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Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period

Claire Granier · Bertrand Bessagnet · Tami Bond · Ariela D'Angiola · Hugo Denier van der Gon · Gregory J. Frost · Angelika Heil · Johannes W. Kaiser · Stefan Kinne · Zbigniew Klimont · Silvia Kloster · Jean-François Lamarque · Catherine Liousse · Toshihiko Masui · Frederik Meleux · Aude Mieville · Toshimasa Ohara · Jean-Christophe Raut · Keywan Riahi · Martin G. Schultz · Steven J. Smith · Allison Thompson · John van Aardenne · Guido R. van der Werf · Detlef P. van Vuuren

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Abstract Several different inventories of global and regional anthropogenic and biomass burning emissions are assessed for the 1980–2010 period. The species considered in this study are carbon monoxide, nitrogen oxides, sulfur dioxide and black carbon. The inventories considered include the ACCMIP historical emissions developed in support of the simulations for the IPCC AR5 assessment. Emissions for 2005 and 2010 from the Representative Concentration Pathways (RCPs) are also included. Large discrepancies between the global and

C. Granier (✉) · A. D'Angiola · J.-C. Raut
UPMC University Paris 06, UMR8190, CNRS/INSU, LATMOS-IPSL, Paris, France
e-mail: claire.granier@latmos.ipsl.fr

C. Granier · G. J. Frost
NOAA Earth System Research Laboratory, Boulder, CO, USA

C. Granier · G. J. Frost
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

C. Granier · S. Kinne · S. Kloster
Max Planck Institute for Meteorology, Hamburg, Germany

B. Bessagnet · F. Meleux
INERIS, Verneuil-en-Halatte, France

T. Bond
University of Illinois at Urbana-Champaign, Urbana, IL, USA

H. Denier van der Gon
TNO Built Environment and Geosciences, Utrecht, The Netherlands

A. Heil · M. G. Schultz
Forschungszentrum Juelich, Juelich, Germany

regional emissions are identified, which shows that there is still no consensus on the best estimates for surface emissions of atmospheric compounds. At the global scale, anthropogenic emissions of CO, NO_x and SO_2 show the best agreement for most years, although agreement does not necessarily mean that uncertainty is low. The agreement is low for BC emissions, particularly in the period prior to 2000. The best consensus is for NO_x emissions for all periods and all regions, except for China, where emissions in 1980 and 1990 need to be better defined. Emissions of CO need better quantification in the USA and India for all periods; in Central Europe, the evolution of emissions during the past two decades needs to be better determined. The agreement between the different SO_2 emissions datasets is rather good for the USA, but better quantification is needed elsewhere, particularly for Central Europe, India and China. The comparisons performed in this study show that the use of RCP8.5 for the extension of the ACCMIP inventory beyond 2000 is reasonable, until more global or regional estimates become available. Concerning biomass burning emissions, most inventories agree within 50–80%, depending on the year and season. The large differences between biomass burning inventories are due to differences in the estimates of burned areas from the different available products, as well as in the amount of biomass burned.

1 Introduction

An accurate knowledge of the spatial and temporal distribution of surface emissions and of their evolution over time is essential to support the analysis and modeling of air quality and climate change issues. Furthermore, up-to-date and consistent emissions are required for the forecasting of the atmospheric composition at global and regional scales. Emission data are

J. W. Kaiser
European Centre for Medium-Range Weather Forecasts, Reading, UK

Z. Klimont · K. Riahi
International Institute for Applied Systems Analysis, Laxenburg, Austria

J.-F. Lamarque
National Center for Atmospheric Research, Boulder, CO, USA

C. Liousse · A. Mieville
Laboratoire d'Aérologie, Toulouse, France

T. Masui · T. Ohara
National Institute for Environmental Studies, Tsukuba, Japan

S. J. Smith · A. Thompson
Pacific Northwest National Laboratory, College Park, MD, USA

J. van Aardenne
European Environment Agency, Copenhagen, Denmark

G. R. van der Werf
VU University Amsterdam, Amsterdam, The Netherlands

D. P. van Vuuren
Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands

D. P. van Vuuren
Utrecht University, Utrecht, The Netherlands

used to drive simulations of changes in the distribution and deposition of atmospheric constituents. Over the past few years, several inventories providing the distribution of surface emissions of gaseous and particulate species were developed, at both the global and regional scales. In 2008–2009, a group of international scientists developed a new emissions dataset covering the 1850–2000 period, based on the combination and harmonization of published and publicly available datasets (Lamarque et al. 2010). This work was undertaken in order to support both the development of new scenarios for climate research (Moss et al. 2010) and the climate model runs as part of the Coupled Model Intercomparison Project phase 5 (CMIP5) of the World Climate Research Programme (WCRP). Details on CMIP5 are given in Taylor et al. (2008). The new 1850–2000 harmonized emissions dataset is called ACCMIP (Emissions for Atmospheric Chemistry and Climate Model Intercomparison Project). The year 2000 ACCMIP emissions act as a starting point for the development of the future projections given by different representative concentrations pathways (RCPs) (Van Vuuren et al., this issue, 2011; Moss et al. 2010).

The quality of the ACCMIP dataset and inventories considered in this paper is difficult to assess, since the methodology, input data, and assumptions vary strongly between the inventories. Several evaluations of surface emissions inventories have been published in the literature, but they have either focused on a few selected inventories, on selected chemical compounds, on a few regions or on short periods of time. For example, the HTAP 2010 assessment report (available at http://htap.org) mainly focuses its analysis on several inventories for Asia, similar to the studies published by Zhang et al. (2009), Lei et al. (2010) and Klimont et al. (2009). Most authors who have described the development of new or updated surface emissions inventories have compared their inventory with other datasets, but few of these comparisons have included several datasets and had a global coverage (Schultz et al. 2008; Lamarque et al. 2010).

Comparisons between observations and model simulations using multiple inventories are another method that could potentially be used to identify errors in inventory data (Parrish 2006; Berglen et al. 2007; Lamarque et al. 2010). Definitive conclusions, however, are difficult to achieve since model biases are often not well quantified, inventories have different time resolution and spatial gridding assumptions, and the most common observational comparison metrics such as aerosol optical depth, particle concentrations and ozone distribution are the result of emissions of multiple species. Furthermore, there are insufficient data to rigorously compare model simulations with observations before the 1990s.

As part of the development of the ACCMIP emissions dataset, a detailed comparison and evaluation of different datasets has started. Based on this work, we focus in this paper on the comparison of several publicly available inventories of anthropogenic and biomass burning emissions for the 1980–2010 period. This period was chosen, because most of the inventories currently available cover at least partially these three decades. For the period beyond 2005, the emissions provided by the RCPs are included in the comparison.

The analysis in this paper will focus mostly on anthropogenic emissions, followed by a brief analysis of biomass burning emissions. The main goal of the paper is to identify the species and regions for which a high degree of consistency exist on emission levels and their trends during the past three decades, and the species and regions for which more work needs to be done to obtain a better consensus. It should however be noted that a consensus in total and regional emissions does not mean that the inventories are accurate. Furthermore, a certain amount of overlap exists between the datasets considered: some data provided by one inventory may have been used for developing another inventory. Another goal of the paper is to compare the emissions provided by the Representative Concentration Pathways (RCPs) for active chemical compounds in 2005 and 2010 with emissions estimated by other methodologies.

Section 2 will present the main characteristics of the global and regional emissions inventories used in this study. In Section 3, we will compare the different datasets, for the global scale, and for a few selected regions, i.e. Europe, the USA, China and India for anthropogenic emissions, and Africa and South America for biomass burning emissions.

2 Datasets used in the study

This section describes the datasets used in this study, i.e. global anthropogenic emissions, regional anthropogenic emissions and biomass burning emissions. The datasets described briefly in the next paragraphs include emission estimates for four primary air pollutants, carbon monoxide (CO), nitrogen oxides (NO_x), black carbon (BC) and sulfur dioxide (SO_2). The analysis of the emissions of volatile organic compounds is not included in this paper: a large number of emission inventories provide only the distribution of the sum of all VOCs emissions. A detailed evaluation of these datasets would require a large amount of work in order to understand the contribution of each individual VOC to the total VOCs emissions, which is beyond the scope of the paper. A list of the global and regional emission inventories considered in this study is given in Table 1.

2.1 Global anthropogenic emissions

All anthropogenic emissions estimates are developed using the same generic method, based on the product of estimates for activity data (such as fuel consumption or commodity production) and emission factors. Activity data usually originate either with country records or with international organizations such as the United Nations or the International Energy Agency; however, since these data are not always consistent, many inventory developers adjust these data for use in their emission algorithms. Emission factors for most gaseous and all particulate species depend on the generating process. This dependence is represented either by specifying the type of technology in each world region ("technology basis"), or by choosing emission factors that are thought to be representative of each region, especially with attention to development characteristics ("representative emission factors"). The following sections indicate the main characteristics of the inventories considered in the paper.

ACCMIP and Representative Concentration Pathways (RCPs) As indicated in the introduction, a community effort during the past few years has led to the development of the ACCMIP emissions, a dataset of monthly, sectoral, gridded anthropogenic and biomass burning emissions covering the historical period (1850–2000) in decadal increments at a horizontal resolution of 0.5° in latitude and longitude (Lamarque et al. 2010). The primary purpose of this work was to provide consistent gridded emissions of reactive gases and aerosols for use in chemistry model simulations needed by climate models for CMIP5. The year 2000 was chosen as the reference year, since 2000 emissions represent a combination of the best information available on existing regional and global inventories in the years 2008–2009 when the inventory was built. For each emission type, 10 emission sources were specified for 40 regions. ACCMIP emissions for historical years were drawn on the basis of several of the emission inventories discussed below and will therefore agree closely with some of them. For example, ACCMIP emissions at the global scale up to 2000 represent a combination of the HYDE, RETRO, PNNL and the Bond inventories described below. For ozone precursors, the ACCMIP emissions are based on a combination of the

Table 1 List of anthropogenic emissions inventories considered in this study

Inventories providing global emissions of all species considered, i.e. CO, NO_x, BC and SO_2			
ACCMIP	1980–2010	0.5×0.5	http://ether.ipsl.jussieu.fr/eccad ftp://ftp-ipcc.fz-juelich.de/pub/emissions/ http://www.iiasa.ac.at/web-apps/tnt/RcpDb Lamarque et al. 2010
MACCity	1980–2010	0.5×0.5	http://ether.ipsl.jussieu.fr/eccad
RCPs	2000–2010	0.5×0.5	http://ether.ipsl.jussieu.fr/eccad ftp://ftp-ipcc.fz-juelich.de/pub/emissions/ http://www.iiasa.ac.at/web-apps/tnt/RcpDb
EDGAR v3	1990, 1995 2000	1×1	http://edgar.jrc.ec.europa.eu Olivier et al. 2005
HYDE	1980, 1990	1×1	Van Aardenne et al. 2001 http://www.pbl.nl/en/themasites/hyde/index.html
RETRO	1980–2000	0.5×0.5	http://retro.enes.org/data_emissions.shtml
GAINS	1990–2010		http://gains.iiasa.ac.at/gains
Global inventories providing a selected number of species			
BOND (BC)	1980–2000	1×1	http://www.hiwater.org/ Bond et al. 2007
J&L / Junker &Liousse (BC)	1980–2000	1×1	Junker and Liousse 2008
AEROCOM (SO_2 and BC)	1980–2006	1×1	http://dataipsl.ipsl.jussieu.fr/AEROCOM
PNNL (SO_2)	1980–2005	0.5×0.5	Smith et al. 2004; Smith et al. 2010
I&P / Ito and Penner (BC)	1980–2000	1×1	Ito and Penner 2005
Novakov (BC)	1980–2000	Not gridded	Novakov et al. 2003
Regional inventories			
EMEP	1980–2010	0.5×0.5	http://www.ceip.at/emission-data-webdab/emissions-used-in-emep-models/
TNO	2003–2007	0.125×0.0625	ftp://neptunus.tno.nl/TNO/MEP/EM/MACC/ Denier van de Gon et al. 2010
INERIS	1998–2007	0.1×0.1 and 0.5×0.5	http://cityzen-project.eu/
EPA	1980–2008	Not gridded	http://www.epa.gov/ttn/chief/trends/index.html
REAS	1980–2010	0.5×0.5	http://www.jamstec.go.jp/frcgc/research/p3/reas_h_a.html Ohara et al. 2007
ACCESS	2000 and 2006	0.5×0.5	http://www.cgrer.uiowa.edu/ACESS/acess_index.htm Streets et al. 2003; Zhang et al. 2009
Garg	1985–2005	Not gridded	Garg et al. 2006

GAINS and REAS emissions for Asia, on the EMEP emissions for Europe and on the EPA inventory for the USA. For SO_2, ACCMIP uses EPA data as a basis for the emissions in the USA. Details on the methodology used to generate the ACCMIP emissions are given in Lamarque et al. 2010.

