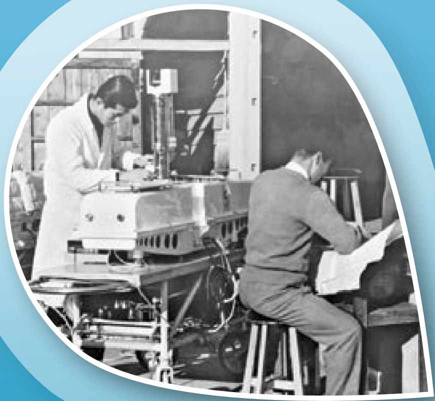
THE GLOBAL ATMOSPHERE WATCH PROGRAMME

25 YEARS OF GLOBAL COORDINATED ATMOSPHERIC COMPOSITION OBSERVATIONS AND ANALYSES



World Meteorological Organization

GLOBAL ATMOSPHERE WATCH

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Cover illustrations: The two photos show the changes in ozone observations from 1957 (International Geophysical Year) until now. On the left, Dobson instruments are being calibrated at the Tateno station in Japan before they are deployed to their individual stations. On the right, Dobson instruments have been set up for a modern intercomparison study. The spectrophotometers are the same, but the measurement and calibration process are now monitored by computers.

CONTENTS

1. HISTORY AND BACKGROUND

Scientific curiosity drove the early observation of atmospheric constituents. But those observations raised many questions: To what extent were the observed increases in certain trace chemicals connected to human activities? What human consequences would there be if the increase continued unabated?

In the 1950s, the World Meteorological Organization (WMO) launched a programme on atmospheric chemistry and the meteorological aspects of air pollution that transformed those early sporadic measurements into regular observations. The new programme soon determined that adequate gathering of such data – and analysis of its anthropogenic impact on a global scale – would require that all measurements be expressed in the same units and on the same scale, so that measurements performed by different countries could be comparable.

The first steps towards reaching this objective were made during the 1957 International Geophysical Year. The World Meteorological Organization began developing standard procedures for uniform ozone observations and established the Global Ozone Observing System (GO3OS), which involved ozonesonde intercomparisons, preparation of the ozone bulletins and ozone assessments, and support of the Ozone Data Centre in Toronto, Canada (later to become the World Ozone and Ultraviolet Radiation Data Centre). The Organization also coordinated the Dobson, and later Brewer, spectrophotometer network to measure total atmospheric ozone.

In the late 1960s, the Background Air Pollution Monitoring Network (BAPMoN) was established, focusing on precipitation chemistry, aerosol and carbon dioxide measurements. The Network included regional and background stations and a WMO World Data Centre in the United States of America.

During the 1970s, three important atmospheric issues were addressed: (i) the threat of chlorofluorocarbons (CFCs) to the ozone layer, (ii) the acidification of lakes and forests in large parts of North America and Europe, caused principally by the conversion of sulphur dioxide into sulphuric acid by precipitation processes in the atmosphere, and (iii) global warming caused by the build-up of greenhouse gases in the atmosphere. Each of these issues is now the subject of international treaties or conventions. The initial development of these agreements and the subsequent assessments of the mitigation measures they contain rely heavily on the information derived from the WMO atmospheric composition observations and analysis programme.

In 1989, the two observing networks, BAPMoN and GO3OS, were consolidated into the current WMO Global Atmosphere Watch (GAW) Programme. As the networks evolved and grew, so did the community involved in atmospheric composition observations and analysis.

Evolution of the GAW greenhouse gas community: group photos of the 1st meeting of greenhouse gas experts in the Scripps Institution of Oceanography, United States, in 1975 (this page) and the 17th meeting in Beijing, China, from 10–14 June 2013 (opposite page)

2. LONG-TERM OBJECTIVES AND APPLICATIONS

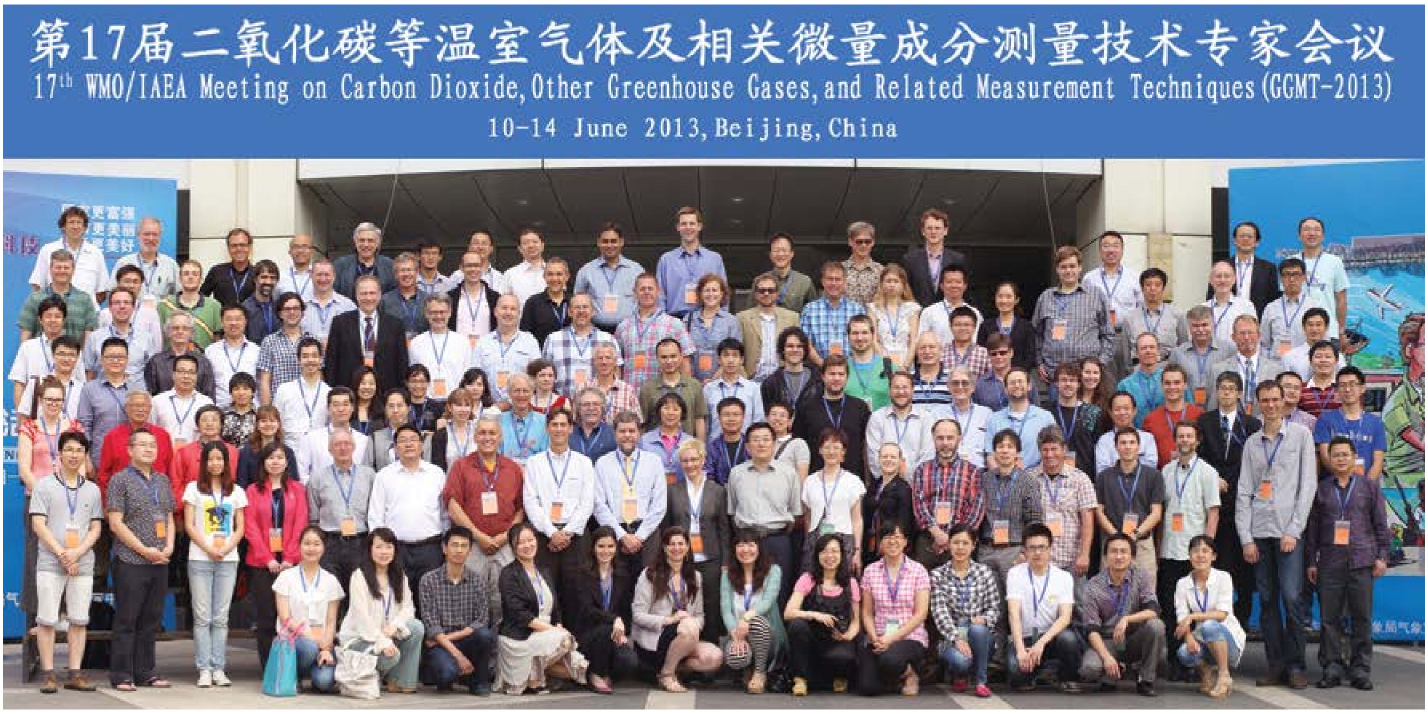
The GAW Programme is driven by the need to understand the variability and trends in the composition of the global atmosphere and the related physical parameters, and to assess the consequences thereof. The foremost challenges it needs to address are:

- Stratospheric ozone depletion and the increase of ultraviolet (UV) radiation
- Changes in the weather and climate related to human influence on atmospheric composition, particularly greenhouse gases, ozone and aerosols
- Risk reduction of air pollution on human health and issues related to atmospheric deposition and the long-range transport of air pollution

Many of these challenges have socio-economic consequences affecting weather, climate, human and ecosystem health, water supply and quality, and agricultural production. Advancing the scientific understanding to address these challenges remains critical. At the same time, GAW increasingly focuses on service delivery in a number of application areas where GAW data can provide important information. These application areas include:

- Assessment of the health impacts of air pollution through health indices
- Air quality forecasting
- Emission verifications using inverse modelling techniques
- Assessment of atmospheric composition changes and impacts on climate
- Eutrophication
- Ecosystem services
- Attribution of the sources of atmospheric species

The GAW Programme is implemented by WMO Members and supported by the international scientific community. Together, WMO Members and scientists around the world perform long-term observations of the chemical composition and selected physical characteristics of the atmosphere on a global scale, paying special attention to quality assurance and quality control of the data and providing integrated products and services of relevance to users.



3. ORGANIZATIONAL STRUCTURE

The GAW Programme addresses six classes of variables: ozone, UV radiation, greenhouse gases, aerosols, selected reactive gases and precipitation chemistry. For these variables, GAW acts as a "steward of global coordination", supporting all components needed for a rational observing system.

The organizational structure of the GAW Programme is outlined in Figure 1, which shows the various building blocks of the Programme.

1) The global observing networks that deliver high-quality measurements constitute the core of the Programme.

2) Observational data and data products are used in a number of applications, and support and contribute to other systems, programmes and research projects. Several data products are used to underpin international conventions.

3) Support for ensuring and controlling the quality of observations and for data and metadata management is provided by the institutions that act as GAW central facilities. They play different roles in the quality assurance system as described in section 5 and include Central Calibration Laboratories (CCLs), Quality Assurance/Science Activity Centres (QA/SACs), World Calibration Centres (WCCs), Regional Calibration Centres (RCCs), World Data Centres (WDCs) and the GAW Station Information System (GAWSIS).

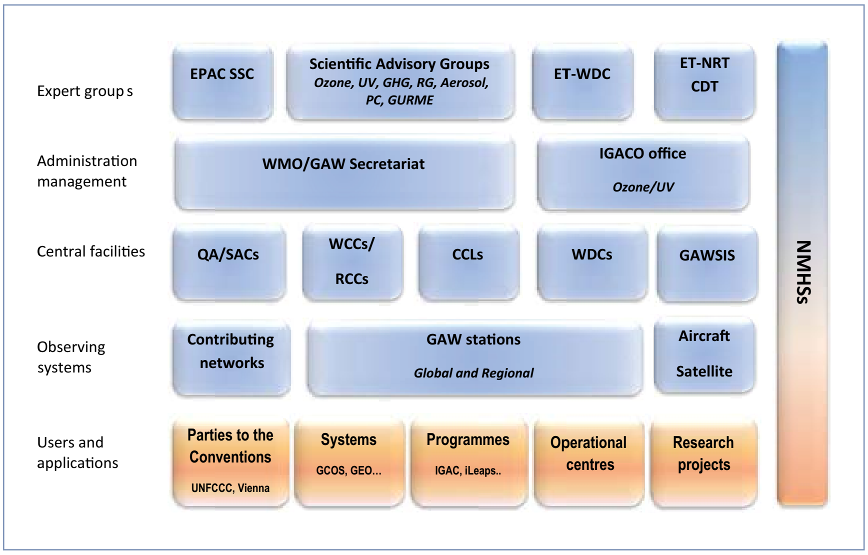
4) The Programme is administered and managed by the WMO Secretariat with the support of the Integrated Global Atmospheric Chemistry Observations (IGACO) office (for ozone- and UV-related issues).

5) General guidance of the Programme, its structural review, the selection of priorities, implementation and other leadership activities are conducted by the Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee (EPAC SSC) under the WMO Commission for Atmospheric Sciences (CAS). Each of the six GAW focus groups has a Scientific Advisory Group (SAG). An additional SAG exists for the GAW Urban Research Meteorology and Environment (GURME) project. Data exchange issues and near real-time chemical data delivery are coordinated by respective expert teams (the Expert Team on World Data Centres (ET-WDC), and the Expert Team on Near Real-time Chemical Data Transfer (ET-NRT CDT)).

The GAW activities are undertaken by WMO Members with a substantial contribution by National Meteorological and Hydrological Services (NMHSs). Many research institutes and universities contribute to and support the Programme with measurements and data analyses. The collaboration between NMHSs and academia is fundamental to the Programme's success.

Capacity development constitutes an important part of all GAW activities. It is organized within and across thematic groups and is coordinated by the WMO Secretariat.

Figure 1. Structure of the WMO Global Atmosphere Watch Programme



4. OBSERVATIONS

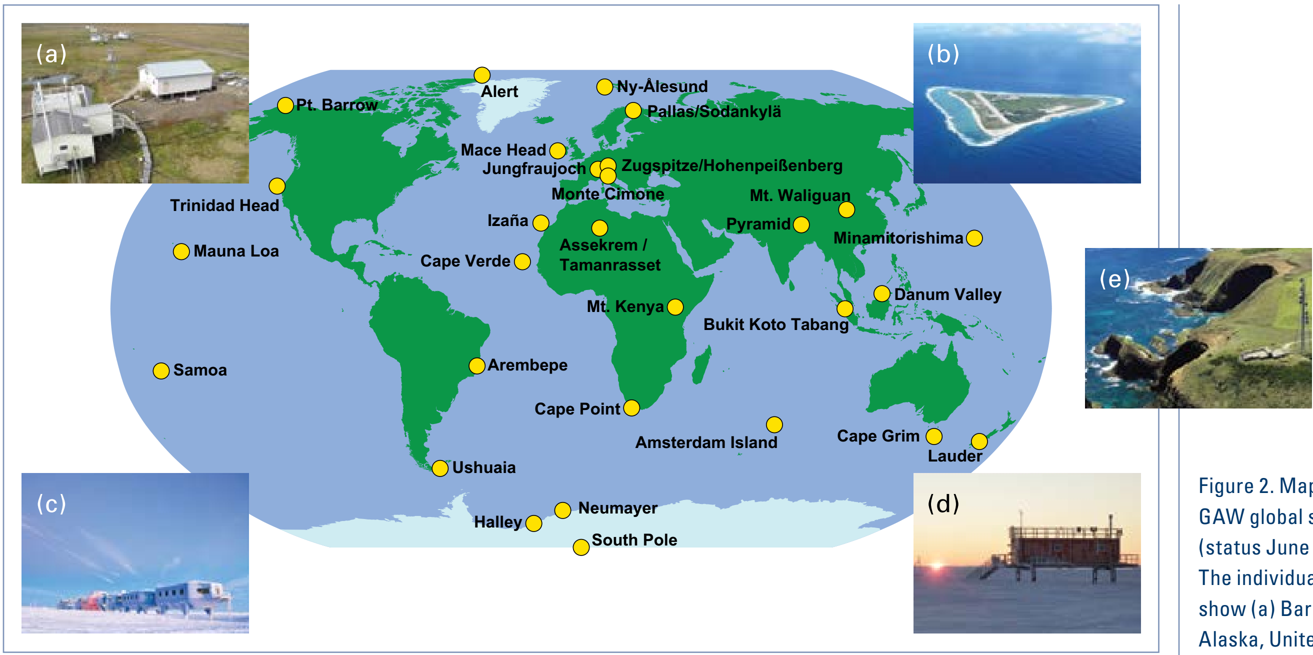


Figure 2. Map of the GAW global stations (status June 2014). The individual pictures show (a) Barrow, Alaska, United States, (b) Minamitorishima, Japan, (c) Halley station, Antarctica, United Kingdom of Great Britain and Northern Ireland (courtesy of Anthony Dubber), (d) Neumayer, Antarctica, Germany, and (e) Cape Grim, Australia.

The **surface-based observational network** comprises global and regional stations operated by WMO Members. These stations are complemented by various contributing networks. In 2014, GAW coordinated activities and data from 29 global stations (see Figure 2), more than 400 regional stations, and around 100 stations operated by contributing networks. All observations are linked to common reference standards and the observational data are made available in the designated World Data Centres. Observations at the GAW stations are performed using in situ methods and surface-based remote-sensing techniques. Examples of the contributing networks that use remote-sensing techniques are the Total Carbon Column Observing Network (TCCON, https://tccon-wiki.caltech.edu/), the individual networks contributing to the GAW Aerosol Lidar Observation Network (GALION, see GAW Report No. 178) and the Network for the Detection of Atmospheric Composition Change (NDACC, http://www.ndsc.ncep.noaa.gov/). Information about GAW stations and contributing networks is summarized in the GAW Station Information System (http://gaw.empa.ch/gawsis/).

Surface-based observations are increasingly complemented by **airborne and space-based observations**, which help to characterize the upper troposphere and lower stratosphere, in particular with regards to ozone, solar radiation, aerosols and certain trace gases. High-frequency and wide-ranging CO_2 data have been obtained by continuous-measuring equipment as part of the Comprehensive Observation Network for Trace gases by Airliner project (CONTRAIL, http://www.cger.nies.go.jp/contrail/) using commercial passenger aircraft. The CO_2 data collected by air sampling equipment between Australia and Japan since 1993 are available at the World Data Centre for Greenhouse Gases, based in Tokyo. The In-service Aircraft for a Global Observing System (IAGOS) project is another aircraft-based contribution to the global observation of atmospheric composition. It is setting up a network of commercial aircraft using small instrumented packages on board of civil aircraft. The project deploys newly developed high-tech instruments for regular in situ measurements of atmospheric chemical species (ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), reactive nitrogen (NOy), nitrogen oxides (NOx) and water vapour (H_2O)), aerosols and cloud particles. The project, recognized as a European Research Infrastructure, builds on the scientific and technological experience gained within the Measurement of Ozone and Water Vapour on Airbus In-service Aircraft (MOZAIC) project and the Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container (CARIBIC) project. A number of national aircraft campaigns (operated, for instance, by the US National Oceanic and Atmospheric Administration (NOAA), the Japan Meteorological Agency and by Brazil) also contribute to the GAW observational network.

5. QUALITY ASSURANCE

The primary objectives of the GAW quality assurance system are to ensure that the data in the World Data Centres are consistent, of known and adequate quality, are supported by comprehensive metadata and are sufficiently complete to describe the global atmospheric state with respect to spatial and temporal distribution. High-quality observational data are required to provide reliable information to policymakers and to ensure confidence in the broader data use in different applications.

