Global Atmosphere Watch Expert Meeting Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition

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

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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) was mandated 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 health, human health effects and food security.

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 and regional chemical transport models. The fusion of measurement and model results requires sophisticated data assimilation and mapping techniques.

The Global Atmosphere Watch Expert Meeting on Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD), held from 26 to 27 February 2019 at WMO Secretariat in Geneva, was a follow-up meeting to the 2017 GAW Workshop on Measurement-Model Fusion for Global Total Atmospheric Deposition, an initiative of the SAG-TAD. Like the previous workshop, the Expert Meeting on MMF-GTAD aimed 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. Likewise, the Expert Meeting aimed to bring the MMF community together to reassess the state-of-the-science of MMF after two years, as well as to chart the project’s path forward in light of new developments in the field.

This two-day Expert Meeting was attended by 28 participants from 12 countries with expertise in atmospheric measurements and modelling, data assimilation, ecosystem effects and food security. Also in attendance were chairs or representatives of the GAW Scientific Advisory Groups for Reactive Gases, Aerosol, Total Atmospheric Deposition and Applications.

The workshop commenced on day one with presentations that provided background and context for the meeting and its outcomes. It was noted that WMO’s “Science for Services” approach is the guiding principle of the MMF-GTAD Initiative. As such, MMF-GTAD constitutes a research initiative of GAW that must deliver a tangible operational or semi-operational product (MMF maps in this case) of benefit to the different stakeholder communities. This therefore necessitates structuring the MMF-GTAD Initiative as a project with clear deliverables and targets.

The day one presentations were given in three sessions: (1) Stakeholder Activities and the Need for Global MMF Maps of Air Composition and Deposition, with presentations from stakeholders in the fields of biodiversity and ecosystem studies, climate change, and agriculture and food communities; (2) Measurement-Model Fusion Research Activities: what
MMF-related research has been done in the two years since the 2017 Workshop, in which updates were given on global and regional measurement data and databases, modelling, marine and remote sensing activities relevant to MMF-GTAD; (3) Specific MMF-GTAD Programmes and Products in which updates were provided on different MMF mapping activities in Sweden, Norway, the United States, the United Kingdom and Canada.

The second day was devoted to four discussion sections, three dedicated to the three goals set out during the 2017 MMF-GTAD Workshop and a fourth to discuss the new MMF-GTAD Project Plan and its implementation. The three goals and their discussion sessions were:

- **Goal 1**: Ensemble Model-Measurement Fusion for the Year 2010
- **Goal 2**: Stitching of Global/Regional Measurement-Model Fusion Products
- **Goal 3**: Global Reanalysis/Assimilation of Concentrations and Deposition Fluxes.

All four discussion sessions focused on whether these goals – being reassessed two years after having been established - are still relevant and how the path forward could best be achieved. During this session, original Goals 1, 2 and 3 from the 2017 Workshop were renumbered as Goals 1a, 1b and 2 in recognition of the fact that Goals 1a and 1b can now be carried out in parallel rather than sequentially. The final session was devoted to discussing the future of the project through the creation of a new MMF-GTAD Initiative Plan and how it should be implemented.

The following general conclusions and recommendations arose from the workshop:

- There was consensus that the anticipated products of the MMF-GTAD Initiative, as envisioned in the 2017 Workshop for MMF-GTAD, were still in demand and relevant, namely, global maps and data files of N, S and O\textsubscript{3} deposition for multiple years.

- Goal 1a (formerly Goal 1) is useful in and of itself and will also provide proof-of-concept that a global-scale semi-operational product with regional detail is feasible.

- A global dataset of observations is required and is key to the success of Goal 1a.

- 2010 remains the best choice as the ‘base year’ for this project, noting that after the proof-of-concept and full development of the appropriate fusion methodologies on regional and global scales, more recent years should be considered, perhaps 2017 or 2018.

- It is not feasible to standardize and/or fuse dry deposition methodologies at the present time. A method to investigate and address the various dry deposition schemes needs to be developed.

- There are regions of the world outside of the USA, Canada, Sweden, Norway and the UK where MMF initiatives are underway and monitoring and modelling results are available to start a model-measurement fusion exercise and consequently develop deposition maps.
• Goal 1b (formerly Goal 2) could serve to highlight the importance of, and uncertainties in, total deposition mapping on a global scale by comparing with existing MMF products in Europe and North America.

• Data assimilation and reanalysis products on a global scale are approaching similar capabilities as regional CTM models in terms of resolution, chemistry, and physical parameterizations. The main limitation with these products as it relates to Goal 2 (formerly Goal 3) is that the assimilation of satellite observations can have a more limited impact on near-surface concentrations (and therefore fluxes) than on the total atmospheric column.

The following recommendations resulted from the discussion sessions:

WMO now has a stronger focus on research activities and thus a Roadmap for the Measurement Model Fusion Initiative has to be made. The Roadmap must have two pillars, that is Research Elements (RE) and Research Infrastructure (RI) that will lead to WMO Products and Services through cross-cutting activities.

• The overarching goal of the Initiative is to produce seamless services that can become operational (or semi-operational) and can be tied to weather forecasts, cities’ management and climate services. Potentially better deposition and concentration maps can be achieved if linked to operational services such as the Copernicus Atmosphere Monitoring Service at the European Centre for Medium-Range Weather Forecasts (ECMWF).

• There is a need to establish how and when the Initiative will reach the broader MMF user communities including ecosystems, human health, food security, agrometeorology, renewable energy, corrosion of building materials, education, etc.

• The Research Infrastructure component of WMO is needed to support the MMF-GTAD Initiative by providing global observational concentration and deposition data.

• The objective of Goal 1a was reaffirmed from the 2017 Workshop as the following: to produce and publish global MMF deposition maps for the year 2010 (and later years if possible). Jeff Geddes (Boston University) agreed to act as the focal point for Goal 1a. Goal 1a activities should include: (a) obtaining and integrating various global model outputs; (b) applying a suitable global MMF technique to produce global deposition maps; (c) publishing a journal article.

• The objective of Goal 1b was redefined from the 2017 Workshop as follows: to publish a set of existing regional and global MMF-GTAD maps in a proof-of-concept journal article. Greg Carmichael agreed to create an outline for the article and a number of attendees agreed to participate in a Writing Team for the paper, namely: Wenche Aas, Greg Carmichael, Amanda Cole, Frank Dentener, Joshua Fu, Stefano Galmarini, Donna Schwede, David Simpson, Johannes Flemming and Lorenzo Labrador (WMO liaison).
A second activity was recommended for inclusion in Goal 1b, namely: to expand the existing regional MMF mapping capabilities beyond those in the USA, Canada, Sweden and Norway to other regions, most notably Europe, Africa and Asia. As a first step, it was recommended that Camilla Andersson (SMHI) be asked to consider applying the Swedish (SMHI) MMF method to all of Europe, and to ask scientists from other regions to investigate whether MMF methods could be applied to those regions, for example Africa, Asia.

The objective of Goal 2 (formerly Goal 3) was reaffirmed from the 2017 Workshop as: to develop a semi-operational capability for producing MMF-GTAD maps using global reanalysis and/or global data assimilation results. As a first step toward this objective, a recommendation was made by Vincent-Henry Peuch (ECMWF) and Johannes Flemming (ECMWF) that they host a visiting scientist at ECWMF to evaluate the CAMS reanalysis results for atmospheric deposition and to publish a journal article on the results.

In order to manage and oversee the MMF-GTAD Initiative, it was recommended that a Scientific Leadership Team (SLT) be formed. The following participants volunteered for membership on the SLT: Wenche Aas, Camilla Andersson (to be asked), Amanda Cole, Frank Dentener, Johannes Flemming, Joshua Fu, Corinne Galy-Lacaux, Maria Kanakidou, Donna Schwede and Lorenzo Labrador (as liaison). One of the many activities of the SLT will be to reach out to potential clients and users to advertise the MMF-GTAD Initiative’s capabilities and products, providing the opportunity to engage their interest and define their specific MMF-GTAD needs.

Given that the MMF-GTAD Initiative will depend on finding suitable funds to carry out Goals 1a, 1b and 2, all participants were encouraged to look for potential funding sources.