The projections of future emissions (Representative Concentration Pathways) are based on the outcomes of four independent modeling teams. The RCPs are named according to their 2100 radiative forcing level, i.e. RCP 8.5 corresponds to a radiative forcing of 8.5 W. m^{-2} in 2100. As a "handshake" requirement, the future emissions were forced to agree with the 2000 estimates, ensuring continuity between past, 2000 emissions and future projections.

In this study, emissions provided by each RCP for 2005 and 2010 are also included in the comparison. Data for each of the four RCPs is available at: http://www.iiasa.ac.at/web-apps/tnt/RcpDb, with further description provided in separate papers in this issue.

MACCity emissions As part of two projects funded by the European Commission, MACC (Hollingsworth et al. 2008; http://www.gmes-atmosphere.eu/) and CityZen (http://cityzen-project.eu/), an extension of the ACCMIP historical emissions dataset to the year 2005 has been developed. Within these two European projects, simulations of changes in the chemical composition of the atmosphere during the past decades have been performed. Since no global database existed which provide emissions of the main tropospheric gases for each year during the 1990–2010 period, a dataset was created, based on the 1990 and 2000 ACCMIP emissions, and the 2005 and 2010 emissions provided by RCP 8.5. This scenario includes some information on recent emissions at the regional scale in Europe and North America. The emissions for each compound were linearly interpolated, for each sector and each year between 2000 and 2005, and for each year between 2005 and 2010, using the ACCMIP and RCP 8.5 emissions. The acronym for the emissions defined by this interpolation is MACCity.

EDGAR and EDGAR-HYDE inventories The EDGAR project was developed by the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Organization for Applied Scientific Research (TNO), during the 1992–2004 period. Since 2005, the EDGAR project has been developed as part of a collaboration between PBL and the European Commission's Joint Research Center (JRC). In this study, we have used the emissions provided by two versions of the EDGAR inventory. EDGARv32 provides emission of direct greenhouse gases for the 1970–1995 period. Emissions of ozone precursors and SO_2 for the 1990–1995 period are also available by country and on a 1×1 degree grid (Olivier and Berdowski 2001). We have also used the EDGARv32-FT2000 inventory, which comprises global anthropogenic emissions for the year 2000, excluding BC. The dataset is based on the EDGARv32 estimates for 1995 and prepared by trend analyses at country level for each standard source category of EDGARv32 (Olivier et al. 2005). In the figures and tables discussed in the paper, the data for 1990, 1995, and 2000 are indicated by the label "EDGAR".

A second inventory was developed by PBL, called EDGAR-HYDE (van Aardenne et al. 2001). EDGAR-HYDE provides emissions of greenhouse gases and precursor gases for the period 1890 to 1990, with a 10-year timestep and a 1×1 degree resolution. HYDE uses representative emission factors to estimate the emissions. In the plots presenting and in the discussion section, EDGAR-HYDE is indicated by "HYDE".

RETRO inventory Within the RETRO project (REanalysis of the TROpospheric chemical composition) (Schultz et al. 2007), global gridded data sets were generated, which provide anthropogenic and vegetation fire emissions of several trace gases, except BC. The species considered are carbon monoxide, nitrogen oxides, and several hydrocarbons. The RETRO dataset covers the period from 1960 to 2000 at a monthly time resolution. Anthropogenic

emissions in the RETRO inventory are derived from a preliminary version of the TNO emissions, described in the section on regional inventories. The anthropogenic emissions in the RETRO inventory cover combustion sources only.

GAINS inventory Emissions for Europe (Kupiainen and Klimont 2007), Asia (Klimont et al. 2009) and at the global scale (Cofala et al. 2007; Isaksen et al. 2009) are developed at IIASA (International Institute for Applied Systems Analysis), using the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model (http://gains.iiasa.ac.at/gains). GAINS enables an examination of the co-benefits of simultaneous reduction of air pollution and greenhouse gas emissions. This model systematically compiles country- and sector-specific information for all countries and regions of the world: it combines national data and sectoral economic development with emission factors that describe the technical features of the emission sources. Emissions of pollutants are calculated as a product of activity level and emission factors; the latter are estimated considering removal efficiency of specific control technology and its implementation level in a given sector. The model does not include international shipping. In the comparisons of global totals with other estimates, shipping emissions from the ACCMIP inventory have been added to the GAINS emissions. The emissions used in the paper up to 2010 are estimated using the World Energy Outlook 2009 (IEA 2009). These data include an assessment of the impact on energy use of the recent economic downturn.

Bond Black Carbon inventory The Bond inventory (Bond et al. 2007) provides trends in the emissions of black and primary organic carbon emissions between 1850 and 2000. The estimates assume that the emissions of particulate matter depend mainly on technology choices. The emissions are calculated, based on a sectoral, fuel-specific reconstruction of fossil fuel consumption and on historical estimates of bioenergy consumption. The methodology described in Bond et al. (2007) includes an analysis of the fossil fuel consumption during the past decades, as well as of the emission factors for different sectors.

Junker and Liousse (J&L) Black Carbon inventory Country by country emission inventories for carbonaceous and organic aerosol for the period 1860 to 2003 are given in the J&L emissions dataset (Junker and Liousse 2008; Assamoi and Liousse 2010). The inventory has been constructed on the basis of historic fuel production, use and trade data sets published by the United Nation's Statistical Division UNSTAT (1997), Etemad et al. (1991) and Mitchell (1992). Three main sectors are considered, i.e. traffic, domestic and industrial. The inventory uses representative emission factors, but these are treated as variable over time, using different levels of economic and technological development in each country. Emission maps have been generated with a 1×1 degree resolution based on the relative population density in each country.

Novakov Black Carbon inventory Historical trends of fossil-fuel BC emissions in six regions, i.e. United States, United Kingdom, Germany, Soviet Union, India and China were estimated (Novakov et al. 2003). In 1990, these countries accounted for about 70% and 60%, respectively, of the world consumption of coal and diesel fuel, which are the principal BC-producing fossil fuels. The estimates were extrapolated to global emissions from 1875 onward. Qualitative features in these trends show rapid increase in the latter part of the 1800s, the leveling off in the first half of the 1900s, and the re-acceleration in the past 50 years as China and India developed.

Ito and Penner inventory The Ito and Penner (2005) inventory for black carbon considers emissions from biofuel and fossil fuel use for the 1870–2000 period. Biofuel emissions are first developed for developing countries for the recent years, and are then scaled forward and backward in time using population statistics and crop production statistics. In developed countries, wood consumption data together with emission factors for cooking and heating practices are used for biofuel estimates. Fuel consumption data (UN for 1950–1970 and IEA for 1970–2000) and specific emission factors for different fuel use categories from Bond et al. (2004) are used to develop an inventory linked with fossil fuel usage. Technology changes in emissions from the diesel transport sector are included.

AEROCOM BC and SO_2 hindcast inventory The AEROCOM-project (http://dataipsl.ipsl.jussieu.fr/AEROCOM) is an open international initiative of scientists interested in the advancement of the understanding of the global aerosol and its impact on climate. These emissions are based on a compilation of emissions dedicated to help the hindcast simulations of aerosols, i.e. the Bond et al. (2004) emissions for BC, the EDGARv32 for SO_2, and yearly emissions from 1980 to 2006 from Streets et al. (2004, 2008). The species provided by this inventory, which include emissions from ships, are black and organic carbon as well as sulfur dioxide.

SO_2 PNNL inventories The SO_2 emissions reported by Smith et al. (2004) provide estimates of sulfur dioxide emissions over the last one and a half centuries. The inventory includes all anthropogenic sources and was constructed using a combination of bottom-up and best available inventory methods. Annual emissions were extrapolated to a 1×1 degree grid for the time period 1850–2000. Emissions factors vary with time to account for sulfur removals from fossil fuels and industrial smelting processes, using mass balance calculations and calibration to country-level inventories. A new inventory has been developed by Smith et al. (2010), which provides global and regional SO_2 emissions for the 1850–2005 period using a similar methodology, incorporating updated datasets.

2.2 Regional anthropogenic inventories

EMEP emissions for Europe The UNECE/EMEP emission inventory for Europe contains national total emissions, sector data and gridded emission data for modeling purposes (Vestreng et al. 2007). Scenarios for the years 2010 and 2020 are also included in the inventory. The emission data are based on officially reported emissions to the extent possible (http://www.emep-emissions.at), but some of the officially reported data have been corrected and gaps have been filled. Only the anthropogenic part of the emissions is used here.

TNO and INERIS emissions for Europe On the basis of the EMEP emissions, TNO (Netherlands Organization for Applied Scientific Research) has developed a gridded emission inventory at a 0.125×0.0625 degree resolution for the year 2005 (Denier van der Gon et al. 2010). TNO performed different consistency checks of the European emissions, and the emissions were distributed according to a set of proxy maps. Emissions for the 2003–2007 period were developed using national emissions when available, and linear interpolations for each source category based on the 2010 projections for countries for which no data other than for 2005 were available.

The EMEP-INERIS inventory is an EMEP-based emission database that uses landcover data at very fine resolution (GlobCover: Bicheron et al. 2006) to remap the emissions from 0.5°×0.5° to 0.1°×0.1° resolutions. GlobCover products are based on the ENVISAT satellite mission's MERIS sensor (Medium Resolution Image Spectrometer) acquired in Full Resolution (FR) mode with a spatial resolution of 300 m. GlobCover LC v2 was derived from an automatic and regionally-tuned classification of a time series of MERIS FR composites covering the period December 2004–June 2006. Agricultural EMEP emissions have been regridded over the "crops" classes and the other anthropogenic emissions were reallocated over "artificial zones".

EPA emissions for the United States In 2009, the US EPA reported the latest information on anthropogenic emissions trends in the USA from 1980 to 2008. These data were obtained through the EPA's National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data database (US EPA, 2001; http://www.epa.gov/ttnchie1/trends/). The EPA trends data sets do not include information for BC. Since 1985, the basis for these emission trends estimates has been the NEI or its predecessors. The NEI methodologies are developed and promulgated by the EPA, while the estimation and submission of the emissions data itself is by state and local air quality agencies working in partnership with the EPA. The methodologies employed depend on the pollutant and the year, but the emission factors used are specific to each installation or source group. The EPA also carries out periodic projections of these data for future years not yet covered by a complete NEI (e.g., 2009). The EPA interpolates emissions data for each source category in years other than the NEI base or projected years.

