GAW Report No. 234

Global Atmosphere Watch Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD)

(Geneva, Switzerland, 28 February - 2 March 2017)

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

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Edited by Silvina Carou and Robert Vet

Contributing authors:
Wenche Aas, Richard S. Artz, Van C. Bowersox, Greg Carmichael, Amanda Cole, Frank Dentener, Hilde Fagerli, David Gay, Jeff Geddes, Christian Hogrefe, Fiona O'Connor, Jacobus J. Pienaar, Ariel Stein and John Walker

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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at:
http://www.wmo.int/pages/prog/lsp/meteoterm_wmo_en.html.
Acronyms may also be found at: http://www.wmo.int/pages/themes/acronyms/index_en.html.

Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Fax: +41 (0) 22 730 80 40
E-mail: publications@wmo.in

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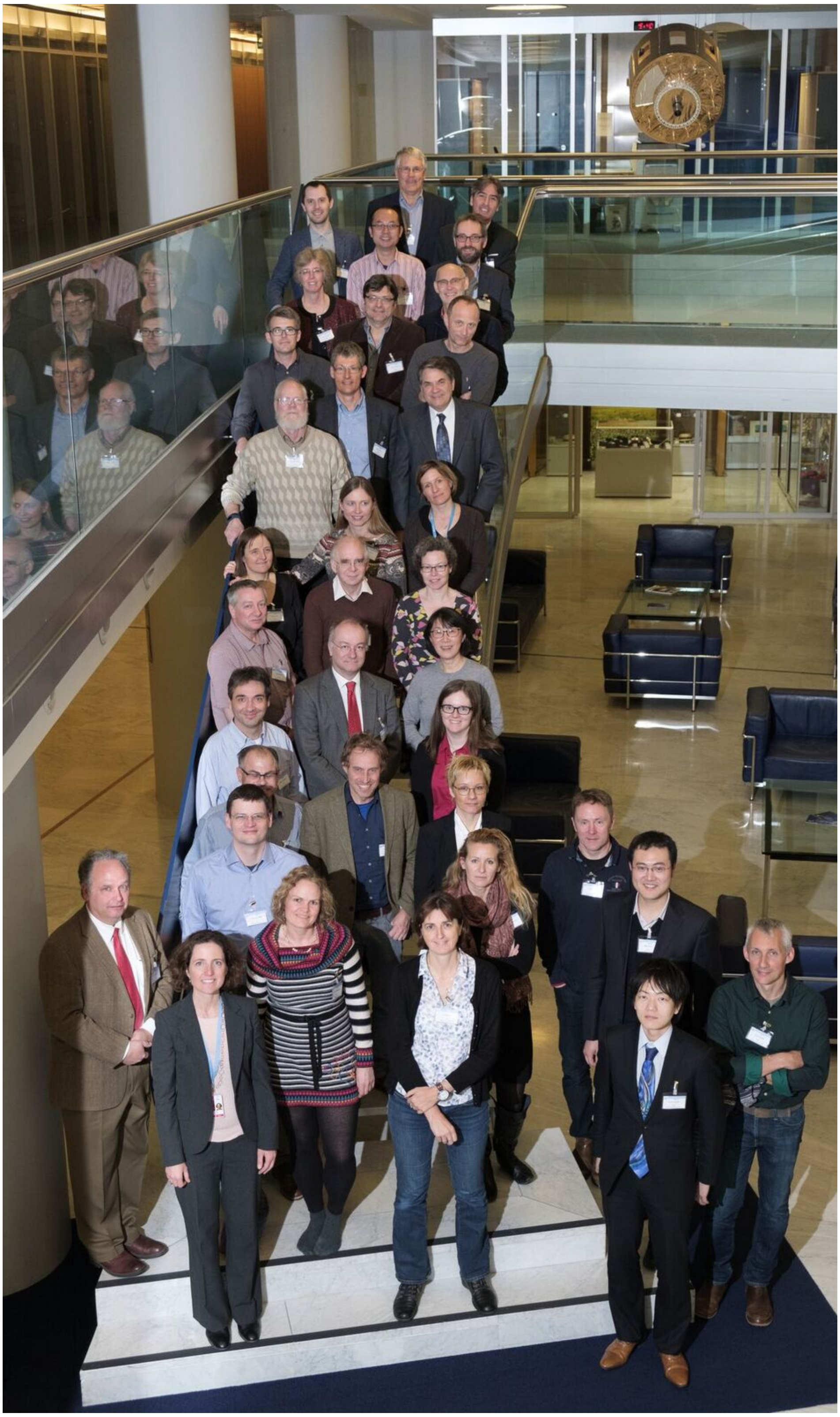

Participants at the Global Atmosphere Watch Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD)
Geneva, Switzerland, 28 February to 2 March 2017

EXECUTIVE SUMMARY

The World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Programme coordinates high-quality observations of atmospheric composition from global to local scales with the aim to drive high-quality and high-impact science while co-producing a new generation of products and services. In line with this vision, GAW's Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD) has a mandate to produce global maps of wet, dry and total atmospheric deposition for important atmospheric chemicals to enable research into biogeochemical cycles and assessments of ecosystem and human health effects.

The most suitable scientific approach for this activity is the emerging technique of measurement-model fusion for total atmospheric deposition. This technique requires global-scale measurements of atmospheric trace gases, particles, precipitation composition and precipitation depth, as well as predictions of the same from global/regional chemical transport models. The fusion of measurement and model results requires data assimilation and mapping techniques.

The objective of the GAW Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD), an initiative of the SAG-TAD, was to review the state-of-the-science and explore the feasibility and methodology of producing, on a routine retrospective basis, global maps of atmospheric gas and aerosol concentrations as well as wet, dry and total deposition via measurement-model fusion techniques; as well as to develop a path forward for a GAW MMF-GTAD project.

The three-day workshop was attended by 41 participants from 12 countries with expertise in atmospheric measurements and modelling, data assimilation, and ecosystem and human health effects; including chairpersons or representatives from all relevant GAW Scientific Advisory Groups. The workshop commenced with keynote presentations on major international science and policy drivers and needs for global maps for total deposition, aerosols and gases from ecosystem services, global nitrogen and human health perspectives. Subsequent sessions, designed to review the state-of-the-science, consisted of overview presentations and panel discussions on ongoing measurement-model fusion projects for total atmospheric deposition in the United States, Canada, Sweden and the United Kingdom; existing and planned ground-based and satellite-based measurements of precipitation, aerosols, reactive gases, wet, dry and total deposition of important atmospheric chemicals; and recent global, hemispheric and regional chemical transport and deposition modelling activities. The feasibility and methodology of possible measurement-model fusion activities in GAW were the focus of a plenary session and two parallel breakout discussions, one on measurements and the other on modelling. A final plenary focused on merging conclusions and recommendations from the breakout groups.

Participants strongly supported the formal establishment of a GAW Project on Measurement Model Fusion for Global Total Atmospheric Deposition, with the objective to produce the best possible global maps of deposition and atmospheric concentrations of gas and aerosol species in order to meet the needs of policy-making and scientific agencies, programmes and communities in the areas of human health, ecosystem health, and climate change. It was agreed the project should focus first on ground-level ozone as well as sulphur and nitrogen species already monitored in regional-scale networks.

The following general conclusions and recommendations arose from the workshop:

- There are many ecosystem- and human health-related national and international policy and science drivers for developing global maps of total atmospheric deposition as well as aerosol species and reactive gases. These include the UN Convention for Biological Diversity's Strategic Plan for Biodiversity and Aichi Target 8, the 2015 Sustainable Development Goals, the Integrated Nitrogen Management System and International Nitrogen Initiative, WHO's Global Burden of Disease Assessment and Air Quality Guidelines, and many more.
- There are commonalities as well as differences in the existing national MMF-TAD projects. In general, all approaches are retrospective and typically based on model reanalyses (except for the United Kingdom). High quality datasets with good temporal resolution at selected global and regional measurement sites are key for MMF-TAD.
- A number of chemical species were recommended for measurement in new and/or existing measurement networks to enhance the MMF-GTAD project in the future and meet the needs of the ecosystem, human health and other user communities. Those considered high priority at the global scale were organic nitrogen, ammonia, nitrogen oxides, iron (over the ocean) and dust.
- There is a need to extend the GAW measurement network into regions that are presently poorly covered. The group recommended the use of models and satellites to prioritize/determine high-value measurements, as well as performing intensive measurements at a few locations (e.g. supersites) to improve process-based modelling.
- The group recommended that GAW adopt low cost measurement methods that can be implemented on a large scale where possible (e.g. passive sampling of NH_3) and accept the associated data if properly documented, and that the Scientific Advisory Group for Reactive Gases establish recommended methods and Standard Operating Procedures (SOPs) for these methods.
- Publicly-available, integrated, high quality global datasets were identified as critical to the success of the MMF-GTAD Project. The WMO World Data Centres (WDCs) and national and international data centres were seen as the major sources of the measurement data.
- There is a need to establish consistency in methods for estimating/measuring dry deposition. Adoption of a common inferential modelling framework using measured concentrations, meteorology, surface characteristics and location-specific parameterizations is recommended for the development of site-specific dry deposition estimates.
- Some aspects of deposition modelling are still very uncertain, including land use and dry deposition schemes and emissions data. There is a need to better link land use/land cover to deposition in order to understand the sensitivity and response of receptors to deposition. The group also identified the need to use new techniques (e.g. inverse modelling) to improve emissions, as well as satellite data as potentially valuable for small emission corrections (e.g. updating emission inventories to a more recent year) and for deducing natural sources.
- A significant body of chemical transport modelling work exists and is suitable for use in a future MMF-GTAD Project (including HTAP, AQMEII, EMEP, etc.).
- Satellite measurements and their products are evolving rapidly and should be included in future measurement-model fusion activities. All available measurements should be further exploited and understood.
- When providing the 'best estimate' of total (dry plus wet) deposition, it is important at the same time to make uncertainty estimates and constrain the results.

- Collaboration with relevant science teams and organizations working on similar issues is important in order to leverage applications in other areas of science to assist with measurement-model fusion.

The final plenary adopted the recommendation of the Modelling Breakout Group that the MMF-GTAD Project be undertaken in three stages that reflect short, medium and long-term goals and work plans:

- **Goal 1 (Short Term). Ensemble Model-Measurement Fusion for the Year 2010.** Multiple existing model and data activities will be used to fuse model-ensemble results with measurement data for the year 2010 to produce global maps of concentrations in air and precipitation and of wet, dry and total deposition for ground-level ozone, sulphur and nitrogen. Other products will include a comprehensive global dataset and model-ensemble output files.
- **Goal 2 (Medium Term). Stitching of Global/Regional Measurement-Model Products.** Existing and newly-developed regional and global MMF products will be stitched together to produce merged global maps of gas, aerosol and precipitation concentrations as well as wet, dry and total deposition fluxes.
- **Goal 3 (Long Term). Global Reanalysis/Assimilation of Concentrations and Deposition Fluxes.** One or more global modelling systems will be developed involving the operational reanalysis and data assimilation of observations of concentration, column burdens, and deposition fluxes.

An Ad Hoc Data Group was created to investigate the workload and needs associated with gathering data from previous and ongoing science assessments and model evaluation activities. In the short term, the Group will focus on the collection of data for two specific years: 2010 and either 2014, 2015 or 2016. In the long term, the Group will consider the feasibility of compiling global datasets every 10 years, with 2020 as the next long-term target year, and examine other data-related issues.

The workshop concluded with a recommendation that a 'Roadmap to the Future' be written to document a path forward for the GAW MMF-GTAD Project that includes the vision, goals, management, work programme, potential participants and scheduling of the project.

