# IAGOS - In-service Aircraft for a Global Observing System

A. Petzold[*], A. Volz-Thomas
*Forschungszentrum Jülich GmbH (FZJ), Institute of Energy and Climate Research, IEK-8 Troposphere, Jülich, Germany*

V. Thouret, J.-P. Cammas
*Laboratoire d'Aérologie, CNRS, and Universite Paul Sabatier Toulouse III, Toulouse, France*

C.A.M. Brenninkmeijer
*Max Planck Institute for Chemistry, Mainz, Germany*

Keywords: Global monitoring, atmospheric observation, MOZAIC, CARIBIC

ABSTRACT: IAGOS is a new European research infrastructure which aims at constructing a global observation system for atmospheric composition by deploying autonomous instruments aboard a fleet of passenger aircraft. IAGOS builds on more almost 20 years of scientific and technological expertise gained in the research projects MOZAIC (Measurement of Ozone and Water Vapour on Airbus In-service Aircraft) and CARIBIC (Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container). The European consortium behind IAGOS includes research centres, universities, national weather services, airline operators and aviation industry. The two elements IAGOS-CORE and IAGOS-CARIBIC are complementary building blocks of one unique global atmospheric observation system. IAGOS-CORE deploys newly developed high-tech instrumentation for regular in-situ measurements of atmospheric chemical species ($O_3$, CO, $CO_2$, $CH_4$, $NO_x$, $NO_y$, $H_2O$), aerosols and cloud particles. Involved airlines ensure global operation of the network. In IAGOS-CARIBIC an extensively instrumented cargo container is operated as a flying laboratory aboard one aircraft. IAGOS provides data for users in science and policy including air quality forecasting, verification of CO2 emissions and Kyoto monitoring, numerical weather prediction, and validation of satellite products. It is considered a major contributor to the in-situ component of GMES Atmospheric Services. In combination with its predecessor programs MOZAIC and CARIBIC, IAGOS allocates long-term observation data of atmospheric chemical composition in the upper troposphere and lowermost stratosphere since 1994, while the most recent IAGOS-CORE aircraft went into service in 2011 and 2012.

## 1 RATIONALE

The largest uncertainties in our current knowledge on climate change are associated with the complex feedback mechanisms in the climate system, for example the amplification of the CO2-induced greenhouse effect by water vapour (Lacis et al. 2010), the effect of aerosol on cloud formation and cloud microphysics (Clarke; Kapustin 2010; Schwartz et al. 2010), the role of deep convection for transport of gases and aerosol particles into the UTLS, in particular over South-East Asia (Monsoon), and its behaviour within a changing climate (Randel et al. 2010), or the modification of biological cycles by climate change (Mahowald 2011) including feedbacks through biogeochemical and bio-geophysical processes which alter the sources and sinks of the greenhouse gases $CH_4$ and $CO_2$ (Friedlingstein et al. 2006). These uncertainties, in turn, imply large unknowns in predicting the future climate, especially at regional scales (Lenton 2011).

The atmospheric greenhouse effect is not confined to the lower atmosphere, but is largely driven by changes in the upper troposphere and the lower stratosphere (UTLS) (Riese et al. 2012). For instance, the small increase of water vapour in the stratosphere (by only ~0.8 ppm between 1980 and 2010) is likely responsible for 25% of the total anthropogenic greenhouse effect of ~0.5°C during this time (Solomon et al. 2010). Climate change also influences air quality by modifying atmospheric transport and weather patterns (Min et al. 2011) with impacts on air quality in Europe and other regions of the world due to long range transport of pollutants, ozone, and aerosol from growing economies (Monks et al. 2009).

In order to reduce the uncertainty of climate predictions, the models require input from measurements, both as boundary conditions and for the evaluation and improvement of parameterizations. Indeed, observational capacity is essential for all aspects of atmospheric research, including the assessment of causes for past changes as well as the prediction of further future changes and the economic and social consequences (e.g., IGACO 2004; IGCO 2004; Solomon et al. 2007). Also, pressing scientific issues require detailed long-term observations of atmospheric chemical composition on a global scale. Of highest scientific interest are data on greenhouse gases like $CO_2$, $CH_4$, and water vapour, reactive trace gases like ozone (being also a short-lived greenhouse gas) and nitrogen oxides, aerosol particles, and clouds.

