OPERATIONAL ATMOSPHERIC CHEMISTRY MONITORING MISSIONS (CAPACITY)

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ABSTRACT

The overall aim of the ESA CAPACITY ('Composition of the Atmosphere: Progress to Applications in the user CommuITY') study (2003-2005) has been to define satellite components of a future operational system to monitor atmospheric composition for implementation by ESA/EU within the Space Component of GMES ('Sentinels 4/5'). Missing observational capabilities for an envisioned future integrated system to monitor atmospheric composition have been identified and the space elements needed to remedy these deficiencies have been defined. The principal time frame covers the period 2010 to 2020 concurrent with the EUMETSAT Polar System MetOp, MSG/MTG and non-European operational systems. Some recommendations have been formulated for the space elements of a post-EPS operational atmospheric composition system (>2020). The CAPACITY final report and technical notes are available via [1].

1 STUDY OVERVIEW

In short, the CAPACITY study objectives were:

- to identify user applications which would benefit from operational atmospheric composition monitoring;
- to quantify the user requirements;
- to derive geophysical data requirements (satellite-borne, ground-based/in-situ, and auxiliary data);
- to assess the capabilities of existing and planned space missions and ground networks;
- to develop space segment concepts that could address discrepancies with the requirements;
- to define instrument and mission concepts from GEO and LEO orbit perspectives, respectively;
- to identify potentially critical space segment issues;
- to identify potentially critical ground segment issues.

A large European consortium was formed consisting of approximately 30 partners from 9 ESA countries (F, D, UK, I, SW, N, DK, B, NL). The core project team consisted of 4 scientific institutes and 2 industrial partners. The consortium included a large group of representatives of user organisations, atmospheric scientists using satellite data in combination with models, space research institutes with core expertise in the retrieval, calibration and validation of satellite data, as well as industry with experience in the space and ground segments. A dedicated user consultation workshop was held on 20th/21st January 2004 at ESTEC, soon after the project kicked off in October 2003. A user feedback meeting was held on 31 August 2004 in conjunction with the mid-term review. Data users and external experts in atmospheric remote sensing were invited to the final presentation of the study on 2nd of June 2005. The final report was finished in October 2005.

The study findings support an integrated and international approach to operational monitoring of atmospheric composition to which space missions, ground-based and in-situ observations and modelling information all contribute. This overall concept is inline with the IGACO recommendations. Candidate operational missions were evaluated taking into account the following criteria:

- The user need for operational services and urgency of the envisioned applications;
- The added value over existing and planned operational systems and space elements;
- The maturity of the mission concept for operational implementation.

CAPACITY concludes that three specific requirements for satellite observations can not be met by the planned operational systems:

- sufficient spatio-temporal sampling for the air quality applications;
- high vertical resolution in the upper troposphere and lower stratosphere for ozone and climate applications;
- measurements of climate gases (CH_4, CO, CO_2) and aerosols with sensitivity into the planetary boundary layer for climate protocol monitoring.

In this paper we focus on the derived user requirements (sections 2 and 3) and the study conclusions and recommendations (sections 4, 5, and 6). The full study report (incl. executive summary) and underlying technical notes are available via [1].

2 USER REQUIREMENTS

The role of representatives of user organizations / communities was considered vital to the study. Users have been active participants in the study as consultants and several users attended the user consultation workshop, user feedback meeting and/or the final presentation.

There has been a strong overlap and continuous interaction with several activities related to operational systems by EU and ESA within the GMES Initial Period and follow-on activities. Relevant projects include GMES-GATO, Daedalus, GEMS, and the ESA GSE Service Element Atmosphere PROMOTE. The user-consultation workshop was organized together with GMES-GATO, with contributions from the aerosol user community via Daedalus. After the workshop several invited organizations became actively involved within PROMOTE.

The potential mission objectives have been organized into three themes, which need to be supported through operational monitoring of atmospheric composition:

- *(A) Stratospheric Ozone and Surface UV radiation*
- *(B) Air Quality*
- *(C) Climate*

For each of the three identified themes three user categories have been identified:

- *(1) Protocol monitoring*
- *(2) Near-real time data use*
- *(3) Assessment*

Protocol monitoring includes policy support for verification of protocols, legislation and international treaties. Near-real time data use includes both forecasting and monitoring by operational (meteorological) centres. Assessment includes scientific assessments of long-term environmental threats and associated policy support. The three themes and three user categories result in a total of nine applications. For each application, the envisaged service to the end users and its quality attributes has been described, together with the expected societal benefits. The services have been translated into requirements on atmospheric composition data and auxiliary data including e.g. meteorological data and bottom-up emission inventories. The user requirements include as much as possible basic information on the geographical and temporal range and resolution of the data, as well as on other relevant quality attributes including accuracy, reliability, stability, delivery time, etc. User requirements are shortly summarized per theme and user category.