A new element to the Initiative was identified as the development of a MMF-GTAD Roadmap or Project Implementation Plan, a requirement of all of GAW’s research projects. The Implementation Plan will detail the strategies to be followed to achieve the goals established during the Expert Meeting. It will also provide guidance on the project, most notably: coordinating with major scientific, stakeholder and policy groups interested in MMF products, updating activities and products and identifying major tasks, timelines, participants, costs and sources of funding.
INTRODUCTION

WMO’s Global Atmosphere Watch (GAW) Programme coordinates high-quality observations of atmospheric composition across global to local scales with the aim of driving high-quality and high-impact science while also co-producing a new generation of products and services. GAW’s Scientific Advisory Group for Total Atmospheric Deposition (SAG-TAD) was given the 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 (MMF-TAD). This technique requires global-scale measurements of atmospheric trace gases, particles, precipitation composition and precipitation depth, as well as predictions of these parameters from global and regional chemical transport models (CTMs). The fusion of measurement and model results requires objective analysis and mapping techniques that produce 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 to the global scale. The February 2019 GAW Expert Meeting on Measurement-Model Fusion for Total Atmospheric Deposition, being reported herein, was organized as a follow-up to the earlier 2017 Workshop on Measurement-Model Fusion for Total Atmospheric Deposition. The purpose of the 2019 Expert Meeting was threefold: to take stock, two years after the previous workshop, of the state-of-the-science of Measurement-Model Fusion, to reassess the project goals set during the 2017 workshop, and to chart the project’s path forward.

The main goals of the 2019 Expert Meeting were similar to the 2017 Workshop and included: (1) exploring the feasibility of and methodology for 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 (2) to develop a path forward to achieve the production of these maps in light of the advances related to Measurement-Model Fusion.

The Expert Meeting was attended by many of the same experts who attended the 2017 Workshop on Measurement-Model Fusion for Total Atmospheric Deposition plus a number of new experts in the associated fields of modelling, measurements and food security.

Ahead of the main meeting discussions, presentations were given to set the scene for the Expert Meeting by (1) summarizing the results of the 2017 Workshop on Measurement-Model Fusion for Total Atmospheric Deposition (MMF-GTAD); (2) identifying the expected outcomes of the present meeting; (3) taking stock of recent scientific advances in Measurement-Model Fusion (referred to as MMF hereafter) techniques. Brief summaries of the presentations are given below.
Summary of the 2017 Workshop on MMF-GTAD (F. Dentener)

A summary of the 2017 Workshop on MMF-GTAD was presented, beginning with the following scientific context:

- A number of model intercomparison studies and evaluations have been completed or are underway which link observations to regional and global modelling.
- These activities have used similar evaluation datasets, allowing progress and improvements to be monitored.
- The quality-controlled WMO datasets for 2001-02 and 2003-05 (Vet et al., 2014) have been useful as a basis for the evaluation of global models.
- Performance of ensemble model results has not necessarily improved over the years.
- There is a large (and sustained) need for high-quality deposition data and maps by ecosystem and agricultural impact communities.

In light of the above, it was recognized that:

- In most global and regional models, deposition has not been the main focus of development.
- A number of studies have pointed to the importance of accurate descriptions of deposition processes – not only for deposition but to ensure that other parts of the models perform properly.
- There are opportunities for better integration of data and models.

During the 2017 Workshop on MMF-GTAD a three-phase MMF-GTAD Project was proposed to address short, medium and long-term goals, focused on nitrogen, sulfur and ozone, and using proposed MMF approaches for deposition. The first phase entailed combining or “stitching” together results from different global and regional model intercomparisons. The second phase was intended to bring together regional and global MMF maps from countries with ongoing MMF projects such as Canada, USA, UK, Sweden, Norway and Asia to produce global maps. The third phase aimed to develop an operational or semi-operational global MMF map production system based on the experience gained in the first two phases.

Expectations of the 2019 Expert Meeting by L. Labrador and R. Vet

The 2019 Expert Meeting on MMF-GTAD was designed to build upon the experience and knowledge gained during the 2017 Workshop as well as the two years following that Workshop. From this, the expected outcomes of the 2019 Expert Meeting were defined as follows:

- Updated knowledge of stakeholder activities and needs, the state of global measurement databases, the state of MMF-related science including chemical transport modelling activities (global and hemispheric), global reanalysis activities and measurement-model fusion/mapping activities.
- A reality check on the suitability of the three goals and other key recommendations of the 2017 Workshop.
• A set of updated goals and a realistic path forward for the Global MMF-GTAD Initiative based on recent advances in the state-of-the-science of Measurement-Model Fusion techniques, modelling and available measurement data.

• A roadmap identifying the specific tasks and experts willing to carry out the project’s agreed-upon updated goals.

• An estimate of the costs involved for each goal and an exploration of possible financing mechanisms.
SESSION 1. STAKEHOLDER ACTIVITIES AND NEEDS FOR GLOBAL MMF MAPS OF AIR COMPOSITION AND DEPOSITION

Session 1 focused on the activities and MMF needs of three specific stakeholder communities, namely: biodiversity, climate change and agriculture/food. Available summaries of the presentations are given below.

1.1 Biodiversity, Ecosystems, Critical Loads and the International Nitrogen Management System (INMS): global activities and needs related to MMF-GTAD by K. Hicks (presented by L. Labrador)

We are getting better at knowing where the main exceedances are but still have a long way to go on the quantification of the biodiversity and ecosystem service impacts at global scale. As some ecosystem service effects are positive (for example carbon sequestration/forest growth) dose-response information for policy making is essential.

For N and S deposition: we know where major exceedances are but not the specifics of the impacts for biodiversity and ecosystems services.

Tropospheric ozone has continuously improving estimates of crop yield reductions but impacts on biodiversity are still relatively unknown.

Effects of dust/ aerosol on crop production are still being debated – can have positive and negative effects through impacts on incident radiation.

Base cation deposition is important for buffering incoming acidity so its estimation relative to PM mitigation around the world is important.

The International Nitrogen Management System (INMS) project is already well known to the MMF–GTAD Community and the next year (2020) will be a crucial time to consolidate linkages as the global assessment is developed.

Furthermore, INMS can help with links to the impact community and the delivery of key messages to the policy arena.

1.2 Climate Change: Global activities and needs related to MMF-GTAD by M. Hegglin

Knowledge of the variability and trends of nitrogen deposition is crucial for the accurate prediction of the response of the climate system to anthropogenic CO₂ emissions. This is because the availability of nitrogen limits the uptake of CO₂ by land, ultimately determining atmospheric CO₂ concentration increases and, as a consequence, radiative forcing. The Future Earth/WCRP SPARC Chemistry-Climate Model Initiative (CCMI) supports ACCMIP6 (a new phase of the WCRP WGCM model intercomparison project) with the generation of historical and future nitrogen deposition-forcing databases for use in climate simulations from models that have no interactive atmospheric chemistry (based on historical emission estimates and eight different future emission scenarios). Initial comparisons of the historical nitrogen deposition database with past observations show reasonable agreement. However, the results also point
out the need for better constraints on nitrogen deposition distributions and changes in the southern hemisphere. This will be achievable only through new observations and a more integrative effort between the modelling and measurement communities to enhance consistency between observed and modelled nitrogen deposition fields taking into account the full process chain from emissions to removal of nitrogen species in the atmosphere.

SESSION 2. MEASUREMENT-MODEL FUSION RESEARCH ACTIVITIES: WHAT MMF-RELATED RESEARCH HAS BEEN DONE IN THE TWO YEARS SINCE THE 2017 WORKSHOP?

The focus of Session 2 was on MMF-related research carried out since the 2017 MMF-GTAD Workshop. Summaries of individual presentations are given below.

2.1  Update on global and regional measurement data and databases relevant to MMF-GTAD by W. Aas

Regional and global measurement data and databases relevant to the MMF-GTAD Initiative were summarized. It was noted that there are already benchmark datasets readily available for use in MMF-GTAD. In order to build additional new global datasets, there are sufficient data available from regional networks in North America, Europe, Asia and Africa. There are however some challenges to gather and quality assure the data into one harmonized global dataset with known data quality, and there are technical obstacles in both data access and data formatting, including the necessary metadata. These are important challenges for the future of the MMF-GTAD Initiative.

2.2  Update on AQMEII activities and plans relevant to MMF by S. Galmarini

Plans and preparations were presented for the 4th Phase of the Air Quality Model Evaluation International Initiative (AQMEII), which will be strictly dedicated to regional-scale modelling of deposition. AQMEII is an across-the-Atlantic initiative started in 2008 by the Joint Research Centre (JRC), US Environmental Protection Agency (EPA) and Environment and Climate Change Canada (ECCC) aimed at a continued collaboration of the European and North American regional-scale modelling communities. During the fourth evaluation exercise the two communities will be asked to perform simulations of two representative years (2010 and 2016 for North America, 2009 and 2010 for Europe) of air quality over the two continents and produce estimates at grid and point level of the model components that contribute to their deposition modules (that is resistances, velocities, land use types, etc.) as well as actual deposition values. Additional ad hoc modelling activities are planned that will be described elsewhere. This evaluation exercise will be the most detailed ever performed that involves such a large number of models and detailed analyses and will allow us to produce an assessment of the differences between models as well as how their results compare with monitoring data. Such analyses will be instrumental to the Measurement-Model Fusion exercise and others in terms of confidence and how model differences should be treated.
2.3 Update on the HTAP2 evaluation of global deposition and the future plans relevant to MMF-GTAD by J.S. Fu

The Task Force on Hemispheric Transport of Air Pollution (TF-HTAP) is an international team studying on the long-range transport of air pollutants and its impact on air quality and deposition. It is authorized by the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). The first phase of HTAP modelling project (HTAP I) involved more than 20 global models to study air pollutants and deposition in year 2001. The second phase (HTAP II) was launched in 2012 to study air pollution in 2010.