Next steps include the following:

- Finalize and publish the workshop report as a formal Global Atmosphere Watch Report (to be made available electronically on http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html).
- Develop a 'Roadmap for the Future' that documents a specific plan forward for the GAW MMF-GTAD Project following the three goals accepted during the workshop.
- Initiate an Ad-Hoc Data Working Group to investigate the workload and needs associated with gathering data from previous and ongoing science assessments and model evaluation activities.
- Initiate Goal 1 of the project as identified in the workshop.
- Share the project plan with existing and potential partners and contributors with a view to securing expertise, collaboration and financial resources to implement the three goals of the project.

1. INTRODUCTION

WMO's Global Atmosphere Watch (GAW) Programme coordinates high-quality observations of atmospheric composition across global to local scales with the aim to drive high-quality and high-impact science while co-producing a new generation of products and services. GAW's Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD) has a mandate to produce global maps of wet, dry and total atmospheric deposition for important atmospheric chemicals. The purpose of the maps is to enable research into biogeochemical cycles and assessment of ecosystem and human health effects.

The most suitable scientific approach for this activity is the emerging technique of measurement-model fusion for total atmospheric deposition (MMF-TAD). This technique requires global-scale measurements of atmospheric trace gases, particles, precipitation composition and precipitation depth, as well as predictions of the same from global/regional chemical transport models. The fusion of measurement and model results requires objective analysis and mapping techniques that are applicable to the production of global maps of selected reactive gases, aerosol species, and wet and dry deposition. By its nature, this is an effort that cuts across many of GAW's focal areas including total atmospheric deposition, aerosol, reactive gases and modelling applications.

MMF-TAD projects are currently being carried out in Sweden, the United Kingdom, the United States and Canada. The methodology employed by each country is different and not necessarily applicable on a global scale. The GAW Workshop on Measurement-Model Fusion for Total Atmospheric Deposition was organized in order to explore the feasibility and methodology of producing, on a routine retrospective basis, global maps of atmospheric gas and aerosol concentrations as well as wet, dry and total deposition via measurement-model fusion techniques; and to develop a path forward to achieve these maps.

The expected outcomes of the workshop were:

- A review of the current state of global measurements (ground-based and satellite), chemical transport modelling (global and hemispheric), and measurement-model fusion/mapping techniques.
- Key recommendations, conclusions and a project plan for moving forward on a GAW project on Global MMF-TAD.
- Identification of MMF-TAD products (global maps) and timelines.
- Identification of project participants, working groups and coordinators.
- Coordination with major science and policy programmes interested in MMF maps.

The workshop was attended by 41 participants from 12 countries with expertise in atmospheric measurements and modelling, data assimilation, and ecosystem and human health effects; including chairpersons or representatives from all relevant GAW Scientific Advisory Groups.

2. SCIENCE AND POLICY DRIVERS FOR GLOBAL MEASUREMENT-MODEL FUSION MAPS OF ATMOSPHERIC CONCENTRATIONS AND DEPOSITION

Three keynote speakers were invited to the workshop to present some of the major international science and policy drivers behind the production of global maps for total deposition, aerosols and gases from the perspective of ecosystems, global nitrogen and human health. The keynote speakers were, Dr Kevin Hicks (University of York), Rognvald Smith (Centre for Ecology and Hydrology), and Dr Sophie Gumy (World Health Organization (WHO)). The main messages conveyed by the speakers are summarized below.

The ecosystem perspective

There are many ways to communicate science to policy-makers. One example is the concept of planetary boundaries by Rockström et al. (2009), which shows that the safe boundaries for nitrogen and biodiversity are exceeded. Challenges related to the atmosphere (climate, human health, ecosystem impacts) are closely inter-linked and there are efforts to move policy toward more integrated approaches (e.g. looking at co-benefits). One of the international drivers for global deposition and ambient concentration estimates from an ecosystem perspective is the Convention for Biological Diversity (CBD)’s Strategic Plan for Biodiversity and its 20 Aichi Targets. Aichi Target 8 specifically deals with reducing pollution: *By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity.* The indicators identified for Aichi Target 8 include trends in emissions and trends in nutrients (e.g. total nitrogen deposition by region per year). Another driver is the 2015 Sustainable Development Goals (SDGs), of which there are 17 SDGs, 169 Targets, and a host of indicators. Atmospheric deposition is linked to several of the goals and targets, including those related to food production (under goal 2), reducing nutrient deposition to coastal zones (under goal 14), and reducing the degradation of land that supports biodiversity and ecosystem services (under goal 16). The Biodiversity Indicator Partnership (BIP), a multidisciplinary expert group that is part of CBD, helps to identify indicators toward SDGs and provides advice on how to best hit the targets. This is a good mechanism for using scientific data to feed into international agreements.

Atmospheric pollutants known to impact ecosystems include wet and dry deposited reduced nitrogen (NHx), oxidized nitrogen (NOy), sulfur oxides (SOx), and dust and base cations, as well as tropospheric ozone (O_3). There are numerous national and global ecosystem effects studies being carried out using atmospheric deposition and concentrations of these pollutants. They include modelling of critical loads and critical levels to inform policy, as well as studies of the effects on vegetation and crop yield. There is an interesting difference between soils and deposition over ecosystems in China/Asia compared to Europe. In China, where high emissions and deposition of base cations have a neutralizing effect on acidification, the scientific recommendation is to reduce sulphur and nitrogen deposition to avoid acidification and reduce base cation deposition regardless of whether the critical load is exceeded or not. There is also an interesting difference between maps of acidity where atmospheric ammonia (NH_3) has a neutralizing effect versus when it enters the soil where it can have an acidifying effect. A global study of the amount of deposition over protected areas under the Convention for Biological Diversity shows that the Aichi Target 8 will not be met. General considerations from an ecosystem perspective for the atmospheric community include the following:

- There are good national and regional examples of science-to-policy links.
- Global policy arenas and delivery of mechanisms exist but the impacts of total atmospheric deposition on biodiversity and ecosystem services is not sufficiently represented.
- Mapping the relationship between total atmospheric deposition and economic ecosystem services (e.g. biodiversity, timber production, water supply) is a challenge.
- There is a need to improve the process by which total atmospheric deposition is included as an official indicator and develop more specific indicators for impacts.
- Several of the SDG targets and indicators are related to total atmospheric deposition, however, there is a need to explore other indicators to improve the link.
- There is a need for the atmospheric community to work with the ecosystem impacts community to improve dose-response functions and to determine which atmospheric species are important to model and measure.
- There is a need for greater consistency in deposition schemes from models matched to the receptors that are sensitive to the pollutants, as well as a need to tune into the atmospheric and ecosystem process scale to look at different sources and sinks.

The nitrogen perspective
For nitrogen (N) on a global basis, there has been an evolution from science-based activities, such as the International Nitrogen Initiative (INI), to a more integrated nitrogen programme like the Integrated Nitrogen Management System (INMS), which encompasses both the science and policy arenas. The INI work has demonstrated the clear role of atmospheric N within the N cycle, but its role within the N cascade (a more complex and realistic concept of how a N molecule affects ecosystems) is less clear. There is a need to look at direct and indirect receptors. A European N assessment identified five key threats of excess N: water quality (water contamination, freshwater and coastal fish, N and P eutrophication), air quality (NOx, $PM_{2.5}$, O_3 and human health effects), greenhouse gas balance (N_20), soil quality (organic N, acidification) and biodiversity (eutrophication, acidification, soil degradation, etc.). There are two versions of an economic argument for why we should care about N. One pertains to the estimated future costs and benefits to human health, ecosystems, climate and agriculture; and the other pertains to the cost associated with the inefficient use of the N that we have introduced into the system. The INMS looks at N as a solution rather than a problem, an important perspective in the policy arena in terms of overcoming barriers and demonstrating profits to be made. In 2015, UNEP and INI launched "Towards INMS", a global initiative that consists of four components: C1 – Tools and methods for understanding the N cycle, C2 – Global and regional quantification of N use, flows, impacts and benefits of improved practices, C3 – Regional demonstration and verification, and C4 – Awareness raising and knowledge sharing. A subcomponent of C1 with a clear link to GAW and of relevance to the MMF-GTAD project is the development of N system indicators and includes work on national N budgets, nitrogen use efficiency (NUE) approaches, and relating different N indicators (i.e. for soils, oceans, crops, natural vegetation, etc.). C2 encompasses a more regional approach and includes the preparation of a Global Nitrogen Assessment by 2020 and future N storylines and scenarios with obvious links to atmospheric modelling and the MMF-GTAD activity. C3 and C4 deal more with management and policy.

The health perspective
From a global human health perspective, the single most studied and most damaging pollutant is particulate matter (PM). While it is not the only pollutant of concern, it is the one used as a proxy indicator for many health studies and one for which there is a large body of evidence. The toxicity of PM, including what chemical constituents are responsible for triggering health

effects, is not well understood. There is a strong relationship between particle size and health effects (the smaller the particle the deeper they penetrate into the respiratory system) with $PM_{2.5}$ being of primary concern. Health outcomes strongly associated with PM include child pneumonia, lung cancer, cataracts, pulmonary and cardiovascular diseases and these are included in WHO’s Global Burden of Disease assessment. There are many other health effects for which the evidence is not as strong and need better quantification. Ambient air pollution is responsible for 3 million premature deaths per year globally while indoor air pollution from household fuel combustion (also influenced by and a contributor to outdoor pollution) accounts for 4.3 million deaths per year globally. Much of the work of the WHO includes gathering data and raising awareness (including air pollution monitoring) in cities around the world. The Global Platform on Air Quality and Health initiative - a collaboration between WHO, WMO and other agencies/sectors – works on combining satellite imagery, chemical transport models and ground level measurements to estimate $PM_{2.5}$ exposure using the Data Integration Model for Air Quality (DIMAQ). Also, as part of its normative work and support to countries, WHO develops air quality guidelines for PM_{10}, $PM_{2.5}$, SO_2, NO_2 and O_3. WHO is also the custodian of three SDG indicators (e.g. annual mean PM in cities). It also promotes the work of the Climate and Clean Air Coalition to find synergies among climate and air quality policies and maximize co-benefits, particularly with respect to reducing short-lived climate pollutants. Estimating population exposure to $PM_{2.5}$ requires accurate estimates of exposure to air pollution at global, national and local scales, including measurement of uncertainty. There is a clear synergy with WMO in terms of enhancing air quality monitoring systems, particularly in countries with no monitoring systems in place. The health sector needs the experience and knowledge of the atmospheric/meteorology community to improve population exposure estimates and to improve understanding of meteorological factors influencing PM levels in cities.

The keynote speakers clearly demonstrated the multi-agency, multi-programme need for global maps of atmospheric deposition and atmospheric gas and particle concentrations.

3. STATE OF THE SCIENCE

3.1 Current projects on measurement-model fusion for total atmospheric deposition and ambient concentrations of gases and aerosol species

This session of the workshop described methods currently used for national/regional scale measurement-model fusion (MMF) projects as well as a detailed description of data assimilation approaches and concepts. Presentations were made on the United States Total Atmospheric Deposition project; the Swedish deposition mapping project; the Canadian ADAGIO project; the objective analysis techniques used in the Canadian project; the United Kingdom's statistical method; satellite-related measurement-model fusion and its application to global health and deposition activities; and a description of chemical data assimilation and its applicability to retrospective measurement-model fusion.

Common themes emerged within and between the existing projects that merge measurements and models. All approaches are retrospective and typically based on model reanalyses (except in the UK's approach). Timescales for measurement data (surface and satellite) range from hourly to monthly. It was concluded that harmonization of different datasets is needed as a first step and that quality datasets with good temporal resolution are extremely valuable. In general, assimilation is performed with concentrations, not fluxes, and dry deposition velocities and precipitation amounts need to be determined separately. Models alone are the source of deposition velocities, which are the largest source of uncertainty. The data assimilation or fusion methods involve deriving correlation lengths or radii of influence and there are different methods for making this derivation.

