Measurement-Model Fusion for Global Total Atmospheric Deposition Initiative

Implementation Plan for 2021–2026
Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD) Initiative

Implementation Plan for 2021–2026

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Chair, 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 81 17  
Email: Publications@wmo.int

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EXECUTIVE SUMMARY

The Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD) Initiative is one of the three initiatives of the Global Atmosphere Watch (GAW) Programme identified under Resolution 60 of the Eighteenth World Meteorological Congress (Cg-18). Following the 'Science-for-Services' concept of the GAW Implementation Plan for 2016–2023, MMF-GTAD seeks to assist countries and other stakeholders in meeting their commitments towards the United Nations’ Sustainable Development Goals (SDGs) for a healthy planet and society. Once operational, MMF-GTAD aims to provide stakeholders access to frequently updated high-resolution, high-quality, global-scale maps of total atmospheric deposition of various atmospheric constituents, and/or relevant parameters and impact indices, as well as associated uncertainty information which is needed for measuring progress towards several SDGs. These maps, formulated from a combination of measurements and models, will serve to inform and support decision-making relevant for a variety of ecosystems and climate impact assessments. Specific applications foreseen include estimating impacts of atmospheric deposition of chemicals to land and ocean ecosystems, agricultural land surfaces and food production, climate change, renewable energy production and, ultimately, on human health.

The MMF-GTAD Initiative’s Implementation Plan presents the suite of actions to be taken in order to articulate needs of users/stakeholders and address them in a consistent way in different geographic locations of the world. The plan describes the approach to coordinating the Initiative’s activities to ensure harmonized and quality-assured global implementation and compatibility of the products derived on different scales. WMO GAW already plays a central role in the data collection and quality-control of surface measurements of deposition and related observations. Within the MMF-GTAD Initiative itself, WMO GAW will also play an important role in advancing the operational production of measurement-model fusion maps of atmospheric deposition on a global scale (and, additionally, on regional scales in areas of the world with poor measurement coverage) and in providing authoritative results and knowledge to the UN agencies and their member states.

With the overall aim of providing, on an operational basis, global deposition maps of high resolution that can be used on global and regional scales for environmental applications, research and policy-setting, the MMF-GTAD Initiative will be executed following its near-, mid- and long-term objectives which reflect on a number of specific activities leading to its goal. The MMF-GTAD Initiative’s Steering Committee defined the following five implementation objectives: 1) Engaging stakeholders in product development; 2) Developing and evaluating methodologies for fusing observations and modelling; 3) Providing technical implementation of the Initiative; 4) Designing and testing operational products; and 5) Building capacity and communicating results. The MMF-GTAD Implementation Plan presents best-practice examples of and methodological guidelines for how model output and measurements can be fused to deliver high-resolution and high-quality deposition products for use by stakeholders. Successful implementation of the MMF-GTAD Initiative depends on intimate dialogue between scientists and users in order to define user requirements and ensure that these requirements are met through the production of user-oriented MMF deposition products. In the near-term, the MMF-GTAD Initiative will focus on ozone, nitrogen and sulfur global deposition products and the ways to merge them with available high-resolution regional MMF products. The Implementation Plan will evolve over time to incorporate scientific advances in the field of atmospheric deposition, capture emerging capabilities and respond to new policy challenges. The MMF-GTAD Initiative will work closely together with GAW’s Scientific Advisory Groups, Expert Teams and WMO’s World Weather Research Programme as well as with national and international partners in order to deliver science-based services to potential stakeholders/users in line with the implementation plan of the GAW Programme.
INITIATIVE BACKGROUND, DRIVERS, CLIENT NEEDS AND STATE OF THE SCIENCE

1. STATE OF KNOWLEDGE OF ATMOSPHERIC DEPOSITION AND ITS IMPACTS

Atmospheric deposition of air pollutants is the ultimate fate of most reactive chemicals in the atmosphere (Figure 1) and a key process in the functioning of the Earth System, having important effects on the environment, for example, on ecosystem health, agricultural production and climate change.

![Atmospheric cycle of air pollutants. Emission, transport and transformation, deposition.](https://www.fws.gov/refuges/AirQuality/sources.html) The impacts of atmospheric deposition are intimately linked to 7 of the 17 United Nations’ Sustainable Development Goals (SDGs) – see Figure 8.

Credit: U.S. Fish and Wildlife Service

A major threat of atmospheric deposition to ecosystems is the loss of biodiversity, i.e. of the reduction of the variety at genetic, species and ecosystem level, which affects not only natural ecosystems, both terrestrial and aquatic, but also food and agriculture utility ecosystems. Biodiversity loss makes ecosystems more vulnerable to stresses, like those induced by climate change or exposure to high ozone levels, since biodiversity makes ecosystems more resilient, which is particularly important for food production systems and livelihoods. According to the Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) and the State of the World’s biodiversity for food and agriculture (FAO, 2019), biodiversity, including that for food and agriculture, is declining and threats to diversity are increasing. While the main drivers of this loss are land and water use and management, in particular transition to intensive production of a reduced number of species (IPBES, 2019), atmospheric deposition is also a significant threat (Erisman et al., 2008; NAS, 2016).
While atmospheric deposition of a variety of air pollutants is of environmental concern, deposition of ozone, nitrogen and sulfur have attracted considerable attention due to their notable impacts. The damage to vegetation from exposure to air pollutants through deposition is expressed as changes in vegetation growth, flowering and seed production, in crop yields, as well as in the vulnerability of vegetation to abiotic and biotic stresses. The concentration, cumulative exposure or cumulative stomatal flux of atmospheric pollutants above which direct adverse effects to sensitive vegetation may occur according to present knowledge are defined as critical levels for vegetation (Convention on Long-Range Transboundary Air Pollution (LRTAP) & Mills et al., 2017). Because of the geographic variability of atmospheric deposition and ecosystems, hotspots and gradients of both of them are observed and need to be considered when assessing impacts (Tulloss and Cadenasso, 2015).

Ozone deposition to vegetation seriously affects the sustainable provision of food (Agathokleous et al., 2020). Percent loss of wheat yield due to ozone deposition has been estimated to exceed 15% in several regions of the globe and particularly in South Asia, around the Mediterranean Sea and the Eastern USA, as shown in Figure 2. The global loss in wheat yields due to exposure to ozone (O$_3$) was estimated to be between 6% and 9% on average in the southern and northern hemispheres, respectively, which resulted in estimated actual total grain losses of approximately 85 Tg (1Tg = 1x10$^9$ grams or 1,000,000 tonnes) per year, corresponding to approximately US $24.2$ billion per year (Mills et al., 2018). Note that the phytotoxic O$_3$ dose varies among species (Figure 3). Due to a genotype-specific susceptibility to O$_3$, long-term changes can happen in the composition of plant communities in areas where O$_3$ levels are high. Regions with high endemic richness, like the Mediterranean basin, the Northern Hemisphere’s Atlantic islands between 15° N and 45° N latitude, equatorial Africa, Ethiopia, the Indian coastline, the Himalayan regions, and Japan, have been shown to be the most vulnerable under climatic scenarios for 2100 (Agathokleous et al., 2020).

![Figure 2. Wheat yield loss due to ozone deposition into plant stomata (adapted from Mills et al., 2018)](image)
Ozone deposition is also intimately linked to climate change. For example, climate change will affect the Earth’s vulnerability to ozone and nitrogen deposition, even under progressive mitigation and adaptation action (Agathokleous et al., 2020; Clifton et al., 2020; Lin et al., 2020). Atmospheric deposition affecting biodiversity (Paulot et al., 2013) can also cause an influx of invasive species that can provide higher fuel loads for fires and thus affecting wildland fires occurrence (Fenn et al., 2003; Rao and Allen, 2010).

Atmospheric deposition of reactive nitrogen and sulfur has direct effects on terrestrial ecosystems causing soil acidification, which leads to nutrient losses, soil microbial community changes, and changes in agricultural production (on both managed and unmanaged lands), affecting the ability of forests and other ecosystems to act as a carbon sink, and thus affecting climate change. It also affects marine ecosystems, primary production and carbon storage into the ocean and thereby climate (Duce et al., 2008; Jickells et al., 2017). In particular, reactive nitrogen deposition plays a major role in the changing climate by affecting carbon uptake in the oceans and on land, thereby co-regulating the earth’s long-term climate system (SDG 13). This is illustrated in Figure 4, which shows the links between human drivers of nitrogen deposition (i.e., emission sources), nitrogen and carbon in the atmosphere, climate warming, and global biogeochemical cycles. Atmospheric deposition is also linked to climate change through several other mechanisms, including the alteration of the nitrogen cycle (emissions to deposition) and therefore the carbon cycle, due to climate-induced changes in temperature and precipitation, which, in turn, regulate the long-term climate.
High levels of nitrogen deposition have been shown to affect vegetation growth, soil/water acidification, water quality degradation, eutrophication, and plant and animal species diversity (Bobbink et al., 2010; Pardo et al., 2011; Phoenix et al., 2012; de Vries et al., 2015; Simkin et al., 2016). Figure 5 illustrates this, showing how cumulative nitrogen deposition can lead to nitrogen saturation of soils, which, in turn, can lead to biodiversity loss, soil acidification, water degradation and forest growth reduction. Note however that plant response to nitrogen additions and associated threshold amounts are species- and time-dependent (Ochoa-Hueso et al., 2011).