This study uses multi-model ensemble results from 12 global models involved in HTAP II to develop global-scale distributions of nitrogen (N) and sulfur (S) deposition for the year 2010. The spatial resolutions of the models vary from $0.5^\circ \times 0.5^\circ$ to $2.8^\circ \times 2.8^\circ$ and all the models are re-gridded to a unified spatial resolution of $0.1^\circ \times 0.1^\circ$ to calculate the multi-model mean. The qualities of model results are checked using two criteria: (1) a mass balance check to make sure that the amounts of deposition are within a $\pm 20\%$ range of emissions and (2) an inter-model consistency check to exclude model results that are not consistent with others (range = median of models $\pm 1.5 \times$ interquartile range of all models).

The multi-model ensemble results are evaluated with observation networks of the National Atmospheric Deposition Program (NADP) over North America, the European Monitoring and Evaluation Programme (EMEP) over Europe and the Acid Deposition Monitoring Network in East Asia (EANET) over East Asia. Compared to previous projects for wet deposition for 2000 such as PhotoComp, HTAP I and ACCMIP, the model performances of HTAP II have improved considerably for simulating wet deposition of $SO_4^{2-}$, $NO_3^-$ and $NH_4^+$. The improvements are most significant at sites over Europe and East Asia. However, the wet deposition of $NH_4^+$ is still somewhat underestimated over all regions.

The deposition in 2010 from HTAP II is compared with that in 2001 from HTAP I to investigate the changes in deposition over 10 years. The results show large decreases of N deposition over North America (3%) and Europe (11%), and increases over East Asia (27%), Southeast Asia (54%) and South Asia (80%), respectively. Reduced N ($NH_x$) is gaining importance in total N deposition and further study is suggested to evaluate the impacts under the condition that fewer control policies and initiatives have been implemented on $NH_3$ emissions than $NO_x$ emissions.

The following are some problems found in previous studies and suggestions for future studies:

- A complete set of quality assessment criteria is needed to ensure the quality of model results. A set of scientifically-sound model performance metrics is also required to facilitate comparison with other projects and campaigns.
- Additional model evaluations are required over East Asia, where the model performance is still unclear due to lack of observations. It is especially important to focus on China and India, where the highest wet deposition rates are modelled. In addition, the model performance on dry deposition has not been fully assessed in the past. It is suggested to perform a comprehensive model evaluation on dry deposition on a global scale.
• For Measurement-Model Fusion, techniques are required to fuse model output and measurement data at different spatial scales. Meanwhile, further study is suggested to constrain the lifetime budget (that is emissions, deposition rates and hemispheric transport) of pollutants in the models using observations.
• Further study is required to review the model algorithms on deposition processes in order to gain a better understanding of the role of vegetation on dry deposition processes.
• Current studies on deposition are focused on land emissions, while oceanic emissions (that is shipping emissions) are equally important sources for deposition, especially over coastal regions. More detailed temporal and spatial observations are therefore needed to understand the deposition of oceanic emissions.

2.4 European deposition modelling and model evaluation by A. Colette

The activities of the Task Force on Measurement and Modelling (TFMM) of EMEP in relation to MMF-GTAD were presented. TFMM recently conducted an air quality modelling hindcast exercise for the 1990-2010 period over Europe under the Eurodelta model intercomparison exercise. This involved eight regional Chemistry-Transport Models (rCTM) run at a spatial resolution of 25 x 25 km using prescribed meteorology, boundary conditions and emissions.

The scope of the experiment was to assess the capabilities of rCTMs to capture observed air quality trends (including deposition) previously published in an EMEP report devoted to observed trends (Colette et al., 2016). The experiment included sensitivity simulations to quantify the relative influence of European emissions, background changes and meteorology. A complete description of the experiment is available in (Colette et al., 2017a). The model validation demonstrates that models capture well the trends in $\text{SO}_2$, $\text{SO}_4^{2-}$ and total nitrate ($\text{NO}_3^-+\text{HNO}_3$), while limitations are found for $\text{NO}_2$ and total ammonia ($\text{NH}_4^++\text{NH}_3$) (Ciarelli et al., 2019). The relative trends in wet deposition are also well captured, although the absolute levels were modelled differently by the different CTMs involved (Theobald et al., 2018). Trends in ozone dry deposition impacts on crops were also presented (Colette et al., 2018). Eurodelta results were also used for a Measurement-Model Fusion analysis of health impacts, which also included a comparison with global estimates from the Global Burden of Diseases and Copernicus Regional reanalyses (Colette et al., 2017b).

The Eurodelta model results are publicly available in the Aerocom database: https://wiki.met.no/aerocom/start, in the /metno/aerocom-users-database/EURODELTA/ directory. Wet and dry deposition of $\text{NO}_x$, $\text{NH}_x$, and $\text{SO}_x$ are available for all models and for the 1990-2010 period as total monthly fluxes.

2.5 An update on Model Inter-Comparison Study for Asia (MICS-Asia) Activities Relevant to MMF-GTAD by S. Itahashi

Deposition rate analyses were carried out for nine models that participated in the MICS-Asia phase III study. Model performance was evaluated using EANET observation data. It was determined that all models generally captured the observed wet deposition; but underestimation of wet deposition of sulfate and ammonium resulted in large differences in
wet deposition of nitrate. The fraction of wet deposition to total deposition was analysed, and a dominance of wet deposition over Asia with respect to dry deposition over land was found. A new precipitation-adjusted approach that linearly scales modelled precipitation to observed precipitation successfully led to improved model performance for wet deposition.

2.6 Update and Future Directions of Satellite/Remote Sensing Activities related to MMF-GTAD by J. Geddes

Investigations of atmospheric concentrations and deposition fluxes can be directly informed by satellite remote sensing. Satellite observations are most powerful at identifying (and often quantifying) new or missing emission sources and can respond in a timely way to changes in emissions. Exciting progress is being made particularly in multi-species assimilations, and satellite retrievals continue to evolve and improve. For some species (such as NO$_2$, CO, and to some extent SO$_2$ and aerosol), the retrievals are operational and provide near-real-time support. For other species (for example NH$_3$, HNO$_3$, C$_2$HO), retrievals continue to be developed largely as research products by individual groups. Grand opportunities exist for further constraining surface fluxes with the next generation of tropospheric composition satellite instruments, including geostationary platforms.

2.7 Update and Future Directions of Satellite/Remote Sensing Activities related to MMF-GTAD by A. Baker

Atmospheric deposition is significant for ocean biogeochemistry through the input of nutrient species (such as nitrogen, phosphorus & iron) and potential toxins (for example copper). The large spatial scales involved (~70% of Earth’s surface) make global CTMs an essential tool for studying these inputs. These models have only been compared effectively to observations over a few areas of the global land mass (using wet deposition networks) and not at all over the oceans.

This presentation summarized the results of a study by the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Working Group 38 (Baker et al., 2017), which compared observations to model outputs for nitrogen deposition over the ocean. Baker et al. (2017) were not able to compare wet deposition because of the very low availability of observational data (a situation that is unlikely to change in the future). Instead, they compared ~3000 observations of aerosol composition to model outputs. Comparisons were rather difficult because model results were often only reported as deposition flux (which cannot be measured directly over the ocean) and for classes of chemicals (such as oxidised nitrogen, NO$_y$, or reduced nitrogen, NH$_x$) that are also not measured. Even when model results were reported for parameters that can be observed (in this case, aerosol nitrate and ammonium concentrations) a number of difficulties remained. These difficulties included: lack of standardization in observational methods, seasonal biases in when observations are taken, the representativeness of observations in comparison to the surface level used by the model. However, direct comparisons of observations to their corresponding parameters in models is essential to better assess the reliability of model results over the ocean. See Baker et al. (2017) for full details.
SESSION 3. SPECIFIC MMF-GTAD PROGRAMMES AND PRODUCTS

Session 3 was dedicated to presentations of new MMF-related activities that were undertaken after the 2017 MMF-GTAD Workshop. The presentations are summarized below.

