IGAC*tivities*
Newsletter
of the International Global Atmospheric Chemistry Project

A Note From the IGAC Chair: *Guy Brasseur*

Towards Phase II of IGAC

As we near completion of the IGAC integration/synthesis document summarizing ten years of exciting scientific research (to be published in 2002 by Springer-Verlag in the IGBP Book Series), IGAC is now evolving from its first to its second phase. To lead this process, a transition team chaired by Dr. Mary Scholes (South Africa) and Dr. Timothy Bates (USA) has been established. This team will host a workshop in Stockholm, Sweden, at the invitation of IGBP. The purpose of this meeting is to define IGAC's new challenges and scientific priorities for the next ten years. Themes like chemistry/climate interactions and air quality will certainly be on the agenda. Specifically, questions involving aerosol/cloud interactions, chemical/dynamical couplings (especially in the upper troposphere and lower stratosphere), organic (gas-phase and aerosol) chemistry, long-range transport of pollutants and the effect of megacities on global change will be central issues for the future. Ocean-atmosphere couplings will be investigated by the newly created Surface Ocean–Lower Atmosphere Study (SOLAS). Another project addressing the biogeochemical interactions between the continental biosphere and the atmosphere is under discussion within IGBP. Increasingly, integrative approaches will be needed to address global change issues, and these will be tested at the regional level. IGAC will also have to work more closely with other programs. Specifically, as the troposphere cannot be isolated from the stratosphere, IGAC and SPARC will have to find new ways to bring their respective communities together, and perhaps merge many of their activities.

Advancements in remote sensing capabilities will dramatically improve our ability to monitor tropospheric composition during the new phase of IGAC. The three articles in this issue provide an overview of some of what is possible today and what is in store. Jim Drummond describes passive techniques for measuring trace gases, while Ed Browell and colleagues review active (lidar) methods. Finally, Bob Charlson discusses global-scale measurements of aerosols from space and the requirement—applicable just as well to trace gases—to overtly coordinate and integrate these remotely-sensed data with *in situ* data, modeling, and analysis of uncertainties.

Before leaving at the end of 2001 my position of IGAC Chair, I would like to welcome the new IGAC Executive Officer, Peter Czepiel, who is succeeding Alex Pszenny. Peter will be based at the University of New Hampshire and will help IGAC through the transition to its second phase. I would also like to thank Alex and also Edmund Carlevale for their constant help and dedication. Both have managed with enthusiasm our office at MIT in Cambridge, MA for several years. Finally, on behalf of myself and Ron Prinn, the first chair of IGAC, I would like to thank all colleagues who have contributed to IGAC's Activities, and specifically the members of the IGAC Scientific Steering Committee and the Convenors of IGAC Activities, who have made the first phase of IGAC so exciting and so successful for more than a decade.

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SCIENCE FEATURES

The View from Above: Passive sounding of the troposphere from space

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1. Introduction

Space instrumentation offers a unique view of the atmosphere which has some particular strengths and weaknesses. On the one hand, it can offer us a comprehensive view of the entire planet; on the other, that view is infuriatingly incomplete. Much effort has gone into making measurements of atmospheric composition from space, and these have brought great returns in our knowledge of the global system.

In this brief overview, I am inevitably going to omit much information. My apologies for any significant omissions. My aim is to review some of the key developments with an emphasis on the lower troposphere, which is an area of great interest not only to scientists, but also to politicians and the general public.

2. Techniques

Although space-based measurements are extremely powerful, they have considerable limitations occasioned by the viewing situation, the technology, and the satellite orbit. There are two viewing geometries used for lower atmospheric observations: limb view and nadir view (Figure 1). The limb view can be made either in thermal emission, using the atmosphere itself as a source, or in occultation, with the sun or, more rarely, the moon or a star as a source. Similarly, the nadir view can either use surface and atmospheric thermal emission, or the reflection of the sun off of the lowest atmospheric layers.

In limb geometry, the atmospheric path is maximized and therefore the sensitivity is enhanced, but the shallow angle of the path around the "tangent" point—the lowest point altitude point on the path—means that the horizontal resolution is rather poor—on the order of several hundred kilometers. On the other hand, the vertical resolution is quite good, and up to 1 km vertical resolution is possible. Refraction also becomes an issue at low tangent heights, and the probability of a cloud occluding the path becomes higher as the tangent height descends. For these reasons, the limb view is more suitable for observing the upper troposphere and the tropopause region, and can rarely be extended down to the ground.

Although clouds are also a problem for the nadir view, the vertical geometry yields a lower probability of cloud obscuration, and therefore a higher probability of measurement success. The geometry also yields a high horizontal resolution which can be easily tailored to a particular mission, consistent with signal-to-noise and other considerations. On the other hand, the vertical resolution must be achieved by some different technique. Most solar reflection techniques only yield a single layer in the troposphere giving a column measurement. Operating in the infrared region using thermal emission affords some vertical resolution, but this is limited to approximately 3-4 km. Finally, if the atmosphere is transparent to the ground, a necessary condition for sounding the lowest levels of the atmosphere, then the surface and the surface emission is visible. Since Earth's surface is extremely heterogeneous, every measurement using the nadir view must include some means to eliminate this effect from the results.

There appear to be three viable types of instruments for tropospheric sounding: correlation radiometers, visible spectrometers, and infrared spectrometers. Correlation radiometers offer a very targeted measurement with high sensitivity for a restricted range of gases. The technique requires a cell of the sample gas within the instrument to provide a reference. Various modulation techniques are applied to measure the correlation between the reference and the incoming atmospheric radiation. Correlation techniques enable the instrument to achieve good selectivity and high signal-to-noise simultaneously within a fairly robust instrument. In theory, the technique can be applied to any gas which can be contained within a gas cell over a period of time, but in practice it will probably be limited to CO, CH_4, and perhaps some of the nitrogen oxides for the foreseeable future. Two spectrometer types, infrared and visible, are widely used. The visible instruments make use of the large solar signals and use spec-
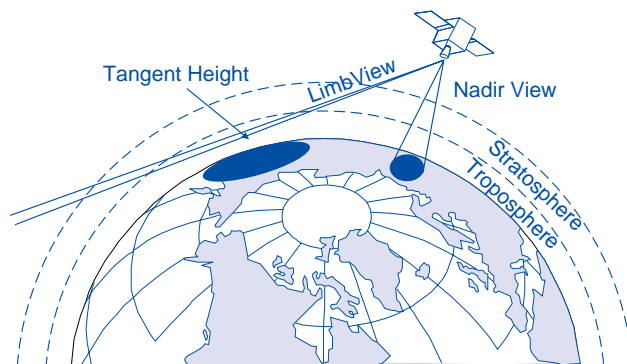

Figure 1. An illustration of the geometry of satellite remote sounding. The two major geometries for satellite remote sensing are the nadir (downward-looking) view, which has good horizontal resolution (represented by the blue circle) but poor vertical resolution, and the limb (sideways-looking) view, which has the reverse—good vertical but poor horizontal resolution.

tral resolution for discrimination of the various gaseous types. Infrared instruments may additionally use thermal emission from the ground and the atmosphere for their signal. As mentioned above, the infrared instruments, spectrometers, and correlation radiometer hold more promise for profile measurements.

3. History

Almost as soon as we could put satellites in space, we started using them for atmospheric research. Radio sounding of the upper atmosphere and television pictures of clouds and cloud motion quickly became a regular part of the space science endeavor. As time progressed, instruments became more advanced and studies of the atmosphere began in earnest.

The middle atmosphere was the first atmospheric region to receive attention. The technologies and scientific understanding necessary for successful measurements were available, and a variety of instrumentation probed the middle atmosphere in order to understand the physics and chemistry of that region.