REAS emissions for Asia An emission inventory for Asia called REAS (Regional Emission inventory in ASia) was developed for the period 1980–2020 (Ohara et al. 2007). REAS integrates historical, present, and future emissions in Asia using a consistent methodology; it uses representative emission factors for each sector. The REAS inventory includes historical emissions for 1980–2003, and projected emissions for 2010 and 2020 from fuel combustion and industrial sources. Total energy consumption in Asia more than doubled between 1980 and 2003 causing a rapid growth in Asian emissions, which are provided by this inventory. Large increases in China were mainly caused by increases in coal combustion in the power plants and industrial sectors. Future emissions in 2010 and 2020 in Asian countries were projected by emission scenarios and from emissions in 2000. For China, three emissions scenarios were developed, PSC (policy success case), REF (reference case), and PFC (policy failure case). In this paper, the emissions from the PFC scenario are used to illustrate the emission increase in China after 2000.

TRACE-P and INTEX-B emissions for Asia from the ACCESS system An inventory providing emissions for Asia, using a technology basis, was developed for the year 2000 (Streets et al. 2003), in support of the NASA TRACE-P (Transport and Chemical Evolution over the Pacific) campaign and ACE-Asia (Asian Pacific Regional Aerosol Characterization Experiment). In order to take into account the economic growth in East Asia since 2000, a new inventory was developed for Asia in support of NASA INTEX-B experiment. Details on this inventory are given in Zhang et al. (2009), which provides updated values for 2001 and new emissions for 2006. The emission changes between the 2000 and 2006 inventories reflect a combination of the actual growth in emissions due to increasing economic development in Asia, the effects of replacing the TRACE-P 2000 inventory by local inventories in several countries, and improvements and corrections made to the original TRACE-P inventory.

Both the TRACE-P and INTEX-B inventories are distributed as part of ACCESS (ACE Asia and Trace-P Modeling and Emission Support System). The acronym ACCESS used in the paper will refer to these two Asian inventories.

Garg inventory for India The Garg et al. (2006) inventory incorporates scientific estimates for Indian emissions for the 1985–2005 period for CO, NO_x and SO_2. The inventory uses the data provided by international databases such as the International Energy Agency (http://www.iea.org), as well as data from national, state and district level administrations in India. India-specific emission factors were used when available, for example for NO_x released from diesel and gasoline used in road transport, or for NO_x and CO emissions from the burning of crop residues.

2.3 Global biomass burning emissions

GFED-v2 and GFED-v3 inventories The Global Fire Emissions Database (GFED) contains emissions from open fires for the 1997–2004 period, which have been updated annually (van der Werf et al. 2006). The methodology relies heavily on satellite data and includes all fires that can be detected from space. Smaller agricultural fires may not be detected, but all grassland, savanna, and forest fires (including deforestation fires) are included. Emissions are calculated as the product of burned area (Giglio et al. 2010), fuel loads, combustion completeness, and emission factors (Andreae and Merlet 2001). Satellite-derived burned areas drive the fire module of a biogeochemical model that calculates fuel loads for each month and grid cell. Combustion completeness is also calculated in the model based on fuel types and moisture conditions. A new version of the inventory that covers the 1997–2009 period, called GFED-v3, was made available at the beginning of 2010 (van der Werf et al. 2010). Both GFED-v2 and GFED-v3 emissions are considered in the paper.

RETRO inventory The RETRO inventory of biomass burning emissions (Schultz et al. 2008) is based on a critical review of the available literature and datasets reporting on the emissions of carbon and several trace species from wildland fires. Quantitative and semi-quantitative information from a large amount of different sources was used to estimate annual total direct carbon emissions for the time period from 1960 to 2000. A numerical model with a semi-physical approach was used to simulate fire occurrence and fire spread, using different satellite products. Vegetation fire emissions were constructed from a large variety of sources with the objective to provide a reasonable estimate of emissions including their seasonal and interannual variability in the major burning regions of the world.

MACCity – ACCMIP emissions The ACCMIP historical dataset (Lamarque et al. 2010) provides decadal monthly mean biomass burning emissions. In order to evaluate the large interannual variability of biomass burning emissions, the decadal ACCMIP emissions was extended: yearly monthly mean emissions of trace species are calculated from spatio-temporally modified RETRO carbon emission data for the years 1980 to 1996 and from GFED-v2 carbon emission data for the years 1997 to 2008, by applying a single set of vegetation-type specific emission factors and the predominant vegetation map used in the GFED-v2 inventory. In areas covered by peat soils, emissions from peat fires are included into the emission calculation. As for anthropogenic emissions, the monthly emissions for the 1997–2008 emissions were built as part of the MACC and CityZen projects, and we will use the MACCity acronym to represent this inventory.

GICC inventory The GICC (Global Inventory for Chemistry Climate Studies) inventory provides emissions of gases and particles from biomass burning on an annual basis for the period 1997–2005, and on a decadal basis for the historical period 1900–2000 (Mieville et al. 2010). For the recent 1997–2005 period, fire emission estimation is based on satellite products (GBA2000 burnt areas, ATSR fire counts), and on the GLC2000 vegetation map. For the 20th century, average annual emissions for each decade are derived from a historical reconstruction of burnt surfaces at 1°×1° (Mouillot and Field 2005).

Kloster inventory The biomass burning inventory by Kloster et al. (2010) is based on simulations performed with the Community Land Model (CLM-CN, Thornton et al. 2007) for the 20th century. The CLM-CN model was extended by a prognostic treatment of fire emissions of carbon and other compounds based on the work by Arora and Boer (2005). The model includes an explicit treatment of human ignition of fires and fire suppression as a function of population density: the probability of human ignition increases with population density, and fire suppression varies as well with population density, with the highest fire suppression rate in densely populated areas. The spatial resolution of the fires emissions dataset is 1.9×2.5°.

2.4 Regional biomass burning inventories

AMMABB inventory The AMMABB biomass burning inventory for Africa was built in order to derive daily gaseous and particulate emissions for the 2000–2007 period, at a resolution of 1×1 km (Liousse et al. 2010). This inventory was developed in the framework of the AMMA (Multidisciplinary Analyses of African Monsoon) program. It is based on the L3JRC burned area product (Tansey et al. 2008, available at http://bioval.jrc.ec.europa.eu/). The inventory uses similar data, i.e. the GLC2000 land cover information, and the same biomass density, combustion efficiency and emission factors as in the GICC inventory. Note that corrections have been applied to the estimated L3JRC burned area for two land cover classes: the deciduous broad-leaved tree (GLC03) and the deciduous shrub cover (GLC12) classes, following an analysis of high resolution satellite data (Landsat Thematic Mapper).

A list of the inventories of biomass burning emissions considered in the paper is given in Table 2.

3 Comparisons of inventories

3.1 Anthropogenic emissions

In this section, we compare the emissions provided by different global and regional datasets. It should be noted that some of the inventories considered in the study are not independent of each other. The ACCMIP and MACCity inventories are by definition based on other inventories. Specifically, as already indicated in Section 2, they represent a combination of the HYDE, RETRO, PNNL and Bond et al. anthropogenic emissions at the global scale up to 2000. ACCMIP and MACCity are also using the EPA, EMEP, REAS and other inventories at the regional scale for 2000. MACCity is also based on RCP8.5 emissions between 2001 and 2010.

Table 2 List of inventories and time periods considered for the evaluation of biomass burning emission

Acronym	Period	Spatial resolution	Reference and/or website
GFED2	1997–2008	1°×1°	http://ess1.ess.uci.edu/~jranders/data/GFED2/ van der Werf et al. 2006
GFED3	1997–2009	0.5°×0.5°	http://www.falw.vu/~gwerf/GFED/index.htm van der Werf et al. 2010
GICC	1997–2005	0.5°×0.5°	http://www.aero.jussieu.fr/projet/ACCENT/GICC.php Mieville et al. 2010
AMMABB	2000–2007	1×1 km	Liousse et al. 2010
Kloster	1980–2005	1.9°×2.5°	Kloster et al. 2010
RETRO	1980–2000	0.5°×0.5°	http://retro.enes.org
MACCity	1980–2008	0.5°×0.5°	http://ether.ipsl.jussieu.fr/eccad ftp://ftp-ipcc.fz-juelich.de/pub/emissions/

3.1.1 Anthropogenic emissions at the global scale

Figure 1 displays the global anthropogenic emissions of BC, CO, NO_x and SO_2 at the global scale. These totals include ship emissions. SO_2 and BC emissions are available from 13 to 12 inventories, respectively, while ten inventories provide emissions for CO and NO_x.

Most of the inventories providing BC show a slight increase in the emissions since 1980. However, the Junker and Liousse (J&L) inventory as well as the Novakov data show a

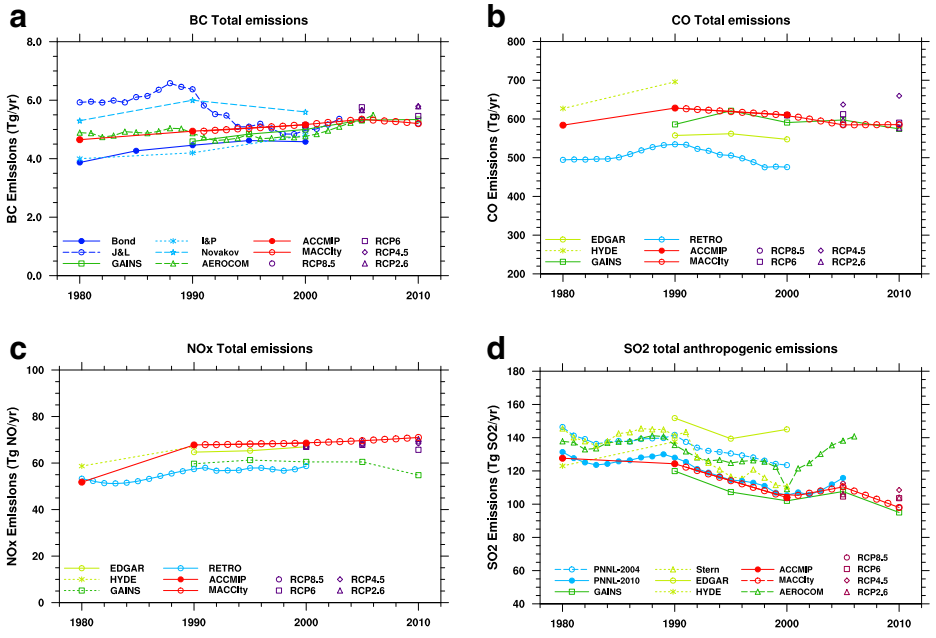

Fig. 1 Comparisons of global emissions of BC (*top left*), CO (*top right*), NO_x (*bottom left*) and SO_2 (*bottom right*) from 1980 to 2010. SO_2 total emissions from Stern (2006) are also included in the figure

decrease in the emissions in the 1990s, though the decline is less pronounced in the Novakov inventory. The larger decrease in emissions until the mid-1990s in the J&L inventory is the result of the larger changes in diesel and gasoline use emissions factors during the 1980s and 1990s, when compared to the other inventories. The differences in BC emissions are rather large in the 1980s and the 1990s, i.e. 53% between the highest and lowest total emissions in 1980, and a 51% difference in 1990. There is a better consensus in the 2000, with a maximum difference of 22% between the inventories. Still, all these differences are within the uncertainty range estimated in Bond et al. (2004), though the authors indicate that this range might be overestimated. In 2010, the GAINS emissions are 5% higher than the MACCity projected emissions. For 2010, RCP2.6 (also referred to as RCP3PD) provides the highest total emissions, which are 20% higher then those provided by RCP 8.5.