3.1 Updates on MMF activities in (some of) Europe by D. Simpson

Updates on MMF activities for Norway, Sweden and the UK were presented such as a Norwegian study (Aas et al., 2017) covering 2012-2016, and an extensive Swedish study covering 1983-2014 (Andersson et al., 2018). The UK Concentration-Based Estimation of Deposition (CBED) model is currently being re-vamped, with new software, updated equations, and testing of Bayesian methods. General difficulties were discussed (such as lack of data on N-partitioning, uneven observational coverage). Still, such MMF methods could be applied in a pan-European approach, and funding will be sought for this.

3.2 Update on the United States Total Deposition (TDep) Measurement-Model Fusion (MMF) Activities by D. Schwede

An update was presented on U.S. measurement-model fusion activities for providing total atmospheric deposition values. In the USA, dry deposition values are obtained from a fusion of concentrations measured at Clean Air Status and Trends Network (CASTNET; https://www.epa.gov/castnet) sites and modelled concentrations and deposition velocities from the Community Multiscale Air Quality (CMAQ) modelling system (https://www.epa.gov/cmaq). Wet deposition values are obtained from a fusion of concentrations and precipitation amounts measured at National Atmospheric Deposition Program (NADP) National Trends Network (NTN) sites (https://nadp.slh.wisc.edu/NTN/) and values from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) model (http://www.prism.oregonstate.edu/). For species that are not measured (such as organic N, NO₂, NO, N₂O₅, PAN), deposition values are taken from CMAQ. Maps and data are currently provided for 2002-2016 and will be updated soon for 2017 (https://nadp.slh.wisc.edu/committees/tdep/tdepmaps/). Future potential updates include a modernization of the scripts used to process the data to make them more flexible and extensible for use with other datasets and methods, replacing the modelling data with a time series from a newer version of CMAQ (that is, v5.3), modifying the measurement-model fusion for wet deposition to include modelled values, and modifying the output to include land-use-specific deposition values. Other efforts by the NADP Total Deposition Science Committee were noted including the development of a white paper on science needs for continued development of total nitrogen budgets in North America and the collection of metadata to develop a global flux and throughfall database.

3.3 Update on the Canadian ADAGIO Project and the United States-Canada Collaborative Project by A. Cole

An update to the Environment and Climate Change Canada measurement-model fusion project ADAGIO (Atmospheric Deposition Analysis Generated by optimal Interpolation from Observations) since the 2017 workshop was presented. A major change is a new version of the optimal interpolation approach that uses a 5-member ensemble whereby 80% of the data are used to generate 5 separate sets of error statistics and the mean values of the statistics...
used in the final analysis. In addition, for each ensemble member, the remaining 20% of data that were not used were compared with the model and analysis values to assess the performance of the analysis. Another change is the additional analysis of ozone deposition on a seasonal basis. Annual deposition maps and gridded values for 2010 at ~10 km resolution over Canada and the United States are being prepared for public release, along with a publication describing the method. Comparison to the results of the U.S. TDep project over a coincident region of the two countries shows good agreement on the whole for both nitrogen and sulfur deposition, with a finer-scale analysis (such as by region and by species) and a mini-ensemble product is currently underway. Additional test years will likely be 2013-2016 and, as of late 2018, the Canadian operational air quality model used in ADAGIO is storing all necessary deposition parameters for the ongoing production of annual maps.

### 3.4 Developments of dry deposition modelling in CAMS by J. Flemming

The Copernicus Atmosphere Monitoring Service (CAMS) provides forecast and reanalysis of atmospheric composition on the global and European scales. The global CAMS system is implemented in the Integrated Forecast System of the European Centre for Medium-Range Forecast. Data assimilation using a 4D-VAR approach of satellite retrievals of aerosol optical depth (AOD) and total columns of NO₂, CO and ozone is applied to improve the realism of the atmospheric concentration fields.

We investigated the dry and wet deposition fluxes of total, reduced and oxidized nitrogen and sulphur as well as desert dust from the CAMS reanalysis (CAMSRA) (Inness et al., 2019). Using CASTNET observations over North America, we found reasonable agreement in spatial patterns and inter-annual variability of N and S deposition. We currently do not find significant differences between the deposition fluxes of a control model run data assimilation and the CAMSRA. This is because: (1) no SO₂ satellite retrievals are assimilated and (2) the assimilation of column NO₂ satellite products, while improving the regional NO₂ burden, does not significantly change the NO₂ surface values. This may improve with improved versions of the CAMS system when (i) less sparse NO₂ products, for example, from Sentinel 5P, will be assimilated or (ii) optimization of the NO₂ emissions will become part of the assimilation procedure.

In contrast to N and S deposition, the assimilation of AOD changes the dust concentration, which also leads to changes in dust deposition fluxes. No adequate observations of dust deposition were available to confirm that the dust emission fluxes of CAMSRA are improved by the assimilation of AOD.

### 3.5 ECCC Global Reanalysis Plans relevant to MMF-GTAD by R. Pavlovic

A second Environment and Climate Change Canada (ECCC) activity of relevance to MMF-GTAD was presented in which ECCC is working on a reforecast and reanalysis of major operational meteorological and air quality systems from 1980 to the present. This reforecast could serve as an input for a global and regional wet, dry, and total atmospheric deposition analysis. In addition, ECCC is planning to work on a regional air quality reforecast, which would provide the MMF-GTAD Initiative with atmospheric concentrations of gas and aerosol species at a 10-km resolution. One of the final products will be pollutant-specific model-measurement fusion fields

An in-depth discussion of the current status of the MMF-GTAD Initiative produced a consensus that the anticipated products of the Initiative (as envisioned at the 2017 Workshop on MMF-GTAD), that is, global maps and data files of N, S and O deposition for multiple years, are still in demand and that the project should proceed based on the three original goals. It was suggested that the timelines of the three goals identified in the 2017 Workshop (that is, short-, medium- and long-term) need not be sequential, since all three goals could advance simultaneously. In particular, original Goals 1 (merging global and regional model deposition products) and 2 (advanced regional model-measurement fusion) from the 2017 Workshop were seen as parallel activities and the recommendation was adopted that they be referred to hereafter as simultaneous Goals “1a” and “1b.” Hence, for the purpose of this report, the original 2017 Goals 1 and 2 are hereafter referred to as Goals 1a and 1b and the original Goal 3 is referred to as Goal 2.

Discussion in this session focused on balancing the competing needs of ongoing research (developing model capabilities, estimating uncertainty) and the production of user-focused products. In the proposed new GAW framework, the MMF-GTAD activity is considered as an applied stakeholder-oriented activity that fits within the “Science for Services” mandate of the Programme, while advancing the science is the role of the Scientific Advisory Groups. It was agreed that keeping the MMF-GTAD activity focused on the proposed products will minimize the risk of not being able to deliver.

A recommendation was made to include ongoing consultation with users and stakeholders as part of Goal 2 in order to (a) ensure the desired/needed products are produced, and (b) ensure the users are aware of the limitations of the products. Other groups, such as the INMS and the CMIP groups, have taken this approach and could provide suggestions for stakeholder engagement strategies.

Goal 1a is useful in and of itself but also acts as a proof-of-concept that a global-scale product with regional-scale detail is feasible. The preparation of measurement data is a non-trivial exercise, so earlier datasets from the global assessment (that is, 2000-2002, 2003-2005) could be used. On the other hand, additional and higher quality data are available for more recent years (for example, 2015-2017). In addition, recent global models are approaching regional models in terms of resolution and performance. However, many modelling intercomparison studies on global and regional scales are available for 2010 and likely will be limited for more recent years in the near future. Therefore, it was agreed that 2010 was still the best option for Goal 1a, and use the validation data used for HTAP2/AQMEII3/MICS-Asia3. Goal 1b could serve to highlight the importance of and uncertainties in global total deposition estimates by comparing a global MMF product with existing regional MMF products in Europe and North America. A further outcome of this goal would be to demonstrate the advances in on a regional scale over North America. ECCC will continue to contribute to MMF-GTAD efforts, with this ECCC initiative and future projects.
capabilities over recent years. For example, Goal 1b could start with global model ensemble output, then layer in regional ensembles in regions that have them, then add in regional MMF products that exist to show improvements (that is, reduced uncertainty). This would justify the need for a global MMF product as well as motivate similar studies on additional species such as dust and black carbon.

Understanding the similarities of this work with ongoing work merging statistical approaches with assimilation models (like CAMS) for the WHO health community was mentioned as also useful in the deposition context.