On the other hand, the lower atmosphere, specifically the troposphere, has been more resistant to examination by space-based methods. The principal reasons for this are that the troposphere has clouds in the upper levels and the surface beneath, both of which present enormous challenges to instrument designers and mission planners. Significant progress in this area has demanded more advanced instrumentation and an improved knowledge of the radiative transfer of the region.

Two developments have put tropospheric sounding on the map: the Measurements of Atmospheric Pollution from Space (MAPS) instrument [Reichle *et al.*, 1986] on the space shuttle, and Jack Fishman's analysis of ozone data [Fishman *et al.*, 1990], both of which contributed new and important information about the troposphere. These studies not only stimulated scientific interest in the troposphere, they also paved the way for the current generations of instruments.

The MAPS instrument was flown three times on the space shuttle: in October 1984, April 1994, and late September 1994. It was a correlation radiometer designed specifically to look at carbon monoxide (CO) in the middle troposphere. In order to increase the reliability of the measurements, a cell of nitrous oxide (N_2O) was included, and by assuming that the N_2O concentration was known and stable, a quality control indicator was developed to identify the good measurements.

The results from the MAPS instrument were extremely significant, providing the first global view of a tropospheric constituent. They provided direct evidence of the influence of biomass burning on the mid-tropospheric CO in low latitudes and the inter-hemispheric gradient in the spring. However, being a shuttle mission, they were necessarily of short duration, and this did not afford enough time to complete even a single global map.

4. The present

The Measurements of Pollution In The Troposphere (MOPITT) instrument was launched on the Terra spacecraft on 18th December 1999. MOPITT was the first instrument devoted solely to measuring tropospheric composition on a free-flying spacecraft. It collected a 14-month data set of CO and CH_4, resolving several levels in the vertical. Using cross-track scanning and a pixel size of 22 x 22 km, it provided a detailed view of the tropospheric CO concentration over the entire globe. In May 2000, a fault in the on-board cooler subsystem somewhat reduced MOPITT's ability to resolve CO concentrations in the vertical, but measurements with reduced vertical resolution are still being made.

MOPITT operates on similar principles to MAPS using correlation radiometry to target specific gases in the troposphere. It increases sensitivity by using cooled detectors and filters to increase considerably the sensitivity to the target gas. The correlation channels operate in the fundamental band of CO at 4.7 µm, and the first overtone band at 2.3 µm. There are also two channels operating in the methane bands at 2.25 µm. The 4.7 µm channels provide CO profiles in both the day and night, but do not have much sensitivity near the ground; the shorter wavelength channels produce column amounts using reflected sunlight and these data are therefore available only during the day.

MOPITT has produced some most intriguing results in the short time since it has been launched. The data are now publicly available at the Langley Distributed Active Archive Center (DAAC) as a "beta" product, which means that the data are still in the process of validation. Figure 2 shows a monthly mean of total column CO for August 2000. MOPITT covers the entire globe in about four days, but due to clouds and other problems, even when averaged over the period of one month, there are still a substantial number of locations where data are not available. Clearly visible are high values of CO over Africa and the western Atlantic, presumably due to entrainment and outflow in the prevailing airstream. There is some evidence of more complex activity in the southern Atlantic. High concentrations are visible over Southeast Asia, and there is a flow northeast out into the western Pacific. The Himalayas, Andes, and Rockies are also visible due to the reduction of CO with surface elevation.

The Global Ozone Monitoring Experiment (GOME) is a nadir-viewing UV / VIS (240-790 nm) spectrometer which was launched in April 1995 aboard the ERS-2 satellite. As the name implies, the principal objective of the GOME instrument is the retrieval of ozone on a global basis, but it has also been able to monitor several other constituents of the troposphere, such as BrO, OClO, SO_2, NO_2, and HCHO. It has a field of view (FOV) of 320 x 80 km; the orbit in combination with an instrument-scanning capability allows the instrument to cover the entire

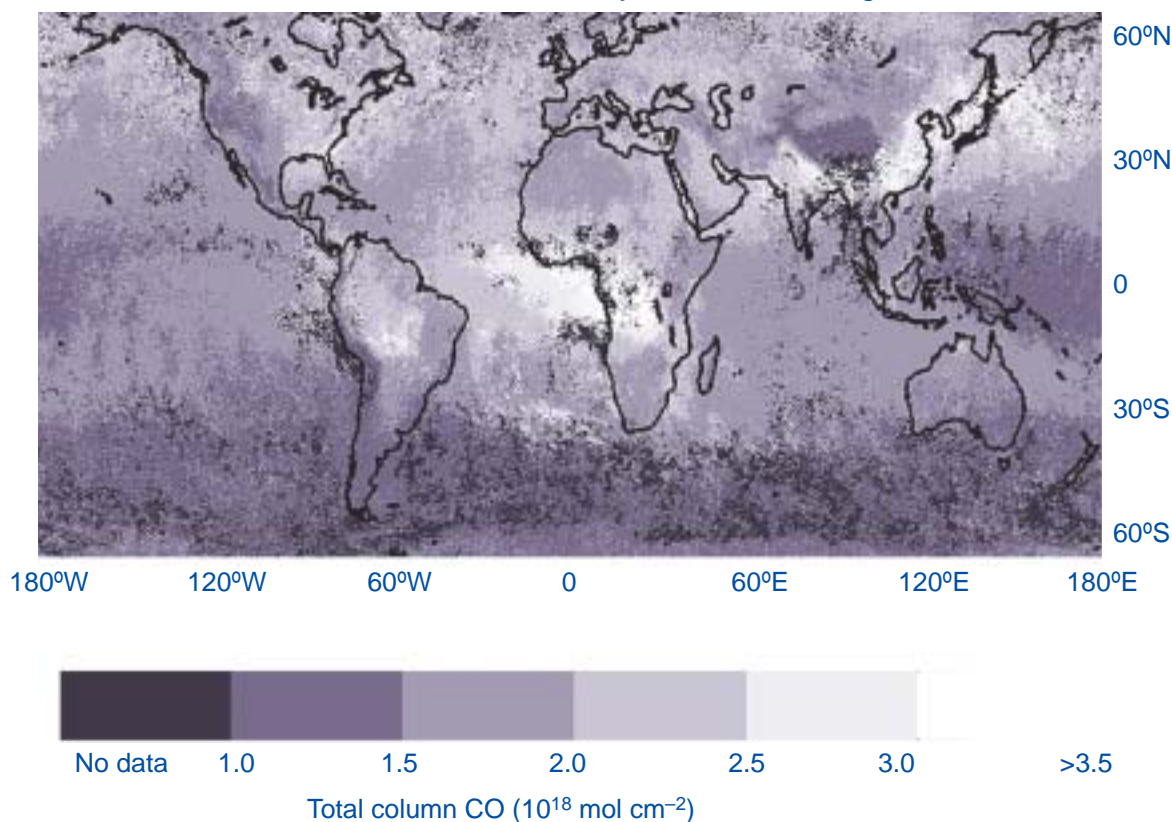## Carbon Monoxide, Monthly Mean, 2000 August

Figure 2. Monthly mean CO concentrations for August 2000 from the MOPITT instrument. The instrument horizontal resolution is 22 x 22 km. In order to effectively display the data, column amounts <1.0 x 10^{18} mol cm^{-2} have been assigned as "no data", and amounts >3.5 x 10^{18} mol cm^{-2} have been assigned to the topmost bin. The combined amount of data reassigned is <2% of the total.

globe every three days. It operates in the short-wave region of the spectrum, using reflected sunlight and therefore only operates during daylight. The results from the GOME experiment have provided an exciting window into the capability of this type of instrumentation, and have set the stage for the successor instruments, SCIAMACHY and GOME-2 discussed below. Figure 3 shows a plot of BrO in the northern hemisphere for March 2001 retrieved from the GOME instrument.