A number of common challenges were also identified. Managing many variables creates large requirements for computer memory and processing. Correlated or anticorrelated diurnal patterns of concentration and deposition velocity can create systematic biases on the order of 30% (dealt with in the U.S. TDEP and Canadian ADAGIO methods, but not explicitly discussed in the other methods). Sub-grid variability of land use and concentrations contribute to the mismatch between model grid values and point measurement values, while out-of-date emissions and land use maps need to be addressed by the models. Aerosol size distributions are very important for particle deposition velocities, and chemical composition of aerosols is needed to assess the fluxes of chemical species, but measurements and models are not well matched or are incomplete for both size and composition of aerosol.

There were some clear differences between the existing national approaches. In Canada and Sweden, precipitation concentration fields are generated by MMF while in the United States they are generated by spatial interpolation between measurement sites. The bidirectional fluxes of NH_3 are included in the U.S. TDEP modelling product, but not in the Canadian or Swedish models. The bidirectionality of the fluxes raises challenges due to the inconsistency of bias-adjusting the NH_3 concentrations. MMF mapping in Sweden is also done for ozone. The UK method does not use a chemical transport model to provide its background field, but rather combines concentration fields (interpolated via conventional or Bayesian kriging), climatic fields, land use maps, and inferential dry deposition calculations to map wet and dry deposition. The UK also implements a version of the EMEP model specifically adapted for the country which provides alternative modelled deposition estimates based on emissions inventories and modelled weather that drives the dispersion and atmospheric chemistry components.

On the topic of satellite MMF, current satellite measurements include O_3, nitrogen dioxide (NO_2) and aerosol optical depth (AOD). Models are used to estimate boundary/surface layer concentration values from total column density measurements. Methods for using satellite values to derive NO_2 and NO_y deposition patterns and trends have been published. Satellite measurements face similar challenges as chemical transport models in terms of comparing grid-average values to point values at surface sites. In general, the sensitivity of satellite measurements to surface values is quite low, however, a major strength of satellites is their ability to constrain the total pollutant budget and improved emission estimates.

Overarching messages and recommendations

A number of overarching messages and recommendations were made during the presentations and during the panel discussion regarding a future project on MMF for total atmospheric deposition. It was agreed that an ensemble model approach is likely the best option (except in cases where a particular model has been demonstrated to perform better than an ensemble of models); however, the models used in the ensemble must be shown to predict ground-level concentrations to reasonable specifications. There is also a need for a common measurement dataset of good quality. In terms of emission estimates in the chemical transport models, these can be refined using satellite data and/or mass-balance approaches. If possible, modellers should look for opportunities to improve/harmonize land cover schemes. Atmospheric process studies need to be undertaken to better understand and constrain the model dry deposition values for different land surface types and chemical species. A realistic assessment of error is part of the MMF process and there is a need to assess and report the uncertainties associated with the final MMF maps. Finally, MMF will require the measurement and modelling communities to work together and will provide guidance and opportunities to improve both areas.

3.2 Surface- and satellite-based measurements for use in MMF-GTAD

This session of the workshop discussed existing and planned ground-based and satellite-based measurements of precipitation, aerosols, reactive gases, and wet, dry and total deposition performed by major measurement programmes or networks that could be applicable for use in global measurement-model fusion projects. Presentations were given on ground-level measurements of reactive gases, aerosols, and precipitation chemistry and deposition in GAW and other networks; satellite measurements of aerosols and related gases; how remote sensing can be used to assess the impact of air quality on vegetation; precipitation data and products available through the Global Precipitation Climatology Centre; and observations and modelling of chemical inputs to the oceans. The main messages from presentations and discussions are summarized below.

Surface measurements of relevant species across GAW regional and national networks are divided into separate datasets with sites for gases, sites for aerosol, and sites for precipitation chemistry, which are seldom collocated. Sustained financial and institutional support for measurements is a challenge, since the impetus for establishing them was originally the monitoring of acid rain. A global data repository that includes all of the raw regional network observations is unlikely. Rather, a repository that gathers and screens finalized statistical summary data from many networks/programmes for a MMF-GTAD project would be useful because it would take advantage of region-specific knowledge and the different protocols/strategies/data quality of the various networks. Ammonia is rarely defined as a programme or network measurement, but higher density observations are needed. Direct observations of dry deposition fluxes exist, but have not been compiled systematically.

Measuring aerosol composition in a network is difficult given there is no single instrument that measures everything. A systematic recommendation of the most important variables would be useful (this speaks to understanding the user requirements). Access to data from developing countries remains a problem, and the quality of the data can be difficult to ascertain. Still, the number of stations reporting aerosol composition is growing (as is the community of users). A number of European sites report online aerosol AMS measurements. There is potential for fitting flux towers with methods for aerosol deposition measurements.

Estimating deposition from satellite data is possible under certain conditions for certain species, but many relevant trace gases have reduced sensitivity in the boundary layer (NO_2 is an exception). Observations of tropospheric composition will soon be vastly improved by a constellation of geostationary instruments. While aerosol speciation cannot be directly measured, dust is an example of a species whose deposition could be successfully estimated from space. For most gas phase species, combining the satellite observations with chemical transport models might be the best way to estimate atmospheric deposition. Such estimates remain unconstrained due to many processes that are not directly observable.

The DO3SE model is an example of a standard resistance scheme that allows for flux-based estimates of vegetation exposure to O_3. Satellite-based estimates of solar-induced fluorescence have the potential to identify instances of plant stress (e.g. air quality impacts on vegetation). Satellite-derived AOD also has potential to inform plant-atmosphere interactions (given the impact of aerosol scattering on diffuse photosynthetically active radiation (PAR)). MODIS has been important for estimating leaf area index (LAI) and vegetation growth. Photosynthesis-stomatal conductance models should ideally be used in the deposition component of chemical transport models. Key challenges related to enhancing the timing and magnitude of LAI data include better understanding of plants in mid-latitudes, evergreens, phenology, and ground-truthing.

The Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD) has compiled global scientifically-acceptable measurements of wet deposition covering national/regional networks and GAW stations. The SAG-TAD has produced a manual for the GAW Precipitation Chemistry Programme, but no such manual exists for dry deposition measurements. The 2014 global assessment of precipitation chemistry and wet deposition (Vet at al., 2014) was a milestone that identified spatial patterns of major ions in precipitation and identified major gaps and uncertainties. A key finding and challenge was that dry deposition is inconsistently and poorly monitored worldwide. Scientific input is needed to identify the most important chemical species that need to be monitored and to guide and initiate measurements of known quality. Large areas of the world remain unmonitored for gases, aerosols and precipitation chemistry.

The Global Precipitation Climatology Centre (GPCC) has more than 25 years of experience in providing gridded fields of precipitation amounts based on precipitation gauge measurements from about 100,000 reporting stations. The products are high-quality data sources that can be used directly for estimating wet deposition. Products in their portfolio include rapid (first guess) daily precipitation amounts, monthly precipitation totals, drought indices, climatologies, etc. at a spatial resolution of 0.5°, 1.0° or 2.5°. Depending on the product, the datasets are publicly available as soon as 5 days to 2 months after measurements.

Atmospheric inputs of N, phosphorous (P) and iron (Fe) are also important to ocean biogeochemistry. While measurement coverage is poor over land, the situation is even worse over the oceans. Ship-based aerosol sampling results for NO_3^- and NH_4^+ have been compiled into a database (based on campaigns from 1995-2012), and comparisons with model output are encouraging, but agreement remains poor in many areas. Ship-based measurements are extremely limited and may not be temporally representative in that they are not fixed in place and not collected continuously. Models indicate the predominant deposition process over the ocean is wet and it is very difficult to establish a large wet deposition database from ship-borne measurements. NH_3 emissions from the oceans were identified as important for global atmospheric deposition modelling.

Overarching messages and recommendations

There is a need for consensus on what measurements should be prioritized. NO_2, HNO_3 and NH_3 are obvious trace species that still lack basic coverage over much of the world. Wet deposition networks are the most mature, but there is a need for organic nitrogen to be included in order to complete our understanding of nitrogen mass balance and biogeochemical cycling. The same is true for phosphorous and organic acids. Intensive measurements at a few locations would be valuable to improve process-based modelling so it may be useful to add supersites at some locations at the expense of reducing coverage elsewhere.

Model output should be used to prioritize/determine high-value measurements that may be low-cost and could be implemented in a large-scale organized effort. This would be especially important in choosing where to invest limited resources in areas such as South America, Africa, and parts of Asia. Meanwhile, the total atmospheric deposition community needs to provide guidance on what modellers can do to accommodate the use and interpretation of model output, including what species/diagnostics are needed, and what is the best temporal resolution.

Documentation of a standard procedure/manual for dry deposition measurements would facilitate consistent methods in the field and laboratory. This would require a consensus on what measurements/methods could constitute a standardized procedure. EANET has a Standard Operating Procedure (SOP) for dry deposition measurements, and could be considered in developing a "world standard". This would include recommendations on minimum data requirements and formatting to establish consistency in the exchange and application of dry deposition datasets for model evaluation.

The question was raised as to whether acid deposition is becoming a less effective driver for sustaining deposition measurements. To add further impetus to global measurements, other policy- and science-related issues include: constraining aerosol lifetimes (given their critical role in climate and radiative transfer) and understanding carbon and other biogeochemical cycles as well as linkages among them. Other scientific communities should be consulted (e.g. ecology) for other relevant questions and drivers.

A harmonized repository for all regional/global network data with uniform units and formats would be of great value to researchers, but was seen as unlikely in the near future. In the meantime, the GAW Station Information System is attempting to make metadata available in a common format.

3.3 Chemical transport and atmospheric modelling for application to MMF-GTAD: global, hemispheric and regional modelling, evaluation and comparability

This session of the workshop discussed global, hemispheric and regional chemical transport and deposition models, modelled species, model evaluation and comparison studies and future plans applicable to measurement-model fusion for total atmospheric deposition, aerosol species and gases. Presentations were given on global/hemispheric chemical transport models, model comparison studies and model-evaluation studies including the Air Quality Model Evaluation International Initiative (AQMEII); global modelling activities of the Copernicus Atmosphere Monitoring Service (CAMS); regional and hemispheric modelling using the American CMAQ model; and regional modelling in Europe and Asia. The main messages from the presentations and discussions are summarized below.

There have been a number of recent benchmark model intercomparison studies and model evaluation studies. PhotoComp, a photochemical multi-model intercomparison aimed at informing IPCC AR4, showed that there were large differences in the ratios of dry/wet deposition between the models. The same was found in later intercomparison studies (e.g. Vet, 2014). PhotoComp found that the ensemble showed the best performance in Taylor diagrams, and there were also indications that the higher resolution models performed better than the lower resolution models. Vet et al. (2014) used the HTAP Phase 1 ensemble for 2000 to create global deposition maps and produced a benchmark set of observations. This set of observations has been very useful and should be updated (e.g. 2010 observations). Vet et al. (2014) found that total deposition relies almost completely on model estimates, and it is important to find a way to provide sufficient constraints on the error in the results (e.g. mass balance consistency with what we know about emissions). In ACCMIP (Lamarque, 2013), chemistry climate models were run for 1850-2100 to inform the IPCC AR5 report. Performance statistics for ACCMIP were found to be very similar to statistics for HTAP1 and PhotoComp, showing that models have not improved much. The reasons for this lack of improvement are not clear, but uncertainties in emission inventories may play a major role. Organic nitrogen is also an important issue (representing 20-30% of N budget, Kanakidou, 2016). Global model intercomparison data are also becoming available from HTAP 2, with regional 'components' in AQMEII and the Model Intercomparison Study for Asia (MICS Asia).

