

**LEOMAC: A Future “Global Atmospheric Composition Mission” (CACM) concept**  
**Nathaniel Livesey, Michelle Santee, Paul Stek, Joe Waters**  
**Jet Propulsion Laboratory, Pasadena, California**

**Pieter Levelt, Pepijn Veefkind**  
**Royal Dutch Meteorological Institute, The Netherlands**

**Jack Kumer, Aidan Roche**  
**Lockheed Martin, Palo Alto, California**

**Abstract**

Resolution of important outstanding questions in air quality, climate change and ozone layer stability demands global observations of multiple chemical species with high horizontal and vertical resolution from the boundary layer to the stratopause. We present a mission concept that delivers the needed atmospheric composition observations, along with cloud ice and water vapor data needed for improvements in climate and weather forecasting models. The mission comprises ultraviolet and infrared nadir and microwave limb viewing instruments observing wide swaths each orbit.

We review the scientific goals of the mission and the measurement capabilities this concept will deliver. We describe how precessing orbits offer significant improvements in temporal resolution and diurnal coverage compared to sun-synchronous orbits. Such improvements are needed to quantify the impact of critical “fast processes” such as deep convection on the composition and radiative properties of the upper troposphere, a region where water vapor and ozone are strong but poorly understood greenhouse gases.

This concept can serve as the “Global Atmospheric Composition Mission” (GACM) recently recommended by the National Academy of Sciences decadal survey as one of 17 priority earth science missions for the coming decade.

**1. Introduction**

The LEOMAC<sup>1</sup> mission addresses crucial issues on how changes in atmospheric composition affect the quality and well-being of life both regionally and for the entire Earth. LEOMAC provides data that are essential for making informed policy decisions on issues related to regional and global air quality and climate change. It determines if regulations on ozone depleting substances are having the desired effect on stratospheric chemistry and ozone recovery. LEOMAC provides data at better horizontal and vertical resolution, and – in the case of LEOMAC-P – at much better temporal resolution; all of which are needed to address critical current questions in atmospheric science and to improve the accuracy of global circulation models used for weather and climate predictions. It continues the measurements from Aura that are needed long-term, but will not be provided by other planned missions, while adding new measurement capabilities that are not currently possible. LEOMAC’s measurements are essential for meeting the goals of NASA’s 2006 Strategic Plan. LEOMAC can serve as the Global Atmospheric Composition Mission (GACM) recommended by the National Research Council Decadal Survey as one of the 14 priority Earth Observation missions for NASA to implement in the next decade.

The specific objectives of LEOMAC are to:

1. Quantify how increasing emissions of pollutants affect air quality globally,
2. Determine how the ozone layer and its chemistry are changing,
3. Quantify how changing atmospheric composition is affecting climate, and
4. Quantify the processes that control upper tropospheric water vapor and cloud ice.

Producing the measurements necessary to meet these objectives – with the needed combination of global coverage, accuracy, precision and resolution – requires multi-spectral measurements covering bands in the

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<sup>1</sup> Either a precessing or sun-synchronous orbit is being considered for LEOMAC. We here use “LEOMAC-P” to denote the precessing orbit version and “LEOMAC-S” to denote the sun-synchronous version. “LEOMAC” is used when referring to items applicable to both orbits.

microwave, thermal infrared, short-wavelength infrared, near-infrared, visible and ultraviolet spectral regions. LEOMAC covers these spectral bands with three instruments. The candidate instruments are either advanced versions of instruments proved successful on previous missions and/or are instruments for which NASA has development programs underway.

The mission implementation would consist of a single satellite in low-Earth orbit producing geolocated mapped data from all instruments. In addition to producing archived data for scientific research, LEOMAC would also produce direct broadcast and near-real-time data, for measurements not available from operational satellites that could also be used operationally.

## 2. Background of the measurements

Human activities are changing atmospheric composition in ways that can adversely affect life on Earth. Unhealthful pollution episodes are common. Increasing pollution worldwide affects global and regional air quality, and can affect the atmosphere's ability to cleanse itself.

Policy decisions related to atmospheric composition – requiring balances between economic and environmental concerns – must be made and continuously validated. Obtaining political consensus needed for making the decisions is difficult, but regulations on ozone depleting substances (Montreal Protocol) demonstrate that consensus on such issues can be reached if sufficient scientific information is produced and adequately communicated. Such information requires global measurements of atmospheric composition. LEOMAC is designed to provide these measurements with the needed (and previously unavailable) combination of horizontal, vertical and temporal resolution. It also provides key measurements needed to improve the accuracy of weather and climate prediction models.

The LEOMAC measurements are chosen to fulfill recognized needs in the following applications areas:

- **Air quality.** LEOMAC makes all the priority tropospheric measurements ( $O_3$ , CO,  $NO_2$ ,  $CH_2O$ ,  $SO_2$ , aerosols) identified by the February 2006 “Community Workshop on Air Quality Remote Sensing from Space: Defining an Optimum Observing Strategy” and the NRC Decadal Study Panel on Human Health and Security. It provides the global measurements that are essential for obtaining international agreements on air quality issues.
- **UV exposure.** LEOMAC makes all the NRC Decadal Study Human Health and Security Panel's ‘UV exposure and skin cancer’ priority chemical measurements ( $O_3$ ,  $H_2O$ ,  $HO_2$ ,  $NO_2$ , ClO, BrO,  $HNO_3$ , HCl,  $H_2CO$ , HDO,  $H_2^{18}O$ ,  $CO_2$ , CO,  $NO_y$ ,  $N_2O$ ,  $CH_4$  – and IO, recently measured by SCIAMACHY, as a goal), except for OH (for which  $HO_2$  is a good proxy) and halogen source molecules (for which HCl and BrO give adequate information). LEOMAC's additional measurements of  $H_2O_2$ , NO, HOCl,  $CH_3Cl$ , and volcanic  $SO_2$  give additional information for tracking ozone layer stability.
- **Climate change.** LEOMAC makes measurements for assessing climate change that have been identified as crucial by many studies, including the NRC Decadal Study Panel on Climate Variability and Change. Its measurements of pollutants, aerosol optical depth and index, cloud ice amount and particle size parameter, cloud height and albedo, water vapor, and temperature – all made simultaneously and with global coverage – will enable progress in quantifying climate change associated with anthropogenic effects on clouds and aerosols. It measures the convective deposition of pollutants that affect ozone in the upper troposphere, where ozone's radiative forcing of climate is greatest. It continues the long-term global aerosol data set from TOMS and OMI that is needed to provide crucial information on changes in aerosol that affect climate.
- **Global circulation models used for climate and weather predictions.** LEOMAC's simultaneous measurements of water vapor and cloud ice amount (with information on ice particle size) – made with resolution needed for progress in quantifying the effects of convection – will improve parameterizations (e.g., of convection, cloud formation and sedimentation) in models used to predict weather and seasonal, interannual, and long-term climate variability. LEOMAC-P's new temporal sampling will improve the performance of data assimilation systems and regional forecast models, and should help improve worldwide extreme-event forecasting and hazard assessment.

LEOMAC's measurements are essential to meeting the NASA 2006 Strategic Plan goal 3A.1:

- *“Progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition”*

They also contribute significantly to goals 3A.2 and 3A.5:

- *“Progress in enabling improved predictive capability for weather and extreme weather events,”*
- *“Progress in understanding the role of oceans, atmosphere and ice in the climate system and in improving predictive capability for its future evolution.”*

### **3. Technical objectives and approach**

The overall objectives of LEOMAC, elaborated in section 4 of this document, are to:

1. Quantify how increasing emissions of pollutants affect air quality globally,
2. Determine how the ozone layer and its chemistry are changing,
3. Quantify how changing atmospheric composition is affecting climate, and
4. Quantify the processes that control upper tropospheric water vapor and cloud ice.

Figure 1 shows the measurements required to meet these objectives and candidate instruments to provide them. Producing these measurements – with the needed combination of coverage, accuracy, precision and resolution – requires a multi-spectral capability covering microwave, thermal infrared, short-wavelength infrared, near-infrared, visible and ultraviolet spectral regions. LEOMAC cost-effectively covers the required bands in these six spectral regions with a combination of three candidate instruments having the required sensitivity, spectral resolution, broad measurement swaths, and spatial resolution. The candidate instruments, all of which have significant heritage from previous satellite instruments and/or have development programs underway, are described below.

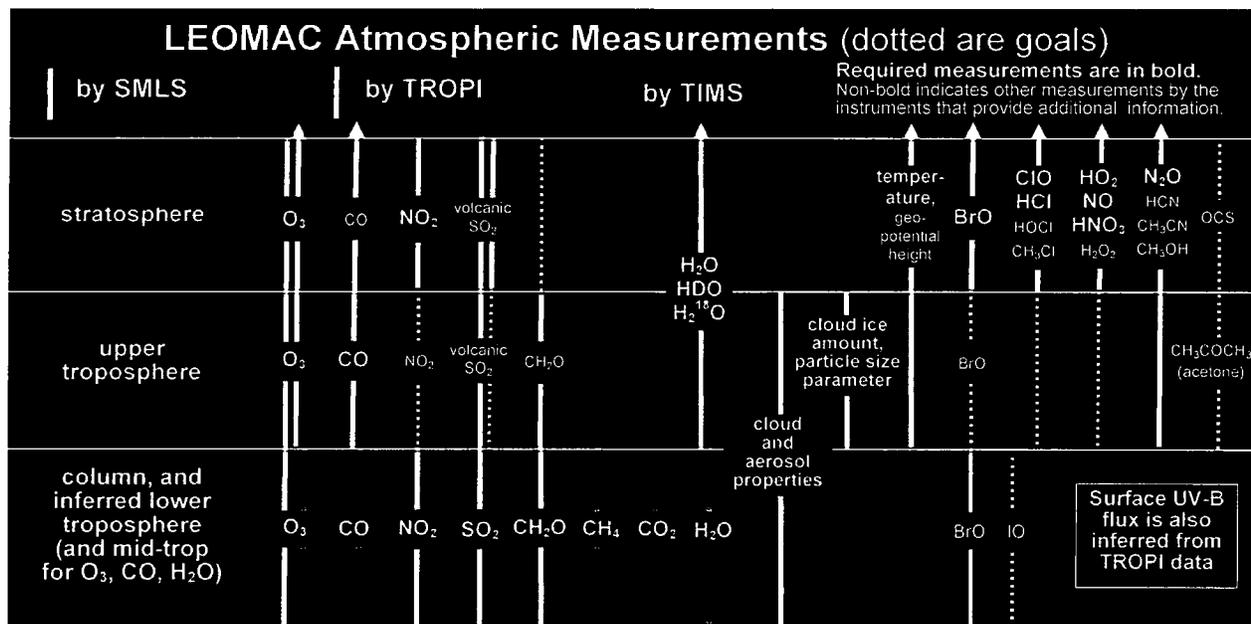


Fig. 1: LEOMAC measurements, indicating candidate instruments to provide them. SMLS is a Scanning Microwave Limb Sounder, TROPI is a Tropospheric Pollution Imager, TIMS is a Tropospheric Infrared Mapping Spectrometer.

