



## Laboratory for Atmospheres 2007 Technical Highlights



**Cover Caption:** Field campaigns are a central element in the research carried out by Laboratory scientists. During 2007, the Tropical Composition, Cloud, and Climate Coupling (TC4) mission was the major effort. The cover photo is a group picture of participants in the DC8 portion of the mission. Over 350 people from NASA, NOAA, NCAR, universities, Costa Rica, and Panama directly participated in TC4. NASA's DC-8 "Flying Laboratory" carried a complement of 26 instruments including upward and downward pointing lidars (ozone, water vapor, and aerosols) and radiometers, as well as instruments for *in situ* measurements of gases, and cloud and aerosol particles. The DC-8 was key for Aura validation objectives as it was able to underfly the afternoon Aura overpass, which was not possible for other TC4 aircraft, the ER-2 and WB-57, because of typical afternoon weather conditions at the airfield.

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**Laboratory for Atmospheres  
2007 Technical Highlights**

National Aeronautics and  
Space Administration

**Goddard Space Flight Center**  
Greenbelt, Maryland 20771

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**Goddard Space Flight Center**  
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Dear Reader:

Welcome to the Laboratory for Atmospheres' 2007 Technical Highlights report. I thank you for your interest. We publish this report each year to describe our research and to summarize our accomplishments.

This document is intended for a broad audience. Our readers include colleagues within NASA, scientists outside the agency, science graduate students, and members of the general public. Inside are descriptions of our organization and facilities, our major activities and science highlights, and our education and outreach accomplishments for calendar year 2007.

The Laboratory's approximately 230 scientists, technologists, and administrative personnel are part of the Earth Sciences Division in the Sciences and Exploration Directorate of the NASA Goddard Space Flight Center. The Laboratory for Atmospheres is continuing our mission of advancing knowledge and understanding of the Earth's atmosphere.

Laboratory scientists continued having a productive year organizing and participating in international field campaigns, developing and refining instruments, analyzing data, expanding data sets, and improving models. The Aura spacecraft, launched in July 2004 is an important component of the Lab's science activities through validation campaigns and data analysis and modeling. These efforts are helping us better understand our home planet's environment, and are increasing our knowledge of the complex chemistry of the atmosphere.

Several noteworthy events took place during 2007. Field campaigns contributing to Aura validation efforts in 2007 began with the SAUNA II campaign in Sodankylä, Finland during February. This year's largest mission, carried out in the summer of 2007, was the Tropical Composition, Cloud, and Climate Coupling (TC4) campaign. This effort involved personnel from all three of the Laboratory's branches, as well as investigators from other NASA Centers, NOAA, NCAR, universities, Costa Rica, and Panama. Other campaigns were the Cloud and Land Surface Interaction Campaign (CLASIC), and the Water Vapor Validation Experiment-Satellite/Sondes (WAVES\_2007) at the Howard University Research Campus in Beltsville, MD. These, and several other field campaigns in which Laboratory members participated are described in detail in Section 4, Major Activities. WAVES\_2007, which involved students from Howard University, as well as Laboratory members, is further discussed in Section 6, Education and Outreach.

As in previous years, Laboratory scientists garnered many top professional honors. Bob Adler (613) received the William Nordberg Award for his outstanding long-term contributions to precipitation science, in particular his dedicated efforts as TRMM Project Scientist in ensuring the phenomenal success of that mission. Tom McGee (613.3) received the Alan Berman Research Publication Award from The Department of the Navy and Naval Research Laboratory (NRL) for technical merit and clarity. Anne Douglass (613.3) and William Lau (613) were

honored as AGU Fellows at the AGU Honors Ceremony held in conjunction with the spring AGU Joint Assembly, Acapulco, Mexico. These, and numerous other awards received by Laboratory members, are described in Section 5.6 of this report.

We continued the very successful Laboratory Monthly Seminar Series, which focused on precipitation, clouds, aerosol and their physical/chemical linkages; details of the series can be found on our Web site.

The year 2007 was also a time to bid farewell to Jean Howard, our Laboratory's secretary for more than 3 years, and to retirees Andy Negri, and Chuck Cote. Andy had a distinguished career spanning 28 years as a Meteorologist in the Mesoscale Atmospheric Processes Branch. Chuck retired after 45 years of Government service. He served as the Associate Chief of our Laboratory for more than 20 years. I am pleased to welcome Ralph Kahn to our Laboratory staff. Ralph is joining the Climate and Radiation Branch where he will continue his work on aerosols carried out during his tenure at JPL. He is also active in educational activities and maintains an educational Web site described in Section 6 of this report.

This report is being published in two media: a printed version, and an electronic version on our Laboratory for Atmospheres Web site, <http://atmospheres.gsfc.nasa.gov>. It continues to be redesigned to be more useful for our scientists, colleagues, and the public. We welcome comments on this 2007 report and on the material displayed on our Web site. Your comments may be submitted online. Please check out our Web site.



William K.-M. Lau,  
Chief, Laboratory for Atmospheres, Code 613

May 2008

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## PREFACE

The Technical Highlights for 2007 is the product of the efforts of all the members of the Laboratory for Atmospheres. Their dedication to advancing Earth Science through conducting research, developing and running models, designing instruments, managing projects, running field campaigns, and numerous other activities has produced many significant results. These can only be briefly highlighted in this report.

Production of this report has been guided by William K.-M. Lau, Chief of the Laboratory for Atmospheres who, along with Charles Cote (retired), our former Associate Chief, and Jim Irons, our current Associate Chief, checked the report for accuracy, made suggestions regarding its content, and contributed to several sections. Walt Hoegy, editor for several years and now an emeritus member of the Laboratory, continued his association with this report by making valuable suggestions concerning the organization of this report and its content. Members of the administrative staff of the Laboratory and its branches: Caroline Maswanganye, Cathy Newman, and Pat Lubber were instrumental in gathering material for the report and soliciting the contributions of Lab members. Elaine Firestone performed the final formatting, turning this report into a polished product in a timely manner.

Special thanks are due to Laura Rumburg who has worked in the scientific environment of the Laboratory for 29 years and on production of the Laboratory's Technical Highlights since its inception 12 years ago. Laura has served in many capacities through these years. At various times she has gathered and edited material for the report, converted the printed version to HTML for the Laboratory's Web site, and posted and maintained the electronic version on that Web site. Most recently, she has gathered material for the Major Activities section, carefully proofread the report, and corrected many errors present in the initial drafts. Laura will be retiring this year. Future editors and staff will miss her dedication to this endeavor.

Paul Przyborski, our Laboratory Web Master, published this report on our Web site:  
<http://atmospheres.gsfc.nasa.gov>.

—*Richard W. Stewart*



**Mission: Advance Knowledge and Understanding of the Atmospheres,  
of the Earth and Other Planets**

## 1. INTRODUCTION

The Laboratory for Atmospheres (Code 613) is part of the Earth Sciences Division (Code 610), formerly the Earth–Sun Exploration Division, under the Sciences and Exploration Directorate (Code 600) based at NASA’s Goddard Space Flight Center in Greenbelt, Maryland.

In line with NASA’s Exploration Initiative, the Laboratory executes a comprehensive research and technology development program dedicated to advancing knowledge and understanding of the atmospheres of the Earth and other planets. The research program is aimed at understanding the influence of solar variability on the Earth’s climate; predicting the weather and climate of the Earth; understanding the structure, dynamics, and radiative properties of precipitation, clouds, and aerosols; understanding atmospheric chemistry, especially the role of natural and anthropogenic trace species on the ozone balance in the stratosphere and the troposphere; and advancing our understanding of physical properties of the Earth’s atmosphere.

The research program identifies problems and requirements for atmospheric observations via satellite missions. Laboratory scientists conceive, design, develop, and implement ultraviolet, infrared, optical, radar, laser, and lidar technology for remote sensing of the atmosphere. Laboratory members conduct field measurements for satellite data calibration and validation, and carry out numerous modeling activities. These modeling activities include climate model simulations, modeling the chemistry and transport of trace species on regional to global scales, cloud-resolving models, and development of next-generation Earth system models. Interdisciplinary research is carried out in collaboration with other laboratories and research groups within the Earth Sciences Division, across the Sciences and Exploration Directorate and with partners in universities and other Government agencies.

The Laboratory for Atmospheres is a vital participant in NASA’s research agenda. Our Laboratory often has relatively large programs, sizable satellite missions, and observational campaigns that require the cooperative and collaborative efforts of many scientists. We ensure an appropriate balance between our scientists’ responsibility for these large collaborative projects and their need for an active individual research agenda. This balance allows members of the Laboratory to continuously improve their scientific credentials.

Members of the Laboratory interact with the general public to support a wide range of interests in the atmospheric sciences. Among other activities, the Laboratory raises the public’s awareness of atmospheric science by presenting public lectures and demonstrations, by making scientific data available to wide audiences, by teaching, and by mentoring students and teachers. The Laboratory makes substantial efforts to attract new scientists to the various areas of atmospheric research. We strongly encourage the establishment of partnerships with Federal and state agencies that have operational responsibilities to promote the societal application of our science products.

This report describes our role in NASA’s mission, gives a broad description of our research, and summarizes our scientists’ major accomplishments during calendar year 2007. The report also contains useful information on human resources, scientific interactions, and outreach activities. This report is published in a printed version, and an electronic version on our Laboratory for Atmospheres Web site, <http://atmospheres.gsfc.nasa.gov/>.



## 2. STAFF, ORGANIZATION, AND FACILITIES

### 2.1 Staff

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The diverse staff of the Laboratory for Atmospheres is made up of scientists, engineers, technicians, administrative assistants, and co-located (Code 603: Administration and Resources Management Office) resource analysts, with a total staff of 230.

The civil servant composition of the Laboratory consists of 53 members; 49 are scientists, 1 an engineer, 2 administrative support, and 1 technical manager. Of the 49 civil servant scientists and engineers, 98% hold doctoral degrees.

An integral part of the Laboratory staff is composed of onsite research associates and contractors. The research associates are primarily members of joint centers involving the Earth Sciences Division and nearby university associations, e.g., the Joint Center for Earth Systems Technology (JCET), the Goddard Earth Sciences and Technology Center (GEST), and the Earth System Science Interdisciplinary Center (ESSIC), or are employed by universities with which the Laboratory has a collaborative relationship, such as George Mason University, University of Arizona, and Georgia Tech. Of the 85 research associates, 76% hold Ph.D.s. The onsite contractors are a very important component of the staffing of the Laboratory. Out of the total of 89 onsite contractors, 20% hold Ph.D.s. In addition to these members, the Laboratory currently hosts 4 NASA Postdoctoral Program (NPP) research associates. All hold Ph.D.s. The makeup of our Laboratory, therefore, is 23% civil servants, 37% research associates, 39% contractors and 2% NPP associates. Round off error accounts for the extra 1%.

The number of refereed publications (from 1993) and proposals (from 1997) written by Laboratory members is shown in Figure 2.1. The number in each category is shown above the bars. The difference between the red and blue bars gives the number of papers that our scientists co-authored with outside scientists and is one measure of our extensive collaboration. The yellow bars show the number of proposals written in recent years. The reduced number of refereed papers in 2004 and 2005 was due in part to the loss of the Atmospheric Experiment Branch, which is no longer part of our Laboratory, to reduction in civil service scientists from attrition, and to the implementation of full cost accounting, which necessitates increased time spent on proposal writing.

### Publications History

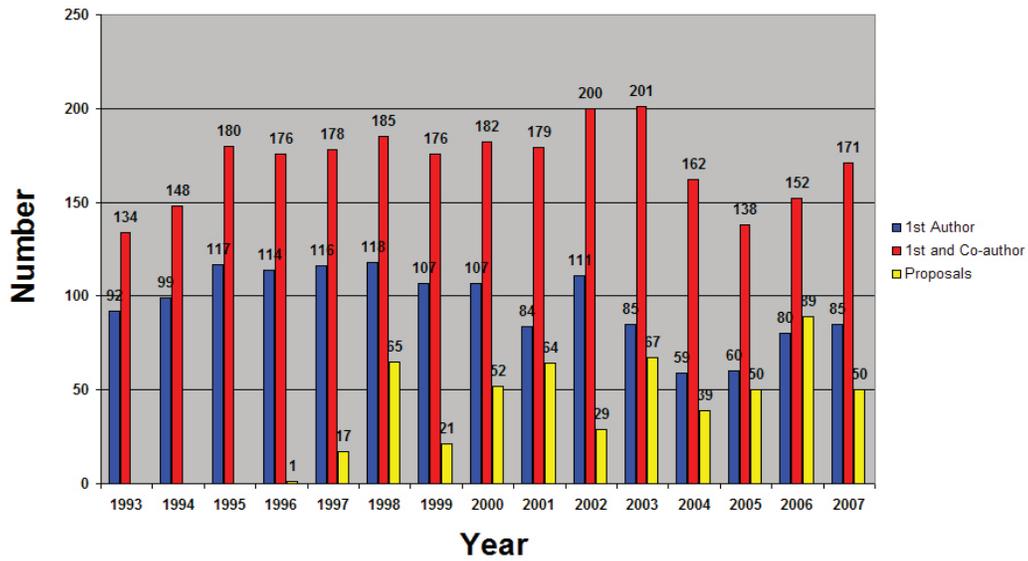


Figure 2.1 Number of proposals and refereed publications by Laboratory for Atmospheres members over the years. The red bar is the total number of publications where a Laboratory member is the first author or co-author, and the blue bar is the number of publications where a Laboratory member is first author. Proposals submitted are shown in yellow.

## 2.2 Organization

The management and branch structure for the Laboratory for Atmospheres at the end of 2007 is shown in Figure 2.2.

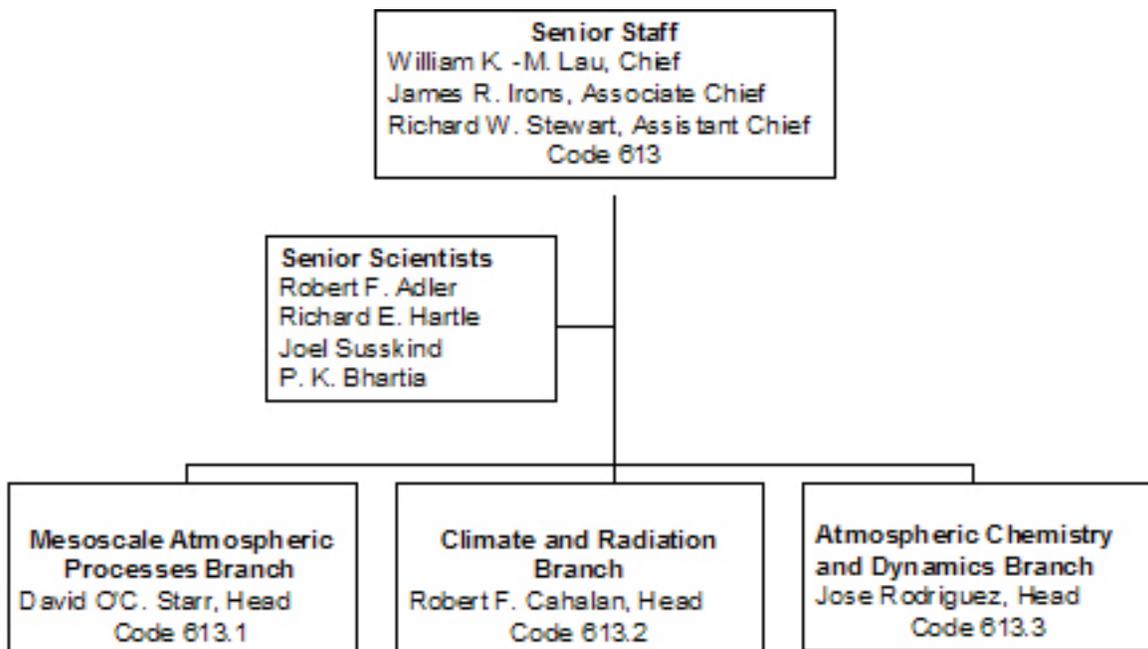


Figure 2.2 Laboratory for Atmospheres organization chart at the end of calendar year 2007.

## 2.3 Branch Descriptions

The Laboratory has traditionally been organized into branches; however, we work on science projects that are becoming more and more cross-disciplinary. Branch members collaborate with each other within their Branch, across branches and Laboratories, and across Divisions within the Directorate. Some of the recent cross-disciplinary research themes of interest in the Laboratory are the Global Water and Energy Cycle, Carbon Cycle, Weather and Short-Term Climate Forecasting, Long-Term Climate Change, Atmospheric Chemistry, and Aerosols. The employment composition of the Senior Staff Office (613) and the three Branches is broken down by Civil Servant, Associate, and Contractor as shown in Figure 2.3.

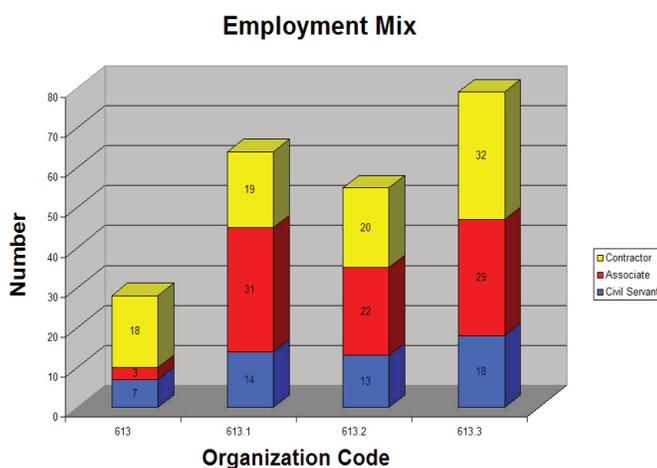


Figure 2.3 Employment composition of the members of the Laboratory for Atmospheres.

