of parameters, such as vertical distribution, removal process split, inter-species differences of loads or temporal variation of loads (*Textor et al., 2006 and 2007*). For example, the range in model-derived vertical aerosol distribution for different experiments, as shown in Figure 1, points to major structural differences in the component mass budgets across models.

Aerosol direct and indirect radiative forcing estimate

AeroCom results from simulations of present day and pre-industrial aerosol distributions have been used to establish anthropogenic aerosol loads, optical depth and radiative effects. These experiments contributed to the IPCC Fourth Assessment Report, with the new radiative forcing bar chart including one estimate for the combined direct aerosol forcing. A combination of observational-based and model-based forcing estimates yielded a best guess for the direct aerosol radiative forcing of -0.5 Wm^{-2}, with a 90% confidence interval for the actual forcing of -0.1 Wm^{-2} to -0.9 Wm^{-2}. The larger number of model estimates, the constraints on total aerosol

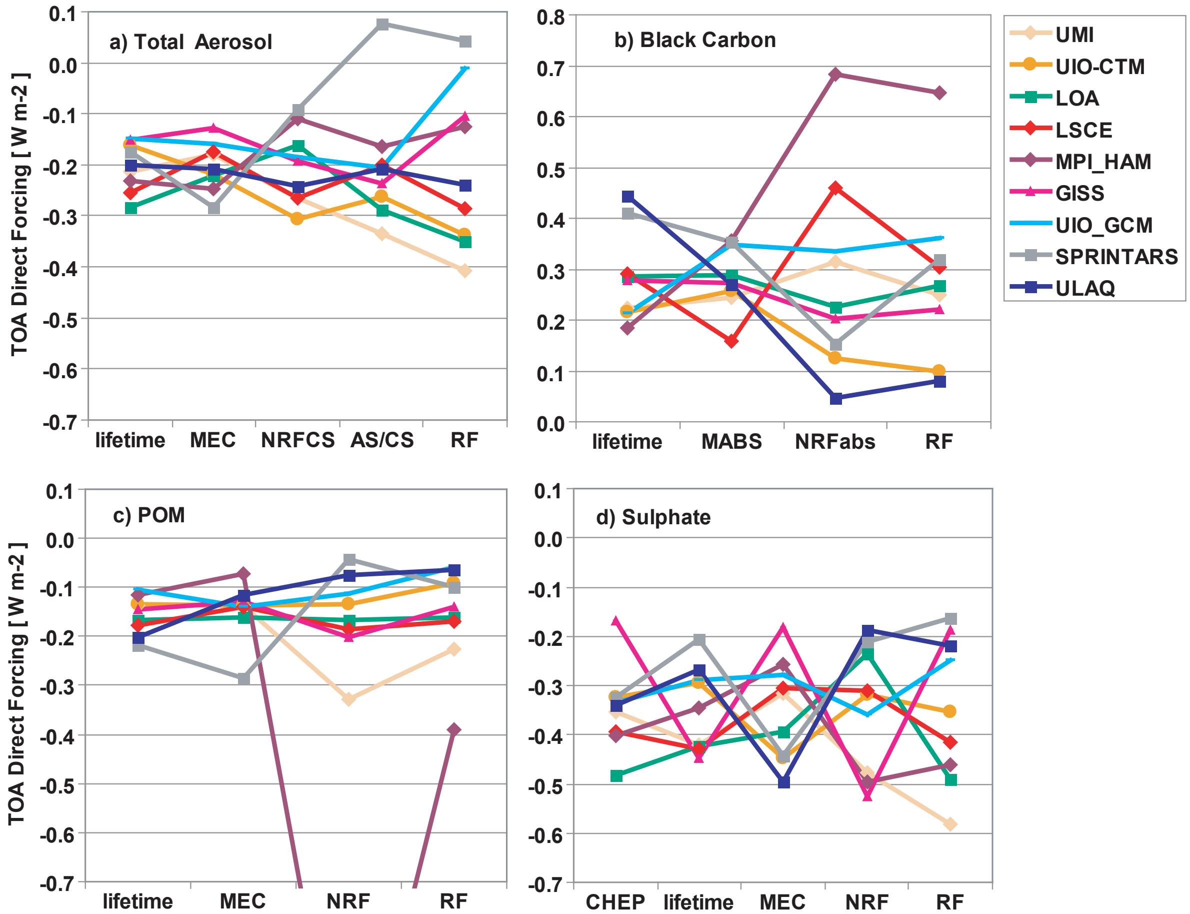

Figure 2. Partial sensitivity of aerosol forcing to variation in different factors x (see below) of the total anthropogenic aerosol and components in AeroCom models. Shown are recalculated forcings Fx,n=xn/<x><RF>; with xn/<x> being the ratio of factor x of model n over its respective AeroCom mean <x>; and with <RF> being the mean AeroCom aerosol or component forcing. The factors x shown are: "CHEP" ratio of sulfate chemical production over emission of SO2; "lifetime": residence time in the atmosphere; "MEC": Dry mass extinction coefficient; "MABS": BC aerosol absorption coefficient; "NRF": Normalized radiative forcing per unit optical depth; "NRFabs" Normalized radiative forcing per unit absorption optical depth; "NRFCS": Normalized clear-sky radiative forcing per unit optical depth; "AS/CS": All-sky over clear-sky RF ratio; "RF"-column: represents original total aerosol or aerosol component forcing in each of the AeroCom models. (from *Schulz et al., 2006*)

optical depth from remote sensing and intensive field campaigns have led to a more certain combined direct aerosol forcing estimate. *Haywood and Schulz* (*2007*) show that the uncertainty in total anthropogenic forcing became appreciably smaller because of the reduction in uncertainty of the direct forcing of aerosol between the fourth and third IPCC Assessment Reports.

However, the uncertainty in the direct aerosol radiative forcing is still large and needs to be reduced. This requires understanding of which processes in the models affect aerosol properties and distributions. Figure 2 shows the range of sensitivity of aerosol radiative forcing to variations in aerosol lifetime, mass extinction coefficient, absorption coefficient, and radiative forcing efficiency per unit optical depth for AeroCom models. The absorption coefficient and the forcing efficiency per unit absorption optical depth in particular are seen to contribute to the range in derived aerosol radiative forcing. However, the uncertainty on all steps from emission to forcing suggests that one could considerably reduce the uncertainty on aerosol radiative forcing if only the link between the optical properties and the forcing was better understood. Models which assimilate aerosol optical depth would then provide a good basis for more robust estimations of the direct aerosol forcing.

Within AeroCom nine different global models with detailed aerosol modules have independently produced instantaneous direct radiative forcing due to anthropogenic aerosols (*Schulz et al., 2006*). The anthropogenic impact is derived from the difference of two model simulations with prescribed aerosol emissions, one for present-day and one for pre-industrial conditions. The difference in the solar energy budget at the top of the atmosphere (TOA) yields a new harmonized estimate for the aerosol direct radiative forcing (RF) under all-sky conditions. On a global annual basis RF is -0.22Wm^{-2}, ranging from +0.04 to -0.41Wm^{-2}, with a standard deviation of ±0.16Wm^{-2}. Anthropogenic nitrate and dust are not included in this estimate. No model shows a significant positive all-sky RF. The corresponding

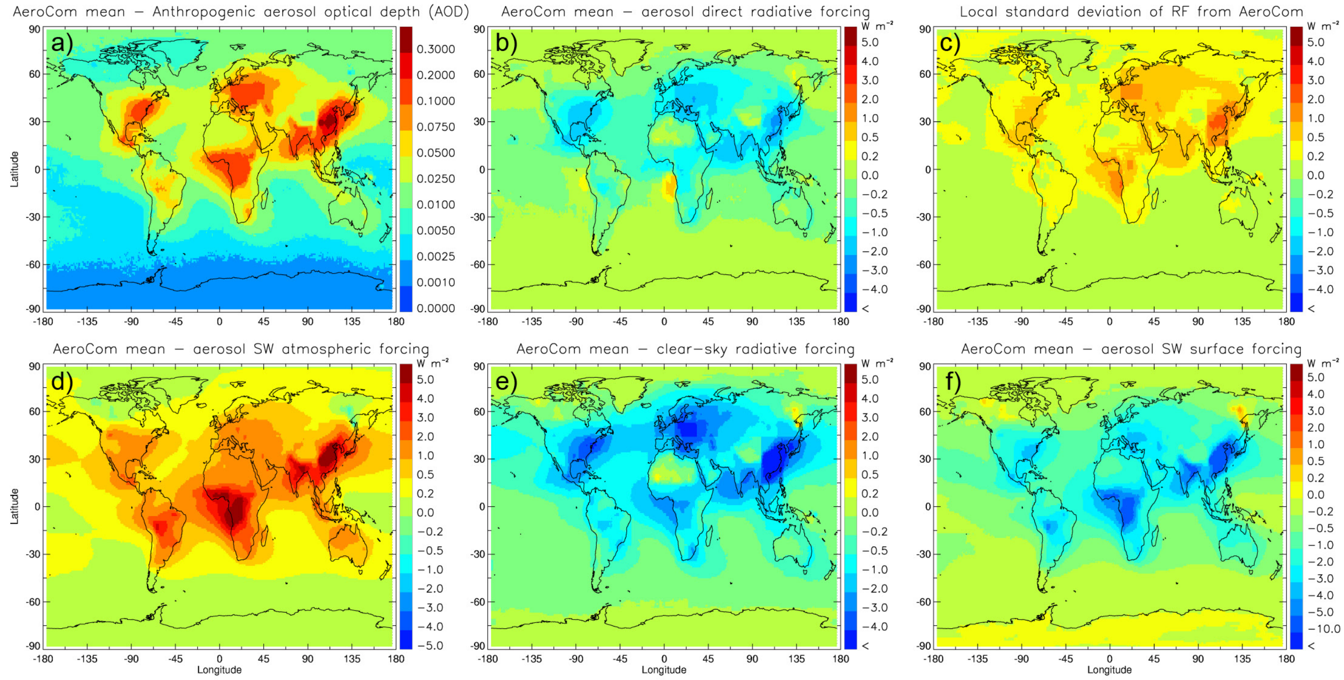

Figure 3. Mean annual fields derived from nine re-gridded AeroCom B and PRE model simulations of a) anthropogenic aerosol optical depth; b) radiative forcing; c) local standard deviation from 9 models of radiative forcing corresponding to b); d) atmospheric forcing of column; e) clear-sky forcing; f) surface forcing. (see also *Forster et al., 2007* and *Schulz et al. 2006*)