## 2 IAGOS OBJECTIVES AND SCIENTIFIC VALUE

The European Research Infrastructure IAGOS (In-service Aircraft for a Global Observing System; www.iagos.org) responds to the increasing requests for long-term, routine in-situ observational data by using commercial passenger aircraft as measurement platforms. Table 1 summarises the objectives of IAGOS and the expected scientific value. Thus IAGOS closes the gap between space borne and ground based observations:

1. In the Tropopause Region: Most important for climate change, and dynamical processes (stratosphere-troposphere-exchange); hardly observable from space or from ground.
2. Vertical profiles in the troposphere: Essential for carbon cycle research, air quality, climate change, and weather prediction.

Table 1. Objectives and Scientific Value of IAGOS

| Objectives | Scientific Value |
|---|---|
| IAGOS-CORE<br>Routine atmospheric observation by 20 long-haul aircraft equipped with scientific instruments for:<br>- atmospheric chemical composition ($H_2O$, $O_3$, CO, $NO_x$, $NO_y$, $CO_2$, $CH_4$)<br>- aerosol number concentration and size<br>- cloud particle number concentration<br>Long-term deployment (20 yrs)<br>Global coverage<br>Open data policy (GMES/GEO/GEOSS)<br>Near real time data provision | Changes in the Tropopause Region<br>- high spatial and temporal resolution of in-situ observations<br>- ozone background and trend<br>- water vapour background and trend<br>Validation of Atmospheric Models and Satellite Retrievals<br>- tropospheric profiles of $H_2O$, $O_3$, CO, $NO_x$, aerosol, $CO_2$, $CH_4$, cloud particles<br>- UTLS data of $H_2O$, $O_3$, CO, $NO_x$, aerosol, $CO_2$, $CH_4$, cloud particles<br>Global Air Quality<br>- influence of developing regions<br>- long-range transport of air pollutants<br>- vertical transport of air pollutants by deep convection |
| IAGOS-CARIBIC<br>Monthly deployment of the instrumented CARIBIC Container:<br>- Large number of species (≅ 100), including those of IAGOS-CORE and VOCs, CFCs, aerosol chemical composition, $H_2O$ isotopologues, and $SO_2$ | International Transfer Standards<br>- use of proven measurement technology<br>- global deployment of same instruments<br>- regular Quality Assurance including calibration against reference instruments, based on GAW standard procedures |

Utilizing global aviation for routine atmospheric observation is cost efficient and makes optimum use of the existing infrastructure. By deploying a set of autonomous instruments aboard a fleet of passenger aircraft of internationally operating airlines, global data of atmospheric chemical composition in the upper troposphere and lower stratosphere are collected. In addition, vertical profiles of trace species are gained during each single landing of instrumented passenger aircraft. IAGOS is designed for global coverage and a lifetime of at least 20 years and will thus provide long-term, frequent, regular, accurate, and spatially resolved in-situ atmospheric observation data to the global scientific community.

## 3 HISTORY

The use of commercial aircraft for in situ observation of the atmosphere has a long history beginning in the 1970s when NASA implemented the Global Atmospheric Sampling Programme (GASP) during the period of March 1975 to July 1979. Parameters measured by the aircraft included various meteorological variables, ozone, carbon monoxide and particle densities, and flight information; for more information visit http://gcmd.nasa.gov/records/GCMD_NCAR_DS368.0.html. The historical evolution of this research area is described in detail in the IGAC Newsletter No. 37 (issued November 2007; www.igacproject.org).