A brief description is given below for each of the Laboratory's three Branches. Later, in Section 5, the Branch Heads summarize the science goals and achievements of their Branches. The Branch summaries are supplemented by a selection of news items, publication lists, and samples of highlighted journal articles given in Appendices 1 through 3, respectively.

### Mesoscale Atmospheric Processes Branch, Code 613.1

The mission of this Branch is to understand the physics and dynamics of atmospheric processes through the use of satellite, airborne, and surface-based remote sensing observations and model simulations. Development of advanced remote sensing instrumentation (primarily lidar and radar) and techniques to measure aerosols, clouds, water vapor and winds in the troposphere is a central focus. Key areas of investigation are cloud and precipitation systems (including aerosol/cloud interaction) and their environments, ranging from the scale of individual clouds and thunderstorms to mesoscale convective systems and cyclonic storms. Characterizing climate impacts at regional and global scales, e.g., El Niño Southern Oscillation (ENSO), is also a major focus. Besides developing and using advanced instrumentation and satellite observations, the Branch has vigorous cloud system modeling activities. We are integrating various NASA Goddard physical packages (microphysics, radiation, and land surface models) into a next generation weather forecast model (known as the weather and research forecast model or WRF), and implementing a mesoscale cloud-resolving model (Goddard Cumulus Ensemble Model) into a global model (super-parameterization). Ultimately, we hope to develop a global cloud-resolving model. In summary, the Branch focuses its research on all aspects of the atmospheric hydrologic cycle, its connections to the global energy cycle, and associated hazards, such as hurricanes, floods and landslides. The Branch plays a key science leadership role in satellite missions, such as the Tropical Rainfall Measurement Mission (TRMM) and the Geoscience Laser Altimeter System (GLAS) on ICESat. Similarly, we contribute to the formulation of new mission concepts, such as the Global Precipitation Mission (GPM), and to mission studies focused on the Decadal Survey Missions (National Academy of Science) for NASA HQ. Participation in field campaigns such

as the NASA African Monsoon Multidisciplinary Analysis (NAMMA), Costa Rica Aura Validation Experiment (CR-AVE), the Calipso/CloudSat Validation Experiment (CC-VEEx), and the Tropical Composition, Cloud, and Climate Coupling (TC4) experiment in 2007 continues to be a high priority. Further information about Branch activities may be found on the Web at <http://atmospheres.gsfc.nasa.gov/meso/>.

### **Climate and Radiation Branch, Code 613.2**

The Climate and Radiation Branch has a threefold mission:

- (1) to understand, assess, and predict climate variability and change, including the impact of natural forcing and human activities on climate now and in the future;
- (2) to assess the impacts of climate variability and change on society; and
- (3) to consider strategies for adapting to, and mitigating, climate variability and change.

To address this mission, a wide range of scales is studied, from the spatial microscales of nucleation processes to the Sun–Earth distance, and from microsecond to geologic time scales. Research focus areas include observational and modeling studies of tropospheric aerosols, cloud processes, rainfall, solar radiation, and surface properties. Key disciplines are radiative transfer, both as a driver for climate studies and as a tool for the remote sensing of parameters of the Earth's climate system; climate theory and modeling over the full range of scales; and the development of new methods for the analysis of climate data. Ongoing projects in cooperation with other NASA centers, Government agencies, and with university partners include development and assessment of observational climate data records, incorporation of microphysical cloud-aerosol interactions in climate models, addressing gaps in the current climate observing system, development and deployment of new instruments, and planning for future space-based and *in situ* missions. Further information about Branch activities may be found at <http://climate.gsfc.nasa.gov/>.

### **Atmospheric Chemistry and Dynamics Branch, Code 613.3**

The Atmospheric Chemistry and Dynamics Branch conducts research on remote sensing of atmospheric trace gases and aerosols from satellite, aircraft, and ground, and develops computer-based models to understand and predict the long-term evolution of the ozone layer, changes in global air quality caused by human activity, and the interaction between atmospheric composition and climate change. The Branch develops and maintains research quality, long-term data sets of ozone, aerosols, and surface ultraviolet (UV) radiation for assessment of the health of the ozone layer and its environmental impact. It continues its long history of providing science leadership for NASA's atmospheric chemistry satellites, such as the recently launched Earth Observing System (EOS) Aura satellite, particularly its Ozone Monitoring Instrument (OMI), and works closely with the National Oceanic and Atmospheric Administration (NOAA) on ozone sensors aboard the operational weather satellites (NOAA-N), the National Polar Orbiting Environmental Satellite System (NPOESS), and the NPOESS Preparatory Project (NPP). The Aura satellite hosts four advanced atmospheric chemistry instruments designed to study the evolution of stratospheric ozone, climate, and air quality. Analysis of Aura data will be the central focus of the Branch activities in the coming years. Modeling activities in the Branch will continue to focus on simulations for the analysis of Aura data, and assessment of the impact of anthropogenic activity on the atmospheric composition and climate. Further information on Branch activities may be found on the Web at <http://atmospheres.gsfc.nasa.gov/acd/>.

Branch Web sites may also be found by clicking on the branch icons at the Laboratory home page <http://atmospheres.gsfc.nasa.gov/>.

## 2.4 Facilities

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### Computing Capabilities

Computing capabilities used by the Laboratory range from high-performance supercomputers to scientific workstations to desktop personal computers. Each Branch maintains its own system of computers, which are a combination of Windows, Linux, and Mac OS X computers. A major portion of scientific data analysis and manipulation, and image viewing is still done on Unix cluster machines with increasing amounts of data analysis and imaging done on single-user personal computers.

### Lidar

The Laboratory has well-equipped facilities to develop lidar systems for airborne and ground-based measurements of clouds, aerosols, methane, ozone, water vapor, pressure, temperature, and winds. Lasers capable of generating radiation from 266 nm to beyond 1,000 nm are available, as is a range of sensitive photon detectors for use throughout this wavelength region. Details may be found in the *Laboratory for Atmospheres Instrument Systems Report*, NASA/TP-2005-212783, which is also available on the Laboratory's home page.

### Radiometric Calibration and Development Facility

The Radiometric Calibration and Development Facility (RCDF) supports the calibration and development of instruments for ground- and space-based observations for atmospheric composition including gases and aerosols. As part of the EOS calibration program, the RCDF provides calibrations for all national and international ultraviolet and visible (UV/VIS) spaceborne solar backscatter instruments, which include the Solar Backscatter Ultraviolet/Version 2 (SBUV/2) and TOMS instruments, and the European backscatter instruments flying on the Environmental Satellite (EnviSat) and Aura. The RCDF also provides laboratory resources for developing and testing of advanced spaceborne instruments being developed in the Laboratory for Atmospheres. In addition, ground-based sky-viewing instruments used for research and validation measurements of chemistry missions, such as Envisat and Aura, are also supported in the RCDF. The facility maintains state-of-the-art instrument radiometric test equipment and has a close relationship with the National Institute of Standards and Technology (NIST) for maintaining radiometric standards. For further information contact Scott Janz, [Scott.J.Janz@nasa.gov](mailto:Scott.J.Janz@nasa.gov).



### 3. OUR RESEARCH AND ITS PLACE IN NASA'S MISSION

The direction of our research effort is influenced by NASA's overall program, outlined in the Agency's 2006 Strategic Plan available at [http://www.nasa.gov/pdf/142302main\\_2006\\_NASA\\_Strategic\\_Plan.pdf](http://www.nasa.gov/pdf/142302main_2006_NASA_Strategic_Plan.pdf). The new vision for space exploration resulted in the transformation of NASA's goals and produced a reorganization of NASA Headquarters and the NASA Centers during 2004 and 2005. The former seven strategic enterprises have been transformed into four directorates: Science Mission Directorate, Space Operations Mission Directorate, Exploration Systems Mission Directorate, and Aeronautics Research Mission Directorate. These directorates are charged with accomplishing six goals described in the 2006 Strategic Plan. In addition, the Laboratory's research is guided by recommendations made in the decadal survey, "Earth Science and Applications from Space: Imperatives for the Next Decade and Beyond", published by the National Academy of Sciences in 2007 (<http://www.nap.edu/catalog/11820.html>).

Following NASA Headquarters, Goddard Space Flight Center has reorganized and formed one Directorate combining Earth and Space Science into the Sciences and Exploration Directorate. The four Divisions under the new Sciences and Exploration Directorate are Earth Sciences (Code 610), Astrophysics Science (Code 660), Heliophysics Science (Code 670), and Solar System Exploration (Code 690). The Laboratory for Atmospheres (Code 613) is under the Earth Sciences Division (ESD). Our three Branches, Mesoscale Atmospheric Processes (Code 613.1), Climate and Radiation (Code 613.2), and Atmospheric Chemistry and Dynamics (Code 613.3) will continue their strong programs of research in Earth Sciences and, in this way, will make significant contributions to the President's Exploration Initiative. In October 2005, the Earth-Sun Exploration Division, now ESD, published a strategic plan outlining the Division's mission and goals in greater detail than the Agency plan. The Laboratory's research is guided by the goals contained in these plans. The remainder of this section outlines the connection of our research to NASA's mission and strategic plans.

The Laboratory for Atmospheres has a long history (40+ years) in Earth Science and Space Science missions studying the atmospheres of Earth and the planets. The wide array of our work reflects this dual history of atmospheric research from:

- (1) the early days of the Television Infrared Observation Satellite (TIROS) and Nimbus satellites with emphasis on ozone, Earth radiation, and weather forecasting; and
- (2) the thermosphere and ionosphere satellites, the Orbiting Geophysical Observatory (OGO), the Explorer missions, and the Pioneer Venus Orbiter, to the more recent Galileo and Cassini missions and the current Earth Observing System (EOS) mission.

A current focus is on global climate change and one goal is to increase the accuracy and lead-time with which we can predict weather and climate change. The Laboratory for Atmospheres conducts basic and applied research in the cross-disciplinary research areas outlined in Table 3.1, and Laboratory scientists focus their efforts on satellite mission planning, instrument development, data analysis, and modeling.

Table 3.1: Science themes and our major research areas.

Science Themes	Major Research Areas
Aerosol	• Aerosol
Atmospheric Chemistry	• Atmospheric Chemistry and Ozone
Carbon Cycle	• Atmospheric Hydrologic Cycle
Climate Change	• Carbon Cycle
Global Water and Energy Cycle	• Clouds and Radiation
Weather and Short-term Climate Forecasting	• Climate Variability and Prediction
	• Mesoscale Processes
	• Precipitation Systems
	• Severe Weather
	• Chemistry-Climate Modeling
	• Global and Regional Climate Modeling
	• Data Assimilation
	• Tropospheric Winds

Our work can be classified into four primary activities or products: measurements, data sets, data analysis, and modeling. Table 3.2 depicts these activities and some of the topics they address.

Table 3.2: Laboratory for Atmospheres science activities.

Measurements	Data Sets	Data Analysis	Modeling
Aircraft	Assimilated products	Aerosol-cloud climate interaction	Atmospheric chemistry
Balloon	Global precipitation	Aerosol	Clouds and mesoscale
Field campaigns	MODIS <sup>a</sup> cloud and aerosol	Atmospheric hydrologic cycle	Coupled climate–ocean
Ground	OMI <sup>b</sup> aerosol	Climate variability and climate change	Data assimilation
Space	OMI surface UV	Clouds and precipitation	Data retrievals
	OMI Trace Species Column Measurements	Global temperature trends	General circulation
	TOVS <sup>c</sup> Pathfinder	Ozone and trace gases	Radiative transfer
	TRMM <sup>d</sup> Global precipitation products	Radiation	Transport models
	TRMM validation products	UV-B <sup>e</sup> measurements	Weather and climate
		Validation studies	

- a. Moderate Resolution Imaging Spectroradiometer
- b. Ozone Monitoring Instrument
- c. TIROS Operational Vertical Sounder
- d. Tropical Rainfall Measuring Mission
- e. Ultraviolet-B

Classification in the four major activity areas: measurements, data sets, data analysis, and modeling, is somewhat artificial, in that the activities are strongly interlinked and cut across science priorities and the organizational structure of the Laboratory. The grouping corresponds to the natural processes of carrying out scientific research: ask the scientific question, identify the variable needed to answer it, conceive the best instrument to measure the variable, generate data sets, analyze the data, model the data, and ask the next question.



## 4. MAJOR ACTIVITIES

The previous section outlined the science activities pursued in the Laboratory for Atmospheres. This section presents summary paragraphs of some of our major activities in measurements, field campaigns, data sets, data analysis, and modeling. In addition, we summarize the Laboratory's support for NOAA's remote sensing requirements. The section concludes with a listing of project scientists, and a description of interactions with other scientific groups.

### 4.1 Measurements

Studies of the atmosphere of Earth require a comprehensive set of observations, relying on instruments borne on spacecraft, aircraft, balloons, or those that are ground-based. Our instrument systems 1) provide information leading to basic understanding of atmospheric processes, and 2) serve as calibration references for satellite instrument validation.

Many of the Laboratory's activities involve developing concepts and designs for instrument systems for space-flight missions, and for balloon-, aircraft-, and ground-based observations. Airborne instruments provide critical *in situ* and remote measurements of atmospheric trace gases, aerosol, ozone, and cloud properties. Airborne instruments also serve as stepping-stones in the development of spaceborne instruments, and serve an important role in validating spacecraft instruments.

Table 4.1 shows the space missions that support scientific disciplines in the Laboratory. Satellites are shown in the left-most column. Instruments used by Laboratory scientists are listed in the Table under the supported disciplines in the first row. These instruments are those that were built in the Laboratory, for which a Laboratory scientist had responsibility as Instrument Scientist, for which Laboratory scientists were responsible for algorithm development, calibration and data analysis, or that provided data used by Laboratory scientists for model validation and development.

Table 4.1: Principal instruments supporting scientific disciplines in the Laboratory for Atmospheres.

Satellite	Atmospheric Structure and Dynamics	Atmospheric Chemistry	Clouds and Radiation
AIM	CIPS	SOFIE	CDE SOFIE
Aqua	AMSU AMSR-E HSB AIRS	AIRS	CERES AMSR-E AIRS MODIS
Aura	TES	OMI	MLS
Calipso			CPL
CloudSat			CRS
DSCOVR*	EPIC	EPIC	NISTAR EPIC
GOES	Sounder		Imager Sounder

GPM	DPR GMI		DPR GMI
NPP*	ATMS CrIS VIIRS	OMPS	VIIRS
POES			AVHRR
Terra		MOPITT	CERES MISR MODIS
ICESat			GLAS

\* Planned mission, not yet launched

AIM:	Aeronomy of Ice in the Mesosphere
AIRS:	Atmospheric InfraRed Sounder
AMSR-E:	Advanced Microwave Scanning Radiometer for EOS
AMSU:	Advanced Microwave Sounding Unit
ATMS:	Advanced Technology Microwave Sounder
AVHRR:	Advanced Very High Resolution Radiometer
CDE:	Cosmic Dust Experiment
CERES:	Clouds and the Earth's Radiant Energy System
CIPS:	Cloud Imaging and Particle Size experiment
CPL:	Cloud Physics Lidar
CrIS:	Cross-track Infrared Sounder
CRS:	Cloud Radar System
DSCOVR:	Deep Space Climate Observatory
DPR:	Dual-frequency Precipitation Radar
EPIC:	Earth Polychromatic Imaging Camera
GLAS:	Geoscience Laser Altimeter System
GMI:	GPM Microwave Imager
GOES:	Geostationary Operational Environmental Satellite
GPM:	Global Precipitation Measurement
HSB:	Humidity Sounder for Brazil
ICESat:	Ice, Cloud, and land Elevation Satellite
MISR:	Multi-angle Imaging SpectroRadiometer
MLS:	Microwave Limb Sounder
MODIS:	Moderate Resolution Imaging Spectroradiometer
MOPITT:	Measurement of Pollution in the Troposphere
NISTAR:	National Institute of Standards and Technology Advanced Radiometer
NPP:	NPOESS Preparatory Project
NPOESS:	National Polar Orbiting Environmental Satellite System
OMI:	Ozone Monitoring Instrument
OMPS:	Ozone Mapping and Profiler Suite
POES:	Polar Orbiting Environmental Satellite
SOFIE:	Solar Occultation for Ice Experiment
TES:	Tropospheric Emission Spectrometer
VIIRS:	Visible/Infrared Imager/Radiometer Suite

Table 4.2 lists instruments used in suborbital missions supporting scientific disciplines in the Laboratory. The left-most column indicates each instruments deployment.

Table 4.2: Instruments used in Suborbital Missions that Support Scientific Disciplines in the Laboratory for Atmospheres. (Acronyms not listed previously are listed below this table.)