Implementation of the quality assurance system requires that all aspects of atmospheric chemistry observations are addressed, including training of station personnel, assessment of infrastructures, operations and the quality of observations at the sites, documentation of data submitted to the World Data Centres as well as improved quality and documentation of legacy data at the WDCs.

Five types of central facilities are operated by WMO Members and form the basis of quality assurance and data archiving for the GAW global observational network. Each of the central facilities is associated with one of the six groups of measurement variables. Central facilities are organizations or laboratories that play a particular role in the quality assurance of the network, although individual GAW stations and laboratories implement local quality assurance systems as well. One of the requirements within GAW is the traceability of all stations and labs to one network standard. Hence, all contributors to GAW are required to have the same set of reference materials (such as reference gases). If such reference materials are not available, comparisons are conducted to compare artificially created samples prepared by dedicated laboratories (such as for precipitation chemistry), or instrumental comparisons are performed using reference observational methods.

The concept of the GAW quality assurance system is presented in Figure 3. The set of central facilities supporting this system includes Central Calibration Laboratories that host primary standards, Quality Assurance/Science Activity Centres that coordinate activities of other central facilities in countries, regions or within the thematic group, World Calibration Centres and Regional Calibration Centres that assist GAW stations to ensure the traceability

Central Analytical Laboratory for precipitation chemistry, Illinois State Water Survey, University of Illinois at Urbana-Champaign, United States

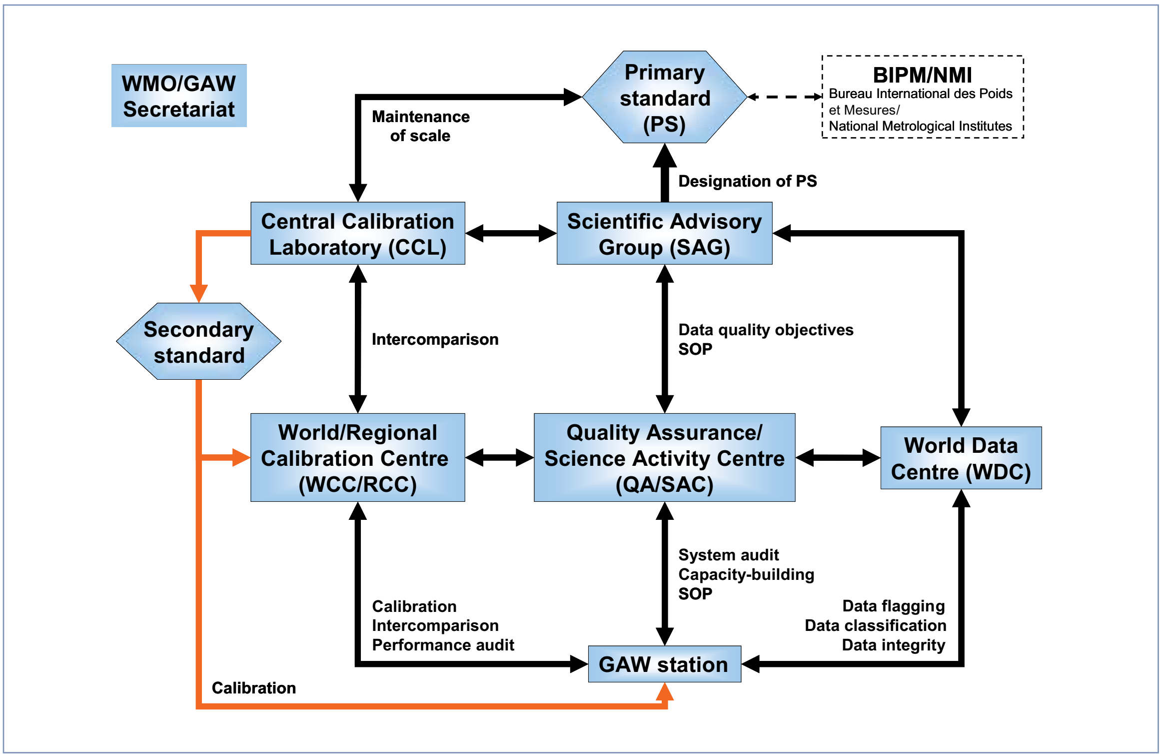


Figure 3. Conceptual GAW quality assurance system

of their observations to primary standards, and World Data Centres which are responsible for archiving and providing access to GAW data. The World Meteorological Organization collaborates with the International Bureau of Weights and Measures (BIPM) on the development of several primary standards. The Scientific Advisory Groups coordinate the implementation of quality assurance systems within thematic groups with support from the WMO Secretariat Research Department.

A comprehensive list of the GAW central facilities is available at http://www.wmo.int/pages/prog/arep/gaw/gaw_cent_facil.html.

The GAW quality assurance system operates under the following principles:

- Network-wide use of only one reference standard or scale (primary standard)
- Full traceability to the primary standard of all measurements made by global and regional stations and contributing networks
- Definition of data quality objectives
- Establishment of guidelines on how to meet these quality targets, that is, harmonized measurement techniques based on measurement guidelines and standard operating procedures (SOPs)
- Accurate and detailed documentation of all measurements using station logbooks containing comprehensive metadata related to the measurements, maintenance and "internal" calibrations
- Regular independent assessments (system and performance audits)
- Timely submission of data and associated metadata to the responsible World Data Centre as a means of permitting independent review of data by a wider community

To ensure network compatibility, World Calibration Centres for different GAW variables regularly perform site audits, global and regional round-robin comparisons and intercomparison campaigns. Some results of comparison campaigns are presented in this brochure.

Long-term education, training, workshops, calibration station audits/visits and twinning between stations are also provided to build capacities in atmospheric sciences within the GAW network. These capacity-building activities are of increasing importance as many GAW stations in developing countries have become operational. The GAW Training and Education Centre (GAWTEC) at the Schneefernerhaus in Germany provides an important contribution in the training of station personnel.

6. FOCAL AREAS

6.1 OZONE

6.1.1 The importance of ozone

Stratospheric ozone depletion, which leads to increased intensity of harmful solar ultraviolet radiation at the Earth's surface, stimulated important scientific activities in the 1980s and 1990s, leading to the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments. Recently (in the late 2000s) the measures taken in the frame of this international agreement proved to be successful in reducing the production and consumption of ozone-depleting substances. The abundances of these substances in the atmosphere have started to decline for most of the concerned compounds, and this will ultimately lead to the recovery of the ozone layer. Ozone is directly linked with climate because it absorbs solar radiation and is a greenhouse gas, but also indirectly because ozone-depleting substances and their substitutes are greenhouse gases. The depletion of ozone in the stratosphere and the global increase in tropospheric ozone have opposing contributions to climate change. An example of the total ozone evolution during the ozone depletion season is shown in Figure 4.

6.1.2 Monitoring of ozone under the Global Atmosphere Watch Programme

Measurements of total ozone are performed within the GAW Programme by Dobson spectrophotometers (designed for manual operation) and Brewer spectrophotometers (designed for automatic operation), thus providing two independent networks. A separate contribution is made by the Russian Federation and some other countries, which operate filter instruments. An important aspect of the GAW implementation strategy is to support capacity-building for ozone monitoring and research in developing countries and countries with economies in transition, following the general commitments anchored in the Vienna Convention for the Protection of the Ozone Layer. In this context, GAW coordinates the relocation and refurbishing of instruments to these countries from stations that ceased operation, and training of local personnel in operational and calibration procedures.

The vertical distribution of ozone is measured either in situ with ozonesondes carried by small balloons, or remotely from the ground by lidars, microwave radiometers and Umkehr inversions of data measured by ozone spectrophotometers

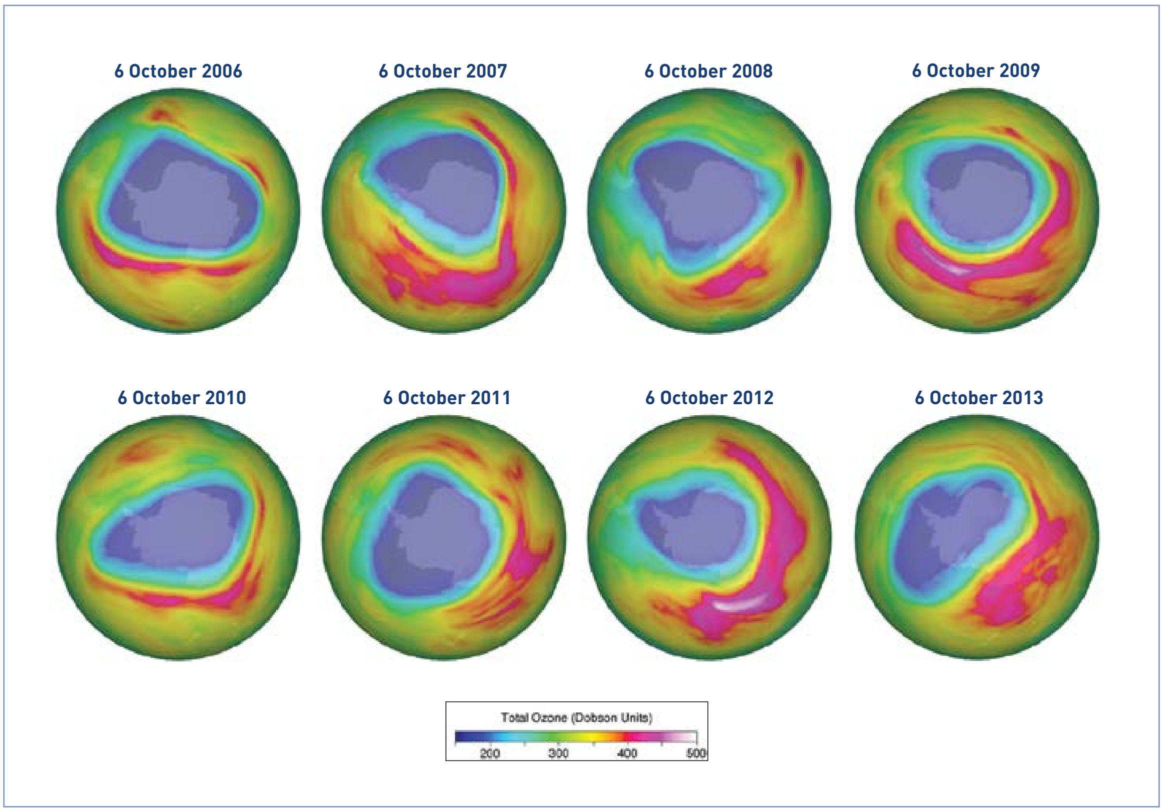


Figure 4. Total ozone maps for 6 October 2006 to 2013 based on data from the Ozone Monitoring Instrument on board the Aura satellite. The data are processed and mapped at the Royal Netherlands Meteorological Institute (KNMI).

Figure 5. Antarctic ozone observations used in the preparation of the ozone bulletins

(Dobsons and Brewers). Ozonesonde stations operate worldwide, thus providing a sufficient coverage particularly in areas of scientific interest like Antarctica and the tropics.

Quality assurance is maintained through intercomparisons and laboratory experiments. Recently, about 30 stations with records of more than 25 years have been reassessed and homogenized. Lidars provide the ozone profiles in the upper atmospheric layers, typically in the altitude range of 10–50 km, while microwave radiometers measure in the range of 20–70 km. The Umkehr provides estimates of the mean concentration of ozone at a few layers.

Data from ground-based networks are used to support the Scientific Assessment of Ozone Depletion reports, prepared jointly by WMO and the United Nations Environment Programme. These reports, published every four years, assess the science and status of the ozone layer. In addition, ground-based ozone observations are important for the validation of satellite-derived ozone data and for ensuring the continuity among different satellite missions. Finally, an important exploitation of the network data is the dissemination of near real-time ozone maps, a service which is provided by several institutions, such as the National Aeronautics and Space Administration (United States), the Royal Netherlands Meteorological Institute, the German Aerospace Centre and the European Organization for the Exploitation of Meteorological Satellites. Near real-time observations from Antarctic stations, shown in Figure 5, are used to prepare the Antarctic ozone bulletins.

6.1.3 Quality assurance of measurements

The quality of network ozone data is ensured through the GAW World Calibration Centres and Regional Calibration Centres. The main tasks of the calibration centres are to link observations

Photo taken the morning of 30 March 2006 during the Sodankylä Total Column Ozone Intercomparison I campaign in Sodankylä, Finland. Temperature was around –26 °C.

to world reference standards and to ensure network comparability and compatibility through intercomparison campaigns and regular audits. For the network of Dobson spectrophotometers, the primary standard instrument (Dobson #83) is maintained by the National Oceanic and Atmospheric Administration at the Mauna Loa Observatory in Hawaii, United States, while for the network of Brewer spectrophotometers, the primary standard is the Brewer triad maintained by Environment Canada in Toronto, Canada. Regional Calibration Centres support the intercomparison campaigns and the regular transfer of calibration to network instruments.

6.2 GREENHOUSE GASES

The WMO GAW long-lived greenhouse gas (LLGHG) measurement community is largely a research community. High-quality measurements of LLGHGs and related tracers can be used to:

- Estimate the trends of these substances and the relation between such trends and the changes in radiative forcing
- Constrain global and large-scale budgets
- Estimate or verify regional and continental scale emissions based on spatial gradients

The Global Atmosphere Watch Programme provides a framework to ensure the quality of these measurements through:

- Meetings of measurement experts every two years
- Detailed recommendations on measurement compatibility selected to meet scientific requirements
- Publication of measurement guidelines

An important aspect of the GAW framework is that all GAW participants focusing on greenhouse gases are asked to use standards to calibrate their analytical instruments derived from Central Calibration Laboratories that maintain common standard scales. Other central facilities help ensure the quality of measurements through standard and measurement comparisons and site audits.

GAW networks for measurements of three essential climate variables – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – are recognized as the Global Climate Observing System (GCOS) Global Baseline Observing Network and the Global Comprehensive Observing Network. While these GCOS networks normally fall within operational regimes of the agencies involved, GAW greenhouse gas observations are driven almost entirely by research needs. Long-lived greenhouse gases are the main drivers of climate change, and long-term GAW observations, shown in Figure 6, are used to calculate radiative forcing as shown in Figure 7. Since 1990, CO_2 has been the largest contributor to the increase in radiative forcing, contributing 80%. It is followed by N_2O at 7.5%, replacements of ozone-depleting substances at 6.5% and CH_4 at 5%. Despite their declining atmospheric abundances in recent years, the sum of the radiative forcing from trichlorofluoromethane (CFC-11) and dichlorodifluoromethane (CFC-12) has increased by 1% since 1990.

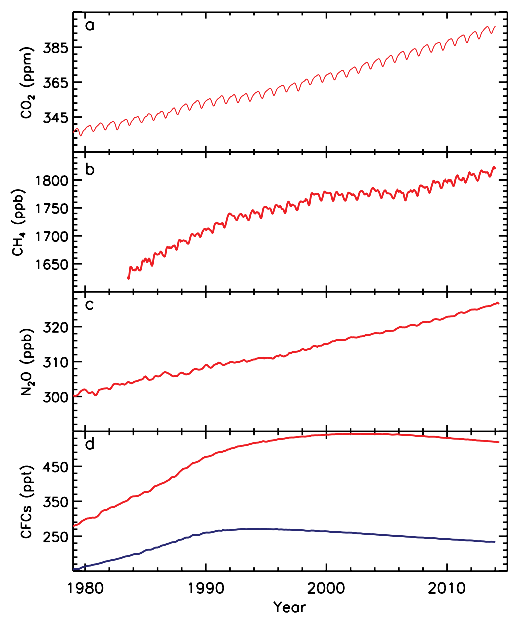


Figure 6. Time series of the five LLGHGs (monthly mean global averaged) that have contributed >95% of radiative forcing since 1750. In panel (d), CFC-11 is in blue and CFC-12 is in red.

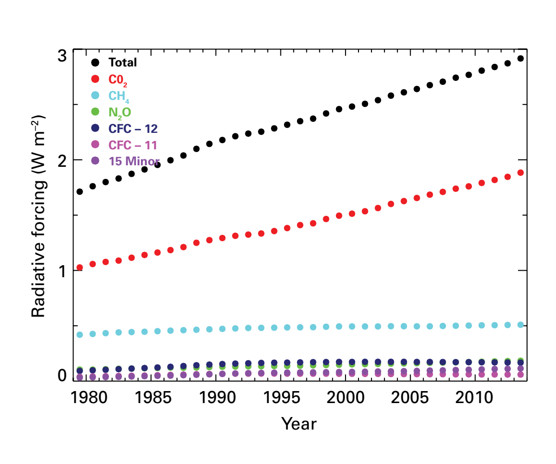


Figure 7. Increase in radiative forcing by LLGHGs since 1750, plotted for 1979 to 2013. Carbon dioxide is the largest contributor to total radiative forcing by LLGHGs, and it is the dominant contributor to the trend in radiative forcing since 1990. *(Source: NOAA Annual Greenhouse Gas Index; http://www.esrl.noaa.gov/gmd/aggi/)*

Measurements of greenhouse gases by GAW members can be used in a mass-balance analysis to provide an important constraint on global emissions when a lifetime can be defined. This approach is not as effective for atmospheric CO_2, which rapidly exchanges with the terrestrial biosphere and surface ocean. However, for gases that are predominantly removed by atmospheric chemistry (for instance, reaction with hydroxyl radical (OH) and photolysis), knowledge of their lifetimes can be used to estimate emissions. A simple example is sulphur hexafluoride (SF_6), which is destroyed predominantly by photolysis and reactions with electrons in the mesosphere and has an estimated atmospheric lifetime of 3 200 years. With the long lifetime, the atmospheric rate of increase is directly related to emissions and can be used to verify emission inventories. Using atmospheric measurements, Levin et al. (2010) showed that emissions reported to the United Nations Framework Convention on Climate Change (UNFCCC) were underestimated by 70% to 80% (Figure 8). Developed nations (which make up Annex I of the Framework, in essence) are significantly underestimating their emissions. This emphasizes the need for estimates of emissions to be verified by direct atmospheric measurements (Nisbet and Weiss, 2010).