There is a rather good consensus on the NO_x global emissions. All the datasets show a slight increase in the emissions during the considered period. In 1980, the difference between the three totals available is 13%. In 1990 and 2000, five inventories are available, and the maximum difference between the totals is 18% and 17%, respectively. In 2010, the emissions from the RCPs are all within an 8% range, while GAINS estimates are about 20% lower.

The global CO emissions show a rather similar pattern, i.e. an increase between 1980 and 1990, followed by a slight decrease until 2000–2005. There is, however, a significant spread among the totals, which differ by about 27% in 1980, 30% in 1990 and 28% in 2000 between the lowest and highest values. For most years, except 1990, the RETRO inventory, which does not include non-combustion sources, provides the lowest estimates of the total emissions. In 2005, the different RCPs provide the same values, around 610 Tg CO/year, within a 9% margin. In 2010, RCPs 8.5, RCP6, RCP2.6 and GAINS provide similar totals, while RCP 4.5 total emissions are 15% higher.

For SO_2, most inventories indicate a significant decrease in the emissions during the period considered in this study. In 1980, the difference between the lowest and highest estimate is 18%, and reaches 42% in 2000, when the EDGAR v3.2 inventory provides larger values than other inventories. The higher values in EDGARv3.2, especially after 1995, are due to different assumptions about changes in activity levels.

After 2000, the emissions from the AEROCOM dataset show a significant increase, contrary to the other inventories, which do not show significant changes. SO_2 emissions have significantly decreased in most part of the world after 2000, except in Asia. In the AEROCOM inventory, SO_2 emissions are also increasing in China, but they are either constant or increasing as well in other parts of the world, which explains the increase in the global emissions totals. It should be noted that the SO_2 ACCMIP emissions up to 2000 are based on the PNNL-2010 dataset, which explains why the emissions totals are very close in these two datasets. A further comparison of SO_2 emissions is provided in Smith et al. 2010.

3.1.2 Anthropogenic emissions at the regional scale

This section discusses a comparison of emissions for several regions, i.e. Western Europe, Central Europe, USA, China and India. These regions were chosen because they are the only regions for which long-term regional anthropogenic emissions are available, as indicated in Section 2. We have used the definition of the regions provided by the IMAGE 24 dataset, except for India, which is not part of the IMAGE 24 regions. The IMAGE 24 regions have been used as a basis of the ACCMIP/RCP inventory (see http://themasites.pbl.nl/en/themasites/image/background/regions/index.html). The regions map is based on the individual country map given in the National Identifier Grid of the Gridded Population of

the World, version 3 (GPWv3) at 2.5 min resolution (available at http://sedac.ciesin.columbia.edu/gpw/). The IMAGE24 region code was assigned to the respective countries and regridded to 0.5°. The countries included in each region are indicated in Table 3. Note that the China region includes Tibet, Mongolia and Taiwan.

For biomass burning emissions, which will be discussed in Section 3.2, the discussion will focus on Africa and South America, where biomass burning emissions are the largest.

European emissions Total emissions for Western and Central Europe are shown in Fig. 2. All the inventories show almost no changes in the BC emissions in Western Europe during the considered period, except from the J&L inventory, which provides emissions of about 0.8 Tg C/year in the 1980s and a strong decrease afterwards resulting from estimated large changes in BC emission factors for diesel and gasoline use. The AEROCOM inventory shows a slight decrease up to the late 1990s, followed by a slight increase. In 2000, all inventories agree within 20%. The agreement between the ACCMIP, AEROCOM, GAINS and RCPs emissions is rather good in 2005, while differences up to 66% exist between the different RCP emissions in 2010, which illustrates the difference in the assessment models used to generate the scenarios.

Large differences are observed in BC estimates for Central Europe. In 1980, the highest value is given by the J&L dataset, i.e. 0.44 Tg C/year, while the lowest value, at 0.18 is given by the Bond inventory, i.e. a difference of a factor of 2.4. The two other available datasets, GAINS and AEROCOM provide values between these two extremes. In 1990 and 2000, the differences are similar, i.e. a factor of 2.5 in 1990 between the lowest and highest estimate, and a somewhat smaller factor of 1.9 in 2000. The rate of change is also quite different between the datasets. After 2000, the GAINS, Bond and ACCMIP inventories show a slight decrease, while J&L and AEROCOM show a slight increase.

CO and NO_x emissions in Western and Central Europe show similar patterns of decreasing emissions during the considered period. One exception is the HYDE inventory which shows an increase in CO emissions in Western Europe up to 1990. In Western Europe, most inventories agree rather well: all the emissions, except for CO from RETRO, agree to within 20%.

Differences in Central Europe emissions are larger, i.e. 43% and 32% in 1980 for CO and NO_x emissions, respectively. After 1990, more inventories are available. The ACCMIP

Table 3 Regions used in the evaluation of regional emissions, based on IMAGE 2.4

Region	Countries included in the region
Western Europe	Austria; Belgium; Denmark; Finland; France; Germany Greece; Iceland; Ireland; Italy; Luxemburg; Malta
	Netherlands; Norway; Portugal; Spain; Sweden
	Switzerland; United Kingdom
Central Europe	Albania; Bosnia and Herzegovina; Bulgaria, Croatia
	Cyprus, Czech Republic, Estonia; Hungary; Latvia
	Lithuania; Macedonia; Poland; Romania
	Serbia and Montenegro; Slovakia; Slovenia
United States	United States of America
China	China, including Tibet, Mongolia and Taiwan
India	India

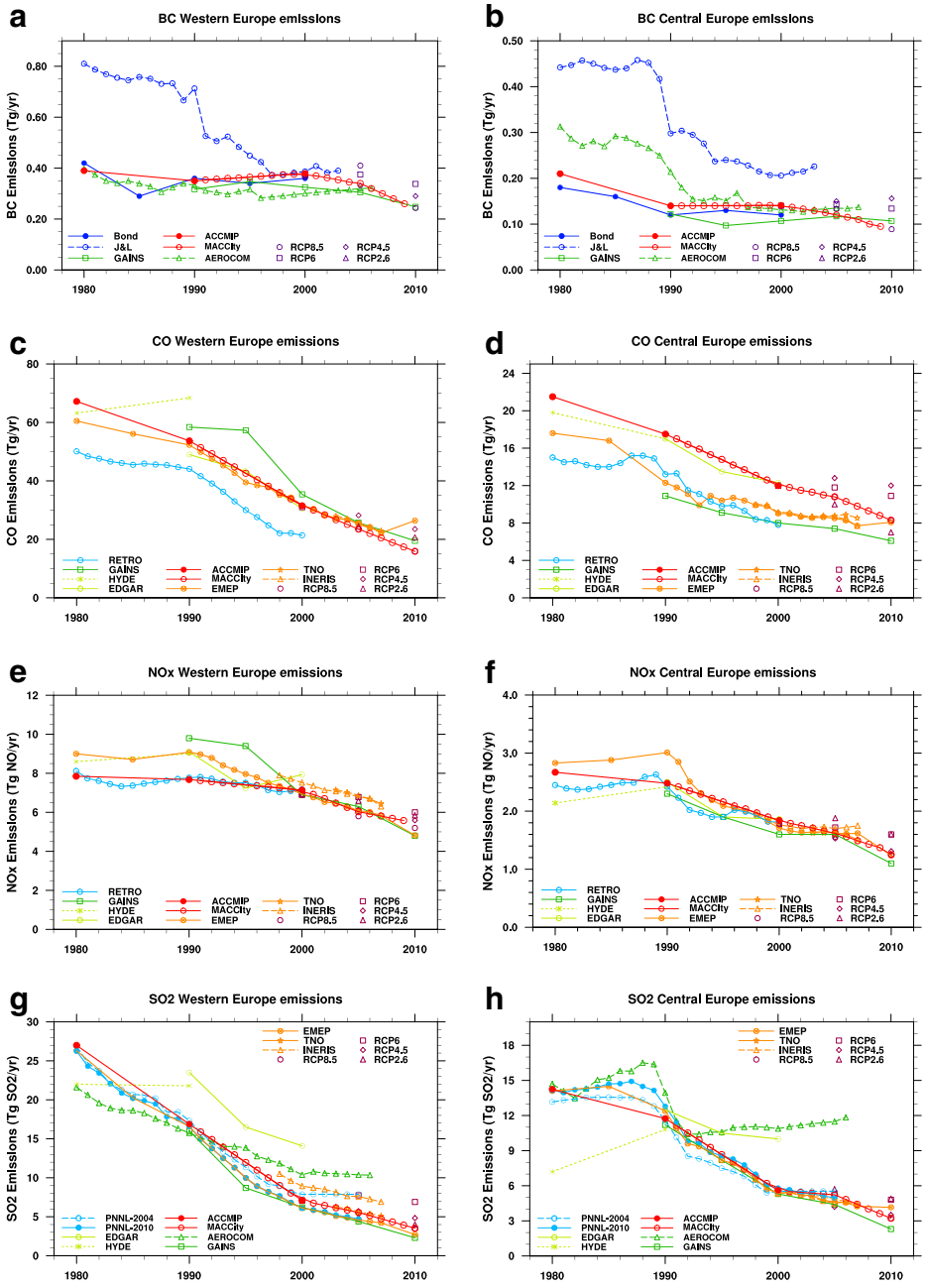

Fig. 2 Evolution of the emissions of the emissions of BC (1st row), CO (2nd row), NO_x (3rd row) and SO_2 (last row) emissions in Western Europe (*left column*) and Central Europe (*right column*) from 1980 to 2010

and EDGAR emissions are rather close, and about 33% higher than the RETRO, EMEP, TNO, INERIS and GAINS, which are close to each other. The difference between the lowest and highest emission reaches 60% in 1990 and 58% in 2000.

According to most inventories considered in this study, SO_2 emissions have decreased constantly in Western Europe during the past 30 years. The inventories differ by about 25% in 1980. From 1980 to 2000, the PNNL-2004, PNNL-2010 and ACCMIP global inventories agree very well with the EMEP regional inventory, and show a decrease of a factor of 3.8–4.5. The AEROCOM inventory also shows a decrease, but with a lower magnitude (factor 2.1). After 2000, the MACCity and EMEP inventories continue to show a decrease in the emissions, by a factor of about 2 between 2000 and 2010. Both inventories are close to RCP 8.5, 4.5 and 2.6 in 2005, and to RCP 8.5 in 2010, while other RCPs predict slightly higher values in 2010. The PNNL-2004 and AEROCOM emissions remain rather constant after 2000, and PNNL-2004 values are close to RCP 6 values. The HYDE and EDGAR inventories display a rather different behavior when compared to the other inventories. The HYDE emissions stay rather constant between 1980 and 1990. The EDGAR emissions, while decreasing between 1990 and 2000, display significantly higher values than the other inventories.

For Central Europe, large differences can be seen between the estimates of total SO_2 emitted. Most inventories provide rather similar totals in 1980, except for the HYDE values, which are more than a factor of 2 lower than the others. The PNNL-2004, PNNL-2010 and EMEP inventories predict a slight increase in the emissions up to year 1987, while the AEROCOM inventory shows a rather large increase up to 1986. In 1990, all the inventories agree within 40%. After the beginning of the 1990s, there is a very large difference between the EDGAR and AEROCOM inventories, which show either a slight decrease (EDGAR) or a 14% increase from 1990 to 2006 for the AEROCOM inventory. All the other inventories show a large decrease after 1990, with values in 2010 about 4.5 times lower than in 1990 for the MACCity, EMEP and PNNL-2010 inventories. The large decrease in the Central European emissions, as well as the decrease in Western Europe, is well documented and has been discussed in papers such as Vestreng et al. (2007). Therefore, the trends shown in the EDGAR and AEROCOM emissions in this part of the world seem inaccurate.