clear-sky RF is $-0.68 Wm^{-2}$. The cloud-sky RF was derived based on all-sky and clear-sky RF and modeled cloud cover. It was significantly different from zero and ranged between -0.16 and $+0.34 Wm^{-2}$. Figure 3 shows the major parameters as maps to illustrate the spatial location of direct aerosol forcing. Positive forcing off South Africa is suggested to be due to absorbing biomass burning aerosols traveling out over the low clouds in the South Atlantic (see figure 3b). It is interesting to note that there is also a higher standard deviation among models in this region, indicating disagreement on whether this aerosol indeed creates a positive forcing contribution to the global forcing.

Other types of studies will also likely elucidate other important sources of uncertainty in model-derived forcing. For example, an initial AeroCom sensitivity study by *Penner et al.* (*2005*) investigated the reasons for the spread in model-simulated aerosol indirect radiative forcings in three models. Fixed aerosol concentrations, the parameterization of droplet concentrations and the autoconversion scheme were specified and compared to an experiment that examines the predicted aerosol indirect forcing when only aerosol sources are specified. The prediction of aerosol concentrations, given a fixed set of sources, leads to the largest differences in the predicted aerosol indirect radiative forcing among the models. *Quaas et al.* (*2008*) suggested investigating the correlations between cloud properties and aerosol abundance in different regions of the world and comparing these to satellite-derived correlations. This has led to a first series of new AeroCom experiments, IND2, to which 10 models have contributed (*Quaas et al., in preparation*).

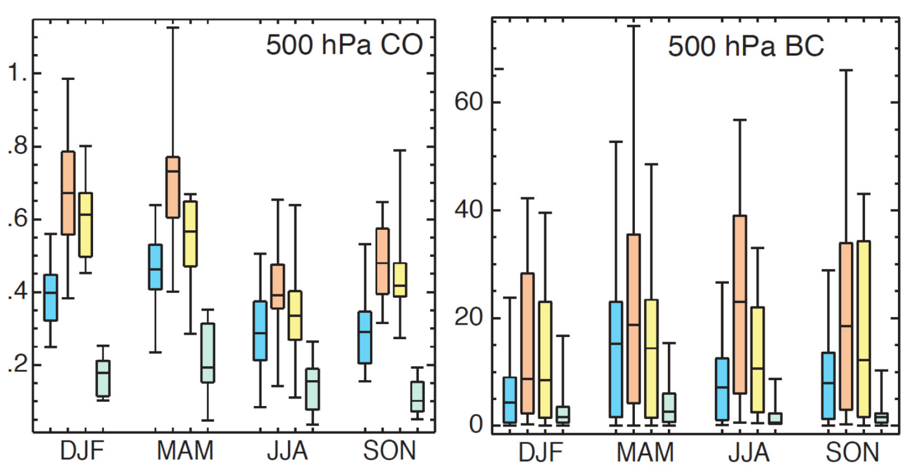

Figure 4. Arctic sensitivity, from a range of HTAP models, to emissions from four continental regions for seasonal averages, of CO (in ppv/Tg per season) and BC (pptm/Tg per season) mixing ratios at the 500 hPa level. Sensitivities are the difference between the simulation perturbing the CO or BC emissions and the control simulation, normalized by the emissions change in the species (CO, BC) in the indicated source region. Blue: East Asia ; Red: Europe ; Yellow: North America ; Light Blue: South Asia. (after *Shindell et al., 2008*).

AeroCom also coordinated with and contributed to the recent exercise in the framework of the UNECE task force on Hemispheric Transport of Long-Range Pollution (HTAP; http://www.htap.org). Within 10 models, aerosol precursor (SO_2, NO_x, and NH_3) and primary (EC, POM and PM2.5) emissions were perturbed by 20% in four source regions (North America (NA), Europe (EU), India (SA), East Asia (EA)). The results have been analyzed for imported surface PM concentrations, deposition and column loads in receptor regions (*Keating and Zuber, 2007*). Results indicate that: a) The import fraction for annual mean surface anthropogenic PM2.5 vary from 5% to 10% in the EU, NA and EA regions, and 25% for SA. b) The import contribution to the aerosol loading is significantly larger that that for the surface concentrations. Regional sulfate aerosol burdens are augmented by 31-59 %, and BC burdens by 13 to 30%, through intercontinental transport. The HTAP results had additional diagnostics on sulfur dioxide. The spatial dispersion (and hence model diversity) of total sulfur appeared to be dominated by sulfur dioxide dry deposition, which occurs rather close to the sources.

From the same set of HTAP model results *Shindell et al., 2009*, documented that inter-model variations in Arctic sensitivity to continental emissions is much larger for BC than for CO (Figure 4). The inter-model variation in residence time for BC among models is roughly a factor of two and accounts for most of the spread. The large variations in how long BC remains in the global atmosphere seems to be more important in determining how much reaches the Arctic than are dry transport differences or local Arctic removal processes (which contribute only a minor fraction of the global removal).

AeroCom Phase II

The unresolved questions and new aerosol data sets – such as from the “A-train” of satellites – have motivated the AeroCom participants to suggest a new round of experiments with adapted diagnostics.

In order to better document aerosol size in AeroCom phase II we propose storing the complete output of all aerosol tracer mixing ratios at selected super sites with a higher frequency (hourly, at a set of predefined super site stations as well as daily in the form of a vertical profile for the period 2006-2008). In addition, we propose storing a monthly 3D distribution of all aerosol tracer mixing ratios for the control year 2006. Together with a description of the size class or mode information it should be possible to pursue more complete comparisons of the actual size distributions in the different models. A representative global list of 50 super sites has been selected through consultation with the GAW aerosol committee. By limiting the model output to those sites where intensive aerosol observations exist and to 3D distributions with only monthly resolution we believe to have found a promising compromise between detail and data storage limitations.

The complex dynamics controlling aerosol distributions necessitate further “switch-off-a-process” experiments to differentiate between the role of coagulation, nucleation and condensation for the aerosol number budget in a global atmosphere. Such experiments have therefore been added to the newest planned AeroCom experiments. It is hoped that these experiments better elucidate how much detailed microphysics is needed in aerosol-climate models.

Aerosol vertical distributions observed from aircraft, from satellite-based lidar (i.e. CALIOP) or ground-based lidar (*Ferrare et al., 2006*) have the potential to constrain models with respect to aerosol residence time. For example, low black carbon concentrations observed with the SP2 instrument in high altitude aircraft have challenged our model understanding of vertical mixing (*Schwarz et al, 2007*), with many models being too diffusive in the upper troposphere or not having efficient enough wet removal of black carbon. Under Phase II, AeroCom is taking advantage of these additional diagnostics. For the years 2006-2008 models are requested to provide daily 3D aerosol extinction as well as 3D monthly wet removal rates, allowing us to better understand the full vertical mass budget. New observations are also available for secondary aerosols such as nitrate and organics. Distinguishing between primary and secondary organic aerosols requires the provision of adequate detail. Thus, model groups are requested to output full mass mixing ratio documentation of all aerosol tracers, as described in the microphysics section of the Phase II AeroCom runs. This will also help us to understand the aerosol mass budget in the models.

A better constraint on aerosol residence times would have direct consequences for the uncertainty estimate of aerosol forcing and regional climate effects. It would allow better long-range transport estimates and improve chances of verifying emission inventories with inversion techniques.

In addition to uncertainties in aerosol distributions and properties, representation of cloudy sky direct radiative forcing by aerosols may be responsible for a significant portion of model diversity in aerosol radiative forcing. Cloud field documentation will therefore be emphasized in AeroCom’s phase II. However, because of the co-variance of clouds and aerosols it is suggested to store explicitly the cloudy sky radiative fluxes in control and pre-industrial simulations. A second pathway would be the 3D prescription of the aerosol optical properties in a specific 1-year experiment, which would be dedicated to understanding the role of the host model environment for aerosol perturbed radiative fluxes.

