Anthropocene 12 (2015) 17–28

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

The international global atmospheric chemistry (IGAC) project: Facilitating atmospheric chemistry research for 25 years

Megan L. Melamed[a,*], Paul S. Monks[b], Allen H. Goldstein[c], Mark G. Lawrence[d], Jeff Jennings[a]

[a] IGAC International Project Office, CIRES, University of Colorado, Box 216 UCB, Boulder, CO, 80309, USA
[b] Department of Chemistry, University of Leicester, Leicester LE1 7RH, UK
[c] Department of Civil and Environmental Engineering and Department of Environmental Science, Policy and Management University of California, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA
[d] Institute for Advanced Sustainability Studies, Berliner Strasse 130, Potsdam14467 Germany

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form 7 October 2015
Accepted 11 October 2015
Available online 19 October 2015

Keywords:
Atmospheric chemistry
Air pollution
Climate change
Earth system
International collaborations

ABSTRACT

This paper outlines the scientific achievements and insights gained from the International Global Atmospheric Chemistry (IGAC) project, which has been jointly sponsored by the international Commission on Atmospheric Chemistry and Global Pollution (iCACGP) and the International Geosphere-Biosphere Programme (IGBP) since 1990. A short history of IGAC is followed by representative key scientific achievements. Over 25 years, IGAC has facilitated international scientific collaborations that have deepened the understanding of how atmospheric composition impacts air quality, climate change, and ecosystems from local to global scales. Activities fostered by IGAC show how the field of atmospheric chemistry has evolved from a focus on the atmosphere as a single natural compartment of the Earth system to an emphasis on its interactions with other Earth components, such as oceans, the cryosphere, the biosphere, and the impact of humans on atmospheric composition. Finally, one of IGAC's significant accomplishments has been building scientific capacity and cooperation in the field of atmospheric chemistry around the globe, especially through its biennial science conferences. As part of IGBP, IGAC has contributed to improving the current state of knowledge of the Earth system and providing the scientific basis to suggest that we have entered the Anthropocene. IGAC will continue to play this role and expand its connections to the larger global change and sustainability research communities, capitalizing on the transition to Future Earth.

Abbreviations: ACPC, aerosols, clouds, precipitation and climate; AICI, air–ice chemical interactions; ASGAMAGE, air–sea gas exchange; ACE-Asia, Asian aerosol characterization experiment; ASTEX, Atlantic stratocumulus transition experiment; ACCMIP, atmospheric chemistry and climate model intercomparison project; BIBEX, biomass burning experiment: impact on the atmosphere and biosphere; BATREX, biosphere–atmosphere trace gas exchange; BATGE, biosphere–atmosphere trace gas exchange in the tropics: influence of land use change; CARBICE, carbon dioxide intercalibration experiment; CCMI, chemistry–climate model initiative; CACR, Commission on Atmospheric Chemistry and Radiation; DEBITS, deposition of biogeochemically important trace species; APARE, East Asia–North Pacific regional experiment; EXPRESSO, experiment for regional sources and sinks of oxidants; FOS/DECAFE, fire of Savannas/dynamics and atmospheric chemistry in the equatorial forest; ACE-1, first aerosol characterization experiment; FAA, focus on atmospheric aerosols; GLOCHEM, global atmospheric chemistry survey; GEIA, global emissions initiative; GHOST, global HO systematic tests; GIM, global integration and modeling; GLOCARB, global tropospheric carbon dioxide network; GLONET, global tropospheric ozone network; HESS, high-latitude ecosystems as sources and sinks of trace gases; IDAF, IGAC/DEBITS/Africa; ITCT-2k2, intercontinental transport and chemical transformations 2002; IAPSO, International Association for the Physical Sciences of the Oceans; IAMAS, International Association of Meteorology and Atmospheric Sciences; iCACGP, international Commission on Atmospheric Chemistry and Global Pollution; IGBP, International Geosphere-Biosphere Programme; IGAC, International Global Atmospheric Chemistry Project; ITOY, International Tropospheric Ozone Years; IUGG, International Union of Geodesy and Geophysics; JOSIE, Jülich ozone intercomparison experiment; MAGE, Marine aerosol and gas exchange; MLOPEX, Mauna Loa observatory photochemistry experiment; MOZAIC, measurements of ozone in airbus in-service aircraft; MAC, multiphase atmospheric chemistry; NASA, National Aeronautics Space Administration; NOAA, National Oceanic and Atmospheric Administration; ITCT 2004, New England air quality study 2004; NOMHICE, nonmethane hydrocarbon intercomparison experiment; ACE-2, North Atlantic regional aerosol characterization experiment; NARE, North Atlantic regional experiment; PEACE, Pacific exploration of Asian continental emissions; PEM-West A, Pacific exploratory mission-west A; PEM-West B, Pacific exploratory mission-west B; PASC, polar atmospheric and snow chemistry; POLARCAT, polar study using aircraft, remote sensing, surface measurements and models of climate, chemistry, aerosols and transport; RCEI, reactive chlorine emissions inventory; RICE, rice cultivation and trace gas exchange; TROPOZ-II, second tropospheric ozone campaign; STARE, south tropical Atlantic regional experiment; SAFARI, Southern African fire/atmospheric research initiative; TRAGEX, trace gas exchange: mid-latitude terrestrial ecosystems and the atmosphere; TRACE-A, transport & atmospheric chemistry near the equator-Atlantic; TARFOX, tropospheric aerosol radiative forcing observational experiment; TRAGNET, U. S. trace gas network; NSF, US National Science Foundation; WMO, World Meteorological Organization.

* Corresponding author. Fax: +1 303 492 1149.
E-mail addresses: megan@igacproject.org (M.L. Melamed), P.S.Monks@leicester.ac.uk (P.S. Monks), ahg@berkeley.edu (A.H. Goldstein), mark.lawrence@iass-potsdam.de (M.G. Lawrence).

http://dx.doi.org/10.1016/j.ancene.2015.10.001
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1. Introduction

Human emissions of pollutants into the atmosphere have caused dramatic transformations of the Earth system, altering air quality, climate and nutrient flows in every ecosystem. These alterations suggest that we have entered a new geological epoch, the Anthropocene. The effects of human emissions are manifold:

- Air quality has a major impact on public health and ecosystems (UNEP/WMO, 2011; OECD, 2012; WHO, 2014):
- Changing atmospheric composition is driving climate change (IPCC, 2013):
- The atmospheric transport and deposition of Saharan dust to the Amazon determines the amount of phosphorus in this vital ecosystem (Artaxo et al., 1990; Koren et al., 2006; Ansmann et al., 2009; Bristow et al., 2010; Yu et al., 2015 and references therein).

The atmosphere is the integrator of the Earth system. Understanding the global atmosphere requires an organization to create an international network of scientists to provide the intellectual leadership in areas of atmospheric chemistry that must be addressed, promoted, and that would benefit from research across disciplines and geographical boundaries. Acknowledgement of this need led to the formation of the International Global Atmospheric Chemistry (IGAC) Project.

The origins of the International Global Atmospheric Chemistry (IGAC) project date back to the 1950s, when the International Association of Meteorology and Atmospheric Sciences (IAMAS) of the International Union of Geodesy and Geophysics (IUGG) initiated the Commission on Atmospheric Chemistry and Radiation (CACR), which was later renamed the international Commission on Atmospheric Chemistry and Global Pollution (iCACGP). At the fifth iCACGP Symposium in 1983, a committee was appointed to explore the sponsorship of an international research program on atmospheric chemistry. A parallel effort began in 1981 when a number of atmospheric chemists and meteorologists wrote a letter to the US National Science Foundation, urging the government to support the development of a coordinated study on global tropospheric chemistry. This effort resulted in a 1984 report of the U.S. National Research Council, entitled *Global Tropospheric Chemistry: A Plan for Action* (National Research Council (NRC), 1984). The report recommended that, "The US undertake a cooperative research effort with other countries in investigating the chemistry of the global troposphere."

As a result of these two simultaneous efforts, a meeting was held in 1988 in Dookie, Australia, on the formation of the International Global Atmospheric Chemistry (IGAC) Project (Fig. 1). Participants defined the initial six foci that would serve as the foundation of the first phase of IGAC. The six foci were: (1) Natural variability and anthropogenic perturbations of the marine atmosphere; (2) Natural variation and anthropogenic perturbation of tropical atmospheric chemistry; (3) The role of polar regions in the changing atmospheric composition; (4) The role of boreal regions in changing atmospheric composition; (5) Global distribution, transformations, trends and modeling; and (6) International support activities. In 1990, IGAC officially became a core project of the International Geosphere-Biosphere Programme (IGBP) and iCACGP (Galbally, 1989), with its International Project Office (IPO) located in and funded by the US National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA).

Throughout IGAC's rich 25-year history, the scientific foci have evolved in ways that reflect how the field of atmospheric chemistry has matured. The first phase of IGAC, 1990–1999, focused on understanding the chemistry of the natural atmosphere. In its second phase, 2000–2010, IGAC fostered scientific collaborations that built upon our understanding of the natural atmosphere and began to examine how human emissions were impacting atmospheric chemistry and composition from local to global scales. In its third and current phase, IGAC's mission is to "facilitate

Fig. 1. Participants of the 1988 meeting in Dookie, Australia that was the formative IGAC meeting.

atmospheric chemistry research toward a sustainable world", recognizing the fundamental role of human activity in determining atmospheric composition and how it relates to sustainability issues such as climate change, human health and ecosystems (Fig. 2). This evolution of IGAC coincides with the transition of IGAC from a core project of IGBP to a project of the new Future Earth initiative, a global research platform designed to provide the knowledge needed to support transformations toward sustainability.