Since atmospheric mixing is not instantaneous, the observed spatial patterns in LLGHGs can be combined with a chemical transport model to estimate emissions at continental to country scales. The quality of the emission estimates depends on the compatibility (internal consistency) of the measurements used. Artificial gradients

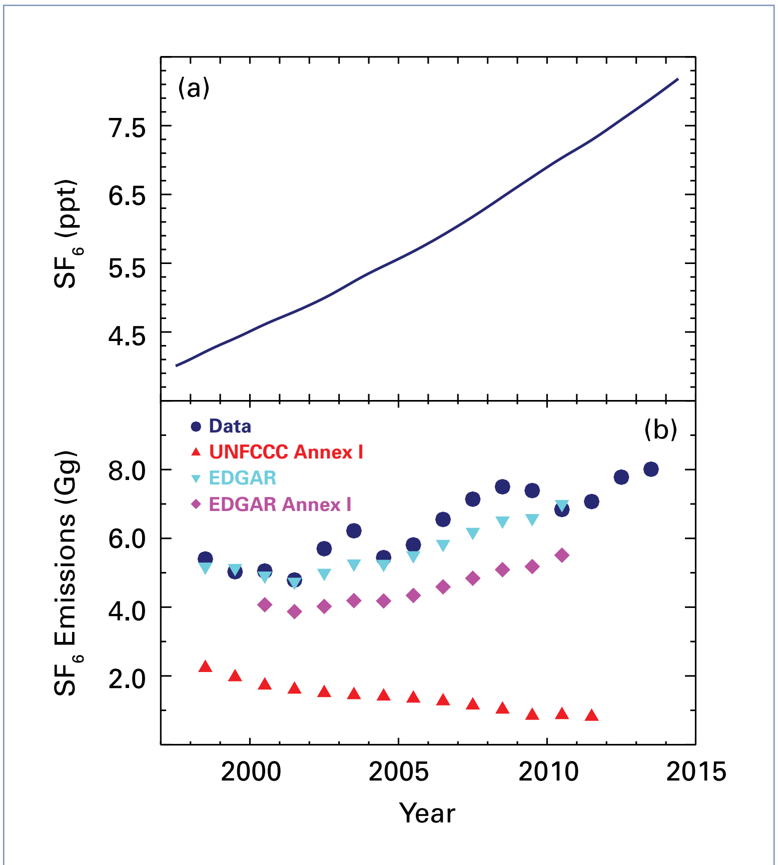


Figure 8.
(a) Globally averaged SF_6 mole fractions determined from GAW measurements;
(b) Comparison of the annual observation-inferred global SF_6 emissions (blue circles), the global emissions estimated by the Emissions Database for Global Atmospheric Research (EDGAR) (cyan triangles), the emissions reported by the nations listed in Annex I to the UNFCCC (red triangles) and the emissions reported by the nations listed in UNFCCC Annex I as estimated in EDGAR (purple diamonds) *(Source: Levin et al., 2010)*

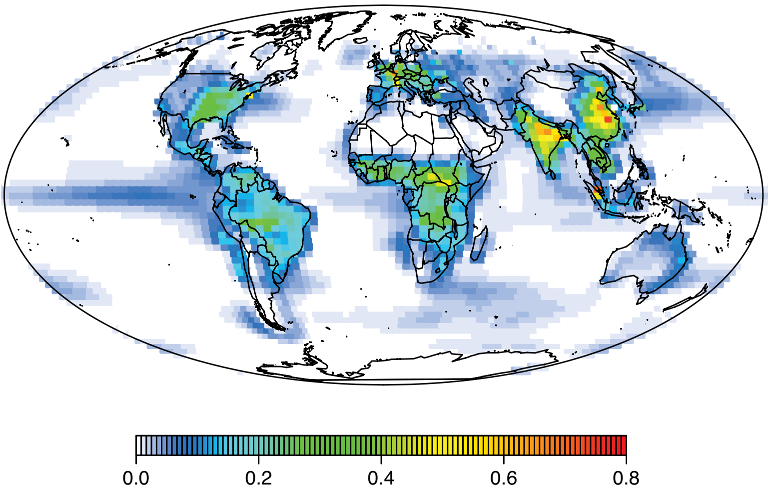


Figure 9. Annual mean N_2O flux (g m^{-2} yr^{-1} N) averaged over 1999–2012 determined from GAW N_2O observations and a chemical transport model *(Source: Thompson et al., 2014)*

resulting from some laboratories using different standards than others will result in errors in emissions. This is especially true for N_2O, which has relatively small, very diffuse emissions and a 130-year lifetime. The pole-to-pole gradient at background sites for N_2O is approximately 1.4 parts per billion. With traditional analytical methods, it is extremely difficult to reach the required compatibility of the network to detect this small spatial gradient. In a model study by Thompson et al. (2014), data were used from GAW partners and contributors to estimate global fluxes. These estimates are shown in Figure 9 in grams per metre squared per year of nitrogen (g m^{-2} yr^{-1} N). The largest source of N_2O is from natural and fertilized soils, which is reflected in the flux map. Similar studies have estimated emissions of CH_4 and other LLGHGs.

Further importance of GAW's long-term high-quality LLGHG measurements is seen in the time series for CH_4 in Figure 6, panel (b). The stabilization of the global atmospheric CH_4 burden from 1999 to 2006 was unexpected. It contradicted the estimates derived from trends in bottom-up emission inventories, which indicated that emissions were increasing. While the specific changes to methane's global budget of emissions and sinks responsible for this stabilization are still under discussion, without high-quality GAW measurements from a globally distributed network of air sampling sites, we may have missed this surprising development.

6.3 REACTIVE GASES

From the viewpoint of an atmospheric chemist, the atmosphere is a huge reactor where many different molecules that are present in tiny amounts undergo a multitude of chemical reactions. A remarkable feature of the atmosphere is its ability to cleanse itself of air pollutants often via oxidation reactions which transform harmful air pollutants into other, more soluble substances that can then be removed from the atmosphere through rainfall or deposition. Some atmospheric reactions, however, lead to the formation of secondary air pollutants such as ozone, peroxyacetyl nitrate (PAN) or aerosols. Reactive gases and aerosols can have adverse effects on human health, the environment and materials. Atmospheric chemical reactions have a direct impact on the climate system, for example by controlling the chemical lifetime of greenhouse gases such as methane or nitrous oxide or the abundance of tropospheric ozone, itself a greenhouse gas. Through their interaction with plants and their involvement in aerosol and cloud formation, reactive gases also exert indirect effects on the climate system. In contrast to long-living greenhouse gases (for example CO_2), the effects of reactive gases show strong regional variations, and regional measures to curb air pollution offer a means to potentially slow the rate of climate warming. Some of these complex chemical interactions are shown in Figure 10. Thus, reactive gases are an essential component of the understanding of both air quality and climate change.

Within the GAW Programme, a substantial number of reactive gas compounds are being measured at a diverse range of locations around the world. The focus of the activities

GAW global station Hohenpeissenberg, Germany, providing ozone time series since 1971 and continuous meteorological observations since 1781

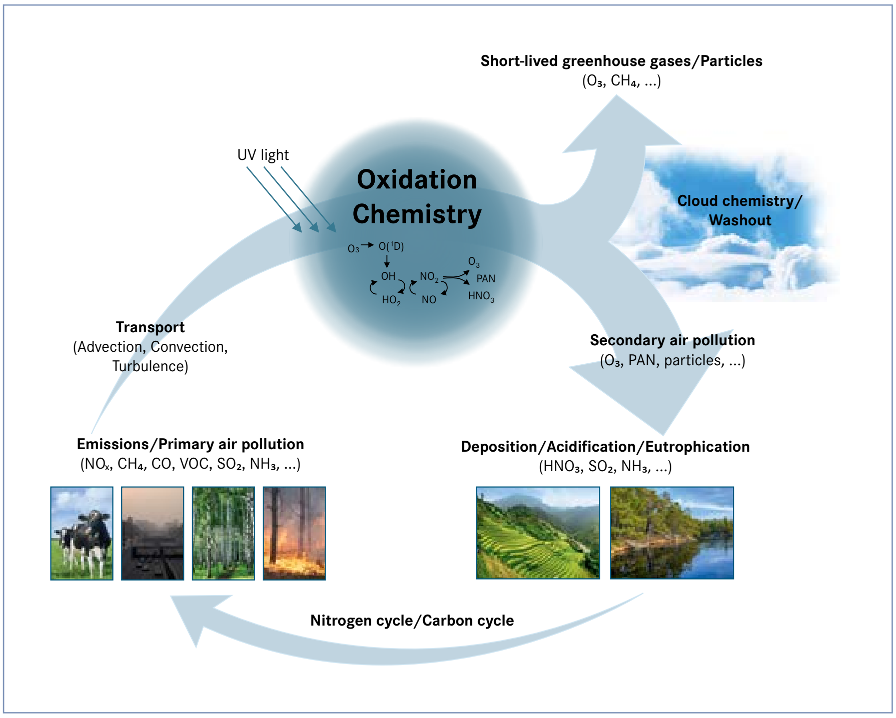


Figure 10. Atmospheric chemistry processes and their relation to air quality and climate change *(Courtesy of M. Schultz)*

is on tropospheric ozone and its precursor substances. Ozone was first observed in the nineteenth century. Current ongoing observations started at a very small number of sites in the early 1970s, for example at the GAW global station Hohenpeissenberg, Germany, at Barrow, Alaska, United States, and at Mauna Loa, Hawaii, United States. After GAW was initiated in 1989, the number of stations in the global network of surface ozone measurements grew rapidly, and surface ozone is now measured and reported from some 100 stations worldwide. The GAW network is the primary source of information on changes of atmospheric composition on a global scale, with a long-term vision and a globally uniform quality control. Monitoring the background levels of reactive gases is essential for understanding long-range transport processes, which in turn is crucial for assessing the success of regional to local emission reduction activities. Data from GAW are supplemented by a number of regional air pollution networks and national air pollution monitoring activities. Figure 11 presents a snapshot of monthly mean surface

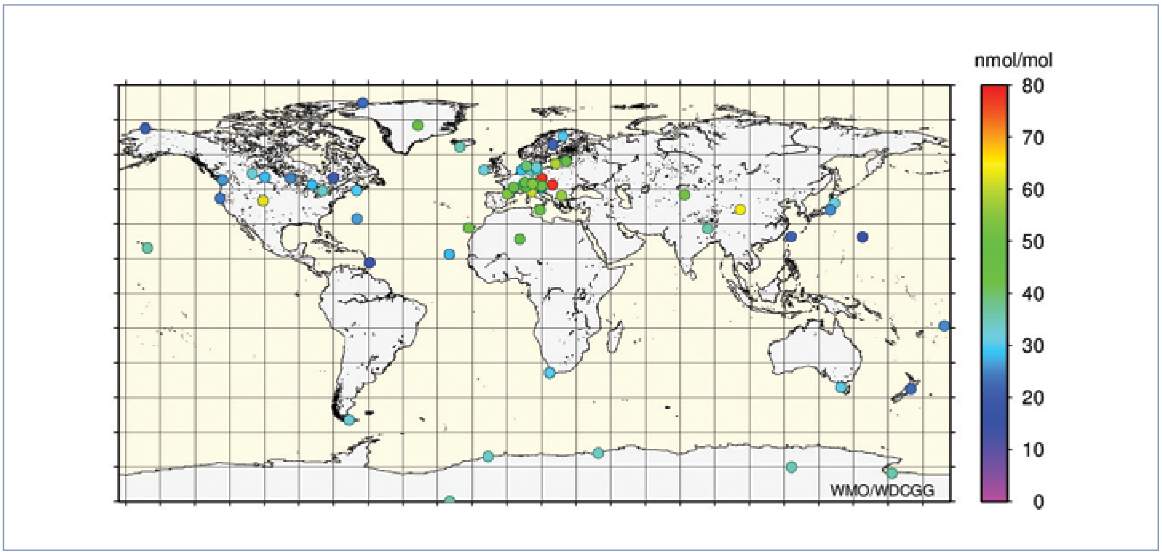


Figure 11. Map of monthly mean surface mole fractions of ozone for July 2008 as measured by the stations in the GAW network and archived at the World Data Centre for Greenhouse Gases (WDCGG).

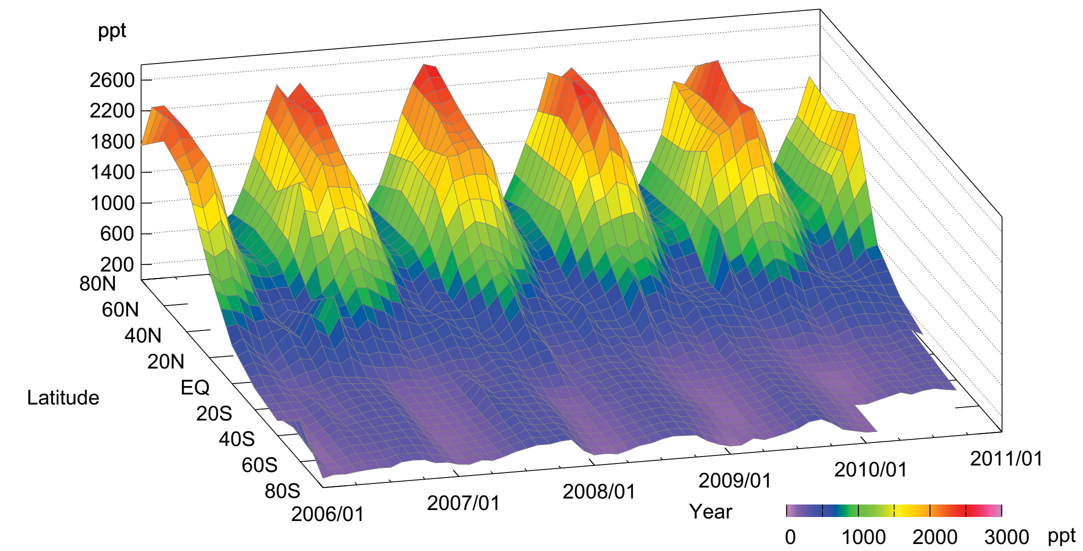


Figure 12. Monthly mean latitudinal variation of ethane from the global reactive gases measurements in the GAW network *(Source: World Data Centre for Greenhouse Gases)*

ozone concentrations from the GAW network in July 2008. This clearly demonstrates the capabilities of GAW to provide a global perspective on surface ozone, even though large areas of the map remain uncovered.

Carbon monoxide has been a key measurement within the GAW reactive gases programme, since it is both a contributor to, and a by-product of, many atmospheric reactions. It is also an excellent tracer of atmospheric emissions and transport. A reasonably good coverage of continuous CO observations has been available since the mid-1990s. Over the last 20 years, a slight negative global CO trend can be observed as a result of the reduction of anthropogenic emissions; however, CO concentrations feature a strong year-to-year variability driven by the extent of biomass burning. More recent additions to the GAW Programme are nitrogen oxides (NO and NO_2), sulphur dioxide (SO_2) and a number of key volatile organic compounds (VOC) (see Figure 12), enabled by developments in measurement technology that now allow for reliable detection of these gases at trace levels.

One of the central elements in GAW is the quality management framework including central facilities for calibration, guidelines for conducting measurements and data archiving and distribution. This system is regularly updated. For example, the new measurement guidelines for tropospheric ozone are described by Galbally and Schultz (2013) (GAW Report No. 209). An overview of the quality assurance system is shown in Figure 3. For reactive gases, Central Calibration Laboratories were established for ozone (at the National Institute of Standards and Technology, United States), carbon monoxide (at the National Oceanic and Atmospheric Administration, United States) and GAW target non-methane hydrocarbons (at the National Physical Laboratory, United Kingdom). World Calibration Centres exist for ozone and carbon monoxide (Swiss Federal Laboratories for Materials Testing and Research (Empa), Switzerland), volatile organic compounds including non-methane hydrocarbons (Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Karlsruhe Institute of Technology, Germany), and nitrogen oxides (Jülich Research Centre, Germany). For most of the audited laboratories, the reported amount fractions of tested GAW VOC targets are within the specified data quality objectives. The central data archive for reactive gases is the World Data Centre for Greenhouse Gases, in Tokyo.