Figure 4. The linkage between nitrogen, carbon, biogeochemical cycles and climate in the Earth System. Arrows in orange indicate direct anthropogenic impacts and in blue natural interactions, which increase (+) or reduce (-) the amount of the factor shown. High degree of uncertainty is marked with (?) (adapted from Gruber and Galloway, 2008).
Atmospheric wet deposition of acidic components (“acid rain”) caused by sulfur and nitrogen compounds resulted in damage to several European forests in the 1980s (Grennfelt et al., 2020). The acidity facilitated solubilisation and leaching of mineral elements from the soil and removed vital minerals and nutrients for plant growth resulting in profound yellowing of the leaves due to deficiencies (Landmann and Bonneau, 1995). This damage from acidification not only to the flora, but also to natural heritage buildings, led to the establishment of amendments to the US’s Clean Air Act, to the United Nations Economic Commission for Europe’s Convention on Long-Range Transboundary Air Pollution (UNECE LRTAP) agreement in 1979, and to legislation for air pollution abatement in order to reduce pollutants’ emissions (Maas et al., 2016). In Europe, this led to a substantial decrease in particulate sulfate atmospheric concentrations over the past 30 years (Aas et al., 2019) and of atmospheric deposition to forested areas downwind of pollution sources (Pierret et al., 2019). Similar reductions have been documented in the US (USEPA, 2019). Despite these reductions in pollutant emissions, reactive nitrogen deposition fluxes remain regionally at levels that affect ecosystems’ health (Figure 6) (Ochoa-Hueso et al., 2011; Aguillaume et al., 2016; Kanakidou et al., 2012, 2016; Clark et al., 2018; Andersson et al., 2018). For example, under semi-arid conditions like those in Mediterranean climates, nitrogen accumulates in the soil. There, even small nitrogen fluxes to the soils may increase soil nitrogen concentrations to levels harmful for vegetation (Ochoa-Hueso et al., 2011). Thus, acidification and eutrophication remain of high concern, affecting biodiversity and leading to a loss of species richness (Dupré et al. 2010; Pardo et al., 2011). Numerous scientific and policy-support activities have identified the need to understand, assess and mitigate the impacts of deposition in order to establish and implement SDG-related policies globally, continentally, nationally, and regionally (e.g. Sutton et al., 2011).
Figure 6. Time evolution of geographic patterns of exceedances for individual Critical Levels (CL) types at the 12-km scale (adapted from Clark et al., 2018).
2. MEASUREMENT/MODEL FUSION: ADDRESSING KNOWLEDGE GAPS AND SERVING STAKEHOLDER NEEDS

Atmospheric deposition is intrinsically linked to economic and societal development as quantified in the United Nations’ SDGs. The deposition of reactive nitrogen, sulfur and other nutrients as well as ozone, metals, black carbon, and persistent organic pollutants, have serious impacts on ecosystems’ health, the quality of soils and waters, agricultural production, climate change and human health (e.g. Gheorghe and Ion, 2011; Engwa et al., 2019).

Over the past decades, atmospheric deposition has changed dramatically due to human intervention, mainly increasing anthropogenic emissions, and if not further controlled in the future, will detrimentally affect the functioning of the atmosphere-land-ocean system and threaten the well-being of society. The impacts of atmospheric deposition are intimately linked to seven of the seventeen SDGs (see Annex 1 and Figure 7) and therefore information on atmospheric deposition is needed to enable countries to track progress on their SDG commitments. In particular, it is extremely important to understand the drivers of atmospheric deposition and derive user-specific products based on deposition distribution and spatiotemporal variability that will be accessible to all interested parties (from national authorities to international governmental and non-governmental organizations) in support of policy implementation. This information will enable quantification of the impacts and track-back to the causes in order to inform implementation of biodiversity conservation, adaptation and mitigation policy.

![Figure 7. Relation of the United Nation’s Sustainable Development Goals to air pollution drivers and atmospheric deposition impacts. Education is bridging knowledge on drivers and impacts (figure modified from Elder and Zusman, 2016).](image-url)
Figure 7 (see details in Annex 1) shows the links between SDGs’ target indicators and atmospheric deposition as well as the information that the WMO’s Global Atmosphere Watch Programme’s Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD) Initiative could provide in support of policy implementation to achieve those targets. The SDG’s potentially relevant custodian agencies are also indicated in Annex 1.

Currently, many countries lack the capability and knowledge to account for atmospheric deposition in their scientific, policymaking and decision planning as they relate to the United Nations’ SDGs. The MMF-GTAD Initiative aims to contribute to filling this gap by supporting national authorities and stakeholders and building regional capacity.

Current estimates of atmospheric deposition on a global scale are based on the predictions of chemistry transport models (CTMs). As a result, they contain large uncertainties as deposition measurements are site specific, sparse or absent in large areas of the world (e.g. South America, Africa, Asia, Australia and the oceans) and chemical transport models contain uncertainties and inaccuracies that need improvement. To overcome this, a new method of creating state-of-the-art deposition maps, called Measurement-Model Fusion (MMF hereafter), has been developed to merge best-available quality-controlled measurement data with estimates from state-of-the-art chemical transport models. Figure 8 provides a conceptual model for this estimation. Several specific approaches have been and are being developed for MMF to produce estimates of air pollution or atmospheric deposition (e.g. Schwede and Lear, 2014; Robichaud et al., 2019; Andersson et al., 2017; Chang et al., 2019; Liu et al., 2020; Xue et al. 2020). They constitute the methodological basis for this initiative.

Figure 8. A methodology to produce MMF-GTAD products
POTENTIAL STAKEHOLDERS/USERS

Known stakeholders, users and customers of global and regional deposition maps, broken down by their specific user communities, include United Nations Organizations and specialized agencies like the International Maritime Organization (IMO) and the Food and Agriculture Organization (FAO), international conventions like CLRTAP and Convention on Biological Diversity, and sponsored programs like the European Union’s Copernicus, national and regional authorities, several non-governmental organizations as well as the Earth sciences community. Some of these users/stakeholders are listed below (Figure 9) as examples to demonstrate the identified potential stakeholder needs.

Figure 9. Potential users and application areas of the MMF-GTAD initiative products.
3. INITIATIVE VISION, MISSION, MODE OF OPERATION, PRINCIPLES OF IMPLEMENTATION, LIST OF VARIABLES FOR SHORT TERM

3.1 Vision

The MMF-GTAD Initiative is one of the three new WMO GAW Initiatives identified under Resolution 60 of the Eighteenth World Meteorological Congress that addresses users’ needs, following the ‘Science-for-Services’ concept of the GAW Implementation Plan for 2016–2023.

The vision of the MMF-GTAD Initiative is to provide stakeholders with access to high-resolution, high-quality, global-scale maps of total atmospheric deposition to meet societal needs as they relate to the environment and sustainable development and to track the progress towards global sustainable development for a healthy planet and society.

In the short-term, the MMF-GTAD Initiative will:

1. mobilize the science community and associated stakeholders to raise awareness of the importance of accurate estimates of atmospheric deposition in support of policy implementation for sustainable development and food and health security,
2. synthesize and disseminate current scientific knowledge and define gaps to be filled by new quality-controlled observations and modelling,
3. develop new skills and modelling capabilities, thus paving the way for operational products that are the long-term vision of the Initiative.

3.2 Mode of Operation – Organizational arrangements

The Initiative will require a highly-integrated and -coordinated approach to activities that span several different atmospheric science disciplines. These activities include atmospheric composition (surface and satellite measurements) and deposition measurements (at the GAW, regional and national levels), chemical transport modelling (at remote area, continental, national, and regional scales), development of improved emission inventories, further development and application of data assimilation/data inversion/measurement-model fusion techniques, database management and data/product dissemination/delivery. The Initiative will involve both developed and developing regions of the world.

Under the auspices of the WMO GAW Programme, the MMF-GTAD Initiative will require cross-cutting cooperation and integration of the experts in GAW’s Scientific Advisory Groups (SAGs) for Total Atmospheric Deposition, Reactive Gases, Aerosols, Applications and GAW Urban Research Meteorology and Environment (GURME), the Expert Teams on Atmospheric Composition Data Management, Expert Team on Atmospheric Composition Network Design and Evolution, and the Steering Committee of the new WMO initiative on Global Air Quality Forecasting and Information Systems (GAFIS). Up-to-date data from high-quality measurements will be obtained from GAW World Data Centres and from national and regional networks. Global, regional and national chemical transport models outputs will be required from major modelling groups as input to the MMF-GTAD Initiative.

WMO Members and partners have the experience and technical knowledge necessary for implementing and operating the MMF-GTAD Initiative. By leveraging existing skills from weather services and ongoing atmospheric composition research from multiple modelling...
groups, WMO can provide the leadership and structure needed to build and deliver MMF-GTAD to support decisions on sustainable development by preserving the environment, food security and human health.

To meet the objectives of the MMF-GTAD Initiative, all services and products provided by the Initiative will be driven by the needs of stakeholders. This will be achieved through consultation and feedback in meetings/workshops designed to discuss and address their specific needs, products and applications.

Other implementation principles for the MMF-GTAD Initiative include designing the Initiative’s overall system and services through the establishment of a clear implementation plan and addressing the Initiative in a staged approach using near-, mid- and long-term objectives.

To reach its overall goal of providing relevant services to society, the implementation of the MMF-GTAD initiative is guided by a dedicated Steering Committee composed of world-leading experts on various aspects of atmospheric deposition modelling and observations, and measurement-model fusion techniques. The Steering Committee was established in the spring of 2020 and will be maintained by WMO to serve as the key technical body in support of the MMF-GTAD Initiative under the GAW implementation plan.

The Initiative’s Steering Committee will:

1. Lead development of the MMF-GTAD implementation plan, updating it when necessary,
2. Implement and oversee activities to reach the Vision of the MMF-GTAD initiative,
3. Evaluate, endorse and advise on the technical merits of project proposals looking for the MMF-GTAD Initiative’s endorsement and partnership,
4. Provide expert support/partnership to MMF-GTAD projects,
5. Follow the scientific developments in the field of MMF, atmospheric deposition modelling, advances in atmospheric measurement techniques, data assimilation, inverse modelling techniques, and other aspects relevant to MMF-GTAD, in view of possible use by the MMF-GTAD initiative,
6. Transfer knowledge on scientific advances in the field of MMF-GTAD to members of the MMF-GTAD Initiative’s community,
7. Develop collaborations within GAW and WMO as well as with stakeholders, relevant organizations and the private sector.