This paper reports how, over the course of 25 years, IGAC has facilitated research in atmospheric chemistry to understand how atmospheric composition impacts air quality, climate change and nutrient flows in ecosystems. This understanding has been achieved through IGAC facilitating activities on:

- Synthesis and integration
- International field measurement campaigns
- Atmospheric chemistry at the Earth system interfaces
- Fundamental science
- Capacity building

Among the results of these efforts are four books, 32 special issues and numerous peer reviewed journal articles. These documents show that IGAC has helped defined the goals, objectives, and priorities, and has acted as initiator, catalyst and coordinator for the international atmospheric chemistry community.

2. IGAC Science achievements in advancing Earth system science

2.1. Synthesis and integration

Gaining an integrated view of atmospheric chemistry has been critical to developing the subject. The global nature of the troposphere has suggested a need to integrate multinational efforts. IGAC has played a central role in organizing, coordinating, and publishing several publications that synthesize international atmospheric chemistry research (see Table 1). These publications underline the importance of IGAC in providing a platform for synthesis efforts without overly emphasizing one institute or nation.

Global Atmospheric-Biospheric Chemistry (Prinn, 1994b) greatly improved the understanding of the chemical and biological processes that determine the composition of Earth's atmosphere. *Atmospheric Chemistry in a Changing World* (Brasseur et al., 2003) is considered the first international assessment of global tropospheric chemistry. Monks et al. (2009) brought to the forefront the point that long-range transport of air pollutants has a significant impact on regional air quality, demonstrating that air pollution is not a local, but a global issue. As the percentage of the world population living in urban areas surpassed the 50% mark in 2008, IGAC released the extensive report *WMO/IGAC Impacts of Megacities on Air Pollution and Climate* (Zhu et al., 2012) that summarized the current state of knowledge regarding air pollution and climate in megacities across Africa, Asia, South America, North America and Europe. In response to a call from policymakers to understand the climate impacts of black carbon, an IGAC-led effort published a hallmark synthesis on *Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment* (Bond et al., 2013). This study showed that black carbon (BC) is not only a major air pollutant, but that previous studies underestimated the direct climate forcing due to BC by about a factor of two, making BC the second most important climate forcer after carbon dioxide (CO_2) (Fig. 3). The study also highlighted the vast complexity of various competing effects and the difficulty of accounting and scenario development, especially due to co-emissions of other climate-forcing pollutants in reaching this estimate (Fig. 4). The IGAC-led synthesis publications indicatd how the field of atmospheric chemistry has evolved from understanding the natural atmosphere, to understanding the importance of human emissions and their role in air pollution at the local to global scale, to emphasizing the pressing need to understand atmospheric chemistry at a city level owing to the impacts of air pollution on human health, to providing policy relevant research to address sustainability issues, such as air pollution and climate change.

2.2. International field masurement campaigns

Exploring the troposphere and gaining insight into its changing trace gas composition remains critical in a number of areas from local air pollution to climate. IGAC has cultivated international scientific collaborations that have led to the coordination of field measurement campaigns on intercontinental transport and chemical transformations, aerosol characterization, biomass burning and ozone chemistry (see Table 2), all of which included substantial international cooperation for in-situ observations, remote sensing, data analysis and modeling efforts. The ability of IGAC to foster scientific collaborations that bring together

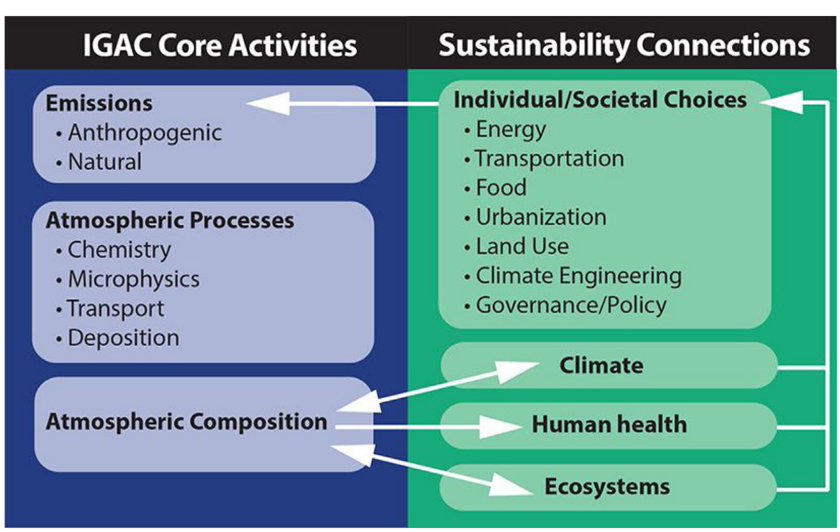

Fig. 2. Current IGAC vision.

Table 1
IGAC led synthesis publications.

Title	Reference
Global Atmospheric-Biospheric Chemistry	Prinn, 1994a,b
Atmospheric Chemistry in a Changing World	Brasseur et al., 2003
Atmospheric Composition Change-Global and Regional Air Quality	Monks et al., 2009
WMO/IGAC Impacts of Megacities on Air Pollution and Climate	Zhu et al., 2012
Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment	Bond et al., 2013

multinational field measurement campaigns into an overarching international research program allows scientists to have more collaborators and observations to draw from. Thus, field campaign fostered by IGAC results in a sum much greater than its parts.

The field campaigns that took place in the early to mid-1990s focused mainly on gas-phase chemistry, which at the time was not well understood and was the dominant research area in atmospheric chemistry. One of the earliest campaigns was the East Asia-North Pacific Regional Experiment (APARE), which advanced understanding of the chemical processes and long-range transport over the north-western Pacific Ocean. Contemporary to APARE, the North Atlantic Regional Experiment (NARE) investigated ozone, its precursors and its photochemical co-products in the near-continent region of North America and Europe. Both APARE and NARE showed that anthropogenic pollution has a large impact on ozone production over the North Pacific and the North Atlantic. This finding highlighted the important need to understand how human emissions impact atmospheric composition. In addition to these field campaigns that focused on long-range transport and chemical transformation of atmospheric gases, IGAC coordinated a series of three field campaigns specifically on ozone chemistry in the early 1990s under the Global Atmospheric Chemistry Survey (GLOCHEM). The GLOCHEM field campaigns provided important observations and modeling studies to reduce the uncertainties in the budget of tropospheric ozone. This effort focused on measurements of key species that play roles in the photochemical transformation of ozone, odd nitrogen, and odd hydrogen species in the remote free troposphere. It also showed that long-range transport of stable trace gases and mineral aerosol had a significant impact on controlling the concentration of these key species.

As gas-phase chemistry became better understood, attention turned more toward aerosols, which were known to also play an important role in determining atmospheric composition, with a significant and uncertain direct and indirect climate forcing. This work led to the emergence of chemical and physical properties of aerosols as the new hot topic in atmospheric chemistry beginning in the late 1990s. At this time, IGAC fostered a series of four international field measurement campaigns designed to quantify the chemical, physical and meteorological processes controlling

