WORLD METEOROLOGICAL ORGANIZATION

ET-SUP-7/Doc. 11
(16.V.2013)

COMMISSION FOR BASIC SYSTEMS
OPEN PROGRAMME AREA GROUP ON INTEGRATED OBSERVING SYSTEMS

EXPERT TEAM ON SATELLITE UTILIZATION AND PRODUCTS

ITEM: 11

SEVENTH SESSION

GENEVA, SWITZERLAND, 27-30 MAY 2013

Original: ENGLISH

ATMOSPHERIC COMPOSITION REQUIREMENTS AND SPACE CAPABILITIES

(Submitted by Richard Eckman, NASA)

Summary and Purpose of Document

This document reports on activities of the Committee on Earth Observation Satellites Atmospheric Composition Constellation to deliver data to develop and improve predictive capabilities for changes in the ozone layer, air quality, and climate forcing associated with changes in atmospheric composition.

ACTION PROPOSED

The seventh session is invited to take note of CEOS ACC activities relating to the status of atmospheric composition space capabilities, and to comment accordingly.

Appendix:
Report of the Committee on Earth Observation Satellites Atmospheric Composition Constellation Workshop on the Impact of Data Gaps on Climate Modeling Validation and Forecasts, 15-17 October 2008.

DISCUSSION

Introduction

The Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Constellation (ACC) is one of seven virtual constellations that assemble a set of space and ground segment capabilities operating together in a coordinated manner to produce a virtual system that overlaps in coverage in order to meet a combined and common set of Earth observation requirements. The goal of the ACC is to collect and deliver data to develop and improve predictive capabilities for changes in the ozone layer, air quality, and climate forcing associated with changes in atmospheric composition. Within the GEOSS framework, ACC supports multiple societal benefit areas, including health, disasters, energy, climate, and ecosystems.

User requirements for atmospheric composition measurements have been developed by national and international panels and user groups. These are mature and are supported by the Agencies in mission definition studies. Specific application for these data includes national forecasting and environmental protection agencies which require even more accurate and faster data delivery. Data for forecasting are needed on a global basis because of the impact of long range transported pollution on regional air quality. Climate and environmental assessment users (e.g., IPCC, WMO/UNEP, US Global Change Research Program, EU Monitoring Atmospheric Composition and Climate Project) require extremely accurate long term data, on a global basis to verify treaty and convention which protect and assess climate change (e.g., Montreal Protocol, Kyoto).

ACC Activities

ACC addresses the following elements to meet the science discipline and application requirements by its member agencies.

- Develop a consensus for priorities based on emerging societal needs and established user requirements from both operational and research communities
- Determine if there are inconsistencies or deficiencies among the various requirements and reconcile differences if necessary
- Evaluate existing and upcoming missions, both operational and research, and compare with requirements
- Define enhancement in the area of calibration/validation, quality control, and data accessibility and interoperability
- Establish how existing and approved missions could work synergistically to meet the international user community requirements and in particular the GEOSS societal benefit areas
- Develop rationale and strategy for new mission(s) to meet existing requirements not being met and for possible new requirements.

Capabilities and Known Missing Components

Satellite observations for applications and decision support are now being actively investigated and implemented. Nevertheless new questions are unfolding as the Earth system begins to respond to climate changes, and new and more accurate observations are becoming apparent. Some of the known issues facing the atmospheric sciences applications communities for remotely sensed measurements include:

- Continuity of trace gas stratospheric measurements involved in ozone chemistry. These are needed to better understand trends and to quantify the effectiveness of the Montreal protocol (Many measurements have ended with the demise of Envisat, while Aura has been in orbit for almost 9 years.)

- Accurate and continued monitoring in the upper troposphere/lower stratosphere, with high vertical resolution, for climate research and applications (Limb measurements are required)

- Improved accuracy and coverage of radiatively active gases and aerosols in the boundary layer needed for surface flux assessment and aerosol/cloud formation remain the largest uncertainties in climate forcing. (Boundary layer measurements for gases remain a challenge)

- Short- and long-term temporal and spatial variation measurements of radiatively and chemically active trace gases and aerosols to determine their impact on air quality for improved inventories, predictions, and assessments. (Geostationary or non-polar/sun-sync orbits needed)

- Tracking trans-continental and trans-oceanic transport of tropospheric pollutants and their precursors. (Continuing global coverage is needed)

- Interoperability of atmospheric composition data across existing and planned missions. Interoperability is a major focus of GEO, CEOS, and WMO.

Implementation

Since 2007, the ACC has held annual or semi-annual meetings of its members to respond to its goals and near-term CEOS needs. These include representatives from national space agencies and researchers from academia. Typical meeting attendance has ranged from 30-50 individuals.

In 2008, ACC met at NASA GISS and reviewed atmospheric chemistry and climate model requirements and assessed space-based measurement gaps. The workshop produced a report (see Appendix) which includes a set of prioritized recommendations, based on expected data gaps of atmospheric composition, for future missions. While this report is now five years old, many of its recommendations remain relevant and useful for consideration by the community.

Key recommendations included the need for limb profiler measurements from multiple agencies and stressed the importance of geostationary air quality measurements to optimize global coverage of air quality observations and forecasts.

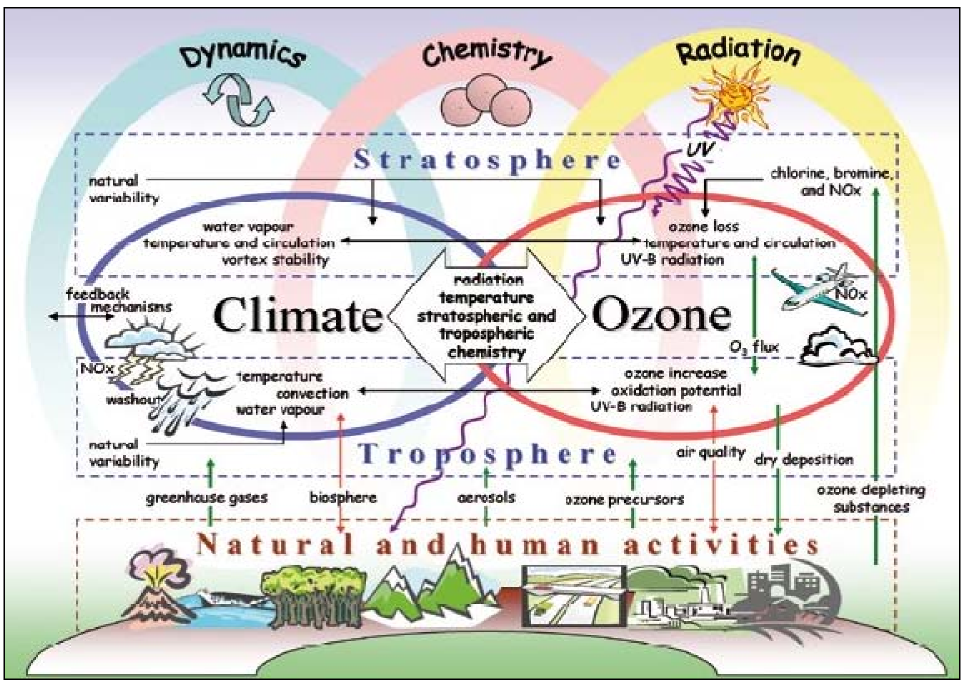
The meeting also noted the need for continuous long-term atmospheric composition data sets from existing and upcoming missions for climate research and assessments. It was also noted that the space agencies which are collecting these data should support the development of climate data records (consistent with the GCOS essential climate variables).

Subsequent meetings addressed the coordination of a future Air Quality constellation based on geostationary satellites planned and in development by Korea (GEMS), ESA (Sentinel-4), NASA (GEO-CAPE and TEMPO), and Japan (GMAP-Asia). The missions would be planned to take advantage of their synergistic capabilities. Cost efficiencies might be achieved if there are common instrument requirements. Coordinated algorithm development, data content and format, and calibration/validation were planned. A community developed white paper was delivered to the CEOS Strategic Implementation Team in 2010 for consideration and endorsement (http://ceos.org/images/ACC/AC_Geo_Position_Paper_v4.pdf). The near-term recommendations of this paper are currently being implemented by through ACC and by the relevant mission science teams. These actions include convening an expert group to develop best-practices recommendations for UV-Visible spectrometer pre-launch instrument characterization; agreement to share pre-launch calibration plans (to the extent allowed by possible proprietary restrictions) and invite cross participation in reviews that cover calibration; share instrument characterization and calibration databases and Level 1-b data, in a common format, to allow application of common algorithms to all datasets; develop a list of desired constellation data products (which may or may not differ from each mission's standard products), strive for consistency in retrieval algorithms; enable cross-agency participation in ATBD reviews; jointly improve retrieval algorithms by conducting inter-comparisons on common radiances; and develop longer term recommendations for possible common post-launch calibration/validation strategies (e.g. supersite instrumentation round-robins, joint airborne campaigns).

More recently, ACC have addressed the issue of total ozone measurement coordination, emphasizing algorithm improvements, uncertainty quantification, validation, and intercomparison activities. ACC decided to facilitate a two-step process that would respond to the new emphasis for the virtual constellations to respond to GCOS actions. Collaborations among the various instrument groups resulted in a best-effort characterization of errors of the individual data sets (i.e., SBUV/TOMS/OMI and the GOME/SCIAMACHY/GOME-2 datasets) that was discussed at the April 2013 ACC meeting in Darmstadt. ACC members also agreed to construct a combined American/European long-term total ozone data set to respond to multiple user requirements. At this meeting, it was also agreed that other satellite data sets (e.g. the Chinese FY3 missions and infrared sensors like IASI) should be included into this data intercomparison with the view to possible merging activities in the future.

Report of the Atmospheric Composition Constellation Workshop on the Impact of Data Gaps on Climate Modeling Validation and Forecasts

Recommendations to the CEOS Agencies



Goddard Institute for Space Studies
October 15-17, 2008

Table of Contents

Front Cover: *Image from: "Feedback Linkages between Climate and Ozone", Isaksen, EC Air Pollution Report No.81, Ozone Climate Interactions, 2003. Upper logos represent organizations supporting this report. Lower logos are space agencies represented in the ACC*

March 15, 2009

Executive Summary

This report summarizes the recent Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Constellation (ACC) workshop focused on atmospheric composition and climate modeling. The workshop included a review of ongoing and planned climate research, a review of atmospheric chemistry and climate model requirements, and a summary of the space-based measurement gaps. The resulting output of the workshop is this report, which includes a set of prioritized recommendations, based on expected data gaps of atmospheric composition, for future missions.

1.0 Introduction

In support of the Group on Earth Observations (GEO) objectives and as a space component of the Global Earth Observation System of Systems (GEOSS), CEOS[1] has developed the concept of virtual space-based Constellations. A *Constellation* is a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular aspect of the Earth system. The Constellation concept builds upon or serves to focus existing projects and activities and provides a means to maximize the value of existing and future space assets among partners. A goal of a Constellation is to demonstrate that added value can result through partnership among the space agencies and their supported institutions. Another major goal of the Constellations is to address key observational gaps.

The Atmospheric Composition Constellation (ACC) focuses on observations needed for understanding and improving predictive capabilities for changes in the ozone layer, climate forcing, and air quality. At the present time, ten space agencies are collaborating in ACC and have established three projects to demonstrate how added value can be obtained by combining satellite data sets. These initial projects (reference CEOS website[1]) are directed towards applications which focus on GEO Societal Benefit Areas (SBAs). With increasing awareness of climate change and the key role the atmosphere plays, ACC initiated a project to determine the impacts of expected AC satellite data gaps in understanding and explaining climate change. ACC fully recognizes the capabilities and the necessities of ground based and airborne measurements that complement satellite data and provide crucial measurements for validation.

To explore the impact of data gaps in space observations, ACC conducted a workshop at the Goddard Institute for Space Science (GISS) in New York City 15-17 October 2008. The workshop was co-sponsored by the Stratospheric Processes And their Role in Climate (SPARC, a WCRP project), the Global Climate Observing System (GCOS), and the World Meteorological Organization (WMO). The attendees were scientists from Japan, Europe and the United States who had conducted research relevant to the workshop. The format of the workshop included keynote speakers with talks from the atmospheric chemistry and climate modeling communities and from the investigators who are compiling various AC data sets using multiple satellites. A panel was held on the last day of the workshop to assess the impact of the data gaps with some discussion on how they might be avoided or mitigated. A major tool for this effort was the recently completed Requirements and Gap Analysis (R&GA) for AC measurements. The minutes of the workshop are found in the Appendix.

This report summarizes the workshop outcomes. The recommendations and options for avoiding the identified gaps appear in the next section. The workshop objectives are followed by a discussion of measurements and modeling related to ozone recovery, climate interactions, and air quality. This is followed by a discussion of the R&GA, then chemistry-climate model capabilities and remaining challenges. The report concludes with the Workshop Outcomes. In addition to the results from the Workshop, this report also includes recent findings from IPCC [2, 3], US CCSP [4], the 20th Meeting of the Parties to the Montreal Protocol [5], and the WMO/UNEP report[6]. The Appendices include the minutes of the workshop and a list of attendees. All the workshop presentations can be found at the CEOS website[1].

2.0 Recommendations

These workshop recommendations are based on the results of a Requirements and Gap Analysis (R&GA), Section 5.4, and panel discussions conducted at the end of the Workshop. The highest priority was given to missing measurements that without them would result in severe gaps or discontinuities in ozone and radiative and chemically active trace gas time series, reduced scientific understanding of atmospheric chemistry and climate processes, and reduced societal benefit. The Workshop attendees determined that continuous measurements of high vertical resolution ozone and chemically active trace gas profiles is the highest priority for atmospheric composition science and applications and requires action on the part of CEOS space agencies. The following recommendations (*in priority order)* would address these critical gaps and continue credible atmospheric composition science through the next 20 years. The rational and justification for these recommendations follow in the rest of the Workshop report.