Instrument Deployment	Atmospheric Structure and Dynamics	Atmospheric Chemistry	Clouds and Radiation
Aircraft/Balloon	EDOP HARLIE TWiLiTE (IIP) URAD HIWRAP (IIP)	AROTAL RASL (IIP) ACAM	CPL THOR Lidar CRS UAV CPL
Ground/Laboratory/ Development	SRL GLOW	STROZ LITE AT Lidar (ATL)  Brewer UV Spectrometer  KILT  Pandora Spectrometers L2-SVIP GeoSpec (IIP)	MPL COVIR SMART COMMIT

- ACAM            Airborne Compact Atmospheric Mapper
- AROTAL       Airborne Raman Ozone, Temperature, and Aerosol Lidar
- ATL            Aerosol and Temperature Lidar
- COMMIT       Chemical, Optical, and Microphysical Measurements of *In situ* Troposphere
- COVIR         Compact Visible and Infrared Radiometer
- EDOP          ER-2 Doppler Radar
- GeoSpec       Geostationary Spectrograph
- GLAS          Geoscience Laser Altimeter System
- GLOW          Goddard Lidar Observatory for Winds
- HARLIE        Holographic Airborne Rotating Lidar Instrument Experiment
- HIWRAP       High-Altitude Imaging Wind and Rain Airborne Profiler
- IIP             Instrument Incubator Program
- KILT           Kiritimati Island Lidar Trailer
- L2-SVIP       Lagrange-2 Solar Viewing Interferometer Prototype
- MPL           Micro-Pulse Lidar
- RASL          Raman Airborne Spectroscopic Lidar
- SMART        Surface-sensing Measurements for Atmospheric Radiative Transfer
- SRL            Scanning Raman Lidar
- STROZ LITE   Stratospheric Ozone Lidar Trailer Experiment

## MAJOR ACTIVITIES

THOR	cloud Thickness from Offbeam Returns
TWiLiTE	Tropospheric Wind Lidar Technology Experiment
UAV	Unmanned Aerial Vehicle
URAD:	Unmanned Aerial Vehicle Radar
UV	Ultraviolet

In most cases, details concerning the instruments listed in these tables are presented in a separate Laboratory technical publication, the Instrument Systems Report, NASA/TP-2005-212783, which is also available on the Laboratory's home page, <http://atmospheres.gsfc.nasa.gov/>.

## 4.2 Field Campaigns

Field campaigns use the resources of NASA, other agencies, and other countries to carry out scientific experiments, to validate satellite instruments, or to conduct environmental impact assessments from bases throughout the world. Research aircraft, such as the NASA ER-2, DC-8, and WB-57F serve as platforms from which remote sensing and *in situ* observations are made. Ground-based systems are also used for soundings, remote sensing, and other radiometric measurements. In 2007, Laboratory personnel supported six such activities as scientific investigators, or as mission participants, in the planning and coordination phases.



Figure 4.1 Instrumentation at the SAUNA site.

### 4.2.1 SAUNA-II

*Sodankylä, Finland, February–April*

The objective of the Sodankylä Total Column Ozone Intercomparison (SAUNA) was to assess the comparative performance of ground-based instruments and algorithms at high latitudes. Total column ozone retrievals show persistent differences of 5–10% at high latitudes under conditions of low Sun, high total column ozone, and high column variability. Once the accuracy of the ground-based systems has been established under these extreme conditions, the accuracy of satellite retrievals can be assessed. For this purpose, the SAUNA campaign was held in Sodankylä, Finland (67°N, 23°E) in March–April of 2006, with a follow-up campaign (called SAUNA-II) in February–April 2007. SAUNA was supported as part of the Aura validation program.

Sodankylä was chosen for the campaign because a combination of high solar zenith angles and very high total ozone can be expected during mid-spring. During the campaign, Dobsons, Brewers, DOAS, sondes, and LIDAR were compared, including World and European standard instruments. The Goddard mobile ozone lidar system and double Brewer participated. The campaign involved more than 30 scientists from 12 institutes in 10 countries.

Initial results showed that the double spectrometer Brewer instruments were needed for accuracy at high ozone high solar zenith angles. The scattered light error in the Dobsons and single Brewers was documented. It was also shown that spatial variability in this region of high ozone gradients could be a significant source of inconsistency in satellite versus ground-based comparisons.

For further information contact Rich McPeters, [Richard.D.McPeters@nasa.gov](mailto:Richard.D.McPeters@nasa.gov).

#### **4.2.2 Cloud and Land Surface Interaction Campaign (CLASIC)**

The Cloud and Land Surface Interaction Campaign (CLASIC) was sponsored by the Department of Energy's Atmospheric Radiation Program to study influences of land surface processes on cumulus convection. It was conducted at the ACRF Southern Great Plains (SGP) field measurement site during the summer of 2007. CLASIC was designated as the core of a 2007 priority for the interagency Water Cycle Working Group of the Climate Change Science Program (CCSP). CLASIC scientists collect data sets, both at the surface and from aircraft, which can be used to improve parameterizations of cumulus convection and associated parameterizations of land surface processes. The results will be used to help decipher the respective roles of local and regional forcing on the observed cloud structure and will lead to improved representation of cloud and land surface feedbacks in climate models.

NASA's involvement in this campaign during June 2007 was to provide the ER-2 aircraft for cloud remote sensing. The ER-2 flights were coordinated with other aircraft and were mainly conducted over the ARM Southern Great Plains site in Oklahoma. Low-flying aircraft measured atmospheric radiation and surface fluxes, while the high-altitude ER-2 aircraft provided remote sensing using the Cloud Physics Lidar (CPL, McGill/613.1), Cloud Radar System (CRS, Heymsfield/613.1), and the MODIS Airborne Simulator (MAS, King and Platnick) instruments. Because the ER-2 was flying an A-Train simulator payload, underflights of the CALIPSO and CloudSat satellites were also performed as part of CLASIC.

The MODIS Airborne Simulator (MAS), a high spatial resolution imaging spectrometer flown on the NASA ER-2, has the spectral coverage to allow for cloud retrievals using algorithms similar to those used to produce operational MODIS cloud products. For the CLASIC campaign, the existing MAS retrieval code was updated to use the latest Collection 5 MODIS algorithm, though some modifications were required and are still being investigated. The emphasis was on retrieval of boundary layer water cloud properties. For more information on MAS and its use in the CLASIC campaign, visit [http://mas.arc.nasa.gov/data/deploy\\_html/clasic\\_home.html](http://mas.arc.nasa.gov/data/deploy_html/clasic_home.html) or contact Steve Platnick ([steven.platnick@nasa.gov](mailto:steven.platnick@nasa.gov)).

#### **4.2.3 Tropical Composition, Cloud, and Climate Coupling (TC4)**

The region of the Earth's tropical atmosphere between 14 and 18 km plays a key role in both climate change science and atmospheric ozone depletion. This layer, the tropical tropopause transition layer or TTL, is one of the coldest locations in the Earth's atmosphere. The TTL controls the inflow into the tropical stratosphere. Many facets of the chemical, dynamical, and physical processes occurring in the TTL are not well understood. Identifying and quantifying such processes are essential to understanding climate change, ozone depletion, and tropospheric chemistry. The TC4 campaign, conducted during July and August 2007, and based in San Jose, Costa Rica, explored this layer using seven NASA satellites and three NASA aircraft, and also obtained ground-based

radar and balloon measurements from San Jose and a site in Panama. The campaign focused on understanding the composition of the TTL and analyzing the impact of the deep clouds that penetrate the atmosphere up into this layer. A special focus was the cirrus clouds produced by the deep convective clouds, and the subsequent life-cycle and chemistry associated with these extensive ice clouds. Convection was plentiful as the Intertropical Convergence Zone passes through this region during the summer.

A-Train satellite observations (Aura, Aqua, CloudSat and CALIPSO), and other satellite observations (Terra and TRMM), provided crucial information on the spatial and temporal variations within this region. Carefully planned TC4 aircraft observations were required, both to validate satellite data in this poorly known region and to provide critical observations not available from the satellites such as details of the ice cloud microphysical composition and measurements of various chemical tracer species, both short- and long-lived, in complex cloud environments.

Over 350 people from NASA, NOAA, NCAR, universities, Costa Rica, and Panama directly participated in TC4. NASA's high-altitude (20 km) ER-2 aircraft served as an A-Train satellite simulator, capable of sampling when and where needed. The ER-2 carried 11 instruments including the MODIS Airborne Simulator (MAS), Scanning HIS (AIRS and TES simulator), Goddard's Cloud Radar System (CRS—a CloudSat simulator), Goddard's Cloud Physics Lidar (CPL—a CALIPSO simulator) and Goddard's Compact Scanning Submillimeterwave Imaging Radiometer (CoSSIR). NASA's WB-57 served as an *in situ* sampling platform collecting cloud and aerosol particle measurements and a wealth of gas measurements from its 27 instruments, both inside clouds as well as in clear air at altitudes from 13–17 km, mostly in the TTL but occasionally extending into the lower stratosphere. NASA's DC-8 "Flying Laboratory" carried a complement of 26 instruments including upward and downward pointing lidars (ozone, water vapor, and aerosols) and radiometers as well as instruments for *in situ* measurements of gases, and cloud and aerosol particles. The DC-8 was key for Aura validation objectives as it was able to underfly the afternoon Aura overpass, which was not possible for the ER-2 or WB-57 because of typical afternoon weather conditions at the airfield. The DC-8 operated mostly below 13 km, and usually collected some data in the tropical boundary layer at altitudes less than 2 km during most missions. A total of 26 science flights were flown over the 23 days of TC4. The majority of these flights included highly coordinated observations with two or more aircraft. Because of a pre-mission mechanical malfunction of the aircraft, the WB-57 did not join the experiment until the final week during which operations were consequently very intensive.

The key TC4 science questions included:

1. How can space-based measurements of geophysical parameters, particularly those known to possess strong variations on small spatial scales (e.g., H<sub>2</sub>O, cirrus), be validated in a meaningful fashion?
2. How do convective intensity and aerosol properties affect cirrus anvil properties?
3. How do cirrus anvils, and tropical cirrus in general, evolve over their life cycle? How do they impact the radiation budget and ultimately the circulation?
4. What controls the formation and distribution of thin cirrus in the TTL, and what is the influence of thin cirrus on radiative heating and cooling rates, and on vertical transport?
5. What are the physical mechanisms that control (and cause) long-term changes in the humidity of the upper troposphere in the tropics and subtropics?
6. What are the source regions, identities, concentrations, and chemical fates of short-lived compounds transported from the tropical boundary layer into the TTL. (i.e., what is the chemical boundary condition for the stratosphere?)

7. What are the mechanisms that control ozone within and below the TTL?
8. What mechanisms maintain the humidity of the stratosphere? What are the relative roles of large-scale transport and convective transport and how are these processes coupled?

Typical missions focused on cloud observations in the morning using multiple aircraft. The DC-8 subsequently took additional measurements more focused on chemistry issues and Aura validation in the early afternoon. For example, the mission on August 8 included observations of cloud profiles in cirrus anvils formed from deep convection rooted in a layer containing Saharan dust at lower levels, chemistry profiles of the TTL to obtain chemical tracers upwind of convection, and chemistry samples at low altitudes over dense tropical jungles in Columbia. Missions were also flown to sample the chemical and aerosol input to the deep convective clouds and to sample volcanic plumes over South America. Overall, the TC4 mission was a great success despite a number of logistical challenges, including recovery from a lightning strike on the DC-8, fuel issues for the ER-2, and the pre-mission WB-57 malfunction. The pilots, aircrews, ground crews, and support staff performed admirably under difficult circumstances to ensure mission success. The science findings spanning a diverse set of questions are much anticipated.

Laboratory scientists on the TC4 leadership team included David Starr (613.1)—Co-Mission Scientist; Steve Platnick (613.2) and Paul Newman (613.3)—ER-2 Platform Scientists; and Mark Schoeberl (610)—DC-8 Platform Scientist. Joanna Joiner (613.3) and Anne Douglass (613.3) represented Aura validation interests, and Steve Platnick served a similar role for MODIS (Aqua and Terra). ER-2 instrument scientists included Michael King (610)—MAS/MASTER; Gerry Heymsfield (613.1)—CRS and EDOP; Matt McGill (613.1)—CPL; and Jim Wang (614.6)—CoSSIR. Gerry Heymsfield also contributed to the success of the DC-8 dropsonde experiment that was operated in the field by personnel from NASA HQ.

A unique aspect of TC4 was the use of a Google Earth application developed at NASA Marshall Space Flight Center to direct the aircraft in real time via Satphone-Internet connections. Additional information about TC4 may be found at <http://www.espo.nasa.gov/tc4/>. TC4 observations and images for various Goddard instruments can be found on the respective instrument Web sites at Goddard.

#### **4.2.4 The Water Vapor Validation Experiment-Satellite/Sondes 2007 (WAVES\_2007)**

*Howard University Research Campus, Beltsville, MD, July 14–August 8*

The WAVES\_2007 campaign took place in July 2007 and was centered at the Howard University Research Campus in Beltsville, Maryland. The goals, similar to those of WAVES\_2006, which occurred in June–August 2006, were to provide a large, robust data set for comparison with and validation of Aura and Aqua satellite measurements of ozone, temperature, and water vapor; to intercompare and validate Raman water vapor lidar measurements; and to improve the summertime water vapor/ozone climatology in a highly populated suburban region near the nation's capitol. The measurement systems used during WAVES\_2007 included many of those in use in WAVES\_2006: Vaisala RS92 radiosonde, ECC ozonesonde, Cryogenic Frostpoint Hygrometer (provided by the University of Colorado), and operational radiosonde packages provided by the National Weather Service; and the large suite of atmospheric sensing instruments located at the Howard University facility (<http://meiyu.atmphys.howard.edu/beltsville/inde3.html>). Two lidar systems from GSFC were used along with others from Howard University (HURL Raman Lidar), and UMBC (ALEX Raman lidar and ELF backscatter lidar). The two NASA GSFC lidar assets that participated were the Code 613.3 AT Raman Lidar system and the Code 613.1 RASL (Raman Airborne Spectroscopic Lidar), which was involved in its first flight tests sponsored by the NASA Instrument Incubator and the GSFC ESTO programs. RASL flew legs along satellite tracks and overflew the Beltsville and UMBC sites permitting comparisons of water vapor and aerosol profiles with the other instruments. An example comparison of RASL, HURL and Vaisala RS92 radiosonde water vapor profiles

from one of the RASL overpasses of the Beltsville site is shown in Figure 4.2. The 10 second resolution of the RASL data corresponds to approximately 1 km horizontal resolution. For further details please contact Dave Whiteman (David.N.Whiteman@nasa.gov) or Tom McGee (Thomas.J.McGee@nasa.gov).

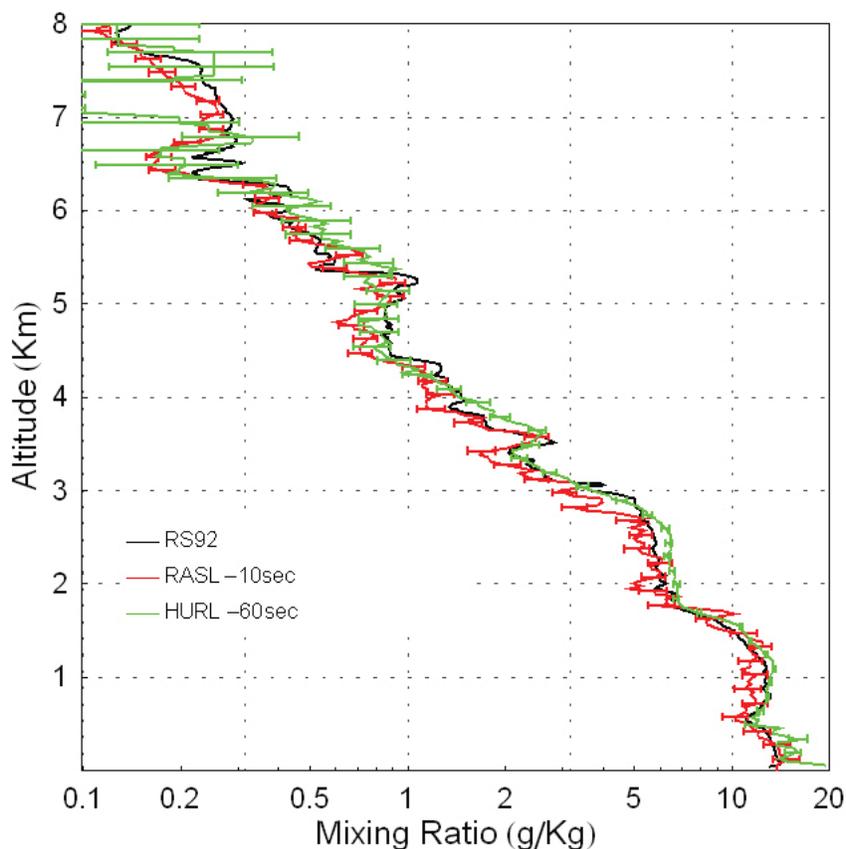


Figure 4.2 Example comparison of RASL, HURL, and Vaisala RS92 radiosonde water vapor profiles from one of the RASL overpasses of the Beltsville site.

#### 4.2.5 Measurements of Humidity in the Atmosphere—Validation Experiments II (MOHAVE II)

October 4–17, 2007, JPL Table Mountain Facility, CA.

The Code 613.3 Aerosol, Temperature and Water Vapor (AT) Lidar, as well as the Code 613.1 ALVICE (Atmospheric Lidar for Validation, Interagency Collaboration and Education) Raman lidar were used in the second MOHAVE campaign at JPL's Table Mountain Facility in Southern California in October 2007. The campaign consisted of these two GSFC lidars, the JPL Water Vapor Lidar (all co-located at TMF) and numerous balloon sonde sensors.