IAGOS builds on almost 20 years of scientific and technological expertise gained in the research projects MOZAIC (Measurement of Ozone and Water Vapour on Airbus In-service Aircraft) and CARIBIC (Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container). The history of IAGOS and its predecessor programmes MOZAIC (www.iagos.org) and CARIBIC (www.caribic-atmospheric.com) is illustrated with more detail in Figure 1. In 1993, the idea of using commercial aircraft for atmospheric observation was revived with the European MOZAIC project in which airborne systems for ozone and water vapour were installed on five A340 aircraft (Marenco et al. 1998), with CO and $NO_y$ added in 2001. More than 35,000 flights have been completed since 1994 and three of the aircraft are still in service. CARIBIC started independently, using a measurement container aboard one Boeing 767 aircraft in 1997. To date, more than 230 ISI referenced publications have emerged from the programmes MOZAIC and CARIBIC.

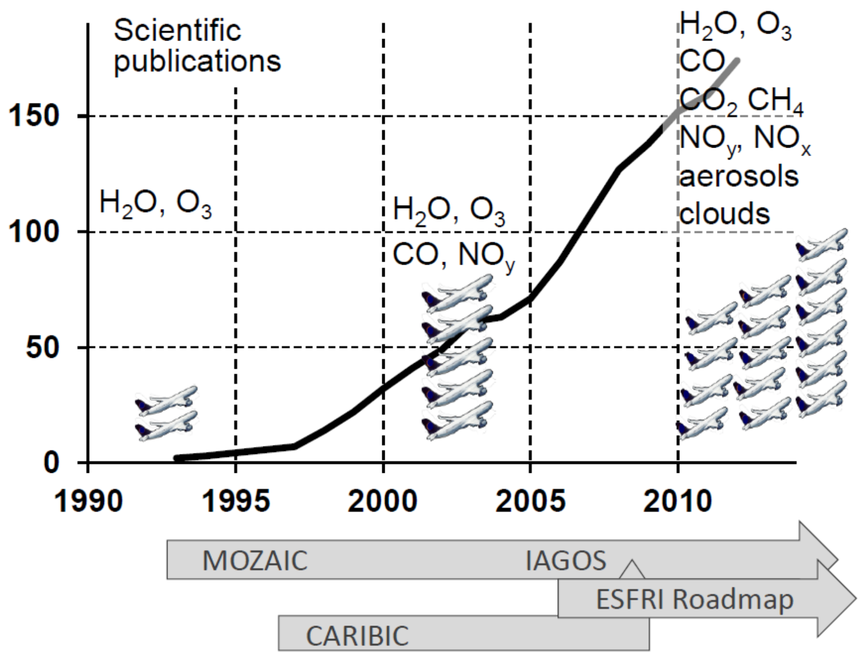


Figure 1. Evolution of airborne observations using instrumented passenger aircraft from programmes MOZAIC and CARIBIC to IAGOS; the graph shows the number of scientific publications from the MOZAIC data set whereas the aircraft represent the number of equipped units in operation. Observation parameters are indicated for the various evolution stages of the programme.

As part of the transformation process from MOZAIC to IAGOS which started in 2005, the set of observation parameters was significantly extended. Formerly separated programmes MOZAIC and CARIBIC have been merged into IAGOS which serves now as a single infrastructure designed for sustainable long-term and global operation (Volz-Thomas; IAGOS-team 2007; Volz-Thomas et al. 2009). The resulting infrastructure is built from two complementary approaches: The CORE component comprises the implementation and operation of autonomous instruments installed on up to 20 long-range aircraft of international airlines for continuous measurements of important reactive gases and greenhouse gases (e.g. carbon dioxide ,and methane and water vapour), as well as aerosol particles, dust and cloud particles. The fully automated instruments are designed for operation aboard the aircraft in unattended mode for several weeks and the data are transmitted automatically.

The complementary CARIBIC component consists of the monthly deployment of a cargo container equipped with instrumentation for a larger suite of components (Brenninkmeijer; CARIBIC-team 2007; Brenninkmeijer et al. 2007). It includes instruments that cannot yet be implemented in full routine operation for measuring, e.g., organic compounds or water vapour isotopologues. The installation combines instrumentation for in-situ measurements and remote sensing and the collection of air and aerosol samples (Andersson et al. 2013) for post-flight analysis in the laboratory. This dual setup of IAGOS should aims at providing global coverage of key observables on a day-to-day basis with a more complex set of observations with lesser reduced coverage. With its partners from leading research institutions in Germany, France, and the UK, IAGOS was successfully established on the roadmap of the "European Strategy Forum on Research Infrastructures" (ESFRI); and is listed among the ESFRI success stories; see ec.europa.eu/research/infrastructures.