(1) **NOAA should consider restoring the OMPS limb profiler measurement on the NPOESS series (C1 and C3).** This would maintain the continuity in the current stratospheric ozone profile data being collected from research satellites. Profile measurements should continue so that attribution of ozone recovery can be established with respect the observance of Montreal Protocol (and its Amendments) and climate change.

(2) **CSA should consider plans to develop an ACE-II instrument.** The current ACE instrument on SCISAT has provided unique and critical high vertical resolution trace gas measurements for improved understanding of atmospheric chemistry processes and their climate links. A follow-on ACE-II instrument would benefit from existing ACE science and data infrastructure, thereby minimizing costs to all CEOS agencies. In addition, **NASA should concurrently consider a flight of opportunity for the SAGE-III instrument** (in storage) for aerosol and ozone profiles. It is believed that climate cannot be adequately addressed with only nadir aerosol optical depth due to uncertainty in height distributions whereas the combination of these missions would address those issues.

(3) **ESA should consider the selection of the PREMIER mission**. This mission would improve on measurement of key trace gas profiles in the upper troposphere and stratosphere following ENVISAT, ACE and Aura. In particular, provide 3-dimensional data of very high resolution, and provide unique data for climate-chemistry interactions in the upper troposphere and stratosphere. Coordination with nadir-sounding instruments on Metop will provide data for long-range transport of air pollutants (see recommendation 4 and 5). PREMIER is now in ESA Earth Explorer Phase-A and competing with two other missions for launch in 2016.

(4**) ESA, Eumetsat, and the EC should commit to flying limb sounders for trace gases on Sentinel 5.** The combination of Sentinel 4 (eastern GEO orbit) with GEO-CAPE (western GEO orbit) and the Sentinel 5 (morning orbit) with GACM (afternoon orbit) would result in a constellation that measures nearly every aspect of atmospheric composition and climate connections. However a gap could still remain with the present schedule

(5) **NASA should coordinate the flight of the GEO-CAPE mission with ESA's Sentinel-4 mission** to optimize global coverage of air quality and improve transport models. Current NASA funding does not allow investment in Phase-3 Decadal Survey missions.

(6) **NASA should consider accelerating the planning of the GACM-1 mission** which would provide high vertical resolution profiles from the upper troposphere through the stratosphere. This mission would complement the Sentinel 5 mission planned for ~2020.

There as growing need for continuous long term Atmospheric Composition data sets from existing and upcoming missions for climate research and assessments. The space agencies collecting these data should support the development of Climate Data Records (consistent with the GCOS ECVs) beyond the support they are providing now to also include data sets across international missions.

Implementation of one or more recommendations above would remove some of pending data gaps and provide measurements needed for critical atmospheric chemistry and climate interactions for both science and applications. A proactive consideration by the CEOS space agencies would ensure continued progress in our understanding of atmospheric chemistry and our ability to understand and predict future climate change.

At the time of the writing of this report it was assumed that both GoSat and OCO would be in orbit, therefore discussion of CO_2 was limited.

3.0 Background

Depletion of the stratospheric ozone layer by human-produced ozone-depleting substances has been recognized as a global environmental issue for more than three decades. Scientific understanding of the observed ozone depletion provided the basis for the Montreal Protocol and its amendments. The science of stratospheric ozone is undeniable based on laboratory measurements of the chemical process, observations of constituents in the atmosphere, and models which confirm and explain the observations. The atmosphere is unquestionably responding to policy to phase out ozone depleting substances. Anthropogenic emissions of compounds containing chlorine and bromine and their chemical by-products in the stratosphere are in decline as a result of policy implementation curtailing ozone depleting substances. While it appears that ozone levels are showing signs of recovery (Figure 1), model calculations predict that ozone not will recover to pre-1980 levels until after few decades.

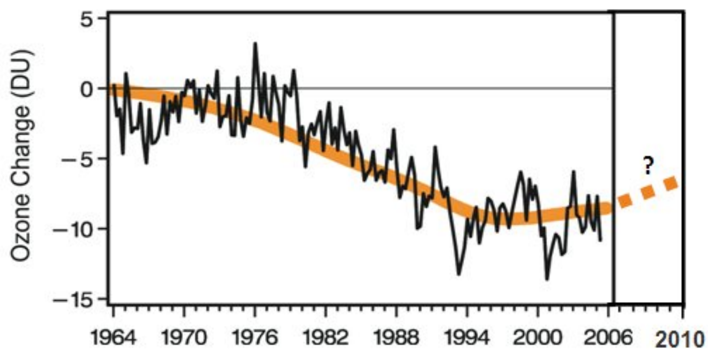


Figure 1. Ozone levels were significantly reduced in the 1980's. Model calculations forecast that ozone will recover to pre-1980 levels in the future in roughly 2040 depending on climate and Protocol abidance. Adapted from WMO UNEP 2006 Chapter 3 (Released in 2007)[6]

Projections of a changing climate have added a new dimension to the issue of the stratospheric ozone layer and its recovery. New data and models show the interconnections between these two global environmental concerns. Climate change is expected to alter the timing of the recovery of the ozone layer through changes in dynamics and temperatures from greenhouse warming. Warming at lower levels is expected to result in stratospheric cooling which promotes ozone recovery by reducing chemical ozone loss, while in the polar regions further cooling will enhance ozone depletion. On the other hand, ozone-depleting chemicals and ozone itself provide positive forcing to climate as shown in Figure 2 (Forster and Shine, JGR 1997)[7]. The curtailment of the ozone-depleting substances not only helped the ozone layer but also lessened positive climate forcing by these substances. Because of the close interaction between climate and the stratospheric processes, there is a continuing need to monitor atmospheric composition throughout the atmosphere. Being able to attribute ozone change relative to decreasing ozone depleting substances from climate forcing is essential for establishing climate policy.

The issues of air quality and climate change have generally been considered as separate problems in environmental research and policy making. However, there is growing evidence that the two are linked much more than once thought. Many of the sources that emit climate-changing greenhouse gases (GHGs) and the sources that contribute to traditional air pollution are largely the same. These linkages between the two issues highlight the urgent need for more comprehensive data in the troposphere so that these parameters can be included in the climate forcing elements in climate forecasts. Finally climate change will also impact air quality through changes in the weather, including cloud cover and temperature changes. Continued monitoring and process studies throughout the atmosphere are essential to fully justify policy decisions to protect the environment.

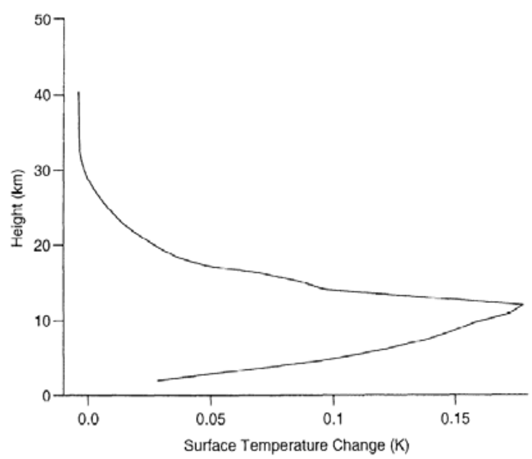


Figure 2. Change in surface temperature in response to a 10 DU ozone increase in a 1 km layer at the indicated height for global mean conditions. Maximum forcing is just above the tropopause at about 12 km

4.0 Workshop Purpose and Expected Outcomes

The workshop is part of a continuing effort by ACC to fully exploit existing and planned international atmospheric composition assets for societal benefits. ACC is also charged to look into the future for missing capabilities needed to predict how climate will change. This workshop is intended to start that process for atmospheric composition. The following were the workshop objectives:

- Review data gaps based on the Requirements and Gap Analysis (R&GA) and agree on their reality. Consider constituents, time, overlap, spatial coverage, and accuracy.
- Review status of on-going and planned research to develop AC Climate Data. Include climate data records, Essential Climate Variables (ECV) as defined by GCOS and IGACO, validity of data and redundancy, and coordination among data producers.
- Review atmospheric chemistry and climate model requirements for observations, validation and improved predictions including results from AC&C, CCMVal, and AeroCom.
- Identify potential impact on climate models from variations in spatial and temporal coverage of data, data gaps, and data drift and biases.
- Identify gaps that are urgent and need immediate attention by the CEOS agencies.
- Recommend longer term data and modeling studies that consider gaps or other data deficiencies
- Define priorities for future space-based measurements and corresponding calibration /validation activities and data products.
- Provide a report to the CEOS Agencies

Not all of these objectives were met in the 3-day workshop. Discussion of air quality and tropospheric composition and its connection to climate did not fully mature due to lack of time, but further discussions were conducted after the Workshop that resulted in recommendations and are included in this report. The next ACC workshop is planned for June 2009 and will focus on tropospheric composition. Recommendations in this report focus on data gaps that result from space agency schedules as of this date. A major portion of the workshop time was spent discussing the on-going development of AC data sets and reviewing the status of atmospheric composition measurements and chemistry-climate models. This workshop appeared to be the first time, or at least one of the few gatherings, where data producers and modelers shared their requirements and future challenges.

5.0 Summary of Workshop Topics and Discussions

5.1 Available Data Sets

Atmospheric composition measurements began about 30 years ago with NASA satellites. The most comprehensive data set is ozone, whose development was driven by concern of ozone depletion resulting from anthropogenic emissions of gases such as CFCs. Ozone trend data quality continues to improve with advanced instruments and algorithms and comprehensive ground based validation activities. Additional ozone data sets are now emerging from Europe that complement the data sets provided by US satellites. Calibration biases and absence of measurement overlap are necessary to overcome biases in the data record. Efforts are currently and will continue through support by CEOS space agencies to interpret ozone changes with respect to climate and anthropogenic connections discussed above. Interpretation of column ozone changes require knowledge of gases that interact with ozone as well how the vertical ozone distribution is changing. Ozone profiles respond differently to anthropogenic by-products and climate changes. This interpretation requires the use of very sophisticated models that employ a full range of atmospheric chemistry and dynamics. These models can also be used for predicting ozone and climate changes. Atmospheric gases and their vertical distribution are being measured from Aura, Envisat, SciSat, Odin and POES (SBUV/2) and Metop (GOME-2). Earlier data are available from satellites that are no longer in operation such as UARS, SAGE, and POAM. The NASA MEaSURES and the ESA Data User Element supported by ESA/GMES programs are providing resources for developing long-term, consistent, and calibrated data and products that are valid across multiple missions and satellite sensors. A similar program supported by NOAA is in its initial phase. These efforts are only in there initial phases and should be continued over the long term.

In addition to ozone data sets, source, radical, and sink gases involved in ozone chemistry are also being measured to test our understanding of how well models work. The need for creating long term data sets of these gases was also discussed at the Workshop. These discussions revealed the difficulties of stitching data sets together due to instrument calibration, algorithm uncertainties, and sampling differences. In general, column measurements of atmospheric species are in fairly good shape (after major efforts), however vertically resolved measurements are critically needed. Discrepancies between profile measurements and model results remain a major challenge and hinder our ability to forecast atmospheric chemistry and climate changes. Long term data sets in the stratosphere have been intensively studied because of Montreal Protocol needs; however data sets in the troposphere are still being developed and analyzed for trends. Further discussions on measurements and models appear in Section 5.5.

5.1.1 Ozone and Chemistry/Climate Connections

The first example of a serious looming gap in upcoming satellite observations is high vertical resolution measurements of ozone profiles throughout the atmosphere, where ozone plays three key roles. Ozone in the stratosphere protects the Earth's surface from harmful ultraviolet radiation and plays a significant role in the radiative balance in both the stratosphere and troposphere. In the lower stratosphere and upper troposphere, ozone is a key GHG. Near the Earth's surface it is a toxic gas and a source of pollution. A typical ozone distribution as a function of altitude is shown in Figure 3.

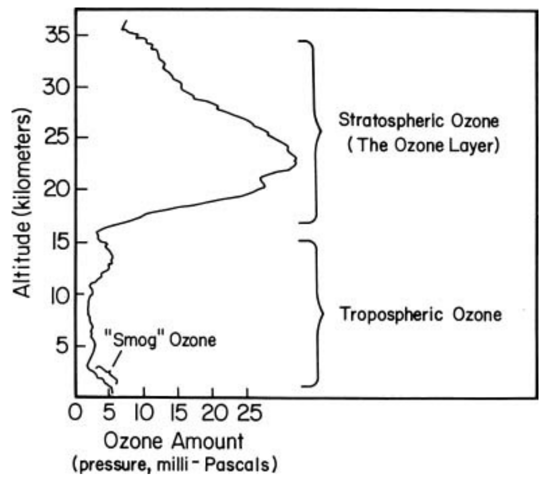


Figure 3. Atmospheric ozone profiles show surface-level "smog" which is a source of pollution while stratospheric ozone is critical to blocking harmful UV radiation reaching the surface. Ozone becomes an important greenhouse gases from about 10 to 20 km.

To date there has been reasonable coverage for ozone profiles from US and European research satellite missions. However this coverage will end after NPP scheduled for launch in 2011. Ozone profile measurements were originally planned for the NPOESS series but this capability was removed due to budget limitations*. At this time, the next opportunity for ozone profile measurements for any planned mission is NASA's Decadal Survey GACM-1 mission. There are also two potential European opportunities which are still under consideration (ALTIUS[8]) or in competition (PREMIER). A final decision to include profile measurements on Sentinel 5 has not yet been confirmed. Further discussion on gaps in profile measurements appears in Section 5.4 (R&GA) and Section 2.0 (Recommendations). It should be noted that all planned nadir viewing instruments for total ozone can retrieve only low vertical resolution profiles. Their resolution is about 8 km and therefore cannot quantify, or even discriminate, ozone changes resulting from climate change or from the effects of ozone depleting substances.