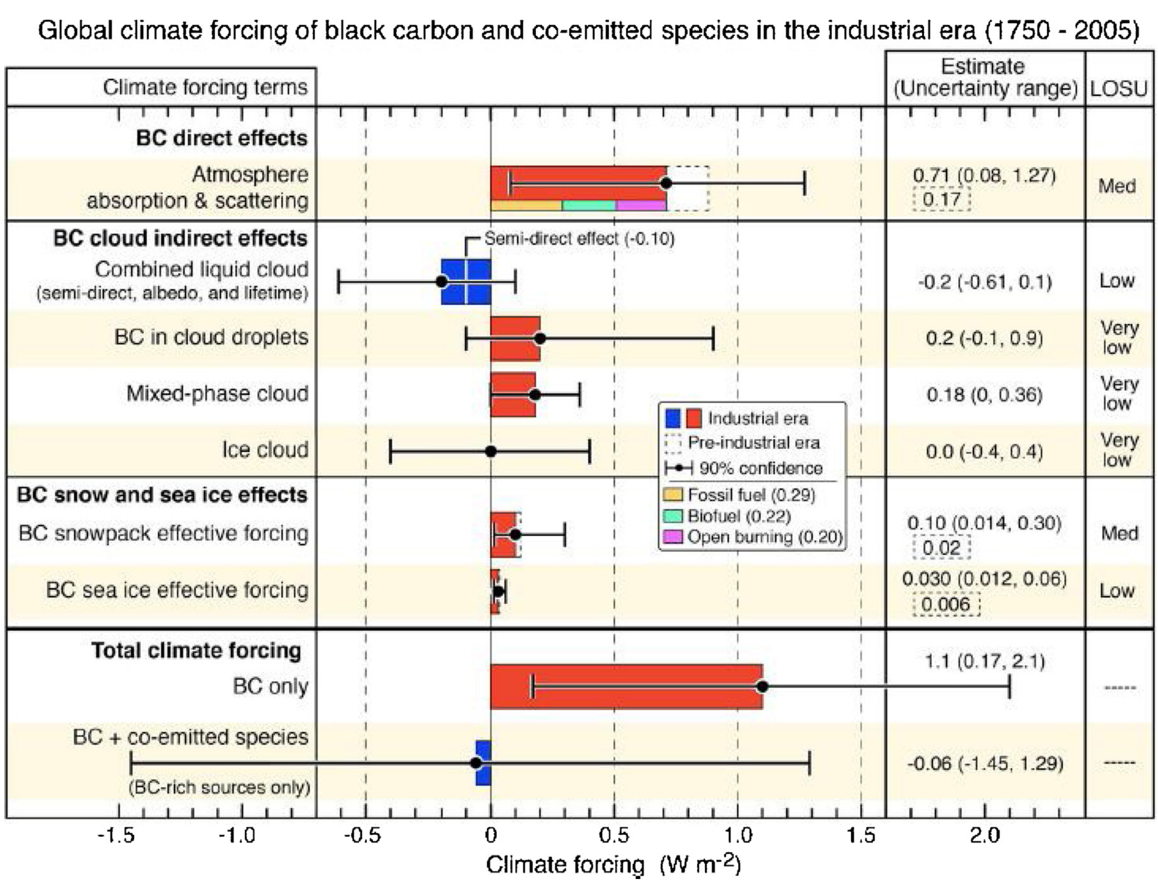

Fig. 3. Globally averaged climate forcing in units of $W\,m^{-2}$ from black carbon emissions in the year 2005 compared to those in 1750 (pre-industrial). The upper red bar indicates a best estimate of 0.71 $w\,m^{-2}$ direct radiative forcing due to black carbon, which is more than 2× greater than the best prior estimate of 0.34 $W\,m^{-2}$ from the IPCC Fourth Assessment report (IPCC, 2007). Figure from Bond et al., 2013.

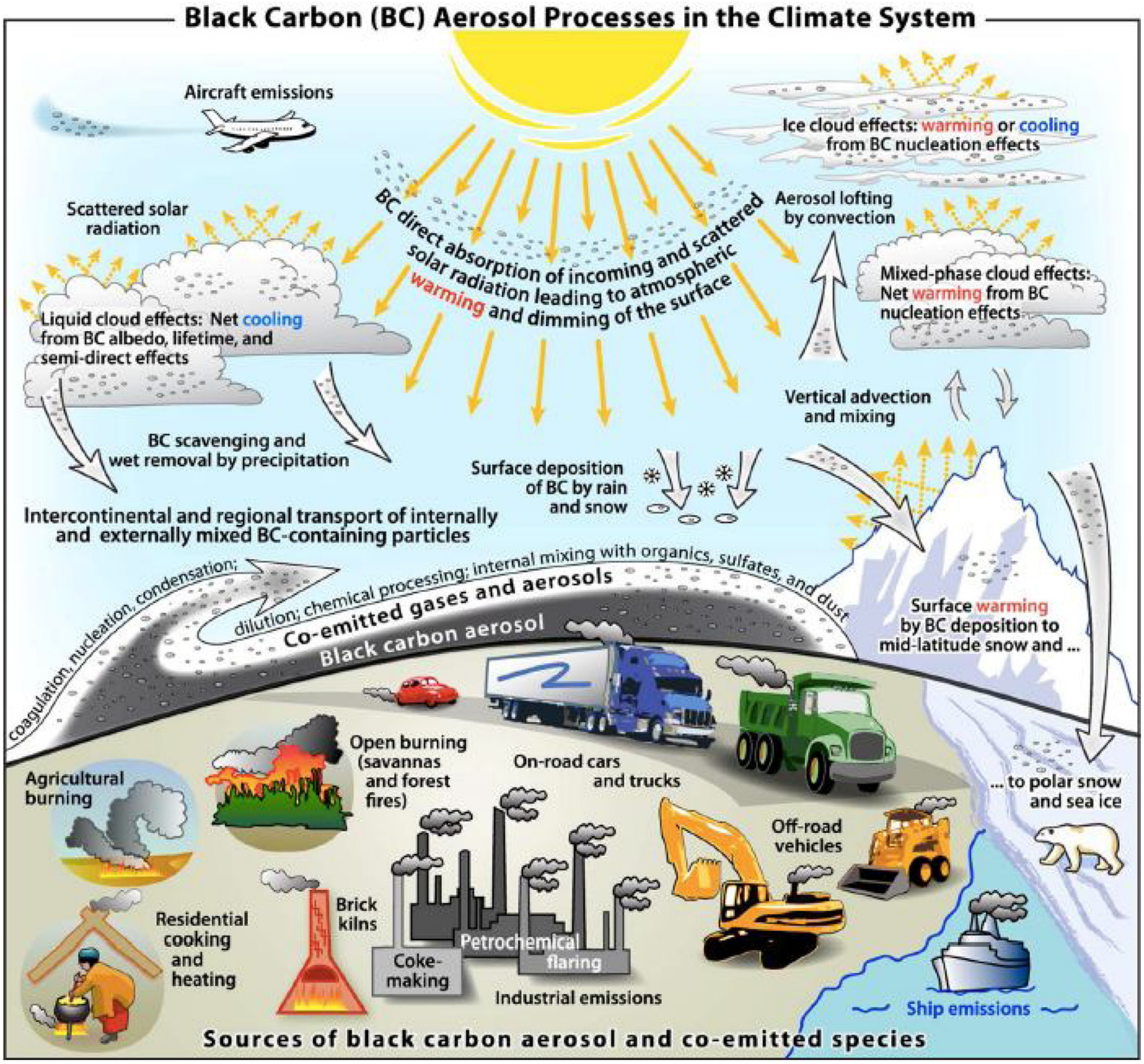

Fig. 4. Schematic overview of the complexity of understanding the role of black carbon in the climate system. Figure from Bond et al., 2013.

the evolution and properties of the atmospheric aerosol relevant to radiative forcing and climate (Fig. 5). The southern hemisphere marine Aerosol Characterization Experiment (ACE-1) was the first in the series and took place in 1995 over the southwest Pacific Ocean, south of Australia. The second in the series was Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), which took place off the East Coast of the US. In 1997, the third experiment in the series, North Atlantic regional Aerosol Characterization Experiment (ACE-2), was carried out over the North Atlantic Ocean between Portugal, the Azores and the Canary Islands. The final experiment is the series, Asian Aerosol Characterization Experiment (ACE Asia), which included both an intensive observation period in the spring of 2001 and a longer-term network of observations to assess seasonal and interannual variability from 2000 to 2003. This series of experiments to characterize aerosols across the globe set the foundation for the next generation of laboratory, field and modeling studies on aerosol characterization (Fig. 6).

Advancements in aerosol characterization beginning in the late 1990s resulted in field campaigns of the 2000s focusing on both gas-phase chemistry and aerosol characterization. Nearly a decade after the successful APARE and NARE campaigns in 2002, the Intercontinental Transport and Chemical Transformations (ITCT-2k2) and Pacific Exploration of Asian Continental Emissions (PEACE) experiments took place to further investigate the transport of Asian emissions across the North Pacific and to the west coast of North America, this time including many instruments to study aerosols. Two years later, as part of the International Consortium for Atmospheric Research on Transport and Transformation, the New England Air Quality Study (NEAQS-ITCT 2004) investigated the chemical process and transport of pollutants from the Midwest of the US, across the US east coast, over the North Atlantic and into Europe. The final field measurement campaign taking place as part of the ITCT studies was the Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models of Climate, Chemistry, Aerosols and Transport (POLARCAT), which investigated the transport of pollutants produced from emissions at mid-latitudes to the Arctic. The ITCT campaigns provided scientific evidence to show that the long-range transport of anthropogenic and natural emissions could interact, in both the gas-phase and in aerosols, toward far reaching impacts across the globe (Monks et al., 2009).

In addition to the long-range transport ITCT and ACE field campaigns, the study of biomass burning was also bringing to the forefront the need to investigate aerosol characterization in addition to gas-phase chemistry to truly understand the impacts of biomass burning on the atmosphere and biosphere. The Biomass Burning Experiment: Impact on the Atmosphere and Biosphere

Table 2
Publications from IGAC Fostered International Measurement Field Campaigns.