- A Scanning Microwave Limb Sounder (SMLS) for measurements of H<sub>2</sub>O, cloud ice, and key chemical species in the upper troposphere and stratosphere. SMLS, an advanced version of MLS on Aura, measures thermal microwave limb emission in broad spectral bands centered at 240 and 640 GHz. Major improvements from Aura MLS are [a] azimuth scanning – simultaneous with vertical scanning – to give 50x50 km horizontal sampling (cross-track sampling 50x better than Aura MLS; along-track 3x better), over a broad ~5000-km wide measurement swath, to quantify convective depositions into the upper troposphere and long-range pollution transport, [b] vertical resolution of ~1.5-2 km (~2x better than Aura MLS), and [c] measurement of NO, NO<sub>2</sub>, HDO and H<sub>2</sub><sup>18</sup>O. SMLS measures more molecules than Aura MLS, while having a simpler signal chain and fewer radiometers.
- A TROPOspheric Pollution Imager (TROPI) for measurements of the key tropospheric pollutants O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, and CH<sub>2</sub>O – and for measurements of aerosol/cloud properties (e.g., aerosol index and optical depth; cloud height and albedo). TROPI, an advanced version of OMI on Aura and with long heritage from TOMS, measures reflected/backscattered solar radiation at ultraviolet/visible (0.3 to 0.5 μm) and near-infrared (0.76 μm) wavelengths. Major improvements over OMI are [a] ~10x10 km horizontal resolution (2-4x better than OMI), needed for resolving pollution sources and obtaining more cloud-free observations, while achieving a broad measurement swath of ~3000 km, [b] addition of a near-infrared band for improved measurements of cloud and surface properties to greatly improve the accuracy of the tropospheric pollution measurements, and [c] improved radiation hardness of the detectors.
- A Tropospheric Infrared Mapping Spectrometer (TIMS) for measurements of the key tropospheric pollutant CO, the key greenhouse gases CO<sub>2</sub> and CH<sub>4</sub>, and measurements of O<sub>3</sub> and CO in the middle troposphere for long-range transport. TIMS measures both reflected and backscattered short-wavelength infrared at 2.1 and 2.3 μm, and thermal infrared at 4.7 and 9.6 μm. Its design, with two compact pushbroom mapping grating spectrometers, is being demonstrated through NASA's Instrument Incubator Program. This design achieves the very high spectral resolution needed for tropospheric measurements of CO, O<sub>3</sub>, CH<sub>4</sub>, H<sub>2</sub>O and CO<sub>2</sub>:  $\lambda/\Delta\lambda$  of 33,000 at 2.1 and 2.3 μm, and 11,000 at 4.7 and 9.6 μm. Each spectrometer uses multiple orders to obtain measurements in at least two channels. TIMS has ~3000-km wide measurement swath, and ~3 km or better horizontal resolution.

These three instruments work together in an extremely synergistic manner to provide the needed measurements. For example, their sensitivities to different height ranges in the troposphere enable vertical profiles of tropospheric pollution to be retrieved with unprecedented capability by combining the simultaneous measurements from SMLS, TIMS, and TROPI. A cloud camera is added to the main instrument suite, to enhance the science return of TIMS and TROPI.

The mission implementation would consist of a single satellite in low-Earth orbit. Figure 2 shows the conceptual design for this observatory and lists its basic characteristics.

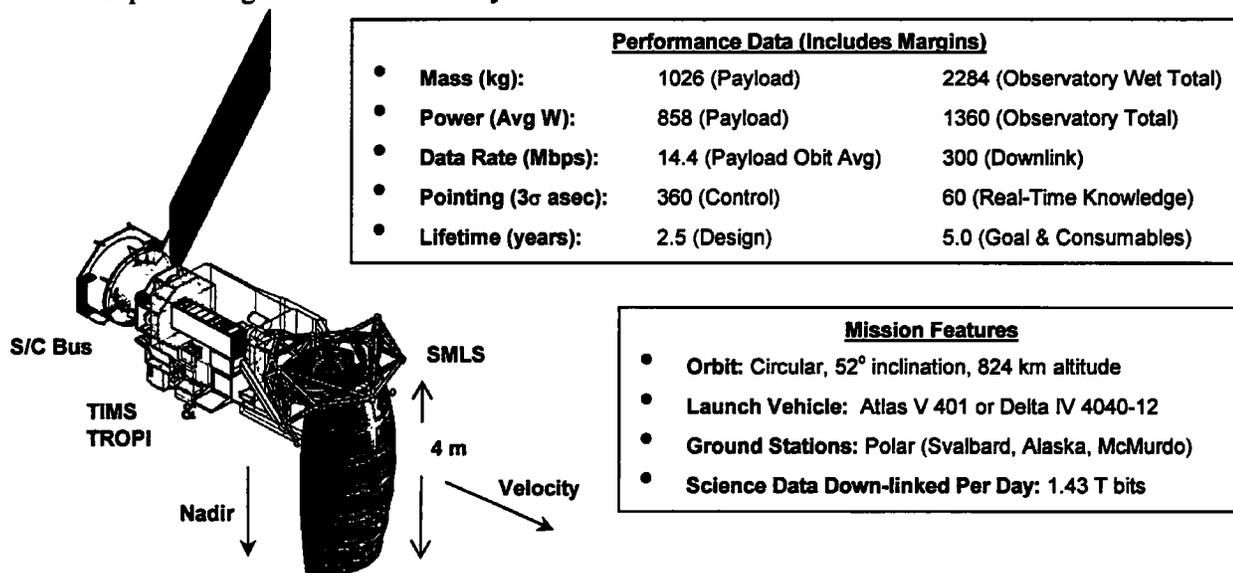


Fig. 2: LEOMAC conceptual design and characteristics.