5.1.2 Gases Controlling Ozone in the Stratosphere

Ozone amounts are controlled by a number of factors including solar flux, atmospheric dynamics, and naturally-occurring and anthropogenic gases. These gases, as discussed above, can be categorized as sources, radicals, and reservoirs. Source gases transform into chemically active gases that destroy ozone. Radicals are by-products of the source gases that catalytically destroy ozone. Reservoirs are inactive gases which tie up the radicals and are no longer chemically active. The existing and past fleet of ozone and atmospheric composition missions (Nimbus, UARS, SciSat, Aura, Envisat, OSIRIS, TOMS, SBUV/2, SAGE, POAM, GOME, and GOME-2) have done a good job in monitoring some of these gases and provided information for assessments and model input and validation. These missions will all end at about 2015 and a series of source, radical, reservoir gases will no longer be measured. In the following sections, two examples of gases (HCl and Water Vapor) that play an important role in both ozone chemistry and climate are discussed. Continuous measurements of active gases and their variation over time are

* *The National Research Council (NRC) report, "Earth Science and Applications From Space: National Imperatives for the Next Decade" recommended that NOAA restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R missions, namely the limb sounding capability of the Ozone Monitoring and Profiling Suite (OMPS). In January 2007, NASA and NOAA transmitted to the White House Office of Science and Technology Policy (OSTP) a joint summary of the impact on climate data and research activities of the restructuring of NPOESS pursuant to the Nunn-McCurdy certification process and gave the OMPS-Limb high priority. However the NRC report "Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft", released in 2008, lowered the priority for flying an OMPS-Limb instrument on the series of NPOESS spacecraft. The 2008 NRC report indicated that vertical profiles improved over those to be recorded with the OMPS-Nadir instrument were not essential to be sustained for long periods.*

essential for both climate model diagnostics and attribution of ozone change. These examples were selected because they demonstrate the difficulty in producing data sets even when missions overlap in time. A data gap, short or long, will result in a serious challenge in understanding ozone and climate.

Hydrogen Chloride (HCl) in the Upper Stratosphere

Hydrogen chloride in the stratosphere represents a reservoir of all of the chlorine gas reaching the stratosphere from anthropogenic sources (CFCs, HCFC, etc). The observed rise and decline of HCl shown from UARS provided the key data to verify the effectiveness of the Montreal Protocol (and amendments). The rise, peak, and decline up to 2005, shown in Figure 4, generally followed the calculated trends with unexplained ups and downs. With UARS ending in 2005 there was about a one year overlap with SciSat and Aura. The bias, within their errors, has been adjusted based on overlapping data[9,10]. If UARS/HALOE data had ended in 2002 (after ~10 years in orbit) there would be no overlap with Aura MLS and SciSat. This would have left a great deal of uncertainty in our understanding of ozone recovery since the observed time series could not be reconciled with the models and would therefore have a major impact on our understanding of stratospheric processes. It should be noted that O_3+Cl chemistry is most active near 1.0 hPa (48 km) meaning that profiles must measure to at least that altitude.

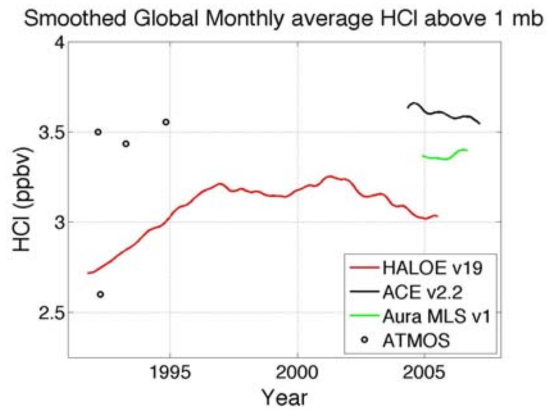


Figure 4. HCl observed amongst four satellites, before adjustments. Adjustments were made normalized to HALOE using an overlap period 2004-2005. It should be noted that the bias varied with latitude. (Lary, 2008)[9]

Water Vapor

Water vapor is a key gas in the atmosphere since it is both chemically and radiatively active. It is the strongest greenhouse gas on the planet, but is not directly anthropogenically produced. In the upper troposphere and lower stratosphere it is a key indicator of convection and radiative forcing. In the stratosphere it is a source gas for OH which is chemically active in the ozone budget. Previous studies reported in WMO/UNEP[6] showed that ozone perturbations are amplified in the upper troposphere and lower stratosphere as a result of feedback processes with water vapor. Any increase in stratospheric water vapor could lead to an increase in the level of odd hydrogen radicals (HO_x). Water vapor entering the stratosphere is nominally controlled by the temperature of the tropical tropopause. The amount of water vapor injected into the stratosphere is also controlled by the intensity of the Brewer Dobson (BD) upwelling in the tropics. There is recent evidence that the BD circulation is changing is changing in the tropics due to climate change, which alters the balance of water vapor in the Upper Troposphere (UT) and Lower Stratosphere (LS) markedly and has a strong feedback on climate change. Recent studies have shown that stratospheric water vapor can be connected to sea surface temperatures through the intensification of tropical convection (Rosenlof and Reid, 2008)[11]

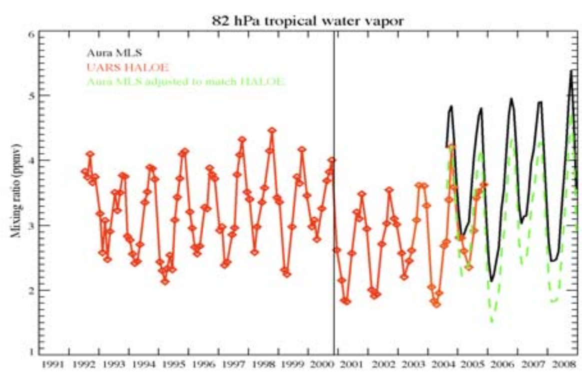


Figure 5. Aura MLS water vapor data is added to the 12 year UARS HALOE data record. Since there was a bias between the two data sets, Aura/MLS (dashed green) was adjusted to the HALOE data using the 2005 to 2006 overlapping data to make a continuous data set. (Rosenlof and Reid, 2008)[11]

Water vapor data go back decades from balloon measurement, but those on the radiosondes are not reliable. Frost point hygrometer water vapor measurements now provide reliable data sets and validation data. Global water vapor records began with the Nimbus-7 (LIMS) satellite and were continued up by UARS, SciSat, Envisat, and Aura. As with HCl above, there are a number of obstacles to overcome in stitching these three data sets together. Figure 5 illustrates the problems encountered in this process. Biases appear in data sets as a function of latitude (only the latitude band from 10N-10S is shown in this example) and altitude which makes this task even more formidable and require more complex functions to make the data fit the overlap period. Nevertheless, important progress is being made to homogenize data sets which can be used to test and refine models. In the case of this water vapor example, if there were no data between 1998 and 2008 a significant event would have been missed (the drop in 2000 of water vapor and what appears to be a small climb upward).

If water vapor concentration increases in the future, there will be both radiative and chemical effects. Increased water vapor cools the stratosphere. Modeling studies suggest increased water vapor concentrations will enhance odd hydrogen (HO_x) in the stratosphere and subsequently influence ozone depletion. Increases in water vapor in the polar regions would raise the temperature threshold for the formation of polar stratospheric clouds, potentially increasing springtime ozone depletion in polar region and delay recovery of the Antarctic ozone hole.

5.2 Air Quality, Troposphere and Climate

Starting with measurements from ERS-2, Envisat, and Aura, satellites have provided a global and regional perspective of tropospheric composition and long range transport of pollution. Of particular interest is the contribution of ozone to poor air quality and climate forcing. If ozone's global distribution and the evolution of that distribution are understood, then many of the important questions about atmospheric chemistry can be answered, including the synergy between climate change and atmospheric composition. The primary challenge lies in the fact that O_3 is both a natural and a man-made component of the lower atmosphere (as opposed to the stratosphere, where ozone is produced only naturally). In order to make this separation, ozone precursors such as CO, NO_2, and Volatile Organic Compounds (VOCs) must also be measured.

Existing LEO missions have only recently collected sufficient data to derive trends of these precursor gases in the troposphere over heavily polluted areas. Measuring trends of these gases provide indications of effectiveness of regulations as well as validating models which couple tropospheric gases and climate. A good example of this capability is shown in Figure 6.

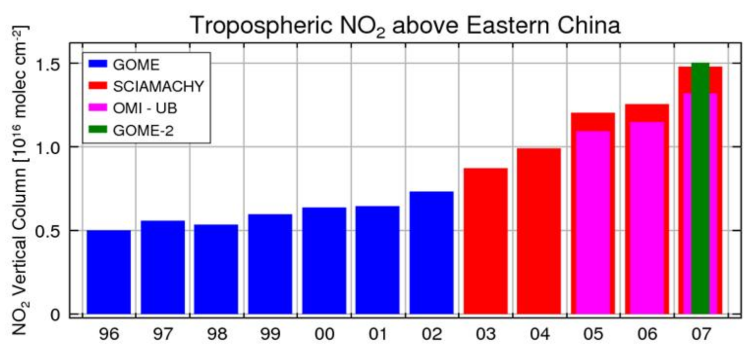


Figure 6. High industrial pollution over Eastern China can be detected from space for model validation and regulation compliance. (Richter et al., 2005)[10]

Ozone and most precursor gases are very short-lived and have a strong diurnal component demonstrating that their formation and destruction happen locally depending on various conditions such as emissions, sunlight, and the presence of other chemically active gases. However, the processes by which formation occurs are still not completely understood.

5.2.1 Diurnal Measurements

At present, northern hemisphere background concentrations of O_3 often reach and exceed levels that impact human health and the terrestrial environment, raising concerns about the global effects of the pollutant. Impacts of O_3 inside the planetary boundary layer on human health are associated with short-term acute effects on the respiratory system, chronic disease and death. High levels of ozone also impact agricultural productivity. Tropospheric measurements with high temporal frequency from Geostationary Earth Orbit (GEO) will revolutionize our understanding of the rapid and complex processes that transform and transport air pollutants and precursors. This information is critical for both air quality and climate policy. Diurnal measurements should provide the temporal (hourly) and spatial resolution (~10 km) to better quantify the mechanisms by which O_3 is formed on regional scales before becoming a component of the global system. In addition to ozone diurnal observations will better quantify the sources of chemical agents causing climate change, particularly those involving natural processes that may be affected by human activity (forcings) or respond to climate change (feedbacks). Detailed justifications for diurnal measurements are well documented in the Sentinel 4 and 5 Mission Requirements Document[13] and NASA's Decadal Survey[14] GEO-CAPE mission and its subsequent workshop report (http://geo-cape.larc.nasa.gov/documents.html. As shown in the mission summary table below, atmospheric composition measurements from GEO orbit begin no earlier than 2012 (more likely 2015 or later due funding limitations) with the majority of those missions flown by China (whose capabilities are uncertain). Global coverage from GEO will require a minimum of three simultaneous satellites orbiting over different longitudes.

5.3 Ground Based Measurements

In-situ, (ground, balloon, and aircraft based) including remote sensing, measurements of atmospheric composition play a key role in the System of Systems. Data are collected from ground based networks such as the NDACC, GAW, SHADOZ and AERONET. Their measurements have been essential in establishing baseline data for numerous atmospheric constituents. The ground measurements provide long term records for trend analysis and therefore highly complementary to the satellite measurements. Aircraft and balloons add a third dimension to this system and can collect high horizontal and vertical resolution data that provides information into processes that are often immeasurable from satellites. Ground, balloon and aircraft measurements are essential for satellite validation but require a rigorous calibration and maintenance program to yield high quality data. In some cases, particularly for the troposphere, new or upgraded instruments are needed. The ground networks are primarily located over land, and therefore have limited global coverage. Aircraft measurements are limited by their deployment location and their endurance in flight. Ground based measurements have limited capability for getting a global view of atmospheric composition variability, but remain essential for validating satellite data.

5.4 Requirements and Gap Analysis (R&GA)

An Atmospheric Composition Constellation (ACC) Gap Analysis Study was conducted by the Rutherford Appleton Lab and funded by the CEOS in 2008. The objectives of the study were to collect atmospheric composition observational requirements, summarize the capabilities of current and planned satellite missions, and then compare those requirements to the current and planned observations to identify potential gaps. The results of these analyses were first presented at the 3rd ACC Workshop. Further details and the complete report (127 pages) can be found on the CEOS website.[1] The following discussion summarizes the approach and results of the study.

Observational Requirements: The requirements were taken from three broad groups covering the United States (NASA, NRC), European (ESA, EUMETSAT) and International agencies (CEOS) and programs (GCOS, IGACO). The requirements documents can be found in Section 7 (References 11 to 20). The requirements were reviewed and distilled into three application areas: Stratospheric Ozone, Composition-Climate Interactions, and Air Quality. Minimum "threshold" requirements were summarized for several altitude domains (three each within the troposphere and stratosphere), resolution (horizontal and vertical), revisit time, accuracy, coverage and stability. The data was summarized in tables for each species or parameter type (H_2O, O_3, CH_4, HNO_3, N_2O, CO, CO_2, ClO, BrO, HCl, NO_2, N_2O_5, SO_2, HDO, SF_6, CH_2O, PAN, VOCs, Aerosol and Clouds). Overall, it was found there was good consistency among the various programs with most differences attributed to variations in research versus operations needs. It should also be noted that atmospheric composition requirements from NOAA, China and Japan were not included in this study but are likely to be a subset of those distilled in this analysis.

Current and Planned Mission Summary: Missions targeting atmospheric composition have been in orbit over the last four decades. The study considered 17 current and 33 planned missions. Additional missions were added to the list after the completion of the study to yield 22 current and 40 planned missions (Table 1). Instruments on each mission were classified into 9 types, including 5 nadir (Infrared, Ultraviolet, Lidar, Polarimeter, Imager) and 4 limb (Infrared, Ultraviolet, Microwave, Occultation) types. The contribution of each measurement type was defined as significant (meets many or all requirements), partial (meets some requirements), or none (does not meet any requirements). These classifications were rather "subjective" but meant to capture the typical performance of an instrument type for measuring a given atmospheric parameter.