United States emissions The different inventories considered in this study show a general decrease in the USA emissions since the 1980s, particularly for BC, SO_2 and CO (Fig. 3). For BC emissions, rather good agreement is seen between the inventories, except for the J&L inventory, which provides much larger emissions than the other datasets in the 1980s. In 2000, all inventories agree within 52%, with the largest emissions proposed by J&L and the lowest by GAINS. Low GAINS emissions are possibly linked to differences in assumptions about vehicle lifetime, and consequently on the impact of non-regulated and high-emitting vehicles. The trend in the emissions after 2000 varies among the inventories: J&L and AEROCOM indicate an increase in emissions, while MACCity and GAINS show a decrease. The spread in BC emissions is also large among the RCPs, with RCP2.6 providing emissions 83% higher than RCP 8.5 in 2010.

Before 1995, there is a significant disagreement between CO emissions provided by the US EPA regional emissions and the emissions provided by the other inventories, as well as after 2004. The EPA emissions are 41% larger than the ACCMIP emissions and 87% larger than the HYDE emissions in 1980. The EPA CO emissions are 19% and 67% larger than ACCMIP and EDGAR emissions in 1990. In 2000, EPA and ACCMIP emissions are very close, and are 28% higher than EDGAR emissions. GAINS estimates are comparable to ACCMIP emissions, and also follow the same trend. An overall decline in US CO emissions over the period 1980–2008 is expected because of motor vehicle emission controls. The differences between the inventories of US CO emissions discussed here appear at least in part to be due to differences in the treatment of traffic emissions, as shown by Parrish (2006).

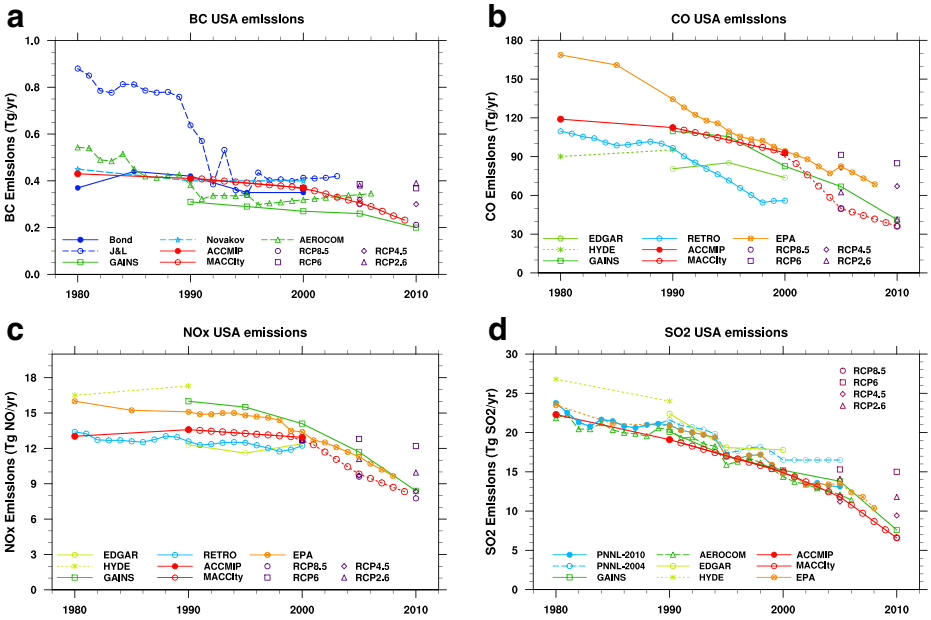

Fig. 3 Emissions of BC (*top left*), CO (*to right*), NO_x (*bottom left*) and SO_2 (*bottom right*) in the United States from 1980 to 2010

The USA is unique among world regions because the emissions of NO_x and SO_2 from the power generation sector are in general directly measured, via Continuous Emission Monitoring Systems (CEMS, http://www.epa.gov/ttnemc01/cem.html). The CEMS data were incorporated in the EPA data set for all years discussed in this paper. Power generation represents a significant portion of USA NO_x and SO_2 emissions (18–26% and 65–72%, respectively). As a result, it is expected that the EPA estimates for total US NO_x and SO_2 emissions are more reliable than estimates from other inventories.

Depending on the inventory, NO_x emissions in the USA display relatively constant values from 1980 to 2000. After 2000, both the ACCMIP and EPA inventories show a decrease with rather similar decreasing trends. This decrease in NO_x emissions results from controls in electric power generation and on motor vehicles that were instituted in the late 1990s and early 2000s. RCP 6 and RCP 4.5 display a relatively small decrease in the 2000s, while the other RCPs project a significant decrease in NO_x emissions in 2005 and 2010.

USA SO_2 emissions as proposed by the different inventories agree rather well, except for the HYDE inventory in the 1980s–1990s, which gives much higher values than other datasets. In 2000, the difference between the highest and lowest emissions is 24%. After 2000, the ACCMIP, AEROCOM, GAINS, PNNL-2010 and EPA inventories provide similar decreasing values, while PNNL-2004 emissions, based on earlier data, show a fairly constant value until 2005.

Asian emissions Figures 4 and 5 display the emissions provided by different inventories for China (Fig. 4) and India (Fig. 5) from 1980 to 2010, for BC, CO, NO_x and SO_2. The large changes between 2000 and 2006 in the ACCESS emissions in China for all species and for BC in India are due to the fact that the 2000 inventory prepared for the TRACE-P mission

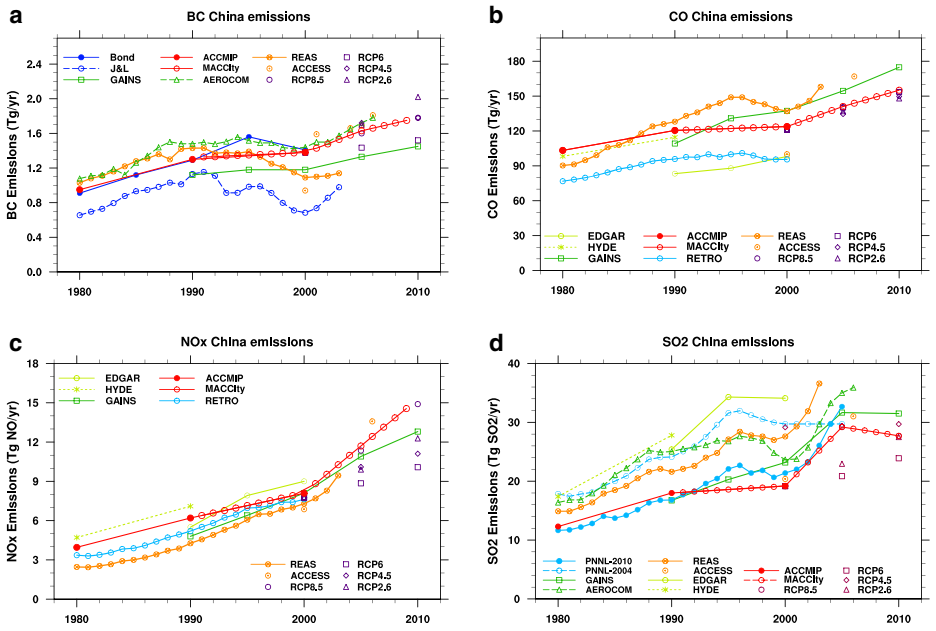

Fig. 4 Emissions of BC (*top left*), CO (*to right*), NO_x (*bottom left*) and SO_2 (*bottom right*) in China from 1980 to 2010

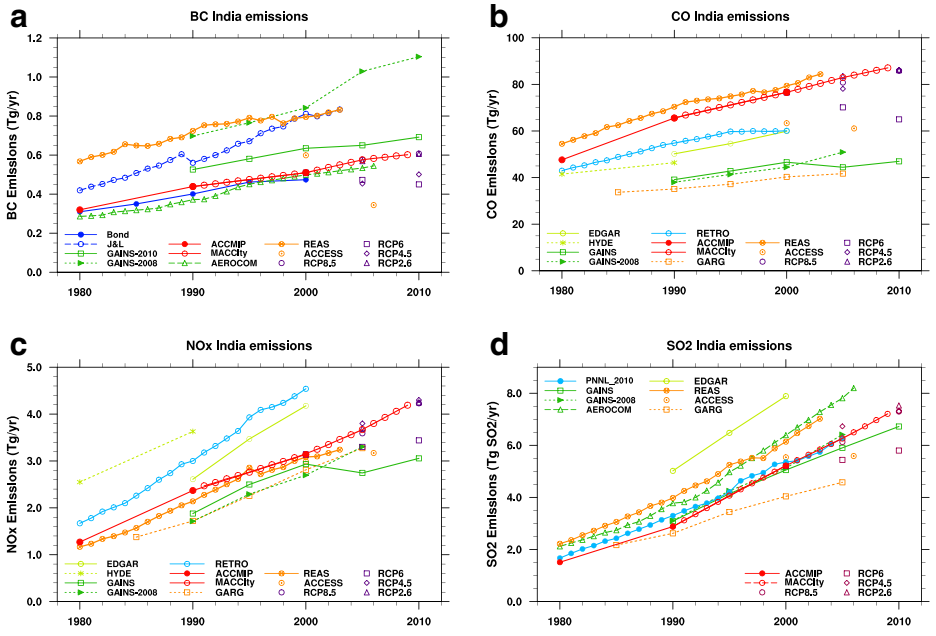

Fig. 5 Emissions of BC (*top left*), CO (*to right*), NO_x (*bottom left*) and SO_2 (*bottom right*) in India from 1980 to 2010

was revised, using an improved methodology for the year 2006 (Zhang et al. 2009), which led to significantly larger emissions.

BC emissions in China (India) differ by 64% (98%) and 32% (95%) for 1980 and 1990, respectively. The J&L dataset provides emissions lower than most other inventories, which are due to a lower estimate in the emissions from biofuel usage in China.

Though most inventories predict a general increase in BC emissions in China after 1980, the rate of increase is quite variable between the inventories. For example, the REAS inventory indicates an increase in the BC emissions from 1980 to 1990, followed by a decrease and again an increase after year 2000. The Bond et al. BC emissions peak in 1995 and decrease slightly afterwards. The global AEROCOM, GAINS and ACCMIP inventories display rather similar changes with time, with differences reaching 29% in 2005. In 2005 and 2010, the GAINS and REAS emissions are close to the emissions provided by RCP6, while the ACCESS inventory provides BC emissions close to the ones predicted by RCP2.6. In India, all inventories predict an increase, but large differences between the different inventories are evident, with the largest values provided by REAS and J&L and the lowest by AEROCOM before 1995 and by the Bond inventory in the 2000s.

The identification of all the reasons for the differences between the inventories is difficult to establish quantitatively. One of the reasons is that emissions inventories are updated regularly, using the most recent activity data and emission factors, which can lead to significant differences between different updates. This issue is illustrated by the differences between the GAINS data and a previous version of the inventory, GAINS_2008 (Klimont et al. 2009) shown in Fig. 5. In the GAINS_2008 data set, national data are used, while IEA (2009) activity data are used in the 2010 inventory. Furthermore, different sets of emission factors are used in both inventories. The differences between the two inventories are very large for BC, reaching 32% in 2000 and 58% in 2005.