The Interferometric Monitor for Greenhouse Gases (IMG) is a nadir-viewing infrared interferometer 3.3 to 14 µm with a spectral resolution of 0.1 cm^{-1}. It was launched on the Advanced Earth Observing Satellite (ADEOS) "MIDORI" spacecraft, developed and managed by the National Space Development Agency of Japan (NASDA), at 10:53 (JST) August 17, 1996. ADEOS operated for approximately 10 months until June 30, 1997.

5. The future

In the near future a number of instruments will be launched to further probe the lower atmosphere. These instruments will continue to expand the data sets in spatial and temporal resolution, as well as measure new species.

The Scanning Imaging Absorption SpectroMeter for Atmospheric ChartographY (SCIAMACHY) is a successor to the GOME instrument, and will be launched on the European ENVISAT satellite in early 2002. Besides continuing the GOME measurement set, SCIAMACHY will extend the wavelength coverage from GOME up to 2.38 µm, which includes further bands of several constituents, especially the first overtone band of CO. SCIAMACHY will be capable of operating in a number of observing modes, such as limb viewing, solar and lunar occultation, and nadir. The maximum horizontal resolution on the ground in nadir view will be 26 x 15 km, and the vertical resolution in the various limb views will be up to 2.6 km.

The Tropospheric Emission Spectrometer (TES) will fly on NASA's Aura spacecraft in 2003. It is a cooled, infrared Fourier transform spectrometer with a number of observing modes including both limb emission and nadir sounding modes. The wavelength range is 3.2 to 15.4 µm, with a spectral resolution of 0.025 cm^{-1}. The nadir FOV is 0.53 x 5.3 km. The sensitivity of this instrument is sufficient to measure a number of tropospheric constituents, such as O_3, CO, CH_4, HNO_3, NO, NO_2, and H_2O, as well as a number of other constituents as research products.
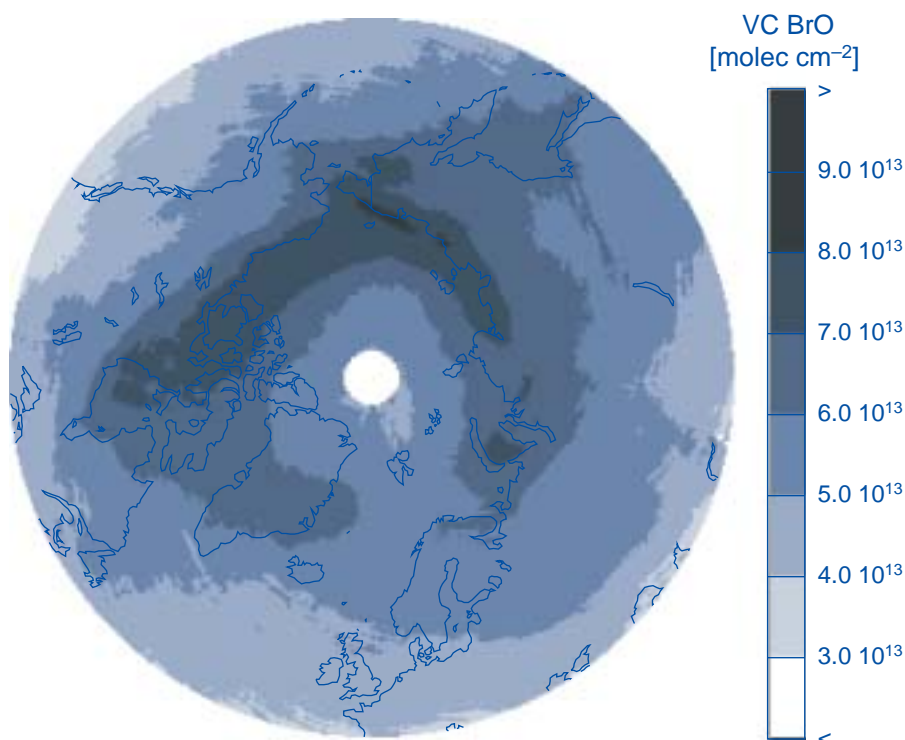
GOME BrO, March 2001

Figure 3. BrO measured from the GOME instrument for March 2001. (Figure courtesy of J. Burrows and the GOME team.)

The Ozone Monitoring Instrument (OMI) will also be launched on NASA's Aura mission in 2003. It is a UV/VIS instrument with a spectral range of 270-500 nm and a resolution of about 1 nm. It is approximately nadir-viewing with a spatial resolution of 13 x 24 km. The data products include O_3, NO_2, SO_2, BrO, and OClO. The combination of scanning and the footprint permits complete global coverage on a daily basis.

The Infrared Atmospheric Sounding Interferometer (IASI) is an interferometer nadir-viewing instrument to be launched on the EUMETSAT Metop series of satellites, the first of which will launched in 2005. The spectral range is 3.6 to 15.5 μm, with a resolution of 0.25 cm⁻¹. The instantaneous FOV at nadir is 12 km in diameter, but the view consists of 4 instantaneous FOVs in an area of 50 x 50 km. Gases to be measured are O_3, CO, CO_2, CH_4, N_2O, and SO_2.

GOME-2 will also be launched on the EUMETSAT Metop series of satellites. It has a spectral range of 0.240 to 0.790 μm and a spectral resolution of 0.2 to 0.4 μm. The pixel size is 40 x 40 km, and complete global coverage is achieved in three days. Like GOME, it will measure concentrations of O_3, NO, NO_2, NO_3, ClO, OClO, BrO, HCHO, and SO_2.

In addition to these specialized instruments, many instruments are focused on the lower stratosphere with the capacity to examine the tropopause region, and then to probe into the troposphere. These are mainly limb-viewing instruments, which will only be able to probe the upper troposphere. These instruments include the HIRDLS instrument on the Aura spacecraft, which operates by limb emission in the infrared, and the FTS and MAESTRO instruments on the Canadian SCISAT-1 satellite, as well as the SAGE III instrument, all of which operate in solar occultation. This is by no means an exhaustive list, and many of the capabilities will need to be honed in practice, but the additional information and species that these instruments contribute will prove to be invaluable.

Looking at the longer term, there are several proposals to place instrumentation on geostationary satellites. The advantage of this placement is that any visible point is observed continuously with high temporal resolution. The disadvantages are that not all places are visible, and Earth is a long distance away, either limiting the amount of energy at the instrument or increasing the size of the telescope, depending upon the requirements. These proposals will take some time to be realized, and it will probably be at least the latter part of this decade before such instruments can be flown.

6. Modeling

Since the data sets acquired from space will be incomplete, some methodology must be adopted to infer the

complete field from the partial fields observed. The measured fields will be biased towards cloud-free areas, and for many instruments towards daylight times only. In many cases, measurements may only be made at specific local times due to the limitations of a sun-synchronous orbit. Finally, the measurement suite will always be incomplete, as many molecules cannot yet be detected from space, and indeed many may permanently elude us.

Data assimilation and similar techniques merge models and data into a synergetic whole, but the results of this process must be treated with caution. The relative weightings of the model and the data must be known and accounted for in any interpretation. The degree to which measurement data contradicts the model-predicted field is an important indicator, which could highlight problems with the instrument, the measurement technique, or the model. I believe that we still have a considerable way to go in understanding how these techniques can be applied effectively on the large scale. However, since tropospheric data sets will always be patchy due to clouds and other problems, and the data field itself may be highly structured on the same scale—for example, the chemistry around clouds is different from the clear air case—the use of models as "smart interpolators" is going to be a necessity, far more than is the case in the stratosphere.