Gap Analyses: The observational requirements for each species or parameter were compared with the current and planned instruments and measurements to determine gaps. These gaps are defined as either a missing measurement in time (science or operational) or the inability to meet a requirement (atmospheric region, resolution, revisit rate). In the most severe cases, it was determined that no missions were planned for the measurement of a key parameter (time gap). In the less severe cases, there were limitations in the measurements that partially met requirements. For example, limb sounding measurements provide good vertical resolution (atmospheric structure) but lack horizontal spatial coverage. The following tables (2, 3, and 4) summarize the mission plans and gaps for the measurement of ozone and aerosols.

Existing Missions			
Mission Name	**Agency**	**Instruments**	**Launch**
ERS-2	ESA	GOME-1, ATSR-2	1995
NOAA-15 (NOAA-K)	NOAA	AVHRR-3, HIRS-3	1998
OceanSat1	ISRO	OCM	1999
Terra	NASA	MOPITT, MODIS	2000
Odin	CNES	SMR, OSIRIS	2001
NOAA-16 (NOAA-L)	NOAA	AVHRR-3, SBUV-2, HIRS-3	2001
ENVISAT	ESA	SCIAMACHY, MIPAS, AATSR, GOMOS, MERIS	2002
MSG-1 (Meteosat-8)	EUMETSAT	SEVIRI	2002
Aqua	NASA	AIRS, MODIS	2002
NOAA-17 (NOAA-M)	NOAA	AVHRR-3, SBUV-2, HIRS-3	2002
SCISAT	CSA	ACE, MAESTRO	2003
ICESAT-1	NASA	GLAS	2003
PARASOL	CNES	Polder	2004
Aura	NASA	MLS, OMI, TES, HIRDLS	2004
NOAA-18 (NOAA-N)	NOAA	AVHRR-3, SBUV-2, HIRS-4	2005
MSG-2 (Meteosat-9)	EUMETSAT	SEVIRI	2005
CALIPSO	NASA	CALIOP-Lidar	2006
Metop-A (Metop-1)	EUMETSAT	GOME-2, IASI, AVHRR-3	2006
FY-3A	CMA	VIRR, IRAS, TOU/SBUS	2008
Meteor-M N1	Russia	MSU-MR	2008
GoSAT	JAXA	TANSO-FTS, TANSO-CAI	2009
NOAA-19 (NOAA-N')	NOAA	AVHRR-3, SBUV-2, HIRS-4	2009
Planned Missions			
Mission Name	**Agency**	**Instruments**	**Launch**
FY-3B	CMA	VIRR, IRAS, TOU/SBUS	2009
FY-3C	CMA	VIRR, IRAS, TOU/SBUS	2009
GLORY	NASA	APS	2009
Meteor-M N2	Russia	MSU-MR	2009
ADM-Aeolus	ESA	ALADIN	2010
NPP / NPOESS	NASA	OMPS, VIIRS, CrIS	2010
FY-3D	CMA	VIRR, IRAS, TOU/SBUS	2010
Chinook	CSA	SWIFT	2011
Metop-B (Metop-2)	EUMETSAT	GOME-2, IASI, AVHRR-3	2011
MSG-3 (Meteosat-10)	EUMETSAT	SEVIRI	2011
ISTAG	MAPI	ISRO	2011
Sentinel-3	ESA	OCLI	2012
FY-3E	CMA	VIRR, IRAS, TOU/SBUS	2012
FY-3F	CMA	VIRR, IRAS, TOU/SBUS	2012
FY-4 O/A	CMA	MCSI, LM	2012
ALTIUS	Belgium	Nadir and Limb Sensors	2013
EarthCARE	ESA-JAXA	ATLID, MSI	2013
MSG-4 (Meteosat-11)	EUMETSAT	SEVIRI	2013
GCOM-C	JAXA	SGLI	2013
ASCENDS	NASA	Lidar	2013
ACE	NASA	Lidar, Polarimeter, UVN Spec	2013
NPOESS-C1	NOAA	OMPS (no limb), VIIRS, APS,CrIS	2013
Sentinel-5 (Precursor)	ESA	UVN Spec	2014
GOES-S	NOAA	ABI	2014
GOES-R	NOAA	ABI	2015
Metop-C (Metop-3)	EUMETSAT	GOME-2, IASI, AVHRR-3	2015
FY-4 O/B	CMA	MCSI, LM	2015
FY-4 O/C	CMA	MCSI, LM	2015
ICESAT-2	NASA	GLAS	2015
PREMIER	ESA-SSC	IMIPAS, STEAM-R	2016
GEO-CAPE	NASA	UVN Spec, IR Spec	2016
FY-3G	CMA	VIRR, IRAS, TOU/SBUS	2016
NPOESS-C2	NOAA	VIIRS, CrIS	2016
Sentinel-4	ESA	IR Spec, UVN Spec	2017
GACM-1	NASA	UVN, IR, MW Limb Spectrometers	2017
NPOESS-C3	NOAA	VIIRS (no OMPS currently),CrIS	2018
FY-4 O/D	CMA	MCSI, LM	2019
FY-4 O/E	CMA	MCSI, LM	2019
NPOESS-C4	NOAA	VIIRS, CrIS	2020
Sentinel-5 (Post-EPS)	ESA	Nadir UV-Vis Spec, Nadir IR Sounder, Limb IR	2020

Table 1. The final gap analysis considered 22 current and 40 planned missions spanning 25 years of launch dates (at the time of this document).

Total Ozone Column Measurements

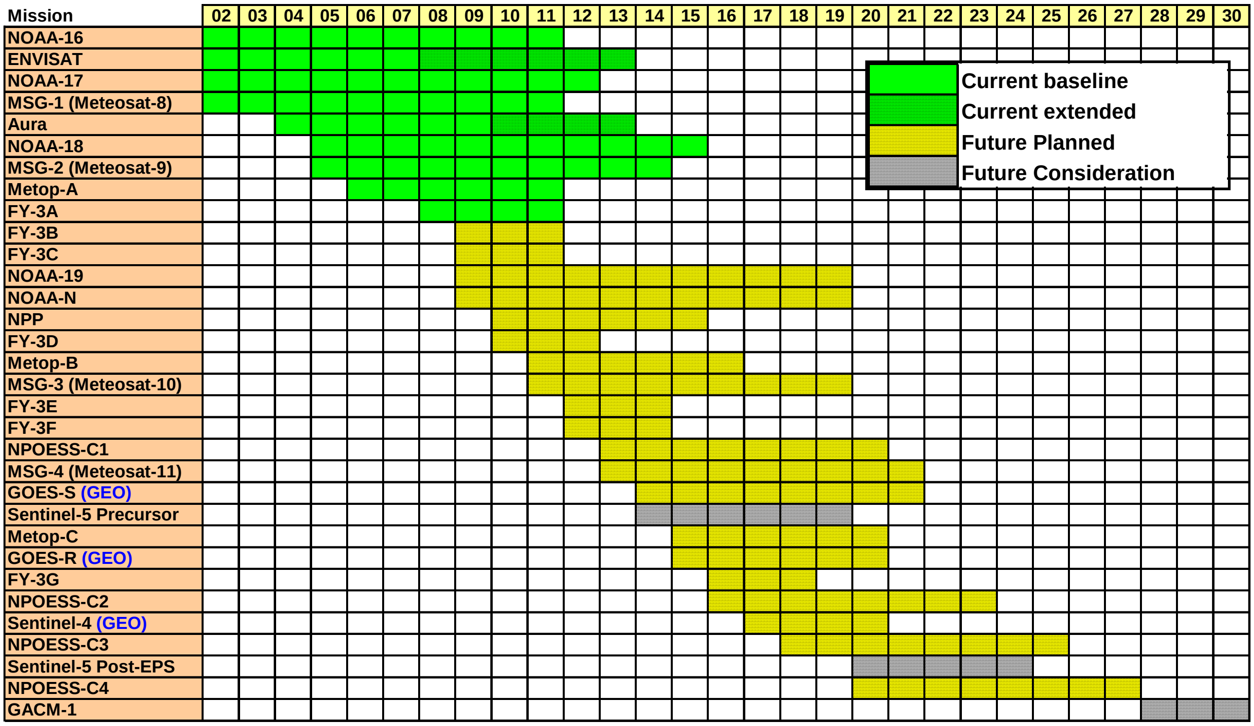


Table 2. There are no gaps in total ozone column measurements due to a large number of operational missions (NOAA, China, and EUMETSAT) though consistency among data sets is still a challenge.

High-Resolution Ozone Vertical Profiles

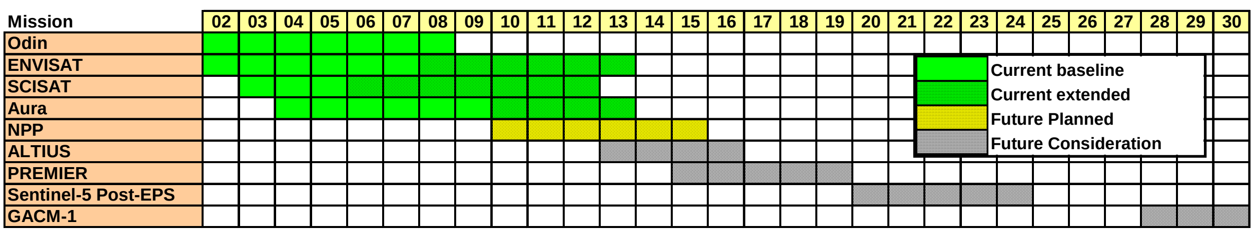
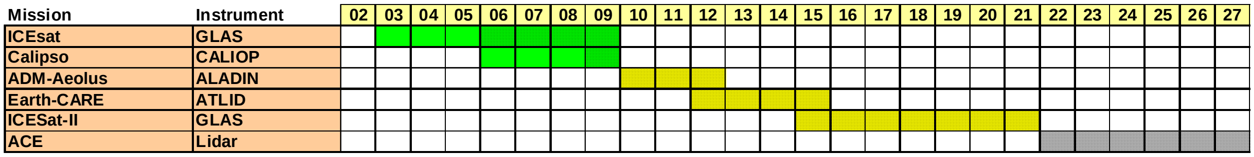


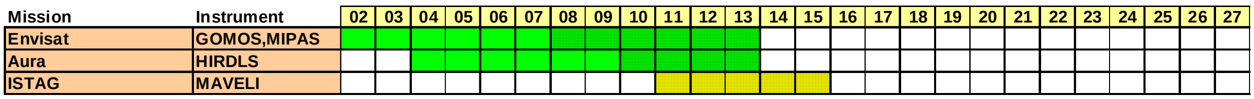
Table 3. Few missions are planned for high vertical resolution ozone measurements and trace gas profiling (via limb or occultation) beyond 2013. Limited redundancy exists due to instrument differences and measured constituents. This gap limits continued evaluation of ozone recovery (Montreal Protocol). Uncertainty exists with future missions since ALTIUS is a proposed concept from Belgium, PREMIER is in competition with two other missions, Sentinel-5, Post-EPS, limb profiling has not been approved, and GACM-1 may be delayed due to limited NASA funding for DS missions.

Aerosol Measurements (Lidar, Limb Spectrometers, Polarimeters)

Lidar Instruments



Limb Spectrometers



Polarimeters

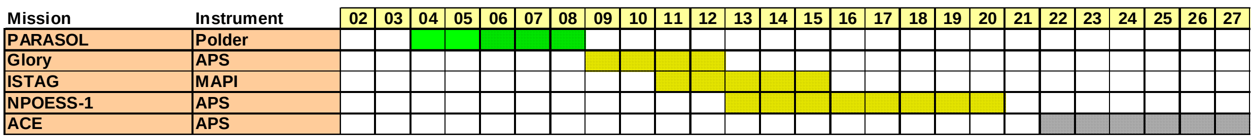
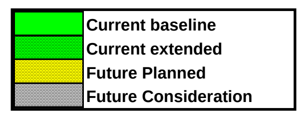


Table 4. Aerosols are the largest uncertainty in climate models. Very few lidar measurements and no limb spectrometers (beyond 2015) are planned for aerosol science which will limit information on vertical extent and transport of aerosols. There are very few polarimeter measurements with a potential gap before the ACE mission near 2020. ACE may be delayed due to limited NASA funding for DS missions. A lack of polarimeters will limit information on aerosol microphysics and optical properties.



In addition to the measurement types above, aerosols are also measured by nadir imagers and spectrometers to determine overall presence and optical depth. There are currently 15 imagers in orbit with 20 more planned for launch through 2022. There are currently 7 spectrometers in orbit with 8 more planned for launch through 2026. These nadir measurements provide sufficient global coverage and redundancy well into the future.

GEO-Stationary Measurements

Geostationary orbits provide a unique vantage for viewing the Earth. Although GEO meteorological satellites have been in service for decades, there have been no measurements of atmospheric composition to date (Table 5). Though there appears to be sufficient overlap of GEO measurements beyond 2015, the differences in orbit position and instrument capabilities are significant. China's FY-4 missions are located over the eastern hemisphere (105-deg east) and utilize an experimental instrument and may measure column NO_2. NOAA's GOES missions are located over the western hemisphere (135-deg west) and are focused primarily on operational meteorology with measurements of aerosol total column but no measurements of gases. NASA's GEO-CAPE mission will be located over the eastern U.S. (80-deg west) and focused on air pollution forecasting and transport using measurements of aerosols, O_3 CO, HCHO, SO_2 and NO_2. ESA's Sentinel-4 mission will be located over Europe (~0-deg) and will have similar capabilities.