The MMF-GTAD Initiative intends to establish strong interaction pathways between the Initiative and the users and stakeholders in order to provide them with the knowledge on global deposition needed to evaluate the impact of deposition changes on the Earth’s climate, ecosystems, biogenic emissions and society through their relationship to the relevant United Nations SDGs. In this respect, effort will be made from early stages of the Initiative to complement the MMF-GTAD Steering Committee with key stakeholders who will provide guidance to the definition of tailored to society needs products.
3.3. Principles of Implementation of MMF-GTAD

The MMF-GTAD implementation plan builds on the Concept Note (endorsed in November 2019 by the Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee that oversees the implementation of GAW) through three steps: First, create awareness of stakeholders to build an extended user community and motivate demand for user-oriented products. Second, demonstrate the feasibility and build confidence in the MMF-GTAD activities. Third, establish the operational system for producing MMF-GTAD products, expanding capacity and ensuring quality. Its implementation requires that all involved parties, MMF-GTAD, lead organizations, participating entities and individuals understand and support the Initiative’s vision, objectives and the way to accomplish them.

The MMF-GTAD implementation formulation is driven by a number of questions related to creating awareness and technical implementation of the Initiative:

ENGAGING STAKEHOLDERS:

1. Who are the customers/users and what are their current and expected future needs?
2. What current research capabilities exist that have demonstrated skills to meet user needs?
3. How can we demonstrate these capabilities to increase the visibility of the value of the MMF-GTAD products and persuade the stakeholders to become active partners in MMF-GTAD initiative?

TECHNICAL IMPLEMENTATION:

1. What improvements are needed both in the existing observational and model capabilities to enhance the quality of the MMF-GTAD products and how can the MMF-GTAD initiative contribute to this improvement?
2. Which activities will assure the high quality of MMF-GTAD products over all regions of the globe?
3. What is the added value of new products that will result from the MMF-GTAD Initiative?

The foundational principles that will enable the achievement of MMF-GTAD objectives are:

1. The information produced will have an impact on preserving the environment and informing sustainable development (e.g. ecosystems diversity, sustainable food production, food and nutrition security, human health, climate mitigation, solar energy production).
2. A standardized methodology will be developed to allow for a unified approach that combines atmospheric measurements with modelling results to provide user tailored quality-controlled products.
3. MMF-GTAD will continuously evolve in concert with evolving user needs, policy and technical capabilities.

The foregoing will ultimately lead to the MMF-GTAD Initiative supporting the implementation of a comprehensive operating global deposition mapping system that incorporates the collection of measurement data and modelling output, the application of
measurement-model fusion techniques, and the development and delivery of products with the associated uncertainties and services (graphical maps, digital data, etc.).

In near-term, the MMF-GTAD Initiative will focus on ozone, nitrogen and sulfur global deposition products and the ways to merge them with available high resolution regional MMF products.

4. MMF-GTAD OBJECTIVES AND PLANS

Initiative’s outlook

The MMF-GTAD Initiative aims to provide access to high-resolution, high-quality, global-scale maps of total atmospheric deposition of various atmospheric constituents, and/or relevant parameters and impact indices, as well as associated uncertainty.

High-quality and high spatial resolution maps of deposition on a global scale, formulated from best estimates of measurements and models, will serve to inform and support decision-making relevant for a variety of ecosystems and climate impact assessments. The high-quality deposition and concentration maps (and associated data) will allow intergovernmental agencies and non-governmental user communities to assess the impacts of atmospheric deposition of chemicals to land and ocean ecosystems, agricultural land surfaces and food production, climate change, renewable energy production and ultimately impacts on human health. WMO GAW already plays a central role in the data collection and quality control of surface measurements of deposition and related observations. Overall, the GAW Programme will play an important role in advancing the operational production of measurement-model fusion maps of atmospheric deposition on a global scale (and, additionally, on regional scales in areas of the world with poor measurement coverage) and in providing authoritative results and knowledge to the UN agencies and their member states.

With the overall aim of providing regional custom-oriented products of high resolution within a global framework, the MMF-GTAD Initiative is established and will be executed following its near-, mid- and long-term objectives which reflect on a number of specific activities leading to its goal (Figure 10):

Objective 1 - Engaging stakeholders in product development,

Objective 2 - Methodologies for fusing observations and modelling,

Objective 3 - Technical implementation of the initiative,

Objective 4 - Designing and testing operational products,

Objective 5 - Capacity building and communication.
4.1. Objective 1 – Engaging stakeholders in product development (demonstrating value, defining user-oriented products)

Currently, there is no wide recognition of the relevance of deposition fluxes as a driver of multiple environmental effects, despite a long history of mapping the impacts of air pollution (e.g. Working Group on Effects (WGE) under the CLRTAP convention, https://www.unece-wge.org/ ECE/EB.AIR/WG.1/2010/3 report; Sutton et al., 2011). For example, the Intergovernmental Panel on Biodiversity’s 2019 Assessment report (PBES, 2019) cursory mentions air pollution as a driver of biodiversity loss but does not explicitly discuss the importance of deposition. Thus, there is a need to educate the global and regional science and policy communities that deposition fluxes and relevant indices are needed to assess environmental damages caused by deposition and to implement measures to protect the well-being of both human populations and the environment in line with the UN’s SDGs.

Therefore, MMF-GTAD Initiative must increase this visibility, within the user community, which is to be identified during the first steps of the Initiative’s implementation. Demonstrating the value of the MMF concept through pilot mapping products, the MMF-GTAD Initiative will motivate stakeholders to identify their needs and further define specific user-oriented products. Therefore, Objective 1 has the following targets:

1. Create awareness, and thereby demand, from stakeholders for deposition-related products and services.
2. Identify potential customers/users and products of interest.
3. Demonstrate the value of the Initiative.
4. Engage stakeholders in dialogue.

5. Define specific user-oriented products through dialogue and stakeholder engagement.

6. Define and implement a resource mobilization strategy for the MMF-GTAD Initiative.

**Task 1.1. Create awareness and mobilize resources (M0-continuous)**

Through presentations at targeted conferences, workshops, stakeholder consultations meetings, media appearances and peer reviewed publications, the MMF-GTAD Initiative will inform stakeholders and the public on how atmospheric deposition critically affects human health, food security and the environment and identify the added-value of the knowledge of deposition fluxes for protecting the well-being of humans and Earth’s environment. Particular attention will be given to raising awareness in developing countries where less observational information is available on deposition fluxes and its impacts on food security, clean freshwater resources, terrestrial and marine ecosystems and human health. Mobilization of FAO, WMO and WHO mechanisms and NGOs in this direction will be beneficial. The Societal and Economic Research and Applications Working Group of WWRP (SERA) and similar groups of international partners could contribute in this Task.

In addition, a resource mobilization strategy for the MMF-GTAD Initiative will be defined and implemented from the early stages of the Initiative. A small sub-group of the Steering Committee will lead this activity.

**Duration:** immediate start and continuous over the duration of the Initiative

**Key performance indicators:** Number of stakeholder interactions, targeted publications to relevant journals and the web, number of presentations of MMF-GTAD at International or National Conferences

**Support in place:** in kind contribution by WMO and the Initiative’s Steering Committee

**Potential supporting agencies:** WMO, WHO, UN Environment, The Food and Agriculture Organization of the United Nations (FAO) as well as environment, forestry, and agricultural services.

**Task 1.2. Engaging stakeholders, defining user-oriented products (M0-continuous)**

Based on the best available scientific knowledge of the environmental impacts of deposition fluxes (see Section 1), a selection of potential users and products of interest will be identified. The identified stakeholders will be informed on the important impacts of atmospheric deposition within the area of their activities and on how MMF-GTAD products could support their objectives during consultation meetings.

Engaging data users, stakeholders and partners in dialogue will lead to defining tailored products resulting from the MMF-GTAD Initiative. The interaction between the Initiative and the customers/stakeholders requires building sustainable mechanism to continuously engage data users, stakeholders and partners to meet their evolving needs and priorities. **Implementation of this task requires dedicated human resources**, supported by GAW and the MMF-GTAD Steering Committee.

**Defining customized procedures, technical advice and tailored products** for specific user and stakeholder needs (e.g. ecosystem-specific deposition, derived indicators, long-term deposition trends, indicators for biodiversity loss) will be done through consultation meetings with stakeholders.
To carry out these tasks, a User/Stakeholder Advisory Group will be formed to define specific products and indicators that can be used by stakeholders for decision-making. The Advisory Group will report to the MMF-GTAD Scientific Committee. Tri-annual meetings or workshops will be held by the Stakeholder Advisory Group to obtain guidance from the stakeholders and update the stakeholders on the user-oriented products to be delivered by the MMF-GTAD initiative.

**Duration:** immediate start and continuous over the duration of the Initiative

**Key performance indicators:** User/Stakeholder Advisory Group established, number of meetings with stakeholders, number of commonly defined user-oriented products

**Support in place:** in kind contribution by WMO and the Initiative's Steering Committee

**Agencies that could support the task:** WMO, WHO, UN Environment, FAO, Environment, forestry, and agricultural services.

Task 1.3. Demonstrating value of the method on global scale (Proof-of-Concept - Ensemble Model-Measurement fusion) (M0-M24)

A number of global, continental and regional scale MMF products are currently available for nitrogen and sulfur deposition fluxes as well as exposure to ozone. This includes North America (USA and Canada) and Sweden, which have used different methodologies (see Table 1 below). These methods will be initially used to support the need and the added-value of MMF-GTAD-derived products compared to more readily available modelling-alone outputs. A comprehensive peer-reviewed article on the MMF-GTAD concept, led by the Initiative's Steering Committee will be published in order to raise awareness of the Initiative, its methodology as well as its implementation effort.