Finally, it should be noted that aerosol radiative forcing has been evolving, due to both anthropogenic aerosol concentration trends and variations in the natural aerosol background. Dimming and brightening, regional aerosol effects and emission changes in different regions of the world should be evident in historic aerosol simulations. The WCRP-SPARC/IGBP-IGAC Atmospheric Chemistry & Climate (AC&C) initiative includes an activity whereby a series of ~5 or more models do a 20-25 year “hindcast” experiment to investigate recent evolution of tropospheric chemistry, and in particular ozone, methane and aerosols. These aerosol runs will be compared against observational data sets, providing a test of model skill. The aerosol component of the AC&C Hindcasts are being conducted under the umbrella of AeroCom.

Complementing the Hindcast runs will be a set of runs simulating future scenarios which will provide "best-guess" aerosol (and other trace species') distributions, using emissions which are consistent with those used in the climate model runs. These "Scenarios" runs will also allow better understanding of sources of sensitivity and uncertainty in the simulation of climatically important short-lived species. (For a full description of the AC&C "Scenarios" activity, see accompanying article by *Shindell and Lamarque*). Unlike the long-live greenhouse gases, climate is expected to respond rapidly to aerosol perturbations and it is important that we understand how changes in concentrations will feed back with climate. The AC&C Scenarios and corresponding CMIP5[2] time-slice experiments are foreseen to obtain a quasi forcing, which includes all fast feedbacks of the climate system to aerosols. It is hoped that model versions employed there can be traced back to the more complete documentation within AeroCom.

New AeroCom Experiments and Diagnostics at a glance

The AeroCom phase II model experiments are proposed for the time frame 2009/2010. Based on a reference and control simulation for the year 2006 it is suggested to provide additional simulations with new diagnostics. Modelers are asked to choose experiments according to their capabilities, resources and interests. New aspects of these runs have been explained above and are summarized below at a glance. Details of the diagnostics required can be found via the AeroCom website (http://nansen.ipsl.jussieu.fr/AEROCOM/protocol.html).

Emissions to be used for the next IPCC assessment and for the AC&C Hindcast simulation are discussed in an accompanying article (*Lamarque, Granier et al.*) and the actual status of these can be best found via the AeroCom website. As these emission scenarios and datasets are themselves a matter of considerable scientific discussion, it is recommended that modelers also do runs using their own choice of emissions. However, the efforts going into the IPCC emission compilation, led by Jean-Francois Lamarque, should be given priority, since this allows harmonization across the reactive gases and aerosol emissions.

It is of course necessary to make a compromise between the number of experiments and a subdivision in diagnostic packages. Already in the first phase of AeroCom not all modelers could participate in all exercises. While it is not necessary that all models participate in all experiments, overlap through a common control experiment and a unified protocol and format for all experiments are intended to facilitate having individual model groups participate in several different analyses. It is hoped that by providing this consistency interested scientists will more easily exploit the AeroCom database.

A difficulty in the interpretation of the climate model runs for the last IPCC report has been the incomplete or altogether missing documentation of the aerosol representation in a given climate model. Adding to this, the model versions used to compute the aerosol radiative forcing (e.g. as reported in *Schulz et al., 2006*) often were different from the model version used to simulate transient climate evolution. In preparation for the next Assessment Report, a small and thus manageable subset of aerosol diagnostics from the AeroCom set is being submitted to the CMIP protocol for inclusion in the next IPCC climate runs. Together with a dedicated experiment to document the fast response due to sulfate (CMIP protocol experiment 6.4), perhaps done also with a total aerosol perturbation, the ability to interpret the role of aerosols in the climate runs will significantly improve for the next IPCC assessment. However, understanding model diversity with respect to the aerosol effect will also require that individual groups link in-house the climate model version to a better documented AeroCom aerosol model run.

AeroCom phase II experiments at a glance

1. **AeroCom control run – *serve as a base for all other model experiments***
   - 2006 simulation (A2-CTRL-06)
   - 2007-2008 simulation (A2-CTRL-07-08) (for comparisons with CALIPSO)
   - Using "reference" emissions (reference means that these should be consistent with emission datasets used for the subsequent experiments)
   - Including sulfate, nitrate, BC, OC (including SOA from anthropogenic, vegetation, and ocean sources), dust (including eventually anthropogenic dust), sea-salt
   - If can, including microphysical processes (will be used in Microphysical exp.)
   - Diagnostic package: Quicklook, direct forcing, organics, microphysics, vertical
   - Submission time: July-September 2009 for A2-CTRL-06, Dec 2009 for A2-CTRL-07-08

2. **Aerosol direct forcing – *for IPCC AR5***
   - Using 2006 emissions (A2-CTRL-06)
   - Using 1850 emissions (A2-PRE) (meteo fields should not be changed from A2-CTRL simulation)
   - No aerosol effect (A2-ZERO) (Radiative fluxes not influenced by natural nor by anthropogenic aerosols, meteo fields as in A2-CTRL)
   - Diagnostic package: Direct forcing
   - Submission time: July-December 2009

[2]CMIP = "Coupled Model Intercomparison Project", for global coupled ocean-atmosphere general circulation models (http://www-pcmdi.llnl.gov/projects/cmip/)

3. **Prescribed forcing – *testing the diversity of the host GCM response to aerosol forcing, eliminating the diversity of aerosol properties (A2-FIX)***
   - Using prescribed, monthly averaged (year 2006) AOD, aerosol single scatter albedo (SSA), and asymmetry parameter (ASY) at 24 wavelength bands, which are interpolated to the desired bands for the individual model's radiative transfer calculations (software for vertical and wavelength interpolation will be provided)
   - Using model's own surface albedo, clouds, water vapor, etc. for radiative transfer calculations
   - Diagnostic package: Direct forcing
   - Submission time: Dec 2009

4. **Radiative transfer code intercomparison– *testing the differences in radiative transfer code (A2-RADCODE)***
   - Base run: A2-CTRL-ZERO facilitates implementation of this experiment
   - No aerosols
   - Surface albedo set to a universal value of 0.2
   - Two standard atmospheres: Tropics and Arctic (provided)
   - Two 1-day simulations (one tropics, one Arctic) for January 1, 2006
   - Diagnostic package: Direct forcing (instantaneous forcing output)
   - Submission time: Dec 2009

5. **Microphysics – *document the diversity in individual microphysical process***
   - Base run: A2-CTRL-06 (with microphysics)
   - Same as A2-CTRL-06 but no condensation (A2-SIZ1)
   - Same as A2-CTRL-06 but no coagulation (A2-SIZ2)
   - Same as A2-CTRL-06 but no primary BC, OC, and SO4 (A2-SIZ3)
   - Same as A2-CTRL-06 but no new particle formation (A2-SIZ4)
   - Diagnostic package: Microphysics
   - Submission time: Dec 2009

6. **Hindcast – *for AC&C***
   - Time period: (a) 1850 + 1980-2007 or (b) 1850 + 2000-2007
   - Using AeroCom HC emissions (HCA-0), let meteorology vary, ideally nudged to reanalysis, observed sea surface temperatures (SSTs)
   - Same as HCA-0, but use fixed emission corresponding to year 2000, let meteorology & SSTs vary as above (HCA-FIX)
   - Using IPCC HC emissions (HCA-IPCC) (year to year variability is needed), let meteorology & SST vary as above
   - Same as HCA-IPCC, using free GCM, only SST prescribed and aerosol direct & indirect effects on climate activated (HCA-MET)
   - Diagnostic package: Hindcast
   - Submission time: HCA-0: July-September 2009; other: December 2009

7. **Indirect forcing (IND2-CTRL/PRE) – *ongoing, results are already on server***
   - Diagnostic package: Indirect
   - Submission time: Ongoing

Organized in cooperation with AeroCom:

8. **ACCMIP** (led by IGAC AC&C activity 4, Drew Shindell; see accompanying article)
   - Coupled climate-aerosol simulation, time slice experiments (see ACCMIP description in accompanying article)
   - 1860-2100 or individual years: 1860, 1930, 1970, 2000, 2030, 2050
   - Diagnostic package: ACCMIP
   - Submission time: 2009/2010

AeroCom Infrastructure

As mentioned above the cooperation within AeroCom builds on yearly scientific workshops to report and discuss joint analysis, recent model developments and new observational datasets. The 8th AeroCom workshop is planned for 5-7 October 2009 in New Jersey, by invitation of the University of Princeton and organized by Paul Ginoux and colleagues, with special emphasis on contributions to the next IPCC report. It is expected that first results from the AeroCom phase II experiments will be available in time for the workshop. Interested colleagues are invited to submit an abstract (deadline: 30 August). A 2010 AeroCom workshop will probably be hosted by Oxford University, U.K., hosted by Philip Stier. An AeroCom email list is kept and used for distribution of relevant news, and interested parties can be added to the list via the AeroCom web page (http://nansen.ipsl.jussieu.fr/AEROCOM/).