NO_x emissions datasets for India and China show a constant increase in the emissions at a rather similar rate. The differences between the inventories are larger in India than in China. In 2003, the regional REAS emissions for China agree within 8% of the MACCity emissions. In 2005 in China, MACCity and GAINS emissions are very close, but higher by 15–30% than REAS, RCP6 and RCP4.5. In 2006, the ACCESS (INTEX-B) emissions are the highest. They agree within 9%, with the MACCity emissions. In 2010, the MACCity and RCP8.5 emissions are similar, while the GAINS projected emissions are closer to the RCP2.6 emissions, and the REAS emissions are close to RCP4.5. In India, the HYDE, RETRO and EDGAR emissions, provide larger emissions than the other datasets. All other inventories agree reasonably well until 2000. In 2005 and 2010, the MACCity emissions are close to the values provided by RCP 8.5, RCP 4.5 and RCP2.6, while the GAINS emissions are closer to the values provided by RCP6.

The various CO emissions estimates in China differ by more than 50% and 40% in 1990 and 2000, respectively. After 2000, emissions increase in all inventories. In 2006, as for NO_x, the ACCESS emissions are the highest, with values 20% higher than the MACCity emissions. In 2010, projected GAINS and REAS emissions agree, with values higher than those provided by the four RCPs. The four RCPs are close to each other in both 2005 and 2010. In India, the differences between the inventories are very large, and fall into three groupings of values. The highest estimates are from MACCity and REAS. The lowest values are from the Garg and the two versions of the GAINS inventory, which provide quite similar values for CO. RETRO, EDGAR and HYDE provide values between the two extrema, and are very close to the ACCESS regional inventory. In 2000 and 2005, the ratio between the highest and lowest values reaches a factor of about 2.

There is no consensus among the different inventories for the emissions of SO_2 for China; emissions strengths and trends differ significantly between inventories. All inventories agree on an increase of emissions up to 2000; after 2000, the sign of the trend varies. Differences in SO_2 emissions reach 66% between the lowest and highest emissions in 2000. This difference is only slightly larger than the uncertainty bound estimated in Smith et al. (2010). Most of the inventories show either a decline or stagnation in the emissions between 1995 and 2000, except for the GAINS inventory, which displays a constant increase during the period considered. In 2005, the AEROCOM and REAS emissions are the highest, about 7% higher than PNNL-2010 and GAINS and 20% higher than MACCity. RCP2.6 and RCP6 emissions are much lower. In 2010, GAINS emissions are higher than all RCPs scenarios. Differences in assumptions regarding coal sulfur content and retention in ash and assumptions on actual implementation of control measures have a large impact on emissions in this region (Smith et al. 2010; Xu et al. 2009), which could explain some of the differences highlighted here.

There is a rather good consensus in India on the SO_2 emission trends: all inventories provide a very large increase over the time period considered. The EDGAR inventory provides much larger emissions than the other datasets. The Garg inventory, which is based on national data gives the lowest emissions, which could be due to differences in the sulfur content of fuels used in India, as well as to differences in assumptions on energy efficiency and fuel quality. It should be noted that a previous version of the Garg inventory (Garg et al. 2001) provides emissions much closer to most other inventories used in this study, i.e. 3.54 Tg in 1990 and 4.64 in 1995.

3.2 Comparisons of biomass burning emissions

3.2.1 Biomass burning emissions at the global scale

Several on-going studies are assessing the currently available biomass burning emissions inventories, such as the BBSO exercise (global Burnt Biomass from Satellite Observations), where the impact of the use of different satellite products and different algorithms for estimating burned biomass is estimated (Stroppiana et al. 2010). Other studies have been recently submitted, which discuss comparisons of methodologies used to derive biomass burning emissions (van der Werf et al. 2010). A detailed literature review on continental-scale estimates of biomass burning emissions can be found in Schultz et al. 2008. In this paper, we will just briefly discuss the differences in current biomass burning inventories, and we will focus on the emissions of two compounds, CO and BC. The goal of this short section is to evaluate the relative differences between biomass burning inventories, and compare these differences with those identified for anthropogenic emissions. The biomass burning emissions files considered in this paper are not independent: ACCMIP and MACCity biomass burning emissions are based on the RETRO and GFED-v2 emissions, and the GFED-v2 and GFED-v3 emissions are developed by the same group.

Biomass burning emissions display a large variability from year to year, as a result of different environmental and human factors. This large variability during the past 20 years is captured by all the inventories considered in this study, as shown in Fig. 6. All the inventories show a maximum of emissions in 1997–1998, when a very intense ENSO episode occurred. The occurrence of maximum and minimum values is rather well correlated during the past two decades. There are however very large differences in the magnitude of the emissions predicted by the different inventories: the GFED-v3 total emissions are

generally the lowest, while the GICC emissions are the highest, after year 2001. Emissions are available from all the six considered inventories only for the 1997–2000 period. Over these 4 years, the lowest values are given by the GFED-v3 (414 Tg CO/year) and Kloster (416 Tg CO/year) inventories, while the highest values are given by the MACCity (509 Tg CO/year) and the GICC (496 Tg CO/year) inventories. In 2005, the difference between the lowest and highest total biomass burning emissions is about 30%. During the 1980–1995 period, the Kloster inventory provides the lowest emissions. The MACCity and RETRO inventories provide rather similar emissions for CO and almost identical values for BC, i.e. 2.38 TgC/year and 2.3 Tg C/year in 1995, respectively.

3.2.2 Biomass burning emissions at the regional scale

Differences among BC and CO emissions estimates in Africa and South America are very large, as seen in Fig. 7. As already indicated, the MACCity is using RETRO and GFED-v2 emissions as a basis, and these inventories show rather similar emitted amounts and interannual variability. The differences between the original RETRO and the MACCity inventory mainly result from the different vegetation map and the emission factors used.

In both regions, and for both species, the emissions provided by GFED-v3 are systematically lower than the GFED-v2 estimates, by 10–25%. This difference is discussed in detail in van der Werf et al. (2010): it is mainly due to the use of a new burned area dataset, revised dry matter carbon content in the fuel, as well as updated emissions factors, in tropical forests, in peatlands as well as for woodland burning.

For both species, the emissions provided by the Kloster inventory are on the lower end for all years in Africa, and the highest emissions are given by the MACCity and GICC datasets. The values provided by the AMMABB inventory for Africa are much higher than any of the other inventories, with CO emissions in 2003 higher by a factor of 1.8 and 1.6 than GFED and GICC, respectively. For BC, the 2003 emissions are a factor 2.4 and 1.6 higher than GFED and GICC, respectively. The AMMABB emissions are estimated using the L3JRC burnt area product (Tansey et al. 2008): the much larger emissions obtained in this inventory are mainly due to the very large burned areas in African savannas, when compared to the satellite products used in the other datasets.

In South America, the emissions estimated by GFED-v3, GFED-2 and MACCity are the lowest among the considered inventories, while the highest values are from the RETRO and Kloster datasets. Part of the differences could be due to the difficulty of the burned area datasets used in the GFED inventories and in MACCity to capture accurately deforestation fires. While this has been taken into account in the GFED-v3 inventory by including active

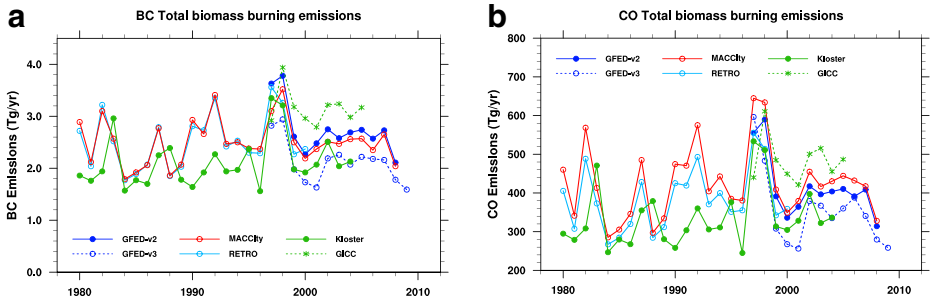

Fig. 6 Annual global biomass burning emissions of CO (*left*) and BC (*right*) from 1980 to 2010

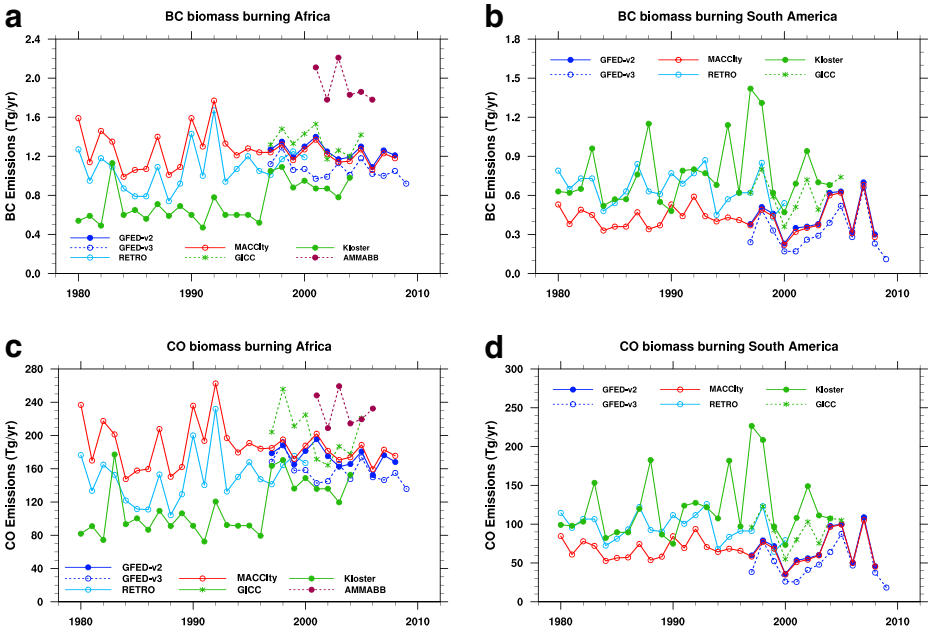

Fig. 7 Emissions of CO (*top*) and BC (*bottom*) in Africa (*left column*) and South America (*right column*) from 1980 to 2009

fires, it is estimated that only 80% of the deforested area is captured (van der Werf et al. 2010). The larger fire emission in South America in the Kloster inventory could be caused by several features from the fire model, including an overestimation of the live aboveground biomass in the Amazon basin simulated within CLM-CN (Kloster et al. 2010).

The differences between the inventories considered in the paper can be in part attributed to the large discrepancies which remain between the different satellite sensor products (Boschetti et al. 2004; Giglio et al. 2010; Stroppiana et al. 2010) as well as between the distribution of biomass densities used in the inventories. The recent study of Stroppiana et al. (2010) has for example emphasized the need for an accurate parameterization of vegetation characteristics and conditions at the time of fire for a better estimation of the emissions.

4 Conclusions

In this study, we compared several inventories of anthropogenic and biomass burning emissions, including the ACCMIP and its new extension, the MACCity dataset. This analysis, which considers past, current and future emissions, is a major step towards the development of consistent emissions across different scales. As part of the development of these new datasets, several different inventories have been assessed, and large discrepancies between the global and regional emissions have been identified.

A detailed identification of the underlying causes for differences between inventories would be very difficult to achieve: activity data and details on the emissions factors that are used to compile the inventories are generally not provided with the inventories. Furthermore, emissions inventories are updated regularly, using the most recent activity data and emission factors, which can lead to significant differences between different

version of one inventory. Another important issue hampering the identification of the reasons for differences between inventories is the fact that each inventory/model differs in the way the data are processed and prepared for the calculations. Such information is either not provided or quite difficult to assess when available. Finally, some inventories estimate the emissions on the basis of general aggregated sectors while others might include much more detail, leading to sometimes important differences.