The Copernicus Atmosphere Monitoring Service (CAMS) provides global and regional atmospheric composition data, forecasts and analyses, as well as emission and supplementary products. The global C-IFS model (as well as many of the regional models in CAMS) assimilate satellite data for a range of components (NO2, CO, SO2, O3, AOD, CH_4, CO_2). A reanalysis for 2003 onwards is available. Data assimilation using a 4D variational approach improves the modelled total column and tropospheric values, but has a small influence on the surface concentrations (due to lack of signal from the satellite at the surface and the strong source/sink terms in the model). Dry deposition velocities are pre-calculated and dry and wet deposition fluxes are archived and can be used but have not been evaluated.

The Air Quality Model Evaluation International Initiative (AQMEII) brings together North American and European regional scale air quality modelling communities to exchange knowledge and support the use of models for policy development, and also to prepare coordinated research projects and model intercomparison exercises. Phase 1 (2009-2012) deposition fields are available but not much analysis has been performed with them to date. Phase 2 (2012-2014) focused on coupled meteorology and chemistry models and showed that model to model differences are generally larger than the effect of feedbacks. The feedbacks were found to be important during summer and intensive fire episodes. Phase 3 (2014-2017) contributes to HTAP 2 and intends to apply and compare modelling techniques for assessing the long range transport influence on regional air quality. There will be a joint HTAP, AQMEII, MICS special issue in the journal *Atmospheric Chemistry and Physics* in 2017. A new phase is being planned now, and there is a possibility for MMF-GTAD objectives to inform AQMEII on what is important to analyse. In a range of past and present AQMEII analyses, dry and wet deposition rates have been found to be highly variable between models and substantial variability has been found in the inorganic aerosol chemistry (e.g. NH_3, NH_4, SO_4, NO_3).

The Community Multi-scale Air Quality (CMAQ) model is a multi-scale model, coupled to the Weather Research and Forecasting (WRF) model (both on-line and off-line). The model has been developed in a transparent way, with many possible parametrization/modules available (e.g. different chemical mechanisms). The code is openly available on GitHub (https://github.com/USEPA/CMAQ). A recent version includes organic nitrogen species and updates to windblown dust (important for base cations). The model is also linked to the Environmental Policy Integrated Climate (EPIC) model (soil biogeochemistry and agricultural management practices for fertilizer application), the Variable Infiltration Capacity (VIC) hydrology model, and the Soil and Water Assessment Tool (SWAT).

In terms of regional modelling in Europe, the EMEP/MSC-W model underpins many policy processes in Europe. A considerable amount of work has been done on the dry deposition schemes within the EMEP model, and the model is well documented and evaluated. Results from the EuroDelta-Trend exercise show a large spread in modelled wet deposition, and partly also in the trend for the period 1990-2010. The NOy deposition per component and region (EMEP/MSC-W model results) indicates that dry deposition of HNO_3 is the most important component. Dry deposition rates are very uncertain and few observations exist. Dynamic ammonia emissions, bidirectional exchange and within-grid variability are other areas currently under development. Data on the partitioning of N are still limited and organic N needs further consideration. A model/concept to downscale regional model results to the urban scale, called uEMEP, is being developed.

In Asia, the MICS-Asia model intercomparison/evaluation consisted of 3 phases: 1998-2000 for S, 2004-2009 including more species, and 2013 for oxidants and PM. There were 10 participating models. Data from the Acid Deposition Monitoring Network in East Asia, EANET, were used to evaluate model results. There was an overestimation of precipitation for South-east Asia and an underestimation for other parts of Asia. The EANET measurement data were relatively well reproduced by the models except in certain countries. In general, for SOx and NOx, wet deposition is important in the south while dry deposition is important in the north. For reduced nitrogen, dry deposition is important over land and wet deposition is important over the ocean. Surface concentrations have also been evaluated.

Overarching messages and recommendations

Some aspects of deposition modelling are still very uncertain. For instance, dry deposition modelling results depend strongly on the land use schemes in the model. A variety of land use data are available, but with varying resolution and quality. More detailed data are available (e.g. for Europe, United States and Canada), however, it is difficult to merge these datasets as they are not consistent.

Uncertainties in emissions are still large, especially for areas outside the United States, Canada and Europe, and new techniques (e.g. inversion modelling) should be used to improve emissions. Model–measurement fusion might not help improve emissions, as there are few observations available in the areas where emissions are most uncertain. Satellite data might be used; however, surface concentrations for most species are needed to validate satellite data in light of the many assumptions made to estimate surface concentrations from satellite data. Satellite data might be valuable for smaller corrections such as updating emission inventories to a more recent year, as well as deducing natural emission sources (e.g. forest fires, sea salt, dust storms). Dust is probably the most reliable emission/concentration output from satellites.

When providing the 'best estimates' of total (dry plus wet) deposition, it is important at the same time to take into account what we know about emissions, models and observations and make error estimates and constrain the results. The need to further exploit available measurements (AMS, American data, satellite data) to understand these issues was highlighted.

4. CONCLUSIONS ON THE FEASIBILITY OF MEASUREMENT-MODEL FUSION: REQUIREMENTS, APPROACHES AND VISION

This session of the workshop focused on the following questions: Can we successfully attempt model-measurement fusion? How do we do it? What are the overarching questions that we must examine to successfully attempt measurement-model fusion for total deposition, aerosol species and reactive gases? As a first step, the plenary discussed some of the pressing needs and specific products related to deposition at global and regional scales important from the ecosystem, weather and climate, and human health perspectives.

From an ecosystem perspective, global measurement-model fusion maps of total deposition are important for understanding the impacts of various materials on ecosystem health. There are societal benefits associated with healthy ecosystems, so-called natural capital. Key issues related to land ecosystems (including lakes) include acidification, eutrophication, loss of biodiversity, links to the carbon cycle, the role of nutrients (nitrogen compounds and phosphorus), and food security (healthy crop yields). Issues related to the oceans include algal blooms, coastal ecosystems, climate change linkages, denitrification, and ocean acidification.

Typically scientists think about atmospheric impacts on ecosystems; however, ecosystems provide feedback to the atmosphere (e.g. the importance of emissions of ammonia from the oceans). The role of land use change is also important and there is a need to better link land use/land cover to deposition in order to understand the sensitivity and response of receptors to deposition.

To define which parameters are important, it is necessary to match the objectives to the specific societal communities being served. For instance, engagement with the agricultural community, which is concerned about ozone impacts on crops, is needed. Observations are central but insufficient, therefore, models are critical to meet the needs of these communities.

The generation of atmospheric research products at appropriate spatial and temporal scales is important to inform policy-making. The highest use of the information would be to address environmental sustainability – defined here as the highest level of economic development possible before we adversely affect ecosystems. Linkages between measurements and models on appropriate scales are necessary. We must consider making changes to the way observations are made in some cases. Temporal effects of deposition should be addressed over decadal periods to determine if national and international policies are producing changes in the right direction. Specific suggestions for approaches to this issue, included making use of satellite trends in emissions, critical loads approaches, and the need for having a good understanding of the receptors and the changes to receptor sensitivity over time (e.g. soybean cultivars are now more sensitive to ozone than previous cultivars).

The plenary also focused on atmospheric concentration and deposition inputs to climate and weather research. Understanding black carbon is a major research area for climate applications, particularly the feedbacks associated with carbon deposition to snow and ice. The importance of resuspension of secondary sources such as volcanic emissions was noted. From a weather perspective, the issue is how to develop an understanding of aerosol effects on predictive models. It was noted that this issue is being addressed in an operational framework – which will also contribute to the improvement of ecosystem models.

From a human health perspective, the key issue is the atmospheric concentration of compounds of concern near the breathing zone, i.e. at the mouth and nose level. Can we establish connections between deposition and respiratory health? A direct link of note was the resuspension of fine particulate matter in some communities. Also, dust impacts are important to the health community, with a need for more measurements at the appropriate size fractions for a better understanding of respirable particulates.

Reference was made to the recent book published by the U.S. National Academies of Science, Engineering and Medicine's titled "The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow.", which outlines five priority science areas. Priority Science Area 2 is to "quantify emissions and deposition of gases and particles in a changing Earth system". A predictive capability of these distributions is key for assessing the impacts of atmospheric processes on human and ecosystem health, weather, and climate. Research is needed to reduce uncertainties in emissions for known sources and constrain emissions of poorly understood constituents as well as to understand deposition processes that remove reactive species. The book cites the need for information to address decisions concerning technology, energy systems, pollution control, agriculture, and transportation and to assess ecosystem feedbacks. It also identifies the need to develop instrumentation and measurement strategies to quantify atmospheric fluxes. Support for long-term measurements, including over the oceans, and strategies need to be employed based on both models and observations to attribute atmospheric concentrations to particular sources. Priority Science Area 5 is to "understand the feedbacks between atmospheric chemistry and the biogeochemistry of natural and managed ecosystems". Expansion of the interaction between the atmospheric and the ocean and land-surface communities, the need for a broader measurement suite of trace gases and particles, and identification of feedbacks between the biosphere and atmosphere are necessary.

The GAW Programme is required to regularly update requirements for application areas as part of the WMO Rolling Review Requirements process. This means that the GAW Programme can ask for resources necessary to perform the measurement-model fusion exercise if we can define the need for the required measurements. It was noted that GAW could assist other WMO application areas in reviewing atmospheric composition requirements.

The definition of what a measurement-model fusion project would look like includes the identification of goals, strengths and weaknesses of current approaches, as well as the way that new observations, such as information from geo-platforms and reanalysis products, may be used. How do new observations and reanalysis products help the situation? Can we manage data better, share model products and develop common datasets? To what extent can we capitalize on operational reanalysis products on global and regional scales that can be used as a platform to assist with some of this? Can we make use of satellites to provide better data coverage? It was noted that satellite products tend to have poor sensitivity near the ground and that aerosol optical depth column measurements may be difficult to relate to surface concentrations.

There are two ways to perform measurement-model fusion: online with assimilation of data and running the models forward, or via post-processing. The point was made that it would be useful to begin with approaches that we do well and to slowly take on approaches that we do not currently do well. Access to a quality assured and well-documented dataset is crucial. Given the uncertainties in measurements and models, it would be appropriate to consider performing measurement-model fusion at regional and global scales at the same time. The need to prioritize various chemicals of interest was mentioned. Also, options for representing and discussing uncertainties must be identified and pursued. The period of time required to perform the model-measurement fusion will be determined by the project goals and the scale, whether we focus on immediate needs or long term emerging questions. Depending on the project design, it may be possible to provide some progress rather quickly. The issue of data management was noted and identified as critical to the project – as well as identification of the GAW data that are currently available to help with this project. For research products we do not currently have but have identified as necessary, if we can formulate our requirements, it may be possible to find someone to produce them.

Involvement with relevant science teams is important in order to leverage applications in other areas of science to assist with measurement-model fusion. There is a need to identify organizations that work on similar issues that could potentially collaborate to ensure that we do not reinvent what has already been done. Finally, it was noted that this group should be involved with other measurement groups outside of those represented at this workshop to consider what measurements are necessary for inclusion in GAW and to evolve the present observing systems.

Two breakout sessions followed the plenary session, one focused on measurement issues related to MMF-GTAD and the other focused on modelling issues. Both sessions included measurement-model fusion experts and representatives of the science and policy programmes/organizations. Reports from the breakout groups follow.

4.1 Measurements - ground-based and satellite

The breakout group discussion addressed the questions in the Workshop Context Document (see Annex III), focusing on the short term and long term requirements for measurements and for establishing benchmark datasets for use with measurement-model fusion.