For stratospheric ozone and surface UV radiation the protocol monitoring user requirements stem from the United Nations Montreal Protocol and its subsequent amendments that regulate the release of ozone depleting substances into the atmosphere. The future evolution of the ozone layer needs to be monitored over a period of decades. Also, the UV radiation incident at the earth surface needs to be monitored together with information on ozone, aerosols, clouds and surface albedo. Episodes of high UV exposure, dangerous to man, require a forecast system that relies on near real time delivery of ozone and some other observations.

For scientific assessment of the ozone layer recovery and in relation to chemistry-climate interactions a broad range of measurements is required, including ozone depleting substances, polar stratospheric clouds and key species in the catalytic ozone destruction cycles. Vertical resolutions of 2 km or better are required in the upper troposphere and lower stratosphere.

User requirements for air quality protocol monitoring are derived from the EC air pollution directives and the UN ECE Convention on Long Range Trans-boundary Air Pollution (CLRTAP). These include the measurement of ground level amounts of aerosols and gases at city (or higher) scale resolution. For aerosol the demand is for data on particulate matter (PM) at increasingly fine scale, ranging from 10 micron to 2.5 micron and possibly sub-micron size in future. For gases the interest is in ozone, nitrogen dioxide, carbon monoxide, and sulphur dioxide. In order to achieve representative sampling and as a result of the short-term variations of the sources and sinks of these species near the surface, high temporal sampling of 1-2 hours is needed during daytime.

The need to make accurate forecasts of air quality for health and regulatory reasons requires near real time delivery of a similar set of observations, with again a high temporal and spatial sampling frequency during daytime and night time measurements being desirable.

For air quality assessment and its long term evolution, the oxidising capacity of the atmosphere is the main driver of the observational requirements. Here, the hydroxyl radical OH plays a pivoting role that needs to be constrained by measurement of key species in the troposphere on a global scale.

Climate protocol monitoring requirements have been derived from the Kyoto Protocol and concern the emissions of greenhouse gases carbon dioxide, methane, nitrous oxide, and some minority gases. Anticipating on future needs, also tropospheric ozone and aerosol are included in these requirements as well as the tropospheric ozone precursor gases carbon monoxide and nitrogen dioxide. The observational requirements for climate gases arise from the need to improve our knowledge on anthropogenic and biogenic sources and sinks and specifically to narrow down the uncertainties in emission inventories.

Climate monitoring and numerical weather prediction by operational centres require near real time availability of several climate relevant gases and aerosols for assimilation. For climate assessment the driver for the requirements is the need to understand climate-chemistry interactions, including radiative, dynamical and chemical processes and feedbacks and their response to global climate change. The requirements include the measurement of water vapour and ozone at 2 km vertical resolution in the upper troposphere and above.

3 GEOPHYSICAL DATA REQUIREMENTS

For each of the nine applications a comprehensive set of measurable geophysical quantities has been compiled, directly traceable to the user requirements. Per application a measurement strategy has been formulated to define how to optimally construct an integrated end-to-end system that is based on three complementary building blocks:

- Satellite data products;
- Ground-based and in-situ observations;
- Auxiliary data, including meteorological data and emission inventories.

Separate data requirement tables have been constructed for the satellite data products (in terms of level-2 products, here defined as retrieved geophysical data products) and for the ground-based / in-situ observations. Therefore, a total of eighteen tables have been compiled for the nine applications [1].

Per theme and user category the most relevant data products and processes (physical, chemical) have been identified and discussed. Drivers have been specified for each of the data product. Typical drivers include, e.g., forecasting, concentration monitoring, emission monitoring, trend monitoring, and validation (for ground-based / in-situ observations). For the assessment drivers include also fundamental processes such as ozone loss and ozone recovery and composition-climate interactions including radiative forcing, the oxidising capacity and the Brewer-Dobson circulation. For each compound height-resolved and height-integrated products have been distinguished. Per product the relevant height range, horizontal sampling and vertical resolution, revisit time and uncertainty have been quantified, based on expert judgments by scientists including atmospheric chemistry modellers. The variability of the compound in the atmosphere has been found to be one useful measure, as well as the typical temporal and spatial scales of the driving processes that lead to the observed variability.