Intercontinental Transport And Chemical Transformations	Indicative Reference
East Asia-North Pacific Regional Experiment (APARE)	Akimoto, 1992
Pacific Exploratory Mission-West A (PEM-West A)	Hoell et al., 1996
Pacific Exploratory Mission-West B (PEM-West B)	Hoell et al., 1997
North Atlantic Regional Experiment (NARE)	Fehsenfeld & Penkett, 1992; Fehsenfeld et al., 1996; Penkett et al., 1998
Pacific Exploration of Asian Continental Emissions (PEACE)	Parish, 2004
Intercontinental Transport and Chemical Transformations (ITCT-2k2)	Parish, 2004
New England Air Quality Study (NEAQS-ITCT 2004)	Parish, 2006
Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models of Climate, Chemistry, Aerosols and Transport (POLARCAT)	Stohl et al., 2009; Law et al., 2014
Aerosol Characterization	
First Aerosol Characterization Experiment (ACE-1)	Bates et al., 1998; Bates et al., 1999
Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX)	Russell, 1999; Hartley et al., 2000
North Atlantic Regional Aerosol Characterization Experiment (ACE-2)	Rodhe, 2000
Asian Aerosol Characterization Experiment (ACE-Asia)	Huebert et al., 2004
Biomass Burning	
Biomass Burning Experiment: Impact on the Atmosphere and Biosphere (BIBEX)	Brasseur et al., 2003
South Tropical Atlantic Regional Experiment (STARE)	Andreae et al., 1996
Transport & Atmospheric Chemistry near the Equator-Atlantic (TRACE-A)	Andreae et al., 1996
Southern African Fire/Atmospheric Research Initiative (SAFARI)	Lindesay et al., 1996
Fire of Savannas/Dynamics and Atmospheric Chemistry n the Equatorial Forest (FOS/DECAFE)	Lacaux, 1995
Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO)	Delmas et al., 1999
Ozone	
Global Atmospheric Chemistry Survey (GLOCHEM)	
Mauna Loa Observatory Photochemistry Experiment (MLOPEX)	Atlas and Ridley, 1996
Second Tropospheric Ozone Campaign (TROPOZ-II)	Jonquières et al., 1998
Measurements of Ozone in Airbus in-service Aircraft (MOZAIC)	Marenco et al., 1998

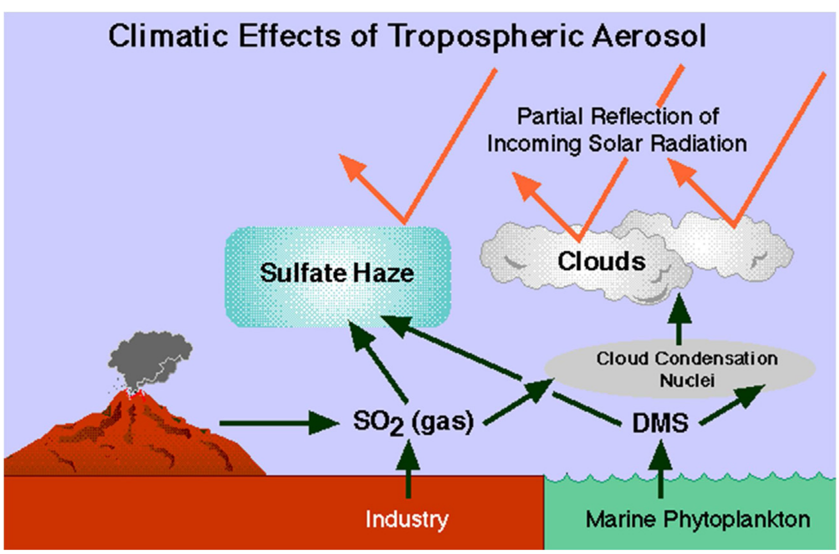

Fig. 5. Schematic of the climate effects of aerosols on climate (source: ACE-1 Project Description, https://www.eol.ucar.edu/field_projects/ace-1).

(BIBEX) coordinated three different international efforts on biomass burning in 1992; South Tropical Atlantic Regional Experiment (STARE), Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A) and Southern African Fire/Atmospheric Research Initiative (SAFARI). The field campaigns within BIBEX investigated chemically important gases and aerosol species resulting from biomass burning, the impact of biomass burning on regional and global scales, the short- and long-term effects of biomass burning on the atmosphere, and improved understanding of biogeochemical consequences due to atmospheric deposition of biomass burning products.

IGAC's leadership in guiding the community to collaborate across geographical boundaries on new and emerging topics in atmospheric chemistry is evident in the evolution of the field of atmospheric chemistry – from gas-phase chemistry to aerosols to the interactions of the two throughout the 1990s and 2000s.

2.3. Atmospheric chemistry at the Earth system interfaces

As the understanding of the atmosphere as a single compartment within the Earth system increased, the need to understand how the atmosphere interacted with other compartments of the

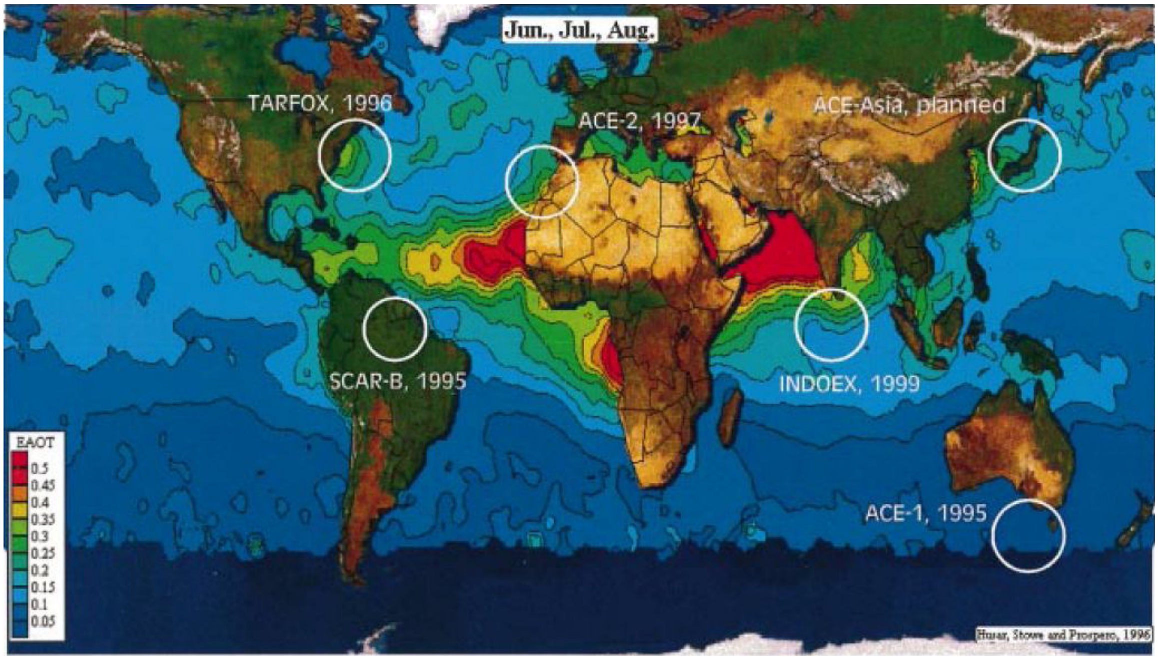

Fig. 6. The global breadth of a series of aerosol characterization experiments that set the foundation for future laboratory, field and modeling studies on aerosol characterization. (Figure from Raes et al., 2000).

Earth system evolved as an emerging area of research in atmospheric chemistry, with the idea that the atmosphere is the integrator of the Earth system. IGAC has and continues to play a prominent role in developing interdisciplinary networks that bring together scientists to address atmospheric chemistry at the Earth system interfaces, including atmosphere-biosphere, atmosphere-ocean and atmosphere–cryosphere (see Table 3) interactions. The interdisciplinary networks fostered by IGAC on atmospheric chemistry at the interfaces eventually led to the formation of two more IGBP core projects, the Surface Ocean Land Atmosphere Study (SOLAS) and the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS). IGAC continues to collaborate closely with SOLAS and iLEAPS on atmospheric chemistry at the biosphere, ocean and cryosphere interfaces.

Atmospheric chemistry at the interfaces requires understanding the emissions to the atmosphere from the biosphere, oceans and cryosphere, as well as the deposition of chemicals from the atmosphere to these interfaces, and how these are coupled to feedbacks in the Earth system. Much of the focus in this area, especially in the early 1990s, was on trace gas exchange. In the early 1990s, IGAC fostered many activities on trace gas exchange from the biosphere, ocean and cryosphere. Specific activities included the Trace Gas Exchange: Mid-Latitude Terrestrial Ecosystems and the Atmosphere (TRAGEX) to Marine Aerosol and Gas Exchange (MAGE) to Tropospheric Chemistry of the Antarctic Region. Important discoveries at this time were the impact of nitrogen fertilizers on the fluxes of methane (CH_4), CO_2, and nitrous oxide (N_2O) to the atmosphere (Smith et al., 1994) and compounds of marine origin,

Table 3
Publications from IGAC Fostered Activities on Atmospheric Chemistry at the Interfaces.

Atmosphere-biosphere	References
High-Latitude Ecosystems as Sources and Sinks of Trace Gases (HESS)	Reeburgh, 1993
The Interactive Atmosphere: Global Atmospheric-Biosphere Chemistry	Prinn, 1994a
Trace Gas Exchange: Mid-Latitude Terrestrial Ecosystems and the Atmosphere (TRAGEX)	Smith & Robertson, 1992
Biosphere-Atmosphere Trace Gas Exchange (BATREX)	Brasseur et al., 2003
Biosphere-Atmosphere Trace Gas Exchange in the Tropics: Influence of Land Use Change (BATGE)	Matson & Delmas, 1992
Rice Cultivation and Trace Gas Exchange (RICE)	Sass & Neue, 1992; Sass & Neue,1994
Deposition of Biogeochemically Important Trace Species (DEBITS)	Ayers et al., 1992; Vet et al., 2014
U.S. Trace Gas Network (TRAGNET)	Ojima et al., 2000
Atmosphere-ocean	
Marine Aerosol and Gas Exchange (MAGE)	Huebert, 1993; Huebert, 1996
Atlantic Stratocumulus Transition Experiment (ASTEX)	Albrecht et al., 1995
Air-Sea Gas Exchange (ASGAMAGE)	Jacobs et al., 1999; Oost, 2013
Atmosphere–cryosphere	
Polar Atmospheric and Snow Chemistry (PASC)	Barrie & Delmas, 1994
Tropospheric Chemistry of the Antarctic Region [Special Issues]	Bodhaine & Barrie, 1992
Tropospheric Chemistry of the Arctic Region [Special Issue]	Gruzden & Sitnov, 1993
Polarstern Expedition	Platt et al., 1992
Polar Sunrise Experiment	Barrie et al., 1994
Air-Ice Chemical Interactions (AICI)	Shepson et al., 2007; McNeill et al., 2013

such as dimethyl sulfide, affect climate, the oxidative capacity of the atmosphere and the stratospheric ozone layer (Bodhaine et al., 1992).