In addition to providing archived data for scientific research, LEOMAC would also produce direct broadcast and near-real-time data for operational applications such as air quality forecasting.

LEOMAC fills measurement goals not covered by other planned satellites. It would implement the international cooperation advocated by the July 2003 Earth Observation Summit: TROPI is anticipated to be developed by the Netherlands. Strong UK participation in SMLS (as on UARS and Aura MLS) is anticipated.

#### 4. Justification and benefits

Justification and benefits are discussed in the following subsections for each of the LEOMAC objectives.

##### 4a. Quantify how increasing emissions of pollutants affect air quality globally.

Near-surface emissions are mixed throughout the global troposphere by convection and large-scale winds. Primary emissions generate secondary pollutants far from their sources, causing the rapidly increasing industrialization in developing countries to affect air quality worldwide.

An especially important example for the United States is the effect of pollution from the newly industrializing Asian countries on American air quality. Models indicate that – for pollutants with >10-day lifetime (which includes ozone and its precursors) – Asia makes the largest contribution to the column over North America, as shown in Figure 3. The models indicate that after being emitted into the boundary layer, the transport of Asian pollution to the United States is predominantly in the upper and middle troposphere and occurs through episodic events.

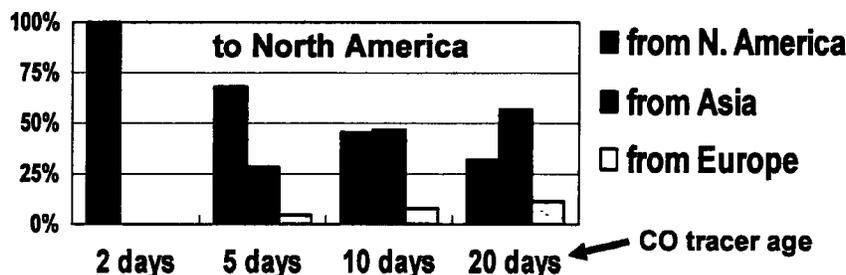


Fig. 3: Relative contributions from domestic, Asian and European sources to the column of pollution over N. America – as a function of the age (time since emitted) of the tracer CO. Sources of pollution from other regions to the N. American column are negligible. [Stohl et al., *J. Geophys. Res.*, vol. 107, No. D23, 4684, 2002.]

The LEOMAC measurements will enable, for the first time, direct observational tracing of pollution around the globe to its emission sources, such as the example of Asian pollution over America discussed above. TROPI and TIMS provide the high spatial resolution required to identify the source emissions of O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and CH<sub>2</sub>O into the boundary layer. (For the measurement of boundary-layer O<sub>3</sub> emissions, which is more difficult because of the large amounts of O<sub>3</sub> in the stratosphere, the combination of TROPI, TIMS, and SMLS simultaneous measurements – with their very different sensitivities to different altitude regions – allow inference of lower tropospheric O<sub>3</sub>. Boundary layer values are inferred by their morphology and temporal variation.) TIMS provides the measurements needed for tracking the long-range transport of CO and O<sub>3</sub> in the middle troposphere, and SMLS for tracking the transport of these pollutants (and possibly others) in the upper troposphere. The improvements of TROPI resolution over that of OMI on Aura, and of SMLS over Aura MLS, are illustrated in Figure 4.

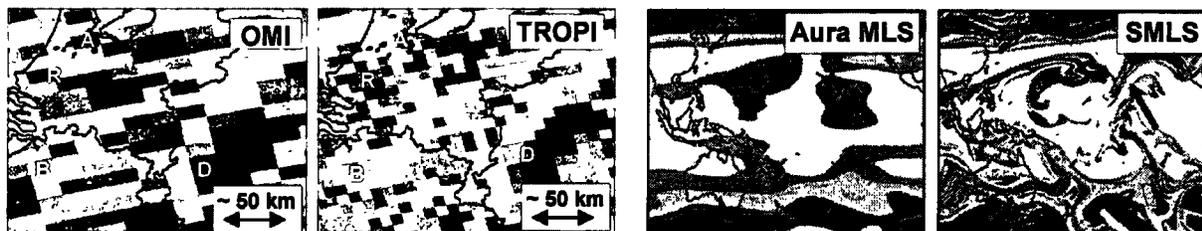
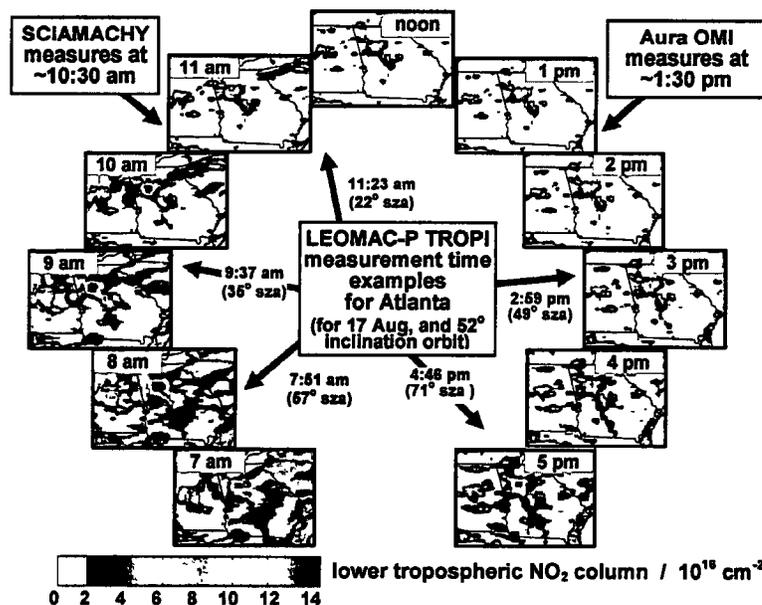