Near real time data delivery for the different applications typically imply that the data needs to be available to an operational modelling environment within a couple of hours after observation. In that case a significant part of today's observations can still be used for the analysis on which forecasts for tomorrow (etc.) can be accurately based.

4 AIR QUALITY

The combination of requirements on revisit time, resolution and coverage, including frequent cloud-free sampling of the planetary boundary layer, is very stringent. The air quality requirements to meet user needs are not adequately addressed by the planned operational missions. Planned operational missions in LEO will contribute to, but by and large do not fulfil stringent qir quality sampling requirements. Nominal mission lifetimes of the Envisat and EOS-Aura missions both end before 2010. Continuation of air quality user services based on these missions requires quick action to be taken. Moreover, planned operational missions have primarily meteorological and climate objectives. The air quality applications could benefit most from denser spatio-temporal sampling over Europe for forecasting and monitoring as well as globally for worldwide air quality monitoring and attribution of pollution episodes. The air quality user requirements include a suite of trace gases as well as aerosols.

CAPACITY concludes on the air quality theme:

- that the monitoring for operational air quality applications needs to be optimised with respect to the density of spatio-temporal sampling of the planetary boundary layer;
- that small ground pixels are needed to maximize (cloud-free) sampling of the boundary layer;

- that it is important to cover diurnal variations for air quality;
- that regional coverage with short revisit time is needed to optimally serve regional air quality forecasting and monitoring in Europe and that global coverage is required for the monitoring and assessment of air quality, the oxidising capacity, and the quantification of continental in/outflow;
- that *afternoon* observations would complement best the observation times of day of MetOp and NPOESS observations in the post-Envisat/post-EOS-Aura time period.

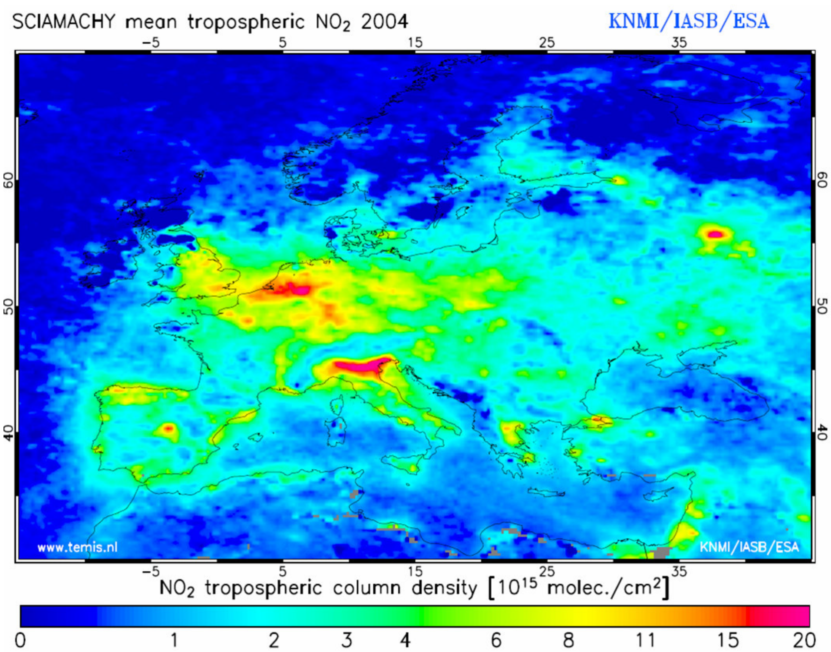

Fig. 1. NO_2 tropospheric column as measured by Envisat SCIAMACHY[2].