Loosely organized working groups within AeroCom foster joint analysis. Group leaders are as follows:

- Microphysics: Graham Mann (Univ of Leeds) & Xiahong Liu (PNL)
- Direct forcing: Philip Stier (Univ of Oxford), Gunnar Myhre (CICERO) & Cynthia Randles (NASA Goddard)
- Indirect forcing: Johannes Quaas (MPI-M)
- Hindcast simulations: Michael Schulz (LSCE) and Mian Chin (NASA-Goddard)
- Organics: Kostas Tsigaridis (GISS) and Maria Kanakidou (Univ of Crete)
- Observational Data: Stefan Kinne (MPI-H)
- Dust: Paul Ginoux (Univ. of Princeton)
- Black Carbon: Dorothy Koch (GISS)
- Emissions: Thomas Diehl (NASA-Goddard) & Tami Bond (Univ. of Illinois)

A database of currently 5 TBytes of model output is kept at the LSCE in Saclay/France and contains all previous AeroCom experiments. Additional model runs executed for the Task Force on Hemispheric Transport of Atmospheric Pollutants (TF-HTAP) – which specifically investigates the influence of emissions from one region on another region within the northern hemisphere – are available via the HTAP archive at the Forschungszentrum Juelich (http://htap.icg.fz-juelich.de/data). The LSCE database contains original AeroCom data submissions and reformatted, standardized netCDF data. Basic submissions have been secured by a copy on a second data server. A computing server is accessible from the outside for expert users to work directly with the data. At this point access is based on a "gentleman's agreement": users are requested to simply declare their analysis project, contact model and data authors before publication and report back during the AeroCom workshops.

Model output is visible directly via the public AeroCom web interface. The perl-based web interface facilitates the inspection of a vast image catalogue, fabricated over the past several years and hosted at IPSL/France. This harmonized visualization facilitates model comparison. Recent developments have also been made to facilitate model-data comparisons (http://nansen.ipsl.jussieu.fr/AEROCOM/surfobs.html). Various types of observational data from different network stations of Aeronet, GAW, IMPROVE, EMEP, AEROCE/SEAREX can now be compared to model data as time series (daily per month or season, monthly for full year). Time series are also plotted against a benchmark data set comprised of the AeroCom Median model and AeroCom A models. Further maps, statistics, histograms, scatter plots and simple scores are produced with an automated idl tool developed at LSCE. This permits the user to produce, upon request, a new image catalogue within a few days of the submission of a new model dataset. This has been used already for monitoring model development of the ECWMF-GEMS-Aerosol model and recent model developments in the European EUCAARI project.

This level of automation requires, of course, that the model output is formatted by the modelers according to the CF convention and using variable names as suggested in the new AeroCom diagnostics. As for the IPCC model submissions, it is highly recommended to use the CMOR tool from PCMDI, to obtain standard files.

Summary

Under AeroCom's Phase I, the aerosol modeling community self-organized to participate in a model comparison project using common diagnostics and a common analysis. This analysis gave us new insight to the range in model representation of aerosol distributions, properties and resulting radiative forcing, and provided some insight as to the sensitivity of these fields to different processes. In addition, a database is now available which allows us to study model progress and get back to earlier model results. A common, automated visualization of model detail is in place for comparison of both past and future model runs and observational datasets. However, the analysis under AeroCom's Phase I made it clear that in order to understand the remaining significant uncertainty in model-derived aerosol radiative forcing, a refined set of model diagnostics is needed. These diagnostics have been established for AeroCom Phase II (described above, and given in more detail on the AeroCom website), and we hope for enthusiastic participation by the modeling community. These new experiments are designed to complement ongoing work for the IGAC Atmospheric Chemistry and Climate initiative and to contribute directly to the next IPCC Assessment Report.

Work is also needed to improve the observational database to test aerosol models and to better understand key processes that affect aerosol distributions and properties. As for measurement campaigns, satellite missions and networks, it is still needed to organize a framework to achieve reliable, comparable results from the internationally available models. We would like to note that a unified aerosol model is neither possible, nor useful at this point, given that there is still considerable uncertainty in how to best represent key processes. Results from AeroCom Phase I instead indicate that ensemble runs of a diversity of models is more useful at this juncture.

Finally, we would like to note AeroCom wouldn't have come all this way without considerable enthusiasm and devotion from the modelers. But also as crucial to this process has been the challenge to the modeling community by colleagues providing aerosol observations from space and ground as an integral part of the AeroCom workshops. In particular we wish to pay homage to Yoram Kaufman for his inspiring contributions in this context. Further progress in reducing uncertainties in aerosol's role in climate will require us to continue to look into new and inspired ways of integrating observational data and model results.

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Gridded emissions in support of IPCC AR5

Contributed by **Jean-François Lamarque**[1,2] (lamar@ucar.edu), **Claire Granier**[1,3] (claire.granier@aero.jussieu.fr), **Tami Bond**[4], **Veronika Eyring**[5], **Angelika Heil**[6], **Mikiko Kainuma**[7], **David Lee**[8], **Catherine Liousse**[9], **Aude Mieville**[3], **Keywan Riahi**[10], **Martin Schultz**[6], **Steven Smith**[11], **Elke Stehfest**[12], **David Stevenson**[13], **Allison Thomson**[11], **John Van Aardenne**[14] and **Detlef Van Vuuren**[12]

[1] *NOAA Earth System Research Laboratory, Chemical Sciences Division, Boulder, CO, USA; Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Colorado, USA*

[2] *National Center for Atmospheric Research, Boulder, USA*

[3] *Laboratoire Atmosphères, Milieux, Observation Spatiales, CNRS UMR 8190, Paris, France; Université Pierre et Marie Curie, Paris, France*

[4] *University of Illinois, Urbana-Champaign, IL, USA*

[5] *Deutsches Zentrum fuer Luft- und Raumfahrt, Oberpfaffenhoffen, Germany*

[6] *Forschungszentrum, Juelich, Germany*

[7] *National Institute of Environmental Studies, Tsukuba, Japan*

[8] *Manchester Metropolitan University, Manchester, UK*

[9] *Laboratoire d'Aérologie, Toulouse, France*

[10] *International Institute for Applied Systems Analysis, Laxenburg Austria*

[11] *Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD, USA*

[12] *Netherlands Environmental Assessment Agency, Bilthoven, Netherlands*

[13] *University of Edinburgh, Edinburgh, UK*

[14] *Joint Research Center, Ispra, Italy*

Atmospheric chemistry modeling requires the specification of emissions as boundary conditions. In most cases, these emissions are available in terms of gridded datasets that are then read in by the atmospheric chemistry models (see for example http://www.aero.jussieu.fr/projet/ACCENT/database_table_inventories.php). There is considerable uncertainty in estimating the emissions of the recent past and up to now, no single data set exists which would describe the geographical and temporal distribution of emissions for all species relevant to climate change in a comprehensive and consistent manner. The calculation of these emissions require a variety of steps involving the knowledge of the source of emission (e.g. fossil fuel combustion), an emission factor (e.g. how much of a given chemical species is emitted for a specific mass of a given fuel burned in a specific technological process) and a procedure for mapping onto a geographical grid (e.g. the location of a source point such as a power plant). Among those three steps, it is often the middle step (i.e. assigning emission factors to processes at a certain point in time and for a specific region), which contains the largest uncertainty, especially in the case of anthropogenic emissions. This large uncertainty leads to a range of possible emissions for a given process and base year. While this issue applies to all types of emissions, we will focus the remainder of the discussion on anthropogenic and biomass burning emissions.

The goal of the effort described here is to create a continuous consistent gridded emissions dataset from 1850 to 2100, consistent across 2000, for modeling studies in support of IPCC (Intergovernmental Panel on Climate Change) AR5. These emissions will be used (a) as boundary conditions for chemistry model simulations and (b) for the calculation of concentrations that will be prescribed as boundary conditions in Earth System Models (ESMs) and General Circulation Models (GCMs) that do not have interactive chemistry (*Taylor et al., 2008*). Emissions of gaseous and particulate species (i.e. aerosols, ozone and aerosol precursors) from anthropogenic activities and biomass burning have been estimated over the full period, using the 2000 dataset for harmonization of the past-to-current (1850-2000) emissions with the future emissions determined by the Integrated Assessment Models (IAMs).

We used expert judgment to combine existing historical and present-day datasets in order to generate a best estimate and most up-to-date emissions datasets from the pre-industrial (defined here as 1850) period to present (defined here as 2000). In order to meet this goal, inventories currently available were evaluated and combined in a standard format and on a consistent regionally-aggregated spatial grid.

In addition, we require that projections of future emissions (i.e. emissions associated with the four IPCC Representative Concentration Pathways (RCPs; *Moss et al., 2008*) and generated by IAMs be identical to our present-day emissions in both amplitude and geographical distribution. This "hand-shake" requirement ensures continuity in emissions between historical and future distributions.

The purpose of this article is to describe the methodology used for generating the IPCC AR5 emissions, together with information on their availability.