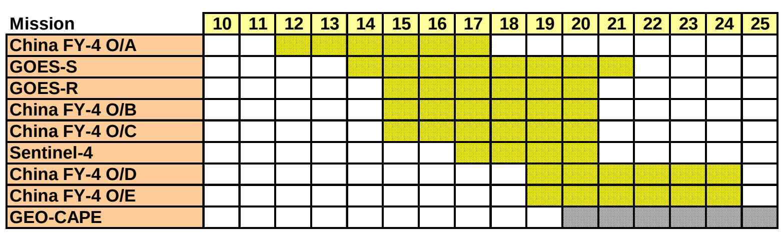


Table 5. No GEO-Stationary missions are planned for atmospheric composition until 2012. Due to differences in their orbit location and measurements capabilities, these missions should not be considered redundant and make very different contributions to global atmospheric composition measurements.

The advantages of observations from GEO were reviewed in Section 5.2.1. Global coverage can be achieved with three GEO missions spaced 180 degrees in longitude. Ideally global GEO coverage with LEO missions providing vertical profiles via limb measurements would result in a comprehensive constellation for atmospheric composition measurements.

5.5 Modeling Challenges and Data Needs

The question of how well chemistry-climate models represent physical, chemical, and dynamical processes in the atmosphere is crucial for successful predictions. The first test is to determine their ability to reproduce variability and past trends. Predictions using an ensemble of models can then be compared to test their basic physics and assumptions. Models from various institutions are being tested under the auspices of the WMO/UNEP Assessments, SPARC, and IGAC.

5.5.1 Stratosphere-Climate Interactions

The primary modeling tool for the study of stratosphere-climate interactions is chemistry-climate models (CCMs), which are IPCC-class climate models augmented with interactive ozone chemistry. Stratospheric ozone is a highly dynamic greenhouse gas which is shaped by the atmospheric circulation, and needs to be specified consistently and interactively with a changing circulation in order to have a reliable simulation of climate. CCMs can be used not only to study the impact of climate and climate change on ozone depletion and recovery but also the role of ozone changes with climate change. CCM simulations of the past and future evolution of climate and stratospheric ozone under the combined forcings of greenhouse gas increases, the past rise and decline of ozone-depleting substances, and natural variability, have now become a critical source of information for the WMO/UNEP Stratospheric Ozone Assessments (mandated by the Montreal Protocol) and were also used by the IPCC AR4. They are expected to play a much more prominent role in future IPCC reports as the climate modeling community moves toward more inclusive Earth System Models.

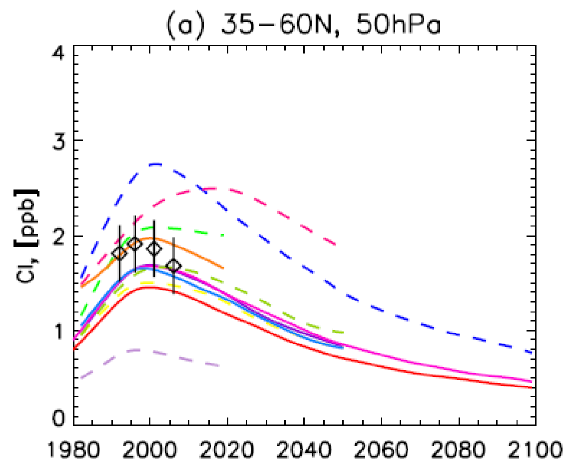


Figure 7. Time evolution of annual mean inorganic chlorine (Cly) at 50 hPa averaged between 35°-60°N for various CCMs, smoothed in time, together with space-borne observational estimates (black symbols). From Eyring et al. (2007).[15]

The Parties to the Montreal Protocol required that CCMs determine both the attribution of past ozone changes and the prediction of future changes, including an understanding of the sensitivity of the latter to the forcing scenarios used. Atmospheric composition measurements are critical for model validation, in terms of both processes and the ability of models to reproduce past behavior (within natural variability). The relevant species include not only ozone but also chemical species affecting ozone (e.g. Cl_y, NO_y, H_2O), as well as tracers of stratospheric transport (e.g. CH_4, N_2O, H_2O). Figure 7 shows the time evolution of Cl_y (where HCl discussed above is one component) in the mid-latitude lower stratosphere predicted by various CCMs. The models all predict a decrease in the future, but there is a wide range of modeled values, far beyond what is consistent with observations. Continued observations of Cl_y are needed to test the accuracy of the model predictions, since Cl_y is the major factor controlling ozone recovery. Stratospheric Cl_y cannot be inferred from measurements of the tropospheric source gases, because of the possibility of an accelerated Brewer-Dobson circulation (predicted by virtually all CCMs) changing the fractional release of chlorine. Without direct observations of Cl_y, the uncertainties on the CCM predictions of ozone recovery will be unacceptably large.

As discussed above with reference to Figure 5, stratospheric water vapor has exhibited large, unexplained variations over decadal timescales, and it is currently impossible to infer a long-term trend in stratospheric water vapor from measurements. CCM predictions of long-term water vapor trends vary widely, even in the sign of the trend, but most CCMs predict a gradual increase (Eyring, V. et al., 2007)[15]. Because of the importance of water vapor trends for both ozone chemistry and stratospheric cooling, it is essential to test the model predictions against data, which requires continued measurements of water vapor profiles.

The predicted acceleration of the Brewer-Dobson circulation mentioned above, if true, will have significant implications for ozone changes in the lower stratosphere which results in further climate feedback (Figure 2). Figure 8 shows the long-term changes in ozone resulting from climate change predicted by the GEOSCCM, and is typical of results from other model calculations. There is a decrease in the tropical lower stratosphere and an increase in the mid-latitude lowermost stratosphere, especially in the northern hemisphere, which reflects the strengthened Brewer-Dobson circulation. These changes are very different in character from those associated with ozone recovery due to the Montreal Protocol and Amendments. If true, they need to be confirmed by measurements both for policy purposes and to validate predictions of climate change. It can be noted that the predicted changes occur over rather small vertical scales (a few km).

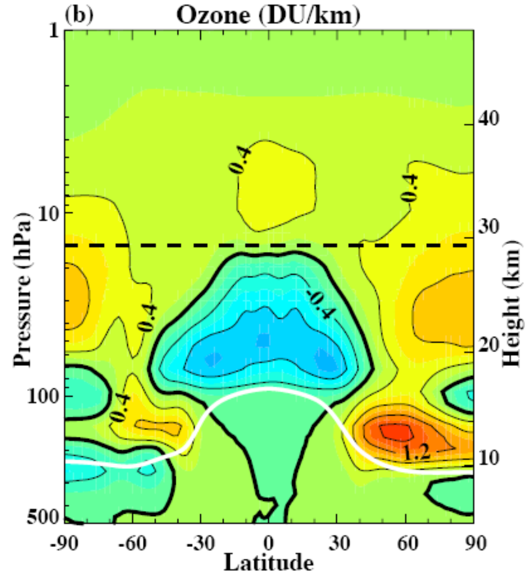


Figure 8. Predicted change in annual mean ozone (in DU/km) between 1975-1984 and 2060-2069, which can be mainly attributed to climate change because chlorine loading is small during both these periods. From Li et al. (2008) [16].

The long-term changes in Cl_y, H_2O and O_3 discussed above all require accurate measurements with 1-2 km vertical resolution, because of the vertical scale of either the predicted changes or the basic spatial distribution of the constituent, or both. Such vertical resolution can only be achieved with limb-sounding measurements. The required accuracy could be achieved either with a small number of accurate measurements, or with a large number of less-accurate measurements. The first of these options is provided by solar occulation. While solar occultation produces very limited spatio-temporal sampling, its ability to accurately quantify long-term changes, especially of long-lived species, is clear from the existing SAGE and HALOE records. Limb emission or scatter instruments can provide nearly equal accuracy but have near global coverage. Because many of the expected changes will occur in the lowermost stratosphere (because of the strengthened Brewer-Dobson circulation), the accuracy and high vertical resolution of the measurements in this region need to be established. This is demonstrated for the ACE-FTS in Figure 9, where correlations between two different species are used to reduce the effects of geophysical variability and obtain what is essentially an ‘instantaneous climatology’. The ACE-FTS measurements (black) are compared with in-situ aircraft measurements (red) and are found to be in very good agreement, demonstrating the high accuracy and vertical resolution of the ACE-FTS measurements. Note that the two data sets were obtained during different years, showing that such a diagnostic is representative of the long-term climatology and can thus be used to identify long-term trends.

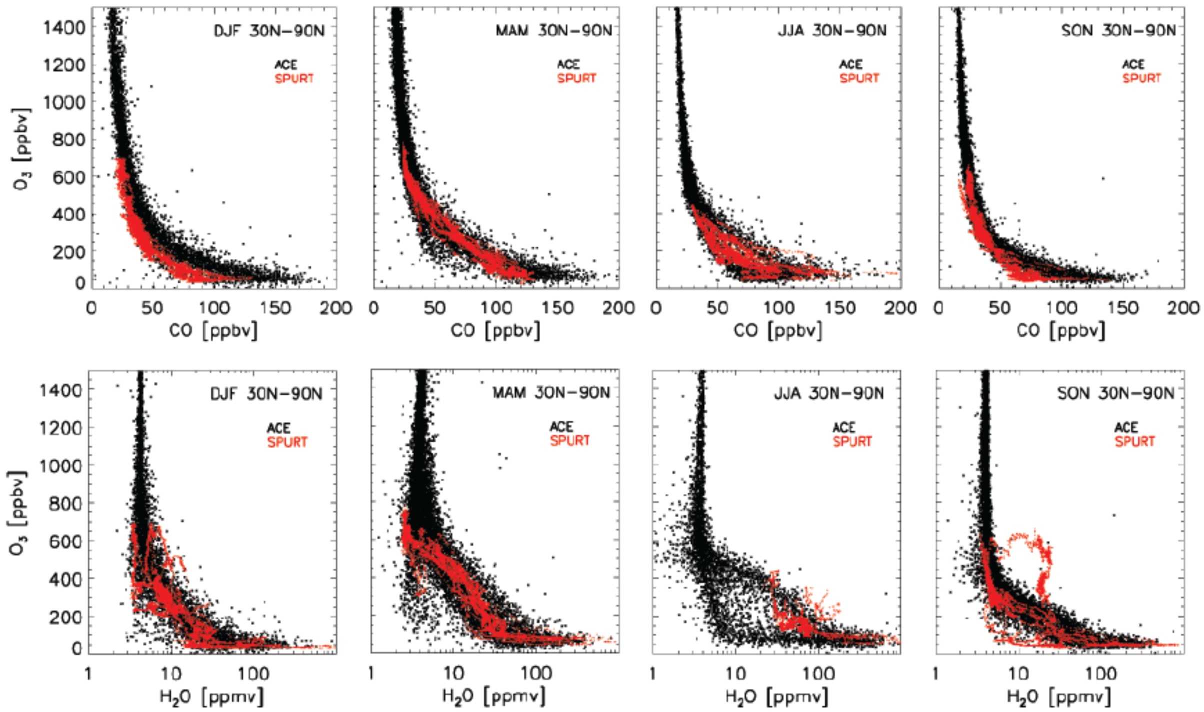


Figure 9. CO-O_3 (upper panels) and H_2O-O_3 correlations (lower panels) for ACE-FTS satellite (black) and SPURT aircraft (red) data between 30°N and 90°N. From left to right: winter, spring, summer, and autumn measurements (Hegglin, M.I., et al.[17] (2008).

5.5.2 AQ-Climate Interactions

Tropospheric ozone and aerosols are both regulated as criteria pollutants for air quality (AQ) and active in radiative forcing (RF) of climate. Ozone is produced by the oxidation of CO and hydrocarbons in the presence of reactive nitrogen oxides that result primarily from combustion. Aerosols enter the atmosphere both directly (e.g., sea salt and dust) and through formation from gaseous precursors (e.g., sulfate, nitrate, ammonia). Tropospheric composition, or air quality, is a complex mixture resulting from the convolution of emissions with photochemistry and meteorology (including clouds and precipitation). Because of this complexity and the inherently high temporal and spatial variability, modeling and prediction of air quality remains challenging, therefore satellite observations offer significant promise to resolving these complexities. Polar orbiting satellite instruments have provided daily observations of total column O_3 and aerosol optical thickness and also of important precursors including CO, NO_2, and HCHO. To date, only limited geostationary observations have been available, consisting of fire and aerosol products from the NOAA GOES and EUMETSAT Meteosat Second Generation (MSG).

The most recent IPCC Assessment[2] summarizes anthropogenic radiative forcing estimates (1750-2005) for tropospheric ozone and aerosols (direct and indirect combined) as +0.35 and -1.2 Wm^{-2}, respectively. The uncertainties in these estimates, approximately a factor of two, are large compared with other forcing agents. Levy[18] et al. (2008) show that these so-called short-lived air pollutants can become a globally significant component of future climate change in the latter half of the 21st century while earlier in the century the contributions from different components largely offset each other. Such estimates are critically dependent on current emissions and projected emission scenarios. Shindell[19] et al. (2008) show estimates of air quality and radiative forcing changes in response to prescribed regional emission reduction targets across North America and Asia. Another aspect is the feedback of climate change onto AQ. Jacob[20] et al. (2009) demonstrate the impact of physical climate change (changes in temperature, winds, and the hydrological cycle) on AQ. Also, biomass burning is a large and variable source of aerosol and O_3 precursors. Climate-related changes associated with drought and species migration (Soja[21] et al.) will change locations and intensities of fires, thereby changing emission amounts and injection altitudes.

Accurate knowledge of precursor emission amounts is fundamental for modeling and prediction of tropospheric O_3 and aerosol concentrations and associated radiative forcings. A powerful use of satellite observations is to provide constraints on uncertain, variable, and changing (whether due to climate change or policy implementation) emission amounts. One example shown in Figure 10 demonstrates the impact on surface O_3 of regulated power plant NO_x emission reductions in the central US. Satellite observations provided both verification of policy-directed reductions of large point source emissions and a timely means of adjusting the standard US EPA emission inventories used in AQ model prediction. Another recent example shows how satellite observations of formaldehyde can be combined with model analyses to better constrain uncertain isoprene emissions (Millet[22] et al., 2008). Such relationships will enable prediction of biogenic emission changes due to climate-induced vegetation changes. Space observations throughout the diurnal cycle would significantly advance knowledge of the currently uncertain role of biogenics in the production of O_3 and secondary organic aerosol.