Fig. 4. Left two panels: the improvement in TROPI resolution over that of OMI on Aura. The improved TROPI resolution allows better identification of the sources of pollution emission. Letters indicate some urban areas (e.g., “B” for Brussels) in this region of Belgium, Holland and Germany. Right two panels: the improvement in SMLS resolution over that of MLS on Aura. This example is of a high-resolution model field of upper tropospheric CO as would be mapped by Aura MLS and by SMLS. Among many features evident from SMLS, but not from Aura MLS, is the thin filament (arrow) connecting enhanced CO over America to pollution from Asia.

LEOMAC-P will provide improved temporal resolution that is needed, on a global scale, for quantifying the variations in pollution throughout the day. It will, for the first time, provide global measurements of pollutants at multiple times per day. Figure 5 shows an example of NO<sub>2</sub> pollution over the southeastern U.S. Here – as in other polluted areas around the world – largest abundances of NO<sub>2</sub> occur early in the morning and late in the day, and are thus missed by the A-Train and SCIAMACHY. They will also be missed by planned operational missions and LEOMAC-S. The LEOMAC-P measurements precess through all times of day over the course of 36 days. All longitudes, over a wide latitude range, are measured each day over month-long periods that switch between northern and southern hemispheres. Measurements at all longitudes are crucial for tracking the worldwide long-range transport of pollution – which is predominantly west to east – and for observationally tracing pollution back to its specific sources. The orbit phase is chosen for summer air quality measurement priorities. Measurement coverages are quantified in section 5.

Fig. 5. Daily variation of NO<sub>2</sub> pollution over the southeastern U.S. on 17 August 2000. Each panel is a map of the lower tropospheric (1000-700 hPa column) NO<sub>2</sub> abundance at different Atlanta local times throughout the day [EPA CMAQ regional model results from Yongtao Hu of Georgia Tech]. Current (and planned) satellite instruments that measure NO<sub>2</sub> make measurements near mid-day and miss the larger values that occur both earlier and later. TROPI on LEOMAC-P will provide the first global measurements of NO<sub>2</sub>, and other pollutants, at multiple times per day and will thus provide needed new information on quantifying the overall magnitude of global pollution events. Blue outward-pointing arrows indicate LEOMAC-P TROPI measurement time examples for 17 August and a particular choice of orbit parameters. The corresponding solar zenith angles, sza, are also indicated. The TROPI NO<sub>2</sub> column measurement noise is  $\sim 0.1 \times 10^{16} \text{ cm}^{-2}$ .



**Benefits:** These measurements give crucial information for quantifying the global distribution of pollutants and their sources, and for progress in determining how pollution may be changing the ability of the atmosphere to 'cleanse itself'. By giving a direct observational connection between the global distribution of pollution and the pollution emission sources, they are essential for supporting the development of national and international policy to maintain and improve the quality of the air we breathe. LEOMAC's measurements of tropospheric O<sub>3</sub>, CH<sub>4</sub>, CO, NO<sub>2</sub>, CH<sub>2</sub>O as a proxy for VOCs, and SO<sub>2</sub> provide information needed for improving assessment of how the atmosphere's oxidizing capacity may be changing.

#### **4b. Determine how the ozone layer and its chemistry are changing.**

Changes in halocarbons and climate are affecting the chemistry of the stratosphere and the upper troposphere, particularly near the tropopause region.

LEOMAC provides the measurements needed to determine how stratospheric chemistry is changing and, thus, determine the stability of the ozone layer. It measures both the dominant chlorine reservoir (HCl) and reactive radical (ClO) involved in stratospheric O<sub>3</sub> depletion, giving crucial information on whether chlorine partitioning is changing with changing climate (e.g., a cooler stratosphere – predicted by climate change models – would cause more chlorine to be in the O<sub>3</sub>-destroying ClO form) and changing halocarbons. Its simultaneous daily maps of lower stratospheric temperature, HNO<sub>3</sub>, H<sub>2</sub>O, ClO, HCl, NO<sub>2</sub> (and possibly measurements of aerosol extinction by thick polar stratospheric clouds) provide needed information for understanding/tracking climate-sensitive microphysical processes that can trigger increased O<sub>3</sub> destruction. Measurements of the long-lived tracers N<sub>2</sub>O, CO (and, in many situations, H<sub>2</sub>O, O<sub>3</sub>, HCl and HNO<sub>3</sub>) give information on dynamics and transport that could also be affected by a changing climate. These measurements, along with temperature and geopotential height, diagnose tropopause structure and other dynamical effects that strongly influence column ozone. Measurements of the chemical species can be made in the presence of volcanic aerosol that can substantially perturb stratospheric chemistry. Measurements of volcanically-injected SO<sub>2</sub> provide information on the formation of aerosols that affect both chemistry and climate.

HCl in the upper stratosphere is indicative of the total chlorine loading of the stratosphere, and its measurement provides crucial information on whether international regulations to reduce stratospheric chlorine are having the desired effect. LEOMAC continues the long-term global HCl measurements from UARS and Aura. The observed decrease in HCl is consistent with the rate at which anthropogenic chlorine is expected to be cleansed from the stratosphere; which will take more than 50 years. We must continue tracking HCl to ensure that chlorine is being cleansed from the stratosphere as expected.