SESSION 5. GOAL 1A DISCUSSION AND PATH FORWARD

The session began with a presentation of a background slide based on the outcome of the 2017 Workshop on MMF-GTAD. The slide noted that the objective was: to develop and apply methodologies for fusing multi-model ensemble results, observational data, and reanalysis results for the year 2010 in order to produce gridded global measurement-model fusion maps (and associated data files) of wet, dry, and total deposition and concentrations of important gas, aerosol, and precipitation species. This objective was reaffirmed and the title of Goal 1a was re-stated as "Global MMF-GTAD for the Year 2010".

Existing model initiatives (as described in the presentations of Session 2 and 3) were noted and it was acknowledged that a global dataset of 2010 observations would be required. Model ensemble outputs of surface air concentrations, modelled deposition velocities, and precipitation concentrations would be used to develop best-estimate ensemble fields, and then fused with observations. Due to the potential mismatch between modelled and observed precipitation amounts, the mass balance between emissions and wet deposition would need to be considered in order to assess confidence in the generated fields and to guide future priorities. It was acknowledged that dry deposition estimates are particularly uncertain and that an intercomparison of modelled dry deposition fluxes is required.

Further discussion was dedicated to a reality check on the original Goal 1 as presented at the 2017 workshop. Key outcomes of the discussion included:

- The feasibility of generating model ensemble outputs and the fusion with precipitation has not been achieved. Identification of a lead research person or persons will be necessary.

- The year 2010 was chosen as a base year for future work by convenience because of the current availability of model outputs and data. In light of the new ACMEII, HTAP, and other available ensemble modelling project results, a reconsideration of a focal year beyond 2010 was suggested. 2016 and 2017 were identified as possible alternative study years, assuming that appropriate global datasets could be made available.

The following comments and recommendations were made taking into consideration progress in the modelling and measurement communities since the 2017 meeting:
• Direct dry deposition models and data cannot be fused at the present time (that is, only concentrations). A method to compare and attempt to make consistent the various dry deposition schemes needs to be addressed.

• A global dataset of observations is required and is key to the success of this activity. Global observational data need to be identified. Paolo Laj noted that under the SAG Aerosols initiative, updates of the database should allow comparison with model outputs for some specific aerosol variables. For aerosols, 2017 would be a good reference year and many more observations are now available compared to 2010. These data are currently housed at various data centers. The SAG-Aerosols recommended 2017 as the base year for future MMF-GTAD work.

• The MMF-GTAD Initiative should leverage modelling initiatives already in place, which is why 2010 was selected as the base year. Stefano Galmarini noted that AQMEII and HTAP output is available for 2010. If these regional and global modelling activities are the only ones available, the initial efforts should be kept simple and Goal 1a should continue with the 2010 base year to provide a proof-of-concept. LRTAP output is available between 1990 and 2010 and the GAW Global Assessment data are available from 2000-2005.

• Data evaluation is difficult. At present, we can rely on the period of 2000-2005 data and build later datasets to compare with global scale models.

• Customers must be identified for whatever base year we pick. For critical loads assessments, a time series possibly going back to 2000, would be useful. Having a final product along with a globally-fused data set allows the project to build a bridge to multiple customers if the community is able to transform final products into something that can be used for exposure or ecosystem applications, such as critical load exceedances.

• After consideration of the various recommendations, it was concluded that 2010 is still the best choice for a base year for this project as a proof-of-concept, noting that after the proof-of-concept and development of the appropriate fusion methodologies, more recent years should be considered, perhaps 2017 or 2018.

• The challenges are to determine how to do the fusion and finding a lead person to guide the development.

Further discussion focused on data and model output considerations related to MMF-GTAD. The question was raised whether deposition velocities are available for all desired chemical species. After some discussion, it was agreed that deposition velocities can be retrieved from models but that it will require a presently unknown level of effort.

David Simpson stated that he is willing to run the EMEP model for the MMF-GTAD Initiative if needed. Terry Keating noted that under HTAP, it may be possible to get additional models to submit data for 2010 runs. It was noted that if we advertise that we are looking for additional information that we may get a number of additional groups coming forward with datasets.
Wenche Aas indicated that the Norwegian Institute of Air Research (NILU) does not have all of the necessary data available but that it could be generated. It will be necessary to determine the required temporal resolution for the data in order to fuse it with the modelling results. She noted that annual data are easy to provide but that generation of a dataset with higher temporal resolution (monthly or even hourly) is a bigger task.

It was noted that maintaining harmonization between the SAGs (Aerosols, Reactive Gases, Applications and TAD) is essential. Documentation of procedures and maintenance of scripts during the initial effort is also essential. While 2010 was selected as the first base-year of study, to be successful, the fusion process will need to be applied to additional years. There is a need to develop a systematic methodology for accomplishing this.

Joshua Fu presented several slides outlining the potential contributions of the HTAP team. These slides addressed 2010 examples, quality assessment criteria, model mass balance checks, a model performance matrix (suggesting a different performance matrix for different user communities.) China was suggested as a potential region for a regional application since modelled chemical species outputs and network data should be available to meet the needs of MMF-GTAD. He noted that different HTAP models have different capabilities, so various modelled data subsets could be made available depending on the species being studied.

Frank Dentener noted that the project must generate journal papers. Papers require that the work be scientifically interesting and that value be added, which could include merging models with data (particularly for data sparse areas) and careful quantification of uncertainties. Assumptions must be identified and the ensemble approach must be described clearly.

Bob Vet framed the issues required to successfully complete Goal 1a. Three major activities were identified: (1) compiling the measurements database (which includes conducting necessary quality assurance activities); (2) assessing the available ensemble model datasets with consideration of how to use them in the same time frame as the available data; (3) carrying out the fusion activity itself. The work doesn’t have to be carried out by a single group but, rather, could involve three or more different groups working collaboratively.

With regard to carrying out the project, it was noted that Wenche Aas currently handles European data. She indicated that it would be possible to handle the development of the full global dataset with sufficient funds. Donna Schwede could handle CMAQ participation with funding for an additional staff person. Collaboration with Amanda Cole would be required to develop the fusion process.

Jeff Geddes volunteered to lead the Goal 1a effort if given sufficient funding for students or postdoctoral fellows. He noted that there are people in his department who could address land surface processes.

It was noted that WMO’s Chief Scientist, Pavel Kabat, pledged his effort to look for funds for the project.
**Major Conclusions and Recommended Actions**

The Goal 1a objective was reaffirmed as follows: to produce and publish global MMF-GTAD deposition maps for the year 2010 (and later years if possible). Jeff Geddes (Boston University) agreed to be the focal point for Goal 1a if funds can be found to support a postdoctoral researcher or suitable graduate students. The recommended activities for proceeding with Goal 1a were identified as: (a) investigating, collecting and integrating various global model outputs; (b) applying a suitable global MMF technique to produce global deposition maps; (c) publishing a journal article.

**SESSION 6. GOAL 1B DISCUSSION AND PATH FORWARD**

The discussions in this session centred on practical aspects of data fusion, taking into consideration the discussions in previous sessions.

The group came to an initial conclusion that there are regions of the world in which both monitoring and modelling initiatives exist and could be made available to start a Measurement-Model Fusion activity for deposition mapping. For example, in Europe, systematic work has already started, in some countries such as Sweden and Norway, whilst in the rest of the continent information is available, but not the funding. A champion institution is needed in Europe to take the lead on this work but is not yet available. In North America (USA and Canada), MMF mapping activities are underway which brings the issue of whether Swedish/Norwegian methodologies and mapping techniques should be harmonized with the North American ones or whether it is sufficient to acknowledge the differences and explore the reasons for them. A consensus was found that in Asia, no MMF activity has been undertaken and that, in view of serious air quality issues there, such work needs to be considered.

A list of detailed technical questions was presented to encourage discussion on the methodologies and variables to be considered (both chemical and micrometeorological), the inclusion of measurements collected using low cost sensors, methods of including biophysical parameters such as stomatal ozone fluxes, whether the developed maps should be consistent with national maps of critical loads, how to account for emissions (that is if values should be normalized by emissions) and the uncertainty in the emission inventory values. All of these were seen as pertinent issues that clearly demonstrate the many factors affecting MMF and the many open issues that need to be addressed methodologically.

A consensus was found that writing one or more scientific publications would be a solution to addressing a number of the open issues scientifically and would also encourage the participation of individual scientists, groups and organizations in the MMF-GTAD Initiative in the absence of funding.