Data management

GAW is moving toward a "federated data management system" that will be based on the GAW Station Information System (GAWSIS), a web-based database of metadata and other information from all GAW stations and contributing network stations. The federated system will be a system of interoperability among the GAW World Data Centres and regional databases and will be built on the existing infrastructure. This was identified as a long-term effort that will ultimately facilitate the gathering of a global dataset. In the short term, an important action for managing MMF-GTAD data is a recommended common data export format.

For datasets and other data products associated with major science assessments and secondary- or third-party data portals, it was recommended that data be collected from originating databases to ensure proper scientific attribution and tracking (to give credit to the original networks and programmes). It was also recommended that satellite datasets be retained in their originating data portals and that, instead, links to data products be provided, i.e. Giovanni, DLR and NASA satellite products. New databases should not be built; instead, money should be spent on improving existing databases. The responsibility for data quality lies with the data provider and the quality needs to be documented in the metadata that accompanies the data files. However, database managers have the responsibility for data screening and quality assurance using standardized checking procedures. It was noted that

Near-Real-Time (NRT) data, process level data and quality assured/approved data have different delivery time frames and quality control/quality assurance levels and therefore need to be handled and used differently.

Chemical species of concern

In addition to the compounds included in existing regional MMF-TAD activities (O_3, inorganic N and S), a number of chemical species were recommended for measurement in new and/or existing networks to enhance the MMF-GTAD project. They are:

Organic nitrogen (ON) contributes on the order of 20-30% of total water soluble nitrogen in precipitation and is the highest priority (also identified as such during the GAW Nitrogen Cycle Workshop) species to be added to measurement programmes. A phased approach was recommended:

1) Establish a recommended method (SOP) for ON sampling in precipitation involving the use of suitable collector materials and preservatives. Arrange a study to include a comparison of the use of buckets, bags and glass materials for the collection of samples and the use of suitable preservatives, including chemical methods and refrigeration to eliminate post-collection losses of ON in the field and laboratory. Implement the approved method on a pilot scale to demonstrate its performance in North America, then expand to other regions. It was noted that the preferred approach is to measure total nitrogen (TN) as well as the inorganic nitrogen species (viz., NH_4^+ and NO_3^-) in precipitation samples, then calculate the amount of water-soluble organic nitrogen by difference. The group agreed that these measurements would be useful for model evaluation exercises as well as the MMF-GTAD Project.
2) Investigate the concentration of organic nitrogen in aerosol form by performing analysis of total nitrogen on filter samples of existing regional monitoring networks (e.g. CASTNET, CAPMoN) that currently speciate inorganic forms of nitrogen (i.e. NH_4^+, NO_3^-). If the method is deemed acceptable, then the group recommends the measurement and analysis of total N at existing and new sites of monitoring networks through the use of low cost filter pack type sampling.

Ammonia (NH_3) measurements using passive low cost methods should be explored (NH_3 monitoring was identified as a priority during the GAW Nitrogen Cycle Workshop). Satellite products are just emerging now for characterizing large-scale surface layer concentrations and dry deposition. Such methods should be encouraged and developed for use in MMF-GTAD applications.

Nitrogen oxides (NOx) are measured at many sites, though mainly in urban areas for assessing human health effects. There are not many regionally-representative sites that measure NOx using the recommended WMO method. NO_2 from satellites is, however, available and used for large-scale mapping of concentrations and dry deposition fluxes, as well as by the modelling community.

Organic Acids. Selected organic acids are important in specific areas of the world to complete the ion balance and assess ecosystem effects, but may not be a top priority for the global community.

Phosphorus is important to soil and marine ecosystems and should be measured in the oceans and selected ecosystems, though it is not top priority globally.

Mercury is important for human health and ecosystem effects, but was not prioritized by this community.

Iron is mainly of interest for marine research and dust transport/deposition to the oceans. It is currently measured in some regional air and precipitation monitoring networks (in Europe and North America) but it is difficult to measure routinely over the oceans. It would be useful to attempt to derive global iron concentrations from satellite measurements of dust and/or aerosol optical depth.

Dust was considered to be important from a human health and ecosystem effect perspective and it was noted that a monthly gridded dataset for dust would be very useful.

It was noted that wet deposition over the oceans needs to be modelled as it cannot be measured routinely, except on a few islands.

Finally, new measurements from Aerosol Chemical Speciation Monitors and Aerosol Mass Spectrometers (ACSM/AMS) can be used for both NRT and retrospective applications and should be explored.

Capacity building
There is a need to extend the GAW measurement network into regions that are presently poorly covered. The group recommended exploring the possibility of finding funding (World Bank, EU, etc.) to add stations and measurement capacities. Existing networks and programmes like NADP, CAPMoN, EANET and EMEP could jointly facilitate and explore funding possibilities.

Low cost methods
The group recommended that GAW explore and adopt low cost measurement methods (e.g. passive sampling for NH_3) and accept these data if properly documented, and that the Scientific Advisory Group for Reactive Gases establish recommended methods and SOPs.

Dry deposition
There is a need to establish consistency in methods for estimating/measuring dry deposition. Adoption of a common inferential modelling framework is recommended for the development of site-specific dry deposition estimates. Such a framework would entail using measured concentrations, meteorology and surface characteristics as well as location-specific parameterizations. For example, the use of a bidirectional modelling framework for ammonia could be specified. Establishing consistency in component flux algorithms in Chemical Transport Models is recommended but will be more difficult, although ensemble analyses can shed light on the variability of fluxes estimated by different dry deposition schemes. For dry deposition flux measurements, a longer-term goal is to expand such measurements and establish a set of minimum data requirements and formats for the flux datasets used for model evaluations (i.e. in addition to chemical fluxes and air concentrations these datasets should contain relevant micrometeorology, surface physical and chemical characteristics, and quality assurance metrics). This work is seen to be outside the current scope of GAW.

4.2 Modelling

In the modelling breakout group, there were extensive discussions on the questions posed in the Workshop Context Document (see Annex III) and the following three-stage vision for the development of model-measurement fusion products was agreed upon. It was noted that the three stages cover different levels of ambition and timescale. They are outlined below.

Short-term goal: model ensemble and fusion
The short-term objective is to develop and apply methodologies for fusing multi-model ensemble results, observational data and re-analyses for the year 2010 in order to produce gridded global measurement-model fusion maps (and files) of concentrations and wet, dry and total deposition of important gas, aerosol and precipitation concentrations. The proposed modelling initiatives that could contribute to the multiple-model global and regional model ensembles include HTAP, AQMEII, MICS-Asia, and possibly CCMI, AEROCOM and ICAP. A global dataset of observations for 2010 will be needed for this effort. Model ensemble outputs of surface air concentrations, concentrations in precipitation, and modelled dry deposition velocities will be used to construct best-estimate ensemble fields. These will then be fused with the observations to determine MMF surface concentrations and, in combination with observed precipitation, MMF wet deposition. The mass balance between emissions and wet deposition will be considered due to the potential mismatch between the modelled precipitation amount (which influences the concentration field) and the observed/analysed precipitation amount. For example, the mass balance results will inform the credibility of the generated fields and identify priorities for longer-term data fusion. Dry deposition was deemed to be more complicated and there will be a need to carry out an intercomparison of the modelled dry deposition fluxes. The Joint Research Centre (JRC) volunteered to scope out the feasibility of generating model ensemble outputs and the fusion with precipitation.

Medium-term goal: global and regional stitching
The medium-term objective is to stitch together new and existing measurement-model fusion products into a global mosaic. The plan is to develop MMF-TAD methodologies and products for Europe (David Simpson and Hilde Fagerli, EMEP) and Asia (Greg Carmichael as point of contact for MICS-Asia and with Kevin Hicks as the point of contact for potential synergies with the Asian Integrated Assessment for Air Quality). These products will be stitched together with existing regional MMF-TAD products for Sweden/Norway (Camilla Andersson, SMHI), Canada (Amanda Cole and Alain Robichaud, ECCC), the United States (Donna Schwede, United States Environmental Protection Agency (US EPA)) and the global product developed in the short-term project identified above. This will require the development of new MMF techniques for the EMEP model and the Asian modelling effort as well as the establishment of agreed-upon binational merged MMF products for Canada and the United States. Donna Schwede will explore the possibility of sharing the US' TDEP Project MMF scripts and expertise. Access to suitable observations underpins the development of these new regional products which, once collected and archived, should be made available to the scientific community as a whole. It is anticipated that this effort will result in a published paper, which will describe the process, the products, the challenges (e.g. cross-border discontinuities) and recommendations for future data-fusing efforts. Environment and Climate Change Canada and the US EPA expressed a willingness to contribute to such a publication but a lead author was not identified.

Long-term goal: global reanalysis of concentrations and deposition fluxes
The long-term objective is to develop multiple global modelling systems, involving data assimilation of observations of concentrations, column burdens, and deposition fluxes. There is a clear need for this type of MMF product and ECMWF/Copernicus has plans over the coming 2-4 years to develop capabilities in this field. This will clearly require a global dataset of observations, ground-based and satellite. Some observations will be withheld for the purpose of independent verification. ECMWF also proposes to do a comparison of deposition velocities.

This will provide a rich time series dataset for the scientific community and for impact analyses (health, ecosystems, and climate). It was noted that there have been chemical reanalysis efforts underway in the United States at NOAA (North America Chemical Reanalysis) and NASA (MERRA). Frank Dentener and Vincent-Henri Peuch, as Co-Chairpersons of the Scientific Advisory Group for Applications, will liaise with these two agencies. For the NASA MERRA analysis, Mian Chin will investigate whether NASA has an interest in developing a global MMF product for deposition. This long-term project should stay abreast of new satellite products as new geostationary platforms/instruments become available.

Numerous conceptual and methodological ideas were identified for incorporation into the three goals of the project, including the following:

- An assessment of the potential for a single consistent land-use scheme for all models.
- An intercomparison study of dry deposition algorithms and outputs of different models
- An investigation into various model-ensemble techniques.
- A consideration of the most suitable temporal period(s) for aggregating model outputs and observations (no coarser than seasonal was proposed).
- Adoption of the guiding principle of establishing measurement-model comparability before undertaking measurement-model fusion.
- An accounting of the co-variance between pollutant concentrations and dry deposition velocities when calculating dry deposition fluxes from the product of time-averaged concentrations and dry deposition velocities (different approaches to handling co-variances were noted between Canada and the United States).
- Consideration of archiving the modelled dry deposition velocities and fluxes by different land use types.
- A determination of specific MMF products that will best meet the requirements of national and international policy and science drivers.

A representative of WHO noted that WHO has undertaken a project to merge ground-based air quality measurements in large cities with model and satellite products to establish pollution exposure fields for the evaluation of urban health effects. Work has been undertaken for 2013, 2014 and 2015 and there is a desire to operationalize the products. The close association between the WHO and GAW MMF-GTAD effort was noted.

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5. RECOMMENDATIONS AND PATH FORWARD FOR A MMF-GTAD PROJECT

The final plenary strongly supported the formal establishment of a Global Atmosphere Watch Project on Measurement Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD). The objective of such a project is to produce the best possible global maps of deposition and atmospheric concentrations of gas and aerosol species in order to meet the needs of policy-making and scientific agencies, programmes and communities in the areas of human health, ecosystem health, and climate change.

The plenary accepted the recommendation of the Modelling Breakout Group to implement the MMF-GTAD Project in three stages, each reflecting short, medium and long-term goals and work plans:

- Goal 1 (Short Term). Ensemble model-measurement fusion for the year 2010
- Goal 2 (Medium Term). Stitching of global/regional measurement-model products
- Goal 3 (Long Term). Global reanalysis/assimilation of concentrations and deposition fluxes.

Brief descriptions follow (based on those in the Modelling Breakout section).