## 4 IAGOS INSTRUMENTATION

The suite of instruments operated on board of IAGOS-CORE aircraft consists of one unit (Package 1), which measures ozone, water vapour, carbon monoxide and cloud particle number concentration, and is deployed on every aircraft. In addition, one option of a second unit (Package 2, option a-d), which targets specific species and properties such as nitrogen-containing compounds, greenhouse gases or aerosol particle properties, will be installed. The atmospheric trace species and properties measured by the IAGOS-CORE instrumentation and applied measurement techniques are compiled in Table 2. The fully equipped IAGOS-CORE instrument rack weighs approx. 120 kg and is mounted in the avionic bay of Airbus A340/A330 aircraft. Figure 2 shows a photograph of the first IAGOS-CORE aircraft operated by Lufthansa. Details on the extensive measurement techniques of CARIBIC are given by Brenninkmeijer et al. (2007) and the CARIBIC team (2007).


Figure 2. IAGOS-CORE installation position aboard the Lufthansa A340-300 "Viersen" (photograph by courtesy of A. Karmazin); the insert shows details of the IAGOS Inlet Plate which carries the inlet probes for trace gas sampling (photograph by courtesy of Lufthansa).

Table 2. IAGOS-CORE Instrumentation

| | | *Parameter* | *Method* | *TR** | *Precision* | *Responsibility/ Reference* |
|---|---|---|---|---|---|---|
| Package 1 | All aircraft | $O_3$ | UV absorption | 4s | ± 2ppb | CNRS (Thouret et al. 1998) |
| | | CO | IR Absorption | 15s | ± 5ppb | CNRS (Nédélec et al. 2003) |
| | | $H_2O$ | Humicap | 4-10s | ± 5% RH | FZJ (Helten et al. 1998) |
| | | Cloud Particles | Backscatter Probe | 4s | | Univ. Manchester, UK |
| Package 2 (1 option) | Opt. a | $NO_y$ | Chemiluminescence Gold converter | 4s | ± 50 ppt | FZJ (Volz-Thomas et al. 2005) |
| | Opt. b | $NO_x$ | Chemiluminescence Photolytic conversion | 4s | ± 50 ppt | FZJ |
| | Opt. c | Aerosol Particles | Condensation Particle Counter (0.01– 3µm)<br>Optical Particle Counter (0.25 – 3µm) | 4s | ± 10 $cm^{-3}$<br>± 5 $cm^{-3}$ | FZJ/DLR |
| | Opt. d | $CO_2$<br>$CH_4$<br>$H_2O$<br>CO | Cavity Ring-Down Spectroscopy | 4s | ± 0.1 ppm<br>± 2 ppb<br>± 6-15 ppm<br>± 10 ppb | Max Planck Institute for Bio-geochemistry, Jena, Germany |

* TR: Time resolution or data rate, whatever is longer

Table 3. IAGOS data set provided to GEOSS

| Parameter | MOZAIC | IAGOS CORE | CARIBIC Phase II |
|---|---|---|---|
| Ozone | 1994 | 2011 | 2004 |
| Water Vapour | 1994 | 2011 | 2004 |
| Carbon Monoxide | 2002 | 2011 | 2004 |
| Odd Nitrogen ($NO_y$) | 2001 | 2011 | 2004 |
| Nitrogen Oxides($NO_x$) | | 2011 | 2004 |
| Carbon dioxide | | 2013 | 2004 |
| Methane | | 2013 | 2004 |
| Aerosol number concentration and size | | 2013/2014 | 2004 |
| Cloud particle number concentration | | 2011 | |
| ~100 trace species | | | 2004 |

The data set which has emerged so far from the IAGOS project and its predecessor programmes is listed in Table 3. These data sets are freely accessible for the global scientific community on request via the IAGOS data base hosted by the French joint venture ETHER at www.iagos.fr/web. As an example for today's use, Figure 3 shows a statistical analysis of vertical profiles of CO over Frankfurt/Main, Germany, for February 2013. In-situ data are used for near-real-time validation of model results from the EU FP7 programme MACC (Monitoring Atmospheric Composition and Climate). Details on the applied models are given at www.iagos.fr/macc/nrt_day_profiles.php and links listed on this website.