From the Initiative’s outset, effort will be put on upscaling current good practices (local to regional to global) to deliver user-oriented products. In particular, this task will focus on valorizing the multiple existing activities of modelling and data collection that can be used to fuse single-model or model-ensemble results with measurement data to produce gridded measurement-model fusion global maps (and data files) and associated uncertainty (range) of concentrations in air and precipitation of wet, dry and total deposition of ground-level ozone, sulfur and nitrogen (main inorganic forms). Merging or “stitching” existing and newly developed regional and global MMF products to produce best-effort merged global maps of gas, aerosol and precipitation concentrations as well as wet, dry and total deposition fluxes is one approach to be investigated. Near-term objectives will demonstrate feasibility by targeting a recent year, for instance 2010, for which ensemble model results are available (e.g. Task Force on Hemispheric Transport of Air Pollution Convention-2, HTAP2) and continue evaluation to more recent years. Existing modelling activities that could potentially contribute to the multiple-model ensemble results include the HTAP (http://htap.org), the Air Quality Modelling Evaluation International Initiative (AQMEII) (https://aqmeii.jrc.ec.europa.eu), the Model Inter-Comparison Study for Asia (MICS-Asia), the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMI, https://www.giss.nasa.gov/projects/accmip), the Chemistry-Climate Model Initiative (CCMI, http://blogs.reading.ac.uk/ccmi, and the International Cooperative for Aerosol Prediction (ICAP) (Xian et al., 2019). 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 and contributing networks data centres, the Global Precipitation Climatology Centre, Africa and Asia. Other products will include a comprehensive dataset and model-ensemble output files.
Table 1. Some examples of MMF deposition fluxes products and methods used

<table>
<thead>
<tr>
<th>Product</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDep: hybrid maps over the US for years 2000–2013 and some 3-year averages for all components of total S and N deposition</td>
<td>Hybrid method using precipitation chemistry and atmospheric concentrations observations with models</td>
<td>Schwede and Lear, 2014</td>
</tr>
<tr>
<td>Annual wet deposition fluxes of major inorganic N and S species over the US for 2002 to 2012 at 12km</td>
<td>Bias correct CMAQ model outputs using observation-based gridded PRISM precipitation and the Wet deposition measurements at the NADP/NTN sites</td>
<td>Zhang et al., 2019</td>
</tr>
<tr>
<td>Total N and S deposition fluxes to specific land use types over Sweden and Baltic Sea from 1983 to 2013 at 11x11km</td>
<td>Variational data analysis of measurements and modelling of monthly deposition</td>
<td>Andersson et al., 2018</td>
</tr>
<tr>
<td>ADAGIO: maps of wet, dry and total annual deposition of nitrogen and sulfur in Canada and the United States</td>
<td>Hybrid method using precipitation chemistry and atmospheric concentrations observations with models</td>
<td>Robichaud, Cole et al., 2019; Schwede et al., 2019</td>
</tr>
<tr>
<td>Surface ozone concentrations, Phytotoxic ozone dose for birch, spruce, wheat, potato over Sweden</td>
<td>Regional modelling with hourly O₃ surface observations over Sweden &amp; Norway using retrospective 2-dimensional variational data analysis</td>
<td>Andersson et al., 2017; Langner et al., 2019</td>
</tr>
<tr>
<td>Global 6-month running mean of the surface O₃ monthly average daily maximum 8 h average mixing ratios (DMA8) derived from fused global surface O₃ concentrations</td>
<td>Statistical approach (M3Fusion) combining surface ozone from multiple atmospheric chemistry models with all available surface ozone observations from TOAR</td>
<td>Chang et al., 2019</td>
</tr>
<tr>
<td>Global NH₄⁺ wet deposition fluxes at 0.1° grids for 2008 to 2016</td>
<td>Use GEOS-Chem model to derive feedback ratio of NH₄⁺ in wet phase and NH₃ concentrations and apply this to satellite NH₃ levels and precipitation rates</td>
<td>Liu et al., 2020</td>
</tr>
</tbody>
</table>
Duration: first 24 months of the Initiative, provided financial support will be made available

**Key performance indicators:** peer-reviewed publication of MMF-GTAD concept. Global merged maps for a recent year (2010 or more recent depending on data availability) available.

**Support in place:** in kind contribution by WMO & SC Team

**Agencies/Organizations that could support the task:** US’s Environmental Protection agency (EPA), Environment and Climate Change Canada (ECCC), the European Monitoring and Evaluation Program (EMEP), the European Centre for Medium-Range Weather forecast (ECMWF) and the Copernicus Atmospheric services (CAMS).

### 4.2. Objective 2 - Methodology for Fusing Observations with Modelling

Consistency between methods for observations and MMF approaches to measure/estimate wet and dry deposition fluxes requires a common inferential modelling framework to be developed and adopted. For wet deposition measured and modelled concentrations and precipitation rates are needed. For dry deposition, measured concentrations, meteorology, surface characteristics, in particular land use/land cover, and location-specific parameterizations are used in order to develop site-specific dry deposition estimates. Continuous improvements in the modelling framework are required to maintain its cutting-edge abilities following the anticipated advances in the field.

**Task 2.1. Assessing current MMF-GTAD techniques.**

Following recent advances in chemistry transport modelling, WMO GAW coordination of surface measurements of concentrations and deposition fluxes, as well as new opportunities from satellite observations, the scientific community is positioned to merge measurement data with model output to produce high-quality maps and estimates of fluxes of atmospheric pollutants. In recent years, global and regional chemistry transport models have become increasingly sophisticated in their treatment of atmospheric deposition. This has been through advances in emission inventories, parameterization of chemical and physical processes, increasing horizontal and vertical resolution, and the availability of high-resolution land cover data sets. Furthermore, the harmonization and quality of wet deposition and atmospheric concentration measurements around the world has improved, in part driven by the GAW Programme. Finally, multiple regional and national measurement-model fusion projects have demonstrated the efficacy of combining measurements and models to generate high quality maps of deposition of selected chemical species including nitrogen, sulfur and ozone, thereby improving the quality of deposition maps over those generated by measurements or models alone (Vet et al., 2014; Lamarque et al., 2013). The latter maps and map files have been widely used by a variety of users for assessing environmental impacts (see examples in Table 2).

MMF methods have been developed and applied successfully in several countries such as Canada, Sweden and the United States, but have not yet been applied on a global scale, which requires methodology development and availability of data. Figure 11 shows examples of high-resolution regional MMF maps of atmospheric deposition produced by Canada and the United States. Some of these deposition products have been used to assess the impacts on specific ecosystem types at high spatial resolution since critical levels may differ among ecosystems (e.g Langner et al., 2016; see also Figure 3).
Figure 11. Measurement-model fusion maps of nitrogen total deposition (in kg N ha\(^{-1}\) yr\(^{-1}\)) for 2010 produced by (left) Environment and Climate Change Canada, (right) the United States Environmental Protection Agency (Schwede et al., 2019).

Table 2. Examples of successful case studies where regional MMF atmospheric deposition data have been used in response to stakeholder needs.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Summary</th>
<th>Relevant Stakeholder</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phytotoxicity O(_3) dose for birch, spruce, wheat and potato in Sweden for 2013–2017. O(_3) concentrations</td>
<td>Used in the ceiling directive ecosystem surveillance &amp; model reporting under IPR</td>
<td>EU</td>
<td>Lagner et al., 2016</td>
</tr>
<tr>
<td>Air pollutants concentrations</td>
<td>Air pollution levels used for a national modelling system (SIMAIR)</td>
<td>Swedish municipalities for evaluating air quality</td>
<td>Andersson et al., 2017</td>
</tr>
<tr>
<td>S and N deposition reanalysis over Sweden 1983–2013</td>
<td>Used in the Swedish national nitrogen budget (atmospheric pool) to the Task Force on Reactive Nitrogen</td>
<td>CLRTAP-TFRN</td>
<td>Andersson et al., 2018</td>
</tr>
<tr>
<td>Operational deposition fluxes</td>
<td>Expressed interest from County Boards, and different national authorities for e.g. water quality and ecosystem impact assessments (lake/sea/terrestrial), e.g. SMHI, IVL, NV (Swedish environmental agency)</td>
<td>County Boards National authorities SMHI, IVL, NV (Swedish environmental agency)</td>
<td>Andersson et al., 2018</td>
</tr>
<tr>
<td>2010 S and N deposition over Canada</td>
<td>Network design for water quality monitoring; analysis of plant species diversity vs. nitrogen deposition; corrosion rate analysis for pipeline engineering</td>
<td>ECCC; university; private consultant</td>
<td>Robichaud et al., 2018</td>
</tr>
<tr>
<td>TDEP N deposition over US</td>
<td>Several studies on biodiversity of ecosystems</td>
<td>US Forestry services; EPA’s critical loads data mapper</td>
<td>Root et al., 2015; Nanus et al., 2017</td>
</tr>
</tbody>
</table>
Existing national and regional MMF research groups are now well-positioned to assist the MMF-GTAD Initiative in advancing toward a global-scale mapping capability. The selection and application of a particular method or set of methods at the global scale has yet to be done. As a starting point of reference for this task, a workshop will be organized to present and discuss the advantages and limitations of measurement-model fusion methods currently used for assessing the impacts of exposure to air pollution and atmospheric deposition fluxes. The workshop will be organized in either a physical or virtual format (depending on the circumstances) and supported by WMO and the GAW Programme. A synthesis assessment report/publication will be issued, critically compiling information on available modelling tools (regional/global) able to provide deposition maps that could support the Initiative.

**Duration:** M0-M12

**Key performance indicators:** workshop on current MMF approaches, critical assessment of MMF approaches.

**Support in place:** in kind contribution by WMO and MMF-GTAD Initiative’s Steering Committee.

**Agencies/Organizations that could support the task:** US EPA, ECCC, EMEP, ECMWF, CAMS

**Task 2.2. Algorithm improvements and new model developments**

MMF products will be continuously **improved** through research and innovations in deposition monitoring, modelling, data assimilation/fusion and new observation systems (e.g. satellite measurements). Anticipated developments in research that would impact the MMF-GTAD initiative are:

1. Investigation of methods for merging regional and global models as well as downscaling global models. Such developments will profit from advances in data assimilation by the Data Assimilation and Observing Systems (DAOS) and the Nowcasting and Mesoscale Research (NMR) working group of WMO’s World Weather Research Programme (WWRP) as well as WMO’s Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), which are carrying out research in chemical weather.