The evaluation of uncertainties in the emissions is a difficult task. The main sources of uncertainties in the emissions have been discussed in the HTAP 2007 assessment. A few inventories provide uncertainties, such as Bond et al. (2004), Schöpp et al. (2005) and Smith et al. (2010), but uncertainties are not quantified for most inventories used in this study. It is therefore not possible at this time to evaluate the overall uncertainties on the emissions estimates discussed here. Furthermore, the quantification of emissions uncertainties due to the propagation of uncertainties on activity data and emission factors is not available for most inventories.

In order to provide a rough classification of the more and less well known emissions at the global scale and for the considered regions, Table 4 gives the ratio between the highest and lowest emissions for 1980, 1990, 2000 and 2005 for the four species considered in this work. Emissions for which the ratio is closest to one can be considered to be the values with the best consensus. It should be emphasized again that consensus does not necessarily imply that uncertainty is low. In some cases, a higher level of consensus may be due to similar assumptions being used because of the lack of detailed information.

From Table 4, it is clear that, for the past three decades, large discrepancies remain for all four species considered. For 2000 and 2005 anthropogenic NO_x emissions exhibit reasonable (better than factor 1.7) agreement, and for several regions the agreement is better than 20%. Recent anthropogenic CO emissions also seem to be reasonably well in agreement with the exception of India (factor of 2 range) and Central Europe (factor 1.7). For SO_2 differences are at least a factor of 1.2 and often exceed a factor of 2. Interestingly, SO_2 differences are smaller for the period before year 2000. For anthropogenic BC the inventory differences after year 2000 are similar as for SO_2, but here the estimates for earlier years show greater diversity.

The United Nations Framework Convention on Climate Change (UNFCCC) has published a set of guidelines for the development of inventories of greenhouse gases emissions, in order to ensure transparency, accuracy, comparability and completeness of the datasets (UNFCCC 2006). Most of the scientific inventories discussed in this paper do not yet apply these guidelines. The discussions of the results obtained in the paper demonstrate that the application of these guidelines in future inventory work would allow more detailed comparisons of the emissions, and help identify the reasons for the differences in the global and regional totals emitted. However, up-to-date inventories are generally not readily available, and the inventories are then prepared using both actual and projected emissions. It should be recognized that such up-to-date inventories will not be able to follow the UNFCCC guidelines.

RCPs emissions for 2005 and 2010 are generally within the boundaries of the values provided by the available global and regional inventories for 2005 and 2010. However, RCP6 emissions are significantly larger than other emissions for all species in the USA, and lower in China, particularly for NO_x and SO_2. In Central Europe, RCP6 and RCP 4.5 provide significantly higher values for CO than other datasets. The comparisons we performed show that the use of RCP8.5 for the extension of the ACCMIP inventory beyond 2000 is reasonable, until more global or regional estimates become available, which will give information on emissions for the past few years.

Table 4 Ratio between the lowest and highest emissions for each species and each region for the different periods considered in this study. Numbers lower than 1.3 appear in green, values between 1.3 and 1.7 are in yellow, and values higher than 1.7 are in red Note that, for CO emissions from biomass burning, the values are given for 2003 instead of 2005, since the AMMABB emissions are currently available only for 2003 for CO

		1980	1990	2000	2005
BC anthropogenic					
	Global	1.53	1.52	1.13	1.28
	Western Europe	2.08	2.04	1.59	1.34
	Central Europe	2.45	2.50	1.92	1.76
	USA	2.38	2.74	1.53	1.48
	China	1.64	1.32	2.12	1.29
	India	1.99	1.95	1.78	2.27
BC biomass burning					
	Global	1.53	1.36	1.74	1.28
	Africa	2.94	2.65	1.50	1.57
	South America	1.49	1.60	3.18	1.42
CO anthropogenic					
	Global	1.27	1.31	1.28	1.09
	Western Europe	1.34	1.55	1.65	1.28
	Central Europe	1.43	1.56	1.58	1.73
	USA	1.87	1.67	1.69	1.66
	China	1.34	1.54	1.43	1.15
	India	1.31	2.01	1.97	2.00
CO biomass burning					
	Global	1.56	1.84	1.68	1.19
	Africa	2.89	2.78	1.51	1.85
	South America	1.35	1.36	3.04	1.20
NO_x anthropogenic					
	Global	1.13	1.18	1.17	1.15
	Western Europe	1.15	1.28	1.15	1.18
	Central Europe	1.32	1.24	1.16	1.23
	USA	1.27	1.41	1.15	1.33
	China	1.91	1.66	1.31	1.32
	India	2.17	2.11	1.68	1.39
SO_2 anthropogenic					
	Global	1.19	1.27	1.40	1.32
	Western Europe	1.25	1.49	2.33	2.36
	Central Europe	2.04	1.32	2.08	2.73
	USA	1.23	1.26	1.24	1.47
	China	1.54	1.66	1.78	1.68
	India	1.59	2.09	1.95	1.70

Concerning biomass burning emissions, most inventories agree within 50–80%. However, one of the newest inventories, AMMABB, currently only available for Africa, is providing emissions about a factor of 2 larger than the other datasets. According to Tummon

et al. (2010), the use of the AMMABB emissions would improve model capabilities to match observations with regard to aerosols. For CO, the study reported by Chevallier et al. (2009) using the GFED-v2 emissions shows that using the larger AMMABB African emissions would likely lead to an overestimation of CO loadings when compared to MOPITT satellite observations. In contrast, the Barret et al. (2010) study indicates that the use of GFED-v2 emissions leads to a significant underestimation of CO concentrations when compared to the MOZAIC aircraft measurements. These conflicting results show that more detailed work, involving results for more burning regions, is needed to evaluate currently available biomass burning emissions distributions. For example, recent developments aim at reducing the errors associated with estimating the available fuel load and combustion completeness by taking the observed fire radiative power quantitatively into account (Wooster et al. 2005; Kaiser et al. 2009).

Several studies have provided estimates of both anthropogenic and biomass burning emissions based on inverse modeling methods for a few species such as CO, NO_x and BC (Kopacz et al. 2010; Chevallier et al. 2009; Tanimoto et al. 2008; Muller and Stavrakou 2005; Petron et al. 2004). The results of such studies will be considered in follow-up work on the evaluation of surface emissions. However, it should be recognized that most inverse modeling studies have focused on the post-2000 period, since observations of the distributions of these species for the 1980s as well as for the early 1990s are rather scarce and do not allow an accurate determination of the emissions using these inverse modeling techniques.

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References

Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15(4):955–966

Arora VK, Boer GJ (2005) Fire as an interactive component of dynamic vegetation models. J Geophys Res 110:G02008. doi:10.1029/2005JG000042

Assamoi E-M, Liousse C (2010) A new inventory for two-wheel vehicle in West Africa for 2002. Atmos Env 44(32):3985–3996

Barret B, Williams JE, Bouarar I, Yang X, Josse B, Law K, Pham M, Le Flochmoën E, Liousse C, Peuch VH, Carver GD, Pyle JA, Sauvage B, van Velthoven P, Schlager H, Mari C, Cammas J-P (2010) Impact of West African Monsoon convective transport and lightning NO_x production upon the upper tropospheric composition: a multi-model study. Atmos Chem Phys 10:5719–5738. doi:10.5194/acp-10-5719-2010

Berglen T, Myhre G, Ivar SA, Isaksen V, Vestreng SS (2007) Sulphate trends in Europe: are we able to model the recent observed decrease? Tellus 59B:773–786

Bicheron P, Leroy M, Brockmann C, Krämer U, Miras B, Huc M, Niño F, Defourny P, Vancutsem C, Arino O, Ranera F, Petit D, Amberg V, Berthelot B, Gross D (2006) Globcover: a 300 m global land cover product for 2005 using ENVISAT MERIS time series. In: Sobrino JA (ed) Proceeding of the Second International Symposium on recent advances in quantitative remote sensing. Servicio de Publicaciones. Universitat de Valencia, Valencia, pp 538–542

Bond TC, Streets DG, Yarber KF, Nelson SM, Woo J-H, Klimont Z (2004) A technology-based global inventory of black and organic carbon emissions from combustion. J Geophys Res 109:D14203

Bond TC, Bhardwaj E, Dong R, Jogani R, Jung S, Roden C, Streets DG, Fernandes S, Trautmann N (2007) Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000. Global Biogeochemical Cycles 21:GB2018. doi:10.1029/2006GB002840

Boschetti L, Eva HD, Brivio PA, Gregoire JM (2004) Lessons to be learned from the comparison of three satellite-derived biomass burning products. GRL 31:L21501

Chevallier F, Fortems A, Bousquet P, Pison I, Szopa S, Devaux M, Hauglustaine DA (2009) African CO emissions between years 2000 and 2006 as estimated from MOPITT observations. Biogeosciences 6:103–111. doi:10.5194/bg-6-103-2009

Cofala J, Amann M, Klimont Z, Kupiainen K, Höglund-Isaksson L (2007) Scenarios of global anthropogenic emissions of air pollutants and methane until 2030. Atmospheric Environment 41:8486–8499. doi:10.1016/j.atmosenv.2007.07.010

Denier van der Gon H, Visschedijk HA, Kuenen J, van der Brugh H, Dröge R, Schaap M (2010) High resolution European emission grids for anthropogenic sources for the years 2003–2007, EGU 2010 special session Monitoring Atmospheric Composition and Climate, Geophysical Research Abstracts, Vol. 12, EGU2010-10800-1

Etemad B, Bairoch P, Toutain J-C, Luciani J (1991) Production mondiale d'énergie 1800–1985. Genève, Librairie Droz

Garg A, Shukla PR, Bhattacharya S, Dadhwal VK (2001) Subregion (district) ans sector level SO2 and NOx emissions for India: assessment of inventories amd mitigation flexibility. Atmos Env 35:703–713

Garg A, Shukla PR, Kapshe M (2006) The sectoral trends of multigas emissions inventory of India. Atmospheric Environment, Elsevier Science 40(24):4608–4620

Giglio L, Randerson JT, van der Werf GR, Kasibhatla PS, Collatz GJ, Morton DC, DeFries RS (2010) Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences 7:1171–1186. doi:10.5194/bg-7-1171-2010

Hollingsworth A, Engelen RJ, Textor C, Benedetti A, Boucher O, Chevallier F, Dethof A, Elbern H, Eskes H, Flemming J, Granier C, Morcrette JJ, Rayner P, Peuch V-H, Rouil L, Schultz M, Simmons A, the GEMS consortium (2008) The Global Earth-system Monitoring using Satellite and in-situ data (GEMS) project: towards a monitoring and forecasting system for atmospheric composition. Bull Amer Meteo Soc 89:1147–1164. doi:10.1175/2008BAMS2355.1

IEA, International Energy Agency, World Energy Outlook 2009 (2009) ISBN 978-92-64-06130-9, available at http://www.iea.org

Isaksen ISA, Granier C, Myhre G, Berntsen TK, Dalsoren SB, Gauss M, Klimont Z, Benestad R, Bousquet P, Collins W, Cox T, Eyring V, Fowler D, Fuzzi S, Jockel P, Laj P, Lohmann U, Maione M, Monks P, Prevot ASH, Raes F, Richter A, Rognerud B, Schulz M, Shindell D, Stevenson DS, Storelvmo T, Wang W-C, van Weele M, Wild M, Wuebbles D (2009) Atmospheric composition change: climate-chemistry interactions. Atmospheric Environment 43(33, ACCENT Synthesis):5138–5172. doi:10.1016/j.atmosenv.2009.08.003