It was concluded that any serious MMF-GTAD work aimed at producing high-quality fusion maps would require funding - even for organizations like the Swedish Meteorological and Hydrological Institute, which is deeply involved in deposition mapping at a national level.
Major Conclusion and Recommended Actions

Goal 1b was given the title: “Publication (Stitching) of Existing Global and Regional Measurement-Model Fusion Maps”, the objectives for which were re-established as follows: (1) to publish a set of existing regional and global MMF-GTAD maps in a proof-of-concept/demonstration-of-capability journal article and (2) to expand the existing regional MMF mapping capabilities beyond those in the USA, Canada, Sweden, Norway and the UK. For the first objective, Greg Carmichael agreed to create, with the help of Joshua Fu, an outline for the suggested journal article and a number of attendees agreed to establish a Writing Team to produce the paper. Volunteers for participating in the Writing Team were: Wenche Aas, Greg Carmichael, Amanda Cole, Frank Dentener, Joshua Fu, Stefano Galmarini, Donna Schwede, David Simpson, Johannes Flemming and Lorenzo Labrador (as liaison).

For the second objective, a recommendation was made to ask Camilla Andersson of SMHI to consider applying the Swedish (SMHI) MMF method to all of Europe, and to ask scientists from other regions to investigate whether MMF methods could be applied to those regions, such as Africa, Asia.

SESSION 7. GOAL 2 DISCUSSION AND PATH FORWARD

The discussion of the MMF-GTAD Goal 2 (a global reanalysis of concentrations and deposition fluxes) was closely tied to the discussion of existing chemical data assimilation capabilities in general. As such, this session’s discussion began with an update and a set of follow-up questions related to data assimilation. In addition to the Copernicus Atmosphere Monitoring Service (CAMS), chemical assimilation is being performed by agencies in Canada, USA, Europe and Japan, and it is therefore not an activity that the MMF-GTAD group needs to reproduce. It was noted that the MMF-GTAD Initiative would benefit from the SAG-Apps taking the lead in gaining buy-in for the project from the various centres already performing chemical data assimilation.

A key point was made that global chemical assimilation and reanalysis products are approaching similar capabilities to regional CTMs in terms of resolution, chemistry and physical parameterizations. The main limitation with the reanalysis products as it relates to the MMF-GTAD goal is that the assimilation of satellite observations (for example, CO, NO₂, AOD) can have less impact on near-surface concentrations (and therefore fluxes) than on the total atmospheric column. However, there is potential for the new and upcoming generation of satellite observations (with higher resolution and higher observational density) to provide stronger constraints on surface processes. At the moment, the chemical assimilation community remains cautious about assimilating surface measurements of chemistry since site representativeness, even at the 10-km scale, could introduce problems. There is also opportunity to make progress towards a more organized and rapid adoption of satellite-based top-down emission inversions so that chemical information near the surface would be affected. There are examples of top-down inventories having improved bottom-up efforts (for example, in the treatment of mobile sources of NOₓ), even if there is no formal service that does this routinely.
The emission inversion community was encouraged to consider how uncertainty in dry deposition fluxes and chemistry (such as rates of NO\textsubscript{x} conversion) can be accounted for (and possibly improved) during the inversion process. Meanwhile, there might be potential for leveraging land surface satellite observations to better constrain surface processes. Updates in land surface datasets are largely decoupled from the assimilation, and processing and incorporating new satellite-derived land maps is not seen as feasible at the moment. To do so would require a large amount of effort and offline data processing. However, there is opportunity for constraining vegetation processes using near-real-time satellite-observed solar-induced fluorescence as an example.

Further discussion focused more closely on MMF-GTAD’s Goal 2, in particular: what does the progress in chemical assimilation and reanalysis mean for our goal of providing some type of global “reanalysis” of concentrations and deposition fluxes to the MMF-GTAD user communities and customers? The main strengths and capabilities that chemical reanalyses offer are near-real-time map production and insight into long-term trends. This is in contrast to CTMs alone (especially multi-model ensembles) which require long lead-times to produce results. It was emphasized that the chemical reanalyses exercises mentioned here are inherently different from the post-processed measurement-model fusion products that are the goal of the MMF-GTAD group. This raised several key questions about how the project can leverage chemical reanalysis products for (semi-)operational deposition mapping. The questions included:

- Do we simply use the chemical reanalysis deposition output directly as an end-product?
- Or do we use the reanalysis deposition output to support our own posteriori calculations where we “fuse” in situ deposition observations?
- Should we use the chemical reanalysis data just to provide or support concentration estimates?
- Is the reanalysis product seen as a replacement for CTM output?

It was agreed that the answers to many of these questions will depend on how the chemical assimilation capabilities evolve in the near future. Developments in this field are happening very quickly, and so we can expect our specific interest in and use of chemical reanalyses results to evolve alongside this. It was suggested that we proceed with including chemical reanalysis datasets in our current activities “as though” they are output from any other independent CTM, and we might discover how both communities can inform each other over the next 2-5 years. It was stated that the assimilation community could indeed benefit directly from our own activities: for example, they would potentially benefit from going through the same evaluations as the CTMs do. One actionable item from this discussion was that a formal evaluation of the deposition estimates from the Copernicus Atmospheric Monitoring System, and an analysis of their long-term trends, would be a valuable research project.

In general, Goal 2 activities for providing some type of global “reanalysis” of concentrations and deposition fluxes were framed as highly important, forward-looking and longer term. It was not clear how often, and for which years, the project would be able to produce global measurement-model fusion products, as this is largely limited by the frequency with which we can compile quality-controlled in situ deposition measurements. There was agreement that a regularly updated global reanalysis of concentrations and fluxes should continue to be viewed as an important goal in the longer term.
There was consensus that the next steps toward Goal 2 will be informed by what is learned from the MMF-GTAD Goal 1a and Goal 1b activities, and by what users and customers need, such as time scales. Many questions were left open and acknowledged to be important for consideration as the Goal 2 activities unfold. Examples include the following: Is providing a global map of deposition roughly every 5 years useful? Or is the user community more interested in an annually-updated global map of deposition? How long (or short) a lag-time is reasonable for the user community? Would users want/need a retrospective product? If so, how far back, and at what time interval? And what are the specific evaluation (and uncertainty) requirements for each user community?

**Major Conclusions and Recommended Actions**

The title of Goal 2 was rewritten as “Semi-Operational MMF-GTAD Map Production using Global Reanalysis Results” and the Goal 2 objective was redefined as: to develop a semi-operational capability for producing MMF-GTAD maps using global reanalysis and/or global data assimilation results. It was recognized that Goal 2 will be longer term than Goals 1a and 1b. In light of the long-term nature of Goal 2, an early building-block activity was identified wherein Vincent-Henri Peuch (ECMWF) and Johannes Flemming (ECMWF) will consider hosting a visiting scientist at ECWMF to evaluate the CAMS Reanalysis deposition results and to publish a journal article on the outcome. This activity was identified as an important first step in assessing and applying the CAMS global results for semi-operational MMF-GTAD global deposition mapping.

**SESSION 8. THE NEW MMF-GTAD INITIATIVE PROJECT PLAN AND ITS IMPLEMENTATION**

WMO now has a stronger focus on delivering Science for Services, which means that a Roadmap for the Measurement Model Fusion Project must be drawn up. The Roadmap must reflect the fact that the project has two pillars, namely, Research Elements and Research Infrastructure, both of which will lead to Products and Services (transversal activity).

- The Research Elements (RE) include those techniques needed to achieve the measurement-model fusion from its initial demonstration to its final operational products.
- The Research Infrastructure (RI) supports research that addresses the science questions and delivers the products (global maps and trends). In this respect, the RI must determine:
  - what measurements are available? Are they sufficient to achieve the goals? Are there more observations needed and where?
  - how will the existing data be used? How will the global datasets be obtained?

Products and Services refers to satisfying the needs of the user community. This transversal activity has as its products the MMF-GTAD maps of and trends in deposition and atmospheric concentrations of atmospheric pollutants that are user-oriented and defined in collaboration with the user community.
Partnerships between different UN agencies with stakeholder interests (such as the World Health Organization and the World Food Programme) need to be established and strengthened. Likewise, the bonds and interactions between the GAW communities with common interests and expertise relevant to the MMF-GTAD Initiative, such as the Scientific Advisory Groups on Aerosols and Reactivate Gases, need to be established.

Leveraging the experience of other programmes (such as the International Nitrogen Management System) and establishing relations with the user community will provide added value to the overall effort. The MMF-GTAD proposed products are not familiar to the agricultural community. For instance, O$_3$ deposition and N deposition issues over China could be valuable but the Project needs to approach the associated communities.

The overarching goal is to produce seamless services that can become operational and can eventually be tied to weather forecasts, city management and climate services. The next-generation model systems will enable such approaches. Weather forecast models now include more explicit chemical components and, in coming years, there will be rapid development of Earth System models that are expected to run operationally.