To understand the impact of clouds on the climate, studying the interactions between aerosols and clouds is critical. In many cases, this study requires understanding the emissions of precursors and/or aerosols from the biosphere, ocean, and cryosphere. Under MAGE, the Atlantic Stratocumulus Transition Experiment (ASTEX) was organized to study the relationship between marine chemistry, aerosols, clouds, and air/sea exchange. A highlight of ASTEX was the discovery that non-sea-salt sulfate and nitrate have a substantial impact on cloud condensation nuclei over the North Atlantic Region (Harrison et al., 1996).

Also important to understanding the exchange between the atmosphere and other interfaces is establishing long-term monitoring networks. IGAC fostered the development of two such networks. The Trace Gas Network (TRAGNET) developed an open database of multiyear trace gas flux and ancillary data from a wide range of ecosystems across North America, Europe and Central America. TRAGNET focused on the fluxes of CH_4, NO_X, and N_2O. The data collected over multiple years were used in a process- oriented model, Intercomparison, to study the controls of ecosystem and land use management on trace gas fluxes. The IDAF (IGAC/DEBITS/Africa) monitoring network provided the first consistent measurement of wet and dry deposition in Africa (Fig. 7). Although the number of monitoring sites in Africa could be increased, especially in East Africa, the current sites provide long- term data sets pivotal in quantifying the future impacts of sulfur emissions in Africa, as the population of many African cities increases energy demand and hence sulfur emissions (Vet et al., 2014).

A hallmark of research at the Earth system interfaces is developing interdisciplinary knowledge. This work often brings together scientists from biology, oceanography and cryospheric science with atmospheric scientists to better understand how processes interacting at these interfaces impact the composition of the atmosphere. By studying atmospheric chemistry at the interfaces, we can begin to fully understand the role of the atmosphere as the integrator of the Earth system, including the impact of humans on the system.

2.4. Fundamental underpinning scientific activities

Recently, IGAC published a position paper on the future of the fundamentals of atmospheric chemistry (Abbatt et al., 2014). The article stressed the importance of maintaining a strong three-legged stool approach of laboratory, ambient observations, and modeling studies to address the most pressing issues of our time. Each leg of the stool is only as stable as the fundamental chemistry that underpins it, i.e. within each leg, the need exists to understand the connections between the fundamental properties and reactivity of molecules and observable atmospheric phenomena (Fig. 8). Over the years, IGAC has fostered, and will continue to foster, activities that focus on research on fundamental atmospheric chemistry in order to keep the three-legged stool balanced (Table 4).

In the early years of research in atmospheric chemistry, much of the laboratory work focused on measuring gas-phase rate constants in order to understand the production of photochemical smog. Through understanding chemical reactions and their rates, going into the field was necessary to apply the knowledge gained in the laboratory to investigate the reactions in the “real world”. These field campaigns often required measurement Intercomparison activities, such as the Nonmethane Hydrocarbon Intercomparison Experiment (NOMHICE), fostered by IGAC, or the Jülich Ozone Intercomparison Experiment. Measurement intercomparison activities are often done in the laboratory after the fundamental development of instruments, or in the field after the instruments have been deployed in atmospheric conditions. NOMHICE, for example, was a laboratory- based intercomparison experiment in which participating groups sent around different samples of ambient levels of various atmospheric non-methane hydrocarbons to identify existing issues within each group’s analysis, correct these issues and therefore ensure quality control of hydrocarbon measurement throughout the world (Apel et al., 1994).

Similar to measurement techniques, models are also important in intercomparison projects to reproduce observations and/or evaluate how they perform compared to each other. IGAC has organized model intercomparison activities such as the Global Integration and Modeling (GIM) and the Atmospheric Chemistry and Model Intercomparison Project (ACCMIP). The Fourth IPCC assessment (IPCC, 2013) included model runs of ACCMIP, providing for the first time atmospheric chemistry in climate modeling. Through ACCMIP, it was shown that the aerosol effective radiative forcing (ERF) has masked a substantial percentage of late 20th and early 21st century global greenhouse forcing, indicating the importance of including atmospheric chemistry when studying climate (Shindell et al., 2013). IGAC is

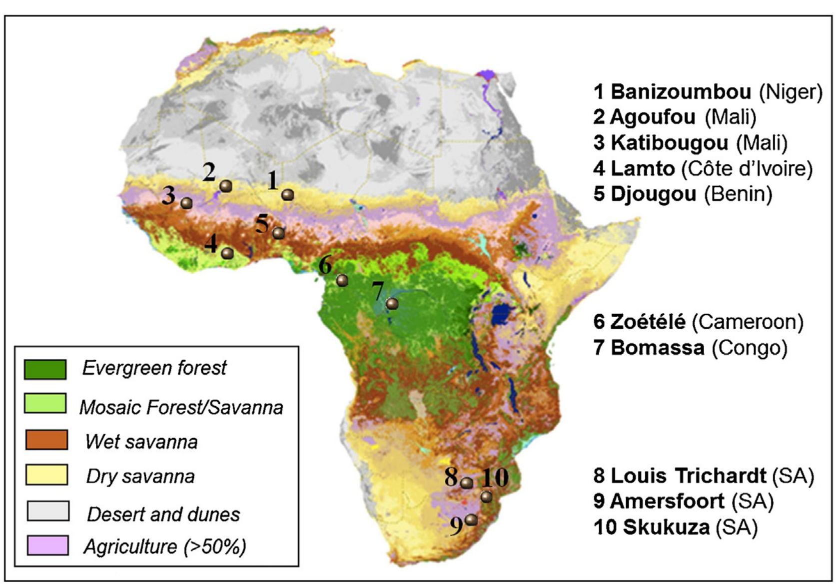

Fig. 7. Vegetation and location map of the 10 measurement stations of the IDAF monitoring network. Figure from Vet et al., 2014.

fostering a new Chemistry-Climate Model Initiative (CCMI) to continue emphasizing atmospheric chemistry in climate modeling. The initiative emphasizes the importance of model development and updates to include the most up to date fundamental science from the laboratory and field.

Understanding emissions is a critical part of studying atmospheric composition and it changes. Since 1990, IGAC has fostered the Global Emissions Initiative (GEIA), which aims to develop and distribute scientifically sound and policy-relevant inventories of gases and aerosols emitted into the atmosphere from natural and anthropogenic sources (Scholes et al., 1994). The development and analysis of emission inventories requires measuring emission factors in the laboratory. These measurements are important for developing bottom-up emissions inventory, in-situ and remote sensing measurements for top-down verification. Atmospheric modeling is also important to compare the two data sets. In many cases, emissions inventories are developed not for scientific research but to support policies, such as the U.S. Clean Air Act. In recognition of this point, GEIA has evolved to become a community effort that builds bridges between environmental science and policy to create and make available, for both scientific and policy applications, the highest quality information about emissions. GEIA is an excellent example of how the field of atmospheric chemistry has evolved toward emphasizing policy-relevant issues rooted in fundamental science.

2.5. Capacity building

A primary role of IGAC is to build scientific capacity in the field of atmospheric chemistry around the globe. IGAC has a strong focus on engaging the next generation of early career atmospheric scientists and scholars from developing countries by providing travel grants to IGAC co-sponsored workshops, meetings, and conferences as well as highlighting their work in the IGAC newsletter. Early career scientists join an international network of atmospheric scientists early in their career that will further facilitate atmospheric chemistry research at an international level. For the developing country scientists, IGAC fosters creating a strong cohesive community of atmospheric scientists in under-represented regions of the world. IGAC also connects the scientists to the larger community in order to foster international collaborations. IGAC also works to communicate atmospheric chemistry research to the international atmospheric chemistry community, and to the wider global change and sustainability communities, including stakeholders, policy makers and the public.

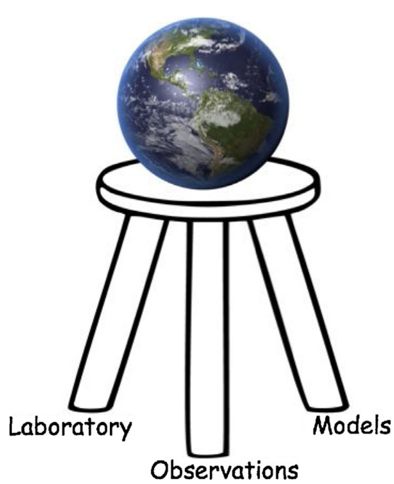

Fig. 8. Keeping the three-legged stool approach to atmospheric chemistry research balanced requires laboratory studies, field observations and modeling that must each be rooted strongly in fundamental science.