An additional use of this modeling capability is to simulate possible measurement scenarios with proposed instrumentation. This capability enables us to effectively model a satellite mission before it is flown. These studies can help to optimize the way in which data are collected and processed, and thus will make the next generation of space instrumentation even better.

7. Conclusions

We are entering a new era of tropospheric monitoring. If the present and proposed instrumentation performs anywhere near as well as expected, then we can expect to have a much better picture of the troposphere in the very near future. We will have height-resolved ozone and CO over a considerable period of time. We will also have column amounts of some nitrogen compounds, with perhaps some additional height resolution. One of the questions which we will have to answer with the data from these instruments is: To what extent is it desirable to have continuous monitoring of some species over the entire globe, and which species should those be? From a purely instrumental point of view, ozone and CO are the easiest to measure, but they may not offer the greatest return in understanding. Some instrumentation is already being proposed for operational use, but we do not have a great deal of experience with these data sets to know exactly how useful they will be. A great deal more work on both measurement techniques and the merging of models with measurements is required in order to understand this problem.

References

Fishman, J., C.E. Watson, J.C. Larsen, and J.A. Logan, Distribution of Tropospheric Ozone Determined from Satellite Data, *J. Geophys. Res*. **94,** 3599-3617, 1990.

Reichle, Jr., H.G, V.S. Conners, J.A. Holland, W.D. Hypes, H.A. Wallio, J.C. Casas, B.B. Gormsen, M.S. Saylor and W.D. Hesketh, Middle and Upper Tropospheric Carbon Mixing Ratios Measured by a Satellite-Borne Remote Sensor During November 1981, *J. Geophys. Res.*, **91**, 10865-10887, 1986.

Appendix

This is a list of websites associated with the various instruments discussed in the paper:

CALIPSO*	(Not yet available)
GOME	www.iup.physik.uni-bremen.de/gome/
GOME-2	www.eumetsat.de/en/area2/cgms/ap10-18.htm
IASI	www.eumetsat.de/en/area2/cgms/ap10-16.htm
IMG	www.eorc.nasda.go.jp/AtmChem/IMG/
LITE	asd-www.larc.nasa.gov/lite/ASDlite.html
LIDAR	asd-www.larc.nasa.gov/lidar/lidar.html
MAPS	oea.larc.nasa.gov/PAIS/MAPS.html
MOPITT	www.atmosp.physics.utoronto.ca/MOPITT/home.html
OMI	aura.gsfc.nasa.gov/omi/
SCIAMACHY	www.iup.physik.uni-bremen.de/ifepage/SCIA/SCIAMACHY.htm
TES	aura.gsfc.nasa.gov/tes/

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*Formerly PICASSO-CENA

Global studies of ozone, water vapor, and carbon dioxide using active remote sensing

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Introduction

Determining the large-scale variations of ozone (O_3), water vapor (H_2O), and carbon dioxide (CO_2) is important to our understanding of a number of atmospheric processes. For example, measurements of O_3 and H_2O distributions can lead to an improved understanding of the relative role of transport versus photochemistry in the tropospheric O_3 budget. Ozone, H_2O, and CO_2 are important radiatively, and contribute to the radiation budget and climate change. H_2O is influential in many different meteorological processes and in the transport of energy on large-scales. CO_2 is the primary climate forcing gas, and an important component of the carbon cycle. For a better understanding of the atmosphere, it is necessary to study the spatial and temporal variations of these gases over many regions of Earth, and ultimately be able to make measurements of them from space. While some passive measurements of these gases in the troposphere can be made from space, active remote sensing holds the potential of being able to provide direct measurements of their profiles across the troposphere.

The Differential Absorption Lidar (DIAL) technique was developed in the mid-1960s for application to remote profile measurements of various gases. Schotland [1966] was the first to demonstrate this technique in his pioneering ground-based measurements of H_2O profiles using a temperature-tuned ruby laser. This was followed by the demonstration of the DIAL technique for the measurement of nitrogen dioxide (NO_2) in the early 1970s [Rothe *et al.*, 1973; Grant *et al.*, 1974], and sulfur dioxide (SO_2) and O_3 in 1975 [Grant and Hake, 1975]. (See Grant *et al.* [1997] for a collection of key papers in the history of the development of lidar.) Following these early demonstrations, a comprehensive evaluation of the DIAL technique for H_2O profile measurements was conducted with a widely tunable laser operating in the 724-nm spectral region [Browell *et al.*, 1979]. Even in the mid 1970s there was considerable interest in making future H_2O DIAL measurements from space [NASA, 1979; Browell, 1982] and in evolving from a ground-based to airborne DIAL system [Browell *et al.*, 1981; Browell, 1982].

> **Note**: A longer version of this article, including references, is available on the IGAC website: www.igac.unh.edu.

The first airborne DIAL system was flown for O_3 and aerosol investigations in conjunction with the Environmental Protection Agency's Persistent Elevated Pollution Episodes (PEPE) field experiment conducted over the east coast of the U.S. in the summer of 1980 [Browell, 1983; Browell *et al.*, 1983]. This initial system has evolved into the advanced UV DIAL system that will be described in the next section. Airborne O_3 DIAL systems have also been developed by several other groups [Uthe *et al.*, 1992; Moosmueller *et al.*, 1994; Wirth and Renger, 1996; Ancellet and Ravetta, 1997, 1998].

The first H_2O DIAL system was flown in 1982 [Browell, 1983; Browell *et al.*, 1984], and several new airborne H_2O DIAL systems were developed and deployed by this same group over the next 16 years [Browell *et al.*, 1991, 1997; Higdon *et al.*, 1994; Browell and Ismail, 1995]. Other groups have also developed airborne H_2O DIAL systems (see [Ehret *et al.*, 1993,1998; Quaglia *et al.*, 1997; Fix *et al.*, 1998; Poberaj *et al.*, 2000; Bruneau *et al.*, 2001a,b; Wulfmeyer *et al.*, 2001a,b]).

Measurements of CO_2 using the DIAL technique are in the early stages of development. Concentrations of atmospheric CO_2 have been detected using laser remote sensing techniques [Taczak and Killinger, 1998; Koch, 2001]; however, the accuracy of these measurements was limited due to the quality of the transmitter and detector systems. Recent technology developments in lasers [Singh *et al.*, 1998] and detectors in the near IR region and improvements in DIAL system operation are expected to enable the measurement of CO_2 to the required accuracy of about 1 part per million by volume (ppmv) using the DIAL technique.

Airborne DIAL systems and applications

The current NASA Langley airborne UV DIAL system has been described in detail in two recent publications [Richter *et al.*, 1997; Browell *et al.*, 1998a]. This system uses two 30-Hz, frequency-doubled Nd:YAG lasers to sequentially pump two dye lasers that are frequency-doubled into the UV to produce the on-line (288.2 nm / 301 nm) and off-line (299.6 nm / 310 nm) wavelengths for DIAL O_3 measurements during tropospheric and stratospheric missions, respectively. The residual 1064- and 590-nm beams from the frequency doubling processes of the Nd:YAG and dye lasers, respectively, are also transmitted for aerosol and cloud measurements. This system has a demonstrated absolute accuracy for O_3 measurements of better than 10% or two ppbv (parts per billion by volume), whichever is larger, and a measurement precision of 5% or 1 ppbv with a vertical resolution of 300 m and an averaging time of 5 minutes (about 70 km horizontal resolution at typical DC-8 ground speeds) [Browell, 1983, 1989; Browell *et al.*, 1983, 1985]. The NASA Langley airborne UV DIAL systems have

made significant contributions to the understanding of both tropospheric and stratospheric O_3. They have been used in 18 international and three national field experiments during the past 21 years, and during these field experiments, measurements were made over, or near, all of the oceans and continents of the world. A few examples of the scientific contributions made by these airborne UV DIAL systems are given in Table A in the electronic extension of this article (see also the data sets obtained by these systems at our website, http://asd-www.larc.nasa.gov/lidar/lidar.html and the review by Browell et al. [1998a]).