In this fast-changing research and technological environment, it is felt that the MMF-GTAD Initiative will need to estimate also the global deposition of nutrients in the longer term, with both seasonal and sub-seasonal predictions. Potentially better deposition and concentration maps can be achieved if linked to operational services like Copernicus.

The project also needs to determine when and how to reach the user communities in various sectors (security, ecosystems, health, food, agrometeorology, renewable energies, corrosion of building materials, and education). Other users include the broader academic community, using the MMF products for their own research. It is apparent that there are multiple user communities and the MMF-GTAD Initiative needs different strategies to reach them as well as different products to address their needs.

There was consensus that a Science Leadership Team (SLT) must be established to communicate with potential users, advertise current MMF-GTAD capabilities and identify specific needs. It was recommended that, in about one year from now, a meeting be organized with stakeholders to discuss the MMF-GTAD capabilities and co-design with the users their desired new products. Such products are expected to continuously evolve in the future following the improvements of models and of observational data.

For the path forward, the Research Infrastructure component of WMO will have to support the MMF-GTAD Project with high-quality observational data. However, the existing observational datasets have significant geographical gaps due to both existing but unreported data (for example data from Asia) and lack of measurements in certain regions (for example, South America, Australia). The need to consolidate global measurement data beyond the 2000-2005 period, as published by Vet et al., 2014, is a necessity for the MMF-GTAD Initiative. Such action requires support with funds and could be done by a PhD or a senior scientist (such as Wenche Aas) with the required experience in data QA/QC, which will enable a faster outcome than from a PhD student. Even if not perfect and highly uncertain, past data collected in regions where current observations are missing could help increase the spatial coverage of the database. In the best case, data have to be collected and archived at the highest resolution at
which they have been measured. Scripts need to be developed to facilitate access to and use of raw data. There is also a need for the continuous flow of metadata for MMF-GTAD activities, and the delivery of semi-operational products has to be taken into account in the development of data acquisition and analysis tools. Common formats for data submission and robust tools must be used to allow users to submit their data while maintaining the initial/raw data in their own database. A decision on the time resolution of all raw and processed data must be made before any new MMF-GTAD activities can proceed.

With regard to the implementation of the MMF-GTAD Initiative, several strategies were identified as important to the process, some of which are already under consideration. For instance, there is a need to establish a methodology for doing multiple-model ensembles, the considerations for which include:

- Does one use ensemble-mean modelled values of both atmospheric concentrations and dry deposition velocities to produce final MMF deposition fluxes?
- Or, does one perform MMF for each of the multiple models in the ensemble in order to derive model-specific MMF deposition fluxes and then compute the ensemble-mean of the MMF deposition fluxes?

Concern was raised that the quality of MMF deposition fluxes might be subject to errors, in particular with regard to mass balance closure in the models. For instance, MMF will improve deposition fluxes but the extent to which these fluxes are consistent with the emissions remains to be determined. The dry deposition fluxes have the largest uncertainties since observational data are not appropriate to constrain them and most are based on model estimates derived from atmospheric concentrations using different deposition modelling approaches.

A recommendation was made that the participants publish a journal article that would demonstrate the scientific proof-of-concept of MMF-GTAD and show some of the global MMF-GTAD results. Greg Carmichael provided an outline of the potential paper, which would integrate and compare both global and regional (for example, Canada, USA, Sweden, Norway, UK) MMF-GTAD results for the year 2010. Greg Carmichael and Joshua Fu agreed to prepare a formal outline for the paper for consideration of those interested in writing the article. A number of participants agreed to contribute to the paper, focusing on the analysis of data and model results currently available for 2010. This could possibly include CAMS and other reanalysis results for 2010 since several ensemble simulations are available from HTAP2, AQMEIII and Eurodelta for that year. Other participants involved in the writing team are: Joshua Fu (representing HTAP and MICS; he will also seek data from East Asia, China), Frank Dentener, Donna Schwede, Wenche Aas, David Simpson, Amanda Cole, and Stefano Galmarini.

A Roadmap or Implementation Plan for the MMF-GTAD Initiative will be drafted by Maria Kanakidou, which will outline a high-level strategy for the project. The Roadmap will describe the full framework for the implementation of MMF activities including procedures, methodologies and objectives. The aforementioned oversight team tentatively named the MMF-GTAD Scientific Leadership Team will help design the Roadmap and to define scientific gaps that could prevent the optimal implementation of MMF-GTAD. The following persons volunteered for the SLT of MMF: Donna Schwede, Amanda Cole, David Simpson, Wenche Aas,
Frank Dentener, Corrine Galy-Lacaux, Joshua Fu, Johannes Flemming. The Roadmap will be continually updated to take advantage of advances in scientific understanding and improvements in methodologies.

Corinne Galy-Lacaux agreed to submit a project proposal to BNP Paribas on Climate and Biodiversity issues. The focus will be on Africa. WMO will help Corinne submit the proposal by the end of April 2019 based on a science plan that she has already written but did not submit to the Horizon call for proposals. This concerns air pollution in Africa and includes intensive campaigns on one or two sites with online flux measurements. Integrated Nitrogen Studies in Africa (INSA) is also interested in this activity.

The Expert Meeting closed with a strong endorsement for moving forward with the MMF-GTAD Initiative.

Summary of Major Conclusions and Recommendations

The presentations and discussions of the Expert Meeting led to the following general conclusions and recommendations.

Conclusions

- There was consensus that the anticipated products of the MMF-GTAD Initiative as envisioned in the 2017 Workshop for MMF-GTAD, were still in demand and relevant, namely, global maps and data files of N, S and O₃ deposition for multiple years.

- Goal 1a (formerly Goal 1) is useful in and of itself, and will also provide proof-of-concept that a global-scale semi-operational product with regional detail is feasible.

- A global dataset of observations is required and is key to the success of Goal 1a.

- 2010 remains the best choice as the ‘base year’ for Goal 1a, noting that after the proof-of-concept and full development of the appropriate fusion methodologies on regional and global scales, more recent years should be considered, perhaps 2017 or 2018.

- It is not feasible to standardize and/or fuse dry deposition methodologies at the present time. A method to investigate and address the various dry deposition schemes needs to be developed.

- There are regions of the world outside of the USA, UK, Canada and Sweden where MMF initiatives are underway and monitoring and modelling results are available to start a model-measurement fusion exercise and consequently develop deposition maps.

- Goal 1b (formerly Goal 2) will serve to highlight the importance of, and uncertainties in, total deposition mapping on the global scale by comparing with existing MMF products in Europe and North America.
Data assimilation and reanalysis products on a global scale are approaching similar capabilities as regional CTM models in terms of resolution, chemistry, and physical parameterizations. The main limitation with these products as it relates to Goal 2 (formerly Goal 3) is that the assimilation of satellite observations can have less impact on near-surface concentrations (and therefore fluxes) than on the total atmospheric column.

**Recommendations**

- WMO now has a stronger focus on research activities which means that a Roadmap for the Measurement Model Fusion Project has to be produced. The Roadmap must have two pillars, that is Research Elements and Research Infrastructure, that will lead to WMO Products and Services through cross-cutting activities.

- The overarching goal of the Initiative is to produce seamless services that can become operational (or semi-operational) and can ultimately be tied to weather forecasts, cities’ management and climate services. Potentially better deposition and concentration maps can be achieved if linked to operational services such as the Copernicus Air Management System at ECMWF.

- There is a need to establish how and when the project will reach the broader MMF user communities including security, ecosystems, human health, food, agrometeorology, renewable energy, corrosion of building materials, education, etc.

- A Science Leadership Team (SLT) will be formed to reach out to potential clients to advertise the MMF-GTAD Initiative’s capabilities and potential products, providing the opportunity to engage their interest and define their specific MMF-GTAD needs.

- The Research Infrastructure component of WMO will have to support the MMF-GTAD Initiative by providing global observational concentration and deposition data.

- The objective of Goal 1a was reaffirmed as the following: *to produce and publish global MMF deposition maps for the year 2010 (and later years if possible).* Jeff Geddes agreed to act as the focal point for Goal 1a. Goal 1a activities should include: (a) obtaining and integrating various global model outputs; (b) applying a suitable global MMF technique to produce global deposition maps; (c) publishing a journal article.