Scope and limitations

In order to perform chemistry simulations with enough resolution to resolve regional structures, we provide monthly emissions at a horizontal resolution of 0.5°

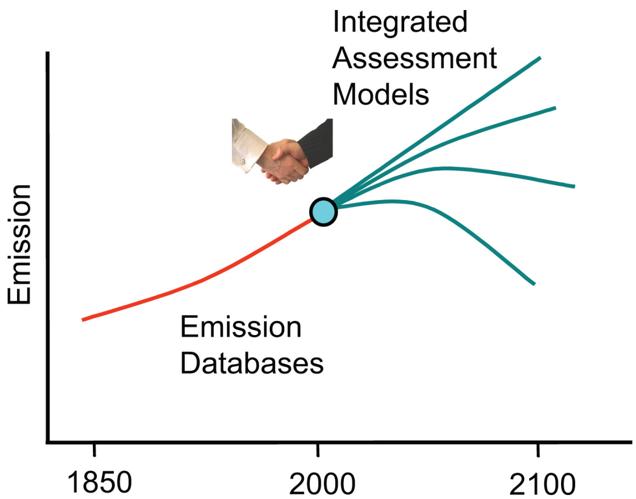

Figure 1. The hand-shake process, highlighting the harmonization point in 2000 between historic and future emissions.

in latitude and longitude every 10 years. Emissions necessary for the simulation of ozone and aerosols are provided, including methane, carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons (NMHCs), ammonia (NH_3), organic carbon (OC), black carbon (BC) and sulfur dioxide (SO_2). Compounds relevant for other issues (e.g. CFCs, HCFCs and HFCs, mercury, persistent organic pollutants) have been left out of this activity so far, for lack of time, but they might be included in an updated version of this inventory. NMHC emissions are given both as a total and by species, following the RETRO approach (*Schultz et al., 2007*), similar to the EDGAR v2 speciation (*Olivier et al., 1996*). The data are provided as an annual value at the start of each decade. Biomass burning emissions (e.g. open fires caused by land-use practices including land-use change, arson or lightning strokes) include a seasonal cycle. All emissions are available for each decade over the full time period. Interpolation of these data sets for specific years will have to be performed by the modeling groups. While interannual changes may be important for the detailed analysis of past pollution trends, we decided that decadal data are overall better suited to fulfill the needs of AR5 for the following three reasons: 1) annual data sets exist only for a limited set of species and generally only for the recent past – for example RETRO (*Schultz et al., 2007, 2008*) and REAS (*Ohara et al., 2007*; *Smith et al., 2004*), 2) emissions become increasingly uncertain going back in time, limiting the usefulness of single year data and 3) future emissions are available from most IAMs only every 10 years, so decadal data for past emissions are consistent with this practice.

Hand-shake process across year 2000

As described earlier, a major contribution of our effort is in the definition of a comprehensive approach to ensure continuity between historical datasets and future projections (Figure 1). One constraint is that IAMs simulate the evolution of the energy system, emissions,

Table 1. List of regions

Region number	Name of Region
1	Canada
2	USA
3	Mexico
4	Rest Central America
5	Brazil
6	Venezuela
7	Argentina
8	Rest South America (Rest of)
9	Northern Africa
10	Western Africa
11	Eastern Africa
12	Southern Africa (Rest of)
13	South Africa
14	France
15	Germany
16	Italy
17	United Kingdom
18	Western Europe (Rest of)
19	Central Europe (Rest of)
20	Baltic States (Estonia, Latvia, Lithuania)
21	Turkey
22	Ukraine+
23	Asia-Stan
24	Russia+
25	Middle East
26	India+
27	South Asia (Rest of)
28	South Korea (Republic of Korea)
29	North Korea (Democratic People's Republic of Korea)
30	China+ (Rest of)
31	Taiwan
32	Thailand
33	Southeastern Asia (Rest of)
34	Indonesia+
35	Japan
36	Australia
37	New Zealand
38	Oceania (Rest of)
39	Greenland
40	Antarctica

and land-use changes for a limited number of regions, with actual number of regions varying amongst models. In addition, both historical and current inventories, as well as projections from IAM models, are traditionally most meaningful at the level of relatively aggregated sectors, where uncertainties of individual sources do not dominate or can at least be assessed. Our approach therefore consisted of defining a minimum set of regions and sectors which will provide sufficient detail to capture regional and sectoral disparities and their evolution with time. The outcome was a definition of 40 regions (Table 1) and 13

Table 2. List of sectors

Sector number	Sector name
1	Energy production and distribution
2	Industry (combustion and non-combustion)
3	Land transport
4	Maritime transport
5	Aviation
6	Residential and commercial
7	Solvents
8	Agriculture
9	Agricultural waste burning on fields
10	Waste
11	Open vegetation fires in forests
12	Open vegetation fires in savannah and grasslands
13	Natural emissions

sectors (Table 2); distribution of emissions from each regional/sectoral aggregate (i.e. gridding) is described in the next section. The "hand-shake" process consists of using the regional-sectoral emissions as the initial conditions for projections.

We chose 2000 as the base year, because this is the last year for which comprehensive inventory data are available. However, as we recognize that there have been tremendous changes in emissions between 2000 and present (especially in Southeast and Eastern Asia), we are making use of available emission inventories (with consistent regional and sectoral averaging) to provide additional information to the IAMs to guide their estimates for the year 2010.

Definition of year 2000 emissions

Continental anthropogenic emissions

Anthropogenic emissions of ozone precursors in 2000 are defined in terms of a variety of global and regional inventories. In this process, where published or reviewed regional inventories are available (namely for Europe, Southeast Asia and North America) they are given preference over the global inventories. In those regions our judgment is that those regional inventories are more appropriate for capturing emissions. The EDGARv32 FT2000 dataset (*Van Aardenne et al., 2005*) and preliminary emissions from EDGAR v4.0 for agriculture and NH_3 (*EC-JRC/PBL, 2009*) are used when regional information is not available. The combination of the various inventories is performed at the level of regional averages; therefore no attempt is made at smoothing potential discontinuities across regional boundaries. Gridding is performed using the EDGAR v4.0 spatial distribution maps specific for each sector at a 0.1° resolution, and aggregated to a 0.5° grid (*EC-JRC/PBL, 2009*). Although additional information is available for several regions, we did not attempt to include those as they were either incomplete (not fitting our requirement of 10 sectors for anthropogenic emissions) or did not pertain to the year 2000. However, we believe that this novel approach will enable the construction of additional datasets in the future which can be used to improve this work. Emissions of BC and OC represent an update of *Bond et al. (2007)* and *Junker and Liousse (2008)*. A harmonization of emission factors was performed for the year 2000 from the very recent literature. Emissions of sulfur dioxide are an update of *Smith et al. (2001, 2004)*, with emissions from UNFCCC submissions where available.

Ship emissions

Total ship emissions, including international shipping, domestic shipping and fishing, but excluding military vessels, are taken from a recent assessment by *Eyring et al. (2009)* to reflect new information on the fleet and emission factors. In this study, estimates of fuel consumption and CO_2 in the year 2000 are based on the International Maritime Organization (IMO) GHG study (*Buhaug et al., 2008*), while the best-estimate for non-CO_2 emission totals is derived as a mean of values from previous studies (*Corbett and Köhler, 2003; Eyring et al., 2005; Endresen et al., 2003; 2007*). Ship emissions are distributed over the globe using the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, *Wang et al., 2007*), with the exception of total hydrocarbon emissions from crude oil transport (evaporation during loading, transport, and unloading). Those follow the emission totals and geographical distribution of *Endresen et al. (2003)* and are added to the gridded ICOADS ship emission dataset. In this approach, ship emission totals are spread onto the large 0.5°x0.5° grid boxes without accounting for dispersion, chemical transformation and loss processes on the sub-grid scale. Neglecting the plume processes in global models may lead to, e.g., an overestimation of O_3 formation.

Aircraft emissions

Aircraft emissions of NO_x and BC were calculated using the FAST model (*Lee et al., 2005*) for the EC Quantify project. Global scheduled and non-scheduled aircraft movements were taken from the AERO2K database (*Eyers et al., 2005*) for the year 2002. Fuel consumption was calculated using the industry-standard PIANO aircraft performance model (*Simos, 2004*) for all the main aircraft types including four categories of turbo-props. Fuel consumption was then assigned to the routes using a great-circle assumption and NO_x emissions calculated with the DLR fuel flow method (*Lecht, 1999*). BC emissions were calculated using the emission factors developed from *Eyers et al. (2005)*. Monthly distributions were calculated and provided on a 3D grid with an original resolution of 1° × 1° latitude/longitude and vertical discretization of flight levels of 2000 feet, which corresponds to the actual (pressure) levels used by air traffic. The vertical distribution of traffic was parameterized from a statistical analysis of EUROCONTROL air traffic data that provided a relationship between mission distance, aircraft type and average cruise altitude (*Lee et al., 2005*). By convention, aviation 'bottom up' inventories underestimate fuel and emissions for a variety of reasons (perfect routing, no stacking, limited data on non-scheduled traffic, military aircraft) when compared with International Energy Agency (IEA) statistics of kerosene sales, so that the 3D inventory is scaled up to the IEA data to ensure that the global and annual totals are the same.

Biomass burning emissions

Given the substantial interannual variability of biomass burning we have decided to use the 1997-2006 average as the base year data set. The actual year 2000 emissions were relatively low and would have led to an underestimation of the emissions from this sector. Furthermore, biomass burning emissions vary regionally from year to year and therefore the use of a snapshot data set for a specific year would not represent an unbiased global picture. Variations of biomass burning emissions with climate indices (e.g. ENSO) will be simulated in various ways by the different climate models in AR5. The biomass burning average for the reference point was constructed from the GFED v2 database (*van der Werf et al., 2006*). The split between forest and grassland is performed using the GFED procedure of assigning a specific land type per grid cell. Emissions were interpolated from 1° to 0.5° by simply splitting each grid box in 4 subsets of equal area and accounting for the land-sea mask in this process. Emissions from fuelwood burning and charcoal production, sometimes also labeled as biomass burning, are accounted for in the residential sector emissions.