2. Improvements in model parameterizations and measurements of dry deposition. There has not been significant progress in the last two decades in this area. Some aspects of deposition modelling are still very uncertain, including land use and dry deposition schemes in models and emissions data. In particular, the parameterization of bi-directional fluxes (for instance for ammonia \( \text{NH}_3 \)) at canopy level remains uncertain (Fiechard et al., 2011). There is also a need to better link land use/land cover to dry deposition in order to understand the sensitivity and response of receptors to deposition (e.g. Schwede et al., 2018; Paulot et al., 2018).

3. Improvements in the modelling of wet deposition including the prediction of precipitation type, rate, amount and removal efficiencies (e.g. Wang et al, 2010). This is to be done together with WMO’s WWRP.

4. Development of methods for aggregating uncertainty estimates, which will be provided together with the MMF deposition maps as a tool to assess the reliability of the MMF products. This will be done by accounting for uncertainties in MMF-GTAD fluxes, which will be reduced through further model and measurement improvements and are associated with:

   (a) measurements and bias corrections of air concentrations (Walker et al., 2019), for instance there is lack of good data on gases such as nitric acid
and ammonia, despite their importance as major deposition components in many areas,

(b) model downscaling (Paulot et al., 2018),

(c) the completeness of chemical species’ budgets, for instance organic nitrogen deposition is not systematically included in N deposition estimates (Kanakidou et al., 2012; Jickells et al., 2013),

(d) model-measurement fusion and mass balance issues introduced by the MMF techniques (Walker et al., 2019),

(e) the bidirectional flux of ammonia (Zhang et al., 2010),

(f) the incorrect magnitude and spatial allocation of emissions, in particular of ammonia agricultural emissions (Walker et al., 2019).

5. Advances in chemistry-transport model inputs, algorithms and predictive capabilities (e.g. higher spatial resolution, vegetation feedback, improved precipitation predictions, updated emission inventories and higher resolution land use data) to improve the MMF deposition estimates.

6. Use of new techniques (e.g. data assimilation and inverse modelling) to improve emission inventories in close collaboration with the GAW Programme partners and research institutes/universities. Valorize the use of new high resolution and increased accuracy satellite data not only as potentially valuable for small emission corrections (e.g. updating emission inventories to a more recent year) and for deducing natural sources, but also for downsampling model results where appropriate. This activity will take place in collaboration with other GAW and international groups working on similar topics, such as IG³IS/GAW and the Amigo activity of the International Global Atmospheric Chemistry (IGAC) project. It will also profit from data assimilation technologies in use within WMO’s WWRP.

**Duration:** continuous, provided sufficient funds are available

**Key performance indicators:** workshop on current MMF approaches, workshop on new techniques on data assimilation and inverse modelling to evaluate sources and deposition fluxes, peer-reviewed publications

**Support in place:** in kind contribution by WMO & MMF-GTAD Initiative's Steering Committee, Postdoctoral support by ECCC and Boston University (2021–2023), PhD support by Uni Bremen (2021–2023)

**Agencies/Organizations that could support the task:** EPA, ECCC, EMEP, ECMWF, CAMS, research supporting international and national agencies

**Task 2.3. Optimizing observational data: quality assurance and geographic representativity**

The successful implementation of the MMF-GTAD Initiative requires the availability of global-scale measurements of atmospheric trace gases, particles, precipitation composition, precipitation depth as well as predictions of the same parameters from global and regional chemistry-transport models, followed by the fusion of measurements and models output using various forms of data assimilation (including flux inversion) and mapping techniques.

Thus, the MMF-GTAD Initiative aims to use high-quality datasets with appropriate temporal resolution at selected global and regional measurement sites. A number of chemical species have been recommended for measurement in new and/or existing
networks that can enable the MMF-GTAD Initiative to address the future needs of the various user communities related to ecosystems, food security, human health and climate. Among those, a limited number of species have been prioritized: ozone, nitrogen species (distinguishing their main categories: inorganic reduced (ammonia, ammonium) and oxidized (nitrogen oxides, nitric acid and nitrate) nitrogen and at a later time organic nitrogen), as well as sulfur (sulfur dioxide and sulfate) and later on iron (over the ocean) and dust, one of the most abundant natural aerosols.

For global data, the existing networks of in-situ observations must be homogenized by applying common/standardized observational methodologies and complemented by new observations from regions where data are missing. Such regions are Africa, Asia, South America as well as the remote ocean (Vet et al., 2014). This task will be performed by, or in close collaboration with, the GAW SAG on Aerosols, SAG on Reactive Gases, SAG on Total Atmospheric Deposition and SAG on Applications, as well as with the WMO Agricultural Meteorology Programme, the Global Energy and Water Exchanges (GEWEX) project of WCRP, The International Surface Ocean - Lower Atmosphere Study (SOLAS), IGAC and other international partners.

Inaccuracies in observations exist and are reduced through the use of state-of-the-art instrumentation and well-defined observational protocols harmonized between regional and global networks. While ozone observations are comparable worldwide, large variations in the measurements of gaseous nitrogen and sulfur are observed when using different sampling methods such as filter pack samplers, passive samplers and continuous monitors. In addition, due to the semi-volatile character of several nitrogen species, gas/particle separation of nitrogen species introduces measuring biases in some methods and increases the uncertainty in these data (Aas et al., 2012).

Concurrent observations of atmospheric concentrations of gases and aerosols are needed to provide input for dry deposition fluxes calculations. Dry atmospheric deposition flux measurements by eddy covariance techniques have high accuracy but are sparse, with extremely limited geographical and temporal coverage. Therefore, atmospheric concentrations measurements from observations or models are commonly used to derive dry deposition fluxes applying calculated dry deposition velocities (Wesely and Hicks, 2000).

Furthermore, high spatial density observations of precipitation chemistry are needed to improve wet deposition in MMF products, in order to account for the important spatial variability of precipitation, in particular in hilly locations and along coastlines. Such an undertaking can profit from the national meteorological and hydrological services’ observations that have a significantly larger spatial coverage than those of regional air pollution networks. In-situ observations of precipitation depth over the oceans are lacking due to logistics. Satellite observations (like the Global Precipitation Climatology Centre’s (GPCC) full data reanalysis, Schneider et al. 2016) can provide certain information on precipitated water but not its chemical composition, which requires in-situ observations and relies on modelling for those areas.

Vertical profiles and column observations of air pollutants are also important constraints for understanding emissions and therefore deposition fluxes. Such information, which will be integrated in the MMF framework at later stages of the Initiative, can be provided by:

1. airborne measurements (aircraft measurements and ozonesondes);
2. ground-based remote sensing instrumentation, such as Lidars (for aerosols properties), Fourier Transform InfraRed (FTIR) spectroscopy (e.g. the Network for the Detection of Atmospheric Composition Change (NDACC)), for measurements of trace constituents absorbing in the IR, such as ozone ($O_3$) and ammonia ($NH_3$), or...
MultiAXis Differential Absorption Spectroscopy (MaxDOAS), for nitrogen dioxide (NO₂), and sulfur dioxide (SO₂).

Satellite observations are developing into a powerful tool for providing global coverage of the atmosphere and thus information at remote locations where observations are lacking. Satellite observations of interest include those of O₃, SO₂, NO₂, NH₃, HNO₃ but also other air pollutants like carbon monoxide (CO), formaldehyde and glyoxal, from various past and current satellite instruments, such as the Global Ozone Monitoring Experiment (GOME), the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCHIAMACHY), the Global Ozone Monitoring Experiment-2 (GOME-2), the Ozone Monitoring Experiment (OMI), the Tropospheric Monitoring Instrument (TROPOMI), the Infrared Atmospheric Sounding Interferometer (IASI), and The Cross-track Infrared Sounder (CrIS). Following the algorithm developments in T2.2, satellite observations will be used to improve MMF-GTAD deposition calculations in the mid-term.

To build and optimize the observational dataset for the production of MMF-GTAD products, the following actions will be undertaken:

1. Standardize (where possible) and quality-assure observations in coordination with the WMO SAGs.
2. Compile information on observational data available for MMF from various location and periods in order to produce, in collaboration with the SAGs and other partners, a quality-controlled metadata database that will support the Initiative.
3. Identify gaps in observations in areas under pollution stress; recommend observational techniques and quality-assurance paths that can be used to fill in these gaps.
4. Use models and satellite observations to determine locations of high-value measurements, as well as additional locations and/or supersites to perform intensive measurement campaigns to improve process-based modelling. Additional observational coverage is needed in under-sampled regions of the world (e.g. oceans, Africa, South America and Australia).
5. Work with WMO GAW's SAGs and existing WMO and UN partners’ regional and national measurement programmes (e.g. networks, satellites), as well as satellite data providers to encourage the expansion of the GAW network and improvement of deposition observations in under-sampled areas where information is needed.
6. Develop and adopt, in conjunction with WMO GAW SAGs, new measurement capabilities such as additional/improved vegetation and land surface observations (for dry deposition modelling) and satellite observations.
7. Investigate the integration of citizen science data into quality-controlled data and metadata databases with potential links to WWRP activities.
8. Working together with other WMO programmes (e.g. WWRP) and international partners to get access to high-quality precipitation data and demonstrate the value of high-resolution precipitation data for air pollution and atmospheric deposition assessments.
9. Support data centres for metadata (regional hubs) that compile information on data needed for MMF-GTAD as well as documentation and relevant open access code for their use.
10. Support national and international data centres and observational networks for wet and dry deposition.

Duration: 36 months, provided sufficient funds become available

Key performance indicators: data centre committed to collecting metadata for MMF-GTAD, countries supporting data collection

Support in place: in kind contribution by WMO and the MMF-GTAD Steering Committee, GAW observational network

Agencies/Organizations that could support the task: national authorities, EPA, ECCC, EMEP, ECMWF, CAMS, ESA, NASA, large research institutions

4.3. Objective 3 - Technical implementation

Task 3.1. Set up the implementation structure

The MMF-GTAD vision will be implemented by developing an "MMF-GTAD operational system" (see Figure 12). This system will combine world, continental, national and regional capabilities into MMF activities organized through three activity centres (data, operations and applications).