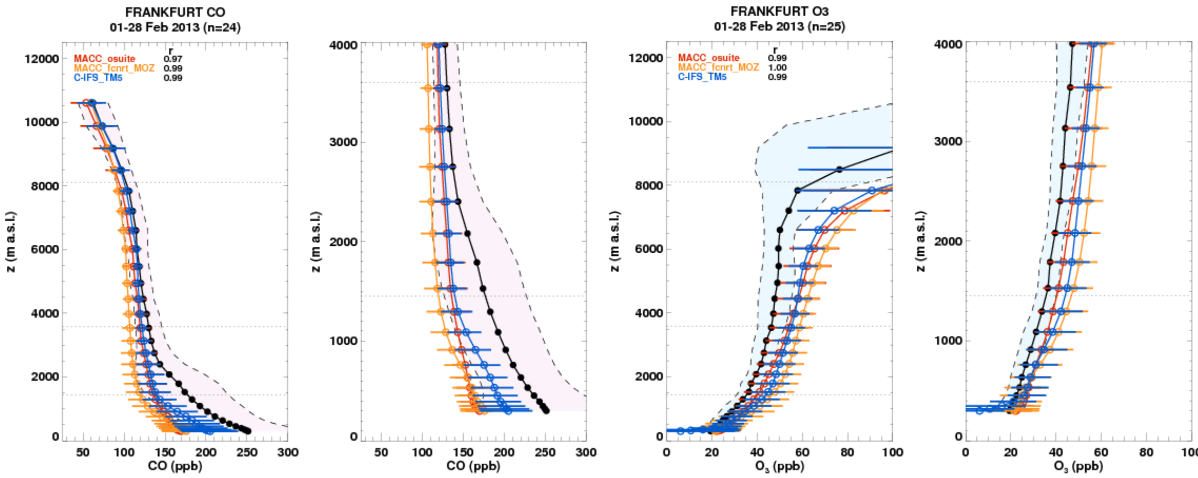


Figure 3. Average vertical profiles of CO and $O_3$ for Frankfurt/Main, Germany (black circles); coloured lines and symbols represent results from model analyses performed in the EU FP7 project MACC (Monitoring Atmospheric Composition and Climate). For details visit www.iagos.fr/macc/nrt_day_profiles.php.

## 5 THE IAGOS GLOBAL NETWORK

The IAGOS Global Network is built from components of the various contributing programmes. In 2010, the CARIBIC container was fully revised and recertified and returned into operation aboard Lufthansa A340-600 with a deployment of four flights per month. Destinations covered by CARIBIC are globally distributed with the majority of flights heading to North America and the Far East, and few directions to South Africa and South America. A map of recent destinations is accessible at www.caribic-atmospheric.com.

Also in 2010, instruments on the remaining three MOZAIC Airbus A340 aircraft went back into service. These aircraft are operated by Air Namibia (one aircraft) and Lufthansa (two aircraft).

IAGOS-CORE has started its operation with Lufthansa A340-300 “Viersen” in July 2011 out of Frankfurt Airport. The second Airbus A340 went into service in July 2012 and is operated by China Airlines from its home base Taipei, Taiwan. In 2013 instrument installations are scheduled for Air France and Iberia, and for an Airbus A330 operated by Cathay Pacific. Thus, by end of 2013 five aircraft will be equipped with IAGOS-CORE instruments. In addition, the CARIBIC aircraft, and three MOZAIC aircraft will be in operation. The emerging global network is illustrated in Figure 4.