Historical emissions 1850-2000

Historical continental anthropogenic emissions

Historical emission estimates for anthropogenic emissions of ozone precursors have been published under the RETRO project for 1960-2000 (*Schultz et al., 2007*) and under the EDGAR-HYDE project for 1860-1990 as described by *Van Aardenne et al. (2001*). The availability of two reconstructions enables us to perform additional analysis of the trend on a regional and sectoral basis for the past four decades. EDGAR-HYDE emissions were extrapolated to 1850 using global fossil fuel consumption estimates from *Andres et al. (1999)* and regional scale data for population from the HYDE dataset (*Van Aardenne et al., 2001*, and http://www.mnp.nl/edgar/model/edgarv32/v32ftmaps/).

The scaling of the anthropogenic emissions using EDGAR-HYDE and RETRO relies on the underlying assumption that these reconstructions have a reasonable representation of the time evolution of emissions. Under this assumption, emissions for decades prior to 2000 can be calculated as a direct scaling (per sector and for each region) of our 2000 emissions, with a weighting factor defined as a linear combination of the RETRO and EDGAR-HYDE scaling factors and increasingly favoring EDGAR-HYDE when going further back in time.

Similarly, black and organic carbon emissions benefited from the comparison of *Bond et al. (2007)* and *Junker and Liousse (2008)* emissions. For the past fossil fuel emissions, both BC and OC emission factor trends and sectoral trend of fuel consumption have been harmonized between the two studies for the 1850-2000 period. Trends in the biofuel emissions of BC and OC have been taken from *Bond et al. (2007)* and from *Fernandes et al. (2007)*. Emissions of SO_2 are an updated version of those from *Smith et al. (2004)*.

The methodology used for gridding the emissions for the 1850-2000 period relies on a weighted mean of the distributions obtained using either the population or the year 2000 gridded emissions. It is applied so that the weighting associated with the 2000 gridded distributions decrease as you go back in time.

Historical ship emissions

To extend the non-CO_2 ship emissions backward in time, the 2000 emission totals from *Eyring et al. (2009)* are scaled with the historical CO_2 emission time series from *Buhaug et al. (2008)* back to 1870. 1850 and 1860 emissions were estimated by scaling by changes in global ship tonnage. For the historical geographical ship distribution we use ICOADS data back until 1950. Prior to 1950s there was much less activity by ships on Pacific routes, with shipping concentrated on the North and South Atlantic oceans, Mediterranean, and Indian/Indonesian trade routes (pers. comm. *J. Corbett, 2008*). To map emissions before 1950, the Pacific trade routes have been forced to go to zero in 1900, which forced the emissions to be concentrated in the other regions. Between 1900 and 1950 a linear interpolation between these patterns is applied to provide the decadal gridded ship emissions.

Historical aircraft emissions

Historical emissions from aviation were provided on an annual total basis. Data from 1940 to 1995 were taken from *Sausen and Schumann (2000)* and extended to 2000 using IEA data (the basis of the time series of *Sausen and Schumann, 2000*).

Historical biomass burning emissions

Only a few inventories provide biomass burning emissions for the past decades. The RETRO inventory (*Schultz et al., 2008*) provides emissions from open fires for each year during the 1960-2000 period, on a monthly basis. The GICC inventory (*Mieville et al., 2009*) gives emissions from fires for the 20th century (1900-2000) on a decadal basis. In order to ensure a consistency of the biomass burning emissions used over the full period considered, the RETRO emissions were scaled so that the totals emissions in 2000 from both forest and savanna fires are similar to the average of the GFED emissions for the 1997-2006 period in each of the major burning regions. The scaled RETRO inventory is used for the 1960-1990 period. For the 1900-1960 period, the GICC inventory was scaled in a similar way, so that the total emissions from forest and savanna fires in the 1960s decade are equal to those obtained from the RETRO inventory. Biomass burning emissions are held constant between 1850 and 1900.

Figure 2 illustrates the method used for combining the emissions available for different periods in order to design a consistent inventory for the full 1850 to 2000 period. It highlights the years 2000, when historic emissions and future projections are harmonized (Figure 1), and 1960, the beginning of the period covered by the RETRO inventory.

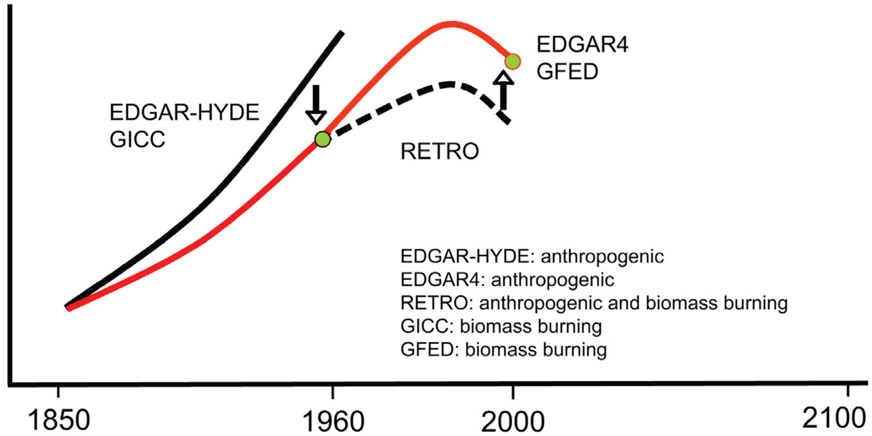

Figure 2. Methodology used for the harmonization of the emissions for the 1850-2000 period, as described in the text.

Future emissions 2000-2100

Future emissions are provided from a set of scenarios termed the RCPs (Representative Concentration Pathways; *Moss et al., 2008*) which are being produced by four IAM modeling teams. As with the historical data sets the underlying scenarios had to be drawn from the published literature.

Four scenarios were selected with the aim of providing a set of scenarios that cover the full range of potential future climate forcing. The scenarios are identified according to their total radiative forcing in 2100. The highest scenario is a reference case with no additional policies in place to limit greenhouse gas emissions and has a 2100 total anthropogenic forcing of 8.5 W/m^2 with forcing still increasing. The remaining three scenarios assume the successful implementation of climate policies with one scenario stabilizing radiative forcing at 6.0 W/m^2, one scenario stabilizing at 4.5 W/m^2, and one scenario with radiative forcing that peaks and then declines to 2.6 W/m^2 in 2100. The four IAM groups responsible for generating the four RCPs are indicated in Table 3.

Anthropogenic emissions for reactive gases and aerosols will be provided for the same sectors and species as described above for past emissions. As with the historic emissions, emissions from the RCP scenarios will be provided at ten year intervals and at 0.5° lat/lon spatial resolution. In addition to the emissions, the RCPs will also provide spatially explicit land-use and land-cover change information at a 0.5° resolution for these same time points.

Data availability

The gridded emission data sets are available for interested modeling teams in NetCDF file format and regional summary tables are provided as spreadsheets. All data can be downloaded from an anonymous ftp server, at ftp://ftp-ipcc.fz-juelich.de/pub/emissions. Some documentation is provided on the server and additional information will be provided there after publication of this article. We also maintain a change history of the data files so that the data set status shall be traceable at least until publication of the IPCC AR5.

The datasets will also be made available to the community on the GEIA emissions portal (Global Emissions Inventory Activity, http://geiacenter.org) by mid-2009. Interactive graphical and statistical tools will also be made available on the web site of the ECCAD (Emissions of Atmospheric Compounds and Compilation of Ancillary Data, http://www.ether.ipsl.jussieu.fr) by the end of 2009.

In addition to the above-mentioned data repositories for the historical emissions inventories, future projections of the four RCPs will be made available through an interactive web-database at http://www.iiasa.ac.at/web-apps/tnt/RcpDb/. The database will be hosted by the IAMC (Integrated Assessment Modeling Consortium), and will comprise regionally aggregated as well as spatially explicit emissions projections in NetCDF format.

Table 3. Overview of Representative Concentration Pathways (RCPs)

	Description	Publication – IAM Model
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100, thereafter increasing	*Riahi et al. (2007)* – MESSAGE
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 with stabilization after 2100	*Fujino et al. (2006)* and *Hijioka et al. (2008)* – AIM
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 with stabilization after 2100	*Clarke et al. (2007)* – MiniCAM
RCP 3	Peak in radiative forcing at ~3 W/m^2 before 2100, thereafter declining	*van Vuuren et al. (2006, 2007)* – IMAGE

Further developments

While this inventory is targeted for a specific purpose, it is our intent and hope that the approach defined and discussed here will be helpful for updating and improving the present inventory (for example using additional regional data), but also for the analysis and intercomparison of future emission datasets.