All reactive gases activities are monitored by the Scientific Advisory Group for Reactive Gases, whose members are responsible for establishing standard operating procedures in order to ensure globally consistent measurements. Furthermore, they establish links between GAW and other regional and global monitoring and research networks such as the Network

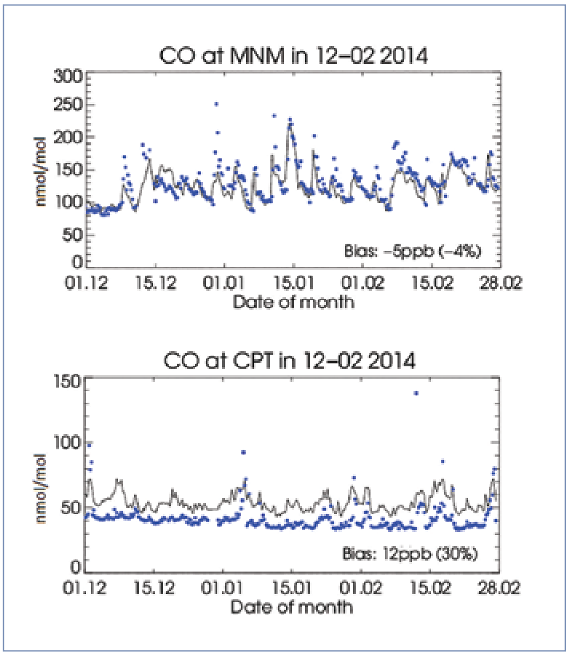


Figure 13. Example of the use of rapid-delivery data from GAW for evaluation of the MACC forecast system. Blue symbols show the GAW measurements of CO and black lines denote the model results at Cape Point, South Africa (bottom) and Minamitorishima, Japan (top), sampled at an appropriate pressure level. *(Courtesy of S. Gilge)*

for the Detection of Atmospheric Composition Change (NDACC), the European Monitoring and Evaluation Programme (EMEP) network, the Acid Deposition Monitoring Network in East Asia (EANET), the Clean Air Status and Trends Network (CASTNET), the In-service Aircraft for a Global Observing System (IAGOS) programme on aircraft observations, or the Aerosols, Clouds, and Trace gases Research Infrastructure Network (ACTRIS). They also promote the use of GAW data and seek communication with data users.

Reactive gases data from the Global Atmosphere Watch Programme have been used in a large number of scientific studies, including review articles (Cooper et al., 2014), trend analyses (Gilge et al., 2010; Parrish et al., 2012; Logan et al., 2012), process studies (Mannschreck et al., 2004) and the evaluation of chemistry climate models (Parrish et al., 2014). GAW stations are often used as a location for short-term intensive measurement campaigns; the continuous and operational reactive gas programme allows such experiments to be placed in an appropriate long-term chemical context. Recently, there has been increasing demand for reactive gases data delivered with fast turnaround times to be used for the validation of global atmospheric composition forecasting systems. The European Monitoring Atmospheric Composition and Climate (MACC) project is such a system, and GAW regularly contributes important data to MACC. Examples of this data use are shown in Figure 13 for a three-month validation with carbon monoxide[1].

6.4 ATMOSPHERIC WET DEPOSITION

Wet deposition is an important process by which precipitation removes anthropogenic and naturally occurring gases and particles from the atmosphere. Quantifying the composition of wet and total deposition regionally and globally is important to understanding the cause and effect of contemporary environmental issues such as acidification, eutrophication, smog and climate change. To better understand these issues, GAW's Scientific Advisory Group for Precipitation Chemistry (SAG-PC) was formed to ensure the harmonization of precipitation chemistry measurements conducted by regional and national programmes, to enable the quantification of patterns and trends of the composition of precipitation on global and regional scales, to improve understanding of biogeochemical cycles of major chemical species, and to provide the data for evaluating ecosystem effects of atmospheric deposition.

Prior to the formation of the SAG-PC, deposition monitoring programmes worldwide had varying degrees of success in addressing important issues related to the causes and effects of atmospheric deposition. Station siting, sample collection methods, laboratory analytical procedures and quality assurance methodologies had not been standardized, resulting in data and information of questionable quality and usefulness. To ensure the harmonization of measurements by national

Typical collector used for precipitation chemistry sampling

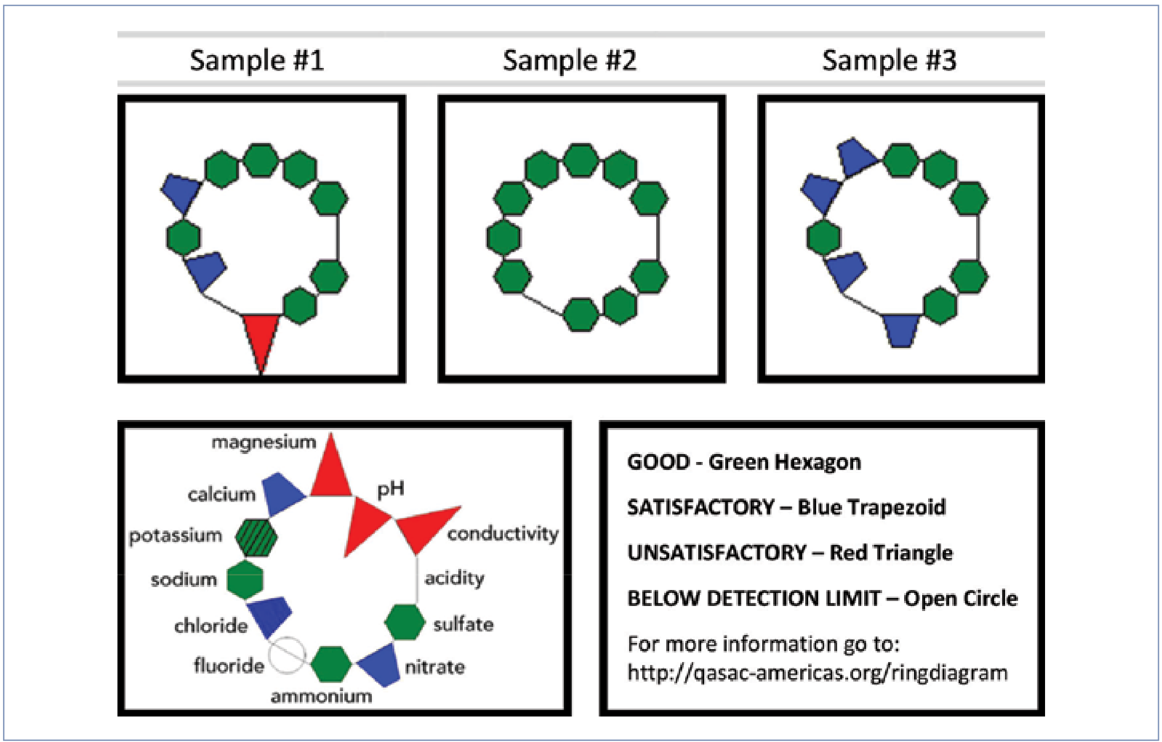
1 Regular updates of MACC validation plots can be found at http://www.gmes-atmosphere.eu/d/services/gac/verif/grg/gaw/gaw_station_ts/.

and regional programmes and improve the quality of global data, the SAG-PC developed a *Manual for the GAW Precipitation Chemistry Programme* (GAW Report No. 160). This manual established data quality objectives and set standard operational procedures for sample collection and handling, laboratory chemical analyses, quality assurance/quality control and data management and analysis. The SAG-PC is working to update and produce an online version of this manual, originally published in 2004.

Recognizing that one important key to the success of any precipitation chemistry measurement programme is the accuracy of sample chemical analyses, the SAG-PC looked to the GAW Laboratory Intercomparison Study, presently conducted by the Quality Assurance/Science Activity Centre for the Americas. Initiated in 1978, this study was designed to track the performance of laboratories using simulated rain samples of known ion concentrations. The SAG-PC doubled the frequency of these laboratory intercomparison studies from one to two per year. Now, more than 80 independent laboratories around the world participate in these studies. Laboratory performance is assessed vis-à-vis accepted data quality objectives for the major ions typically found in precipitation. The Quality Assurance/Science Activity Centre develops a simple visual summary of the laboratories' performance called a ring diagram (Figure 14), based on a statistical analysis of the results of each chemical measurement reported by all of the study participants. A ring diagram is produced for each test sample for each participating laboratory, indicating the quality of each analysis as acceptable, marginal or unacceptable. The diagrams serve to alert laboratory managers and data users of potential problems and offer data users a tool for deciding whether the level of performance is appropriate for their needs. Results of the Laboratory Intercomparison Study are posted on the website of the Quality Assurance/Science Activity Centre for the Americas (http://qasac-americas.org).

Efforts to improve and document data quality from the world's major precipitation chemistry measurement networks made it possible to address data appropriateness in state-of-the-science assessments at a level not previously possible. This was one of several scientific drivers behind the production of "A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus" (Vet et al., 2014). The SAG-PC and other scientists with expertise in atmospheric deposition recognized a need to update the global trends in precipitation chemistry and deposition and improve the

Figure 14. Ring diagrams used to summarize the level of confidence in precipitation chemistry samples from laboratories participating in the GAW Laboratory Intercomparison Study



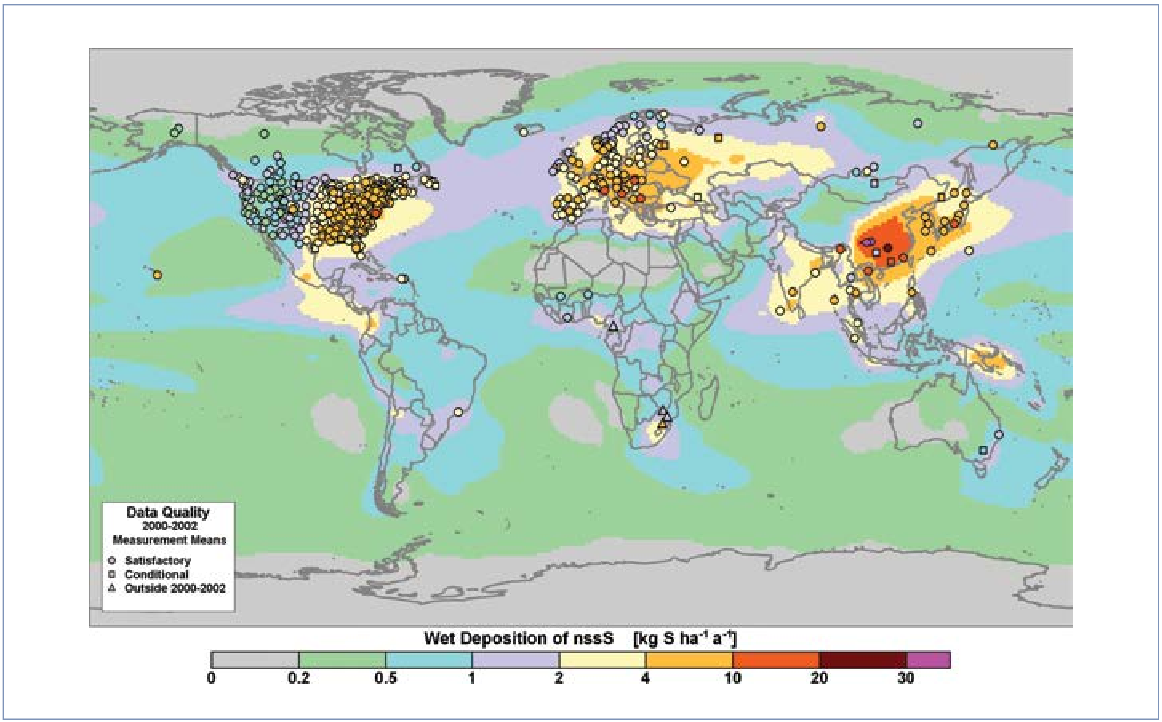


Figure 15. Measurement-model wet deposition of non-sea-salt sulphur in kilogram per hectare per year (nssS in kg S ha^{-1} a^{-1}). Measurement values represent three-year averages for 2000–2002; model results represent the 2001 model year. *(Source: Vet et al., 2014)*

availability of information, especially in areas poorly served by national and regional monitoring programmes. Nearly two decades had passed since the data supporting the first comprehensive *Global Acid Deposition Assessment* (GAW Report No. 106) had been collected, and much had changed concerning global emissions and deposition. Over that period, improvements in global chemistry models had made it possible to complement precipitation chemistry measurements with chemical transport and deposition model estimates for poorly sampled regions. The response of the SAG-PC was to embark on an examination of precipitation chemistry and deposition data for sulphur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus from almost every region of the world, including the oceans. Measurement data and model results were used to generate global and regional maps of concentrations in precipitation and deposition (see example in Figure 15). A major product of the assessment was a database of quality-assured ion concentration and wet deposition data gathered from regional and national monitoring networks. The database is available for download from the World Data Centre for Precipitation Chemistry (http://wdcpc.org/). The full assessment by Vet et al. (2014) is available online at http://dx.doi.org/10.1016/j.atmosenv.2013.10.060 and in hard-copy form from the WMO.

Vet et al. (2014) offer a number of recommendations to address knowledge gaps and provide information that meets the needs of other scientific communities. These recommendations, some of which are summarized below, will shape the direction taken by the SAG-PC in the coming years.

A strategic approach to monitoring is required for future improvements to estimating global deposition. This will require increased spatial coverage of long-term and regionally representative precipitation chemistry measurements in locations where data are sparse or affected by changing regional emissions and where ecosystems are most vulnerable. A closer connection to global and regional science programmes such as the Deposition of Biogeochemically Important Trace Species (DEBITS), which is part of the International Global Atmospheric Chemistry (IGAC) project, will be very important in the establishment of new sites.

Monitoring site in Bondville, Illinois, United States, operated by the US National Atmospheric Deposition Program since 1979. Bondville is the flagship station of the monitoring effort in the United States.

In the future, we expect a greater demand for total deposition estimates, defined as the sum of wet (precipitation) and dry (particle and gas) deposition. These estimates are needed in order to adequately characterize the contribution of atmospheric pollutants to various environmental effects and problems. Accurate estimates of total deposition will require a much greater emphasis on the development of a robust method to routinely estimate dry deposition. Collaboration among the SAG for Precipitation Chemistry, SAG for Aerosols and SAG for Reactive Gases can facilitate this effort. Given that it is not financially or logistically feasible to measure all compounds of interest everywhere, information gaps will best be addressed by combining long-term measurements, including satellite and remote-sensing observations, with chemical transport model information. Ongoing programmes designed to establish and improve data quality, train new field operators and adopt emerging field monitoring and laboratory efforts will continue as a basic role of the SAG-PC.

6.5 ULTRAVIOLET RADIATION

The radiation component of GAW has concentrated its efforts on UV radiation, while specialized WMO programmes have dealt with other aspects of solar radiation (for example, radiation measurements are part of the WMO Commission for Instruments and Methods of Observation). In this frame, WMO established in 1994 the WMO Scientific Steering Committee on UV Monitoring, which, after March 1999, became the Scientific Advisory Group for UV Radiation (SAG-UV).

During the last decades, the impact of total ozone on UV irradiance has been studied quite extensively. Since UV radiation is linked to health issues, ecosystem effects and material damage, the need to monitor surface UV radiation, establish a UV climatology and quantify future changes has been, and still is, of great interest. In this regard, GAW and associated stations have been successful in providing data for environmental studies covering different fields.

As a consequence of this interest in UV measurements, many instruments have been developed throughout the years. A wide range is available at present, which includes spectroradiometers, array spectroradiometers, broadband UV and multichannel narrowband instruments and dosimeters. Through the UV Instrumentation Sub-group associated with the SAG-UV, GAW has developed several documents (GAW Reports No. 125, 164, 190 and 191) in order to define instrument specifications and guidelines for characterization, which are necessary for reliable UV measurements. In addition, GAW Reports No. 126, 146 and 198 were produced in order to promote the implementation of data quality control and quality assurance at the stations. A number of regional and global calibration facilities support quality assurance of the global UV radiation observations.

In the last three decades, the accuracy of UV measurements has substantially improved. An important contribution of GAW in this sense has been the establishment of World Calibration Centres and Regional Calibration Centres for UV. In addition, GAW has encouraged intercomparisons and many of them have been carried out under the auspices of WMO.

The UV data requirements, archiving and distribution have been mainly centralized in the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). At present, data are also submitted to other data centres (such as to the European UV Database and the NDACC database), with WOUDC having a project underway to automate the mirroring of the data from NDACC into WOUDC.

Encouraging efforts to improve modelling of the radiative transfer of UV has been an important part of GAW activities. This enhancement has made it possible to apply radiative transfer models in the development of satellite-based methodologies to estimate UV irradiance at the Earth's surface.

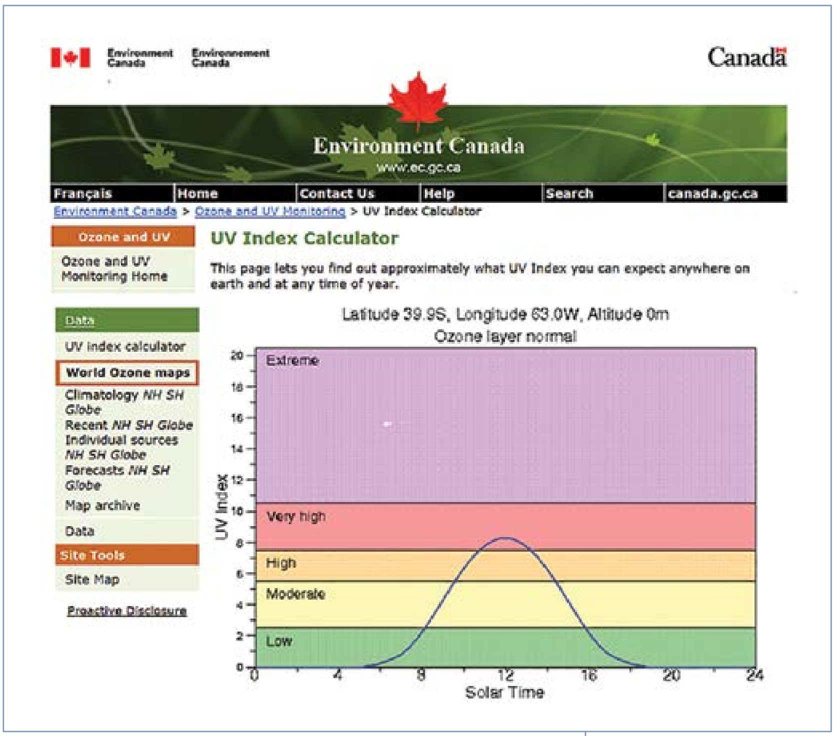
Ultraviolet monitoring from space is a powerful instrument, since it offers the opportunity to achieve a global daily coverage of the UV

The Physikalisch-Meteorologisches Observatorium, World Calibration Centre (PMOD/WRC) in Davos, Switzerland (http://www.pmodwrc.ch/wcc_uv/wcc_uv.html) radiation field. It is a useful tool in supporting environmental assessments and information for the public, for example in the form of a UV index. A comparison of ground and space measurements shows that satellite observations have an advantage of daily worldwide coverage, including oceans, while ground-based measurements can provide better space and time resolution, though the stations are scarce in some areas and are not available over the oceans. In addition, some discrepancies were noted between two sets of data showing that, while satellites are good for climatologies and seasonal data, local values derived from space measurements remain an issue, mainly due to aerosols, and also clouds and snow. Hence, harmonization of satellite and ground-based data remains a critical issue.