BrO, also measured by LEOMAC, is both the dominant form of bromine in the stratosphere and the dominant form of bromine that destroys O<sub>3</sub>. There are still regulatory issues regarding certain bromine compounds, and the BrO measurement provides information needed for policy decisions balancing economic and environmental concerns.

The LEOMAC measurements of H<sub>2</sub>O, HO<sub>2</sub>, and H<sub>2</sub>O<sub>2</sub> provide information to track destruction of ozone by hydrogen chemistry. The measurements of N<sub>2</sub>O, HNO<sub>3</sub>, NO<sub>2</sub>, and NO provide information to track destruction of ozone by nitrogen chemistry.

LEOMAC's high-resolution data will enable progress in stratospheric and upper tropospheric dynamics that was planned for Aura but lost due to a HIRDLS mishap at launch. The improved temporal resolution will help quantify the extent to which fast convective processes might be transporting short-lived ozone-depleting substances into the stratosphere.

**Benefits:** These measurements will provide data needed for assessing how changes in halocarbons and climate are affecting the stability of the ozone layer and for determining if international regulations are having the desired effect.

#### **4c. Quantify how changing atmospheric composition is affecting climate.**

Atmospheric pollutants can affect the formation and properties of aerosols and clouds that influence climate. Short-lived pollutants can also affect the concentration of long-lived atmospheric constituents that have climate impact, such as ozone, water vapor, ice clouds, carbon dioxide, and methane.

**Fig. 6:** Upper tropospheric CO pollution and cloud ice averages for 25 Aug through 6 Sep 2004 from Aura. LEOMAC will provide such measurements with better resolution multiple times per day, and provide additional key measurements such as CO in the lower and middle troposphere.



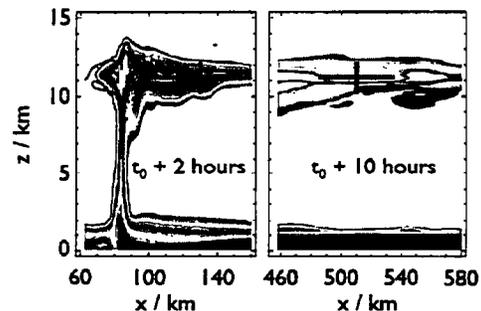
Determining the extent to which pollution and anthropogenic aerosols affect upper tropospheric cloudiness is crucial for improving the accuracy of climate change predictions. Figure 6 shows Aura MLS observations of correlations in large values of upper tropospheric cloud ice and uplifted pollution.

Has anthropogenic pollution contributed to the observed enhancement in clouds? This question is starting to be addressed with Aura data, but much better resolution in the microwave measurements, as can be provided by SMLS, is required. As also needed to improve climate models, TROPi will distinguish between reflecting and absorbing aerosols and continue the long TOMS/OMI global aerosol dataset. It is crucial that this record be continued, with key related measurements, in order to make progress in quantifying the effects of changing atmospheric composition on climate. Quantifying the processes that affect upper tropospheric O<sub>3</sub> is also crucial for reducing uncertainties in predictions of climate change. The increase in tropospheric O<sub>3</sub> since pre-industrial times is estimated to give the third-largest increase in direct radiative forcing of climate, and it is in the upper troposphere that the effect of O<sub>3</sub> is largest. LEOMAC provides needed information on the processes affecting upper tropospheric O<sub>3</sub> that will reduce the existing uncertainties in climate forcing by upper tropospheric O<sub>3</sub>.

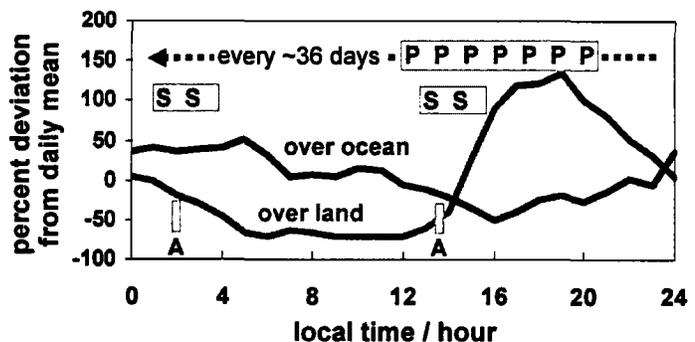
An important question, which applies to how atmospheric composition affects both upper tropospheric aerosols and ozone, is the extent to which the upper troposphere is 'short-circuited' to the boundary layer by convection. This has serious implications for climate change, long-range transport of pollution, and ozone layer stability. Figure 7 illustrates the typical spatial and temporal scales for convective deposition of boundary layer air into the upper troposphere. Figure 8 shows the diurnal variation of convection, and how LEOMAC provides needed new sampling to quantify its effects. LEOMAC's simultaneous measurements of cloud ice, H<sub>2</sub>O, H<sub>2</sub><sup>18</sup>O and HDO allow unique identification of air masses associated with convection.

**Benefits:** These measurements will improve our ability to understand and predict the effects of changes in atmospheric composition on climate forcings, and thus improve the accuracy of prediction models.

**Fig. 7.** Deposition of boundary layer air into the upper troposphere. Model predictions from Figure 5 of Mullendore et al. [*J. Geophys. Res.*, vol. 110, D06113, 2005] with crosses added to show the SMLS resolution. Color indicates the abundance of a boundary layer tracer at 2 and 10 hours into a convective simulation.



**Fig. 8.** Diurnal variation of convection, where the green curve is for convection over land and the blue is over ocean. For 208 K infrared temperature thresholds from Figure 4 of Chen and Houze [*Q. J. Roy. Met. Soc.*, vol. 123, pp. 357-388, 1997] with the temporal samplings of the 'A-train' (A) and of SMLS on LEOMAC-P (P), and LEOMAC-S (S), added.