IGAC's Science Conference is a primary mechanism for IGAC to build cooperation and disseminate scientific information across its international community. The first IGAC Science Conference was held in 1993 in Eilat, Israel. Since, IGAC has held fourteen science conferences, consistently becoming a biennial conference starting in 2002 (see Table 5). The conference is jointly held with the iCACGP Symposium every four years. The biennial IGAC Science Conference is regarded as THE international conference on atmospheric chemistry and participation in the conference is typically in the range from 350 to 650 participants. Since 2004, IGAC has included an Early Career Scientists Program as part of the conference to foster the next generation of scientists. The IGAC conferences and the Early Career Program have shown that helping young scientists to form an international network of colleagues enhances future international collaborations in atmospheric chemistry. In addition to participating in the Early Career Science Program at the biennial IGAC Science Conferences, IGAC encourages young scientists to join the IGAC community by participating in IGAC Activities and attending IGAC workshops and training schools, for which IGAC Early Career Travel Grants are often available (www.igacproject.org, clink on "Join IGAC" to receive announcements on opportunities for early career scientists).

In addition to cultivating the next generation of scientists, IGAC supports capacity building in the developing world. Many great scientists work in many regions of the world, but often their research is conducted independently and their results often do not reach, or in turn benefit from, the international community. As research questions in atmospheric chemistry and their connections to societal issues become more global, engaging these scientists is important to incorporate their research and local knowledge of these regions of the world. Therefore, since 2011, IGAC has fostered the formation of national/regional working groups that aim to facilitate scientific collaborations both within the nation/region and between the nation/region and the international atmospheric chemistry community. The goal of IGAC National/Regional Working Groups is two-fold: to create a strong cohesive community of atmospheric scientists in a specific nation/region that together have a sum greater than their parts; and to connect the National/Regional Working Groups to the larger multilateral IGAC community to foster international collaboration. The IGAC National/Regional Working Groups have already resulted in enhanced collaborations between the international IGAC community and China, Latin America and Southeast Asia.

3. Looking forward

A prescient need remains for research in global and regional atmospheric chemistry to address the coupled scientific challenges of air quality and climate in the Anthropocene. IGAC is responding to this challenge by *facilitating atmospheric chemistry research toward a sustainable world.* This challenge is achieved through IGAC's three focal activities: fostering community, building capacity, and providing leadership.

- Fostering community

IGAC is an international community of atmospheric scientists actively collaborating across geographical boundaries and disciplines in order to contribute to addressing the most pressing global change and sustainability issues through scientific research.

- Building capacity

IGAC is building scientific capacity through its national and regional working groups, its early career scientists program, its biennial conferences and support of numerous thematic workshops.

Table 4
Publications from IGAC Fostered Activities on Fundamental Science.

Emissions	References
Joint North American-European Workshop on Measurement and Modeling of Methane Fluxes from Landfills	Smith & Bogner 1997
Reactive Chlorine Emissions Inventory (RCEI)	Graedel and Keene, 1999
Global Emissions Initiative (GEIA)	Graedel & Pacyna 1992; Frost et al., 2013
Aerosol	
Focus on Atmospheric Aerosols (FAA)	Hobbs and Huerbert, 1995
Aerosols, Clouds, Precipitation and Climate (ACPC)	Andreae et al., 2009
Gas Phase	
Nonmethane Hydrocarbon Intercomparison Experiment (NOMHICE)	Calvert and Fehsenfeld, 1992 Apel et al., 1994; Apel et al., 1999
Global Tropospheric Carbon Dioxide Network (GLOCARB)	Keeling and Tans, 1993
Carbon Dioxide Intercalibration Experiment (CARBICE)	Keeling & Cundari, 1993
Global Tropospheric Ozone Network (GLONET)	Mohen, 1996
International Tropospheric Ozone Years (ITOY)	Mohen, 1996
Jülich Ozone Intercomparison Experiment (JOSIE)	Smit and Kley, 1996
Global HO Systematic Tests (GHOST)	Jöckel et al., 2003
Modeling	
Multiphase Atmospheric Chemistry (MAC)	Charlson, 1992
Global Integration and Modeling (GIM)	Kanakidou et al., 1999
Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)	Dameris et al., 2013

Table 5
IGAC Scientific Conferences.

Conference	Location	Conference	Location
1993 IGAC	Eilat, Israel	2002 IGAC/iCACGP	Crete, Greece
1994 IGAC/iCACGP	Fuji-Yoshida, Japan	2004 IGAC	Cristchurch, NZ
1995 IGAC	Beijing, China	2006 IGAC/IGACGP/WMO	Cape Town, SA
1997 IGAC/SPARC/WMO	Toronto, Canada	2008 IGAC	Annecy, France
1997 IGAC/iCACGP/IAPSO	Melbourne, AUS	2010 IGAC/iGACGP	Halifax, Canada
1998 IGAC/iCACGP	Seattle, WA, USA	2012 IGAC	Beijing, China
1999 IGAC	Bologna, Italy	2014 IGAC/iCACGP	Natal, Brazil

• Providing leadership

IGAC provides intellectual leadership by identifying and fostering activities on current and future areas within atmospheric chemistry that would benefit from research across geographical boundaries and/or disciplines.

The field of atmospheric chemistry is at its core interdisciplinary. Since its inception, the field has also engaged societal partners. Atmospheric scientists are an amalgam of engineers, physicists, meteorologist, biologists, computer scientists, and chemist, all fields required to fully understand the role of the atmosphere as the integrator of the Earth system. IGAC works closely with other global environmental change organizations to increase understanding of the interactions between the atmosphere-biosphere, atmosphere-ocean, atmosphere–cryosphere, and atmosphere-human interactions. The discipline of atmospheric chemistry began in the 1950s to address pressing issues related to air quality. Engagement with societal partners has included co-designing research and co-producing solutions in order to tackle air pollution, an issue that is still a major concern across the world. IGAC will continue to work with societal partners to facilitate co-design and co-production of knowledge where appropriate for addressing global change and sustainability issues.

Therefore, the transition of IGAC to a research project of the new international initiative Future Earth in 2015 (Future Earth, 2013, 2014) is an appropriate and exciting opportunity for the international atmospheric chemistry community. Future Earth is a global research platform designed to provide the knowledge needed to support transformations toward sustainability. It works with societal partners to co-develop knowledge around three research themes (Dynamic Planet, Global Sustainable Development, and Transformations toward Sustainability) to support decision makers and societal change. IGAC will continue to lead the community to address Future Earth Research Priorities across the three themes, such as understanding how atmospheric emissions of pollutants are changing in different regions and sectors, understanding the lifecycle implications of different energy sources, and understanding the opportunities and risks that might arise from new technologies, e.g. geoengineering.

Through Future Earth, IGAC will continue to foster community, build capacity, and provide intellectual leadership. It will also extend its efforts toward engaging societal partners to co-design actions (research, policies, etc.) and solutions required to respond effectively to the challenges and opportunities of global change and sustainability. IGAC aims to continue to represent the international atmospheric chemistry community by fostering activities that underpin fundamental scientific research on emissions, atmospheric processes, and atmospheric composition in ways that link to global change and sustainability. It will make a central contribution to the overall mission of Future Earth. As a project of Future Earth, IGAC will be part of a global platform for international scientific collaboration that will promote the development of knowledge required for the world's societies to face risks posed by global change and to seize opportunities in its efforts to transition toward global sustainability.

Acknowledgements

The International Global Atmospheric Chemistry (IGAC) Project would like to thank the continued support of the US National Science Foundation (NSF), National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) for funding the IGAC International Project Office since 1990 and a special thank you to our co-sponsors, iCACGP and IGBP. IGAC is also grateful to all the other organizations that have supported its mission throughout the years through in kind or financial support (including but not limited to ACCENT+, WMO, ESA, Academica Sinica, amongst many others). IGAC would also like to thank the numerous volunteers who have contributed their time to IGAC in a myriad of ways, in particular members of the SSC and conference organizing committees over the years. Please note: Other versions of portions of this manuscript may exist to describe the history and significance of IGAC.