A recent report issued by the Royal Society[23] (2008) summarizes the growing impact of widespread ozone pollution on both human health and vegetation, especially in the Northern Hemisphere. The report points out that it is the ubiquitous nature of the increasing background that is most damaging to the environment and to various ecosystems. Damage to living matter is a function of exposure, which is a product of the length of time multiplied by the concentration. Thus, GEO and a possible drifting LEO satellite will provide much better information for determining exposure with sufficient spatial and temporal resolution. As discussed earlier in this report, a constellation (minimum of three around the globe) of GEO platforms would provide the observing capability necessary for enabling the use of chemical transport models to discriminate locally produced versus global background contributions to regional air quality. Because of the sensitivity of RF to the vertical location of aerosols and O_3, it is also important to complement these observations with continued high-vertical-resolution measurements of O_3 and aerosols in the upper troposphere from polar orbiters. As with other climate data records, long term monitoring will be necessary for verification of emission reduction and mitigation strategies. Monitoring will also provide the data for disentangling the inter-related and often opposing interactions between emissions, AQ, and climate.

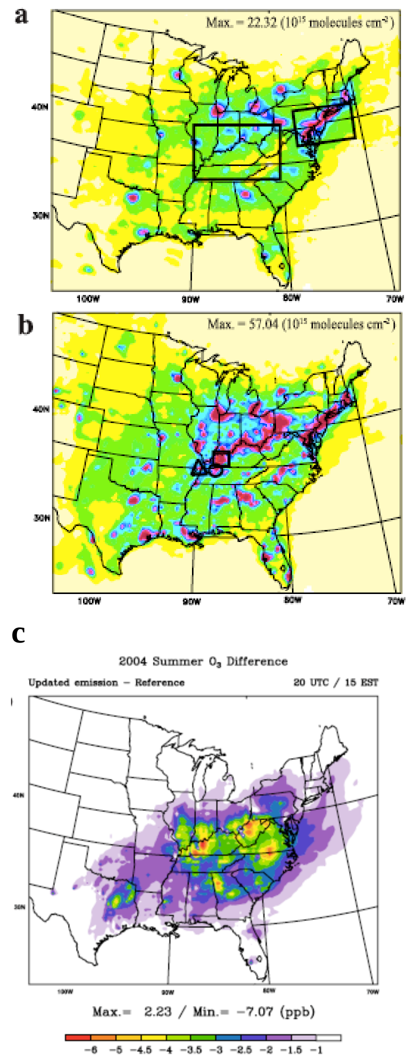


Figure 10. Spatial distribution of tropospheric NO2 columns time averaged over June–August 2004 from (a) SCIAMACHY satellite observations and (b) WRF-Chem reference emission case runs based on the US EPA 1999 National Emissions Inventory. (c) Change in WRF-Chem predicted O_3 resulting from updated power plant NOx emissions (Kim et al., 2006)[24]

6.0 Workshop Outcomes and Summary

The Workshop focused on the development of long term data sets and the requirements for climate predictions. Discussions on requirements were consistent with those established by the ESA CAPACITY (Composition of the Atmosphere: Progress to Applications in the user CommunITY) Study[25], the EUMETSAT Post-EPS Atmospheric Chemistry Position Paper[26], and the Integrated Global Atmospheric Chemistry Observations (IGACO) theme report [27]. Also included were NASA existing missions requirements in NASA's Science Plan 2007-2016[28], and the National Academy's NRC report[14]. The primary focus was on Stratospheric Ozone and Chemistry and Climate coupling. Other areas discussed included Air Quality, Aerosols and Greenhouse Gases. The two and a half day discussions ended with a panel review of the topics discussed and formulated the following conclusions. The Workshop Recommendations are listed in Section 2 above.

Stratospheric Ozone and Montreal Protocol Monitoring: This was one of main topics of the Workshop. In addition to total column measurements, high vertical resolution ozone profiles from the upper troposphere to the upper stratosphere are needed to support continued evaluation of ozone recovery and the impact of regulatory controls on ozone depleting substances. It was determined that gaps in future limb profiling and occultation measurements will limit continued assessments and attribution of ozone recovery in the future. NASA and NOAA have Congressional mandates through the Clean Air Act and Amendments to monitor and conduct research on the stratosphere and ozone depletion to understand the impact of the Montreal Protocol and its amendments.

Ozone Chemistry and Climate: This was one of main topics of the workshops and will be important in IPCC 2013. A continuous balance of nadir measurements (broad coverage and concentrations) and high vertical resolution profile measurements of radiatively and chemically active trace gases are needed to improve chemistry/climate models particularly in the upper troposphere and lower stratosphere. The objective is to understand the attribution of ozone change to climate versus chlorine changes and the attribution of radiative gases to climate such as water vapor. It was determined that gaps in future limb profiling and occultation measurements will limit this assessment. Even in the absence of gaps, the lack of overlaps from on mission to the next could result in serious problems. Ideally the over lap should be two years.

Air Quality/Upper Troposphere: This topic area was discussed during the workshop with the focus on climate. This will be the primary topic in a future ACC workshop in 2009. Tropospheric composition effects of air quality on climate require the measurement of key species in the near-surface boundary layer and free troposphere. Limb measurements partially satisfy these requirements, but geosynchronous missions are also needed for higher temporal sampling to support forecasting and study long term effects of pollution events. It was determined that gaps in limb profile missions and delays in GEO mission plans will impact advancements needed to determine the impact on Air Quality and Climate forecasts and assessments.

Aerosols: This topic area was briefly discussed during the workshop because of the limited scope of the workshop due to time. Climate models need improved measurements of aerosol properties (type, size, shape, scattering, absorption, optical depth) and abundance (horizontal location, vertical profiles) to reduce large modeling uncertainties. This requires a variety of measurements such as nadir imagers/spectrometers, limb spectrometers, lidars, and polarimeters. Further analysis of aerosol requirements and measurement plans is needed to assess potential measurement gaps. This will be pursued by the ACC in the future.

Greenhouse Gases (GHG): These measurements from space were briefly discussed during the workshop. GHGs are the largest contribution to radiative forcing and are critical components of the carbon cycle. The GOSAT (and OCO) missions will result in pioneering data on the sources and sinks of atmospheric carbon. JAXA plans to propose an International Committee on Global Greenhouse Gases – ICGGG) within the coming year.

7.0 References

[1] CEOS Website: http://www.ceos.org . Select the "Atmospheric Composition" link under the "Constellations Menu" on the main page. The resulting "ACC Menu" included links for "Members", "Meetings", "Documents", and "Projects".

[2] Climate Change 2007 - The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report (AR4) of the IPCC (Chapter 2)

[3] IPCC/TEAP, 2005 Cambridge University Press, UK. pp 478, IPCC Special Reports Safeguarding the Ozone Layer and the Global Climate System Chapter 1

[4] U.S. Climate Change Science Program (US-CCSP) Synthesis and Assessment Product 2.4, November 2008. Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure

[5] UNEP/OzL.Pro.WG.1/27/3 United Nations Environment Programme 22 February 2008, Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer Twenty-seventh meeting Nairobi, Synthesis Report, 4–7 June 2007

[6] WMO/UNEP assessment, Scientific Assessment of Ozone Depletion: 2006, Released Feb 2007 (Chapter 5)

[7] Forster, P. and K. Shine (1997), Radiative forcing and temperature trends from stratospheric ozone changes, *J. Geophys. Res*, *102*(D9), 10841-10855.

[8] Fussen, D. et al., "The ALTIUS Project: a Belgian Atmospheric Limb Sounder Aboard a Micro-Satellite Platform", Physicalia Mag. 30 (2008), 239-259.

[9] Lary, D. J. et al. (2007), Variations in stratospheric inorganic chlorine between 1991 and 2006, *GRL, 34*(21).

[10] Lary, D. J. and O. Aulov (2008), Space-based measurements of HCl: Intercomparison and historical context, *J. Geophys. Res. – Atmospheres*, *113*(D15).

[11] Rosenlof, K. and G. C. Reid (2008), Trends in the temperature and water vapor content of the tropical lower stratosphere: Sea surface connection, *J. Geophys. Res*., *113*(D06)107, doi:10.1029/2007JD009109.

[12] Richter, A. et al. (2005), Increase in tropospheric nitrogen dioxide over China observed from space, *Nature*, 437.

[13] "Sentinel 4 & 5 Mission Requirements Document", April 2007.

[14] National Academies' National Research Council, "Earth Science and Applications from Space - National Imperatives for the Next Decade and Beyond", 2007.

[15] Eyring, V. et al. (2007), Multi-model projections of stratospheric ozone in the 21st century, *J. Geophys. Res., 112*(D16)303, doi:10.1029/2006JD008332.

[16] Li, F., R. S. Stolarski, and P. A. Newman (2008), *Atmos. Chem. Phys. Discuss*., *8*, 20223-20237, SRef-ID: 1680-7375/acpd/2008-8-20223.

[17] Hegglin, M. I. et al. (2008), Validation of ACE-FTS satellite data in the upper troposphere/lower stratosphere (UTLS) using non-coincident measurements, *Atmos. Chem. Phys.*, *8*, 1483–1499.

[18] Levy II, H. et al. (2008), Strong sensitivity of late 21st century climate to projected changes in short-lived air pollutants, *J. Geophys. Res,. 113*(D06)102, doi:10.1029/2007JD009176.

[19] Shindell et al. (2008),Climate forcing and air quality change due to regional emissions reductions by economic sector, *Atmos. Chem. Phys.*, *8*, 7101–7113.

[20] Jacob, D. and D. Winner (2009), Effect of climate change on air quality, *Atmos. Env.*, *43*, 51-63.

[21] Soja, A. J. et al. (2007), Climate-induced boreal forest change: predictions versus current observations, *Science Direct: Global and Planetary Change*, *56*, 274-296.

[22] Millet et al. (2008), Spatial distribution of isoprene emissions from North America derived from formaldehyde column measurements by the OMI satellite sensor, *J. Geophys. Res.*, *113*(D02)307, doi:10.1029/2007JD008950.

[23] Royal Society (2008), Ground-level ozone in the 21st century: Future trends, impacts and policy implications, RS Policy Document 15/08, The Royal Society, London, 132 pp.

[24] Kim et al. (2006), Satellite-observed U.S. power plant NOx emission reductions and their impact on air quality, *Geophys. Res. Let.*, *33*, doi:10.1029/2006GL027749.

[25] CAPACITY – "Composition of the Atmosphere: Progress to Applications in the user Community, Operational Atmospheric Chemistry Monitoring Missions", October 2005.

[26] "Position Paper on Post-EPS Atmospheric Chemistry Data User Requirements for Operational Atmospheric Chemistry Monitoring in the Post-EPS Time Frame beyond 2020", March 2006 and "Post-EPS Mission Requirements Document", January 2007.

[27] "The Changing Atmosphere, an Integrated Global Atmospheric Chemistry Observation Theme for the IGOS Partnership", September 2004.

[28] "Science Plan for NASA's Science Mission Directorate 2007-2016".

8.0 Acknowledgements

The editors acknowledge the major contributions to this report by T. Shepherd, M. Heglin, J.A. Al-Saadi, B. Killough, and E. Hilsenrath. The thoughtful comments by the meeting attendees are also acknowledged. Members of the GISS staff who organized the Workshop are greatly appreciated.

9.0 Appendices

9.1 Minutes of Workshop

CEOS Atmospheric Composition Constellation (ACC) 3rd Workshop
October 15-17, 2008
New York City (Hosted by GISS)

Presentations can be found at the new CEOS website: http://www.ceos.org
Menu selection: Constellations Menu, ACC-Atmospheric Composition; ACC Menu, Meetings

Day 1 – October 15, 2008

Presentation Agenda

ACC Overview and Workshop Objectives	Ernest Hilsenrath/NASA HQ
Using Satellite Data on Atmos. Composition to Understand Climate Change	Drew Shindell/GISS
Current Issues in stratospheric processes and role in climate	Marvin Geller/SUNY
SPARC Overview and Data needs	Ted Shepherd/Univ of Toronto
SPARC CCMVal and Data Initiative	Darryn Waugh/Johns Hopkins Univ
NASA Program for Climate Data Records	Martha Maiden/NASA HQ
Long term Aerosol Records using Deep Blue Algorithm	Christina Hsu/GSFC
Aerosol Trends in the Stratosphere	Steve Massie/NCAR
Long term stratospheric aerosol data sets	Christine Bingen/BIRA-IASB
Aerosol and Tropospheric Ozone Trends	Richard Siddans/RAL
Global Aerosol Climatology Project	Brian Cairns/GISS
A Multi-sensor Water Vapor Climate Data Record Using Cloud Classification	Eric Fetzer/JPL
Continuation of Trends in Stratospheric Water Vapor and Ozone	Karen Rosenlof/NOAA
Global Ozone Chemistry and Related Trace Gas Data	Lucien Froidevaux/JPL
Stratospheric and Tropospheric Trace Gas Trends from Solar Abs. Spectra	Curtis Rinsland/LaRC
Long-term Monitoring of Tropospheric Composition	Mark Weber/U of Bremen
Bro and HCHO Data sets	/BIRA-IASB
Trends and variability in tropospheric constituents	Folkert Boersma/KNMI

Discussion highlights

- Hilsenrath – Discussed the objectives of the workshop and the expected outcomes. He gave an overview the Atmospheric Composition Constellation (ACC) objectives and implementation. This Workshop is one of several projects supported by ACC, which up until this time have focused on applications. Workshop objectives are to establish priorities for future missions and measurements needed for atmospheric chemistry climate interactions based on identified gaps and justification that impact climate models. The concept of gap is broadly defined, and includes missing constituents, a break in a time series, lack of sufficient in time series, insufficient coverage or insufficient sampling rate. The goal was to deliver a report to CEOS in the early March 2009
- Shindell - Keynote presentation, highlighting the use of observations to provide confidence in radiative forcing estimates and in the climate response, including feedbacks involving constituents such as H2O, CO2, CH4, and O3. The importance of long-term data records was illustrated using observations of total solar irradiance. This talk also provided a broad outline for reduction of uncertainties in climate simulations; many questions remain concerning the direct and indirect effects of aerosols, which is the largest uncertainty in the models. Some other topical highlights included: merging of measurements made with different sensors is not trivial, and overlap in time is critical; vertical resolved measurements are critical to understand current discrepancies between measurements and model results; measurements of long lived species are very important for sensitivity studies (not only trend analysis); global tropospheric ozone measurements are needed to force models in a consistent way. Products derived from total column measurements have residual left from stratosphere; comparisons of measurements of single species with models may lead to ambiguous results, whereas multi-species measurements are needed to study processes and understand discrepancies; the problem of larger error bars on

forcing by aerosols remain as it was several years ago. When asked about the climate temporal sampling requirements (GCOS-3hr, GMES-12hr), he was uncertain about how these requirements will impact modeling uncertainty, but this topic might be further explored in the future. He also noted that there are not only gaps in the future, but also gaps in the past and suggested the community must determine how to concert their effort to fill these in.