In the initial step towards the development of a space-based H_2O DIAL system, the first airborne H_2O DIAL system was developed and demonstrated in 1982 [Browell, 1983]. This system was based on Nd:YAG-pumped dye laser technology, and it was used in the first airborne H_2O DIAL investigation of the marine boundary layer over the Gulf Stream [Browell et al., 1984]. This laser was later replaced with a flashlamp-pumped solid-state alexandrite laser, which had high spectral purity, and this system was used to make accurate H_2O profile measurements across the lower troposphere [Higdon et al., 1994]. A third H_2O DIAL system called LASE (Lidar Atmospheric Sensing Experiment) was developed as a prototype for a space-based H_2O DIAL system [Browell and Ismail, 1995; Browell et al., 1997a; Moore et al., 1997]. This system was designed to operate autonomously from a high-altitude ER-2 aircraft, and it used a Ti:sapphire laser and 1-3 different H_2O absorption line positions to make H_2O measurements across the entire troposphere. While the LASE system was initially designed for operation from the NASA high-altitude ER-2 aircraft, it was modified to also fly on conventional medium-altitude aircraft [Ferrare et al., 2000a,b, 2001; Ismail et al., 2001].

LASE uses a Ti:sapphire laser that is pumped by a double-pulsed, frequency-doubled Nd:YAG to produce laser pulses in the 815-nm absorption band of H_2O. The wavelength of the Ti:sapphire laser is controlled by in-

jection seeding with a diode laser that is frequency locked to a H_2O line using an absorption cell. Each pulse pair consists of an on-line and off-line wavelength for the H_2O DIAL measurements. Operation of LASE on the side of the H_2O absorption line permits the use of the same H_2O line for different absorption cross sections [Sachse et al., 1993, 1995], permitting the measurement of H_2O concentrations across 4 orders of magnitude of dynamic range. The accuracy of LASE H_2O profile measurements was determined to be better than 6% or 0.01 g/kg, whichever is larger, over the full dynamic range of H_2O concentrations in the troposphere [Browell et al., 1997a]. LASE has participated in over eight major field experiments since 1995 [e.g., Browell et al., 1997a, 2000a,b, 2001; Ferrare et al., 1999, 2000a,b, 2001; Ismail et al., 2000, 2001; Clayton et al., 2001]. See Table B in the electronic extension of this paper for a listing of topics studied using airborne H_2O DIAL systems.

Space-based DIAL systems

The idea of putting DIAL systems in space has been discussed since the late 1970s, starting with interest in putting lidar systems on the space shuttle [e.g., Wright et al. 1975; Remsberg and Gordley, 1978; Abreau, 1980; Browell and Ismail, 1984]. In particular, DIAL experiments have been evaluated with an emphasis on future measurements of H_2O and O_3 from space [NASA, 1979; Browell and Ismail, 1984; Ismail and Browell, 1989; Browell, 1994; Browell et al., 1997b, 1998a]. This possibility became more likely with the successful deployment of the first cloud and aerosol lidar system on the space shuttle, LITE (Lidar In-space Technology Experiment), in 1994 [Winker et al., 1996].

The rationale for putting DIAL systems in space is to provide high vertical resolution measurements of gases such as O_3, H_2O, and CO_2 (along with aerosol and cloud measurements) across the troposphere and O_3 and aerosols across the stratosphere. This is especially important in light of anthropogenic influences on O_3, CO_2, and climate during the past several decades.

Global O_3 measurements

A number of key issues could be addressed by a space-based O_3 DIAL system, including those related to O_3, such as photochemical O_3 transport and production/ destruction in the troposphere, location of the tropopause, and stratospheric O_3 depletion and dynamics. High resolution airborne O_3 DIAL and other aircraft measurements show that, in order to study tropospheric processes associated with biomass burning, transport of anthropogenic pollutants, tropospheric O_3 chemistry and dynamics, and stratosphere-troposphere exchange, a vertical profiling capability with a resolution of 2-3 km is needed [e.g., Fenn et al., 1999; Newell et al., 1999]; this capability is not currently available from passive remote sensing satellite observations.
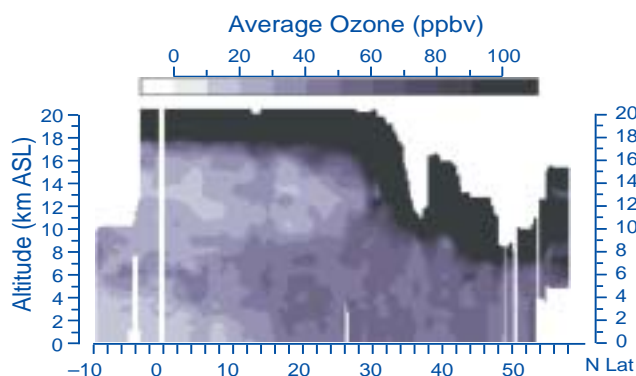

Figure 1. Average O_3 cross-section observed over western Pacific using airborne UV DIAL and *in situ* data obtained during PEM West B field experiment.

A space-based O_3 DIAL system would be able to make critically needed profile measurements of O_3 across the troposphere, which would yield a much better understanding of tropospheric O_3 production and transport, especially in remote regions. An example of the type of latitudinal O_3 cross section that could be provided by a space-based O_3 DIAL system is shown in Figure 1 [Browell *et al*., 1998a]. This figure shows many different aspects of O_3 loss and production and vertical and horizontal transport and stratosphere-troposphere exchange that occur from the tropics to high latitudes. This type of data would be available from just one pass from a space-based O_3 DIAL system. In addition, a space-based O_3 DIAL system optimized for tropospheric O_3 measurements (see system description in Table 1) would also permit high-resolution O_3 measurements in the stratosphere (1 km vertical, 100 km horizontal), along with high-resolution aerosol measurements (100 m vertical, 10 km horizontal). In addition, these DIAL measurements will be useful in assisting in the interpretation of passive remote sensing measurements and in helping to improve their data processing algorithms [e.g., Browell, 1994; Grant *et al*., 1998]. The development of a space-based O_3 DIAL system has been described recently by Browell *et al*. [1997b, 1998a], and the system parameters and measurement objectives for this system are given in Table 1.

Figure 2 shows a simulation for expected random error as a function of altitude for an O_3 DIAL system at an altitude of 400 km for the lidar parameters given in Table 1 and the U.S. Standard Midlatitude O_3 model [Krueger *et al*., 1976]. In the middle of the stratosphere, where O_3 number densities are highest, the random error drops to about 2%. In the troposphere, it increases to about 10% for altitudes below 6 km, which is similar to that currently obtained using the airborne UV DIAL system.

Global H_2O measurements

Water vapor and O_3 are important to the formation of OH in the troposphere, and OH is at the center of most of the gas-phase chemical reactions in the lower atmosphere. In addition to influencing the production of OH, H_2O is an excellent tracer of vertical and horizontal transport of air masses in the troposphere, and it can be used as a tracer of stratosphere-troposphere exchange. Increased aerosol sizes due to high relative humidities can also affect heterogeneous chemical processes in the boundary layer and in cloud layers. Thus, knowledge of H_2O distributions can be used in several different ways to better understand chemical and transport processes that influence the composition of the global troposphere.