Figure 12. Components of the MMF-GTAD operational system.

The MMF-GTAD Data Activity will gather, quality assure, archive and prepare global/regional measurement metadata that will facilitate the MMF Operations Activity in coordination with regional, national and world Data Centres. This will likely be executed by a single facility (e.g. at NILU, which already ingests and/or gathers data from major air and precipitation monitoring networks worldwide) but could also be a distributed facility.

The MMF-GTAD Operations Activity will apply model fusion techniques to the measurements data and model outputs to meet the Vision Statement. One or more fusion techniques may be used but all of the approaches will require retroactive measurement-model fusion using measurement data coupled with the results of a single global model or, preferably for better accuracy, model ensembles, and/or global reanalysis fields or accumulated outputs of operational models that involve data assimilation of selected available measurements. The MMF-GTAD Operations Activity could be hosted and supported by international and national weather and chemical weather forecasting centres such as the Copernicus Atmosphere Monitoring Service (CAMS).

The MMF-GTAD Application Activity will operate in consultation with the User/Stakeholder Advisory Group with the objective of converting the MMF deposition products into
user-specific products for specific applications. Downscaling methods could be applied to satisfy specific user demands. The products (graphical maps, digital data, etc.) will be delivered with their associated uncertainties.

**Duration:** 36 months, provided sufficient funds become available

**Key performance indicators:** MMF-GTAD activity centres put in place and operating

**Support in place:** WMO data centres

**Agencies that could support the task:** US Environmental Protection agency (EPA), Environment and Climate Change Canada (ECCC), the European Monitoring and Evaluation Programme (EMEP), ECMWF, CAMS, and WMO-affiliated World and Regional Specialized Meteorological Centres

**Task 3.2. Global Measurement-Model Fusion Products**

The implementation of the MMF-GTAD Initiative follows a three-step approach to achieve the ultimate operational products (demonstration, global products produced by either “stitching” regional MMF maps to a global product or applying MMF techniques on global scale, and finally, operational products). The global products will progressively evolve from deposition maps based on model output only to MMF products using surface concentrations and eventually also assimilating satellite observations. Regional products will be developed for Europe and Asia where observational data are available but not the high-resolution MMF-GTAD products. A procedure will be put in place for global product development based on surface observations and reanalysis products that already partially ingest satellite data. Different approaches to using satellite data will be developed and tested.

Initially, a pilot project will develop a global deposition estimates product from existing multi-model studies and estimates of variability for the year 2010 (or later). This pilot project will (a) demonstrate the type of global results that are possible, (b) give a better understanding of the major uncertainties and limitations inherent in the MMF method(s), (c) assess whether user-groups, such as ecosystem modellers or biodiversity experts, would rather use MMF products over raw CTM output, and (d) assess in a realistic way whether a semi-operational system possesses significant advantages over earlier re-constructions. Regional MMF maps over the USA and Canada (products already available), Europe (to be developed) and Asia (to be developed), using different MMF techniques will be stitched together. Already-available regional MMF products will be compared to evaluate the different MMF techniques and their associated uncertainties. Working toward a semi-operational product, a global product for 2010 (or later) that uses one single MMF technique globally will be produced. Such procedures will facilitate MMF estimates over regions where observations are not currently available.

After a near- to mid-term demonstration of a global MMF-GTAD product for the year 2010, or later, that should serve as a proof-of-concept both for method development and for stakeholder engagement, the product will be extended from past (at least until the year 2000) to recent years by producing global MMF deposition and variability estimates from existing multi-model studies for additional years. Thus, regional high-resolution global maps (approximately 50km x 50km) of gas, aerosol and precipitation concentrations as well as wet, dry and total deposition fluxes, will be produced using either one model or an ensemble of models together with publicly available data for past and recent years. Downscaling methods could be applied to satisfy specific user demands.

The use of an ensemble of models for MMF will allow the evaluation of the variability associated with the MMF-GTAD maps. These maps, based on quality-controlled observational data, will be therefore quality assured. The uncertainty estimates will be provided as additional information to the users. Such year-specific global products with at least monthly temporal resolution will make it possible to investigate the trends in
atmospheric deposition following policy implementations and enable accounting of their impacts as well as of the potentially-important cumulative effects on ecosystems. This is the case of nitrogen deposition’s impact on vegetation. These MMF-GTAD results will be fed into the MMF Operations Activity, will be stored in a dedicated data centre and will be made available to additional users identified in the future.

**Duration**: 48 months starting before the end of T1.3, provided sufficient funds become available

**Key performance indicators**: regional high resolution MMF-GTAD products for Europe and Asia, global regionally high resolution MMF-GTAD maps for at least one year and potentially for time slices for past years until present.

**Support in place**: in kind contribution by WMO and the MMF-GTAD Steering Committee

**Agencies that could support the task**: EPA, Environ Canada, EMEP, ECMWF/Copernicus Atmosphere Services, WMO World and Regional Specialized Meteorological Centres

**Task 3.3 Provide user tailored products and interact with stakeholders for their use**

In consultation with the Users/Stakeholders Advisory Board, a number of **user-specific indicators will be defined**, such as phytotoxic ozone dose, AOT40, cumulative nitrogen deposition, deposition per ecosystem type etc. Then, the MMF-GTAD maps from T3.2 will be converted to the specific indicators and provided to users.

Action will be also taken to **collaborate with and enable users and stakeholders to apply current and future knowledge of global deposition** from the MMF-GTAD Initiative to evaluate the impact of deposition changes on changes in the Earth’s climate, ecosystems, emissions and society through their relationship to the relevant United Nations SDGs.

**Customized procedures, technical advice and tailored products** for specific user and stakeholder needs (e.g. ecosystem-specific deposition, derived indicators, long-term deposition trends etc.) will be also provided.

**Duration**: 12 months (after T3.2), provided financial support will become available

**Key performance indicators**: global maps of MMF-GTAD indicator for past years until present

**Support in place**: MMF-GTAD Steering Committee

**Agencies that could support the task**: EPA, Environment and Climate Change Canada, EMEP, ECMWF/Copernicus Atmosphere Services, ASIA, WMO

**4.4. Objective 4 - Designing and Testing Operational products**

One challenge of the global scientific community in general, and the MMF-GTAD Initiative in particular, is to develop and implement MMF mapping techniques on a global scale in an operational manner (3rd step of the MMF-GTAD Initiative’s implementation process). Thus, the long-term objective is to develop at least one global modelling system, involving data assimilation of observations of surface concentrations, column burdens, and deposition fluxes. Establishing a service that creates measurement-model fusion maps of deposition on a regular basis is the objective of the MMF-GTAD Initiative. Once produced, these high-quality global MMF maps and high-spatial-resolution data products of atmospheric deposition on an operational basis (including the associated quality-assured measurement data sets and model outputs) will be then disseminated.

ECMWF/Copernicus and other national and international institutions have plans over the coming 2–4 years to develop capabilities in this field. This will clearly require a global
dataset of observations, both from ground-based and satellite data. Some observations will be withheld for the purpose of independent verification. The inclusion of MMF products in chemical reanalysis will provide a rich time series dataset for the scientific community and for impact analyses (human health, food security, ecosystems health, and climate).

By providing guidance on incorporating atmospheric deposition into an *Earth system modelling* approach for land, ice, oceans and the atmosphere, the MMF-GTAD Initiative’s Steering Committee will also strive to enhance and improve deposition, air quality and climate predictions.

**Task 4.1. Observational database interface (contributing networks, GAW, other EPAs, citizen science etc.)**

In order to develop a global operational MMF-GTAD product, the extension of the GAW network is needed into regions that are presently under-sampled (T2.3). Other networks at continental and national levels, as well as citizen science and air pollution data from the urbanization and the aviation projects of WMO, could be integrated in the database as long as they comply with the Initiative's data quality standards. The use of output models and satellite data will allow the determination of high-value measurement locations. The MMF-GTAD Initiative, together with the WMO SAGs, will provide incentive for additional observational coverage in under-sampled regions of the world (e.g. oceans, Africa, South America and Australia). Satellite data that provide global coverage will be used in data assimilation or in an inverse modelling framework. However, these data will be complemented by near-surface observations, since satellite-derived near-surface observations are subject to large uncertainties. Both measurements of deposition and near surface atmospheric concentrations of ammonia are needed, along with the characterization of emissions from agricultural (for instance agricultural management details such as the timing and type of fertilizer applications) and natural land covers and biogeophysical modelling to unravel the challenges associated with bi-directional fluxes (Zhang et al., 2010; Walker et al., 2019).

Additional measurements used to derive MMF-GTAD products, such as boundary layer height, meteorological parameters and precipitation could contribute to reducing model errors. Working together with other WMO Programmes and international partners will provide access to high-quality precipitation data. While model development is not the scope of the MMF-GTAD initiative, new developments in research will be continuously incorporated into MMF products (Task 2.2) and Task 4.1 work will evolve accordingly.

Task 4.1 will set up the data flow to the operational data activity through interfaces to be developed that operationally link these observational data to the MMF modelling framework.

**Duration:** 48 months (during the mid-term phase of the Initiative), provided sufficient funds become available

**Key performance indicators:** data/model interface build

**Support in place:** in kind contribution by WMO and the MMF-GTAD Initiative’s Steering Committee,

**Agencies that could support the task:** EPA, ECCC, EMEP, ECMWF/Copernicus/CAMS

**Task 4.2. Global reanalysis/Assimilation of Concentrations and Deposition Fluxes**

A model-measurement framework for operational calculations of MMF products will be established using satellite data with global coverage and surface observations to provide near-surface information where the satellite observations carry large associated uncertainty. 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. New techniques such as inverse modelling will be used to improve emission inventories and thereby deposition estimates. Particular attention needs to be paid to regions and chemical species with bi-directional fluxes, i.e. simultaneous emission and deposition of a species as is the case for ammonia, as well as to mass conservation in the model. Once the operational methodology is established, annual deposition maps from the year 2000 forward will be produced (Long-Term Operational Priority). The accuracy of higher time resolution products (e.g. monthly, or weekly) will be also examined in connection with Task 2.2 (algorithms improvements).