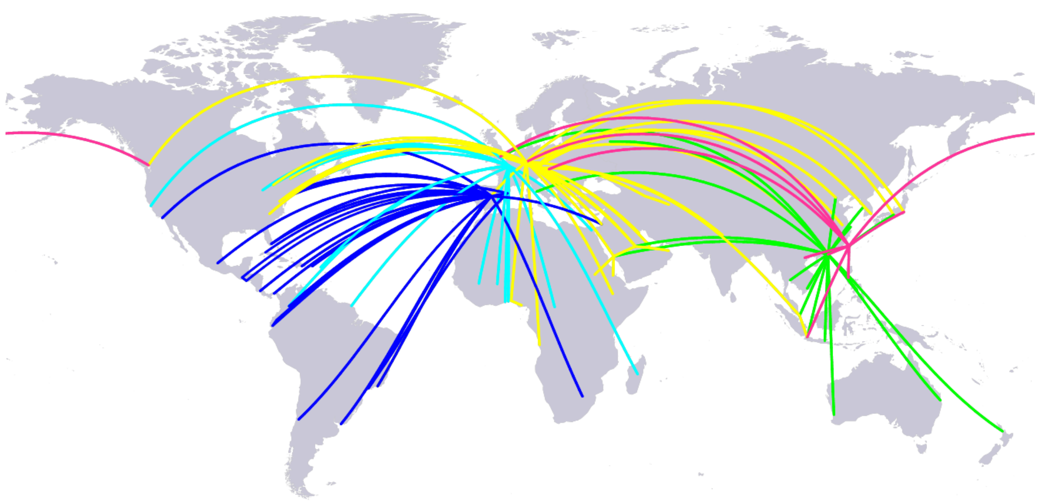

Figure 4. IAGOS-CORE Global Network 2013; coloured lines represent participating airlines Lufthansa (yellow), Air France (cyan), Iberia (blue), Cathay Pacific (green) and China Airlines Taiwan (magenta).

## 6 SUMMARY AND OUTLOK

Routine aircraft observations are providing valuable information on atmospheric composition that improve the understanding of global and regional air quality, as well as the potential impact of greenhouse gases on climate change. The comparability of measurements from an airborne monitoring network that collects data on a global scale by few identical systems with identical QA procedures, is inherently better than that from many stations operated by different institutions and using different instrumentation. . In that respect, routine aircraft observation could even provide useful information for harmonisation of different global networks.

IAGOS builds on previous European initiatives with novel technological developments and a strong emphasis to expand the network to the Pacific, North America and into the Southern Hemisphere. The success relies heavily on the willingness of airlines to support the operation. Besides contributing airlines Lufthansa, Air France, China Airlines, Cathay Pacific, and Iberia, South African Airlines has already expressed its interest in participating in the new IAGOS infrastructure. Discussions are also underway with US scientists to enable a partnership with IAGOS in the USA, in addition to expanding the NOAA network of small aircraft.

Sustainable operation of IAGOS has been addressed by securing a sustainable funding stream in the frame of international observing strategies such as GEOSS and its European component GMES, and from national funding institutions. Furthermore, a sustainable governance structure, which is currently in preparation, will be implemented by the end of year 2013 in order to ensure long term operation and continuous data provision from IAGOS.

## 7 ACKNOWLEDGMENTS

IAGOS gratefully acknowledges financial support during its preparation, implementation and operation phase from the European Commission in FP6 and FP7 programmes, national research programmes in Germany (BMBF), France (INSU-CNRS, MESR, CNES) and UK (NERC), in addition to institutional resources in Germany (Helmholtz Association, Max-Planck-Society, Leibniz Association), France (Université de Toulouse, Météo-France) and the UK (University of Manchester, University of Cambridge), and the continuing support by participating airlines.

## REFERENCES

Andersson, S. M., and Coauthors, 2013: Composition and evolution of volcanic aerosol from eruptions of Kasatochi, Sarychev and Eyjafjallajökull in 2008–2010 based on CARIBIC observations. *Atmos. Chem. Phys.*, **13,** 1781–1796.

Brenninkmeijer, C., and CARIBIC-team, 2007: The CARIBIC aircraft system for detailed, long-term, global-scale measurement of trace gases and aerosol in a changing atmosphere. *IGAC Newsletter*, **37,** 2-9.

Brenninkmeijer, C. A. M., and Coauthors, 2007: Civil Aircraft for the regular investigation of the atmosphere based on an instrumented container: The new CARIBIC system. *Atmos. Chem. Phys.*, **7,** 4953-4976.