Goal 1 (Short Term). Ensemble model-measurement fusion for the year 2010.
Goal 1 is to use multiple existing model and data activities to fuse model-ensemble outputs with measurement data for the year 2010. The final products will include a comprehensive global dataset, model ensemble output files, and gridded measurement-model fusion global maps (and files) of concentrations and wet, dry and total deposition of important gas, aerosol and precipitation concentrations. Existing modelling activities that could potentially contribute the multiple-model ensemble results include HTAP, AQMEII, MICS-Asia, CCMI, AEROCOM and ICAP. The observational data will include datasets already gathered in North America and Europe for 2010 by the European Commission Joint Research Centre (Ispra, Italy) and the Norwegian Institute of Air Research (NILU), supplemented by appropriate datasets from the GAW World Data Centres, GAWSIS, the Global Precipitation Climatology Centre, Africa and Asia.

Goal 2 (Medium Term). Stitching of global and regional measurement-model fusion products
Goal 2 is to stitch together existing and newly-developed regional and global MMF products to produce merged global maps of gas, aerosol and precipitation concentrations as well as wet, dry and total deposition fluxes. The approach will require the development of new MMF methods and products for Europe (David Simpson and Camilla Anderson as contacts) and Asia (Greg Carmichael as contact for MICS-Asia; Kevin Hicks as contact for the Asian Integrated Assessment for Air Quality) and merging them together with existing Swedish (Camilla Andersson), United Kingdom (Ron Smith), United States (Donna Schwede), and Canadian (Amanda Cole) MMF products. To facilitate this process, the US EPA will explore the possibility of sharing the EPA MMF scripts with the community at large. As will be done for Goal 1, a comprehensive dataset will be compiled, archived and made available to the community. After

all regional MMF maps/files are created, a methodology will be developed to stitch the regional maps with the global maps developed for Goal 1 (as described above). A journal article will be written to describe the methods, results, challenges and future approaches.

Goal 3 (Long Term). Global reanalysis/assimilation of concentrations and deposition fluxes

Goal 3 is to develop one or more global modelling systems involving the operational reanalysis and data assimilation of observations of concentration, column burdens, and deposition fluxes. ECMWF/Copernicus identified their plans to develop such capabilities over the next 2 to 4 years and will potentially lead the Goal 3 effort. A global dataset of observations, both ground-based and satellite (including deposition fluxes), will be compiled and used. Other chemical reanalysis/assimilation efforts underway in the United States at NOAA (North America Chemical Reanalysis) and NASA (MERRA) were identified as additional potential contributors to Goal 3. The Co-Chairpersons of the GAW Scientific Advisory Group-Applications, Frank Dentener and Vincent-Henri Peuch, will liaise with the U.S. agencies to explore their participation.

A number of associated model-related projects were identified to contribute to the development of the project including: an investigation of the dry deposition algorithms and predictive capabilities in the contributing chemical transport models; a study of the feasibility of fusing model results with both urban (i.e. high spatial resolution) and regional/global (i.e. low spatial resolution) data; and an evaluation of reasonable temporal resolution for the measurement-model fusion activities (e.g. weekly, monthly, or seasonally).

The plenary agreed that the MMF-GTAD project will require 'benchmark' datasets over the short, medium and long term. Goal 1 of the project will address mapping of ground-level ozone as well as sulphur and nitrogen species already monitored in regional-scale networks, namely, air concentrations and dry deposition of SO_2, particle-SO_4^{2-}, HNO_3, particle-NO_3^-, particle-NH_4^+, and precipitation concentrations and wet deposition of SO_4^{2-}, NO_3^- and NH_4^+. Ideally, additional species need to be measured over the long run including:

- NO_2 and NH_3 in air
- organic nitrogen in air and precipitation
- organic acids, Fe and P in precipitation
- aerosol Fe, dust, and size distributions in air

For most of the foregoing, suitable measurement techniques must be developed before implementation in regional-scale monitoring networks. Satellite measurements (and their products) of SO_2, NO_2, NH_3 and AOD are available and improving rapidly, showing great promise for estimating ground-level concentrations and dry deposition fluxes over large, unmeasured areas of the world. These evolving measurements and products should be included in future measurement-model fusion activities.

Publicly-available, integrated, high quality global datasets were identified as critical to the success of the MMF-GTAD Project. A single data centre was considered to be a high priority for collecting, quality assuring, formatting, archiving and disseminating the data, although no existing data centre was identified for the project. The WMO World Data Centres and national and international data centres were seen as the major contributors of the measurement data.

Given that data collection and management are difficult and time-consuming, a decision was made to create an Ad Hoc Data Group to investigate the workload and needs associated with gathering data from previous and ongoing science assessments and model evaluation activities. Members of the group were identified as: Donna Schwede (US EPA), John Walker (US EPA), Wenche Aas (NILU), Greg Carmichael (point of contact for Asian data) and (lead) Amanda Cole (ECCC). Representatives of the World Data Centres Expert Team and GAWSIS will liaise with the group.

In the short term, the Ad Hoc Data Group will focus on the collection of data for two specific years: 2010 and 2014 (the focus of CMIP6/AEROCOM), 2015 (WHO base year), or 2016 (a focus of AEROCOM 2016 and US EPA emissions inventory compilation). In the long-term, the Group will consider the feasibility of compiling global datasets every 10 years, with 2020 as the next long-term target year. The Group will also consider a number of other data-related issues including: the optimal time resolution of the data collected (monthly recommended), collecting urban data to supplement regional and global data, and the potential for establishing and documenting standard methods for the calculation of inferential dry deposition fluxes. The Group committed to a conference call in June of 2017 to be organized by Silvina Carou (WMO) to discuss their progress and ongoing activities.

The plenary again reviewed the many international activities, initiatives and programmes relevant to the proposed GAW MMF-GTAD Project, including:

- UN Convention for Biological Diversity (Strategic Plan for Biodiversity and Aichi Target 8, Biodiversity Indicators Partnership)
- 2015 Sustainable Development Goals, Targets and Indicators
- World Health Organization (WHO Air Quality Guidelines, Global Burden of Disease Assessment)
- Global Platform on Air Quality and Health
- Climate and Clean Air Coalition
- International Nitrogen Management System
- International Nitrogen Initiative
- UN Framework Convention on Climate Change
- Global Partnership on Nutrient Management

Participants agreed that the planned outcomes and products of the MMF-GTAD Project will be highly relevant and beneficial to all of these activities, initiatives and programmes.

The workshop concluded with a recommendation that a 'Roadmap to the Future' be written to document a path forward for the GAW MMF-GTAD Project. The roadmap should define the vision, goals, management, work programme, potential participants and scheduling of the project. The lead for writing the roadmap document will be Robert Vet of Environment and Climate Change Canada. The workshop closed with participants expressing their strong encouragement for establishing and implementing the GAW MMF-GTAD Project. The next steps following the workshop are to:

- Finalize and publish the workshop report as a formal Global Atmosphere Watch Report (to be made available electronically on http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html).
- Develop a 'Roadmap for the Future' that documents a specific plan forward for the GAW MMF-GTAD Project following the three goals accepted during the workshop.

- Initiate an Ad-Hoc Data Working Group to investigate the workload and needs associated with gathering data from previous and ongoing science assessments and model evaluation activities.
- Initiate Goal 1 of the project as identified in the workshop.
- Share the project plan with existing and potential partners and contributors with a view to securing expertise, collaboration and financial resources to implement the three goals of the project.

REFERENCES

Kanakidou, M., S. Myriokefalitakis, N. Daskalakis, G. Fanourgakis, A. Nenes, A. Baker, K. Tsigaridis, and N. Mihalopoulos, 2016: Past, present and future atmospheric nitrogen deposition. *Journal of Atmospheric Science*, 73, no. 5, 2039-2047, doi:10.1175/JAS-D-15-0278.1.

National Academies of Sciences, Engineering, and Medicine: 2016. The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow. Washington, DC: The National Academies Press. doi: 10.17226/235730

Rockström, J., W.L. Steffen, K. Noone, Å. Persson, F.S. Chapin III, E.F. Lambin, T.M. Lenton, M. Scheffer et al., 2009: "Planetary Boundaries: Exploring the Safe Operating Space for Humanity" (PDF), *Ecology and Society*, 14 (2): 32

Vet, R., R.S. Artz, Silvina Carou, Mike Shaw, Chul-Un Ro, Wenche Aas, Alex Baker, Van C. Bowersox, Frank Dentener, Corinne Galy-Lacaux, Amy Hou, Jacobus J. Pienaar, Robert Gillett, M. Cristina Forti, Sergey Gromov, Hiroshi Hara, Tamara Khodzher, Natalie M. Mahowald, Slobodan Nickovic, P.S.P. Rao, Neville W. Reid, 2014: Special Issue: A global assessment of precipitation chemistry and deposition of sulphur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorous, *Atmospheric Environment,* 93: 3-100. http://dx.doi.org/10.1016/j.atmosenv.2013.10.060

WMO, 2017: Global Atmosphere Watch (GAW) Implementation Plan: 2016-2023, GAW Report No. 228. Available at http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html

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ANNEX I

GLOBAL ATMOSPHERE WATCH WORKSHOP ON MEASUREMENT-MODEL FUSION FOR GLOBAL TOTAL ATMOSPHERIC DEPOSITION (MMF-GTAD) (Geneva, Switzerland, 28 February – 2 March 2017)

List of participants

Aas, Wenche	NILU	waa@nilu.no	Norwegian Institute for Air Research
Andersson, Camilla	SMHI	camilla.andersson@smhi.se	Swedish Meteorological and Hydrological Institute
Artz, Richard	NOAA	Richard.artz@noaa.gov	United States National Oceanic and Atmosphere Administration
Baklanov, Alexander	WMO	abaklanov@wmo.int	World Meteorological Organization
Becker, Andreas	DWD	Andreas.Becker@dwd.de	Deutscher Wetterdienst
Bowersox, Van	QASAC - A	soxxos@sbcglobal.net	Quality Assurance Science Activity Centre - Americas
Carmichael, Gregory	U of Iowa	Gregory-carmichael@uiowa.edu	University of Iowa
Carou, Silvina	WMO	scarou@wmo.int	World Meteorological Organization
Chin, Mian	NASA	mian.chin@nasa.gov	National Aeronautics and Space Administration
Cole, Amanda	ECCC	Amanda.cole@canada.ca	Environment and Climate Change Canada
Dentener, Frank	IJC	frank.dentener@ ec.europa.eu	European Commission, Joint Research Centre
Duan, Lei	THU	lduan@tsinghua.edu.cn	Tsinghua University
Emberson, Lisa	U of York	l.emberson@york.ac.uk	University of York
Fagerli, Hilde	MET Norway	hildef@met.no	EMEP MSC-W / Norwegian Meteorological Institute
Flemming, Johannes	ECMWF	Johannes.flemming@ecmwf.int	European Centre for Medium-Range Weather Forecast
Galy-Lacaux, Corinne	CNRS	lacc@aero.obs-mip.fr	Laboratoire d'Aéronomie / CNRS
Gay, David	NADP	dgay@illinois.edu	United States National Atmospheric Deposition Program
Geddes, Jeffrey	Boston U	jgeddes@bu.edu	Boston University
Gumy, Sophie	WHO	bonjourso@who.int	World Health Organization
Hicks, Kevin	U of York	Kevin.hicks@york.ac.uk	University of York
Hogrefe, Christian	US EPA	hogrefe.christian@epa.gov	United States Environmental Protection Agency
Huo, Mingqun	ACAP	mqhuo@acap.asia	Asia Center for Air Pollution Research Network Center for Acid Deposition Monitoring Network in East Asia (EANET)
Itahashi, Syuichi	CRIEPI	isyuichi@criepi.denken.or.jp	Central Research Institute of Electric Power Industry
Jickells, Tim	U of EA	T.Jickells@uea.ac.uk	University of East Anglia