Weather forecasting organizations, such as ECMWF, Copernicus Atmospheric Service/CAMS, the Earth monitoring system of Europe, as well as Environment and Climate Change Canada, The National Center for Environmental Prediction (NCEP)/ The National Air and Space Administration (NASA)/ The National Oceanic and Atmospheric Administration (NOAA) as well as the Global Data-processing and Forecasting System (GDPFS) could support operational products of the MMF-GTAD Initiative with use of all available data including satellite data.

Duration: 60 months, provided sufficient funds become available

Key performance indicators: reanalysis/assimilation year-specific global monthly mean deposition fluxes of nitrogen, sulfur and ozone operationally available

Support in place: in kind contribution by WMO and the MMF-GTAD Initiative’s Steering Committee

Agencies that could support the task: EPA, ECCC, EMEP, ECMWF/Copernicus/CAMS, NOAA, SMHI (Swedish Meteorological and Hydrological Institute)

4.5. Objective 5 – Capacity building and outreach

The implementation of the MMF-GTAD Initiative will benefit from the building of technical/institutional/individual capacity and reaching out to relevant science/policy communities and organizations wherein information on deposition is unknown, underused or limited. Outreach activities can be in the form of dedicated workshops with hands-on training and student exchanges associated to the network extension. Web-based documentation (e-learning, videos etc.) can contribute to continuous training.

Three general types of capacity building workshops are foreseen:

1. One on advanced measuring techniques, methodology, artifacts, measurement data interpretation, potentially provided by GAW Training and Education Centre (GAWTEC);

2. the second one on advanced modelling techniques (global CTM developments, dry deposition mechanisms, data assimilation, inverse modelling, use of satellite data) profiting from potentially relevant educational activities by WCRP or other organizations;

3. and the third on User/Stakeholder advice and input, which will require the active contribution of the User/Stakeholders Advisory Board on the science–stakeholders' interactions (how should scientists inform stakeholders and how stakeholders can ask and valorize scientific results).

The MMF-GTAD Initiative will benefit from a number of anticipated advances in the fields listed in the methodology development (Objective 2), as well as from facilitating communication between regional MMF groups (e.g. work meetings, web portal information), and encouraging new research directions based on user input by maintaining links to the research and monitoring communities.
Regular MMF-GTAD Steering Committee meetings will facilitate communication of scientific advances, adaptation of services to user needs and decision-making. At least half of these meetings will be virtual in order to keep a low carbon footprint. Every two to three years, an in-person consultation meeting with the Stakeholder Advisory Board will be held with the objective of maintaining the interest of stakeholders by updating the available products and redefining user-oriented products.

<table>
<thead>
<tr>
<th>Duration: continuous – follows the development of the Initiative</th>
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<tbody>
<tr>
<td>Key performance indicators: Web-based documentation, Workshops, training personnel (PhD and postdoctoral positions)</td>
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<tr>
<td>Support in place: in kind contribution by WMO &amp; MMF-GTAD Initiative’s Steering Committee</td>
</tr>
<tr>
<td>Agencies that could support the task: EPA, Environment and Climate Change Canada, EMEP, ECMWF/Copernicus</td>
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## SWOT Analysis

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<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td><strong>Weaknesses</strong></td>
<td><strong>Opportunities</strong></td>
<td><strong>Threats</strong></td>
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<tr>
<td>MMF-GTAD scientific community has recently developed approaches to merge atmospheric deposition measurements with numerical modelling to produce atmospheric deposition maps of high resolution and high quality.</td>
<td>Issues to be resolved - mass balance in numerical modelling - bi-directional fluxes (e.g. ammonia) - acquisition of good data on major gaseous deposition components for dry deposition estimates where such data are missing or scarce</td>
<td>There is no such product on operational basis.</td>
<td>Changes in regulatory environment</td>
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<td>There are high-quality data from the GAW network and WMO’s and other international organizations and MMF-GTAD will motivate their extension to improve geographic coverage.</td>
<td>Resources limitations</td>
<td>Data assimilation techniques used in atmospheric chemistry modelling and weather services can be used for MMF-GTAD.</td>
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<tr>
<td>MMF-GTAD initiative is inclusive, open to contributors that will continuously bring new knowledge and technologies.</td>
<td>Market to be defined</td>
<td>Emerging need for globally consistent high-resolution atmospheric deposition fluxes maps</td>
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<td></td>
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<td>Ongoing developments of Earth System models</td>
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There are a number of weaknesses identified with regard to both the scientific tools used, which are under further improvement by the scientific community, as well as to the current resource limitations and the need to raise awareness of the potential users. The MMF-GTAD initiative will profit from the opportunities arising from ongoing scientific developments to improve its tools and dedicated actions to attract support from potential users of targeted products. A possible constraint are possible changes in the regulatory environment, which are extremely unlikely, considering the continuous societal needs for sufficient and of good quality food and fresh water, clean air, limiting climate change, all of which are affected by atmospheric deposition.
GANNT DIAGRAM (provided that financial support is put in place)

The following Gannt Diagram has to be seen as an ideal case in which all financial support needed is put in place. Delays are to be expected due to the flow in the acquisition of the financial support.

<table>
<thead>
<tr>
<th>Task</th>
<th>Near Term</th>
<th>Mid Term</th>
<th>Long Term</th>
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<tbody>
<tr>
<td>1.1 Create awareness</td>
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<td>0 6 12</td>
<td>18 24</td>
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<td>1.2 Engaging stakeholders</td>
<td>6</td>
<td>30 36</td>
<td>42 48</td>
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<tr>
<td>1.3 Demonstrating value</td>
<td>18</td>
<td>54 60</td>
<td>66 72</td>
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<tr>
<td>2.1 Assessing current MMF-GTAD techniques</td>
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<td>24 30 36</td>
<td>42 48</td>
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<td>2.2 Algorithm development</td>
<td>12 18</td>
<td>54 60</td>
<td>66 72</td>
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<tr>
<td>2.3 Gathering observational data</td>
<td></td>
<td>18 24</td>
<td>42 48</td>
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<tr>
<td>3.1 Establish implementation structure</td>
<td>6</td>
<td>30 36</td>
<td>42 48</td>
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<tr>
<td>3.2 Demonstration global MMF products</td>
<td>6</td>
<td>30 36</td>
<td>42 48</td>
</tr>
<tr>
<td>3.3 Multiyear tailored products</td>
<td></td>
<td>18 24</td>
<td>42 48</td>
</tr>
<tr>
<td>4.1 Observational dataset interface</td>
<td></td>
<td>6</td>
<td>30 36</td>
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<tr>
<td>4.2 Operation MMF products</td>
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<td>18</td>
<td>30 36</td>
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<tr>
<td>5 Capacity building and outreach</td>
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<td></td>
<td>42 48</td>
</tr>
</tbody>
</table>

SUMMARY OF NEEDS FOR NEAR-TERM IMPLEMENTATION

The above Gannt Diagram depicts the anticipated progress flow for MMF-GTAD implementation provided that all financial support is put in place.

For near-term implementation, the MMF-GTAD Initiative must:

1. Establish and implement a resource mobilization strategy for raising the necessary funds to support the near- and mid-term Implementation Plan activities.

2. Secure funds and initiate contracts for specific tasks identified in the Implementation Plan.

3. Establish a method for engaging stakeholders, end-users and partners in the Initiative’s activities, e.g. a stakeholder advisory group that holds tri-annual meetings or workshops.
4. Monitor and use evolving scientific research and development to upgrade and improve the MMF-GTAD system, methods and products.

5. Focus on ozone, nitrogen and sulfur global deposition products and how to merge them with high resolution regional MMF products available.

Informing and engaging stakeholders in product development requires mobilization of dedicated personnel (supported by WMO/GAW Secretariat and by a small sub-group of the Initiative’s Steering Committee members) as well as the proof of concept of MMF-GTAD global products with high resolution at regional scales. The duration of the task and the financial support needed are indicated in parentheses where available.

1. The publication of a journal article on the MMF-GTAD concept in the journal “Environmental Science and Technology” (12 months).

2. The development of global MMF maps for the year 2010 (Task 1.3) which will involve collecting, homogenizing and documenting the 2010 datasets of concentrations in air and precipitation, available wet and dry deposition fluxes, and precipitation rates (24 months, US$ 100 K).


4. The evaluation of MMF methods will be supported by a virtual workshop – to be hosted by WMO/GAW facilities (Task 2.1, no direct cost).

5. Regional high resolution MMF-GTAD products for Europe need to be developed using observational data from T1.3 and model outputs: Task Force Hemispheric Transport of Air Pollution – 2 (HTAP2), the Air Quality Modelling Evaluation International Initiative – 3 (AQMEII-3), initially for year 2010 (24 months, US$ 160K).

6. Regional high-resolution MMF-GTAD products for Asia need to be developed, initially for the year 2010 (24 months, cost to be determined).

7. Joint SAGs meetings (Steering Committee meetings), in-person consultation meetings/3rd workshop to evaluate the status of implementation (month 24, US$ 100K).

8. Development of the operational system for creating, archiving and distributing MMF products. This requires a clear idea of data storage and handling structure and make use what is available in WMO already (to be supported by research grants).


**CONTRIBUTING AND SUPPORTING INDIVIDUALS AND INSTITUTIONS/AGENCIES**

The oversight, implementation and operation of the MMF-GTAD Initiative requires the involvement of myriad contributors, collaborators and supporters, both as individual scientists and as institutions/agencies. To date, many scientists and their institutions/agencies involved in the fields of atmospheric measurement, modelling, measurement-model fusion, climate change and ecosystem/human health effects, as well as related policy-setting fields, have supported the Initiative through their support and participation in the 2017 MMF-GTAD Workshop, the 2019 MMF-GTAD Expert Meeting, the
2019 MMF-GTAD Concept Note Meeting and the MMF-GTAD Steering Committee meetings. Lists of these supporters, contributors and collaborators are available in the reports of the foregoing meetings. The implementation and execution of the MMF-GTAD Initiative will require the ongoing support of these individuals and institutions as well as the extension to new partnerships and collaborations.