References

Abbatt, J., George, C., Melamed, M., Monks, P., Pandis, S., 2014. New directions: fundamentals of atmospheric chemistry: keeping a three-legged stool balanced. Atmos. Environ. 84, 390–391. doi:http://dx.doi.org/10.1016/j.atmosenv.2013.10.025.
Akimoto, H., 1992. East Asian/North Pacific Regional Experiment (APARE). IGAC Core Project Office, MIT. USA, Cambrdige, MA.
Albrecht, Bruce A., Bretherton, Christopher S., Johnson, Doug, Scubert, Wayne H., Frisch, A. Shelby, 1995. The Atlantic Stratocumulus Transition Experiment—ASTEX. Bull. Am. Meteor. Soc. 76, 889–904. doi:http://dx.doi.org/10.1175/1520-0477(1995)076<0889:TASTE>2.0.CO;2.
Andreae, M.O., Fishman, J. and Lindesay, J. (Eds). (1996). Southern Tropical Atlantic Regional Experiment (STARE): TRACE A and SAFARI [Special Section]. Journal of Geophysical Research-Atmospheres, 101 (D19).
Andreae, M.O., Stevens, B., Feingold, G., Fuzzi, S., Kulmala, M., Lau, W.K., Lohmann, U., Rosenfeld, D., Siebesma, P., Reissell, A., O'Dowd, C., Raga, G., Ackerman, T., 2009. Aerosols, Clouds, Precipitation and Climate (ACPC). Science Plan & Implementation Stategy.
Ansmann, A., Baars, H., Tesche, M., Muller, D., Althausen, D., Engelmann, R., Pauliquevis, T., Artaxo, P., 2009. Dust and smoke transport from Africa to South America: lidar profiling over Cape Verde and the Amazon rainforest. Geophys. Res. Lett. 36 doi:http://dx.doi.org/10.1029/2009GL037923 L11802.
Apel, E.C., Calvert, J.G., Fehsenfeld, F.C., 1994. The nonmethane hydrocarbon intercomparison experiment (NOMHICE) tasks 1 and 2. J. Geophys. Res. 99 (D8), 16651–16664. doi:http://dx.doi.org/10.1029/94JD00086.
Apel, E.C., Calvert, J.G., Gilpin, T.M., Fehsenfeld, F.C., Parrish, D.D., Lonneman, W.A., 1999. The nonmethane hydrocarbon intercomparison experiment (NOMHICE) tasks 3. J. Geophys. Res.: Atmos. 104 (D21), 26069–26086. doi:http://dx.doi.org/10.1029/1999JD900793.
Artaxo, P., Maenhaut, W., Storms, H.H., Van Grieken, R., 1990. Aerosol characteristics and sources for the Amazon Basin during the wet season. J. Geophys. Res. 95 (D10), 16971–16985.
Atlas, E.L. and B.A. Ridley (Eds.). (1996). Mauna Loa Observatory Photochemistry Experiment (MLOPEX 2) [Special Section]. Journal of Geophysical Research-Atmospheres, 101 (D9).
Ayers, G., Artaxo, P., Galloway, J., Lacaux, J.P., Rodhe, R., 1992. Deposition of Biogeochemically Important Trace Species. IGAC Core Project Office, MIT, Cambridge, MA, USA.
Barrie, L.A., Delmas, R.J., 1994. Polar Atmospheric and Snow Chemistry (PASC). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Barrie, L.A., Bottenheim, J.W., W.R. Hart (Eds.) (1994). Polar Sunrise Experiment (PSE 1992) [Special Section]. Journal of Geophysical Research-Atmospheres, 99 (D12).
Bates, T.S., Huebert, B.J., J.L. Gras (Eds). (1998). First Aerosol Characterization Experiment (ACE-1) [Special Section]. Journal of Geophysical Research-Atmospheres, 103 (D13).
Bates, T.S. (Eds). (1999). First Aerosol Characterization Experiment (ACE-1) Part 2 Special Section. Journal of Geophysical Research-Atmospheres, 104 (D17).
Bodhaine, B.A. and L. A. Barrie (Eds.). (1992). Tropospheric Chemistry of the Antarctic Region [Special Issue]. Tellus Series B, 44 (4).
Bodhaine, B.A., Barrie, L.A., Schnell, R.C., Shaw, G.E., McKie, J.K., 1992. Symposium on the tropospheric chemistry of the Antarctic Region. Tellus 44B, 250–251.
Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C. S., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. J. Geophys. Res. 118 (11), 5380–5552. doi:http://dx.doi.org/10.1002/jgrd.50171.
Brasseur, G.P., Prinn, R.G., A.A.P. Pszenny (Eds.). (2003). Atmospheric Chemistry in a Changing World. Heidelberg, Germany: Sprinter Verlag. ISBN 978-3-642-62396-7.
Bristow, C.S., Hudson, K.A., Chappell, E.A., 2010. Fertilizing the Amazon and equatorial Atlantic with West African dust. Geophys. Res. Lett. 37, L14807. doi:http://dx.doi.org/10.1029/2010GL043486.
Calvert, J.G., Fehsenfeld, F., 1992. Non-Methane Hydrocarbon Intercomparison Experiment (NOMHICE). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Charlson, R.J., 1992. Multiphase Atmospheric Chemistry (MAC). IGAC Core Project Office, MIT. USA, Cambridge, MA.
Dameris, M., Spracklen, D., Tost H. (Eds.). (2013). The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) [Special Issue]. Atmospheric Chemistry and Physics.
Delmas, R., Druilhet A., Cros, B. (Eds). (1999). Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO) [Special Section]. Journal of Geophysical Research-Atmospheres, 104 (D23).
Fehsenfeld, F.C., Penkett, S.A., 1992. North Atlantic Regional Experiment (NARE). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Fehsenfeld, F.C., Trainer, M., Parrish, D.D. (1996). North Atlantic Regional Experiment (NARE) [Special Section]. Journal of Geophysical Research-Atmospheres, 101 (D22).
Frost, G.J., Middleton, P., Tarrason, L., Granier, C., Guenther, A., 2013. New directions: GEIA's 2020 vision for better air emissions information. Atmos. Environ. 81, 710–712. doi:http://dx.doi.org/10.1016/j.atmosenv.2013.08.063.
Future Earth. (2013). Future Earth Initial Design. Future Earth. Paris, France. ISBN 978-0-930357-92-4.
Future Earth. (2014). Future Earth Strategic Research Agenda 2014. Future Earth. Paris, France. ISBN 978-0-930357-96-2.
Galbally, I.E. (Ed.). (1989). The International Global Atmospheric Chemsitry (IGAC) Programme. Commission on Atmospheric Chemistry and Global Pollution of the International Association of Meteorology and Atmospheric Physics. ISBN 0643050620.
Graedel, T.E., Pacyna, J.M., 1992. Global Emissions Inventory Activity (GEIA). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Graedel, T., Keene, W. (Eds.). (1999). Reactive Chlorine Emissions Inventory (RCEI) [Special Section]. Journal of Geophysical Research-Atmospheres, 104 (D7).
Gruzden, A.N. and Sitnov, S.A. (Eds.) (1993). Tropospheric Chemistry of the Arctic Region [Special Issue]. Tellus Series B, 45 (2).
Harrison, R.M., Peak, J.D., Kaye, A.D., 1996. Atmospheric aerosol major ion composition and cloud condensation nuclei over the northeast Atlantic. J. Geophys. Res. Atmos. 101 (D2), 4425–4434.
Hartley, W., Hobbs, P., Ross, J. (Eds.). (2000) Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) [Special Section]. Journal of Geophysical Research-Atmospheres, 105 (D8).
Hobbs, P., Huerbert, B., 1995. IGAC's new focus on atmospheric aerosols. IG Activit. Newsl. (2), 4–5.
Hoell, J.M., Davis, D.D., Liu, S.C. (Eds). (1996). Pacific Exploratory Mission-West Phase A [Special Section]. Journal of Geophysical Research-Atmospheres, 101 (D1).
Hoell, J.M., Davis, D.D., Liu, S.C. (Eds). (1997). Pacific Exploratory Mission-West Phase B (PEM-West B) [Special Section]. Journal of Geophysical Research-Atmospheres, 102 (D23).
Huebert, B.J., 1993. Marine Aerosol and Gas Exchange (MAGE). IGAC Core Project Office, MIT, USA Cambridge, MA.
Huebert, B.J (Ed). (1996). Atlantic Stratocumulus Transition Experiment/Marine Aerosol and Gas Exchange [Special Section]. Journal of Geophysical Research-Atmospheres, 101 (D2).
Huebert, B., Bates, T., Russell, P.B. (Eds.). (2004). Characterization of Asian Aerosols and Their Radiative Impacts on Climate. Journal of Geophysical Research-Atmospheres, 107 (D23)-109 (D23).
IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 996 pp.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1535 pp.
Jacobs, C.M.J., wim Kohsiek, Oost, W.A., 1999. Air-sea fluxes and transfer velocity of CO_2 over the North Sea: results from ASGAMAGE. Tellus B 51 (3) doi:http://dx.doi.org/10.1034/j.1600-0889.1999.t02-2-00005.x.
Jöckel, P., Brenninkmeijer, C.A.M., Singh, H.B., Crutzen, P.J., 2003. Investigation of the global atmospheric oxidation efficiency and its trends: a proposal to initiate IGAC-GHOST (Global HO Systematic Tests). IGACtivities Newsl. (28), 2–5.
Jonquières, I., Marenco, A., Maalej, A., Rohrer, F., 1998. Study of ozone formation and transatlantic transport from biomass burning emissions over West Africa during the airborne Tropospheric Ozone Campaigns TROPOZ I and TROPOZ II. J. Geophys. Res. Atmos. 103 (D15), 19059–19073.