Klausen, Jörg	MétéoSwiss	Joerg.klausen@meteoswiss.ch	MétéoSwiss
Laj, Paolo	UGA	Paolo.laj@univ-grenoble-alpes.fr	Université-Grenoble-Alpes
O'Connor, Fiona	UK MO	Fiona.oconnor@metoffice.gov.uk	United Kingdom Met Office Hadley Centre
Peuch, Vincent-Henri	EMCWF	Vincent-Henri.Peuch@ecmwf.int	European Centre for Medium-Range Weather Forecast
Pienaar, Jacobus	NWU	Kobus.Pienaar@nwu.ac.za	North-West University
Robichaud, Alain	ECCC	Alain.robichaud@canada.ca	Environment and Climate Change Canada
Shaddick, Gavin	Bath U	g.shaddick@bath.ac.uk	University of Bath
Schwede, Donna	US EPA	schwede.donna@epa.gov	United States Environmental Protection Agency
Simpson, David	MET Norway	David.simpson@met.no	Norwegian Meteorological Institute
Smith, Rognvald	CEH	ris@ceh.ac.uk	Centre for Ecology and Hydrology
Solomon, Fabien	CNRS	fabien.solmon@aero.obs-mip.fr	Laboratoire d'Aérologie OMP CNRS/UPS and ICTP Italy
Stein, Ariel	NOAA	Ariel.stein@noaa.gov	National Oceanic and Atmosphere Administration
Tarasova, Oksana	WMO	otarasova@wmo.int	World Meteorological Organization
Tørseth, Kjetil	NILU	KT@NILU.no	Norwegian Institute for Air Research
Vet, Robert	ECCC	robert.vet@canada.ca	Environment and Climate Change Canada
Walker, John	US EPA	Walker.johnt@epa.gov	United States Environmental Protection Agency
Yang, Li	CMA	liyang@cma.gov.cn	China Meteorological Administration, Meteorological Observation Centre

ANNEX II

GLOBAL ATMOSPHERE WATCH WORKSHOP ON MEASUREMENT-MODEL FUSION FOR GLOBAL TOTAL ATMOSPHERIC DEPOSITION (MMF-GTAD) (Geneva, Switzerland, 28 February – 2 March 2017)

Workshop Agenda

Tuesday 28 February	**DAY 1**	
8:00 - 8:30	Arrival	All
8:30 - 8:40	Welcome and Opening	Oksana Tarasova, WMO / Ariel Stein, NOAA
8:40 - 9:00	Workshop Context, Objectives, Expected Outcomes and Introductions	Robert Vet, ECCC / Silvina Carou, WMO
Session 1. Keynote Talks: Science and Policy Drivers for Global Measurement -Model Fusion Maps of Atmospheric Concentrations and Deposition		**Chair/Rapporteur: Kobus Pienaar and Silvina Carou**
9:00 - 9:20	Keynote Address 1. Hitting the target: Improving Deposition Estimates for Assessment of Impacts on Biodiversity and Ecosystem Services for Policy Needs	Kevin Hicks, UY
9:20 - 9:40	Keynote Address 2. The International Nitrogen Initiative (INI) and International Nitrogen Management System (INMS): Links to Atmospheric Composition and Total Atmospheric Deposition	Rognvald Smith, CEH (for Mark Sutton, CEH)
9:40 - 10:00	Keynote Address 3. Science and Policy Needs from the Human Health Perspective	Sophie Gumy, WHO
10:00 - 10:25	*Break*	
Session 2. Current Projects on Measurement-Model Fusion for Total Atmospheric Deposition and Ambient Concentrations of Gases and Aerosol Species		**Chair/Rapporteur: Amanda Cole and David Gay**
10:25 - 10:45	The United States Total DEPosition (TDEP) Project for Sulphur and Nitrogen	Donna Schwede, USEPA
10:45 - 11:05	Annual Swedish Deposition Mapping with the MATCH Sweden System	Camilla Andersson, SMHI
11:05 - 11:25	The Canadian ADAGIO Project for Mapping Total Atmospheric Deposition	Amanda Cole, ECCC
11:25 - 11:40	Total Deposition Approaches in the United Kingdom	Rognvald Smith, CEH
11:40 - 12:00	Objective Analysis Techniques for Multi-Pollutant Surface Concentration and Deposition Maps	Alain Robichaud, ECCC
12:00 - 13:20	***Lunch***	
13:20 - 13:40	Satellite Measurement-Model Fusion for Global Deposition and Health Assessments	Jeffrey Geddes, BU
13:40 - 14:00	Chemical Data Assimilation: Lessons Applicable to Retrospective Measurement-Model Fusion	Gregory Carmichael, UI
14:00 - 14:30	*Session 2 Panel Discussion: MMF Methods, Issues and Uncertainties*	*Chair, Rapporteur, Speakers*

Session 3. Surface- and Satellite-Based Measurements for Use in MMF-TAD		**Chair/Rapporteur: Van Bowersox and Jeffrey Geddes**
14:30 - 14:50	Ground-Level Measurements of Relevant Reactive Gases in GAW, Regional and National Networks (GAW Scientific Advisory Group for Reactive Gases)	Kjetil Tørseth, NILU
14:50 - 15:10	Ground-Level Measurements of Relevant Aerosol Chemical Species in GAW, Regional and National Networks (GAW Scientific Advisory Group for Aerosols)	Paolo Laj, UGA
15:10 - 15:30	Satellite measurements of aerosols and related gases and applications for aerosol deposition	Mian Chin, NASA
15:30 - 16:00	***Break***	
16:00 - 16:20	Recent Workshop Results Related to Satellite-Model Fusion	Lisa Emberson, UY
16:20 - 16:40	Global and Regional-Scale Measurements of Precipitation Chemistry and Wet Deposition (GAW Scientific Advisory Group for Total Atmospheric Deposition)	Ariel Stein, NOAA
16:40 - 17:00	Data Availability through the Global Precipitation Climatology Centre (GPCC) suitable for wet deposition assessment	Andreas Becker, DWD
17:00 - 17:20	Observation- and Model-Based Estimates of Atmospheric Input to the Oceans (GESAMP)	Timothy Jickells, UEA
17:20 - 17:25	***Close***	Silvina Carou, WMO
Wednesday 1 March	**DAY 2**	
8:45 - 9:30	*Session 3 Panel Discussion: Measurement Methods, Issues and Uncertainties*	*Chair, Rapporteur, Speakers*
Session 4. Chemical Transport and Deposition Modelling for Application to MMF-TAD: Global, Hemispheric and Regional Modelling, Evaluation and Comparability		**Chair/Rapporteur: Ariel Stein and Hilde Fagerli**
9:30 - 9:50	An Overview of Global/Hemispheric Chemical Transport Models, Model Comparison Studies and Model-Evaluation Studies for Use in Global MMF-TAD	Frank Dentener, IJC
9:50 - 10:10	Global Modelling Activities of the Copernicus Atmosphere Monitoring Service	Johannes Flemming, ECMWF
10:10 - 10:40	*Break*	
10:40 - 11:00	The Air Quality Model Evaluation International Initiative (AQMEII)	Christian Hogrefe, USEPA
11:00 - 11:20	Community Multi-scale Air Quality (CMAQ) Modelling for Regional and Hemispheric Scales	Donna Schwede, USEPA
11:20 - 11:40	Regional Modelling for Europe	David Simpson and Hilde Fagerli, MET Norway
11:40 - 12:00	Regional Modelling and Model Evaluation for Asia	Syuichi Itahashi, CRIEPI
12:00 - 13:20	*Lunch*	
13:20 - 14:00	*Session 4 Panel Discussion: Modelling requirements, Problems and Issues Related to MMF-TAD*	Chair, Rapporteur, Speakers

Session 5. Plenary on Measurement-Model Fusion: Approaches, Objective Analysis Methods, Mapping and Management		**Chair/Rapporteur: Gregory Carmichael and Richard Artz**
14:00 - 15:20	Plenary Discussion and Assignment of Breakout Groups	
15:20 - 15:40	*Break*	
Session 5A. Simultaneous Breakout Group Sessions on Measurement-Model Fusion: Approaches, Objective Analysis Methods, Mapping and Management		
15:40 - 17:00	Breakout Group 1: Ground-Based and Satellite Measurements	Lead/Rapporteurs: Wenche Aas, John Walker, Amanda Cole
	Breakout Group 2: Modelling	Lead / Rapporteurs: Frank Dentener, Fiona O'Connor, Christian Hogrefe
17:00 - 17:15	Combined Plenary. End-of-Day Issues: Chairs to raise questions and ideas relevant to next day's discussions	
17:15 - 17:20	*Close*	
Thursday 2 March	**DAY 3**	
Session 5B. Continuation of Simultaneous Breakout Group Session Discussions		
8:45 - 10:00	Breakout Group 1: Ground-Based and Satellite Measurements	Lead/Rapporteurs: Wenche Aas, John Walker, Amanda Cole
	Breakout Group 2: Modelling	Lead / Rapporteurs: Frank Dentener, Fiona O'Connor, Christian Hogrefe
10:00 - 10:30	*Break*	
10:30 - 11:00	Breakout Group 1 (Continued): Ground-Based and Satellite Measurements	Lead / Rapporteurs: Wenche Aas, John Walker, Amanda Cole
	Breakout Group 2 (Continued): Modelling	Lead / Rapporteurs: Frank Dentener, Fiona O'Connor, Christian Hogrefe
Session 6. Final Combined Plenary: Recommendations and the Path Forward		**Chair/Rapporteur: Robert Vet and Silvina Carou**
11:00 - 11:05	Introduction	Robert Vet
11:05 - 11:35	Report of Breakout Group 1 (Measurements) and Discussion	Wenche Aas / John Walker / Amanda Cole
11:35 - 12:05	Report of Breakout Group 2 (Modelling) and Discussion	Frank Dentener / Fiona O'Connor / Christian Hogrefe
12:05 - 13:30	*Lunch*	
13:30 - 15:30	Combined Discussion	All
15:30 - 16:00	*Break*	

Session 7. Final Comments and Close		**Rapporteur: Silvina Carou**
16:00 - 16:30	Summary, Conclusions, Workshop Report	Robert Vet
16:30 - 16:45	*Close*	Ariel Stein, NOAA

ANNEX III

Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD)
Global Atmosphere Watch Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD)
World Meteorological Organization,
(Geneva, Switzerland, 28 February – 2 March 2017

Workshop Context and Discussion Topics

Workshop objectives

To review the state-of-the-science and establish a Global Atmosphere Watch (GAW) project on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD) for the purpose of generating global maps of total atmospheric deposition and ambient gases and particle species.

Background

The Global Atmosphere Watch (GAW) Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD) has a mandate to produce global maps of total atmospheric deposition for a number of important atmospheric chemicals. The most suitable scientific approach for this activity is the emerging technique of measurement-model fusion for total atmospheric deposition (MMF-TAD). This technique requires global-scale measurements of atmospheric trace gases, particles, precipitation composition and precipitation depth, as well as predictions of the same from global/regional chemical transport models. The fusion of measurement and model results requires objective analysis and mapping techniques that are applicable to the production of global maps of selected reactive gases, aerosol species, and wet and dry deposition.

MMF-TAD projects are currently being carried out in Sweden, the United Kingdom, the United States and Canada. The methodology employed by each country is different and not necessarily applicable on a global scale. To assess the feasibility and establish a path forward for a SAG-TAD project on global measurement-model fusion, a group of experts will be convened to discuss relevant MMF-TAD techniques and global measurements and modelling. These experts will include the Chairpersons or representatives of other Scientific Advisory Groups of the Global Atmosphere Watch.