- The objective of Goal 1b was redefined as follows: *to publish a set of existing regional and global MMF-GTAD maps in a proof-of-concept journal article.* Greg Carmichael agreed to create an outline for the article and a number of attendees agreed to participate in a Writing Team for the paper, namely: Wenche Aas, Greg Carmichael, Amanda Cole, Frank Dentener, Joshua Fu, Stefano Galmarini, Donna Schwede, David Simpson, Johannes Flemming and Lorenzo Labrador (WMO liaison).
• A second activity was included in Goal 1b, namely: to expand the existing regional MMF mapping capabilities beyond those in the USA, Canada, Sweden and Norway to other regions, most notably Europe, Africa and Asia. As a first step toward this activity, Camilla Andersson (SMHI) will be asked to consider applying the SMHI MMF method to all of Europe, and scientists from other regions will be asked to investigate whether MMF methods could be applied to those regions, for example Africa, Asia.

• The objective of Goal 2 (formerly Goal 3) was reaffirmed as: to develop a semi-operational capability for producing MMF-GTAD maps using global reanalysis and/or global data assimilation results. As a first step toward this objective, a recommendation was made by Vincent-Henry Peuch (ECMWF) and Johannes Flemming (ECMWF) that they host a visiting scientist at ECWMF to evaluate the CAMS reanalysis results for atmospheric deposition and to publish a journal article on the results.

• To manage and oversee the MMF-GTAD Initiative, it was recommended that a Scientific Leadership Team (SLT) be formed. The following participants volunteered for membership: Wenche Aas, Camilla Andersson (to be asked), Amanda Cole, Frank Dentener, Johannes Flemming, Joshua Fu, Corinne Galy-Lacaux, Maria Kanakidou, Donna Schwede and Lorenzo Labrador (as liaison).

• Given that the MMF-GTAD Initiative will depend on finding suitable funds to carry out Goals 1a, 1b and 2, all participants were encouraged to look for potential funding sources.

Finally, a recommendation was made that the SLT create a MMF-GTAD Initiative Implementation Plan, a requirement of all GAW research projects. The Implementation Plan will describe all of the strategies to be followed to achieve the goals established during the Expert Meeting. It will also provide guidance on the following activities: coordinating with major science, stakeholder and policy groups interested in MMF products, updating goals/products and identifying major tasks, timelines, participants, costs and sources of funding.
REFERENCES


ANNEX 1

GLOBAL ATMOSPHERE WATCH

EXPERT MEETING ON MEASUREMENT-MODEL FUSION FOR GLOBAL TOTAL ATMOSPHERIC DEPOSITION (MMF-GTAD)

Geneva, Switzerland, 26-27 February 2019

List of Participants

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ANNEX 2

GLOBAL ATMOSPHERE WATCH

EXPERT MEETING ON MEASUREMENT-MODEL FUSION
FOR GLOBAL TOTAL ATMOSPHERIC DEPOSITION (MMF-GTAD)
Geneva, Switzerland, 26-27 February 2019

Agenda

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<th>Tuesday 26 February</th>
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<td>08:15 - 08:30</td>
<td>Arrival</td>
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<tr>
<td>08:30 – 08:35</td>
<td>Welcome</td>
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<tr>
<td>08:35 – 08:45</td>
<td>Opening Remarks</td>
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<tr>
<td>08:45 – 09:15</td>
<td>The Restructuring of WMO and GAW’s Vision for the Future of MMF-GTAD</td>
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<tr>
<td>09:15 – 09:30</td>
<td>Summary and Conclusions of the 2017 Workshop on MMF-GTAD</td>
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<tr>
<td>09:30 – 09:45</td>
<td>Introduction to Expert Meeting: Background, Context, Objectives, Expected Outcomes and Participant Introductions</td>
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<tr>
<td>09:45 – 10:15</td>
<td><strong>Break</strong></td>
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**Session 1. Stakeholder Activities and Needs for Global MMF Maps of Air Composition and Deposition**
Chair: Corinne Galy-Lacaux, UPS

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<tr>
<th>Time</th>
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<tr>
<td>10:15 – 10:35</td>
<td>Biodiversity, Ecosystems, Critical Loads and the International Nitrogen Management System (INMS): global activities and needs related to MMF-GTAD</td>
<td>Kevin Hicks, UY, presented by Lorenzo Labrador</td>
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<tr>
<td>10:35 – 10:55</td>
<td>Climate Change: global activities and needs related to MMF-GTAD</td>
<td>Michaela Hegglin, UR</td>
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<tr>
<td>10:55 – 11:15</td>
<td>Agriculture and Food: the FAO Geospatial Unit and global activities and needs related to MMF-GTAD</td>
<td>Douglas Muchoney, FAO</td>
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**Session 2. Measurement-Model Fusion Research Activities: what MMF-related research has been done in the two years since the 2017 Workshop?**
Chair: Van Bowersox, WDPC

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<tr>
<th>Time</th>
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<tr>
<td>11:15 – 11:35</td>
<td>Update on global and regional measurement data and databases relevant to MMF-GTAD</td>
<td>Wenche Aas, NILU</td>
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</table>
11:35 - 11:55  Update on AQMEII activities and plans relevant to MMF-GTAD  
Stefano Galmarini, JRC

11:55 – 13:15  Lunch

13:15 – 13:35  Update on the HTAP2 evaluation of global deposition and aerosols and the future plans relevant to MMF-GTAD  
Joshua Fu, UT

13:35 – 13:55  European deposition modelling and model evaluation under the TFMM (UNECE Task Force on Measurements and Modelling)  
Augustin Colette, INERIS

13:55 – 14:15  Update and future directions of MICS-Asia activities relevant to MMF-GTAD  
Syuichi Itahashi, CRIEPI

14:15 – 14:35  Update and future directions of satellite/remote sensing activities related to MMF-GTAD  
Jeff Geddes, BU

14:35 – 14:55  GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) activities related to MMF-GTAD  
Alex Baker, UEA

14:55 – 15:25  Break

### Session 3. Specific MMF-GTAD Programmes and Products

**Chair: Wenche Aas**

15:25 – 15:45  Update on MMF activities in Europe  
David Simpson, NMI

15:45 – 16:05  Update on the United States Total Deposition (TDEP) MMF activities  
Donna Schwede, USEPA

16:05 – 16:25  Update on the Canadian ADAGIO Project and the United States-Canada Collaborative MMF Project  
Amanda Cole, ECCC

16:25 – 16:45  Results and plans of the ECMWF CAMS (Copernicus Atmosphere Monitoring Services) global reanalysis relevant to MMF-GTAD  
Johannes Flemming, ECMWF

16:45 – 16:55  Global reanalysis plans of ECCC (Environment and Climate Change Canada) relevant to MMF-GTAD  
Radenko Pavlovic, ECCC

16:55 – 17:15  Activities and results of other global reanalysis projects relevant to MMF-GTAD  
Greg Carmichael, UI

17:15 – 17:20  Plan for Day 2  
Bob Vet/Lorenzo Labrador

17:20  Close
Wednesday 27 February Day 2

08:15 - 08:30 Arrival All

08:30 - 08:45 Introduction to Day 2 Bob Vet/Lorenzo Labrador

**Session 4. Discussion of the three Goals of the 2017 MMF-GTAD Workshop: Should the 2017 Plan and its Goals be Modified in Light of Recent Progress and Activities?**
**Moderator/Rapporteur:** Frank Dentener and Amanda Cole

08:45 - 09:45 Discussion of the 2017 MMF-GTAD Plan

09:45 - 10:15 Break

**Session 5. Goal 1 Discussion and Path Forward**
**Moderator/Rapporteur:** Ariel Stein and Rick Artz

10:15 - 11:15 Discussion of Goal 1

**Session 6. Goal 2 Discussion and Path Forward**
**Moderator/Rapporteur:** David Simpson and Stefano Galmarini

11:15 - 11:55 Discussion of Goal 2

11:55 - 13:15 Lunch

13:15 - 13:35 Discussion of Goal 2 continued

**Session 7. Goal 3 Discussion and Path Forward**
**Moderator/Rapporteur:** Vincent-Henri Peuch and Jeff Geddes

13:35 - 14:55 Discussion of Goal 3

14:55 - 15:25 Break

**Session 8. The New MMF-GTAD Initiative Project Plan and its Implementation**
**Moderator/Rapporteur:** Greg Carmichael and Maria Kanakidou

15:25 - 16:45 Discussion of the New MMF-GTAD Plan, its stakeholder, its funding and the path forward

16:45 - 17:00 Meeting summary and concluding remarks Bob Vet/Lorenzo Labrador

17:00 Close
LIST OF RECENT GAW REPORTS*


246. Thirteenth Intercomparison Campaign of the Regional Brewer Calibration Center Europe (RBCC-E), Arosa Lichtklimatisches Observatorium, Switzerland, 30 July to 8 August 2018.


238. The Magnitude and Impacts of Anthropogenic Atmospheric Nitrogen Inputs to the Ocean, Reports and Studies GESAMP No. 97, 47 pp., 2018


A full list is available at: 
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