The Global Atmosphere Watch Programme collaborates with other programmes and agencies to produce documents related to public health and awareness. An important achievement for public information has been the UV Index (UVI), developed jointly with the World Health Organization, United Nations Environment Programme (UNEP) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). In addition, the GAW SAG-UV has established a public site where the UV index of anywhere in the world can be checked. Another example of collaboration is the GAW Report No. 211, which was produced jointly with the International Commission on Illumination (CIE). This report aims at rationalizing nomenclatures for different UV doses. Members of the SAG-UV also contribute as authors and/or reviewers to the UNEP/WMO Scientific Assessment on Ozone Depletion reports and to the reports of UNEP on the environmental effects of ozone depletion.

In the last years, the focus of UV effects has been moving towards the positive effects of UV radiation (from skin cancer and cataracts to vitamin D and immune system benefits), and is expected to continue in this direction.

In the past, UV objectives were mainly focused on climatologies and the increase of surface UV radiation as a consequence of ozone depletion. Despite the fact that ozone recovery may lead to decreased UV irradiance, new UV objectives appear triggered by climatological variations in other parameters affecting UV, such as cloud cover and types, earth reflectivity (albedo), aerosols and other parameters related to global change.



The UV Index for anywhere, anytime. Adjustments for altitude, ozone and variation due to parameters such as snow are available (http://exp-studies.tor.ec.gc.ca/cgi-bin/clf2/uv_index_calculator?lang=e&printerversion=false&printfullpage=false&accessible=off)

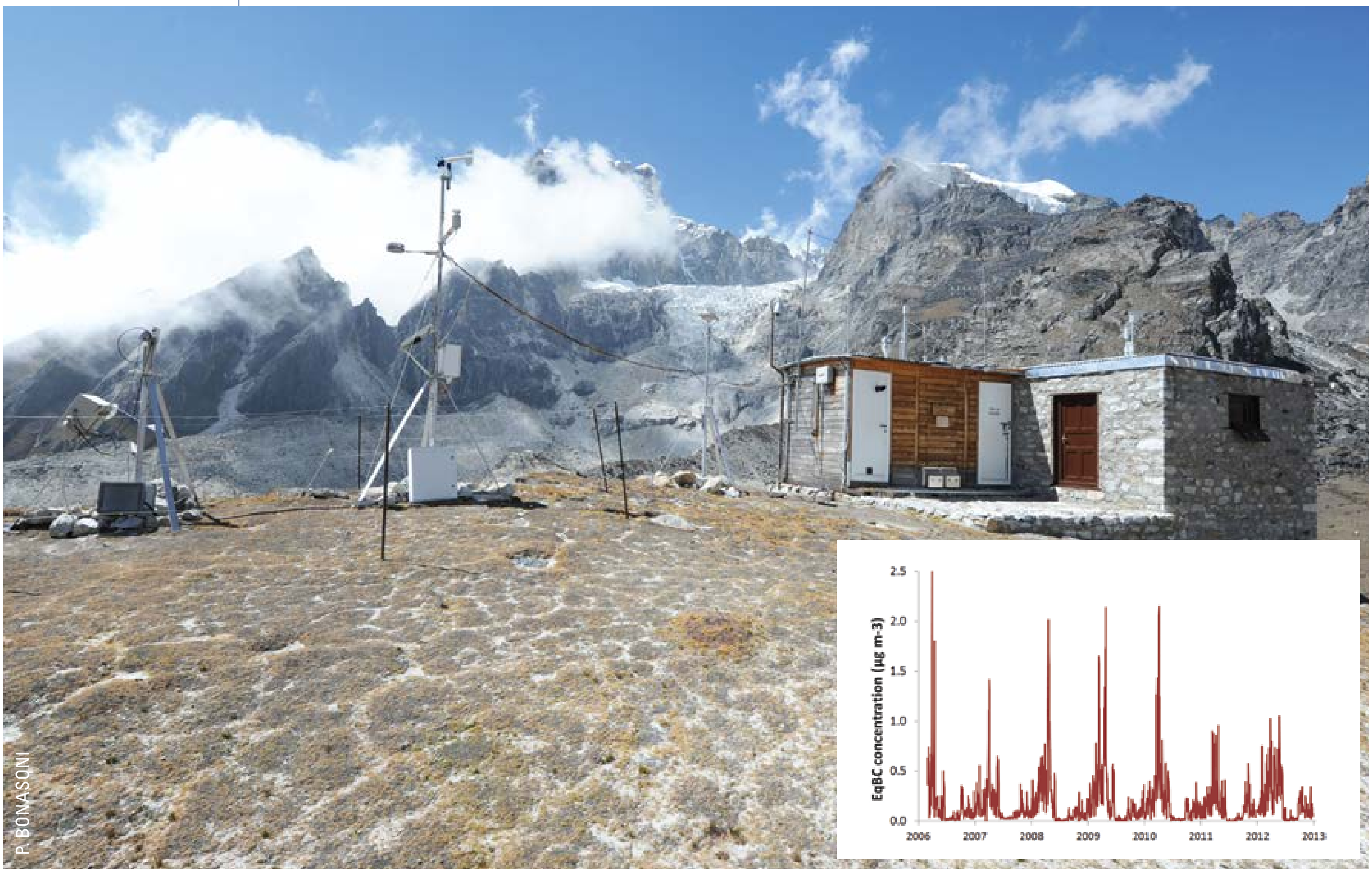
The above-mentioned variations could lead to spectral, geographical and seasonal changes in solar radiation reaching the Earth's surface, which would result in beneficial and detrimental changes in the effects of UV on living organisms (erythema, vitamin D production, DNA damage, etc.). This would have subsequent effects on humans and ecosystems, leading to socio-economic consequences. Long-term UV measurements as well as measurements of all the parameters involved in this change will be encouraged, with the aim of following the evolution of UV radiation under global change.

6.6 AEROSOLS

Comprehensive observational networks are foundational to all aspects of our understanding of the environmental system and the interactions of society therewith. Without long-term observations, we would have little chance of fully understanding the system, recognizing important processes and signals as they emerge and planning accordingly. All the assessments of climate change by the Intergovernmental Panel on Climate Change (IPCC), beginning with the first in 1990, have strongly emphasized the analyses of evidence of climate change from atmospheric observations, highlighting the challenges for developing long-term, high-quality observation records that can be used to constrain models at global and regional scales. While improved monitoring capabilities developed in the last decades, both from satellites and ground-based stations, have clearly yielded more reliable data records, the latest IPCC assessment report (IPCC, 2013) still highlights the need for maintaining and enhancing the capacity of observing atmospheric composition to provide additional constraints, in particular for the derivation of trends.

This is particularly true for aerosols, which continue to contribute the largest uncertainty in estimates and interpretations of climate change. Moreover, aerosol particles play a key role in air quality, human health, ozone depletion and the long-range transport and deposition of toxics and nutrients. Aerosols have many sources ranging from sea spray and mineral dust particles, which are mechanically generated by wind at the Earth's surface, to sulphate, nitrates and organics produced by chemical reactions of gases in the atmosphere and which yield non-volatile products that condense to form particles. Aerosols range in size from stable molecular clusters of a few nanometers in diameter to mineral dust and sea-salt particles, which can be as large as tens of micrometres. The dynamics of aerosol particle production, transformation and removal that govern size distribution and composition are affected not only by clear-air processes, but also by interaction with cloud processes and precipitation. The complexity of aerosol processes in our environment is so great that it leads to large uncertainties in our quantitative understanding of their role in many of the major environmental issues listed above. For the Earth's climate, the magnitude of aerosol direct forcing is assessed to be –0.45 (–0.95 to +0.05) Watts (W) m^{-2} if we consider the impact of aerosol alone. When aerosol/cloud feedbacks are taken into account, this effect reaches –0.9 (–1.9 to –0.1) W m^{-2}, though both effects have only a medium level of confidence. The uncertainty in the estimates of aerosol radiative forcing is still very high, despite the substantial progress made to understand climate-relevant aerosol processes. These average estimates mask a very strong spatial and temporal heterogeneity resulting from the relatively short lifetime of aerosol particles and the complexity of emission sources.

One of the most recently established and the highest GAW site in the network of global stations, the Nepal Climate Observatory – Pyramid has offered a very comprehensive set of aerosol (and trace gases) measurements since 2006. In particular, the record of equivalent black carbon shows very elevated values during the pre-monsoon season as shown in the insert.

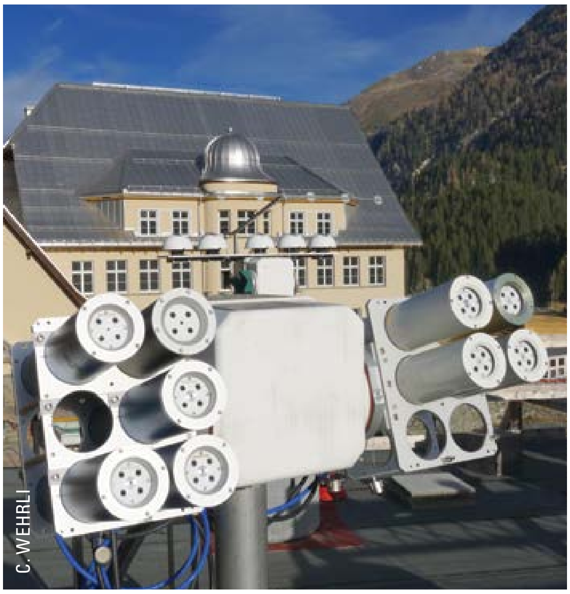


The availability of long-term records of aerosol properties is the key to reducing this uncertainty, but the required observations are complex, as a large number of variables are needed for a comprehensive description of aerosol particle properties. Aerosol particles cannot be characterized solely in terms of mass concentration but also require measurements of their optical, chemical and physical properties and their spatio-temporal evolution as part of a 4D observing system. This explains why, while atmospheric records of 50 years or more exist for CO_2 or O_3, only a few time series spanning more than two decades are available for aerosol properties.

The GAW Programme played a key role in the initiation, 25 years ago, of the first global network for measuring aerosol properties and, since the very early stage, in recognizing the need for standardized techniques, harmonized measurement protocols, quality assurance, calibration and validation procedures across the network (GAW Report No. 153; Petzold et al., 2013). Despite the intrinsic complexity of aerosol observations, GAW, through its network of 109 GAW and contributing stations, provides exceptional records to determine the spatio-temporal distribution of aerosol particle properties related to climate forcing and air quality on multidecadal timescales and on regional, hemispheric and global spatial scales. Through scientific and technological recommendations to station operators, GAW managed to address changes in observing practices, the evolution of technologies and the evolving demand for additional monitored variables from the scientific community (Laj et al., 2009).

The GAW network consists of three different components:

- The GAW in situ aerosol network contains (as of July 2014) more than 34 regional stations and 54 contributing stations, in addition to 21 global stations reporting data – some of them in near real-time – to the World Data Centre for Aerosols (WDCA) hosted by the Norwegian Institute for Air Research (NILU). These data are then made freely available to all. The GAW in situ network also receives contributions from regional networks such as EMEP in Europe or the Interagency Monitoring of Protected Visual Environments (IMPROVE) network in the United States. These data help calibrate aerosol-type representations in climate models and in aerosol retrievals with satellite data.



Several precision filter radiometers being calibrated against the WORCC triad of reference PFRs at Davos, Switzerland

- The GAW Precision Filter Radiometer (GAW-PFR) sun-photometer network for aerosol optical depth is coordinated by the World Optical Depth Research and Calibration Centre (WORCC). A total of 21 stations are currently providing daily data to the WORCC. These data complement other ground-based network data (such as the Aerosol Robotic Network (AERONET) or SKYNET). Sun-photometer data provide highly accurate estimates for aerosol optical properties and even allow for estimates of microphysical properties in terms of averages for the entire atmospheric column. They are thus complementary to ground in situ data. These data are essential for the calibration of satellite retrievals and are widely used to evaluate aerosol modules in climate models.
- The GAW Aerosol Lidar Observation Network (GALION) provides the vertical component of aerosol distributions through advanced laser remote-sensing in a network of globally distributed ground-based stations. Several regional lidar networks, such as the Asian Dust and Aerosol Lidar Observation Network (AD-Net); the Latin America Lidar Network (ALINE); the Commonwealth of Independent States (Belarus, Russian Federation and Kyrgyzstan) Lidar Network (CIS-LINET); the Canadian Operational Research Aerosol Lidar Network (CORALNet); the CREST Lidar

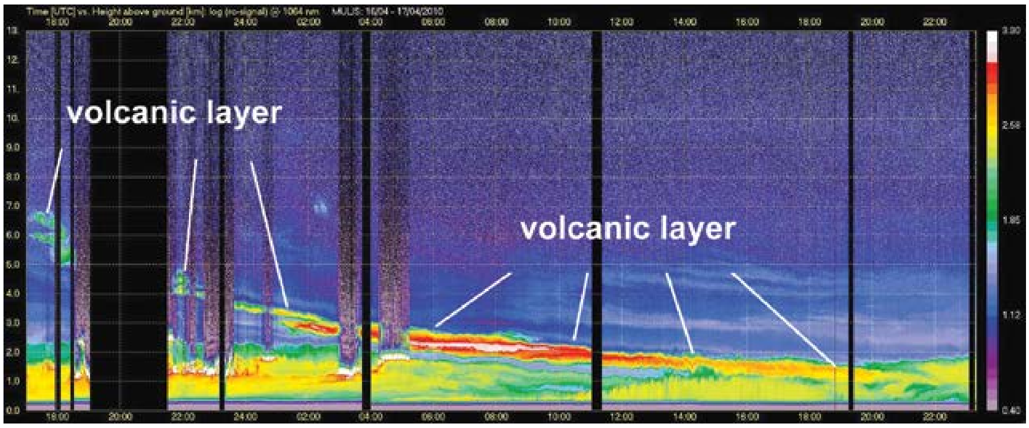


Figure 16. Lidar profile measured above Munich, Germany, during the 2010 Eyjafjallajökull eruption in Iceland. The plume was detected by the EARLINET component of GALION in Europe. *(Source: Pappalardo et al., 2013)*

Network for eastern North America; the Micro-Pulse Lidar Network (MPLNET); the European Aerosol Research Lidar Network (EARLINET); and the NDACC for the global stratosphere, are all participants in GALION. An example of the data from a lidar station is presented in Figure 16, in which lidar observations of the vertical profiles of aerosol properties are used to detect volcanic ash layers.

Overall, the GAW integrated network covers different types of aerosols including clean and polluted continental, marine, Arctic, dust, biomass burning, and free tropospheric aerosols. Quality assurance across the GAW network is critical and addressed through World Calibration Centres, which include the World Calibration Centre for Aerosol Physics (WCCAP) hosted by the Leibniz Institute for Tropospheric Research (TROPOS) in Leipzig, Germany, and the World Optical Depth Research and Calibration Centre hosted by the Physikalisch-Meteorologisches Observatorium World Radiation Centre in Davos, Switzerland. Education and training are essential for the success of the network and for maintaining and developing the proper level of scientific and technical expertise, in particular linked to aerosol data collection, storage and distribution. The GAW Training and Education Centre as well as data management training within the World Data Centre for Aerosols have contributed to building expertise all around the world.

Scientists involved in calibration exercises at the World Calibration Centre for Aerosol Physics at TROPOS

A direct result of the efforts initiated more than 20 years ago to better coordinate the observation system and data distribution to the entire scientific community is the capability to derive long-term trends for non-CO_2 climate forcers on the global scale. The current picture shows the consistent observation of important regional variability for the aerosol burden, with an apparent decline over Europe and the eastern United States since the mid-1990s and, in contrast, an apparent increase over eastern and southern Asia in the last decade (Asmi et al., 2013; Collaud Coen et al., 2013). However, despite large efforts from GAW, the amount of data elsewhere in the world is insufficient to derive any long-term trends with statistical significance. In fact, the lack of information along with the strong inter-annual variability, the regional heterogeneity of particle loads and the limited timespan of the available records still limits the identification of long-term trends.

Maintaining the capacity to monitor changes in atmospheric composition will be essential in the next decades. Perturbations of the Earth's biogeochemistry and climate caused by man are unlikely to stop anytime soon. Since natural cycles are highly variable and strongly influence aerosol composition and concentrations, establishing a baseline in an ever-changing system is extremely complex. Climate-induced feedbacks may lead to the amplification or dampening of the aerosol/cloud climate forcing, leading to an even more complex picture (Carslaw et al., 2010). For example, some studies show that such feedback from natural processes only may lead to positive forcing on climate as high as 1 W m^{-2} globally by the end of the century. In parallel, stronger regulations on anthropogenic emissions for improving air quality will affect particle burdens, changing the climate forcing at least at the regional scale. Climate change, together with air quality regulations, will therefore increase the number of drivers of change in a very complex coupled system.