Ito A, Penner JE (2005) Historical emissions of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870–2000. Global Biogeochem Cycles 19:GB2028. doi:10.1029/2004GB002374

Junker C, Liousse C (2008) A global emission inventory of carbonaceous aerosol from historic records of fossil fuel and biofuel consumption for the period 1860–1997. Atmos Chem Phys 8:1195–1207. doi:10.5194/acp-8-1195-2008

Kaiser JW, Suttie M, Flemming J, Morcrette J-J, Boucher O, Schultz MG (2009) Global real-time fire emission estimates based on space-borne fire radiative power observations. AIP Conf Proc 1100:645–648. doi:10.1063/1.3117069

Klimont Z, Cofala J, Xing J, Wei W, Zhang C, Wang S, Kejun J, Bhandari P, Mathura R, Purohit P, Rafaj P, Chambers A, Amann M, Hao J (2009) Projections of SO_2, NO_x, and carbonaceous aerosols emissions in Asia. Tellus B. doi:10.1111/j.1600-0889.2009.00428.x

Kloster S, Mahowald NM, Randerson JT, Thornton PE, Hoffman FM, Levis S, Lawrence PJ, Feddema JJ, Oleson KW, Lawrence DM (2010) Fire dynamics during the 20th century simulated by the Community Land Model. Biogeosciences 7:1877–1902

Kopacz M, Jacob DJ, Fisher JA, Logan JA, Zhang L, Megretskaia IA, Yantosca RM, Singh K, Henze DK, Burrows JP, Buchwitz M, Khlystova I, McMillan WW, Gille JC, Edwards DP, Eldering A, Thouret V, Nedelec P (2010) Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES). Atoms Chem Phys 10:855–876

Kupiainen K, Klimont Z (2007) Primary emissions of fine carbonaceous particles in Europe. Atmospheric Environment 41(10):2156–2170. doi:10.1016/j.atmosenv.2006.10.06

Lamarque J-F, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, Lee D, Liousse C, Mieville A, Owen B, Schultz MG, Shindell D, Smith SJ, Stehfest E, Van Aardenne J, Cooper OR, Kainuma M, Mahowald N,

McConnell JR, Naik V, Riahi K, van Vuuren DP (2010) Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. Atmos Chem Phys 10. doi:10.5194/acp-10-7017-2010, 7017-7039

Lei Y, Zhang Q, He KB, Streets DG (2010) Primary aerosol emission trends for China, 1990–2005. Atmos Chem Phys Discuss 10:17153–17212. doi:10.5194/acpd-10-17153-2010

Liousse C, Guillaume B, Grégoire JM, Mallet M, Galy C, Pont V, Akpo A, Bedou M, Castéra P, Dungall L, Gardrat E, Granier C, Konaré A, Malavelle F, Mariscal A, Mieville A, Rosset R, Serça D, Solmon F, Tummon F, Assamoi E, Yoboué V, Van Velthoven P (2010) Western african aerosols modelling with updated biomass burning emission inventories in the frame of the AMMA-IDAF program. Atmos Chem Phys Discuss 10:7347–7382. doi:10.5194/acpd-10-7347-2010

Mieville A, Granier C, Liousse C, Guillaume B, Mouillot F, Lamarque J-F, Grégoire J-M, Pétron G (2010) Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction. Atmospheric Environment 44:1469–1477

Mitchell BR (1992) International historical statistics, Europe, 1750–1988. Macmillan, 942 pp

Moss RH, Edmonds JA, Hibbard K, Manning M, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl G, Mitchell J, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson A, Weyant J, Wilbanks T (2010) The Next Generation of Scenarios for Climate Change Research and Assessment. Nature. doi:10.1038/nature08823

Mouillot F, Field CB (2005) Fire history and the global carbon budget: a 1°x1° fire history reconstruction for the 20th century. Glob Chang Biol 11:398–420

Muller J-F, Stavrakou T (2005) Inversion of CO and NO_x emissions using the adjoint of the IMAGES model. Atmos Chem Phys 5:1157–1186

Novakov T, Ramanathan V, Hansen JE, Kirchstetter TW, Sato M, Sinton JE, Sathaye JA (2003) Large historical changes of fossil-fuel black car bon aerosols. Geophys Res Lett 30(6):1324. doi:10.1029/2002GL016345

Ohara T, Akimoto H, Kurokawa J, Horii N, Yamaji K, Yan X, Hayasaka T (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. Atmospheric Chemistry and Physics 7:4419–4444

Olivier JGJ, Berdowski JJM (2001) Global emissions sources and sinks. In: Berdowski J, Guicherit R, Heij BJ (eds) The climate system, pp 33–78. A.A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, The Netherlands. ISBN 90 5809 255 0

Olivier JGJ, Van Aardenne JA, Dentener F, Ganzeveld L, Peters JAHW (2005) Recent trends in global greenhouse gas emissions: regional trends and spatial distribution of key sources. Environ Sci, 2 (2–3):81–99. doi:10.1080/15693430500400345

Parrish DD (2006) Critical evaluation of US on-road vehicle emission inventories. Atmos Environ 40:2288–2300. doi:10.1016/j.atmo-senv.2005.11.033

Petron G, Granier C, Khattatov B, Yudin V, Lamarque JF, Emmons L, Gille J, Edwards DP (2004) Monthly CO surface sources inventory based on the 2000–2001 MOPITT satellite data. Geophys Res Lett 31: L21107. doi:10.1029/2004GL020560

Schöpp W, Klimont Z, Suutari R, Cofala J (2005) Uncertainty analysis of emission estimates in the RAINS integrated assessment model. Environmental Science and Policy 8:601–635

Schultz M, Rast S, van het Bolscher M, Pulles T, Pereira J, Spessa A, Dalsøren S, van Nojie T, Szopa S (2007) REanalysis of the TROpospheric chemical composition over the past 40 years, A long-term global modeling study of tropospheric chemistry funded under the 5th EU framework programme. Tech. rep., EU-Contract No. EVK2-CT-2002-00170, http://www.retro.enes.org/reports/D1-6final.pdf

Schultz MG, Heil A, Hoelzemann JJ, Spessa A, Thonicke K, Goldammer J, Held AC, Pereira JM (2008) Global emissions from wildland fires from 1960 to 2000. Global Biogeochem Cycles 22:GB2002. doi:10.1029/2007GB003031

Smith SJ, Andres R, Conception E, Lurz J (2004) Sulfur Dioxide Emissions: 1850–2000 (JGCRI Report. PNNL-14537)

Smith SJ, van Aardenne J, Klimont Z, Andres R, Volke A, Delgado Arias S (2010) Anthropogenic sulfur dioxide emissions: 1850–2005. Atmos Chem Phys Discuss 10:16111–16151. doi:10.5194/acpd-10-16111-2010

Stern, D.I. (2006) Reversal of the trend in global anthropogenic sulfur emissions, Global Environ Change, 16:207–220

Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, He D, Klimont Z, Nelson SM, Tsai NY, Wang MQ, Woo J-H, Yarber KF (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J Geophys Res 108(D21):8809. doi:10.1029/2002JD003093

Streets DG, Bond TC, Lee T, Jang C (2004) On the future of carbonaceous aerosol emissions. J Geophys Res 109(D24):D24212. doi:10.1029/2004JD004902

Streets D, Yu C, Wu Y, Chin M, Zhao Z, Hayasaka T, Shi G (2008) Aerosol trends over China, 1980–2000. Aerosol Res 88:174–182

Stroppiana D, Brivio PA, Grégoire J-M, Liousse C, Guillaume B, Granier C, Mieville A, Chin M, Pétron G (2010) Comparison of global inventories of monthly CO emissions derived from remotely sensed data. Atmos Chem Phys Discuss 10:17657–17697. doi:10.5194/acpd-10-17657-2010

Tanimoto H, Sawa Y, Yonemura S, Yumimoto K, Matsueda H, Uno I, Hayasaka T, Mukai H, Tohjima Y, Tsuboi K, Zhang L (2008) Diagnosing recent CO emissions and ozone evolution in East Asia using coordinated surface observations, adjoint inverse modeling, and MOPITT satellite data. Atmos Chem Phys 8:3867–3880. doi:10.5194/acp-8-3867-2008

Tansey K, Gregoire JMC, Defourny P, Leigh R, Pekel J-F, van Bogaert E, Bartholomé E, Bontemps S (2008) A new, global, multi-annual (2000–2007) burned area product at 1 km resolution and daily intervals. Geophys Res Lett 35:L01401, doi:10.1029/2007GL031567

Taylor KE, Stouffer RJ, Meehl GA (2008) A Summary of the CMIP5 Experiment Design, https://cmip.llnl.gov/cmip5/docs/Taylor_CMIP5_dec31.pdf

Thornton PE, Lamarque JF, Rosenbloom NA, Mahowald NM (2007) Influence of carbon-nitrogen cycle coupling on land model response to CO2 fertilization and climate variability. Global Biogeochem Cycles 21:GB4018. doi:1029/2006GB002868

Tummon F, Solmon F, Liousse C, Tadross M (2010) Simulation of the climatic impacts of the natural aerosol loading over southern Africa during the biomass burning season using RegCM3, accepted for publication in. J Geophys Res

UNFCCC, Updated UNFCCC reporting guidelines on annual inventories (2006) FCCC/SBSTA/2006/9, available at: http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf.

UNSTAT (1997) The United Nations energy statistics database, Tech. rep., Stat. Div., New York

US Environmental Protection Agency (2001) Procedures document for National Emissions Inventory, Criteria Air Pollutants, 1985–1999. Tech. rep., EPA-454/R-01-006, US EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, USA. Available at http://www.epa.gov/ttn/chief/trends/

van Aardenne JA, Dentener FJ, Olivier JGJ, Klein Goldewijk CGM, Lelieveld J (2001) A 1×1 degree resolution dataset of historical anthropogenic trace gas emissions for the period 1890–1990. Global Biogeochemical Cycles 15(4):909–928

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano AF (2006) Interannual variability in global biomass burning emissions from 1997 to 2004. Atmospheric Chemistry and Physics 6:3423–3441

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, Morton DC, DeFries RS, Jin Y, van Leeuwen TT (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos Chem Phys Discuss 10:16153–16230. doi:10.5194/acpd-10-16153-2010

Van Vuuren DP, Edmonds J, Thomson A, Riahi K, Kainuma M, Matsui T, Hurtt GC, Lamarque J-F, Meinshausen M, Smith S, Granier C, Rose SK, Hibbard KA (2011) Representative Concentration Pathways: an overview. Climatic Change. This Issue. doi:10.1007/s10584-011-0148-z

Vestreng V, Myhre G, Fagerli H, Reis S, Tarrasón L (2007) Twenty-five years of continuous sulphur dioxide emission reduction in Europe. Atmos Chem Phys 7:3663–3681

Wooster MJ, Roberts G, Perry GLW, Kaufman YJ (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. JGR 110:D24311

Xu Y, Williams RH, Socolow RH (2009) China's rapid deployment of SO2 scrubbers. Energy Environ Sci 2:459–465

Zhang Q, Streets DG, Carmichael GR, He KB, Huo H, Kannari A, Klimont Z, Park IS, Reddy S, Fu JS, Chen D, Duan L, Lei Y, Wang LT, Yao ZL (2009) Asian emissions in 2006 for the NASA INTEX-B mission. Atmos Chem Phys 9:5131–5153. doi:10.5194/acp-9-5131-2009