The combination of active and passive measurements can provide significant benefits for H_2O, temperature, aerosol, and cloud information. The high vertical resolution H_2O (≤ 1 km), aerosol (≤ 100 m), and cloud top (≤ 50 m) measurements from the lidar along the satellite ground-track can be combined with the horizontally
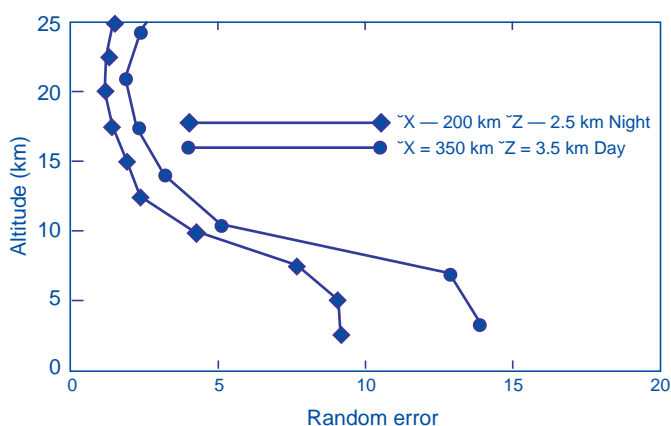

Figure 2. Simulations of expected measurement performance for a space-based O_3 DIAL system using the parameters given in Table 1, and nighttime and daytime background conditions.

contiguous data from nadir passive sounders [Smith, 1991] to generate a more complete high-resolution H_2O, aerosol, and cloud field for use in the various studies indicated above. There is also strong synergism with aerosol and cloud imaging instruments and with future passive instruments that are being planned or proposed for missions addressing atmospheric chemistry, radiation, hydrology, natural hazards, and meteorology.

The technology for a space-based H_2O DIAL system is rapidly maturing in the areas of: high-efficiency, high-energy, high-spectral-purity, long-life lasers with tunability in the 815- and 940-nm regions (see e.g., [Barnes, 1998]); low-weight, large-area, high-throughput, high-background-rejection receivers; and high-quantum-efficiency, low-noise, photon-counting detectors. See Table 1 for the parameters and expected performance of a 940-nm H_2O DIAL system. With the expected advancements in lidar technologies, a space-based H_2O DIAL system could be flown on a long-duration space mission by about 2006.

Global CO_2 measurements

To fully understand the global atmospheric CO_2 budget requires measurements of atmospheric CO_2 profiles on continental and global scales that are not currently available. The difficulty in making profile measurements arises from CO_2 exhibiting small variations in concentration over large spatial scales [see Feely *et al*., 1999 and Gerbig *et al*., 2000]. High-precision global measurements of atmospheric CO_2 profiles from space are essential to derive global atmospheric CO_2 flux distributions that are needed to enhance the present understanding of sources and sinks of CO_2 in the atmosphere. The feasibility of making high precision CO_2 DIAL measurements, initially from the ground and aircraft and ultimately from space, was recently evaluated by Ismail *et al*. [2001]. To meet the science objectives of understanding carbon cycle processes, a CO_2 measure-

Table 1. System parameters and performance goals for space-based O_3, H_2O, and CO_2 DIAL measurements from low Earth orbit (400 km).

Parameters/Goals	O_3 DIAL	H_2O DIAL	CO_2 DIAL
Laser Transmitter:			
Wavelength (λ): $\lambda_{on}/\lambda_{off}$ or λ region & $\Delta\lambda = \lambda_{on} - \lambda_{off}$ (nm)	308 / 320	940 region $\Delta\lambda < 70$ pm	2050 region $\Delta\lambda < 100$ pm
Pulse energy, each λ (mJ)	500	500	1000
Pulse-pair rep. freq (Hz)	10	10 (2 alt. λ_{on}'s)	10 (2 alt. λ_{on}'s)
Linewidth (pm)	50	< 1	< 0.06
Spectral purity (%)	> 99	> 99	> 99.5
Beam divergence (mrad)	< 0.15	< 0.2	< 0.2
Pulse width (ns)	20	200	200
Receiver:			
Area (m²)	3.0	0.7	4.0
Field-of-view (mrad)	0.3	0.3	0.3
Filter bandwidth (night) (nm)	0.5	1.0	10
Overall optical efficiency (%)	40	65	60
Detector QE* (%)	31	40	40
NEP* (W Hz$^{0.5}$)	10^{-15}	10^{-15}	10^{-15}

CO_2 profiles. Further, a number of strong CO_2 absorption lines that are temperature insensitive and void of absorption due to H_2O are located within the tunable range of the 2 μm lasers.

Space-based CO_2 measurement simulations were conducted using the transmitter and receiver parameters listed in Table 1. The transmitter parameters are based on technology developments in progress at NASA LaRC, and the detector parameters are based upon the characteristics of a cooled InGaAsSb APD that is also under development. A large-collection-area deployable telescope receiver system and a direct detection system will be needed to achieve the required high precision measurements. Initial performance simulations indicate that space-based CO_2 DIAL systems would meet or exceed the measurement goals specified in Table 1.

Airborne DIAL systems are currently making significant contributions to understanding O_3, H_2O, aerosol, and cloud distributions in investigations of atmospheric chemistry, dynamics, meteorology, and radiative processes. While field deployment of airborne DIAL systems will continue, the use of airborne platforms does not provide the spatial and temporal coverage that can be provided by a space-based DIAL system. Significant progress has been made in identifying the system requirements and enabling technologies needed for space-based DIAL systems, and progress is being made in the development of such technologies. It is expected that DIAL systems will be deployed in space for H_2O, O_3, and, possibly, CO_2 in the next decade.

ment precision of about 1 ppmv over several altitude intervals in the troposphere and total CO_2 column measurements with 1-2 ppmv precision is needed. This represents a CO_2 DIAL measurement accuracy of about 0.3% for both range-resolved and column measurements.

Emerging new technologies in lasers and near IR detectors have the promise to make lidar active remote sensing from space a viable technique for such measurements. In particular the DIAL technique is well suited for measuring atmospheric CO_2 profiles and column distributions. A CO_2 DIAL system would follow the heritage of the LASE system that operates on narrow water vapor absorption lines [Browell *et al.*, 1997a]. Recent technology breakthroughs in narrowband tunable lasers near 2 μm [Singh *et al.*, 1998] and developments of new antimonide-based (InGaAsSb) APD detectors with AlGaAsSb multiplication layers in the near IR make DIAL an attractive technique for measuring atmospheric

Extending atmospheric aerosol measurements to the global scale

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1. Introduction

Three disparate approaches have heretofore been employed to study atmospheric aerosols: 1) *in situ* observations of microphysical and chemical properties; 2) long-path/column and remote sensing of their influence on propagation of radiation in the atmosphere (including satellite observations); and 3) modeling on all spatial/temporal scales, which depends on accurate and realistic knowledge from (1) and (2), or on assumptions. While these different approaches have been useful in the exploratory stages of research on atmospheric aerosols, applications of them to current scientific questions regarding climate forcing and other global-scale issues requires an integrative strategy that is defined by the scientific questions themselves. Simultaneous and coordinated use of all three approaches is required for generating a complete and integrated description of these complex systems, particularly for understanding and quantifying large-scale to global effects of aerosols. Accomplishing the needed integration requires consideration of the spatial/temporal variability of aerosols as well as the influences of and correlations with the thermodynamic state (particularly the relative humidity). Rationalization of the data from the three required approaches in the context of clearly stated scientific questions cannot be achieved without coordination. While a need still exists for exploratory observations, e.g., in order to discover new processes or properties, data from such experiments must be clearly labeled as not belonging to the integrated set.