- Geller - The stratosphere is an essential part of climate models which requires long term measurements. The next IPCC (2013) will benefit from an improved understanding of the stratosphere (need to measure in the stratosphere in order to get the troposphere right). This talk was the first of many that pointed out the coming lack of vertical profile measurements of stratospheric constituents. One common element of the response of CCMs to climate change is an increase in tropical upwelling. It is not clear what observations will show if this predicted change in circulation is actually occurring.
- Shepherd - SPARC (Stratospheric Processes and their Role in Climate). Extremely concerned about looming future lack of vertical profile measurements of stratospheric composition. There was a discussion about the continuity of people for stratospheric science measurements (Specifically, there is no group of core people actively involved with and concerned primarily with profiling. Someone mentioned that Jack Kaye is funding a group, but long-term continuity is needed).
- Waugh - Summarized current efforts in the SPARC sponsored activity to use observations for process oriented evaluation of chemistry climate models (CCMVal). Diagnostics that have been selected in the past several years are found on the CCMVal web site. Application of these diagnostics to the various models is a key element of an upcoming SPARC report and will provide a framework for interpretation of the predictions that will be part of the next WMO ozone assessment. The initial requirement is for monthly climatologies. There is also a desire for a single website for ACC data sets.
- Maiden - Presentation centered on MEaSUREs program ($15M, 29 projects). The challenges to development of climate records using information from different instruments appeared often in the workshop. It is important to maintain information not just about the data record, but of the calibration and validation work that underlies the data record and is specific to each instrument (to ensure joined datasets can be trusted… and some of that needs to happen at the research side, i.e., Jack Kaye's program).
- Hsu - Reported on efforts to develop long term aerosol records. The obstacles to developing a representative climatological record are significant. The local variability is high, and temporal sampling must be frequent to develop a representative monthly mean. Monthly AOT is problematic to modelers because of the different sampling rate and measurement times. This variability must be taken into account in comparing data sets. Aerosols are short-lived so there is a high spatial and temporal variability, making global distribution important (accomplished via space measurements). The new MODIS Deep Blue algorithm can better retrieve dust over desert so the picture is more complete from source to sink. Angstrom exponent is important to distinguish the coarse (dust has low angstrom exponent) from fine (pollution has high angstrom exponent). Single scattering albedo is also important because not all dust is the same (regional variation). AOT is not enough… need aerosol properties to derive direct forcing. Data assimilation is the only way we can merge satellite data into a central framework that will help with this sampling issue. NPP VIIRS is the best data we could have to extend beyond the MODIS era.
- Massie - Reported on trends in stratospheric sulfate aerosols. Recommendation to fill in gaps with ancillary data or have instrumentation that measure at a wavelength that will not saturate during a major sulfate eruption. The modeling community is concerned with surface area density... satellite vs. in situ agreement is better at higher volume densities. Models use mainly thermodynamic info to identify PSCs, but modeling needs more accurate description of PSC microphysics. A catalog of PSC SAD would be useful with multiple satellite analyses.
- Bingen - Reported on long-term stratospheric aerosol data sets. Measurement gaps of vertical gas profiles were noted for 2013-2016, which is consistent with the RAL gap analysis report. All current missions (ODIN, Envisat, ACE, Aura) are extended. There are a few measurements from 2016-2019 but very small profiling capability. While occultation is best for aerosols, limb scattering are promising. Need continuous aerosol measurement capabilities and complementarity between in situ measurements and extinction measurements from space with high vertical resolution and global coverage. Need to improve data accessibility from space agencies and maintain existing access to older data. Discussed ALTIUS project: limb sensor using imaging technique (under development). Also discussed MOSTRA model and PROMOTE database project.
- Siddans - Reported on an effort called GlobAerosol to develop a unified aerosol data set from four instruments (ATSR-2, AATSR, MERIS, and MSG-SEVIRI) by using the same microphysical model to fit radiance from

each. An animation for a long time period showed seasonal and El Nino characteristics but no secular trends. Need a post Aura/Envisat limb sounder

- Cairns - Reported on the Global Aerosol Climatology Project. The issues with this project were exemplified by the finding that at the pixel level MODIS and MISR Angstrom exponents are anticorrelated (opposite seasonal cycle). This certainly suggests that trends are poorly characterized.
- Fetzer - Proposed an important question for remote measurements of water vapor in the upper troposphere. Since H2O is measured only in 'cloud free' conditions, are the measurements representative. The hypothesis is that the H2O variability within cloud classes is much less than the variability between cloud classes.
- Rosenlof - Reported on an effort to develop a zonal average time series appropriate as input to models. The variability in stratospheric ozone is significant, as use of 'real' variability in the stratosphere improves simulations of the troposphere. Since use of a realistic time-varying data set for stratospheric ozone is demonstrated to be important to producing a realistic simulation for the troposphere in long integrations, this could be a reason to maintain a profiling capability for measurements of stratospheric ozone. Lacking satellite measurements at the poles.
- Froidevaux - Reported on an effort to produce global climatologies of ozone and trace gases related to ozone as part of NASA's MEASURES program. Need efficiency in providing/obtaining data records from fewer sources (not different data sets from different people).
- Rinsland - Provided a long presentation on discoveries from ATMOS and the benefits of the Canadian ACE instrument.
- Weber – Presented the challenges of obtaining trends in tropospheric trace gases due in part to the dependence of the retrieval on a priori assumptions. Aerosol loading, surface albedo, cloud cover and profile shape all affect signals. These must be dealt with in addition to normal issues when a data set includes information from different instruments and different calibrations. The need for vertically resolved measurements were discussed for trend analysis and that there is a potential gap on those measurements (limb sensors are not in the plans). Ozone is needed but other constituents are also needed for studying climate.
- Boersma - Continued the discussion of the issues of application of a statistical model to obtaining trends in tropospheric constituents. There have been small decreases in the NO2 observed in China, perhaps due to new efforts to apply pollution controls to poser plants. The different causes for trends in NO2 were also considered. If the NO2 source is primarily traffic, then diurnal dependence will reflect traffic patterns, with peaks in the sources early and late in the day. If the NO2 source is primarily biomass burning, the peak occurs nearer to midday. Such behavior is needed to interpret differences in NO2 observed by SCIAMACHY (morning equator crossing) and OMI (early afternoon equator crossing).
- Errera/Van Roosendael - Reported on efforts to interpret observations of polar BrO and impact on stratospheric ozone and HCHO impacts in the troposphere from UV/VIS measurements using the various CTM model. Trends will require careful calibrations among the various instruments

Day 2 – October 16, 2008

Presentation Agenda

Past and Future Trace gas observations	C. Clerbaux/CNRS
NOAA AC Programs and International collaboration	L. Flynn/NOAA
CSA AC Programs and Missions	S. Melo/CSA
Aerosols and Climate and Proposed Cooperation on GHGs	M. Mukai/JAXA
Proposed ESA Climate Program	C. Zehner/ESA
Global Climate Observing System	G. Braathen/WMO
Challenges in measuring trends from satellite data	P.K. Bhartia/GSFC
ACC Project - NO2 Diurnal variations	S. Kondragunta/NOAA
ACC Project - Smoke Dust Predictions	J. Al-Saadi/LaRC
ACC Project - Aviation Hazard Avoidance	C. Zehner/ESA
Requirements and Gap Analysis for AC and Climate	B. KilloughLaRC
Ozone and Trace Gas Trends	E. Remsberg/LaRC
Ozone Trends	M. Weber/U. of Bremen
Creating a Long Term Multi-Sensor Ozone Data Record	R. McPeters/GSFC
Ozone Time Series from European Satellites	D. Loyola/DLR
UV and Radiation trends	A. Lindfors

Surface and Atmospheric Reflectivity Since 1979	J. Herman/GSFC
Chemical Data Assimilation of UARS and Envisat data	Q. Errera/IASB
Dealing with Missing data in the Stratosphere	S. Tegtmeier/U. of Toronto
Evaluation of UT/LS in CCMs using ACE-FTS data	M. Hegglin/U of Toronto

Discussion highlights

- Clerbaux - Reported on observations from IASI, comparing with MOPITT, AIRS and TES, all of which provide information about tropospheric CO. TES has somewhat better spectral resolution than IASI, but IASI has far superior signal to noise. There are plans to launch future IASI instruments. For tropospheric measurements there is always the issue of the influence of the a priori on the retrieved quantity and how best to interpret the limited information available from this sort of measurement.
- Flynn - Reported on future measurements for ozone. The OMPS platform will include a limb measurement on NPP, but not on later platforms. Flynn emphasized the need to account for drifts in orbits and changing equator crossing time when developing a unified long record for ozone observations, since the dependence on the time of day of each measurement is significant. China has launched their FY-3 satellite that has SBUV and TOMS type instrument, and NOAA is collaborating with developing retrieved quantities. Discussed the push for the CrIS instrument to make detailed CO measurements. Currently CO is measured, but the downlinked data does not have the detailed information needed for the retrievals.
- Melo - Reported on efforts of the Canadian Space Agency, including missions presently in operation (MOPIT, OSIRIS/ODIN, SciSat, CloudSAT) for which CSA has been at least in active collaboration. A MOPITT II is in development, with a plan to improve horizontal resolution. SciSat is presently observational, and measurements will continue to March 2009 and perhaps beyond if the instrument maintains its present performance. There were several comments about the ACE instrument on SCISAT and the importance of its data to the ACC community. The Chinook mission is under review and its payload may be redefined. However, the CSA continues investments in further development of the SWIFT instrument. New mission concepts under study – APOCC (Atmospheric Processes of Climate and its Change), MCAP, MEOS, STEP, SOAR (ACE follow-on), TICFIRE. After community review, it is likely there will be one selected.
- Mukai - Reported on proposed plans from JAXA to develop a platform including an FTS and a cloud aerosol imager.
- Zehner – Jan 2009 will be the selection time for the Earth Explorer missions (6 under consideration). ESA plans to pick one mission. Nov 2008 is the decision for a gap-filling mission (Sentinel-5 Precursor) to branch ENVISAT to Posts-EPS Sentinel-5. New initiative by ESA for Climate Change with a total proposed budget of 250 MEuro (6 years).
- Braathen – GAW data center for satellite atmospheric composition data sets is funded by DLR (Bitner) and planned for Aug 09. This is part of the WDC-RSAT (World Data Center for Remote Sensing of the Atmosphere). WMO produces a GHG bulletin with the next release planned for Nov 08.
- Bhartia - Outlined lessons learned from years of experience obtaining trends from Ozone satellite data. The problems in producing the long data record using observations from several sources have been technical and intellectual. The three main areas include sampling, calibration and algorithm. The UV measurements of ozone rely on backscatter, and thus only take place on the sunlit portion of the globe. Drifting orbits pose their own issues. The TOMS instrument cannot provide accurate column measurements at high solar zenith angles. There are various ways to combine and extend the data to global coverage, and the choice depends on the application. After discussing the issues that concern instrument calibration and the choices that can be made, Bhartia pointed out that the algorithm that is best for daily maps is not necessarily the best algorithm for long term trends. Algorithms tend to eliminate random errors which affect maps but not time series analysis. The long term changes could depend on the a priori, and if there is a time dependence in the climatological mean, there could be false time dependence in the derived trend if such effects are not accounted for. Bhartia supported the concept that there should be a few well instrumented ground stations that will assist in developing and maintaining the long data sets.
- Flynn for Kondragunta – Presented an effort to understand diurnal variation in NO2 using data from OMI and GOME-2. There are real differences in slant column that impact the retrieval. One approach to understanding instrument differences is to make use of the fact that OMI and GOME provide coincident measurements at high latitude (74N), and comparisons of data at this latitude focus on differences in the instruments by eliminating differences in viewing conditions.
- Al-Saadi – Presented modeling the transport of smoke and dust which is a current ACC project.