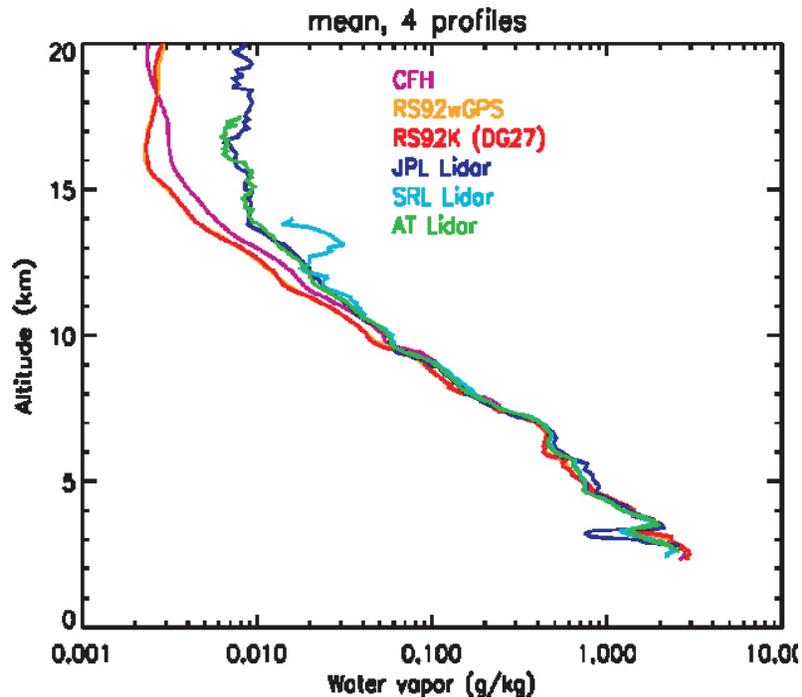
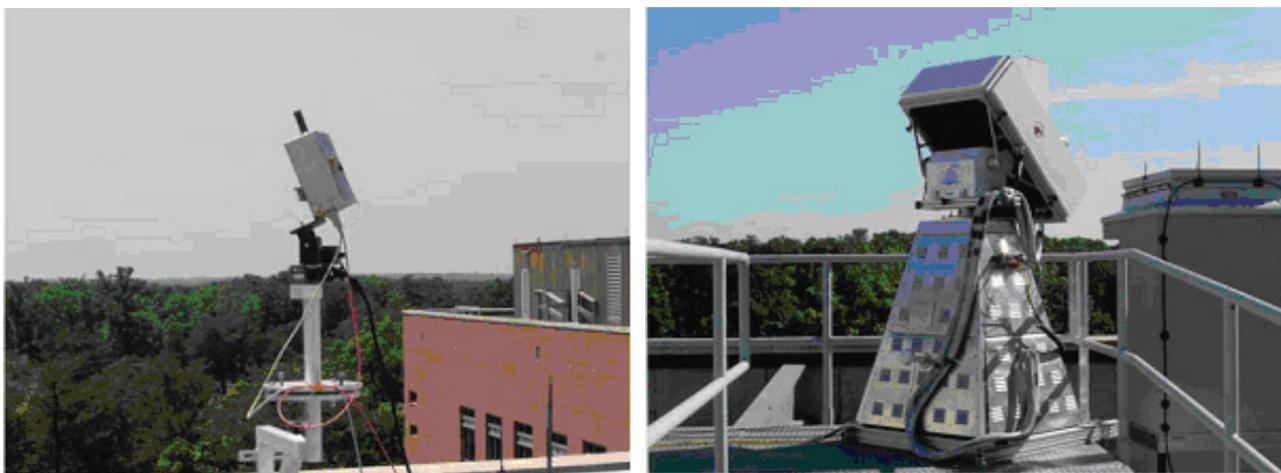


Figure 4.3 MOHAVE-I water vapor comparisons.

During the first MOHAVE-I campaign, which occurred in October of 2006 and also at TMF, it was noted that all of the lidars had a bias with respect to the sonde instruments at low water vapor concentrations (see Figure 4.3). This wet bias was presumed to be due to fluorescence from internal optical components of the lidar instruments. This was the major finding from the first campaign, and the second campaign was conducted to determine if the proposed solutions to the interference were successful and if high power-aperture Raman lidars, when located at a high altitude station (2385 m MSL) such as TMF, are able to accurately quantify water vapor to the tropopause and beyond. Preliminary data indicates that the lidar water retrievals are improved at high altitudes and the data are currently being analyzed in detail. For further details please contact Tom McGee (Thomas.J.McGee@nasa.gov) or Dave Whiteman (David.N.Whiteman@nasa.gov).

#### 4.2.6 Measurement of NO<sub>2</sub>

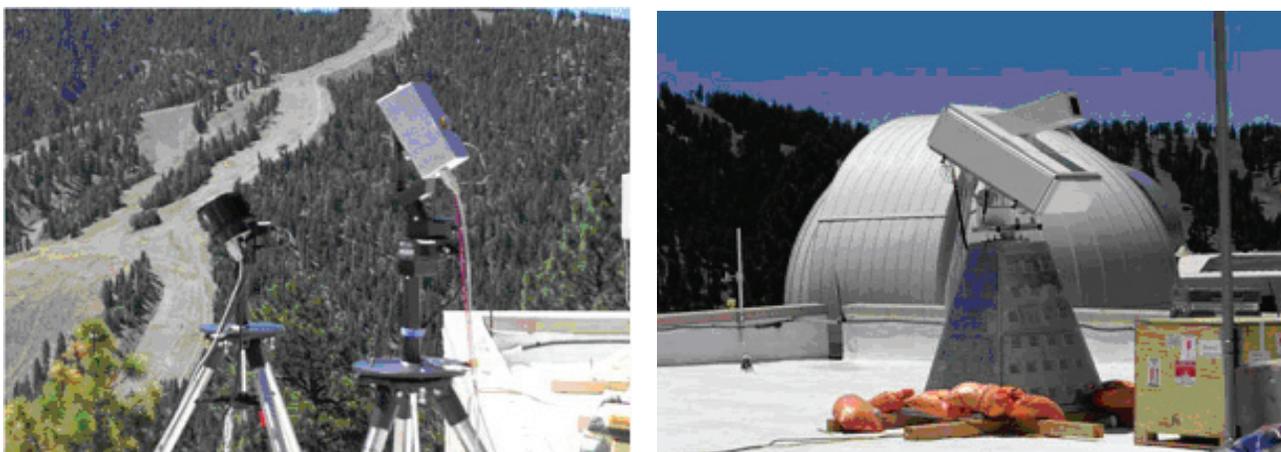
New compact low-cost (~\$10K) solar-viewing spectrometers (PANDORA) have been developed at GSFC to measure aerosols, NO<sub>2</sub>, and other trace gases in the atmosphere (H<sub>2</sub>O, HCHO, O<sub>3</sub>, SO<sub>2</sub>). The goal in developing these new spectrometer instruments was to be able to deploy them at multiple sites for detection of atmospheric pollution and to validate Aura/OMI satellite data. Before deploying large numbers of these systems, two field campaigns at GSFC and JPL's Table Mountain Facility (TMF) were designed to validate their performance against a larger more expensive system, MF-DOAS, developed by George Mount of Washington State University. Two versions of the PANDORA spectrometers have been developed, one to only make direct sun observations, PAN-1, and the other to measure both direct sun and diffuse sky radiances, PAN-3.



*Figure 4.4 PAN-1 and the University of Washington MF-DOAS mounted on the roof at GSFC in May 2007. As shown, PAN-1 only observes the direct Sun, while MF-DOAS can observe both the direct Sun and diffuse sky radiances.*

The first set of field measurements was obtained at GSFC (38.993°N, 76.840°W) during a comparison campaign of PAN-1 with the University of Washington's MF-DOAS instrument located on the roof of Building 33, about 88 m above sea level with a view of the horizon in most directions. A picture of both instruments is shown in Figure 4.4. The GSFC location is close to two major highway systems and a busy local road, which are strong sources of NO<sub>2</sub> emissions. In addition, aerosols are almost always present with a typical optical depth of a few tenths.

The second campaign was held in late June 2007 at JPL's Table Mountain Facility (34.382°N, 117.681°W) which is an extremely clean site even though it is fairly near Los Angeles, California. Once again, PAN-1 and MF-DOAS were located on the same rooftop (Figure 4.5) approximately 2.2 km above sea level with a view of the horizon to the east, but with other directions partly obscured by terrain, structures, or trees.



*Figure 4.5 PAN-1, PAN-3, and MF-DOAS at Table Mountain Facility California July 2, 2007. The view is looking to the north.*

The results from the two campaigns are summarized in Figures 4.6 and 4.7, which compare the measured slant columns of NO<sub>2</sub> obtained by the two instruments. The campaign at GSFC was designed to compare PAN-1 with similar measurements made by the University of Washington's MF-DOAS spectrometer in a moderately

polluted area. A similar comparison was made at the very clean Table Mountain Facility in California where the expected total column  $\text{NO}_2$  values do not differ much from the stratospheric  $\text{NO}_2$  amount. When combined with the GSFC campaign, the data demonstrates the performance of both spectrometer systems for sites with low and substantial amounts of  $\text{NO}_2$ . The differences between the instruments are not statistically significant and range from 0.4% at low values of  $\text{NO}_2$  to about 1% at higher values.

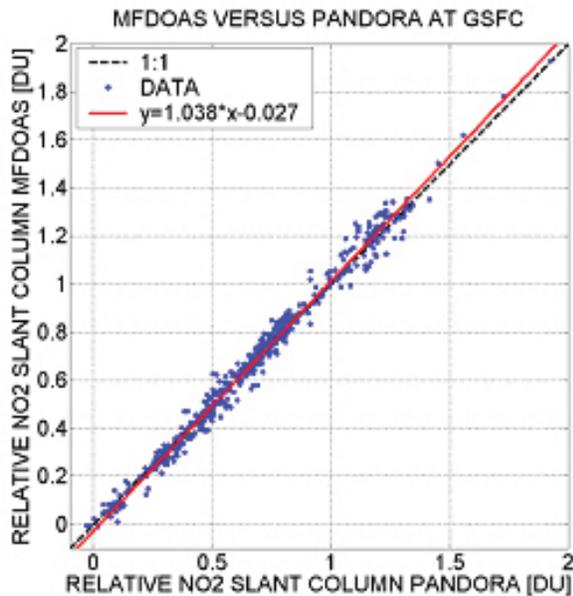


Figure 4.6 A comparison of PAN-1 and MF-DOAS at GSFC (May 2007).

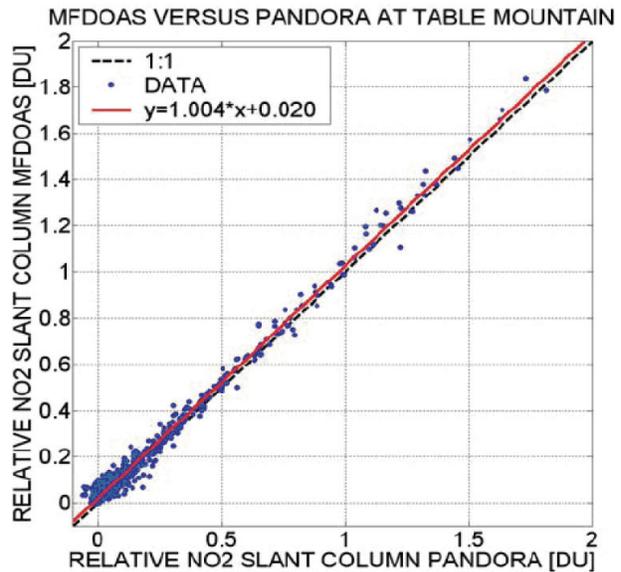


Figure 4.7 A comparison of PAN-1 and MF-DOAS at TMF (July 2007).

Now that the PANDORA results have been validated in two field campaigns, multiple copies are being made to deploy within the Washington metropolitan area to map out the distribution of  $\text{NO}_2$  and other trace gases. Instruments will be located at GSFC, NASA Headquarters, the Smithsonian Environmental Research Center on the Chesapeake Bay, and other locations. In addition, instruments will be located at remote sites such as Houston, Atlanta, and Los Angeles to measure pollution levels and to validate corresponding OMI measurements. For further details contact Jay Herman, (Jay.R.Herman@nasa.gov).

## 4.3 Data Sets

In the previous discussion, we examined the array of instruments and some of the field campaigns that produce the atmospheric data used in our research. The raw and processed data from these instruments and campaigns are used directly in scientific studies. Some of this data, plus data from additional sources, is arranged into data sets useful for studying various atmospheric phenomena. Some major data sets are described in the following paragraphs.

### 4.3.1 Global Precipitation

An up-to-date, long, continuous record of global precipitation is vital to a wide variety of scientific activities. These include initializing and validating numerical weather prediction and climate models, providing input

for hydrological and water cycle studies, supporting agricultural productivity studies, and diagnosing climatic fluctuations and trends on regional and global scales.

At the international level, the Global Energy and Water Cycle Experiment (GEWEX) component of the World Climate Research Programme (WCRP) has established the Global Precipitation Climatology Project (GPCP) to develop such global data sets. Scientists working in the Laboratory are leading the GPCP effort to merge data from both low-Earth orbit satellites and geosynchronous satellites, and ground-based rain gauges, to produce research-quality estimates of global precipitation.

The GPCP data set provides global, monthly precipitation estimates for the period January 1979 to the present. Updates are being produced on a quarterly basis. The release includes input fields, combination products, and error estimates for the rainfall estimates. The data set is archived at NOAA's National Climatic Data Center in Asheville, North Carolina, and at the Goddard Earth Sciences Data and Information Services Center (GES DISC). Evaluation is ongoing for this long-term data set in the context of climatology, El Niño Southern Oscillation (ENSO)-related variations, and regional and global trends. The 10-year TRMM data set is being used in the assessment of the longer GPCP data set. A daily, globally complete analysis of precipitation is also being produced by Laboratory scientists for GPCP for the period 1997 to the present and is available from the archives.

An even finer time resolution, a TRMM-based quasi-global, 3-hour resolution rainfall analysis, the TRMM Multi-satellite Precipitation Analysis (TMPA) is available from the GES DISC for the period of January 1998 to the present. This product uses TRMM data to calibrate or adjust rainfall estimates from other satellite data and combines these estimates into rainfall maps at a frequency of every 3 hours at a spatial resolution of 0.25° latitude-longitude. A real-time version of this analysis is available through the TRMM Web site. For more information, contact Robert Adler ([Robert.F.Adler@nasa.gov](mailto:Robert.F.Adler@nasa.gov)).

#### **4.3.2 Merged TOMS/SBUV Data Set**

We have updated our merged satellite total ozone data set through May of 2007. We have transferred the calibration from the original six satellite instruments to the NOAA 16 and NOAA 17 SBUV/2 instruments. We have further extended this intercalibration to include the OMI instrument on the Aura satellite. We also have a merged profile data set from the SBUV instruments. The data, and information about how they were constructed, can be found at [http://code916.gsfc.nasa.gov/Data\\_services/merged](http://code916.gsfc.nasa.gov/Data_services/merged). It is expected that these data will be useful for trend analyses, for ozone assessments, and for scientific studies in general. For further information, contact Richard Stolarski ([Richard.S.Stolarski@nasa.gov](mailto:Richard.S.Stolarski@nasa.gov)) or Stacey Frith ([smh@code916.gsfc.nasa.gov](mailto:smh@code916.gsfc.nasa.gov)).

#### **4.3.3 Moderate Resolution Imaging Spectroradiometer (MODIS)**

MODIS operational Atmosphere Team algorithms produce both Level-2 (pixel-level or swath data) and Level-3 (gridded) products. There are six categories of Level-2 and Level-3 MODIS products collected from the Terra and Aqua platforms. Over the past year, the latest processing stream (referred to as "Collection 5") was completed. In addition, a new algorithm designed to retrieve aerosols over desert surfaces was added in collection 5.

The Level-2 product files are grouped by Cloud Mask, Cloud, Aerosol, Precipitable Water, and Atmospheric Profile geophysical retrievals. In addition, a joint Atmosphere Team file contains a spatial sample of the more popular Level-2 retrievals. Level-3 MODIS Atmosphere products provide statistics on a 1° × 1° global grid and are produced for daily, eight-day, and monthly time periods.

### *Level-2 Products*

The **Aerosol Product** provides aerosol optical thickness over the oceans globally and over a portion of the continents. Further, information regarding the aerosol size distribution is derived over the oceans, while the aerosol type is derived over continents. A new aerosol algorithm for bright desert surfaces (referred to as the “Deep Blue” algorithm) was included in the Aqua MODIS collection 5 processing; this algorithm provides aerosol optical depth as well as single scattering albedo for dust aerosol. Level-2 aerosol retrievals are at the spatial resolution of a  $10 \times 10$ , 1 km (at nadir) pixel array.

The **Precipitable Water Product** consists of two-column water vapor retrievals. During the daytime, a near-infrared algorithm is applied over clear land areas, ocean sun glint areas, and above clouds over both land and ocean. An infrared algorithm used in deriving atmospheric profiles is also applied both day and night.

The **Cloud Product** combines infrared and visible techniques to determine both physical and radiative cloud properties. Cloud optical thickness, effective particle radius, and water path are derived at a 1 km resolution using MODIS visible through mid-wave infrared channel observations. Cloud-top temperature, pressure, and effective emissivity are produced by infrared retrieval methods, both day and night, at a  $5 \times 5$ , 1 km pixel resolution. Cloud thermodynamic phase is derived from a combination of techniques and spectral bands. Finally, the MODIS Cloud Product includes an estimate of cirrus reflectance in the visible at a 1 km pixel resolution; these retrievals are useful for removing cirrus scattering effects from the land-surface reflectance product.

The **Atmospheric Profile Product** consists of several parameters: total column ozone, atmospheric stability, temperature and moisture profiles, and atmospheric water vapor. All of these parameters are produced day and night at a  $5 \times 5$ , 1 km pixel resolution when a  $5 \times 5$  region is suitably cloud free.