#### 4d. Quantify the processes that control upper tropospheric water vapor and cloud ice.

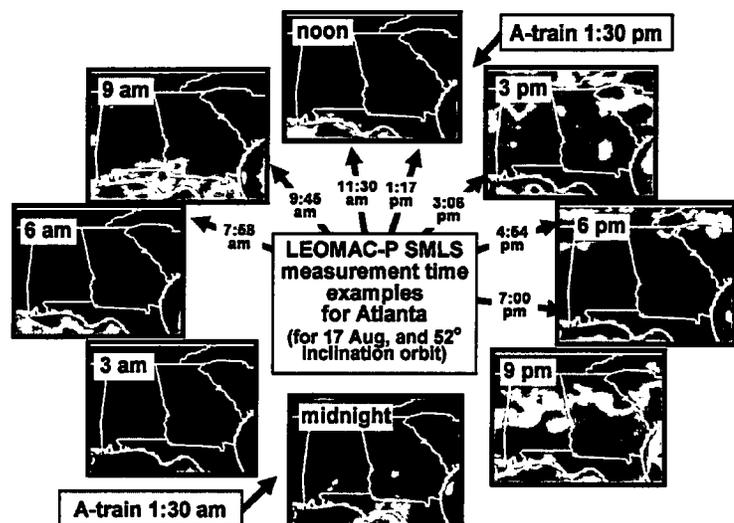
Upper tropospheric H<sub>2</sub>O and cloud ice are poorly measured by the existing operational network. Global data with better spatial and temporal resolution are needed for parameterizing convection and cloud formation processes to improve weather and climate prediction models.

Upper tropospheric H<sub>2</sub>O can either amplify or attenuate the climatic effects of increases in other greenhouse gases, depending upon the process affecting it and the spatial and temporal scales of the process. Measurement of upper tropospheric H<sub>2</sub>O has historically been very difficult – due both to its relatively small abundance and to the presence of ice clouds that degrade or prevent its measurement by many techniques. Microwave limb sounding, however, is well-suited to this measurement because of its combination of good vertical resolution, sensitivity and long wavelengths that can measure both gas phase abundances in the presence of ice clouds and the larger ice amounts that saturate or block shorter wavelength techniques. (Scattering is inversely proportional to the 4<sup>th</sup> power of wavelength: small particles affect 1 mm wavelength microwaves 10<sup>8</sup> times less than 10 μm infrared.). The dramatic improvement in coverage and resolution of SMLS on LEOMAC – particularly on LEOMAC-P – compared to previous MLS instruments, and its additional measurements of H<sub>2</sub><sup>18</sup>O and HDO (which yield key information on convection and condensation processes) will provide crucial details of mechanisms affecting upper tropospheric H<sub>2</sub>O and its influence on climate variability.

One of the most significant shortcomings in current weather and climate models is the representation of clouds and their feedbacks on the global water and energy cycles. This shortcoming includes both convective and non-convective clouds, applies to both global circulation models (GCMs) and regional models, and impacts both weather and climate predictions. The accurate depiction of clouds and related hydrological processes in the upper troposphere is essential for predicting climate change. It is in the upper troposphere that water vapor feedbacks are most acute and cloud feedbacks – in this case from deep convective and high cirrus/ice clouds – are undeniably significant. Aura MLS has demonstrated simultaneous observations of cloud ice and water vapor, which are important for understanding cloud formation. These data have been used by the European Center for Medium Range Weather Forecasting (ECMWF) to justify changing ice supersaturation parameters in their Integrated Forecast System, which has led to clear improvements in performance – in particular the simulation of the location and intensity of tropical deep convection, through indirect radiative feedbacks. SMLS on LEOMAC-P provides the improvement in resolution needed for additional progress to improve the accuracy of model predictions. Figure 9 shows, for example, the diurnal variation of convection over the southeastern U.S. in summer and measurement time examples for SMLS on LEOMAC-P.

**Benefits:** These measurements will provide data needed to improve quantification of processes that control upper tropospheric water vapor and cloud ice and, thus, should improve the accuracy of global circulation models used for weather and climate predictions.

**Fig. 9.** Diurnal variation of convection over the southeastern U.S. in summer, and temporal coverage example for SMLS on LEOMAC-P. Each panel shows the Jun-Jul-Aug 1999 average occurrence of strong convection (to at least ~10 km height) at different local times throughout the day [from Baijun Tian of JPL, and based on GOES 11 μm brightness temperatures less than 230 K]. Red colors, for 6 hours per day typical of this region, corresponds to ~5 inches of rain over Jun-Jul-Aug. Dark blue colors indicate essentially no convection. Blue outward-pointing arrows indicate LEOMAC-P SMLS measurement time examples for for 17 August and a particular choice of orbit parameters. The A-train makes measurements at ~1:30 am and ~1:30 pm, and misses the evolution and intense convection in late afternoon.