Background

Exploratory and monitoring observations of atmospheric aerosols over the last several decades have emphasized three features of those particulate systems: chemical composition and concentration, physical characterizations (primarily particle size distribution and number population), and cloud nucleating properties. Observations of optical depth or turbidity from the ground, along with lidar observations show that the non-cloud aerosol is a major factor governing the amount of sunlight reaching the ground; however, most such observations are sporadic, for short periods of time and for only a few places on Earth. Taken together, these *in situ* and column observations show that there are large variations in both the extensive and intensive properties of the aerosols, and that these variations occur on many time and space scales, especially in the vertical direction. In spite of this high degree of variability, aerosols occur globally and

have large-scale (regional to global) effects, ranging from climate forcing to acidification of precipitation and modification of biogeochemical balances. Hence, there are substantial reasons for extending observations from the regional to global scale, primarily to provide quantification of such large-scale effects. The remainder of this paper focuses on the single scientific question of climate forcing; however, the approach would be the same for the other large-scale effects as well.

While these existing aerosol observations have resulted in enough information to allow preliminary model-based estimates of direct and indirect climatic forcing by both natural and anthropogenic aerosols, there are questions of whether the observations are representative; and there are large uncertainties (+/- a factor of two in concentration for the best-known case of anthropogenic sulfates in the PBL, and much worse for the upper troposphere or for anthropogenic organic aerosols or for indirect effects on clouds). Given the existing suite of *in situ* observational capabilities, it is clearly impossible to obtain enough data by those means alone to guarantee global representation. On the other hand, data from satellite-based radiometers have shown the great benefits of global geographical coverage but, so far, have been of limited use, also because of large uncertainties [Mischenko *et al.*, 1999] and limitations imposed by satellite orbital characteristics. These uncertainties and limitations, along with a need for vertical resolution and much more accurate inferences of aerosol optical depth, became the basis for implementation of a lidar in the CALIPSO satellite, which will be orbited in formation with the EOS-PM (AQUA) system and CLOUDSAT beginning in 2004. Prior to that time, numerous satellite-borne sensors capable of providing some aerosol information are already deployed (or soon will be), including other lidars [GLAS, 2002], high resolution spectrometers operating in the oxygen A-band (e.g., GOME), and polarization of upwelling reflected sunlight (e.g., POLDER). But, however extensive these observations may be and however promising these new technologies may seem, especially given the global extent of their observations, they cannot by themselves measure the actual chemical composition of the detected aerosol, nor provide information on key intensive aerosol parameters, and, most significantly, they cannot quantify the proportion of natural and anthropogenic components. Even the combination of satellite observations and models together cannot adequately remedy the inherent, unacceptably large uncertainties of the models such that *in situ* aerosol characterizations are still necessary. This requirement poses a series of questions of how to coordinate in time and

space the *in situ* observations and how to formulate model results so that in combination with satellite observations it is possible to seek closure; that is, ask to what degree the entire set of remote and *in situ* data and model outputs (moputs) are internally consistent. To put these thoughts in a different way, the different modes of observation—satellite instruments and *in situ* devices— do not and cannot observe exactly the same aerosol properties, and models are only models such that it is necessary to develop means to connect them and test whether they agree with each other.

2. Basis for integrating data from satellite-borne lidar, radiometers, models and *in situ* observations

First, it is necessary to recognize that no single mode of observations or modeling can provide a complete or adequate integrated output, viz.:

- Satellite (usually polar) orbital characteristics bring the remote sensors over a given site only rarely and for sun-synchronous systems only at one time of day. Hence, models and *in situ* continuous observations are needed for temporal interpolation.

- Satellite radiometers can image large geographical areas (in the x-y horizontal dimensions only) and can cover the whole Earth daily, but cannot view the whole Earth continuously, on time scales on which aerosols and clouds vary (hours to fractions of a day).

- Satellite lidar yields vertical (z) information along the orbital ground track (x), but requires extrapolation in the cross-track direction and interpolation between repeats of visits to a given site.

- *In situ* observations at fixed sites give no information on the x, y or z axes. Ground-based lidar yields information on the z axis (not x or y), but both can be run for unlimited periods of time to provide connections between orbital visits, hence allowing interpolation during times when the satellite-borne lidar and radiometers are not present.

- *In situ* observations with aircraft can yield some information on x, y and z, but only for very short time periods. Large numbers of short flights can, in principle, yield data over lengthy periods of time but would require dedicated use of such facilities.

- Models of atmospheric aerosols can yield outputs with short (few hour) time resolution over all three dimensions (x, y, z) over any time frame. However, the uncertainties in the models (parametric, structural and mechanistic) require continuous validation via *in situ* and remote measurements. Models also may not adequately describe such factors as subgrid-scale correlations between aerosol parameters and the thermodynamic state of the air (esp. RH; see Charlson *et al*. [1999]) and hence again require *in situ* measurements for confirmation.
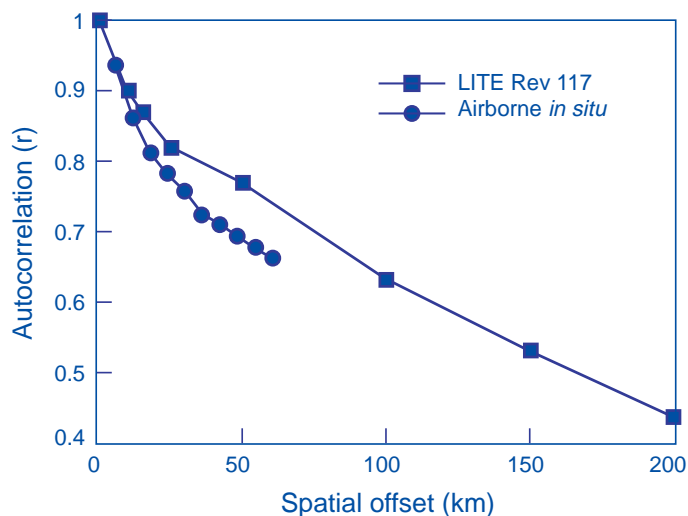

Figure 1. Autocorrelation coefficient versus log distance (km) down the orbital or flight ground track.

Second, it is essential to coordinate *in situ* and satellite observations so that the resultant multivariate data sets strictly and demonstrably apply to the same exact air parcel, and so that the integrated data set includes all of the independent variables that control the column-integral properties. This includes both the relevant extensive properties (EP)—such as scattering and absorption coefficients, lidar backscatter, and species mass concentrations—and intensive properties (IP) (see Table 1) and their dependence on the thermodynamic state (TS), particularly RH. Numerous factors are involved in achieving such coordination:

- Horizontal variability of all extensive variables
- Vertical variability and stratification in the atmosphere of the extensive parameters
- Variations in time and space of the thermodynamic factors influencing column properties
- Correlations among the above.

Implementation of such coordinated observations regarding direct climate forcing thus requires some degree of knowledge of the nature of spatial and temporal variability of both the extensive and intensive aerosol parameters, and the relevant thermodynamic state variables.

3. Defining the role of thermodynamic state as an dependent variable that influences column properties

Thermodynamic state (TS) is defined here as the aggregate of temperature- and vapor-pressure related quantities that influence phase changes, particle size, and refractive index in the multiphase aerosol system. The optical properties of any column or path within the atmosphere are determined by both the amounts (EP) and properties

(IP) of the aerosol-particle substances and TS, and both are functions of length along the path, such that measurement of one variable alone (whether at a point or over the path) clearly cannot describe the whole path.

Relatively large amounts of water are expected to be in the particles under typical atmospheric conditions. Eighty percent RH is the average of the Earth's PBL, and at eighty percent RH, soluble particles are approximately eighty mole percent water.