One great challenge for the future will therefore be to maintain and optimize the current observing system at its nominal performance over a sufficiently long time period to be able to detect response from the system early enough to take action. It is equally important to develop new observing capabilities where long-term measurements are critical for understanding the rapidly changing environment. In this context, it is obvious that the actions of GAW for monitoring aerosol properties worldwide will, even more than before, be an essential pillar of this endeavour.

6.7 THE GAW URBAN RESEARCH METEOROLOGY AND ENVIRONMENT PROJECT

The GAW Urban Research Meteorology and Environment (GURME) project is a component of GAW. It focuses on improving urban meteorological and environmental services through research applied to operations. The GURME project was set up in response to the requests for assistance from many NMHSs dealing with urban issues, recognizing that the management of urban environments requires special attention. The project originated in the Twelfth World Meteorological Congress (1995) where it was determined that meteorological and climatological aspects of urban environments should receive increasing attention within WMO programmes. In response, the WMO Executive Council added the field of urban atmospheric environment to the terms of reference of the Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry. A Meeting of Experts on Atmospheric Urban Pollution and the Role of National Meteorological Services was convened in Geneva in October 1996 to define issues and needs and to plan future WMO activities related to urban environments. This meeting led to the establishment of GURME in the same year.

Cities affect the atmosphere in many ways (Figure 17): by causing alterations in weather and climate due to changes in land use and surface properties and large increases in heat, and through significant emission of pollutants associated with transport, residential heating/cooling and other activities needed to support urban living. Because of the important roles – economic, political and cultural – that cities play and the adverse effects on society of poor air quality and high-impact weather events such as heatwaves and floods, there is a growing need for more comprehensive weather, climate and environmental services to support urban areas.

The GAW Urban Research Meteorology and Environment project was established to address these needs, with the following goals:

- To enhance the capability of NMHSs to provide urban environmental forecasting and effective air quality services, thus illustrating the link between meteorology and air quality.

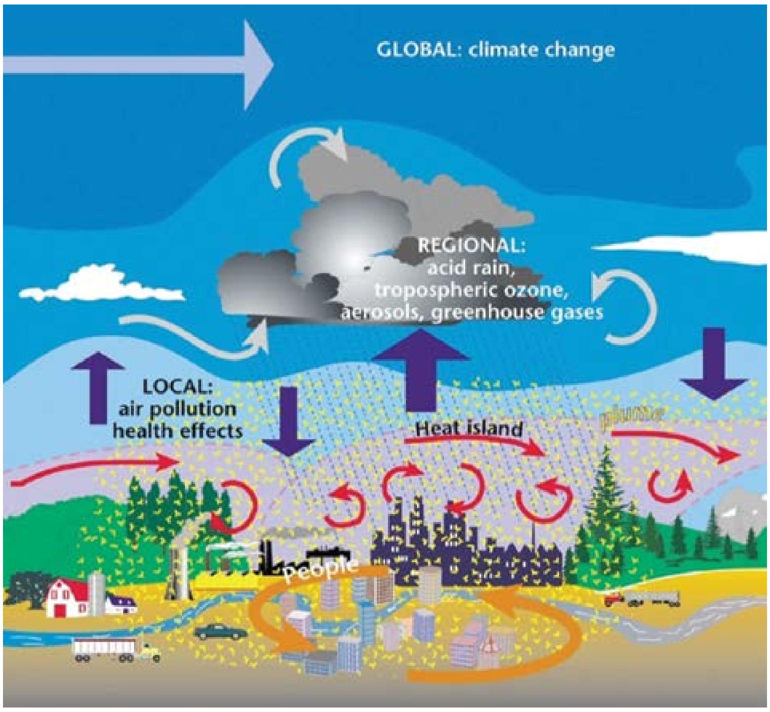


Figure 17. GURME focuses on better understanding the impacts of urban areas on the atmospheric environment.

- In collaboration with other WMO programmes, the World Health Organization and environmental agencies, to better define meteorological and air quality measurements focusing specifically on those that support urban forecasting.
- To provide NMHSs with easy access to information on measurement and modelling techniques.
- To promote a series of pilot projects to demonstrate how NMHSs can successfully expand their activities to include urban environment issues, showcase new technologies at appropriate conferences and provide examples.

Pilot projects

Pilot projects are an important mechanism for promoting air quality and related services. To demonstrate how meteorological and other organizations can successfully expand their urban-focused services, GURME has promoted a number of pilot projects, some of which are described below.

Latin American Cities – This project grew out of the GURME meeting of experts held in Cuernavaca, Mexico, in October 2002, which was attended by 25 participants from 11 countries. The purpose of this activity is to build capacity and share experiences in areas related to air quality throughout Latin America. The first Workshop on Air Quality Forecasting in Latin American Cities was held in Santiago, Chile, in October 2003.

Since then, a number of workshops and training events on air quality forecasting and modelling have taken place in several Latin American cities.

In 2013, GURME hosted the Fifth International Workshop on Air Quality Forecasting Research (IWAQFR) in Santiago, Chile. One notable outcome of this activity was the development of a new air quality system for Santiago to forecast urban PM2.5 pollution in winter. This system is now run by the Chilean Meteorological Service, in collaboration with local universities.

Santiago (Chile) is often affected by air pollution in winter.

More recently, a new initiative, Pollution and its Impact on the South American Cryosphere (PISAC) was launched to deal with emission sources, measurement and transport of pollutants, monitoring stations and modelling of the potential impacts of black carbon and co-pollutants on the Andean cryosphere, and policy measures dealing with the impacts of pollution. This activity will involve the GAW stations in the region and promote the establishment of new stations.

System of Air Quality Forecasting and Research – The Indian Institute of Tropical Meteorology (IITM), in Pune, is spearheading the country's first major air quality forecasting initiative known as System of Air Quality Forecasting and Research (SAFAR). This system was successfully tested during the 2010 Commonwealth Games for Delhi National Capital Region. It includes new comprehensive air quality monitoring networks reporting data in near real-time, a citywide meteorological and air quality forecast system at kilometre scale, and a multimedia forecast dissemination system (Figure 18). The System of Air Quality Forecasting and Research provides location-specific information on air quality in near real-time and forecasts 1–2 days in advance. It is complemented by the weather forecasting system designed by the India Meteorological Department, in New Delhi. The ultimate objective is to raise awareness among the general public of the air quality in their city, in a timely manner, so that appropriate mitigation measures can be taken to improve air quality and tackle related health issues. The plan is to replicate SAFAR in other major cities in India, placing the country at the forefront of air quality forecasting research. To date, SAFAR is operational in Delhi, Pune and, as of August 2014, in Mumbai.

Air quality component of the Multi-hazard Early Warning System, Shanghai Expo 2010 – A new air quality component of the Multi-hazard Early Warning System (Figure 19) was presented at the Shanghai Expo in 2010. The project, under the leadership of the Shanghai Regional Meteorological Centre of the China Meteorological Administration, was designed to

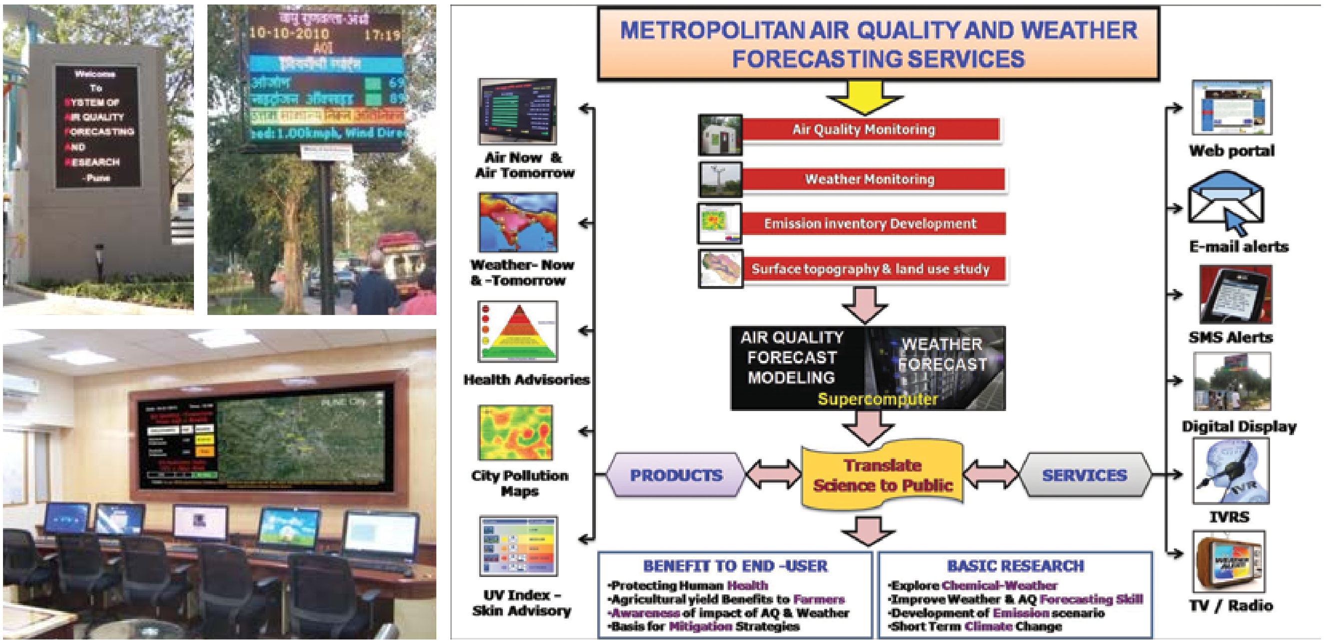


Figure 18. Components of the System of Air Quality Forecasting and Research (SAFAR)

explore the full potential of an air quality system for urban life in the twenty-first century. The key objectives of the project were to disclose the physical and chemical mechanisms during the formation, transport and transformation of the main air pollutants in the Shanghai area; to establish the air pollution prediction system for the same area; and to improve the techniques for assessing environmental quality. New and comprehensive forecast products based on various measurements (meteorological measurements, environmental observations and disease diagnostics) had been developed to support public health services and were presented during the Expo. Through public health services such as those dealing with air quality, pollen-related allergies, food poisoning and heatstroke, effective measures to protect the health of individuals, especially those in sensitive groups, will be designed. This project is part of a comprehensive service designed for the Shanghai metropolitan area.

Near Real-time Data Application to Air Quality Forecasts – This is the newest pilot project under the leadership of the Chinese Academy of Meteorological Services. The project objectives are: (a) to develop and establish a near real-time chemical data transfer system to collect and process both ground-based and satellite observations, following the WMO data transfer protocols for conventional weather data; (b) to illustrate the capacity of near real-time data to enhance the accuracy of air quality forecasts in China; (c) to develop a system for estimating emissions using near real-time data and inverse modelling methodology; and (d) to exchange research results with other national and international agencies.

These projects illustrate some of the ways in which research is being applied to enhance weather and air quality services, particularly through addressing the complex interaction

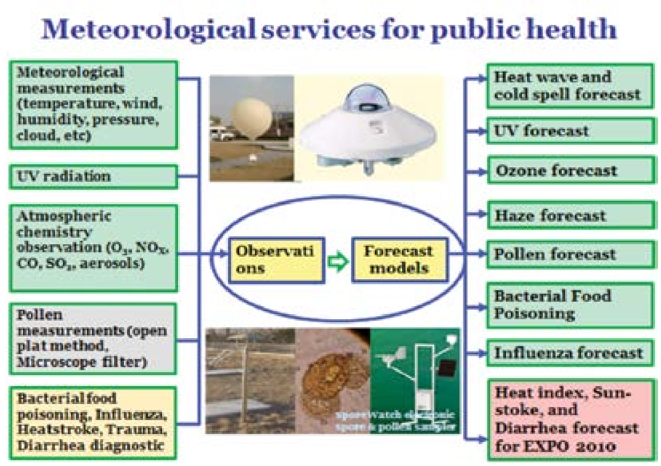


Figure 19. The public health component of the comprehensive service designed for the Shanghai metropolitan area

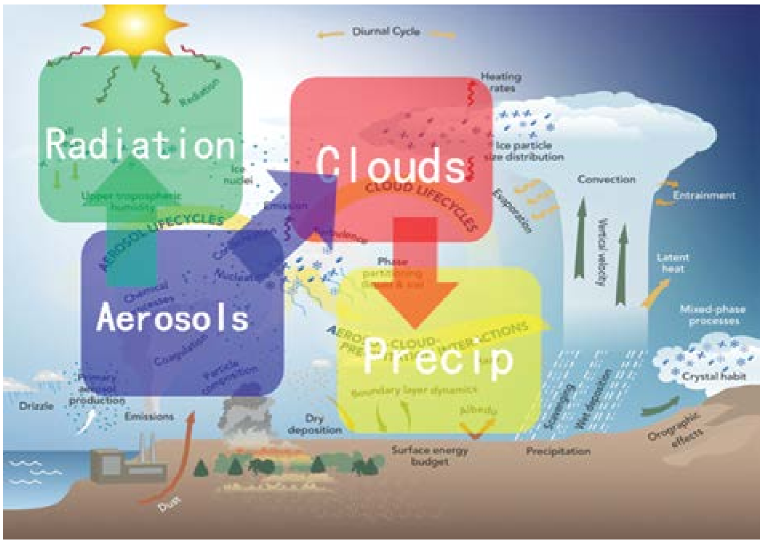


Figure 20. Illustration of aerosol interactions with weather and climate. The possibility of improving predictions, by assimilating near real-time aerosols observations, is under study at the Chinese Academy of Meteorological Services.

of aerosols with the weather and climate system (Figure 20). To support those services, modelling capabilities are being improved and meteorological and chemical observations in and around urban areas are being expanded. As a result, the requirements for the near real-time delivery of air chemistry observations for use in weather and environmental forecasting are also increasing.

Collaboration

Collaboration is necessary to address the pressing problems facing urban environments. The GAW Urban Research Meteorology and Environment project actively collaborates with various partners on capacity-building, research and joint studies. Examples include the report on megacities developed jointly with the International Global Atmospheric Chemistry (IGAC) project, studies on short-lived climate pollutants done with UNEP, activities carried out with the World Health Organization, such as the publication of the *Atlas of Health and Climate*, and participation in a variety of research projects supported by the European Union and the European Cooperation in Science and Technology (COST).

Greater collaboration will be essential to tackle urban air quality issues. A large fraction of the world's population lives in large cities, and many of these are at risk from natural hazards besides air pollution (Figure 21). Within WMO there is an increasing focus on megacities and large urban complexes and GURME is expected to play a major role in this area.

Further details about GURME can be found at http://mce2.org/wmogurme/.

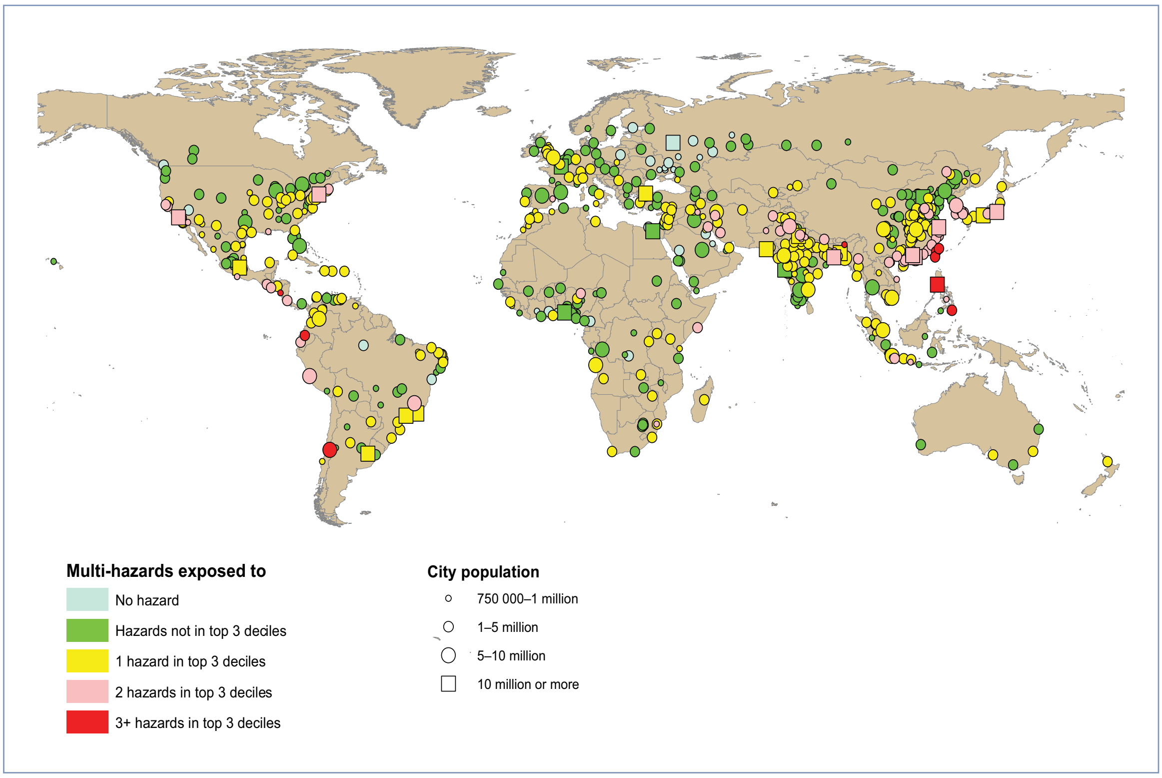


Figure 21. Between half and two thirds of the cities with 1 million or more inhabitants are located in regions at high risk of exposure to natural disasters. *(Source: United Nations, Department of Economic and Social Affairs, Population Division: World Urbanization Prospects: The 2011 Revision. New York)*

7. GLOBAL ATMOSPHERE WATCH DATA MANAGEMENT

The Global Atmosphere Watch subscribes to a "fair use" data policy

"For scientific purposes, access to these [GAW] data is unlimited and provided without charge. By their use, you accept that an offer of co-authorship will be made through personal contact with the data providers or owners whenever substantial use is made of their data. In all cases, an acknowledgment must be made of the data providers or owners and of the data centre when these data are used within a publication."