- Zehner – Presented data indicating the cost of encounters of aircraft with volcanic clouds. The volcanic plume cannot be seen at night or in the presence of natural clouds, and is not visible on radar. The only solution for aircraft safety is to avoid the plume. ESA is financing a project to develop a dedicated service for Volcanic Ash Advisory Centres worldwide by including also NOAA activities (budget of 500K Euro, 3 years duration).
- Killough – Presented results from the preliminary gap analysis report. The goal of this analysis is to identify any high priority measurements that are missing from the plans when the plans of various space agencies are considered together. Three topic areas are considered separately (ozone, chemistry/climate interactions, and air quality monitoring and forecasting). It is an action item for the ACC group to review documentation and give feedback on this process by Nov 30. Responses will be used to update the report by January 31 in preparation for the GCOS meeting in February and the CEOS SIT-23 meeting in March 2009. At that time, ACC will make a set of justified recommendations to the CEOS agency leaders.
- Remsberg - Reported on trends that are obtained from the long record of the HALOE instrument on UARS. Solar effects calculated from three long data records (HALOE, SBUV, SAGE) do not agree with each other.
- Weber - Discussed ozone trends in the changing climate. Trends in the lower stratospheric ozone are influenced by the ozone hole and chemical processes but also by changes in stratospheric dynamics. Ozone profiles of higher resolution than can be obtained from a nadir measurement are identified as an important element of future observing strategies. Several outstanding issues were identified: determining the cause of decadal variation in the planetary and gravity waves that force polar temperatures and vortex strength; quantitative determination of the bromine budget and the role of very short lived substances; solar effects and errors due to attempting to obtain solar sensitivity from short data records. There was also a discussion of the ALTIUS instrument (possible 2012 launch) from Belgium for high resolution measurements of gap species. This mission would be launched on ESA Proba satellite.
- McPeters - Reported on ozone and trace gas trends. Important things to consider when developing a data record using observations from several instruments include instrument effects, calibration, and the need for overlap among instruments to have confidence in the continuing series. A drifting orbit (the norm for past SBUV instruments) can put diurnal and tidal effects that may be interpreted as a trend into a merged data set. There are several merged data sets for total ozone, and these are in good shape. The profiles pose more difficult problems.
- Loyola - Presented results for a merged ozone time series from GOME, SCIAMACHY and GOME-2. Some ad hoc corrections, a latitudinal correction that uses polynomials and a time dependent correction were required to develop this product.
- Lindfors - Described difficulties in obtaining trends in ultraviolet radiation. Spatial and temporal coverage are limited, and serious efforts to obtain trend quality ground measurements did not start until 1990. A procedure of ‘UV reconstruction’ takes into account sunshine, total O3, and pyranometer measurements. A goal of this effort is to understand the atmosphere of the past.
- Herman - Described trends in reflectivity since 1979. For example, in the Hudson bay area, the reflectivity shows that the high latitude winter has become shorter because the incidences of high reflectivity that would indicate the presence of ice have are less frequent. Some wavelengths are insensitive to latitude, season and land surface, and the change in reflectivity can provide information about changes in cloud cover. There are many issues with high latitude reflectivity – field of view, terrain shadow, clouds and haze. Production of a climate data record for reflectivity is a work in progress.
- Errera – Presented a report on chemical data assimilation
- Tegmeier - Reported on an effort to deal with missing data based on persistence of winter anomalies. Although this effort shows promise scientifically for interpretation of observations and also as a test for model realism, it is not likely to be useful for filling gaps in the observation record.
- Hegglin - Reported on evaluation of the UT/LS in CCMs using data from the ACE instrument on SCISAT. This work stresses the importance of using a vertical coordinate that is with respect to the tropopause to make sense of sparse observations and compare the behavior of tracers measured by ACE with measurements from aircraft and simulations from climate models.

Day 3 – October 17, 2008

Presentation Agenda

Modeling the stratospheric contribution to tropospheric composition changes and climate	D. Rind/GISS
Trends in Trace Gases and the Impact of Gaps	A. Douglass/GSFC
Trace Gas Modeling and Assimilation for the GMES/Kopernikus	J. Kaiser/ECMWF
Confronting Coupled Climate-chemistry Models with Data	A. Gettelman/NCAR

Discussion highlights

- Rind - Spoke on experience with the GISS model, emphasizing the need to develop observational requirements that would tell how changes in dynamics impact composition change. All CCM simulations show a decrease in mean age of stratospheric air in the future atmosphere. Requirements to test whether this speed up in the circulation is actually happening are unclear. Various other examples of results from the GISS model support his contention that it is important to understand the changes in the atmospheric dynamical state to understand the climate response. Continued measurements of SF6 in the troposphere and stratosphere are needed. Wind measurements in the stratosphere are recommended. One of the challenges we face is to determine the magnitude of solar forcing.
- Douglass - Showed the time series of HCl from HALOE, MLS and ACE to emphasize the importance of overlap in resolving differences among instruments. Results from a CCM were compared with ground based column measurements of HCl and ClONO2. The future lack of an HCl profile measurement would make it difficult to interpret time series from columns as Cly changes. It is important to monitor and understand the changes in Cly that are expected under international agreements. Supported the need for an ACE-FTS follow on.
- Kaiser - Reported on the Kopernikus project, an effort to assimilate constituents. Radiance assimilation is felt to be a superior approach because this eliminates dependence on the a priori. Variational bias correction, using a trusted set of observations, is felt to be an approach for construction of long-term data sets from different instruments.
- Shindell for Gettelman – Presentation on confronting climate models with observations. He is engaged in an effort to develop a community diagnostic tool to evaluate global models using observations. The flexible system (under construction) would facilitate this practice of model evaluation.

Panel Discussion

General Comments

- Discussions focused on two areas: (1) Vertically resolved composition profiles in the upper troposphere and lower/upper stratosphere that are needed for Montreal protocol monitoring (ozone recovery) and connections to climate change, and (2) Better information on the troposphere and how air quality impacts climate and vice-versa.
- Occultation measurements (ACE on SCISAT, ALTIUS and PREMIER) are ideal to address topic (1) above. The Sentinel-5 Precursor mission can address topic (2) above.
- It was agreed that the group would limit the topic of tropospheric air quality to its influence on climate, noting that local or regional air quality forecasts drive a broad set of requirements that will not be considered.
- The ACC will develop a report by Jan 31, 2009 to address 3 areas: stratospheric ozone chemistry, climate chemistry and aerosols, lower tropospheric air quality for climate. The report will include sections for impacts, key requirements (columns, profiles, sampling), mission status for each type of measurement and potential gaps, recommendation to CEOS.
- Aura fuel limitation is 2015, at which time it starts to de-orbit, but slowly. Additional science is still likely even with orbit degradation as long as the instruments are functioning. Stella Melo confirmed that SCISAT could last for many more years, but its continued operation is more dependent on instrument functionality rather than spacecraft constraints.

Stratospheric Ozone Chemistry

- Typical vertical resolutions are: Nadir soundings (~7 km), Limb (~3 km), Occultation (~1 km).
- Residual circulation effects are critical. Age-of-air can help (SF_6, CO_2).
- Vertical measurements (profiles) of ozone in the troposphere is important to climate models.
- Montreal Protocol and ozone recovery studies should be a focus. Age-of-air (SF_6) and Bromine (BrO) and Chlorine (ClO) products are important.
- There must be a balance between occultation (high vertical resolution of key species), limb profiling (improved coverage), nadir sounding (columns). The continuity of measurements must also be considered.
- Priority species are: O_3, H_2O, Chlorine (HCl, ClO). Desired species are: BrO, though this requires a technology advancement. Profiling is needed for each, as nadir in not sufficient.
- Nadir profiles do not give a clean separation of the stratosphere and troposphere.
- Attribution of ozone change (to climate change vs. chlorine change) is a key motivation for profile measurements.
- The total column measurements appear to be in good shape for the future.

Climate Chemistry and Aerosols

- Aerosols have an order of magnitude higher uncertainty in climate models over chemistry constituents. Climate models need improved measurements of aerosol properties (type, size, shape, scattering, absorption, optical depth) and abundance (horizontal location, vertical profiles). This requires a variety of measurements such as nadir sounders, imagers, lasers, and polarimeters. Key missions include Glory, CALIPSO, and EarthCare. In addition, imaging instruments such as MODIS, SEVIRI also make contributions to aerosols.
- The time varying nature and the short tropospheric lifetime for aerosols (in spite of their global significance) is challenging for measurement programs and for global models.
- Column measurements of CO_2, CH_4, and CO are needed for sources and sinks. It is likely OCO and GoSat have this covered well for the near-term.
- Profile measurements (1 km) of O_3, H_2O, NO_x is needed the troposphere.

Air Quality

- Discussions limited to tropospheric composition effects of air quality on climate, distinguishing from air quality forecasting that requires frequent sampling. This might include VOCs and total column measurements.
- There was a particular concern about getting vertical information in the troposphere at least discriminating the BL from the free troposphere needed for long range transport.
- Although there was not a lot of discussion, the participants thought a delay until GEO-CAPE and Sentinel 4 for high temporal air quality sampling was serious.

Workshop Outcomes

"What are the impacts of data gaps on climate modeling"?

Stratospheric Ozone Chemistry – a continuous balance of nadir measurements (broad coverage and concentrations), limb profile measurements (separation of stratosphere and troposphere composition and dynamics), and occultation (high resolution trace species) is required to improve climate models and measure ozone recovery (Montreal Protocol). A primary focus is to understand the attribution of ozone change to climate change vs. chlorine change. Potential gaps in future limb profiling and occultation measurements will limit these advancements.

Carbon Sources and Sinks – Climate models depend on the knowledge of sources and sinks of CO_2, CH_4, and CO. Near-term missions plan to address the column measurement needs (OCO and GoSat). Additional profile measurements are needed by future missions to understand transport and vertical variations within columns.

Aerosols – Climate models need improved measurements of aerosol properties (type, size, shape, scattering, absorption, optical depth) and abundance (horizontal location, vertical profiles). This requires a variety of measurements such as nadir sounders, imagers, lasers, and polarimeters. A detailed analysis of the aerosol measurement plans is needed to assess potential measurement gaps.

Air Quality - Tropospheric composition effects of air quality on climate require the measurement of key species in the near-surface boundary layer and free troposphere. Profiling and occultation partially satisfy these measurement requirements, but geosynchronous missions are needed for higher temporal sampling. Potential gaps in limb profile missions and delays in GEO mission plans will impact advancements in this area.

<u>Workshop Actions</u>

ACTION: SEO/RAL will update the ACC Gap Analysis Report.
(1) Add Metop (IASI), NPOESS (SBUV, HIRS) and NPP (OMPS, CrIS) to the set of missions making O3 measurements for O3-Chemistry and Climate in the gap analysis report.
(2) Add more detail to the gap analysis for aerosols. Summarize the requirements, GEO impacts, model needs, products, missions, instrument types, and potential gaps.
(3) Split the gap analysis summary into profiles and columns to better understand potential gaps.
(4) Summarize the vertical, horizontal, and gas sampling capabilities of each ACC instrument to compare to the requirements. (5) Review the requirements for Climate and Air Quality revisit times to understand their justification. Discuss with GCOS and GMES.
(6) Consider a separation between “threshold” and “target” requirements

ACTION: Clarify the role of ACC in the new JAXA proposed International Committee for GreenHouse Gas observations from Space (ICGGO-Space).

NEXT MEETING: Planned for 2nd quarter 2009 at ESRIN in Frascati, Italy.

9.2 List of Attendees

ACC-3 Workshop at GISS

Name	Email	Organization
Ernest Hilsenrath	ernest.hilsenrath@nasa.gov	NASA HQ, UMBC
Cathy Clerbaux	catherine.clerbaux@aero.jussieu.fr	EUMETSAT
Larry Flynn	Lawrence.E.Flynn@noaa.gov	NOAA
Richard Engelen	Richard.Engelen@ecmwf.int	ECMWF
Stella Melo	Stella.Melo@space.gc.ca	CSA
Claus Zehner	Claus.Zehner@esa.int	ESA
Shobha Kondragunta	Shobha.Kondragunta@noaa.gov	NOAA
Brian Killough	Brian.D.Killough@nasa.gov	NASA LaRC
DeWayne Cecil	ldcecil@usgs.gov	USGS
Kim Keith	kim.e.keith@gmail.com	NASA LaRC
Martha Maiden	martha.e.maiden@nasa.gov	NASA HQ
David Rind	David.H.Rind@nasa.gov	NASA/GISS
Drew Schindell	Drew.T.Shindell@nasa.gov	NASAGISS
Karen Rosenlof	krosenlof@al.noaa.gov	NOAA
Marvin Geller	marvin.geller@sunysb.edu	SUNY
Pawan (P.K.) Bhartia	pawan.k.bhartia@nasa.gov	NASA GSFC
Christina Hsu	Christina.Hsu@nasa.gov	NASA GSFC
Eric Fetzer	Eric.J.Fetzer@jpl.nasa.gov	NASA JPL
Jay Herman	herman@tparty.gsfc.nasa.gov	NASA GSFC
Lucien Froidevaux	Lucien.Froidevaux@jpl.nasa.gov	NASA JPL
Richard McPeters	Richard.D.McPeters@nasa.gov	NASA GSFC
Steve Massie	massie@ucar.edu	NCAR
Geir Braathen	gbraathen@wmo.int	WMO
Mark Weber	mark.weber@iup.physik.uni-bremen.de	Univ. Bremen
Quentin Errera	Quentin.Errera@bira-iasb.oma.be	BIRA-IASB
Diego Loyola	diego.loyola@dlr.de	DLR
Christina Bingen	Christine.Bingen@bira-iasb.oma.be	BIRA-IASB
Theodore Shepherd	tgs@atmosp.physics.utoronto.ca	Univ. of Toronto
Michaela Hegglin	michaela@atmosp.physics.utoronto.ca	Univ. of Toronto
Richard Eckman	Richard.S.Eckman@nasa.gov	NASA
Anne Douglass	anne.r.douglass@nasa.gov	NASA/GSFC
Anders Lindfords	Anders.Lindfors@fmi.fi	FMI
Darryn Waugh	waugh@jhu.edu	JHU
Charles Jackman	Charles.H.Jackman@nasa.gov	NASA/GSFC
Curtis Rinsland	Curtis.P.Rinsland@nasa.gov	NASA/LaRC
Jay Al-Saadi	jessim.a.al-saadi@nasa.gov	NASA/LarC
Makiko Mukai	mikiki.mukai@jaxa.jp	JAXA
Richard Siddans	R.Siddans@rl.ac.uk	RAL
Susann Tegtmeier	susann@atmosp.physics.utoronto.ca	Univ. of Toronto
Brian Cairns	brian.cairns-1@nasa.gov	NASA/GISS