The **Cloud Mask Product** indicates to what extent a given instrument field of view (FOV) of the Earth’s surface is unobstructed by clouds. The cloud mask also provides additional information about the FOV, including the presence of cirrus clouds, ice/snow, and sun glint contamination.

The **Joint Atmosphere Product** contains a subset of key parameters gleaned from the complete set of operational Level-2 products: Aerosol, Water Vapor, Cloud, Atmospheric Profile, and Cloud Mask. The Joint Atmosphere product was designed to be small enough to minimize data transfer and storage requirements, yet robust enough to be useful to a significant number of MODIS data users. Scientific data sets (SDSs) contained within the Joint Atmosphere Product cover a full set of high-interest parameters produced by the MODIS Atmosphere Group, and are stored at 5 km and 10 km (at nadir) spatial resolutions.

### *Level-3 Products*

The Level-3 MODIS **Atmosphere Daily Global Product** contains roughly 600 statistical data sets, which are derived from approximately 80 scientific parameters from four Level-2 MODIS Atmosphere Products: Aerosol, Water Vapor, Cloud, and Atmospheric Profile. Statistics are sorted into  $1^\circ \times 1^\circ$  cells on an equal-angle grid that spans 24 hours (0000 to 2400 UTC). A range of statistical quantities is computed, depending on the parameter being considered. In addition to simple statistics, the Level-3 files include a variety of one- and two-dimensional histograms. Similarly, the Level-3 Eight-Day and Monthly Global Product contain roughly 800 statistical data sets that are derived from the Level-3 Daily and Eight-Day products, respectively. For further information, contact Steven Platnick (Steven.Platnick@nasa.gov) or visit the MODIS Web site at <http://modis-atmos.gsfc.nasa.gov/>

### 4.3.4 MPLNET Data Sets

The NASA Micro Pulse Lidar Network (MPLNET) is a federated network of Micro Pulse Lidar (MPL) systems designed to measure aerosol and cloud vertical structure continuously, day and night, over long time periods required to contribute to climate change studies and to provide ground validation for models and satellite sensors in the NASA Earth Observing System (EOS). At present, there are fourteen permanent sites worldwide, and four more are to be completed soon (Figure 4.8). Numerous temporary sites have been deployed in support of various field campaigns since the start of MPLNET in 2000, and three more are planned in 2008. Most MPLNET sites are co-located with sites in the NASA Aerosol Robotic Network (AERONET) to provide both column and vertically resolved aerosol and cloud data.

In addition to continuation of expansive network growth during 2007, MPLNET data have been reprocessed using a new data release, version 2. Version 2 data include many new data products. Scene classification is now provided continuously at 1 minute time resolution, including identification of multiple cloud layer heights (base and top), planetary boundary layer height, and the height of the highest aerosol layer. Existing aerosol products have been enhanced to include continuous aerosol extinction profiles and associated products throughout the day (previously only available at AERONET observation times). PBL heights are generated using a wavelet technique. Cloud products are currently under development. The optical depth of detected cloud layers will be provided to the limit of detection capability, including thick cloud optical depths up to 100 using a novel technique based on the lidar background signal. Further information on the MPLNET project, and access to data, may be obtained online at <http://mplnet.gsfc.nasa.gov>. For questions on the MPLNET project, contact Judd Welton (Judd.Welton@nasa.gov).

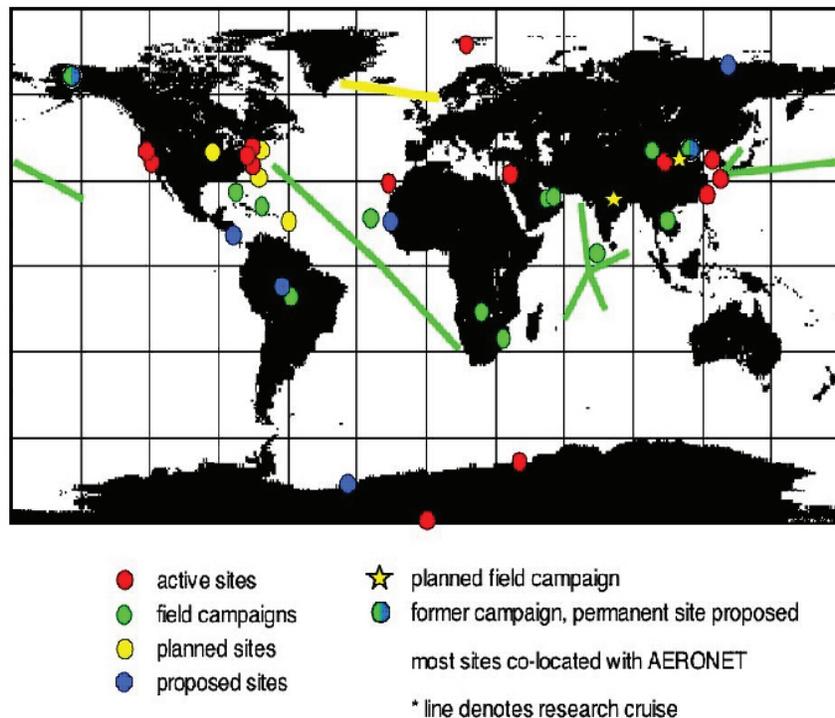


Figure 4.8 MPLNET Sites as of December 2007

### 4.3.5 TIROS Operational Vertical Sounder (TOVS) Pathfinder

The Pathfinder Projects are joint NOAA–NASA efforts to produce multiyear climate data sets using measurements from instruments on operational satellites. One such satellite-based instrument suite is TOVS. TOVS is composed of three atmospheric sounding instruments: the High Resolution Infrared Sounder-2 (HIRS-2), the Microwave Sounding Unit (MSU), and the Spectral Sensor Unit (SSU). These instruments have flown on the NOAA Operational Polar Orbiting Satellite since 1979. We have reprocessed TOVS data from 1979 until April 2005, when NOAA 14 stopped transmitting data. We used an algorithm developed in the Laboratory to infer temperature and other surface and atmospheric parameters from TOVS observations.

The TOVS Pathfinder Path A data set covers the period 1979–2004 and consists of global fields of surface skin and atmospheric temperatures, atmospheric water vapor, cloud amount, cloud height, Outgoing Longwave Radiation (OLR), clear sky OLR, and precipitation estimates. The data set includes data from TIROS N, and NOAA 6, 7, 8, 9, 10, 11, 12, and 14. We have demonstrated with the 25-year TOVS Pathfinder Path A data set that TOVS data can be used to study interannual variability, trends of surface and atmospheric temperatures, humidity, cloudiness, OLR, and precipitation. The TOVS precipitation data are being incorporated in the monthly and daily GPCP precipitation data sets.

We have also developed the methodology used by the AIRS science team to generate products from AIRS for weather and climate studies, and continue to improve the AIRS science team retrieval algorithm. A new improved algorithm, AIRS Science Team algorithm Version 5.0, is now operational at the GES DISC. The GES DISC has been producing AIRS level-2 soundings beginning September 2002 using Version 5 of the AIRS science team retrieval algorithm. Version 5 level 3 gridded products should be up to date early in 2008 and be generally available for climate studies by the scientific community. All products obtained in the TOVS Pathfinder data set are also produced from AIRS. The AIRS products are of higher quality than those of TOVS, but have been shown to be compatible in the anomaly sense. AIRS products can be used to extend the TOVS 25 year climate data set for longer term climate studies.

In joint work with Robert Atlas, Version 5.0 AIRS temperature profiles derived using this improved retrieval algorithm have been assimilated into the Laboratory forecast analysis system and have shown a significant improvement in weather prediction skill. Forecast results assimilating quality controlled temperature soundings were shown to be superior to those obtained assimilating AIRS radiances, as done operationally at NCEP and ECMWF (Joel.Susskind-1@nasa.gov).

### 4.3.6 TOMS and OMI Data Sets

Since the Atmospheric Chemistry and Dynamics Branch first formed, it has been tasked with making periodic ozone assessments. Through the years the Branch has led the science community in conducting ozone research by making measurements, analyzing data, and modeling the chemistry and transport of trace gases that control the behavior of ozone. This work has resulted in a number of ozone and related data sets based on the TOMS instrument. The first TOMS instrument flew onboard the Nimbus-7 spacecraft and produced data for the period from November 1978 through May 6, 1993 when the instrument failed. Data are also available from the Meteor-3 TOMS instrument (August 1991–December 1994) and from the TOMS flying on the Earth Probe (EP-TOMS) spacecraft (July 1996–present).

TOMS data are given as daily files of ozone, reflectivity, aerosol index, and erythemal UV flux at the ground. A new Version 8 algorithm was released in 2004, which addresses errors associated with extreme viewing conditions. These data sets are described on the Atmospheric Chemistry and Dynamics Branch Web site, which is linked to the Laboratory Web site, <http://atmospheres.gsfc.nasa.gov/>. Click on the “Code 613.3” Branch site,

and then click on “Data Services.” The TOMS spacecraft and data sets are then found by clicking on “TOMS Total Ozone data.” Alternatively, TOMS data can be accessed directly from <http://toms.gsfc.nasa.gov>.

Very similar data are being produced by the OMI instrument on the recently launched Aura spacecraft and are also available from the TOMS Web site <http://toms.gsfc.nasa.gov>. Because of calibration problems with the aging EP-TOMS instrument, OMI data should be used in preference to TOMS data beginning in 2005. The following sections describe two of the recently developed OMI data sets. For more information, contact Rich McPeters, [Richard.D.McPeters@nasa.gov](mailto:Richard.D.McPeters@nasa.gov).

#### 4.3.6.1 Sulfur Dioxide, SO<sub>2</sub>

Sulfur dioxide (SO<sub>2</sub>) is a short-lived atmospheric constituent that is produced primarily by volcanoes, power plants, refinery emissions and burning of fossil fuels. It can be a noxious pollutant or a major player in global climate forcing, depending on altitude. Fossil fuel burning occurs at the surface where SO<sub>2</sub> is released in the boundary layer or, with tall smokestacks, into the lower troposphere. Where SO<sub>2</sub> remains near the Earth's surface, it has detrimental health and acidifying effects. Emitted SO<sub>2</sub> is soon converted to sulfate aerosol by reaction with OH in air or by reaction with H<sub>2</sub>O<sub>2</sub> in aqueous solutions (clouds). The mean lifetime varies from ~1–2 days or less near the surface to more than a month in the stratosphere. In the free troposphere, wind speeds are stronger and aerosol sulfate can be carried to remote regions where it can change radiative forcing directly as well as through altered cloud microphysics. The concentration of SO<sub>2</sub>, the meteorological mechanisms that loft it above the PBL, and the efficiency of those mechanisms remain major unanswered questions in global atmospheric chemistry and climate science.

The first quantitative data on the mass of SO<sub>2</sub> in a major eruption (El Chichón, 1982) was obtained from the six-UV band NASA Nimbus-7 Total Ozone Mapping Spectrometer (TOMS). All significant eruptions since 1978 have now been measured by the series of TOMS instruments (Nimbus-7, Meteor-3, ADEOS I, Earth Probe (EP): <http://toms.umbc.edu>). The SO<sub>2</sub> detection sensitivity was limited to large volcanic clouds by the discrete TOMS wavelengths that were designed for total ozone measurements.

The Ozone Monitoring Instrument (OMI), launched in July 2004 on the polar-orbiting EOS/Aura satellite, offers unprecedented spatial and spectral resolution, coupled with global contiguous coverage, for space-based UV measurements of SO<sub>2</sub>. The OMI SO<sub>2</sub> data set is continuing the TOMS record (e.g. <http://toms.umbc.edu>) but the improved sensitivity and smaller footprint of OMI have extended the range of detection to smaller eruptions, degassing volcanoes, and older clouds, and to anthropogenic pollution (<http://so2.umbc.edu/omi/>). Heavy anthropogenic emissions and volcanic degassing in the lower troposphere and boundary layer can be detected on a daily basis (e.g., <http://aura.gsfc.nasa.gov>; <http://aura.gsfc.nasa.gov/science/gallery-omi.html>; and <http://www.knmi.nl/omi/research/news/>). Using monthly or annual average SO<sub>2</sub> maps, one can detect weaker degassing and pollution, e.g., [http://aura.gsfc.nasa.gov/science/top10\\_smelters.html](http://aura.gsfc.nasa.gov/science/top10_smelters.html)).

Visualization of daily OMI SO<sub>2</sub> data allows rapid appraisal of the most significant volcanic SO<sub>2</sub> emitters, which in 2007 included Tungurahua and Reventador (Ecuador), Popocatépetl (Mexico), Sheveluch (Shiveluch, Kamchatka, Russia), Piton de la Fournaise, (Réunion) Nyiragongo (Democratic Republic of Congo), Manda Hararo (Afar, Ethiopia), Mt. Etna (Sicily, Italy) and Jebel al-Tair (Yemen). These measurements highlight the deficiencies of previous compilations of volcanic SO<sub>2</sub> emissions, which were biased towards accessible, frequently monitored volcanoes. The eruption of Jebel al-Tair (Yemen) volcano in the Red Sea on October 1, 2007 was the first since 1883 and produced an SO<sub>2</sub> cloud that was carried a long distance by the subtropical jet stream (Figure 4.9).

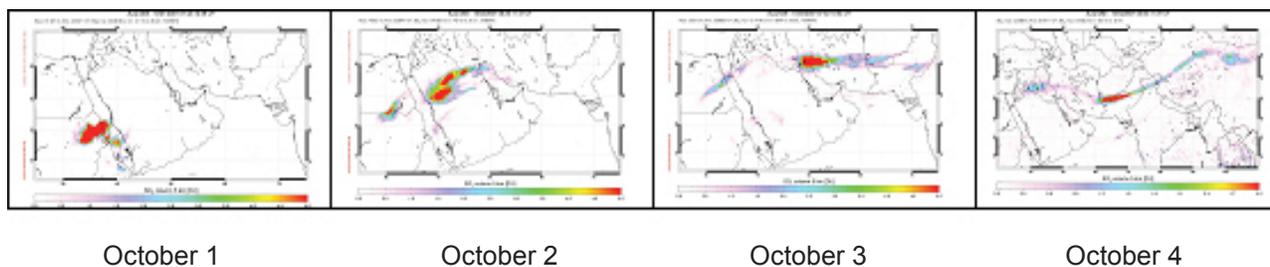


Figure 4.9 Long-range transport of the Jebel al-Tair volcanic  $\text{SO}_2$  cloud by the subtropical jet stream observed by Aura/OMI instrument, on October 1–11, 2007 [<http://so2.umbc.edu/omi/>].

Using OMI data, one can directly compare daily global  $\text{SO}_2$  emissions from anthropogenic and volcanic sources for the first time, and thus provide important new constraints on the relative magnitude of these fluxes. Anthropogenic  $\text{SO}_2$  has been detected over eastern China, South America and Europe. An OMI  $\text{SO}_2$  validation study was conducted using aircraft *in situ*  $\text{SO}_2$  data collected over Shenyang in northeast China as part of the EAST-AIRE field campaign. (Figure 4.10).

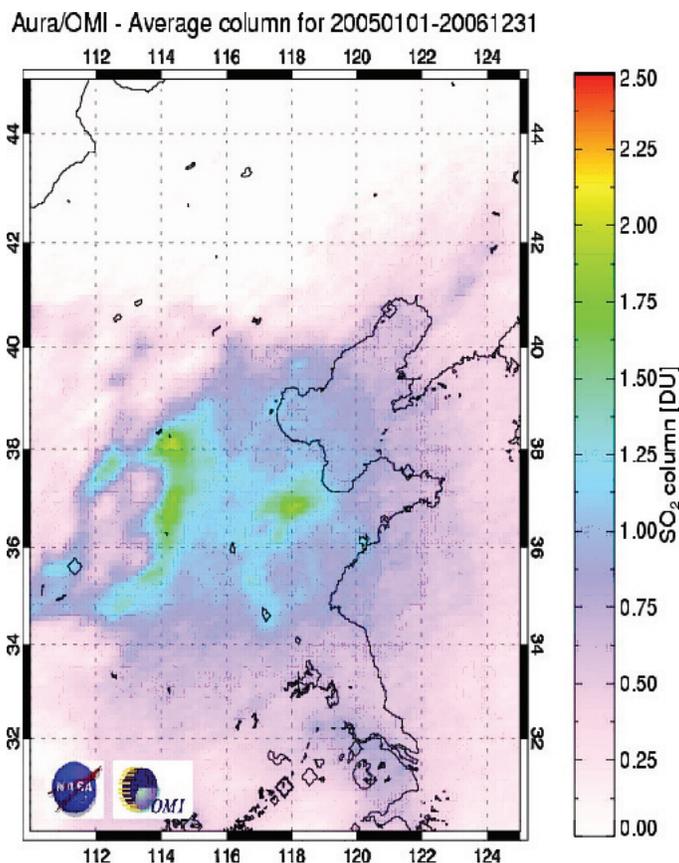
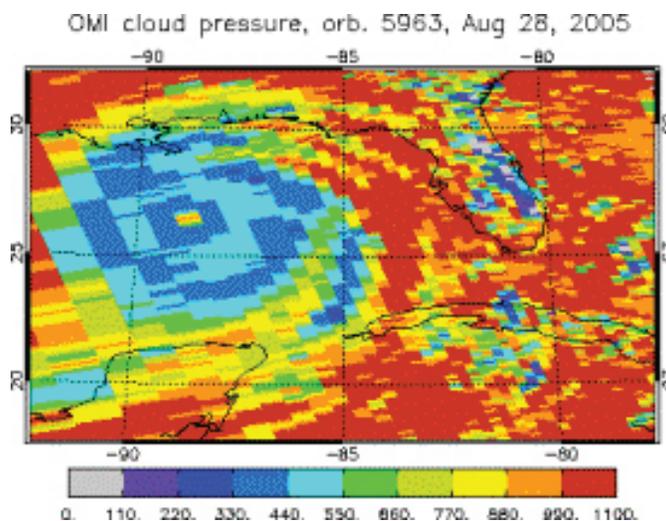


Figure 4.10 A 2-year average OMI  $\text{SO}_2$  map over Eastern China in Dobson Units ( $1 \text{ DU} = 2.69 \times 10^{16} \text{ molecules/cm}^2$ ) showing persistent areas of high  $\text{SO}_2$  concentrations in a triangle between Beijing, Shanghai, and the Sichuan basin in agreement with emission inventories. Smaller  $\text{SO}_2$  enhancements ( $\sim 0.5 \text{ DU}$ ) over the Shenyang region in North East China (black square) are also significant as compared to the background regions. This was the place of the first OMI  $\text{SO}_2$  validation study.