Statement endorsed by the WMO Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry

When the GAW Programme came into existence in 1989, programme-wide data management became possible through the establishment of GAW World Data Centres. Two of these centres had been in existence for decades: the World Radiation Data Centre (WRDC) which opened in 1964, while the World Ozone Data Centre had already begun fonctioning in 1962. With the designation of the World Ultraviolet Radiation Data Centre, this became the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) in 1992. The World Data Centre for Greenhouse Gases (WDCGG) began operations in 1990. The World Data Centre for Aerosols (WDCA) was set up in Ispra, Italy, and was integrated in 2007 with the EMEP data centre. Given the importance of regional networks, the World Data Centre for Precipitation Chemistry (WDCPC) was established under the auspices of NOAA as a portal providing links to existing data archives. The purpose of the GAW World Data Centres, each focusing on a specific range of observations, is long-term management of quality-assured GAW data and user-friendly access to these data.

In 2001, the GAW Station Information System (GAWSIS) was established as the official catalogue of stations and platforms contributing to the GAW network. The purpose of GAWSIS is to collect station metadata, including photos, information on all GAW-related observations and contact information, as well as to provide access to bibliographic references, from both the GAW WDCs and other long-term archives storing GAW data. The GAW Station Information System is also linked to the Observing Systems Capabilities Analysis and Review (OSCAR) tool, a central element for the rational evolution of the global observing systems. The WMO Integrated Global Observing System (WIGOS) emphasizes the importance of metadata for the efficient exchange of information and adequate use of observations.

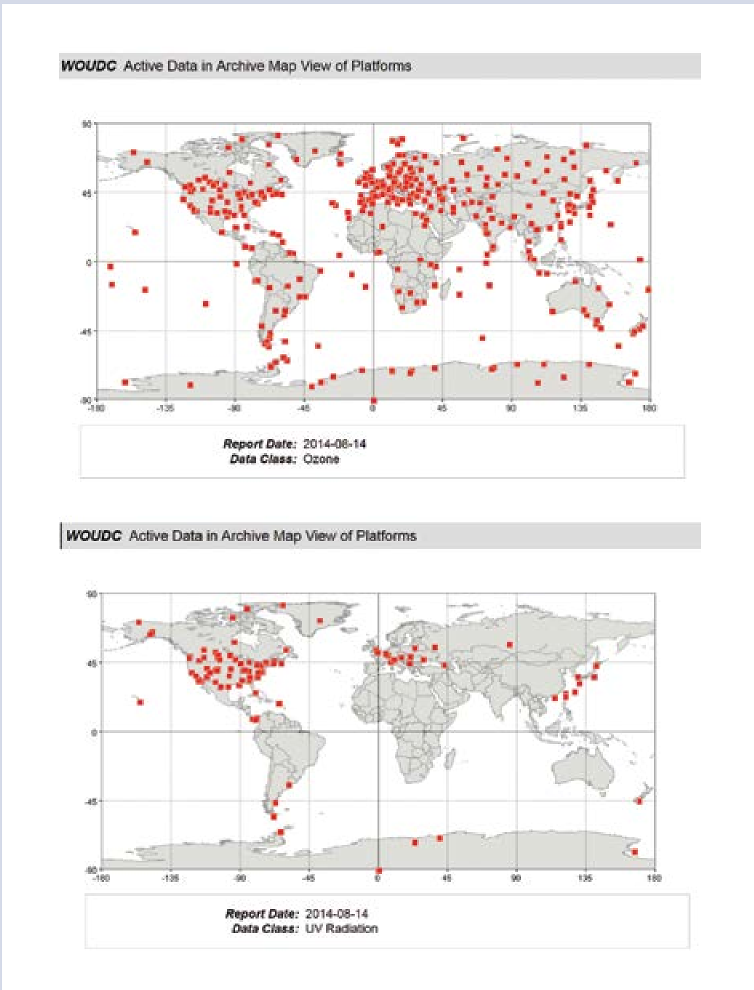
In 2006, the Expert Team on World Data Centres (ET-WDC) was established, formalizing a long-standing tradition of cooperation among data centres involved in GAW. The ET-WDC takes on a leading role in improving interoperability of the existing WDCs and engaging with experts in Earth science data management worldwide. A crucially important aspect in this regard is the standardization of metadata, both for metadata representation and for terminology. Much of this effort goes unnoticed, but it is the prerequisite for the efficient exchange of available data and for enabling users to make adequate use of the information they obtain. Thus, the role of ET-WDC is that of a facilitator, building and maintaining bridges between data providers and data users. Specifically, ET-WDC works with other WMO bodies to formulate GAW requirements relating to data management and contributes to the development of the WMO Information System (WIS).

The future of GAW data management is all about further integration, improved interoperability and better services for data users within the overarching framework of WIGOS. The WMO Information System is the Organization's information highway for the twenty-first century. Most GAW WDCs already contribute directly to WIS, and GAWSIS provides machine-readable metadata for all GAW observations. The Expert Team on World Data Centres supports WIGOS by defining and coordinating services for operational, time-critical applications so that GAW and other environmental observational data are available to users online and, when possible, in near real time. The GAW World Data Centres are embracing the use of web services and other machine-to-machine interfaces to facilitate the automatic exchange of information, while at the same time paying attention to the legitimate property rights of the data providers. The vision is one of seamless data flows from instruments to data users, whereby all significant interventions between the acquisition of a raw signal and the archiving of fully quality-assured datasets are properly documented with standardized metadata. Access to the (meta)data will be facilitated through WIS, and adequate use of data will be supported with WIGOS metadata.

Box 1. World Ozone and Ultraviolet Radiation Data Centre

(http://www.woudc.org)

A scientific archive and database for ozone and ultraviolet radiation data is maintained at the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) which is hosted and operated by Environment Canada. The Centre provides a variety of ozone datasets to the international scientific community, including total column ozone from ground-based ozonometers, as well as vertical profile data from ozonesonde flights and lidar measurements. Value added data products include total ozone time series graphs and near real-time ozone maps. The solar ultraviolet radiation dataset includes spectral, multiband and broadband ultraviolet measurements. After more than 50 years of service, WOUDC, under the supervision of the WMO Scientific Advisory Group for Ozone (SAG-Ozone) is currently under renovation with the inclusion of data centre metrics, restructured data products, calibration metadata, quality assurance summaries, automated quality control, linkages with related data centres and near real-time data submission. There are over 500 registered stations in the archive from more than 150 agencies (see figure below).

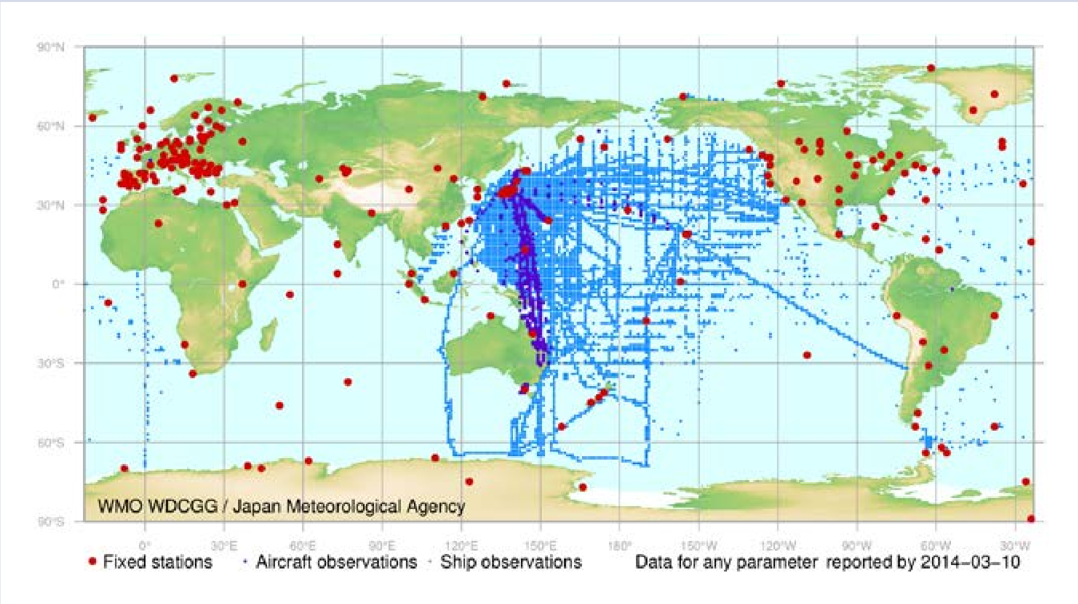


Maps of the stations that provide data to WOUDC

Box 2. World Data Centre for Greenhouse Gases

(http://ds.data.jma.go.jp/gmd/wdcgg/)

Operated by the Japan Meteorological Agency, the World Data Centre for Greenhouse Gases (WDCGG) gathers greenhouse gas (CO_2, CH_4, N_2O, SF_6, CFCs, etc.) and reactive gas (tropospheric ozone, CO, NOx, SO_2, VOC, etc.) observations. Thanks to close cooperation with the relevant scientific communities, the archive has been growing steadily over the last 25 years and today comprises some 230 1°x1° grid cells with data (see figure below). The World Data Centre for Greenhouse Gases is one of the Data Collection or Production Centres (DCPCs) of the WMO Information System.



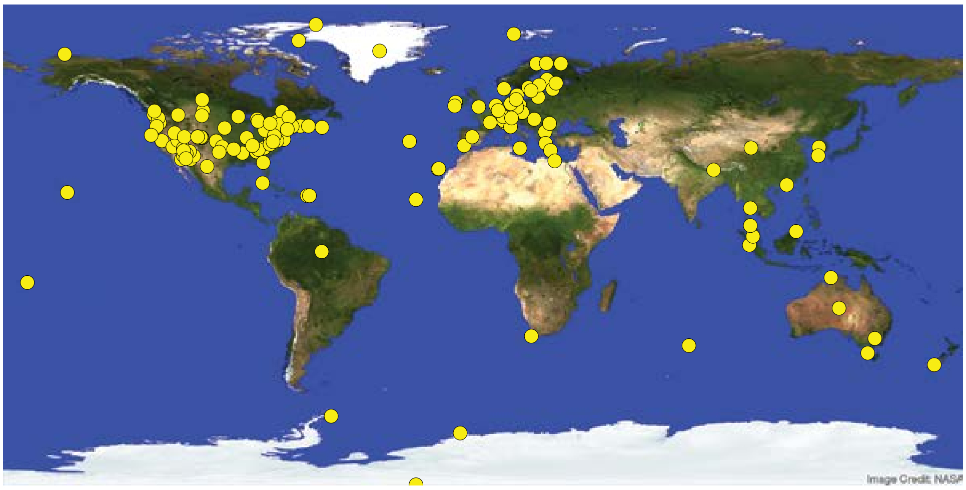
Observational locations submitting data to WDCGG

Box 3. World Data Centre for Aerosols

(www.gaw-wdca.org)

Operated by the Norwegian Institute for Air Research (Norsk institutt for luftforskning, NILU), the World Data Centre for Aerosols (WDCA) gathers observational data on chemical, optical and microphysical properties of aerosols in the atmosphere, from around 120 stations (see figure below). About 45 stations also submit data in near real time. The World Data Centre for Aerosols is co-hosted on the EBAS database, which contains data from a large number of research projects, and by the European Monitoring and Evaluation Programme (EMEP).

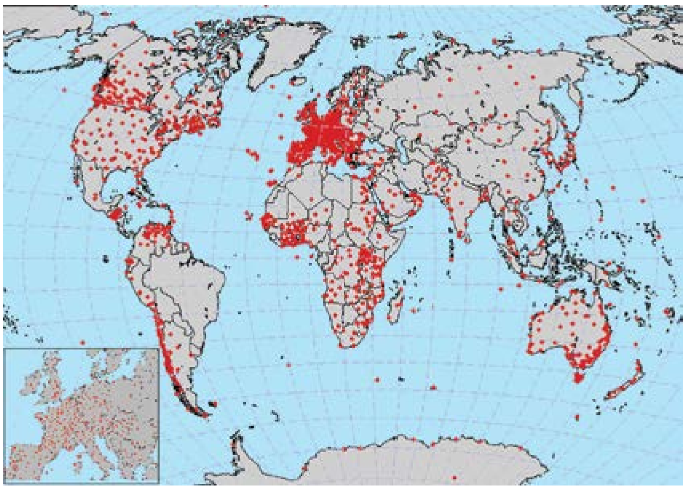
Observational stations with data records in WDCA



Box 4. World Radiation Data Centre

(http://wrdc.mgo.rssi.ru/)

Operated by the Main Geophysical Observatory of the Russian Meteorological Service (Roshydromet), the World Radiation Data Centre (WRDC) stores mostly daily totals of various radiation balance components from some 1 500 stations. The majority of data-sets (ca 1 250 stations) consist of global radiation observations and sunshine duration (ca 1 350 stations). A subset of ca 250 stations is labelled as GAW stations that provide hourly data on global, direct, diffuse, and/or spectral radiation (see figure below).

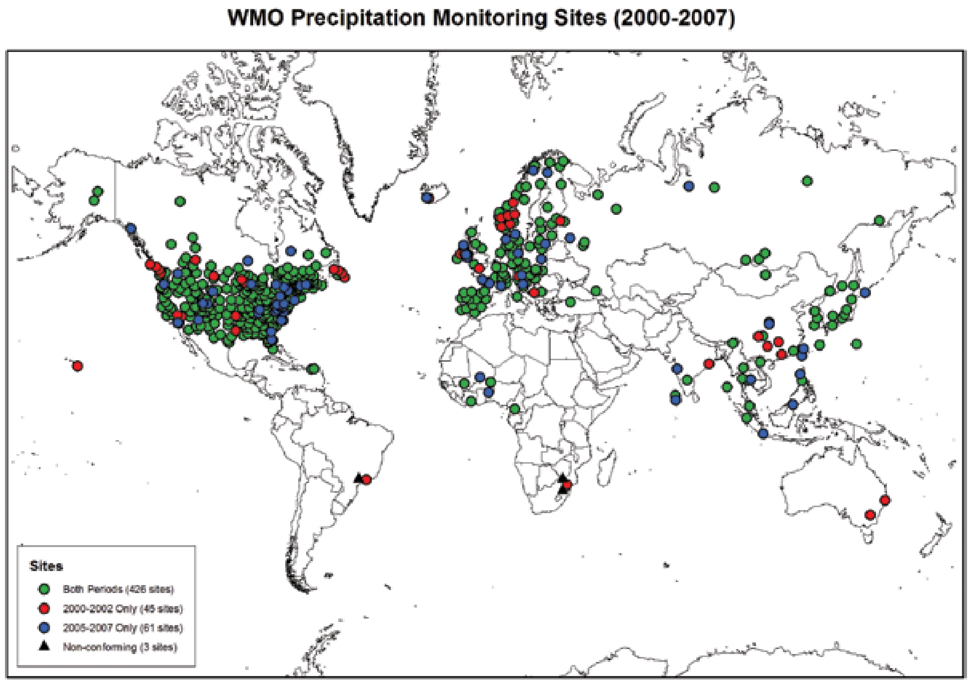


GAW stations listed in WRDC

Box 5. World Data Centre for Precipitation Chemistry

(http://wdcpc.org/)

Operated on behalf of the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (United States), the World Data Centre for Precipitation Chemistry (WDCPC) receives and archives precipitation chemistry data and complementary information from stations around the world (see figure below). Precipitation chemistry data from regional and national programmes that maintain their own websites are accessible via links between WDCPC and those sites. Researchers and other users can readily assess the quality of data for their applications through links between WDCPC and the Quality Assurance/Science Activity Centre for the Americas.

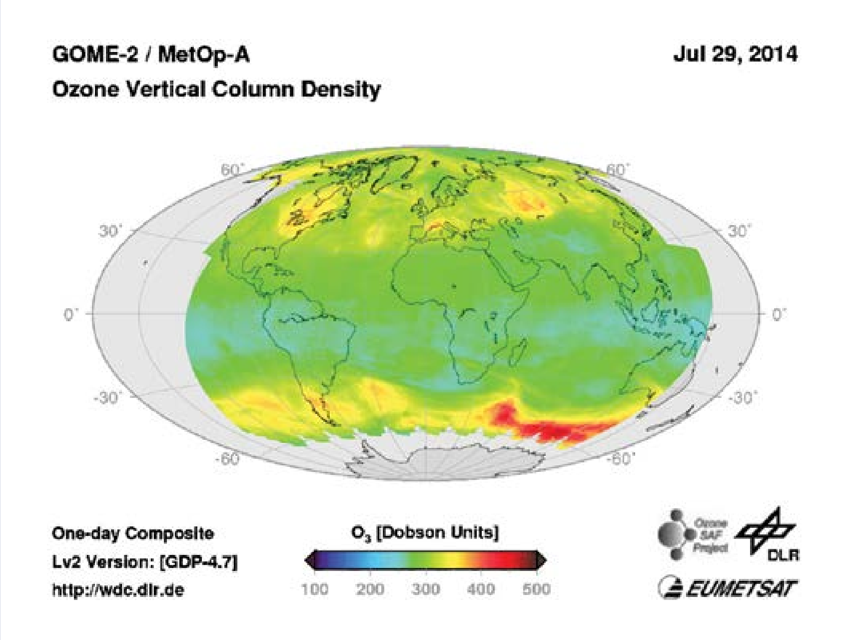


Precipitation chemistry monitoring stations, 2000–2007. Sites shown include stations archived and those linked to collaborating networks via WDCPC. *(Source: Vet et al., 2014)*

Box 6. World Data Centre for Remote Sensing of the Atmosphere

(https://wdc.dlr.de)

Operated by the German Aerospace Centre (Deutsche Luft- und Raumfahrt, DLR), the World Data Centre for Remote Sensing of the Atmosphere (WDC-RSAT) is both a data archive and a portal providing information on space-based observations of atmospheric composition. Satellite retrievals of aerosols can complement ground-based measurements, while the latter are needed for a thorough validation of all underlying assumptions in the retrievals. To facilitate access to satellite data, a one-stop shop (http://wdc.dlr.de/data_products/AEROSOLS/) was set up at WDC-RSAT. It provides a list of satellite-based aerosol products (see example below) with a standardized description of each product, including algorithm characteristics, and direct links to other products and relevant documentation.