For implementation of the air quality mission CAPACITY recommends:

- to enhance observational capabilities in the 2010-2020 time period and afterwards for operational air quality applications with respect to the density of spatio-temporal sampling of the planetary boundary layer by a combination of space elements in Geostationary Orbit (GEO) and Low-Earth Orbit (LEO). The global (LEO) and regional (GEO) missions are of equal importance;
  - A LEO mission with a UV-VIS-NIR-SWIR nadir viewing spectrometer with ground pixel size significantly smaller than GOME-2 and OMPS and daily global coverage in a polar orbit with *afternoon* equator crossing time optimally chosen to complement on the times of day of MetOp and NPOESS observations in the post-Envisat/post-EOS-Aura time period and to maximize (cloud-free) sampling of the boundary layer. Global coverage is required for the monitoring and assessment of Air Quality, the oxidising capacity, and the quantification of continental in/outflow;
  - A combined GEO mission with a UV-VIS-NIR-SWIR spectrometer and TIR sounder with small ground pixel sizes to cover diurnal variations in O_3, CO, NO_2, SO_2, HCHO, HNO_3, PAN, N_2O_5, organic nitrates and aerosols, height-resolved tropospheric O_3 and CO, and to significantly improve upon the cloud-free sampling of the planetary boundary layer over Europe;
  - Taking into account maturity, cost and risk issues, it is recognised that a LEO mission could have a somewhat shorter lead time, even though it will only partially fulfil the requirements of European air quality users.
- to prepare for phase A studies for LEO and GEO missions targeting air quality (protocol monitoring, forecasting and assessment) based on the given definitions of the instrument / mission concepts and requirements and their subsequent evaluation, and taking into account the importance of cloud statistics on lower tropospheric observations.

5 CLIMATE PROTOCOL MONITORING

For the monitoring of greenhouse gas and precursor emissions the planned operational missions fall short in their capabilities to observe CH_4, CO and CO_2 with sensitivity to, and frequent cloud-free sampling of the planetary boundary layer which is required to derive surface emissions. In addition, improved aerosol observations are required.

CAPACITY concludes on the climate protocol monitoring theme:

- that concentration and emission monitoring is needed for O_3, NO_2, SO_2, CO_2, CO, CH_4, and aerosols;
- monitoring for operational climate protocol applications needs to be optimised with respect to the density of spatio-temporal sampling of the planetary boundary layer;
- that small ground pixels are needed to maximize (cloud-free) sampling of the boundary layer;
- that it is limited important to cover diurnal variations for climate protocol monitoring;
- that global coverage is required, while regional coverage with short revisit time will optimally serve climate protocol monitoring in Europe.

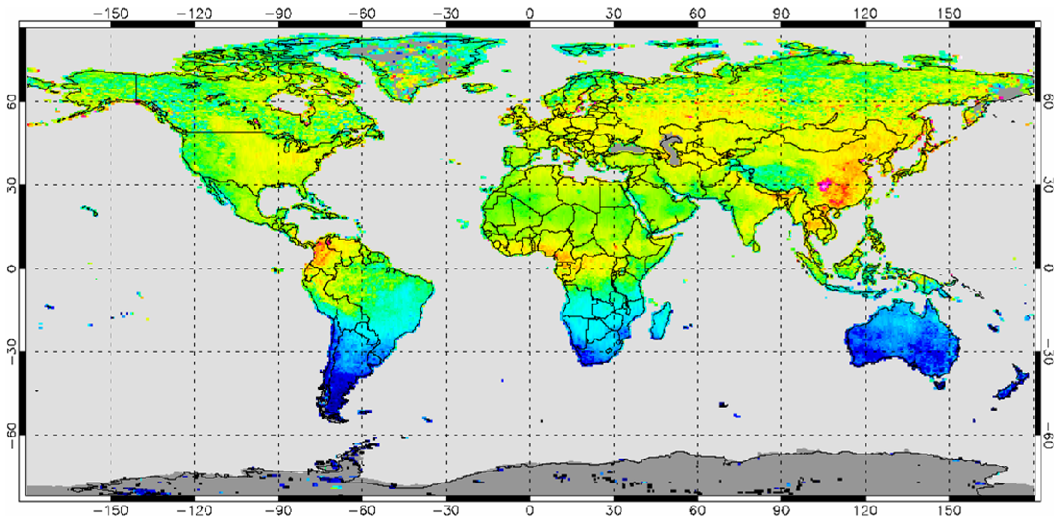

Fig. 2. Two-year (2003+2004) average of CH_4 column averaged mixing ratios as measured by Envisat SCIAMACHY [3]. The colour scale ranges between approximately 1650 ppb (blue) and 1780 ppb (red).