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Atmospheric Chemistry & Climate Model Intercomparison Project (ACC-MIP)

Under the auspices of Atmospheric Chemistry and Climate (AC&C), a project of IGAC and SPARC under IGBP and WCRP

Contributed by **Drew Shindell** (dshindell@giss.nasa.gov), *NASA Goddard Institute for Space Studies, New York, New York, USA*, **Jean-Francois Lamarque** (lamar@ucar.edu), *NOAA Earth System Research Laboratory, Chemical Sciences Division; Cooperative Institute for Research in Environmental Sciences, University of Colorado; national Center for Atmospheric Research, Boulder, USA,* & **the AC&C "Scenarios" team**

Background & Motivation

The simulations performed for the CMIP3[1] activity in support of the IPCC AR4 have provided a tremendously useful resource for exploring issues of climate sensitivity, historical climate and climate projections, having generated more than 500 publications. The simulations driven by CO_2 increasing at a rate of 1% per year used identical concentration changes in all models, leading to fairly similar radiative forcings (*Forster and Taylor, 2006*). However, the radiative forcings imposed in both the simulations of the 20th century and the future projections varied from model to model due to varying assumptions about emissions, differences in the behavior of physical processes affecting short-lived species that were included, and differences in which processes and constituents were included at all. For example, only 8 of 23 CMIP3 models included BC while less than half included future tropospheric ozone changes (*Meehl et al., 2007*). Furthermore, the CMIP3 archive does not include diagnostics of radiative forcing from aerosols, ozone, or greenhouse gases other than CO_2. Hence it is not straightforward to understand how much of the variation between simulated climate in the models results from internal climate sensitivity and how much results from differences in the forcings.

A recent study examined the feedbacks in the various CMIP3 models via their response in the 1% per year CO_2 increase simulations (*Soden et al., 2008*). Further work has then used those feedbacks and the climate response seen in the CMIP3 20th century simulations to estimate the forcing that was applied to the individual models (*B. Soden, personal communication, 2009*). Examination of those results reveals that the models used vastly different forcings for the 20th century. Clearly, negative forcing from aerosols was so large in some models that it dominates the total in much of the Northern Hemisphere, while others appear to have very little aerosol forcing. A similar calculation for the future projections shows that global mean radiative forcing differs by up to a factor of two across models while regional forcings vary enormously in magnitude and are, like in the historical case, not consistent in sign.

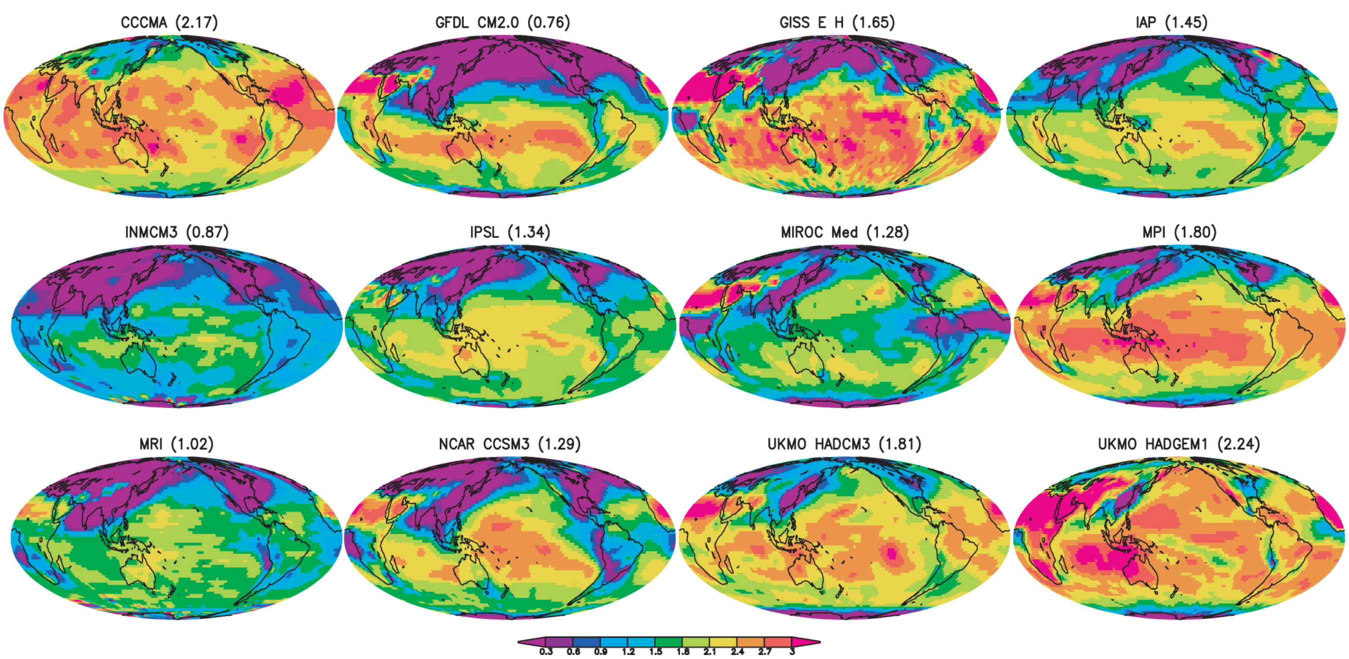

Figure 1. Radiative forcing in the CMIP3 20th century simulations as inferred from the geographic distribution of surface temperature change and climate sensitivity/feedbacks of each model (*B. Soden, personal communication, 2009*). The model and the global mean radiative forcing is given above each plot.

[1] CMIP = "Coupled Model Intercomparison Project", for global coupled ocean-atmosphere general circulation models (http://www-pcmdi.llnl.gov/projects/cmip/)

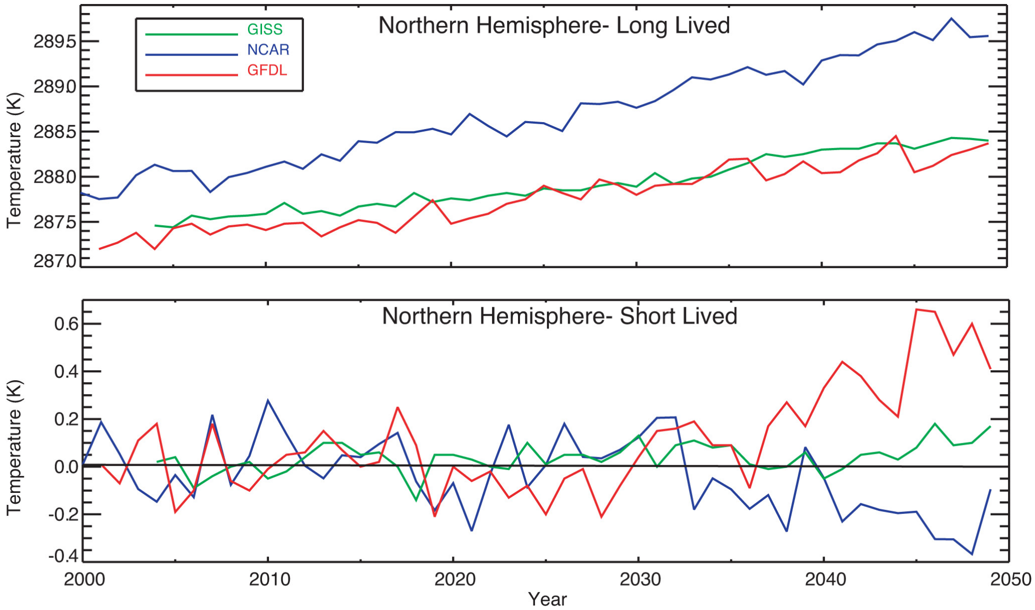

Figure 2. Northern Hemisphere mean surface temperature trends under an A1B scenario due to long-lived species (greenhouse gases) and short-lived species (aerosols and ozone) in the CCSP coupled models (*Shindell et al., 2008*).

Similar conclusions about the variation across models were obtained in the US Climate Change Science Program report on climate projections due to short-lived and long-lived species (*CCSP, 2008*). The science supporting that report (*Shindell et al., 2007; Levy et al., 2008; Shindell et al., 2008*) showed that differences in climate projections due to short-lived species were substantial across models, and that these arose due to uncertainties in the representation of aerosol physical processes, in stratosphere-troposphere exchange of ozone, in the emissions projections themselves, and the different processes included in the models (e.g. aerosol indirect effects were present in some, but not all, models). These led to substantial variations in regional climate, especially in the Northern Hemisphere (Figure 2). A substantial body of work now supports the conclusion that regional forcing from ozone and aerosols has an important impact on regional climate change and that the regional impacts are not necessarily collocated with the forcing (*Berntsen et al., 2005; Boer and Yu, 2003; Hansen et al., 2005; Mitchell et al., 1995; Shindell and Faluvegi, 2009; Taylor and Penner, 1994*).

While the emission scenarios created for the CMIP5/AR5 specify the ozone and aerosol precursors in great detail, unlike the earlier SRES scenarios, the other sources of uncertainty will persist in these simulations. Additionally, as models progress to a more Earth System approach including more interactions with the biosphere, a larger number of climate-sensitive emissions are being incorporated into models, which will lead to diversity in the projected emissions even though anthropogenic emissions should be quite uniform across models. Hence there is a need for characterization of the forcings imposed in the CMIP5 historical and future simulations, as well as diagnostics to allow us to understand the causes of the differences in forcings from model to model. Under the CMIP5 project, minimal data concerning chemistry or aerosols will be archived from the historical or future transient runs (concentrations for some species only, and no radiative forcings other than CO_2 and no chemistry/aerosol diagnostics).