The workshop will explore the feasibility and methodology of producing, on a routine retrospective basis, global maps of atmospheric gas and aerosol concentrations as well as wet, dry and total deposition. The purpose of the maps is to be used for research into biogeochemical cycles and ecosystem and human health effects.

Expected outcomes

The expected outcomes of the workshop are:

- A review of the current state of global measurements (ground-based and satellite), chemical transport modelling (global and hemispheric), and measurement-model fusion/mapping techniques.

- Key recommendations, conclusions and a project plan for moving forward on a GAW project on Global MMF-TAD.
- Identification of MMF-TAD products (global maps) and timelines.
- Identification of project participants, working groups and coordinators.
- Coordination with major science and policy programmes interested in MMF maps.

Participants
Invited global experts in the fields of:

- Measurement-model fusion for total atmospheric deposition, precipitation depth and ambient concentrations of reactive gases and aerosols.
- Global/regional measurements of wet, dry and/or total deposition.
- Global precipitation depth measurement, modelling and mapping.
- Global/regional measurements of reactive gases (ground-based and satellite-based).
- Global/regional measurements of aerosols and aerosol species (ground-based and satellite-based).
- Global/hemispheric chemical transport modelling.
- Global science programme/driver/client representatives for nitrogen, critical loads, biodiversity and human health.

Representatives from:

- GAW Scientific Advisory Groups on Aerosol, Reactive Gases and Modelling Applications, and relevant World Data Centres.
- International science and policy programmes with a need for global/regional maps of total atmospheric deposition, aerosol and gases.

Session 1. Keynote Talks: Science and policy drivers for global measurement-model fusion maps of atmospheric concentrations and deposition

Session 1 will offer an overview of some of the key science and policy drivers behind the production of global deposition maps for total deposition, aerosols and gases from an ecosystem and human health perspective.

Session 2. Current projects on measurement-model fusion for total atmospheric deposition and ambient concentrations of gases and aerosol species

Session 2 will focus on descriptions of specific ongoing national and regional measurement-model fusion projects for total atmospheric deposition and ambient aerosol and reactive gas concentrations for sulphur, nitrogen, base cations, ozone, and phosphorus. Speakers will present methods, results, problems, issues, uncertainties, concerns and future plans. A panel of speakers at the end of the session will discuss overarching topics.

Panel Discussion: MMF methods, issues and uncertainties
Discussion topics:

- What are the advantages and disadvantages of the MMF methods used in the national efforts described above?
- What are the major roadblocks, problems and uncertainties related to MMF on a global scale including data storage and management, highly heterogeneous observation

density, model uncertainties and comparability, temporal variability of observations, dry deposition covariance?
- Is there an objective analysis method that can combine both non-urban (i.e. regional) and urban measurement and model results for MMF given their different spatial scales and site representativeness?

Session 3. Surface- and satellite-based measurements for use with MMF-TAD

Session 3 will consist of overview presentations of existing and planned ground-based and satellite-based measurements of precipitation, aerosols, reactive gases, wet, dry and total deposition related to sulphur, oxidized and reduced nitrogen, ozone, base cation species (and/or dust and sea salt) and phosphorus. Speakers will provide summaries of major measurement programmes, monitoring networks, analysis products, and satellite sensors suitable for use in global measurement-model fusion projects and address related topics including measurement methods, data availability/access, problems, uncertainties and future outlook. Following the session, a panel of speakers will discuss overarching topics.

Panel Discussion: Measurement methods, issues and uncertainties
Discussion topics:

- What chemicals can and should be addressed by MMF and in what order of priority?
- What is the suitability of gridded precipitation depth datasets for wet deposition (availability, temporal resolution, spatial resolution)?
- For the identified chemical species, are there additional measurement data available to supplement what was collected in the global precipitation chemistry and deposition assessment, especially in remote and sparsely monitored areas including the oceans?
- How do satellite measurements of gases and particles compare with ground-level measurements? Is it feasible to use both in MMF? If so, what time resolution?
- Are aerosol size distribution data available and, if not, what assumptions can be made about size distributions in order to estimate dry deposition velocities?
- Are there special difficulties or uncertainties related to measurements over or near the oceans?

Session 4. Chemical transport and deposition modelling for application to MMF-TAD: global, hemispheric and regional modelling, evaluation and comparability

Session 4 will focus on overview presentations of global, hemispheric and regional chemical transport and deposition models for sulphur, nitrogen, ozone, phosphorus and base cation species (and dust and sea salt). Speakers will provide overviews of the models, the species modelled, related model comparison studies, modelling uncertainties and future plans. A panel of speakers at the end of the session will discuss overarching topics.

Panel Discussion: Modelling requirements, problems and issues related to MMF-TAD
Discussion topics:

- What chemical species can be suitably modelled and applied to MMF-TAD?
- Is model-to-model and model-to-measurement comparability sufficient for MMF? Are there specific models that should/should not be included in MMF?
- What are potential modelling ensemble schemes for MMF-TAD? Can we "piggyback" on other planned modelling projects?

- How can model uncertainty be minimized/quantified?
- How can dry deposition velocities/fluxes from the model(s) or the MMF product be validated?
- What are the key issues related to modelling atmospheric exchange/deposition mechanisms (e.g. bidirectional fluxes)?

Session 5. Plenary on measurement-model fusion: approaches, objective analysis methods, mapping and management

This plenary will focus on feasibility and issues related to a global measurement-model fusion project. The plenary will highlight common issues and objectives for discussion in the two breakout sessions, thereby allowing the MMF experts to contribute to these sessions.

- Does a measurement-model fusion project for atmospheric concentrations and total atmospheric deposition seem feasible on a global or hemispheric scale? Alternately, could national and/or regional efforts be merged into a single global/hemispheric map?
- What MMF-TAD paradigm and what optimal analysis and mapping method(s) could be used?
- Are there chemicals other than sulphur, nitrogen (oxidized and reduced) and ozone that should be included, and what are their relative priorities?
- What measurement and model input variables are needed and at what temporal and spatial scales?
- What practical issues and uncertainties would have to be overcome, e.g. data and model output management?
- What are the options for estimating and/or representing uncertainty?

Breakout Group 1: Ground-based and satellite measurements

- How/where can the ground and satellite measurement data be obtained, screened, archived and managed in an efficient manner, including urban data?
- What is the best path forward to obtain global precipitation depth fields for use in MMF-TAD?
- What special measurement issues need to be addressed, e.g. spatial and temporal resolution, missing species, aerosol size distribution?
- Are key new sites, measurements, species, time frames, etc. needed and can their establishment be set in motion now?
- Can we quantify measurement errors by species/location/instrument?

Breakout Group 2: Modelling

- What specific models or ensembles of models could be used for global MMF-TAD? What spatial resolution is possible for a global product?
- How could model output be managed and accessed?
- If ensembles of models are to be used, what ensemble scheme would be best/possible, or what criteria will be used to make that decision?
- What inputs to the models should be used, e.g. emission inventories, land use categories/schemes?
- How can the appropriate modelling agencies be engaged and their model outputs obtained, archived and managed, e.g. through HTAP?
- Can/should focused regional models (e.g. CMAQ, GEM-MACH, others) be used to complement global or hemispheric models? If so, how?

Session 6. Final Plenary: Recommendations and the path forward
Plenary discussion will address the following questions:

- Is the Global MMF-TAD Project possible? Should we proceed with a Project Plan?
- What are the needed and expected products/deliverables of the project and where would they be published/disseminated (e.g. what global gas, aerosol and deposition maps)? What are the time frames for delivery?
- Assuming that such a project is possible, do we do start with a pilot project for a specific year (or set of years) before adopting a routine approach? What year(s)?
- Who could lead and participate in the project, i.e. what leaders/champions, coordinator(s), modellers, measurement groups, data management groups, objective analysis/mapping groups?
- How can the project be coordinated/carried out and in what time frame, e.g. where and how would the data and modelling output be archived, analysed, mapped and managed?
- What are the priority chemicals?
- Can we create a Project Plan that includes the key tasks, major contributors and potential timelines broken down into the following sections:
    - Management and coordination
    - Measurements (ground and satellite)
    - Modelling
    - Objective analysis and mapping
    - Ongoing MMF-TAD development and research
- What are the key recommendations for the measurement, modelling, and MMF communities to advance the Project (e.g. key new sites, new satellite measurements, new model algorithms)?

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233. Report of the Third Session of the CAS Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee (EPAC SSC), Geneva, Switzerland, 15-17 March 2016

232. Report of the WMO/GAW Expert Meeting on Nitrogen Oxides and International Workshop on the Nitrogen Cycle, York, UK, 12-14 April 2016, 2017.

231. The Fourth WMO Filter Radiometer Comparison (FRC-IV), Davos, Switzerland, 28 September – 16 October 2015, 65 pp., November 2016.

230. Airborne Dust: From R&D to Operational Forecast 2013-2015 Activity Report of the SDS-WAS Regional Center for Northern Africa, Middle East and Europe, 73 pp., 2016.

229. 18th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (GGMT-2015), La Jolla, CA, USA, 13-17 September 2015, 150 pp., 2016.

228. WMO Global Atmosphere Watch (GAW) Implementation Plan: 2016-2023, 81 pp., 2017.

227. WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations, 2nd Edition, 2016, WMO-No. 1177, ISBN: 978-92-63-11177-7, 101 pp., 2016.

226. Coupled Chemistry-Meteorology/Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research, Geneva, Switzerland, 23-25 February 2015 (WMO-No. 1172; WCRP Report No. 9/2016, WWRP 2016-1), 165 pp., May 2016.

225. WMO/UNEP Dobson Data Quality Workshop, Hradec Kralove, Czech Republic, 14-18 February 2011, 32 pp., April 2016.

224. Ninth Intercomparison Campaign of the Regional Brewer Calibration Center for Europe (RBCC-E), Lichtklimatisches Observatorium, Arosa, Switzerland, 24-26 July 2014, 40 pp., December 2015.

223. Eighth Intercomparison Campaign of the Regional Brewer Calibration Center for Europe (RBCC-E), El Arenosillo Atmospheric Sounding Station, Heulva, Spain, 10-20 June 2013, 79 pp., December 2015.

222. Analytical Methods for Atmospheric SF6 Using GC-μECD, World Calibration Centre for SF6 Technical Note No. 1., 47 pp., September 2015.

221. Report for the First Meeting of the WMO GAW Task Team on Observational Requirements and Satellite Measurements (TT-ObsReq) as regards Atmospheric Composition and Related Physical Parameters, Geneva, Switzerland, 10-13 November 2014, 22 pp., July 2015.

220. Report of the Second Session of the CAS Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee (EPAC SSC), Geneva, Switzerland, 18-20 February 2015, 54 pp., June 2015.

219. Izaña Atmospheric Research Center, Activity Report 2012-2014,157 pp., June 2015.

218. Absorption Cross-Sections of Ozone (ACSO), Status Report as of December 2015, 46 pp., December 2015.

217. System of Air Quality Forecasting And Research (SAFAR – India), 60 pp., June 2015.

216. Seventh Intercomparison Campaign of the Regional Brewer Calibration Center Europe (RBCC-E), Lichtklimatisches Observatorium, Arosa, Switzerland, 16-27 July 2012, 106 pp., March 2015.

A full list is available at:
http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html
http://library.wmo.int/opac/index.php?lvl=etagere_see&id=144#.WK2TTBiZNB

For more information, please contact:

World Meteorological Organization

Research Department

Atmospheric Research and Environment Branch

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Tel.: +41 (0) 22 730 81 11 – Fax: +41 (0) 22 730 81 81

E-mail: GAW@wmo.int

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

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