For implementation of the climate protocol monitoring mission CAPACITY recommends:

- that the air quality monitoring missions (LEO and GEO) be most efficiently extended to include climate protocol monitoring by addition of SWIR channels;
- to extend the phase A studies to investigate the added value of the air quality missions for climate protocol monitoring based on the identified instrument / mission concepts and requirements and their subsequent evaluation;
- that given the very stringent uncertainty requirements on CO_2 the implementation of operational monitoring of CO_2 for emission monitoring is not recommended until useful capability has been shown by the planned OCO (NASA) and GOSAT (JAXA) research missions.

6 CLIMATE AND STRATOSPHERIC OZONE MONITORING AND ASSESSMENT

Planned operational missions fall short in the monitoring and assessment of composition-climate interactions. Specifically, it is needed to better resolve (long-term changes in) the vertical structure of the atmosphere, especially with respect to ozone and water vapour, which are very important, radiatively (climate forcing), chemically (ozone recovery, oxidizing capacity) and dynamically (stratosphere-troposphere connections, Brewer-Dobson circulation).

For stratospheric ozone/UV the planned operational missions fall short in their capability to resolve (long-term changes in) the vertical structure of the atmosphere for several long-lived compounds. Adequate vertical resolution of the order of a few kilometres in the upper troposphere and stratosphere is needed for scientific assessments of the ozone shield and would also allow improvement of the forecasting applications.

CAPACITY concludes on the climate and stratospheric ozone/UV themes:

- that planned operational missions contribute significantly to protocol monitoring ('Montreal') for the ozone and UV applications;
- that user needs for height-resolved data on O_3, H_2O, and other trace gases and aerosols in the upper troposphere and lower stratosphere can not be met because planned operational missions have only nadir-viewing instruments – with the exception of OMPS, which mainly targets O_3.

For implementation of the climate and stratospheric ozone/UV applications CAPACITY recommends:

- to move incrementally towards an optimal operational monitoring system for these applications, in line with the GMES overall concept;
- to enhance the observational capabilities in vertical resolution already in the 2010-2020 time period;
- instrument specifications for limb-MIR and limb-MM techniques – feasible options with complementary capabilities – be consolidated to meet user requirements for a future operational limb-sounding component;
- to prepare for a phase A study for a limb sounding component to the LEO mission targeting climate and stratospheric ozone.

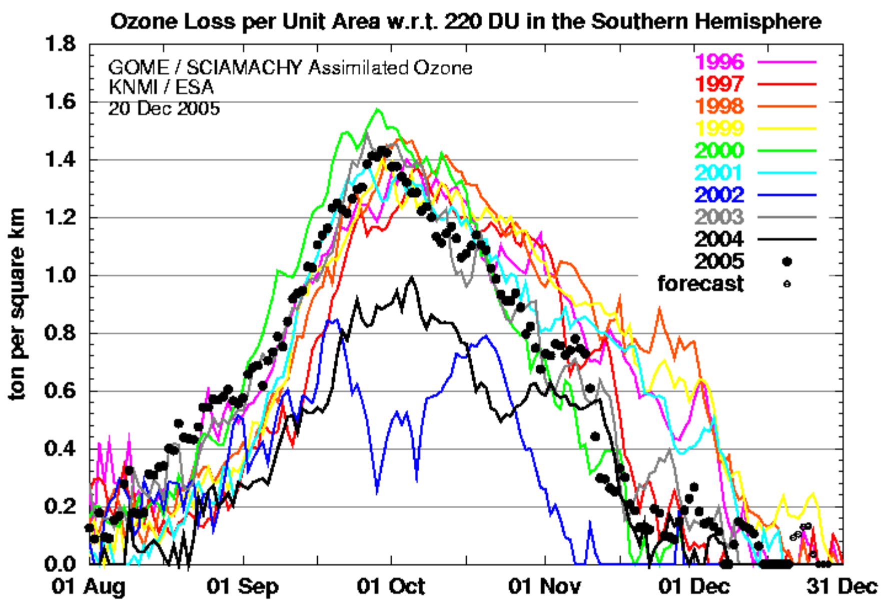

Fig. 2. Antarctic O_3 loss monitoring by ERS-2 GOME and Envisat SCIAMACHY [4]

Finally, a more general recommendation is made to investigate the possibility, advantages and disadvantages of a constellation of satellites in low inclination orbit to addresses the envisioned operational applications for all themes.

7 REFERENCES

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