Goals and timeframe

To characterize the radiative forcing from individual species in the CMIP5/AR5 simulations, and to diagnose causes of inter-model differences, we have created a set of simulations to be performed by the chemistry/aerosol modeling community to complement those performed directly under the CMIP5 project. This Atmospheric Chemistry and Climate Model Intercomparison Project (ACC-MIP) consists of several sets of simulations that have been designed to facilitate useful evaluation and comparison of the AR5 transient climate model simulations. Two sets of simulations are designed to be run on the AR5 timeline (ACCMIP_1 and ACCMIP_2), while two others of lower priority are to examine additional sensitivities and may not be completed until after the AR5 period (ACCMIP_3 and ACCMIP_4). Specifically, we intend to have output archived for at least ACCMIP_1 and ACCMIP_2 by the end of 2009 so that model intercomparison results can be analyzed and written up in 2010 so as to be available during the 2011 writing of the AR5.

The proposed list of experiments and diagnostics is aimed at providing necessary information for scientific studies spanning the AC&C interests, along with AeroCom, HTAP and CCMVal.

Groups that have agreed to participate thus far (in alphabetical order):

CCC (Canada), CCSR (Japan), DLR (Germany), ECHAM (Germany), Hadley Centre/Met Office (UK), LSCE/IPSL (France), NASA GISS (USA), NCAR (USA), NOAA GFDL (USA), MRI (Japan)

Experiment specifications

ACCMIP_1: Timeslice runs complementing CMIP5

Timeslice runs including detailed chemistry diagnostics and separating aerosol indirect effects. Each run 4 years with prescribed SSTs taken from AR5 runs (SSTs should ideally be decadal means around given years), 2-month initialization suggested.

8 historical times (1850_I, 1890, 1910_I, 1930, 1950_I, 1970, 1990, 2000_I)

5 future times (2010_I, 2030, 2050_I, 2070, 2100_I), each with 2.6 W/m^2 Representative Concentration Pathway (RCP), 4.5 W/m^2 RCP and 8.5 W/m^2 RCP.

2 cases for those marked with an I (separate run without AIE, to be done in every other time)

For 2050 and 2100 (RCP 8.5), additional run with that year's SSTs/GHGs but 2000 emissions.

Historical simulations

Emissions/ Configuration	1850	1890	1910	1930	1950	1970	1990	2000
Historical/with AIE	A	B	A	B	A	B	A	A
Historical/no AIE	A		A		A			A

Future simulations

Emissions/ Configuration	2010	2030	2050	2070	2100
RCP 2.6/with AIE	A	B	A	B	A
RCP 2.6/no AIE	A		A		A
RCP 4.5/with AIE	A	B	A	B	A
RCP 4.5/no AIE	A		A		A
RCP 8.5/with AIE	A	B	A	B	A
RCP 8.5/no AIE	A		A		A
Year 2000/with AIE, RCP 8.5 SSTs/GHGs			B		B

A=required, B=second priority, blank=not requested

[Total of 38 simulations, so ~158 model years (years not marked with I are second priority except 2000, as are year 2000 emissions/future SST runs, leaving those out gives 27 simulations).]

ACCMIP_2: Emission sensitivity studies
Run at year 2050 (SSTs from *ACCMIP_1*), 1 year runs (+2-month initialization), model's own distribution of given emission scaled uniformly:
2.1: +100 Tg isoprene
2.3 +20% biomass burning (all species)
2.4: +50 Tg methane (3 year run in this case, only applicable for models with sources/sinks of methane rather than prescribed)
2.5: +2 Tg N/yr lightning NOx
We assume the effects of varying dust, sea-salt and DMS emissions can be adequately accounted for with emission and removal diagnostics.
[total model years requested is 6.5]

ACCMIP_3: Testing the variation in socio-economic modeling of emissions
This set of runs requests the same 4 year timeslice runs as in ACCMIP_1 for 2050 and 2100 but using emissions for the 2.6 and 4.5 RCPs from the other available Integrated Assessment models (IAMs). Runs without AIE only (as these are not climate runs)
[8 runs, 32 model years if 2 additional IAM datasets used]

ACCMIP_4: Spread in models using standardized composition

Rerun of 1860, 1930, 1970 and 2000 4 year timeslices with standard 3D constituent fields from ACC Activity 4 Phase 1 climatology. Only applicable to models that did not use climatology in ACCMIP_1 runs. [~17 model years]

Motivation: Variation in the climate response across models will be a function of (a) different climate sensitivity in the GCMs, (b) different impact of aerosols on climate (due to location with respect to clouds, water uptake, natural aerosols, mixing, etc), and (c) different 3D constituent fields from the composition models. ACCMIP_4 will allow us to separate the effect of step 'c' from steps 'a' and 'b'.

Output specifications

Minimal data will be archived from the AR5 transient runs. This will include concentrations only. Additional output from the ACCMIP runs will include concentration/mass of radiatively active species, aerosol optical properties, and radiative forcings (clear and all sky) as well as important parameters that do not direct influence climate such as hydroxyl, chemical reaction rates, deposition rates, emission rates, surface pollutants and diagnostics of tracer transport.

A spreadsheet has been created with detailed output specifications, largely based on fields archived for HTAP, AeroCom, and/or CCMVal. This can be downloaded from the HTAP/AC&C Wiki page (http://htap.icg.fz-juelich.de/data; "Atmospheric Chemistry & Climate (AC&C) Initiative Experiment Descriptions"). All data will follow standardized formats and use CF-compliant names whenever available (CMOR tables are being created and will be provided to all participants). Newly created diagnostics are highlighted in the referenced spreadsheet. These include a stratospheric ozone tracer. The stratospheric ozone tracer is defined as equal to ozone in the stratosphere, and including standard ozone removal (but not production) in the troposphere, where the tropopause is the WMO meteorological tropopause. We also include a passive tracer of transport within the troposphere as defined in the HTAP project. Fields requiring high temporal resolution (surface pollutants) have been designated secondary priority. Submission of these fields is encouraged, but we recognize that these can be quite large files and many global models are not ideally suited to air quality studies. Submission of all other fields are required (those that are available, e.g. models without stratospheric chemistry do not need to submit the stratospheric diagnostics).

We plan to archive data at a major center such as the BADC (as was done for CCMVal), with a data access policy providing one year of access to participating groups only followed by general public access. Target date for submission is ~October 2009. Though soon, this is necessary to have results in time to feed into the AR5 process, including at least a small amount of time for general public analysis (writing during 2011; revision 2012; publication 2013).

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IGAC Core Project Office
NOAA-PMEL
7600 Sand Point Way
Seattle, WA 98115-6349 USA

email: igac.seattle@noaa.gov

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Editor: Sarah Doherty
Production manager: Ho Ching Lee
Newsletter formatting: Beth Tully
IGAC logo: Linda Kubrick

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臺灣郵政台北誌字第 137 號執照登記為雜誌交寄
發行人：劉紹臣
發行所：中央研究院環境變遷研究中心
發行地址：台北市 115 南港區研究院路二段 128 號 1-55 號信箱

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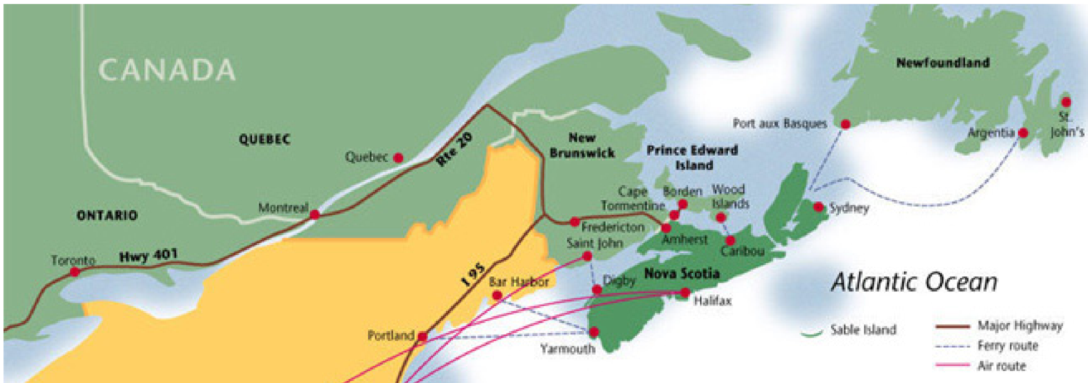


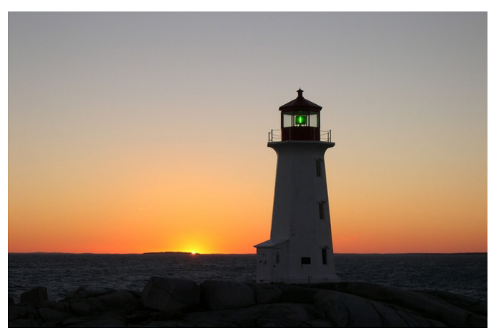

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IGAC Core Project Office
RESEARCH CENTER FOR ENVIRONMENTAL CHANGE
ACADEMIA SINICA
128 Academia Rd. Sect. 2
P.O. Box 1-55 NanKang
Taipei, 11529 Taiwan

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