Such measurements are essential given the growing concern over the response of the Earth to anthropogenically-forced climate change and intercontinental transport of air pollution. Because  $\text{SO}_2$  is the major precursor of sulfate aerosol, which has climate and air quality impact, OMI  $\text{SO}_2$  measurements will contribute to better understanding of the sulfate aerosol distribution and its atmospheric impact. The fast OMI  $\text{SO}_2$  retrieval is also amenable to operational  $\text{SO}_2$  alarm development, and near real-time application for aviation hazards and volcanic eruption warnings. For more information contact Nick Krotkov (Nickolay.A.Krotkov@nasa.gov).

### 4.3.6.2 Cloud

The OMI cloud algorithm retrieves cloud pressures from the filling in of solar Fraunhofer lines in the ultraviolet due to rotational Raman scattering of air molecules. Clouds shield the atmosphere below them from rotational Raman scattering as observed from a satellite above. Therefore, the higher the cloud, the less filling in that is observed. When there are multiple cloud decks and the upper deck is relatively thin, the retrieved cloud pressure is closer to the pressure of the lower cloud deck. In contrast, cloud pressures derived from thermal infrared sensors such as on the MODIS instrument are closer to the upper cloud deck. The cloud pressures derived from OMI are appropriate for use in retrievals of trace gases, such as ozone,  $\text{NO}_2$ , and  $\text{SO}_2$ , that utilize similar spectral regions. Over the past year, the OMI Raman cloud group has assessed potential errors in the algorithm using radiative transfer calculations. They also performed validation of the cloud pressure product using data from the recently launched CloudSat cloud profiling radar.



*Figure 4.11 OMI cloud image over Hurricane Katrina, Aug. 28, 2005. The colors represent effective pressure of clouds, in hPa, as seen by OMI.*

For more information contact Joanna Joiner (Joanna.Joiner@nasa.gov).

### 4.3.7 Southern Hemisphere Additional OZonesondes (SHADOZ)

Initiated by NASA's Goddard Space Flight Center in 1998, in collaboration with NOAA and meteorological and space agencies from around the world, SHADOZ augments balloon-borne ozonesonde launches in the tropics and subtropics. SHADOZ presently includes 12 operational sites, including 3 that are north of the equator (Costa Rica, Suriname, and Malaysia). Each station launches weekly or monthly, depending on the resources available. SHADOZ archives ozone and temperature profile data at a user-friendly, open Web site: <http://croc.gsfc.nasa.gov/shadoz>. The year 2008 will mark 10 years of operations. SHADOZ ozone data are used for a number of purposes:

- (1) Satellite algorithm retrievals and validation of satellite measurements,
- (2) Mechanistic studies of processes affecting ozone distributions in the tropical stratosphere and troposphere, and
- (3) Evaluation of photochemical and dynamical models that simulate ozone.

By having so many profiles, it has been possible to improve accuracy and precision of the ozonesonde measurement under tropical conditions. All SHADOZ stations fly a radiosonde Electrochemical Concentration Cell (ECC) ozonesonde combination. The World Meteorological Organization (WMO) uses SHADOZ as the paradigm for developing new ozone sounding stations in WMO's Global Atmospheric Watch (GAW) program.



*Figure 4.12 Currently, twelve active sites are participating in SHADOZ. The sites are at Ascension Island; American Samoa; Fiji; Irene, South Africa; Watukosek, Java, Indonesia; Nairobi, Kenya; Alajuela, Costa Rica; Natal, Brazil; Paramaribo, Surinam; La Réunion; San Cristóbal, Galapagos; and Kuala Lumpur, Malaysia.*

For additional details, contact Anne Thompson ([anne@met.psu.edu](mailto:anne@met.psu.edu)) or Jacquie Witte ([Jacquelyn.C.Witte@nasa.gov](mailto:Jacquelyn.C.Witte@nasa.gov)). The archive URL is located at <http://croc.gsfc.nasa.gov/shadoz>.

#### 4.3.8 Tropospheric O<sub>3</sub> Data

Measurements from the Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) on board the Aura satellite have been used to develop several years of daily and monthly-mean global measurements of tropospheric O<sub>3</sub> beginning late August 2004. The tropospheric O<sub>3</sub> data are given as both tropospheric column O<sub>3</sub> (in Dobson Units) and mean equivalent volume mixing ratio (in ppbv). The tropospheric O<sub>3</sub> data are made available to anyone via the TOMS home page <http://toms.gsfc.nasa.gov>. The Web site also provides long time records of both tropospheric and stratospheric O<sub>3</sub> in the tropics for the time period January 1979 through December 2005. For more information, contact Jerry Ziemke ([Jerald.R.Ziemke@nasa.gov](mailto:Jerald.R.Ziemke@nasa.gov)) the Principal Investigator on the American OMI science team for tropospheric ozone.

## 4.4 Data Analysis

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A considerable effort by our scientists is spent in analyzing the data from a vast array of instruments and field campaigns. This section details some of the major activities in this endeavor.

### 4.4.1 Aerosol and Water Cycle Dynamics

Aerosol can influence the regional and global water cycles by changing the surface energy balance, modifying cloud microphysics, and altering cloud and rainfall patterns. On the other hand, condensation heating from rainfall, and radiative heating from clouds and water vapor associated with fluctuations of the water cycle, drive circulation, which determines the residence time and transport of aerosols and their interaction with the water cycle. Understanding the mechanisms and dynamics of aerosol-cloud-precipitation interaction, and eventually implementing realistic aerosol-cloud microphysics in climate models are clearly important pathways to improve the reliability of predictions by climate and Earth system models. Laboratory scientists are involved in analyses of the interrelationships among satellite-derived quantities such as cloud optical properties, effective cloud radii, aerosol optical thickness (MODIS, TOMS, CloudSat, and CALIPSO), rainfall, water vapor, and cloud liquid water (TRMM, AMSR), in conjunction with analyzed large scale circulation and estimated moisture convergence in different climatic regions of the world, including the semi-arid regions of southwest U.S., the Middle East, northern Africa, and central and western Asia. Field campaigns for measurement of aerosol properties, including ground-based and aircraft measurement, play an important role in this research.

Observations from satellite and field campaigns are being coordinated with numerical studies using global and regional climate models and cloud-resolving models coupled to land surface, vegetation, and ocean models. A major goal of this research activity is to develop a fully interactive earth system model, including data assimilation, so that atmospheric water cycle dynamics can be studied in a unified modeling and observational framework. Currently, the use of Multi-Model Framework (MMF), including the embedding of cloud-resolving models in global general circulation models, is being pursued. This research also calls for the organization and coordination of field campaigns for aerosol and water cycle measurements in conjunction with GEWEX, Climate Variability and Predictability Programme (CLIVAR), and other WCRP international programs on aerosols and water cycle studies. Laboratory scientists have played key roles in major international research projects such as the Joint Aerosol Monsoon Experiment (JAMEX), a core element of the Asian Monsoon Years (2008-2012) under the World Climate Research Program (WCRP), involving both field observations, satellite data utilization and modeling effects. For more information, contact William Lau (William.K.Lau@nasa.gov), Christina Hsu (Christina.Hsu@nasa.gov), Mian Chin (Mian.Chin@nasa.gov), Si-Chee Tsay (Si-Chee.Tsay-1@nasa.gov), Eric Wilcox (Eric.Wilcox@nasa.gov) or W.K. Tao (Wei-Kuo.Tao-1@nasa.gov).

### 4.4.2 Atmospheric Hydrologic Processes and Climate

One of the main thrusts in climate research in the Laboratory is to identify natural variability on seasonal, interannual, and interdecadal time scales, and to isolate the natural variability from the anthropogenic global-change signal. Climate diagnostic studies use a combination of remote sensing and historical climate data, model output, and assimilated data. Diagnostic studies are combined with modeling studies to unravel physical processes underpinning climate variability and predictability. The key areas of research include ENSO, monsoon variability, intraseasonal oscillation, air-sea interaction, and water vapor and cloud feedback processes. Recently, the possible impact of anthropogenic aerosol on regional and global atmospheric water cycles has been included. A full array of standard and advanced analytical techniques, including wavelets transform, multivariate empirical orthogonal functions, singular value decomposition, canonical correlation analysis, nonlinear system analysis, and satellite orbit-related sampling calculations are used. Maximizing the use of satellite data for better interpretation, sampling, modeling, and eventually prediction of geophysical and hydroclimate systems is a top

priority of research in the Laboratory. Laboratory scientists are also engaged in research involving effects of Saharan dust on hurricanes and possible linkage between tropical cyclones and global warming.

Satellite-derived data sets for key hydroclimate variables such as rainfall, water vapor, clouds, surface wind, sea surface temperature, sea level heights, and land surface characteristics are obtained from a number of different projects: MODIS, AMSR, TRMM, the Quick Scatterometer Satellite (QuikSCAT) and Topography Experiment (TOPEX)/Poseidon, the Earth Radiation Budget Experiment (ERBE), Clouds and the Earth's Radiant Energy System (CERES), the International Satellite Cloud Climatology Project (ISCCP), Advanced Very High Resolution Radiometer (AVHRR), the Atmospheric Infrared Sounder (AIRS), TOMS, Special Sensor Microwave Imager (SSM/I), MSU, and TOVS Pathfinder. Diagnostic and modeling studies of diurnal and seasonal cycles of various geophysical parameters are being conducted using satellite data to validate climate model output, and to improve physical parameterization in models. For more information, contact William Lau (William.K.Lau@nasa.gov), Tom Bell (Thomas.L.Bell@nasa.gov), or Yogesh Sud (Yogesh.C.Sud@nasa.gov).

#### 4.4.3 Rain Estimation Techniques from Satellites

Rainfall information is a key element in studying the hydrologic cycle. A number of techniques have been developed to extract rainfall information from current and future spaceborne sensor data, including the TRMM satellite and the AMSR on EOS Aqua (AMSR-E).

The retrieval techniques include the following:

- A physical, multifrequency technique that relates the complete set of microwave brightness temperatures to rainfall rate at the surface. This multifrequency technique also provides information on the vertical structure of hydrometeors and on latent heating through the use of a cloud ensemble model. The approach has recently been extended to combine spaceborne radar data with passive microwave observations for improved estimations.
- An empirical relationship that relates cloud thickness, humidity, and other parameters to rain rates, using TOVS and Aqua–AIRS sounding retrievals.

The satellite-based rainfall information has been used to study the global distribution of atmospheric latent heating, the impact of ENSO on global-scale and regional precipitation patterns, diurnal variation of precipitation over both land and ocean, and the validation of global models. For more information, contact Robert Adler (Robert.F.Adler@nasa.gov).

#### 4.4.4 Rain Measurement Validation for TRMM

The objective of the TRMM Ground Validation Program is to provide reliable, instantaneous area- and time-averaged rainfall data from several representative tropical and subtropical sites worldwide for comparison with TRMM satellite measurements. Rainfall measurements are made at Ground Validation (GV) sites equipped with weather radar, rain gauges, and disdrometers. A range of data products derived from measurements obtained at GV sites is available via the GES DISC. With these products, the validity of TRMM measurements is being established with accuracies that meet mission requirements. For more information, contact Robert Adler (Robert.F.Adler@nasa.gov).

## 4.5 Modeling

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Modeling is an important aspect of our research, and is the path to understanding the physics and chemistry of our environment. Models are intimately connected with the data measured by our instruments: models are used to interpret data, and the data is combined with models in data assimilation. Some of our modeling activities are highlighted below.

### 4.5.1 50-Year Chemical Transport Model (CTM) Output

A 50-year simulation of stratospheric constituent evolution was completed using the Code 613.3 three-dimensional (3-D) chemistry and transport model. Boundary conditions were specified for chlorofluorocarbons, methane, and N<sub>2</sub>O appropriate for the period 1973–2023. Sulfate aerosols were also specified, and represent the eruptions of El Chichón and Mt. Pinatubo. Simulations with constant chlorine (1979 source gases) and low chlorine (1970 levels) and without the volcanic aerosols have also been completed to help distinguish chemical effects from effects of both interannual variability and a trend in the residual circulation in the input meteorological fields. The model output from all simulations is available on the Code 613.3 science system; software to read the output is also available. Although the CTM itself is run at 2° × 2.5° latitude/longitude horizontal resolution; the output is stored at 4° × 5° latitude/longitude. Higher resolution files are available from UniTree, the Code 606.2 archive. The model output stored on the science system is for six days each month; daily fields are saved on UniTree. Details about this and other CTM simulations are available from the Code 613.3 Web site at <http://code916.gsfc.nasa.gov/Public/Modelling/3D/exp.html>, which provides information about the various simulations.

Output from the three-dimensional Chemistry and General Circulation Model (CGCM) is also available on the Code 613.3 science system. Like the CTM simulations, these include boundary conditions that are specified for various trace gases. The simulations use either observations or model results for the ocean temperatures. Readers for this output, a description of the files that are available, and some details of the simulations are found on [http://hyperion.gsfc.nasa.gov/Personnel/people/Frith/webdir/GEOSCCM/gcm\\_data\\_transfer.html](http://hyperion.gsfc.nasa.gov/Personnel/people/Frith/webdir/GEOSCCM/gcm_data_transfer.html). Questions or comments should be addressed to Anne Douglass ([Anne.R.Douglass@nasa.gov](mailto:Anne.R.Douglass@nasa.gov)).

### 4.5.2 Aerosol Modeling

Aerosol radiative forcing is one of the largest uncertainties in assessing global climate change. Aerosol is also a key component determining air quality. The Goddard Chemistry Aerosol Radiation and Transport (GOCART) model, developed by researchers in the Laboratory in collaboration with the Global Modeling and Assimilation Office (GMAO, Code 610.1), has been used in a wide range of scientific investigations on aerosol related research by many groups worldwide. The research topics include:

- Satellite data analysis
- Intercontinental transport of atmospheric pollutants
- Aerosol effects on precipitation and clouds
- Aerosol effects on climate forcing
- Aerosol effects on surface air quality
- Atmospheric chemistry and climate interactions
- Inverse modeling of aerosol sources

Furthermore, the GOCART aerosol modules, to expand their modeling and application capabilities, have been implemented in several modeling frameworks. For example, the aerosol simulation capability developed in the GMAO GEOS General Circulation Model has made it feasible to use the aerosol forecast to support field experiments, such as the Tropical Composition, Cloud, and Climate Coupling (TC4) campaign in summer 2007. GOCART has also been incorporated into the Global Modeling Initiative (GMI) modeling framework to inter-

face with multiple meteorological fields for a better understanding of the model uncertainties and for coupling with chemistry simulations. Recently, the NOAA NCEP/NWS has started to adapt the GOCART modules for improving their weather and climate predictions and air quality forecasts.

For more information on aerosol modeling contact Mian Chin (Mian.Chin@nasa.gov), Thomas Diehl (Thomas.Diehl@nasa.gov), Peter Colarco (Peter.R.Colarco@nasa.gov), Arlindo da Silva (Arlindo.DaSilva@nasa.gov), or Huisheng Bian (Huisheng.Bian-1@nasa.gov).

### 4.5.3 Chemistry-Climate Modeling (CCM)

This project brings together the atmospheric chemistry and transport modeling of the Atmospheric Chemistry and Dynamics Branch and the General Circulation Model (GCM) development of the GMAO. The initial goal is to understand the role of climate change in determining the future composition of the atmosphere. We have coupled our stratospheric chemistry and transport into the Goddard Earth Observing System (GEOS) general circulation model and will use this to study the past and future coupling of the stratospheric ozone layer to climate. Our emphasis is on the testing of model processes and model simulations using data from satellites and ground-based measurement platforms. We have run simulations of the past starting in 1950 and have extended them into the future to the year 2100. These simulations led to the discovery that ozone has increased in the middle stratosphere over the Antarctic during summers of the last two decades. The simulation was confirmed by examining data from the SBUV series of satellites. We are now setting up to run the scenarios being defined for the next ozone assessment using the same chemistry coupled into a new version of the general circulation model, GEOS-5. The GEOS-5 version has now been coupled to the Combined Stratospheric–Tropospheric Model (COMBO) that has been developed under the Global Modeling Initiative (GMI). The GEOS-5/COMBO version of the CCM is being tested and will be used to attack scientific questions concerning the composition of both the troposphere and stratosphere and their interactions with the climate system.

Co-PIs are Richard Stolarski (Atmospheric Chemistry and Dynamics Branch) and Steven Pawson (Global Modeling and Assimilation Office). For further information, contact Richard Stolarski (Richard.S.Stolarski@nasa.gov), Steven Pawson (Steven.Pawson-1@nasa.gov), or Anne Douglass (Anne.R.Douglass@nasa.gov).