Kanakidou, M., Dentener, F.J., Brasseur, G.P., Berntsen, T.K., Collins, W.J., Hauglustaine, D.A., Houweling, S., Isaksen, I.S.A., Krol, M., Lawrence, M.G., Muller, J.-F., Poisson, N., Roelofs, G.J., Wang, Y., Wauben, W.M.F., 1999. 3-D global simulation of tropospheric CO distributions—results of the GIM/IGAC intercomparison 1997 exercise. Chemosphere—Global Change Sci. 1 (1–3), 263–282. doi:http://dx.doi.org/10.1016/s1465-9972(99) 00029-x.
Keeling, C.D., Cundari, V., 1993. Carbon Dioxide Intercalibration Experiment (CARBICE). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Keeling, C.D., Tans, P., 1993. Global Tropospheric Carbon Dioxide Network (GLOCARB). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Koren, I., Kaufman, Y.J., Washington, R., Todd, C.C., Rudich, Y., Martins, J.V., Rosenfeld, D., 2006. The Bod'el'e depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest. Environ. Res. Lett. 1, 1–5.
Lacaux, J.P., 1995 (Ed.). (1995). Fires of Savanas and Dynamoque et Chimie Atmospherique en Foret Equatorial (FAS, DECAFE 91) [Special Issue]. Journal of Atmospheric Chemistry, 22 (1–2).
Law, K.S., Stohl, A., Quinn, P.K., Brock, C., Burkhart, J., Paris, J.D., Ancellet, G., Singh, H. B., Roiger, A., Schlager, H., Dibb, J., Jacob, D.J., Arnold, S.R., Pelon, J., Thomas, J.L., 2014. Arctic air pollution: new Insights from POLARCAT-IPY. Bull. Am. Meteorol. Soc. doi:http://dx.doi.org/10.1175/bams-d-13-00017.1.
Lindesay, J.A., Andreae, M.O., Goldammer, J.G., Harris, G., Ammegarn, H.J., Garstang, M., Scholes, R.J., van Wilgen, B.W., 1996. International geosphere-biosphere programme/international global atmospheric chemistry SAFARI-92 field experiment: background and overview. J. Geophys. Res. Atmos. 101 (D19) 23,521–23,530.
Marenco, A., Thouret, V., Nédélec, P. (Eds). (1998). First Results From the MOAZIAC I Program [Special Section]. Journal of Geophysical Research-Atmospheres, 103 (D19).
Matson, P.A., Delmas, R. (1992). Biosphere-Atmosphere Trace Gas Exchange in the Tropics: Influence of Land-Use Change. IGAC Core Project Office, MIT, Cambridge, MA, USA.
McNeill, V.F., Wolff, E., Bartels-Rausch, T., Pfeiffenberger, H. (Eds.). (2013). New Perspectives on Air-Ice Chemical Interactions (AICI) [Special Issue]. Atmospheric Chemistry and Physics.
Mohen, V.A. (1996). Update on IGAC's Global Tropospheric Ozone Network (GLONET) Activity and the International Tropospheric Ozone Years (ITOY). IGACtivities Newsletter, Issue 3, 4–6.
Monks, P.S., Granier, C., Fuzzi, S., Stohl, A., Williams, M.L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R.S., Carslaw, K., Cooper, O.R., Dentener, F., Fowler, D., Fragkou, E., Frost, G.J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H.C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I.S.A., Jenkin, M.E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M.G., Lee, J.D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J.J., O'Dowd, C.D., Palmer, P.I., Parrish, D.D., Petzold, A., Platt, U., Pöschl, U., Prévot, A.S.H., Reeves, C. E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van der Werf, G.R., Vautard, R., Vestreng, V., Vlachokostas, C., von Glasow, R., 2009. Atmospheric composition change'global and regional air quality. Atmos. Environ. 43, 5268–5350. doi:http://dx.doi.org/10.1016/j.atmosenv.2009.08.021.
National Research Council (NRC), 1984. Global Tropospheric Chemistry: A Plan for Action. The National Academies Press, Washington, D.C. http://www.nap.edu/catalog/177.htm.
OECD, 2012. OECD Environmental Outlook to 2050. OECD Publishing doi:http://dx.doi.org/10.1787/9789264122246-en.
Ojima, D., Mosier, A., Del Grosso, S., Parton, W.J. (Eds.). (2000). TRAGNET Analysis and Synthesis of Trace Gas Fluxes [Special Section]. Global Biogeochemical Cycles, 14 (4).
Oost, W., 2013. ASGAMAGE, the Air-Sea Gas Exchange/MAGE Experiment. Gas Transfer at Water Surfaces. In: Donelan, M.A., Drennan, W.M., Saltzmann, E.S., Wanninkof, R. (Eds.), American Geophysical Union, Washington, D.C doi:http://dx.doi.org/10.1029/GM127p0219.
Parish, D.D. (Ed). (2004). Intercontinental Transport and Chemical Transformation 2002 (ITCT-2k2) and Pacific Exploration of Asian Continental Emissions (PEACE) Experiments [Special Section]. Journal of Geophysical Research-Atmospheres, 109 (23).
Parish, D.D. (Ed). (2006). International Consortium for Atmospheric Research on Transport and Transformation (ICARTT): North America to Europe [Special Section]. Journal of Geophysical Research-Atmospheres, 111 (10–23).
Penkett, S.A., A. Volz-Thomas and D. D. Parrish (Eds). (1998). North Atlantic Regional Experiment (NARE II) [Special Section]. Journal of Geophysical Research-Atmospheres, 103 (D13).
Platt, U., J. Rudolph, T. Brauers, and G.W. Harris (Eds.). (1992). Polarstern Expedition [Special Issue]. Journal of Atmospheric Chemistry, 15 (3–4).
Prinn, R., 1994a. The interactive atmosphere: global atmospheric-biospheric chemistry. Ambio 23 (1), 50–61. http://www.jstor.org/stable/4314161.
Prinn, R.G. (Ed). (1994b). Global Atmospheric-Biospheric Chemistry. New York, NY. Springer Science+Business Media. ISBN 978-1-4613-6075-9.
Raes, F., Bates, T., McGovern, F., van Liedekerke, M., 2000. The 2nd aerosol characterization experiment (ACE-2): general overview and main results. Tellus 52B, 111–125.
Reeburgh, W.S., 1993. High Latitude Ecosystem as Sources and Sinks of Trace Gases (HESS). IGAC Core Project Office, MIT. USA, Cambridge, MA.
Rodhe, H. (Ed). (2000). The Second Aerosol Characterization Experiment (ACE-2) [Special Issue]. Tellus B, 52 (2).
Russell, P., P. Hobbs and L. Stowe (Eds.). (1999). Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) [Special Section]. Journal of Geophysical Research-Atmospheres, 104 (D2).
Sass, R.L., Neue, H.U., 1992. Rice Cultivation and Trace Gas Exchange (RICE). IGAC Core Project Office, MIT, Boston, MA, USA.
Sass, R.L., Neue, H.U., 1994. Global Measurement Standardization of Methane Emissions from Irrigated Rice Cultivation. IGAC Core Project Office, MIT, Cambridge, MA, USA.
Scholes, M.C., Matrai, P.A., Andrea, M.O., Smith, K.A., Manning, M.R., 1994. Biosphere-atmosphere interactions. In: Brasseur, G.P., Prinn, R.G., Pszenny, A.P. (Eds.), Atmospheric Chemistry in a Changing World. Springer, Heidelberg, pp. 18–71.
Shepson P., B. Sturges, E. Wolf (Eds.). (2007). Air Ice Chemical Interactions (AICI) [Special Issue]. Atmospheric Chemistry and Physics.
Shindell, D.T., Lamarque, J.-F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P.J., Lee, Y.H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W.J., Conley, A.J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S.T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J.-H., Lo, F., 2013. Radiative forcing in the ACCMIP historical and future climate simulations. Atmos. Chem. Phys. doi:http://dx.doi.org/10.5194/acp-13-2939-2013.
Smith, K.A., Robertson, G.P., 1992. Trace Gas Exchange: Mid-Latitude Terrestrial Ecosystems and the Atmopshere (TRAGEX). IGAC Core Project Office, MIT, Cambridge, MA, USA.
Smit, H.G.J., Kley, D., 1996. The Jülich ozone sonde intercomparison experiment (JOSIE). IGACtivities Newsl. (5), 4–7.
Smith, K.A., Robertson, G.P., Melillo, J., 1994. Exchange of trace gases between the terrestrial biosphere and the atmosphere at midlatitudes. In: Prinn, R.G. (Ed.), Global Amtospheric-Biospheric Chemistry. Plenum Press, New York, NY, pp. 179–302.
Smith, K.A., Bogner, J., 1997. Joint North American-European Workshop on Measurement and Modeling of Methane Fluxes from Landfills. IGAC Core Project Office, Cambridge, MA, USA.
Stohl, A., K. Law, J.W., Bottenheim, P. Monks and P. Quinn (Eds). (2009). POLARCAT (Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models of Climate, Chemistry, Aerosols, and Transport) [Special Issue]. Atmospheric Chemistry and Physics.
UNEP/WMO (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. UNON/Publishing Services Section/Nairobi, ISO 14001:2004.
Vet, R., Artz, R.S., Carou, S., Shaw, M., Ro, C.-U., Aas, W., Baker, A., Bowerbox, V.S., Dentener, F., Galy-Lacaux, C., Hou, A., Piennar, J.J., Gillett, R., Forti, M.C., Gromov, S., Hara, H., Khodzher, T., Mahowald, N.M., Nickovic, S., Rao, P.S.P., 2014. A global assessment of precipitation chemistry and deposition of sulphur, nitrogen, sea salt, base cations, organic acids, acidity and PH, and phosphorus. Atmos. Environ. doi:http://dx.doi.org/10.1016/j.atmosenv.2013.10.060.
WHO. (2014). WHO Mortality Data Base. http://www.who.int/healthinfo/mortality_data/en/.
Yu, H., M Chin, T., Yuan, H., Bian, L.A., Remer, J.M., Prospero, A., Omar, D., Winker, Y., Yang, Y., Zhang, Z. Zhang, and C. Zhao. (2015). The fertilizing role of African dust in the Amazon rainforest: A first multilayer assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. Geophysical Research Letters. 42, 6, 1984-1991. DOI: 10.1002/2015GL063040.
Zhu, T., M.L. Melamed, D., Parrish, M., Gauss, L. Gallardo Klenner, M., Lawrence, A. Konare, and C. Liousse (2012). WMO/IGAC Impact of Megacities on Air Pollution and Climate. Geneva, Switzerland: World Meteorological Organization (WMO). ISBN 978-0-9882867-0-2.