Potential known contributors and supporters of the implementation of the necessary steps to achieve the MMF-GTAD Initiative’s near- medium- and long-term goals are described below.

1. Administration and coordination of the Initiative will be carried out by the Secretariat of the World Meteorological Organization under the Global Atmosphere Watch Programme.

2. Overall project management of the Initiative - from design to implementation to eventual routine operation (per the ‘MMF-GTAD Operational System’ in Task 3.1) - will be the responsibility of the MMF-GTAD Initiative’s Steering Committee and, by definition, the supporting institutions and agencies of the members. As the MMF-GTAD Initiative evolves, the Steering Committee is expected to broaden its membership to new contributing scientists and institutions/agencies. WMO organizational and scientific oversight of the Steering Committee and the Initiative will be provided by the GAW Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee (EPAC SSC).

3. The implementation and operation of the three main activity centres that comprise the ‘MMF-GTAD Operational System’, namely, the Data Activity, the Operations Activity and the Applications Activity, will be carried out by yet-to-be-determined contributing scientists and institutions/agencies. Identifying and engaging these individuals and institutions/agencies will be the responsibility of the Steering Committee, the Secretariat and the EPAC SSC.

4. Engaging the collaboration, cooperation and guidance of stakeholders, users and clients will be the responsibility of the User/Stakeholder Advisory Board which will report directly to the MMF-GTAD Steering Committee.

5. Building capacity will be the responsibility of the MMF-GTAD Steering Committee and the WMO Secretariat.
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Langner, J., Alp Bjord Wylde, H., Andersson, C. Mapping of phytotoxic ozone dose for birch, spruce, wheat and potato using the MATCH-Sweden system, SMHI Meteorologi report 166, ISSN: 0283-7730283-7730 © SMHI, 2019


USEPA, 2019: https://www3.epa.gov/airmarkets/progress/reports/acid_deposition_figures.html

Vet, R. et al., A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus, Atmospheric Environment, 93, 3-100 2014.


## ANNEX 1 - DEPOSITION IN THE CONTEXT OF SDGS

*Table A1. SDGs and relevant topic of concern that is impacted by atmospheric deposition*  
(*) from ‘Tier Classification for Global SDG Indicators’ as updated on 26 October 2020. (**) relevant to atmospheric deposition

<table>
<thead>
<tr>
<th>SDG</th>
<th>Topic of concern</th>
<th>Targets (*)</th>
<th>Indicators (*)</th>
<th>Cause of damage (**)</th>
<th>Driver</th>
<th>Custodian agencies</th>
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</thead>
<tbody>
<tr>
<td>2. Zero Hunger</td>
<td>Central for hunger and poverty eradication are the food and agriculture sectors.</td>
<td>2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round; 2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment 2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality</td>
<td>2.1.1 Prevalence of under-nourishment 2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES) 2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size 2.4.1 Proportion of agricultural area under productive and sustainable agriculture</td>
<td>Reduced production yields  Biodiversity loss  Changes in soil microbial community</td>
<td>Exposure to high O3 N and S deposition  POP deposition + metals</td>
<td>FAO  WHO  UNICEF  OECD  WTO</td>
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<td>SDG</td>
<td>Topic of concern</td>
<td>Targets (*)</td>
<td>Indicators (*)</td>
<td>Cause of damage (**)</td>
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<td>3:</td>
<td>Healthy lives and well-being for all</td>
<td>3.4. By 2030 reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being</td>
<td>3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease</td>
<td>Air pollution and pollutant penetration in food and water</td>
<td>Exposure to high O₃ (and PM) N and S and toxic substances deposition</td>
<td>WHO</td>
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<td>3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination</td>
<td>3.9.1 Mortality rate attributed to household and ambient air pollution</td>
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<td>3.d Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks</td>
<td>3.d.1 International Health Regulations (IHR) capacity and health emergency preparedness</td>
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<td>6:</td>
<td>Clean, accessible water for all (improve water quality by reducing pollution; protect and restore water-related ecosystems)</td>
<td>6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.</td>
<td>6.1.1 Proportion of population using safely managed drinking water services</td>
<td>Penetration of pollutants in the water</td>
<td>N, S deposition POP deposition Toxic metals deposition</td>
<td>WHO, UNICEF UNEP Ramsar</td>
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<td>6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally (UNEP)</td>
<td>6.3.2 Proportion of bodies of water with good ambient water quality</td>
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<td>6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes UNEP, Ramsar</td>
<td>6.6.1 Change in the extent of water-related ecosystems over time</td>
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<tr>
<td>SDG</td>
<td>Topic of concern</td>
<td>Targets (*)</td>
<td>Indicators (*)</td>
<td>Cause of damage (**)</td>
<td>Driver</td>
<td>Custodian agencies</td>
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<td>7</td>
<td>Affordable and clean energy</td>
<td>Efficient use of renewable energy</td>
<td>7.2 By 2030, increase substantially the share of renewable energy in the global energy mix 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support</td>
<td>7.2.1 Renewable energy share in the total final energy consumption 7.b.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)</td>
<td>Extinction of solar radiation reaching solar energy collectors (dimming, Shadowing by aerosols and their deposition)</td>
<td>Dust deposition, Aerosol optical depth</td>
</tr>
<tr>
<td>11</td>
<td>Sustainable cities and communities</td>
<td>Healthy green spaces inside the cities</td>
<td>11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities</td>
<td>11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities (deposition impact not directly related to this indicator)</td>
<td>Acidification</td>
<td>Exposure to N and S deposition, POP deposition and metals</td>
</tr>
<tr>
<td>13</td>
<td>Climate action</td>
<td>Climate change affects everyone, everywhere</td>
<td>13.2 Integrate climate change measures into national policies, strategies and planning</td>
<td>13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans, strategies as reported in adaptation communications and national communications (Not directly related to this indicator)</td>
<td>Changes in C cycle partially caused by deposition, extinction of solar radiation, GHG effect</td>
<td>PM, N, S deposition, O3 levels and impact on vegetation functioning, Aerosol optical depth</td>
</tr>
<tr>
<td>SDG</td>
<td>Topic of concern</td>
<td>Targets (*)</td>
<td>Indicators (*)</td>
<td>Cause of damage (**)</td>
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<td>14. Life below water</td>
<td>Careful management of life below water that is an essential global resource for a sustainable future. (This follows the UN convention on the Law of the Sea)</td>
<td>14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels</td>
<td>14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations</td>
<td>Ocean acidification</td>
<td>Atmospheric deposition of nutrients (N, S, Fe, P, Cu etc), toxic substances (e.g. POPs), CO₂ influx</td>
<td>IOC-UNESCO, UN-DOALOS, FAO, UNEP, ILO, other UN-Oceans agencies</td>
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<td>14.4 By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics</td>
<td>14.4.1 Proportion of fish stocks within biologically sustainable levels</td>
<td>Nutrient limitation</td>
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<td>14.5 By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information</td>
<td>14.5.1 Coverage of protected areas in relation to marine areas</td>
<td>Toxicity</td>
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<td>14.c Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of “The future we want”</td>
<td>14.c.1 Number of countries making progress in ratifying, accepting and implementing through legal, policy and institutional frameworks, ocean-related instruments that implement international law, as reflected in the United Nations Convention on the Law of the Sea, for the conservation and sustainable use of the oceans and their resources</td>
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<tr>
<td>SDG</td>
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<td>15. Life on Land</td>
<td>Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss (forest, mountain, dry lands, wetlands following obligations under international agreements- protect and prevent the extinction of threatened species)</td>
<td>15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements</td>
<td>15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type</td>
<td>Soil, freshwater acidification, Biodiversity loss of terrestrial vegetation and of soil microbial community</td>
<td>Sulfur deposition, Nitrogen deposition, Fe, P, Cu, toxic substances, Ozone levels (climate change, Land-use change)</td>
<td>FAO, UNEP-WCMC, UNEP, IUCN, UNODC, CITES</td>
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<td>15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally</td>
<td>15.2.1 Progress towards sustainable forest management</td>
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<td>15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development</td>
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<td>15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species</td>
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<td>15.7 Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products</td>
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ANNEX 2 - AUTHOR LIST

Wenche Aas, Norwegian Institute for Air Research (NILU), Kjeller, Norway

Leonard Barrie, Department of Atmosphere and Ocean Science, McGill University, Montreal, Quebec, Canada

Camilla Andersson, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden

Gregory Carmichael, Center for Global and Regional Environmental Research, University of Iowa, Iowa City, IA USA

Amanda Cole, Air Quality Research Division, Science and Technology Branch, Environment and Climate Change Canada (ECCC), Toronto, Ontario, Canada

Frank Dentener, European Commission’s Joint Research Centre (JRC), Italy

Johannes Flemming, European Centre for Medium-Range Weather Forecast, UK

Joshua Fu, Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN USA & Computational Earth Sciences Group, Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN USA

Corinne Galy-Lacaux, Laboratoire d’Aérologie, Université de Toulouse, CNRS, UPS, France

Jeffrey Geddes, Department of Earth & Environment, Boston University, Boston, MA USA

Maria Kanakidou, Environmental Chemical Processes laboratory, Department of Chemistry, University of Crete, Heraklion, Greece & Institute of Environmental Physics, University of Bremen, Bremen, Germany (coordinating author)

Lorenzo Labrador, Atmospheric Environment Research Division, Science and Innovation Department, World Meteorological Organization, Geneva, Switzerland

Fabien Paulot, National Oceanographic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, NJ USA

Donna Schwede, Center for Environmental Measurement and Modeling, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC USA

Oksana Tarasova, Atmospheric Environment Research Division, Science and Innovation Department, World Meteorological Organization, Geneva, Switzerland

Robert Vet, retired from Environment and Climate Change Canada (ECCC), Canada