### 4.5.4 Cloud and Mesoscale Modeling (Multi-scale Modeling)

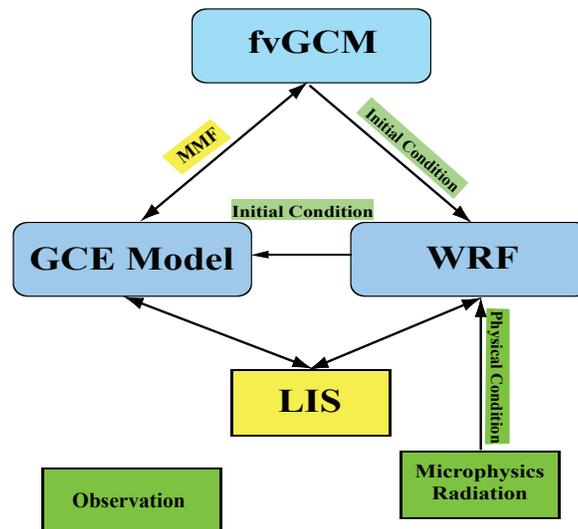
Three different coupled modeling systems were again improved over the last year. These models are used in a wide range of studies, including investigations of the dynamic and thermodynamic processes associated with cyclones, hurricanes, winter storms, cold rain-bands, tropical and mid-latitude deep convective systems, surface (i.e., ocean and land, vegetation and soil) effects on atmospheric convection, cloud–chemistry, cloud–aerosol, and stratospheric–tropospheric interactions. Other important applications include long-term integrations of the models that allow for the study of transport, air–sea, cloud–aerosol, cloud–chemistry, and cloud–radiation interactions and their role in cloud–climate feedback mechanisms. Such simulations provide an integrated system-wide assessment of important factors such as surface energy, precipitation efficiency, radiative exchange processes, and diabatic heating and water budgets associated with tropical, subtropical, and mid-latitude weather systems.

In the first modeling system, the NASA Goddard finite volume GCM (fvGCM) is coupled to the Goddard Cumulus Ensemble (GCE) model (a cloud-resolving model). The fvGCM allows for global coverage, and the GCE model allows for explicit simulation of cloud processes and their interactions with radiation and surface processes. This modeling system has been applied and its performance tested for two different climate scenarios, El Niño (1998) and La Niña (1999), for the diurnal variation of precipitation processes, and for flood/drought events during three different years (2005–2007). The new, coupled modeling system produced more realistic propagation and intensity of tropical rainfall systems, intra-seasonal oscillations, and diurnal variation of precipitation over land, which are very difficult to forecast using even state-of-the-art GCMs. In addition, the fvGCM is being

used to conduct very high-resolution simulations (global mesoscale modeling) to model the tropical cyclone formation and the Madden-Julian Oscillation (MJO). Preliminary results for five tropical cyclones indicate that the high-resolution global model is capable of predicting their genesis about two to three days in advance as well as predicting their subsequent movements.

The second modeling system couples various NASA Goddard physical packages (i.e., microphysics, radiation, and a land surface model) into the next generation weather forecast model known as the Weather Research and Forecasting (WRF) model. WRF is being developed at NCAR by a consortium of Government entities for research applications by the scientific community, and ultimately as the basis for a future operational forecast model at the National Center for Environmental Prediction (NCEP). This coupled modeling system allows for better forecasts (or simulations) of convective systems in Oklahoma, snow events in Canada, severe weather in Taiwan, monsoons in India, and hurricanes in the Atlantic. The WRF is being improved to provide real-time forecasting for NASA field campaigns. This real-time system could give better guidance on flight missions for NASA aircraft.

The third modeling system is the improved GCE model, which has been developed and improved at Goddard over the last two decades. The GCE model has recently been improved in its abilities to simulate the impact of atmospheric aerosol concentration on precipitation processes and the impact of land and ocean surfaces on convective systems in different geographic locations. The improved GCE model has also been coupled with the NASA TRMM microwave radiative transfer model and precipitation radar model to simulate satellite-observed brightness temperatures at different frequencies. This new coupled model system allows us to better understand cloud and precipitation processes in the Tropics as well as snow events at higher latitudes and to improve both precipitation retrievals from NASA satellites and the representation of moist processes in global and climate models. Figure 4.13 shows a schematic of the Goddard multi-scale modeling systems.



*Figure 4.13 Goddard Multi-scale Modeling Systems. The coupling between the fvGCM and GCE is two-way [termed a multi-scale modeling framework (MMF) or super-parameterization], while the coupling between the fvGCM and WRF, and WRF and the GCE is only one-way. LIS is the land information system developed in the Goddard Hydrological Sciences Branch (Code 614.3). LIS has been coupled interactively with both WRF and GCE. Additionally, WRF has been enhanced by the addition of several of the GCE model's physical packages (i.e., microphysical scheme with four different options and short- and long-wave radiative transfer processes with explicit cloud-radiation interactive processes). Observations play a very important role in providing data sets for model initialization and validation, and consequently improvements.*

In addition, a cloud library that consists of clouds and cloud systems that developed in different geographic locations is being generated and posted on a Goddard Web site for the public. The cloud data is being used for improving the performance of GPM snow retrievals, for improving the representation of moist processes in large-scale models, and for improving our understanding of precipitation processes associated with impact weather (i.e., hurricane, monsoon, and severe precipitation events). The Web address for the Goddard cloud library is <http://portal.nccs.nasa.gov/cloudlibrary/index2.html>.

The same microphysical, long- and shortwave radiative transfer, explicit cloud-radiation, and cloud-surface interactive processes are applied in all three modeling systems (called multi-scale modeling system with unified physics). The results from these modeling systems were compared to physical parameters estimated from NASA EOS satellites (i.e., TRMM, CloudSat, Aqua-MODIS, AMSR-E) in terms of surface rainfall and vertical cloud and precipitation structures. In addition, simulated physical parameters (i.e., condensates or hydrometeors, temperature, and humidity profiles) from the Multi-scale Modeling can be used to simulate top-of-atmosphere radiance and backscattering profiles consistent to the NASA EOS satellite measurements through the end-to-end NASA Goddard Earth Satellite Simulator. This permits a) better evaluation of the Goddard physical packages by comparing model results with direct EOS satellite measurements and b) support for NASA's satellite missions (e.g., A-Train, TRMM and GPM) by providing virtual satellite measurements as well as simulated atmospheric environments as an a priori database of physically-based precipitation retrieval algorithms. The model results were also compared to NASA and non-NASA field campaigns.

The scientific output from the modeling activities was again exceptional in 2007 with more than 10 new papers published, in press or accepted. For more information, contact Wei-Kuo Tao ([Wei-Kuo.Tao-1@nasa.gov](mailto:Wei-Kuo.Tao-1@nasa.gov)).

#### 4.5.5 Global Modeling Initiative (GMI)

The GMI was initiated under the auspices of the Atmospheric Effects of Aviation Program in 1995. The goal of GMI is to develop and maintain a state-of-the-art modular 3-D chemical transport model (CTM), which can be used for assessment of the impact of various natural and anthropogenic perturbations on atmospheric composition and chemistry, including, but not limited to, the effect of aircraft. The GMI model also serves as a testbed for model improvements. The goals of the GMI effort follow:

- reduce uncertainties in model results and predictions by understanding the processes that contribute most to the variability of model results, and by evaluating model results against existing observations of atmospheric composition;
- understand the coupling between atmospheric composition and climate through coordination with climate models; and
- contribute to the assessment of the anthropogenic perturbations to the Earth system.

The different components of the GMI model have been recoded for compliance with the Earth Science Modeling Framework. The GMI model is being evaluated through comparison to satellite, aircraft, and ground-based measurements. The Combined Stratospheric-Tropospheric Model (COMBO), has been very successful in simulating the temporal and spatial distribution of ozone measured by Aura instruments, both in the stratosphere and upper troposphere. A “tape recorder” effect in CO measurements from MLS is reproduced by the model. This “tape recorder” is driven by the seasonality of biomass burning. The model has also compared well with tropospheric ozone columns derived from OMI and MLS measurements, and with CO from the AIRS instrument. Comparison to OMI tropospheric column of NO<sub>2</sub>, as well as to surface ozone measurements over Europe also show good agreement. Further testing with satellite data, aircraft, and ground-based measurements are also underway.

The GMI model has participated in the assessment carried out by the Hemispheric Transport of Atmospheric Pollutants (HTAP) international effort. Results of the model have been incorporated in the HTAP interim report, and will contribute to several scientific publications. For more information, contact Jose Rodriguez (Jose.M.Rodriguez@nasa.gov).

#### 4.5.6 Cloud Radiation Parameterization in Atmospheric GCM

The main stumbling block in climate evaluations with a General Circulation Model (GCM) is due to the inability of the GCM to simulate realistic climate change. Better accuracy of the sub-models of physical processes (commonly called physical parameterizations) is vital to improving simulations. Thus, more subtle unsolved problems require more accurate models that simulate smaller biases; this implies more attention to physical processes that were previously ignored or poorly represented. The cloud parameterizations are among the primary hurdles. We use the Microphysics of Clouds with the Relaxed Arakawa-Schubert Scheme (McRAS), an in-house developed prognostic cloud-scale dynamics and cloud water substance scheme. McRAS includes representation of source and sink terms of cloud-scale condensation, microphysics of precipitation and evaporation, as well as horizontal and vertical advection of cloud water substance. It tries to capture physical attributes of cloud life cycles, effects of convective updrafts and downdrafts, cloud microphysics within convective towers and anvils, cloud-radiation interactions, and cloud inhomogeneity effects for radiative transfers. Most of these are based on algorithms developed by Laboratory scientists.

Whereas the GMAO has the overall responsibility for developing basic state-of-the-art climate models that are bias free; nevertheless, cloud-physics and aerosol-cloud-radiation interaction issues are among the primary interests of several scientists of the Goddard Laboratory for Atmospheres. New parameterizations are being developed for internally and externally mixed aerosols interacting with clouds. Since activated aerosols nucleate clouds as well as determine the number of cloud drops, at inception, aerosols species, mass concentrations and size distributions are central to cloud optical properties and precipitation microphysics. We have instituted a version of the Nenes and Seinfeld aerosol-nucleation scheme for water clouds. The ice-cloud processes are much more complex; some of them are not well understood; however, empirical relations from satellite and other *in situ* field measurements help to bridge the gap. Active research is in progress to make fundamental advances in this area. We have implemented the Liu and Penner ice nucleation parameterization. The total aerosol-cloud interaction complex, called McRAS-AC, is an upgrade to McRAS. Laboratory scientists are evaluating all aspects of the aerosol cloud and precipitation processes that include cloud optical properties, precipitation intensity, and cloud drop/particle size distribution, as well as validation of model simulations against *in situ* and satellite data.

For atmospheric radiation, we have developed efficient, more accurate, and modular longwave and shortwave radiation codes with parameterized direct effects of man-made and natural aerosols, and clouds that depend upon aerosol nucleation and precipitation microphysics. The climate model simulates liquid/ice mass, the number and size-distribution of cloud drops whereas the radiation code converts this data into optical properties of clouds. The radiation codes are also upgraded for efficient computation of climate sensitivities to water vapor, cloud optical properties and aerosols to simulate the direct effects of aerosols on shortwave and longwave radiative forcing. The codes also allow us to compute the global warming potentials of carbon dioxide and various trace gases.

Our simulation research involves the prognostic cloud-water schemes with aerosol cloud radiative effects using observations from the ARM Cloud and Radiation Test Bed (ARM CART) and Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA COARE) intensive observing periods, as well as satellite data. Biases in the GCM-simulated diurnal cycle of rainfall are large and show widely different characteristics in different regions of the world. TRMM satellite rainfall retrievals also provide the essential validation statistics. We have conducted ensemble simulations for the West African Monsoon Modeling

and Evaluation intercomparison project. Preparing the model for the above studies required major upgrades to the existing cloud physics in McRAS, as well as producing aerosol data sets for cloud-aerosol interactions and validation. We have utilized our model for a number of simulation studies that include two 10-year Atmospheric Model Intercomparison Project style simulations for investigating the local and remote influences of sea-surface temperatures on precipitation. Thus, focused model development and evaluations of aerosol-cloud-radiation sub models are the primary thrusts of model upgrades. For more information, contact Yogesh Sud (Yogesh.C.Sud@nasa.gov).

#### 4.5.7 Trace Gas Modeling

The Atmospheric Chemistry and Dynamics Branch has developed two- and three-dimensional (2-D and 3-D, respectively) models to understand the behavior of ozone and other atmospheric constituents. We use the 2-D models primarily to understand global scale features that evolve in response to both natural effects, such as variations in solar luminosity in ultraviolet, volcanic emissions, or solar proton events, and human effects; such as changes in chlorofluorocarbons (CFCs), nitrogen oxides, and hydrocarbons. Three-dimensional stratospheric Chemical Transport Models (CTMs) simulate the evolution of ozone and trace gases that affect ozone. The constituent transport is calculated using meteorological fields (winds and temperatures) generated by the GMAO or using meteorological fields that are output from a GCM. These calculations are appropriate to simulate variations in ozone and other constituents for time scales ranging from several days or weeks to seasonal, annual, and multi-annual. The model simulations are compared with observations, with the goal of illuminating the complex chemical and dynamical processes that control the ozone layer, thereby improving our predictive capability. We are participating in an ongoing collaboration with GMAO through which the photochemical calculation of the CTM is combined with a general circulation model; changes in radiatively active gases feedback to the circulation through the radiative code. The chemistry and general circulation model (CGCM) is being used to investigate the impact of trace gases changes on ozone and climate on long time scales (multi-decadal to century).

The modeling effort has evolved in the following directions:

1. Lagrangian models are used to calculate the chemical evolution of an air parcel along a trajectory. The Lagrangian modeling effort is primarily used to interpret aircraft and satellite chemical observations.
2. Two-dimensional noninteractive models have comprehensive chemistry routines, but use specified, parameterized dynamics. They are used in both data analysis and multi-decadal chemical assessment studies.
3. Two-dimensional interactive models include interactions among photochemical, radiative, and dynamical processes, and are used to study the dynamical and radiative impact of major chemical changes.
4. Three-dimensional CTMs have a complete representation of photochemical processes and use input meteorological fields from either the data assimilation system or from a general circulation model for transport.
5. Three-dimensional CGCMs combine a complete representation of photochemical processes with a general circulation model.

The constituent fields calculated using winds from a new GCM developed jointly by the GMAO and NCAR exhibit many observed features. We are also using output from this GCM in the current CTM for multi-decadal simulations. The CGCM reproduces features in the ozone trends derived from SBUV observations that are not produced by the CTM because they are caused by interaction of ozone changes with the meteorological fields. Through the Global Modeling Initiative, the CTM is being improved by implementation of a chemical mechanism suitable for both the upper troposphere and lower stratosphere. This capability is needed for interpretation

of data from EOS Aura, which was launched in July 2004. Within the next two years this combined mechanism will be implemented in the CGCM.

The Branch uses trace gas data from sensors on the Upper Atmosphere Research Satellite (UARS), on other satellites, from ground-based platforms, from balloons, and from various NASA-sponsored aircraft campaigns to test model processes. The integrated effects of processes such as stratosphere-troposphere exchange, not resolved in 2-D or 3-D models, are critical to the reliability of these models. For more information, contact Anne Douglass (Anne.R.Douglass@nasa.gov).

## **4.6 Support for NOAA Operational Satellites**

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In the preceding sections, we examined the Laboratory for Atmosphere's Research and Development work in measurements, data sets, data analysis, and modeling. In addition, Goddard supports NOAA's operational remote sensing requirements. Laboratory project scientists support the NOAA Polar Orbiting Environmental Satellite (POES) and the Geostationary Operational Environmental Satellite (GOES) Project Offices. Project scientists ensure scientific integrity throughout mission definition, design, development, operations, and data analysis phases for each series of NOAA platforms. Laboratory scientists also support the NOAA SBUV/2 ozone measurement program. This program is now operational within the NOAA/National Environmental Satellite Data and Information Service (NESDIS). A series of SBUV/2 instruments fly on POES. Postdoctoral scientists work with the project scientists to support development of new and improved instrumentation and to perform research using NOAA's operational data.

The Laboratory is supporting the formulation phase for the next generation GOES mission, known as GOES-R, which will supply a hundredfold increase in real-time data. Laboratory scientists are involved in specifying the requirements for the GOES-R advanced imager, high-resolution sounding suite, solar imaging suite, and *in situ* sensors. They participate in writing each Request for Proposal (RFP), serve on each Source Evaluation Board (SEB) for the engineering formulation of these instruments, and review vendors' progress during construction and testing of the instruments. For more information, contact Dennis Chesters (Dennis.Chesters@nasa.gov).

### **4.6.1 GOES**

GSFC project engineering and scientific personnel support NOAA for GOES. GOES supplies images and soundings for monitoring atmospheric processes, such as moisture, winds, clouds, and surface conditions, in real time. GOES observations are used by climate analysts to study the diurnal variability of clouds and rainfall, and to track the movement of water vapor in the upper troposphere. The GOES satellites also carry an infrared multi-channel radiometer, which NOAA uses to make hourly soundings of atmospheric temperature and moisture profiles over the United States to improve numerical forecasts of local weather. The GOES project scientist at Goddard provides free public access to real-time weather images via the World Wide Web (<http://goes.gsfc.nasa.gov/>). For more information, contact Dennis Chesters (Dennis.Chesters@nasa.gov).