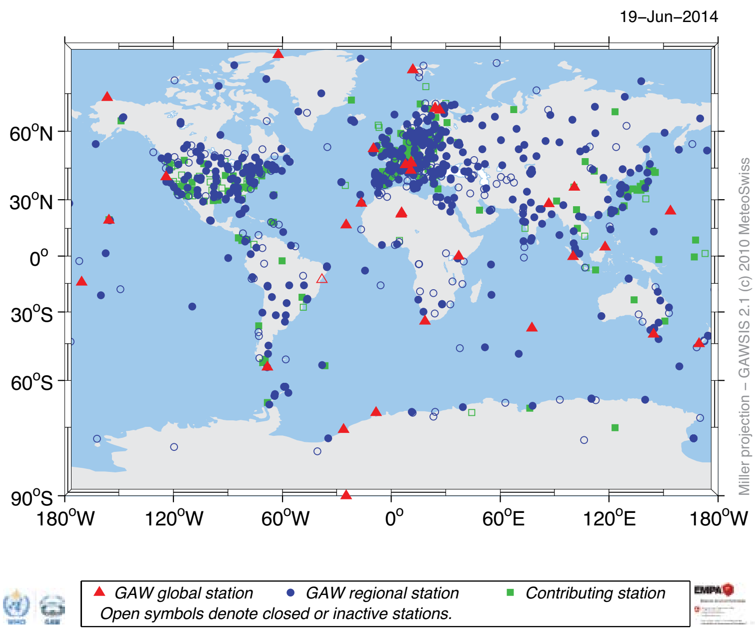
An example of a data product available at WDC-RSAT

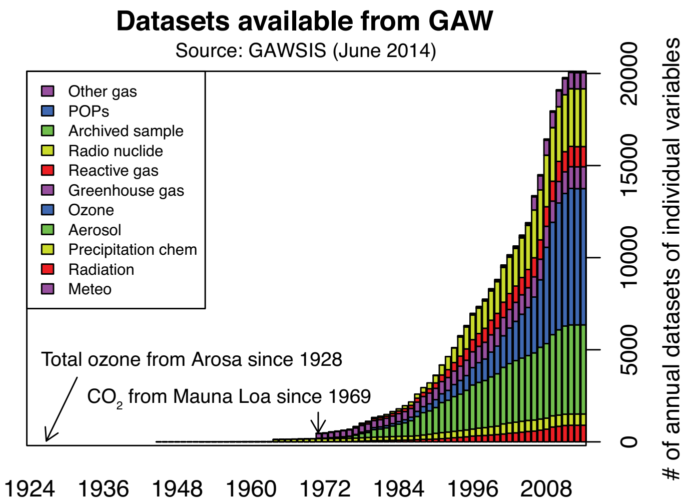
Box 7. GAW Station Information System

(www.meteoswiss.ch/gawsis)

Operated by the Federal Office of Meteorology and Climatology MeteoSwiss, the GAW Station Information System (GAWSIS) is the official catalogue of surface-based GAW stations/platforms, both fixed and mobile. It hosts metadata provided by individual station operators and GAW World Data Centres, as well as a number of other data archives.

Statistics of the datasets available from GAW, contributing networks and predecessor programmes in WDCs





8. TRAINING

Education and training are critical to the long-term success of the GAW Programme, particularly in those developing countries that have committed themselves to maintaining and operating global or regional stations. In addition to training in the operational aspects of the GAW Programme, there is a need to enhance the overall scientific capacity and further expand the scientific infrastructure in the host developing countries. The development of scientific capacity requires a commitment by the host country to providing university trained scientists who will remain in the GAW Programme for many years, to put into practice the GAW specific training they have received.

As part of the WMO capacity development strategy, the German Quality Assurance/Science Activity Centre, funded by the German Federal Environment Agency (Umweltbundesamt) and the Bavarian State Ministry of the Environment and Public Health, established the GAW Training and Education Centre (GAWTEC) in 2001.

The GAW Training and Education Centre (http://www.gawtec.de) is located at the Environmental Research Station Schneefernerhaus, just below the summit of the Zugspitze (2962 m above sea level), the highest mountain in Germany. The Centre provides scientific guidance and instructions to personnel from GAW global and regional stations. These courses are organized at GAWTEC twice a year and cover measurement and laboratory techniques, the theoretical background of atmospheric physics and chemistry, and data handling and interpretation. These courses are intended mainly for station operators and junior scientists from GAW stations located in developing countries and from those stations that still do not meet the required high-quality measurement criteria.

Between its establishment (in 2001) and 2014, more than **280 persons from 58 countries** were trained at GAWTEC. The Centre not only helps with knowledge transfer but also facilitates international networking between the operators of GAW stations.

Each course deals with two or three major topics, covering all relevant parameters in the GAW measurement programme:

- Surface ozone
- Physical properties of aerosols
- Aerosol optical depth
- Precipitation chemistry
- Ultraviolet radiation
- Carbon monoxide
- Volatile organic compounds
- Nitrogen oxides
- Greenhouse gases
- Data evaluation and quality control

In addition to GAWTEC activities, GAW provides support for young scientists who wish to participate in other training events, such as the GURME training courses, the MACC workshops, the educational activities of the Atmospheric Composition Change – The European Network (ACCENT), the summer schools organized by the Siberian Center for Environmental Research and Training, and the European Research Course on Atmospheres, run by the National Centre for Atmospheric Science, in Leeds (United Kingdom). Furthermore, GAW facilitates the participation of early career scientists in the Programme, by supporting their attendance at large international conferences and symposia.

The GAW Training and Education Centre at the Environmental Research Station Schneefernerhaus, Germany

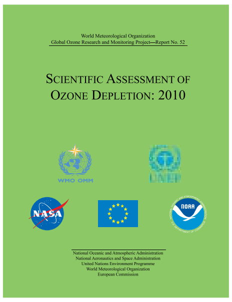
Group photo of GAWTEC trainees, in May 2014, at GAWTEC 26

9. GLOBAL ATMOSPHERE WATCH PUBLICATIONS

The GAW WDCs provide convenient access to the observational data required to generate products and international environmental assessments. As highlighted in the chapters related to GAW foci, there are several application areas that utilize or can potentially utilize GAW data, including chemical data assimilation in numerical weather prediction systems and air quality models, chemical reanalysis, inverse modelling, validation of chemical climate/ weather modelling systems and trend analysis.

One major aspect of the GAW mission is to organize, participate in and coordinate assessments of the chemical composition of the atmosphere on a global scale. In this way, GAW provides reliable scientific information for national and international policymakers, supporting international conventions on stratospheric ozone depletions, climate change and long-range transboundary air pollution. The Global Atmosphere Watch data are used in the following assessments:

Cover page of the WMO/UNEP Scientific Assessment of Ozone Depletion



- WMO/UNEP Scientific Assessment of Ozone Depletion (http://www.esrl.noaa.gov/csd/assessments/ozone/)
- Global Precipitation Chemistry Assessment (http://www.sciencedirect.com/science/journal/13522310/93/supp/C)

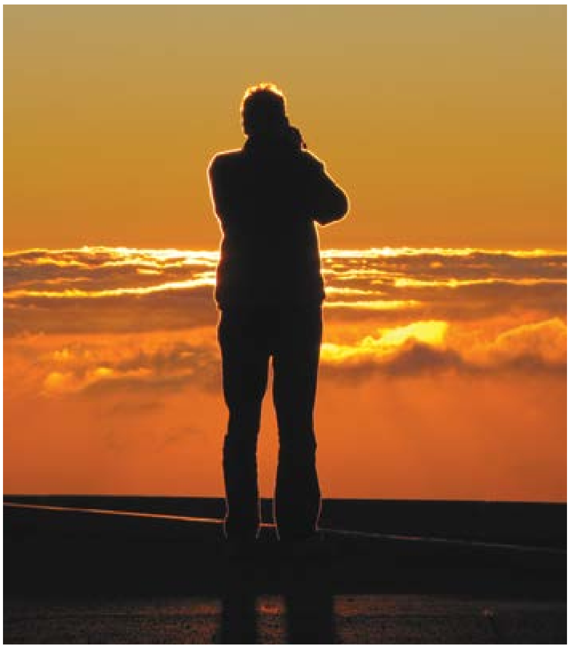
Data from GAW feed several bulletins, including:

- WMO Antarctic ozone bulletins (http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html)
- Greenhouse gas bulletins (http://www.wmo.int/pages/prog/arep/gaw/ghg/GHGbulletin.html)
- Aerosol bulletins (http://www.wmo.int/pages/prog/arep/gaw/aerosol.html)

The Global Atmosphere Watch community contributes to the preparation and publication of GAW reports which include measurement guidelines, standard operating procedures, recommendations, and reports of workshops and expert meetings (http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html).

A number of scientific papers have been published, based on the individual station data and as overview papers (see Collaud Coen et al., 2013; Asmi et al., 2013; Cooper et al., 2014; Petzold et al., 2013). The GAW community is encouraged to mention the Programme in its publications to ensure even better visibility of GAW.

10. THE FUTURE OF THE GLOBAL ATMOSPHERE WATCH



Dobson Langley Absolute Calibration Campaign at Izana Observatory, Tenerife, in September–October 2012

While much has been accomplished over the past 25 years, GAW will continue to evolve in response to societal needs for meteorological and environmental services to reduce risks from high-impact weather and air pollution, and to mitigate the impacts of, and adapt to, changing climate. These services will move towards user-driven products that require integrated observing and prediction systems.

The future will rely on the GAW measurement networks, which remain the backbone of the Programme by providing long-term "climate quality" data on trends and the spatial distributions of important chemical and climate parameters. In order to ensure the availability of reliable information when needed, it will be of paramount importance to maintain a healthy and robust global measurement network and to further expand the network in areas that are still under-sampled. The comprehensive information on atmospheric chemicals provided by GAW will continue to be used in a wide range of applications: to estimate changes in radiative forcing, to constrain budgets of emissions and losses at global and regional spatial scales, and to verify bottom-up emission inventories and process models.

The GAW data will be used increasingly to support advanced numerical weather prediction and climate models, and to further develop warning networks for long-range tracking of intense, episodic events such as volcanic eruptions, sand/dust storms, wildfires and nuclear accidents. Surface-based observations will continue to be useful in the validation of retrievals of atmospheric chemical constituents from satellite radiance measurements. This use will become ever more important as the space-based observing system evolves and the assimilation of satellite retrievals of aerosols and trace gases in weather forecast systems and climate models grows.

The GAW products and services will further expand to meet the needs of megacities and large urban complexes. These will require enhanced efforts to downscale GAW networks and to extend collaborations across a wide spectrum of organizations and authorities such as local governments, public health services, city planning and environmental agencies.

The Global Atmosphere Watch will have to direct efforts at:

- Encouraging and supporting the use of GAW data for global and regional scale model evaluation.
- Improving observational systems and data processing to allow near real-time provision of GAW data for data assimilation.
- Supporting scientific and technical integration of surface, vertical profile and column datasets from different platforms to provide a unified understanding of aerosol and gas distributions.

Further efforts will be made to minimize gaps in the in situ measurement networks at the Earth's surface and in vertical profiles, particularly in data-poor regions like the tropics, climate-sensitive regions like the Arctic and other regions where observations are used to verify compliance with emission-reduction treaties.

These activities will need to be accompanied by enhanced database architectures, allowing for improved metadata exchange and interoperability to promote and facilitate the near real-time delivery of data, fully integrated with WIGOS and WIS.

The GAW Programme is at the dawn of a new and exciting phase of its evolution. There is much to look forward to, building on the significant achievement over the 25 years since its establishment.

WE LOOK FORWARD TO CONTINUED AND EXPANDED COLLABORATIONS AROUND THE GLOBE TO CARRY OUT THE OBSERVATIONS AND RESEARCH NEEDED TO ENABLE SERVICES!

ACKNOWLEDGEMENTS

This brochure is the result of a joint effort of the Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee, GAW scientific advisory groups and expert teams, who contributed the text and plots and reviewed the brochure. The GAW community at large is acknowledged for contributing photos and for its loyalty and commitment to the Programme over many years.

The current composition of the GAW scientific advisory groups, expert teams and Scientific Steering Committee is available at:

http://www.wmo.int/pages/prog/arep/gaw/ScientificAdvisoryGroups.html

http://www.wmo.int/pages/prog/arep/gaw/ExpertTeams.html

http://www.wmo.int/pages/prog/arep/gaw/JSC_OPAG_EPAC.html

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LIST OF ABBREVIATIONS

ACCENT	Atmospheric Composition Change – The European Network
ACTRIS	Aerosols, Clouds, and Trace gases Research Infrastructure Network
AD-Net	Asian Dust and Aerosol Lidar Observation Network
AERONET	Aerosol Robotic Network
AGGI	Annual Greenhouse Gas Index
ALINE	Latin America Lidar Network
BAPMoN	Background Air Pollution Monitoring Network
BIPM	International Bureau of Weights and Measures
CARIBIC	Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container
CAS	Commission for Atmospheric Sciences
CASTNET	Clean Air Status and Trends Network
CCL	Central Calibration Laboratory
CFC	chlorofluorocarbon
CIE	International Commission on Illumination
CIS-LINET	Commonwealth of Independent States (Belarus, Russian Federation and Kyrgyzstan) Lidar Network
CONTRAIL	Comprehensive Observation Network for Trace gases by Airliner
CORALNet	Canadian Operational Research Aerosol Lidar Network
COST	European Cooperation in Science and Technology
DCPC	Data Collection or Production Centre
DEBITS	Deposition of Biogeochemically Important Trace Species
DLR	German Aerospace Centre
EANET	Acid Deposition Monitoring Network in East Asia
EARLINET	European Aerosol Research Lidar Network
EDGAR	Emissions Database for Global Atmospheric Research
EMEP	European Monitoring and Evaluation Programme
EPAC SSC	Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee
ET-NRT CDT	Expert Team on Near Real-time Chemical Data Transfer
ET-WDC	Expert Team on World Data Centres
GALION	GAW Aerosol Lidar Observation Network
GAW	Global Atmosphere Watch Programme
GAWSIS	GAW Station Information System
GAWTEC	GAW Training and Education Centre
GCOS	Global Climate Observing System
GHG	greenhouse gases
GO3OS	Global Ozone Observing System
GURME	GAW Urban Research Meteorology and Environment
IAGOS	In-service Aircraft for a Global Observing System
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IGAC	International Global Atmospheric Chemistry

IGACO	Integrated Global Atmospheric Chemistry Observations
IITM	Indian Institute of Tropical Meteorology
IMPROVE	Interagency Monitoring of Protected Visual Environments
IPCC	Intergovernmental Panel on Climate Change
IWAQFR	International Workshop on Air Quality Forecasting Research
KNMI	Royal Netherlands Meteorological Institute
LLGHG	long-lived greenhouse gas
MACC	Monitoring Atmospheric Composition and Climate
MOZAIC	Measurement of Ozone and Water Vapour on Airbus In-service Aircraft
MPLNET	Micro-Pulse Lidar Network
NDACC	Network for the Detection of Atmospheric Composition Change
NILU	Norwegian Institute for Air Research
NMHSs	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration, United States
OSCAR	Observing Systems Capabilities Analysis and Review
PAN	peroxyacetyl nitrate
PFR	Precision Filter Radiometer
PISAC	Pollution and its Impact on the South American Cryosphere
PMOD/WRC	Physikalisch-Meteorologisches Observatorium World Radiation Centre, Switzerland
POP	persistent organic pollutant
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
PS	primary standard
QA/SAC	Quality Assurance/Science Activity Centre
RCC	Regional Calibration Centre
SAFAR	System of Air Quality Forecasting and Research
SAG	Scientific Advisory Group
SAG-PC	Scientific Advisory Group for Precipitation Chemistry
SAG-UV	Scientific Advisory Group for Ultraviolet Radiation
SOP	standard operating procedure
SSC	Scientific Steering Committee
TCCON	Total Carbon Column Observing Network
TROPOS	Leibniz Institute for Tropospheric Research, Germany
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	ultraviolet
UVI	UV Index
VOC	volatile organic compound
WCC	World Calibration Centre
WCCAP	World Calibration Centre for Aerosol Physics
WDC	World Data Centre
WDCA	World Data Centre for Aerosols

WDCGG	World Data Centre for Greenhouse Gases
WDCPC	World Data Centre for Precipitation Chemistry
WDC-RSAT	World Data Centre for Remote Sensing of the Atmosphere
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WORCC	World Optical Depth Research and Calibration Centre
WOUDC	World Ozone and Ultraviolet Radiation Data Centre
WRDC	World Radiation Data Centre

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