Clarke, A., and V. Kapustin, 2010: Hemispheric Aerosol Vertical Profiles: Anthropogenic Impacts on Optical Depth and Cloud Nuclei. *Science*, **329,** 1488-1492.

Friedlingstein, P., and Coauthors, 2006: Climate-carbon cycle feedback analysis: Results from the (CMIP)-M-4 model intercomparison. *J. Climate*, **19,** 3337-3353.

Helten, M., H. G. J. Smit, W. Strater, D. Kley, P. Nedelec, M. Zoger, and R. Busen, 1998: Calibration and performance of automatic compact instrumentation for the measurement of relative humidity from passenger aircraft. *J. Geophys. Res.*, **103,** 25643-25652.

IGACO, 2004: Integrated Global Observing Strategy for the Monitoring of our Environment from Space and from Earth, 54 pp.

IGCO, 2004: Integrated Global Carbon Observation Theme - Executive Summary.

Lacis, A. A., G. A. Schmidt, D. Rind, and R. A. Ruedy, 2010: Atmospheric CO2: Principal Control Knob Governing Earth's Temperature. *Science*, **330,** 356-359.

Lenton, T., 2011: 2 degrees C or not 2 degrees C? That is the climate question. *Nature*, **473,** 7-7.

Mahowald, N., 2011: Aerosol Indirect Effect on Biogeochemical Cycles and Climate. *Science*, **334,** 794-796.

Marenco, A., and Coauthors, 1998: Measurement of ozone and water vapor by Airbus in-service aircraft: The MOZAIC airborne program, An overview. *J. Geophys. Res.*, **103,** 25631-25642.

Min, S. K., X. B. Zhang, F. W. Zwiers, and G. C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470,** 378-381.

Monks, P. S., and Coauthors, 2009: Atmospheric composition change - global and regional air quality. *Atmos. Environ.*, **43,** 5268-5350.

Nédélec, P., and Coauthors, 2003: An improved infra-red carbon monoxide analyser for routine measurements aboard commercial Airbus aircraft: Technical validation and first scientific results of the MOZAIC program. *Atmos. Chem. Phys.*, **3,** 1551–1564.

Randel, W. J., and Coauthors, 2010: Asian Monsoon Transport of Pollution to the Stratosphere. *Science*, **328,** 611-613.

Riese, M., F. Ploeger, A. Rap, B. Vogel, P. Konopka, M. Dameris, and P. Forster, 2012: Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *J. Geophys. Res.*, **117**.

Schwartz, S. E., R. J. Charlson, R. A. Kahn, J. A. Ogren, and H. Rodhe, 2010: Why Hasn't Earth Warmed as Much as Expected? *J. Climate*, **23,** 2453-2464.

Solomon, S., K. H. Rosenlof, R. W. Portmann, J. S. Daniel, S. M. Davis, T. J. Sanford, and G. K. Plattner, 2010: Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming. *Science*, **327,** 1219-1223.

Solomon, S., and Coauthors, 2007: *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of IPCC.* Cambridge University Press, 996 pp.

Thouret, V., A. Marenco, J. A. Logan, P. Nédélec, and C. Grouhel, 1998: Comparisons of ozone measurements from the MOZAIC airborne program and the ozone sounding network at eight locations. *J. Geophys. Res.*, **103,** 25695–25720.

Volz-Thomas, A., and IAGOS-team, 2007: In-service Aircraft for Global Observations – the future. *IGAC Newsletter*, **37,** 18-22.

Volz-Thomas, A., J.-P. Cammas, C. A. M. Brenninkmeijer, T. Machida, O. Cooper, C. Sweeney, and A. Waibel, 2009: Civil Aviation Monitors Air Quality and Climate. *EM Magazine, Air & Waste Manage. Assoc.***,** 16-19 (Oct. 2009).

Volz-Thomas, A., and Coauthors, 2005: Measurements of total odd nitrogen (NOy) aboard MOZAIC in-service aircraft: instrument design, operation and performance. *Atmos. Chem. Phys.*, **5,** 583-595.