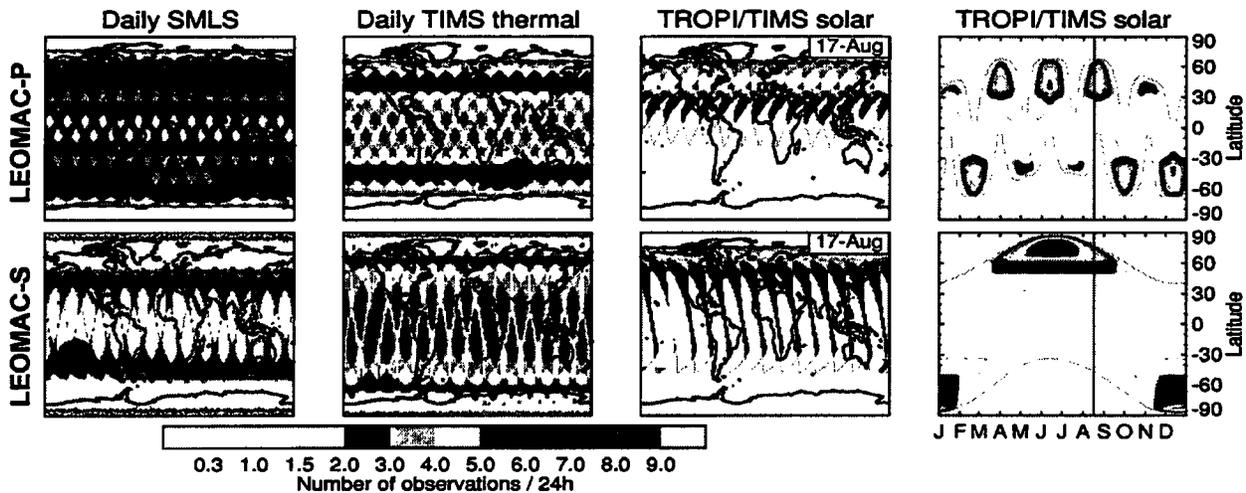
## 5. Measurement coverage and resolution comparisons

Figures 10 and 11 compare coverage and resolution for LEOMAC-P, LEOMAC-S, and GEOMAC (a geosynchronous satellite atmospheric composition mission also being studied). As quantified in Figure 10, LEOMAC-P gives more frequent measurements at mid-latitudes where most of the population lives, whereas LEOMAC-S gives measurements heavily weighted to polar regions where planned operational missions will provide a wealth of such observations. Planned operational measurements will fill the 'gaps' where the LEOMAC-P coverage switches monthly between northern and southern hemispheres.

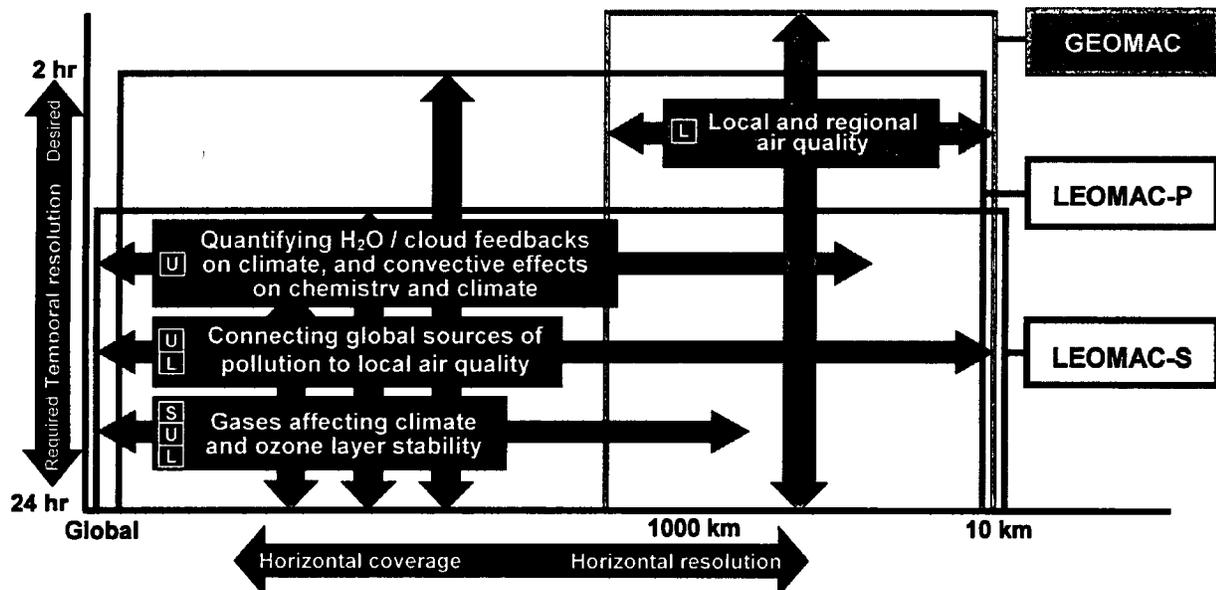
Figure 11 is an overview of the overarching scientific issues that need to be addressed by future atmospheric composition missions, the coverage and resolution needed to address these issues, and the capabilities of LEOMAC-P, LEOMAC-S and GEOMAC. LEOMAC-P provides global measurements with better temporal resolution than LEOMAC-S, and provides both the global coverage and vertical resolution not available from GEOMAC.

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**Fig. 10.** Number of observations per each 24 hour period for LEOMAC-P (top row) and LEOMAC-S (bottom row). Everywhere in a given color is measured that number of times, with  $10 \times 10$  km horizontal resolution for TROP/TIMS and  $50 \times 50$  km for SMLS. The left three columns show an example for Aug 17. The rightmost column shows the annual variation for the TROP/TIMS solar measurements, where the vertical line is 17 August. (The number of measurements per 24 hour period for SMLS and TIMS/thermal has only a minor variation throughout the year.)



**Fig. 11.** Overarching scientific issues that need to be addressed by future atmospheric composition missions – and LEOMAC-P, LEOMAC-S, and GEOMAC horizontal, vertical and temporal coverage and resolution. For the various measurement objectives, “L” indicates that observations are needed in the lower troposphere; “U” that they are needed in the upper troposphere; and “S” that they are needed in the stratosphere. The right end of each

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