4. Consideration of the influences of the spatial and temporal characteristics of aerosols on sampling and measurement protocols

Two related approaches are available for observing the spatial–temporal variability of aerosol EP, IP and TS: 1) Measurements over a spatial dimension, for example with a mobile sampling platform such as an aircraft or non-geo-stationery satellite; and 2) Measurements over time. The two are related in that the spatial dimension of the former is replaced by the time dimension of the latter along with a mean velocity. The first satellite-borne lidar data that were acquired in LITE reveal the existence of synoptic (1000 km) horizontal scale aerosol masses, with substantial variability down to 10 to 100 km scales. Lengthy time series reveal the same sort of variability, with large aerosol masses passing by on the time scale of a day and variability on time scales of an hour to a few hours. Figure 1 is an autocorrelation plot of LITE data, showing that at distances of greater than 100 km or times greater than three to four hours, the auto-correlation coefficient drops below about 0.8. This means that any attempt to obtain correlative *in situ* data for satellite observations is expected to result in less than a 0.8 correlation coefficient if the samples are acquired, or the observations made, outside the ~100 km or the three to four hour space/time window, respectively.

5. Consideration of the effects of aerosol characteristics and thermodynamic state on the sampling protocols

Not all particle size classes are important to the scattering and absorption of solar radiation, with sub-micrometer particles having much larger influence per unit mass of aerosol substance. Also, it is generally observed that sub-micrometer particles have a systematically different composition than super-micrometer ones, and sub-micrometer particles often have a significant anthropogenic component (e.g., sulfates). Sub-micrometer (so-called accumulation mode) particles are formed from the gas phase via either low or high temperature nucleation processes (gas-to-particle conversion), while coarse, super-micrometer ones are primarily from mechanical production (e.g., wind-blown dust or sea salt). Hence if it is desired to separate out and identify the optically important particles and to estimate the fraction that is anthropogenic, it is necessary to separately analyze the sub-micrometer fraction. This can be achieved by intertial separation prior to sampling, e.g., with a cyclone separator operating at 10 and 1 μm. However, this separation cannot yield consistent samples if the RH is sufficiently high because as shown above, the particles grow at RH well below 100%. Hence, it is necessary to control the RH by slight (a few degrees) heating prior to imposing the size cut. This RH control (e.g., at RH<40%) also achieves measurement of the needed EP values (mass concentrations, m_i) at a reference low RH at which the thermodynamic state has little influence. But, it also requires that f(RH) also be measured so that the EP values at higher RH (e.g., aloft) can be accurately calculated. The actual choice of 40% RH and 1 and 10 μm is what is practiced by the U.S. aerosol monitoring performed by NOAA-CMDL. And, once again, it is necessary to make these observations in one-and-the-same air parcel seen by the satellite instruments if meaningful correlations are to be obtained.

Table 1. Aerosol measurements for direct forcing of climate.

Extensive Properties		Intensive Properties		
$\sigma_{sp}(\lambda)(m^{-1})$:	Scattering component of extinction, scattering coefficient	å:	$d \log \sigma_{sp}/d \log \lambda$	Wavelength dependence (Ångström exponent)
$\sigma_{bsp}(\lambda)(m^{-1})$:	Hemispheric backscatter coefficient	f(RH):	$\sigma_{sp}(RH)/\sigma_{sp}(low\ RH)$	Humidity dependence
$\sigma_{ap}(\lambda)(m^{-1})$:	Absorption coefficient *	B:	σ_{bsp}/σ_{sp}	Backscatter ratio
m:	Mass concentration	ω:	$\sigma_{sp}/(\sigma_{sp}+\sigma_{ap})$	Single scatter albedo *
m_i:	Species mass concentration (chemical composition as f(r))	α_m:	$\partial\sigma_{sp}/\partial m (m^2_{g}{}^{-1})$	Mass scattering efficiency
		α_i:	$\partial\sigma_{sp}/\partial m_i$ (mg)	Species scattering efficiency
$\beta_{180}(m^{-1}sr^{-1})$:	Lidar backscatter coefficient	S(sr):	$(\sigma_{sp}+\sigma_{ap})/\beta_{180}$	Lidar ratio
				Ratios of chemical components

_____

* Most uncertain property

6. Considerations of the applications of the data to scientific questions in the design of observational protocols and modeling

As is evident from Sections 2 to 5 above, every aspect of the measurement strategy is in one way or another dictated by the scientific question at hand. The key variables to be measured (Table 1) are all parameters that are needed for either modeling climate forcing or for inputs into the retrieval of data from satellite-borne instruments. Other scientific questions would require a different set of variables. Most importantly, it is seldom possible to utilize data acquired for one problem (e.g., health effects) for another scientific question (e.g., relationship to satellite data for climate forcing estimates). It is necessary to keep all of the constraints on measurement in mind when developing the overall observational and modeling strategy.

7. Conclusions: Suggestions for strategies of coordination

The final point of this brief tutorial is that this integrative strategy would appear to require overt coordination. "Business as usual", with individual scientists measuring one or a few parameters as they always have done cannot provide a coherent dataset for correlation with satellite data. Intensive campaigns likely will be replaced by longer term measurement programs, and models will be developed that attempt to optimize the use of the data. Given that the data are imperfect (and always will be), appropriate uncertainty analyses must be carried throughout the entire integrative activity. Just how to organize and coordinate this effort is not clear; but, what is clear is that it cannot work without coordination.

There also is a clear need for close collaboration of modelers with both the satellite and *in situ* measurers. Indeed, it will be necessary to develop new sorts of models that actually calculate (or use) the data from satellite instruments or *in situ* observations. Data assimilation techniques appear to hold considerable promise.

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A changing of the guard

As Guy Brasseur mentioned in his introductory note for this issue of IGAC*tivities*, Dr. Peter Czepiel is the new IGAC Executive Officer, effective 5 November 2001. Peter is an expert in the production and consumption of radiatively active trace gases. He is primarily interested in the biogeochemical cycling of carbon and nitrogen in both natural and anthropogenic systems. While a doctoral candidate at the University of New Hampshire, he devised new techniques to assess the magnitude, variability, and environmental influences on the sources and sinks of methane, carbon dioxide, and nitrous oxide in liquid and solid waste processing systems, as well as disturbed and undisturbed soils. As a Postdoctoral Research Fellow at Harvard University, he also developed a gas-tracer method to determine the area of influence of a micrometeorological tower, and studied the effect of weather patterns on the ambient concentrations of non-methane hydrocarbons. Most recently, Peter has been working at the University of New Hampshire with two long-time contributors to IGAC research, Michael Keller and Patrick Crill, investigating carbon and nitrogen trace gas exchange in tropical forests as a participant in the Large Scale Biosphere-Atmosphere Exchange in the Amazon (LBA) project.

Because this is the last issue of IGAC*tivities* that I will edit, I want to take the opportunity to add my thanks to all members of the scientific community who over the years have carried out research that addresses the goals of IGAC and IGBP. I also want to thank especially those of you who have somehow found time to contribute directly to this newsletter. Your articles have provided concise summaries of important developments, as well as views toward the future in many areas of biospheric-

The IGAC Core Project Office has relocated to the University of New Hampshire. New contact information is:

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atmospheric chemistry research. They have been particularly valuable sources of information for colleagues in developing countries where even major libraries sometimes cannot afford to purchase books or subscribe to major journals.

Finally, I want to thank Ron Prinn and Guy Brasseur for allowing me to serve as IGAC Core Project Officer for nearly nine years. It has been a high privilege to work closely with these two wonderful people whose vision and leadership have benefited IGAC and the entire Earth system research enterprise in ways that will continue to be realized for many years to come.

— Alex Pszenny

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