### **4.6.2 NPOESS**

The first step in instrument selection for NPOESS was completed with Laboratory personnel participating on the SEB as technical advisors. Laboratory personnel were involved in evaluating proposals for the Ozone Mapper and Profiler System (OMPS) and the Crosstrack Infrared Sounder (CrIS), which will accompany the Advanced Technology Microwave Sounder (ATMS), and Advanced Microwave Sounding Unit (AMSU) crosstrack microwave sounder. Collaboration with the IPO continues through the Sounder Operational Algorithm Team (SOAT) and the Ozone Operational Algorithm Team (OOAT) that will provide advice on operational algorithms and technical support on various aspects of the NPOESS instruments. In addition to providing an advisory

role, members of the Laboratory are conducting internal studies to test potential technology and techniques for NPOESS instruments. We have conducted numerous trial studies involving CrIS and ATMS, the advanced infrared and microwave sounders, which will fly on NPP and NPOESS. Simulation studies were conducted to assess the ability of CrIS to determine atmospheric CO<sub>2</sub>, CO, and CH<sub>4</sub>. These studies indicate that total CO<sub>2</sub> can be obtained to 2 ppm (0.5%) from CrIS under clear conditions, total CH<sub>4</sub> to 1%, and total CO to 15%. This performance is comparable to what is being obtained from AIRS. For more information, contact Joel Susskind (Joel.Susskind-1@nasa.gov).

#### 4.6.3 CrIS for NPP

CrIS is a high-spectral resolution interferometer infrared sounder with capabilities similar to those of AIRS. AIRS was launched with AMSU-A and the Humidity Sounder for Brazil (HSB) on the EOS Aqua platform on May 4, 2002. Scientific personnel have been involved in developing the AIRS Science Team algorithm to analyze the AIRS/AMSU/HSB data. Current results with AIRS/AMSU/HSB data demonstrate that the temperature sounding goals for AIRS, i.e., root mean squared accuracy of 1K in 1 km layers of the troposphere under partial cloud cover, are being met over the ocean. AIRS radiances are now assimilated operationally by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the NOAA/National Center for Environmental Prediction (NCEP). Simulation studies were conducted for the IPO to compare the performance of AIRS/AMSU/HSB with that expected of CrIS/ATMS, and results show comparable performance is expected.

Methodology has been developed and implemented to generate proxy CrIS/ATMS data based on AIRS/AMSU observations. This data is representative of what CrIS/ATMS “would see” given the actual geophysical conditions observed by AIRS/AMSU. We are using this data to test the performance of the Northrop Grumman Space Technology (NGST) prototype operational CrIS/ATMS retrieval algorithm and compare it with a government CrIS/ATMS algorithm modeled after the AIRS Science Team (Joel.Susskind-1@nasa.gov).

#### 4.6.4 Ozone Mapper Profiler Suite (OMPS)

OMPS will become the next U.S. operational ozone sounder to fly on NPOESS. The instrument suite has heritage from TOMS and SBUV for total ozone mapping and ozone profiling. The need for high performance profiles providing better vertical resolution in the lower stratosphere resulted in the addition of a limb scattering profiler to the suite. The limb scattering profiler instrument has heritage from the two Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment (SOLSE/LORE) shuttle demonstration flights in 1997 (STS-87) and 2003 (STS-107). These missions were developed by our Laboratory with partial support by the IPO. Data from these experimental flights are being used by Laboratory staff personnel to characterize the OMPS instrument and algorithm. (Note: the limb profiler currently has been de-scoped from NPOESS for cost reduction reasons but may fly on NPP. A final decision is pending.)

Laboratory scientists continue to support the IPO through the OOAT and the NPP mission science team. Laboratory scientists are conducting algorithm research, advising on pre- and post-launch calibration procedures, and providing recommendations for validation. They participate in reviews for the OMPS instrument contractor and the NPOESS system integrator. The Laboratory staff members are also assessing OMPS data for climate research. An algorithm has been developed to analyze the SAGE III data when SAGE III operates in a limb scattering mode, which will simulate retrievals expected from the OMPS profiler. This work is an extension of the retrievals used for the SOLSE-1 and SOLSE-2 missions. The advanced ultraviolet and visible radiative transfer models developed in the Laboratory over the last two decades enable this research. The two decades of experience in TOMS and SBUV calibration and validation will also be applied to OMPS. For more information, contact Richard McPeters (Richard.D.McPeters@nasa.gov).

### 4.6.5 Tropospheric Wind Profile Measurements

Measurements of tropospheric wind profiles from ground, air, and spaceborne platforms are important for understanding atmospheric dynamics on a variety of time scales. Numerous studies have shown that direct measurement of global winds will greatly improve numerical weather prediction. Because of this importance, the operational weather forecasting communities have identified global tropospheric winds as the number one unmet measurement requirement in the Integrated Operational Requirements Document (IORD-II) for NPOESS, the next generation polar orbiting weather satellite. The Laboratory is using these requirements to develop new Direct Detection Doppler Lidar technologies and systems to measure tropospheric wind profiles, first from the ground and on high altitude aircraft, and then from satellites. Ground-based (GLOW) and airborne (TWiLiTE) Doppler lidar systems provide critical validation of new technologies proposed for eventual spaceborne operation. ESTO and the NPOESS IPO are supporting the effort. For more information, contact Bruce Gentry (Bruce.M.Gentry@nasa.gov).

## 4.7 Project Scientists

Spaceflight missions at NASA depend on cooperation between two upper-level managers - the project scientist and the project manager - who are the principal leaders of the project. The project scientist provides continuous scientific guidance to the project manager while simultaneously leading a science team and acting as the interface between the project and the scientific community at large. Table 4.3 lists the project- and deputy project scientists for current missions; Table 4.4 lists the validation and mission scientists and major participants for various campaigns.

Table 4.3: Laboratory for Atmospheres Project and Deputy Project Scientists.

Project Scientists		Deputy Project Scientists	
Name	Project	Name	Project
Robert Adler	TRMM	Christina Hsu	NPP
Pawan K. Bhartia	OMI	Joanna Joiner	EOS Aura
Robert Cahalan	EOS SORCE	Hans Mayr	AIM
Dennis Chesters	GOES	Steve Platnick	EOS Aqua
James Gleason	NPP	Si-Chee Tsay	EOS Terra
Jay Herman	DSCOVR	Warren Wiscombe	ARM, Chief Scientist

Table 4.4: Laboratory for Atmospheres Validation and Mission Scientists, and Major Participants/ Instruments.

EOS Validation Scientist	Field/Aircraft Campaigns		
Name	Mission	Name	Campaign Leaders
David Starr	EOS	Paul Newman	TC4
		Judd Welton	MPLNET
		Name	Campaign/Instrument
		Bojan Bojkov	SAUNA II/Ozonesondes
		Alexander Cede	SAUNA II/Double Brewer
		Rich McPeters	SAUNA II/Double Brewer

		Tom McGee	SAUNA/STROZ-LITE WAVES_2007/AT Raman Lidar MOHAVE II/ATL
		Matt McGill	TC4, CLASIC /CPL
		Gerry Heymsfield	TC4, CLASIC /CRS
		Jay Herman	NO <sub>2</sub> Measurement/PAN-DORA Spectrometer
		David Whiteman	WAVES_2007/RASL

## 4.8 Interactions with Other Scientific Groups

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### 4.8.1 The Academic Community

The Laboratory relies on collaboration with university scientists to achieve its goals. Such relationships make optimum use of Government facilities and capabilities and those of academic institutions. These relationships also promote the education of new generations of scientists and engineers. Educational programs include summer programs for faculty and students, fellowships for graduate research, and associateships for postdoctoral studies. A number of Laboratory members teach courses at nearby universities and give lectures and seminars at U.S. and foreign universities. (See Section 6 for more details on the education and outreach activities of our Laboratory.) The Laboratory frequently supports workshops on a wide range of scientific topics of interest to the academic community.

NASA and non-NASA scientists work together on NASA missions, experiments, and instrument and system development. Similarly, several Laboratory scientists work on programs at universities or other Federal agencies.

The Laboratory routinely makes its facilities, large data sets, and software available to the outside community. The list of refereed publications, presented in Appendix 2, reflects our many scientific interactions with the outside community; over 85% of the publications involve coauthors from institutions outside the Laboratory.

Prime examples of the collaboration between the academic community and the Laboratory are given in this list of collaborative relationships via Memoranda of Understanding or cooperative agreements:

- Cooperative Institute of Meteorological Satellite Studies (CIMSS), with the University of Wisconsin, Madison;
- ESSIC, with the University of Maryland, College Park;
- GEST Center, with the University of Maryland, Baltimore County (and involving Howard University);
- JCET, with the University of Maryland, Baltimore County;
- Joint Center for Observation System Science (JCOS), with the Scripps Institution of Oceanography, University of California, San Diego; and
- Cooperative agreement with Colorado State University, Fort Collins, Colorado.

These collaborative relationships have been organized to increase scientific interactions between the Laboratory for Atmospheres at GSFC, and the faculty and students at the participating universities.

In addition, university and other outside scientists visit the Laboratory for periods ranging from one day, to as long as three years. Some of these appointments are supported by the NASA Postdoctoral Program administered by the Oak Ridge Associated Universities; others, by the Visiting Scientists and Visiting Fellows Programs currently managed by the GEST Center. Visiting Scientists are appointed for up to two years and perform research in pre established areas. Visiting Fellows are appointed for up to one year and are free to carry out research projects of their own design.

### 4.8.2 Other NASA Centers and Federal Laboratories

The Laboratory maintains strong, productive interactions with other NASA Centers and Federal laboratories. Our ties with the other NASA Centers broaden our knowledge base. They allow us to complement each other's strengths, thus increasing our competitiveness while minimizing duplication of effort. They also increase our ability to reach the Agency's scientific objectives.

Our interactions with other Federal laboratories enhance the value of research funded by NASA. These interactions are particularly strong in ozone and radiation research, data assimilation studies, water vapor and aerosol measurements, ground-truth activities for satellite missions, and operational satellites. An example of interagency interaction is the NASA/NOAA/National Science Foundation (NSF) Joint Center for Satellite Data Assimilation (JCSDA), which is building on prior collaborations between NASA and NCEP to exploit the assimilation of satellite data for both operational and research purposes.

### 4.8.3 Foreign Agencies

The Laboratory has cooperated in several ongoing programs with non-U.S. space agencies. These programs involve many of the Laboratory scientists.

Major efforts have included the Tropical Rainfall Measuring Mission (TRMM), with the Japanese National Space Development Agency (NASDA); the TOMS program with NASDA and the Russian Scientific Research Institute of Electromechanics (NIIEM); the OMI Program with Netherlands's Agency for Aerospace Programs (NIVR); the Neutral Mass Spectrometer (NMS) instrument, with the Japanese Institute of Space and Aeronautical Science (ISAS); and climate research with various institutes in Europe, South America, Africa, and Asia. Another example of international collaboration was in the SOLVE II (SAGE III Ozone Loss and Validation Experiment) campaign, which was conducted in close collaboration with the Validation of International Satellites and study of Ozone Loss (VINTERSOL) campaign sponsored by the European Commission. More than 350 scientists from the United States, the European Union, Canada, Iceland, Japan, Norway, Poland, Russia, and Switzerland participated in this joint effort, which took place in January 2003. In 2004, another international collaboration started with the upload of instruments for the Polar Aura Validation Experiment (PAVE). PAVE is an Aura satellite validation involving instruments on the DC-8. Many of the experimenters from SOLVE II are involved in this campaign, which took place in late January and early February of 2005. This cooperation continued during 2006 in campaigns such as CR-AVE, INTEX-B, and MILAGRO, and in 2007 in campaigns such as TC4 and others described in Section 4.2

Laboratory scientists interact with about 20 foreign agencies, about an equal number of foreign universities, and several foreign companies. The collaborations vary from extended visits for joint missions, to brief visits for giving seminars or working on joint science papers.

## 4.9 Commercialization and Technology Transfer

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The Laboratory for Atmospheres fully supports Government–Industry partnerships, SBIR projects, and technology transfer activities. Successful technology transfer has occurred on a number of programs in the past and new opportunities will become available in the future. Past examples include the MPL, holographic optical scanner technology, and Circle to Point Conversion Detector. New research proposals involving technology development will have strong commercial partnerships wherever possible.



## 5. HIGHLIGHTS OF LABORATORY ACTIVITIES IN 2007

This section highlights the Laboratory's accomplishments for 2007. The summaries of Branch activities in sections 5.1, 5.2, and 5.3, expand on the introductory paragraphs in section 2. They are written by the Branch Heads and give examples of the research carried out by Branch scientists and engineers. Additional activities are described in Section 5.4, Laboratory Research Highlights. These highlights are supplemented by news items related to the Laboratory in Appendix 1, by a complete listing of refereed articles that appeared in print in 2007 in Appendix 2, and by the first page of highlighted journal articles in Appendix 3. For more details on Branch science activities, the Branch Web sites can be accessed from the Laboratory for Atmospheres home page at <http://atmospheres.gsfc.nasa.gov/>.

### 5.1 Mesoscale Atmospheric Processes Branch, Code 613.1

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The Mesoscale Atmospheric Processes Branch (MAPB) seeks to understand the contributions of mesoscale atmospheric processes to the global climate system. Research is conducted on the physical and dynamical properties and on the structure and evolution of meteorological phenomena, ranging from synoptic scale down to micro-scales, with a strong focus on the initiation, development, and effects of cloud systems. A major emphasis is placed on understanding energy exchange and conversion mechanisms, especially cloud microphysical development and latent heat release associated with atmospheric motions. The research is inherently focused on defining the atmospheric component of the global hydrologic cycle, especially precipitation, and its interaction with other components of the Earth system. Branch members participate in satellite missions and develop advanced remote sensing technology with strengths in the active remote sensing of aerosols, water vapor, winds, and convective and cirrus clouds. There are also world-class research activities in cloud system modeling, and in the analysis, application, and visualization of a variety of data.

The MAPB currently consists of 62 on-site personnel. Demographically, there are 12 civil service scientists (10 with Ph.D.s) and one civil servant clerical. The Branch maintains Cooperative Agreements with four institutions (UMBC/GEST, UMBC/JCET, GMU and UMCP/ESSIC), which collectively, comprise 23 scientists and programmers (21 Ph.D.s). Since 1990, the Branch has had a contractual relationship with SSAI of Lanham, MD, for scientific, engineering, computer and administrative support. The level of support is currently 21 onsite and 3 off-site personnel. Five other support persons are employed by RSIS, SGT, SAIC, Caelum, and Ecotronics. Three additional retired civil servants maintain Emeritus positions, as well as the GPM Project Scientist (Arthur Hou/GMAO) who is co-located in the Branch.

The Branch maintains a Web site at <http://atmospheres.gsfc.nasa.gov/meso/>, where current information on projects, field campaigns, publications, and personnel listings can be found. An important Branch asset is the GOES Project Science Web site (<http://goes.gsfc.nasa.gov/>) which displays real-time GOES imagery, and provides high-quality data to the scientific community. For example, in a non-hurricane month (May 2006), the site served 50 GBytes/day to 46 thousand distinct hosts at the average rate of 2 requests per second. During a hurricane, the Web server typically hits its limit of 10 requests per second to 150 simultaneous guests. The TRMM Web site (<http://trmm.gsfc.nasa.gov/>) provides near-real time precipitation estimations every 3 hours (with daily and weekly accumulations) as well as flood potential maps. A brief synopsis of virtually every major hurricane, typhoon, and flood event around the globe with attendant maps of accumulated precipitation can be found at [http://trmm.gsfc.nasa.gov/publications\\_dir/multi\\_resource\\_tropical.html](http://trmm.gsfc.nasa.gov/publications_dir/multi_resource_tropical.html).

The Branch activities fall into three main subject areas, precipitation (and attendant climate-scale research), instrument development and data analysis (primarily lidars and radars), and numerical modeling. These are described in more detail below.

### *Precipitation*

Branch scientists develop retrieval techniques to estimate precipitation using satellite observations from TRMM and other satellites, such as GOES and the AMSR-E sensor on EOS Aqua. The major accomplishments this year were in the areas of TRMM algorithm improvement, application of TRMM precipitation data sets to flood and landslide detection and monitoring, and achievement of continued operation of the TRMM satellite. In particular, there were significant publications on the TRMM Microwave Imager precipitation and latent heating profile products (Huffman et al. 2007; Olson et al. 2007; Shige et al. 2007; Tao et al. 2007). The overall accuracy of the TRMM algorithms continues to improve. The TRMM Ground Validation team supports this achievement through processing and analysis of data from rain gauge networks and ground-based radars. This team provides reliable, instantaneous area- and time-averaged rainfall data from several representative tropical and subtropical sites worldwide for comparison with TRMM satellite measurements. Ten years of high quality TRMM data are now available through the GES DISC. TRMM and other precipitation/latent heating data are used within the Branch for a wide spectrum of studies on precipitating cloud systems, the global water and energy cycles, and precipitation variability, particularly as it relates to ENSO (Curtis et al. 2007; Gu et al. 2007 - see Section 5.4.3). Increasingly, these activities integrate global or regional data sets with modeling. Research is conducted on the assimilation of TRMM observations into models to explore the potential benefits to weather forecasting, such as for hurricanes, and to improve understanding of precipitating cloud systems, particularly the diurnal cycle. An experimental global monitoring system for rainfall-triggered floods and landslides using the 3-hour TRMM precipitation product is currently under development.

Branch scientists also made significant contributions to the development of the Global Precipitation Measurement (GPM) mission in a wide range of areas including (1) definition of mission requirements and descoping options, (2) GPM participation in the highly successfully Canadian CloudSat/CALIPSO Validation Program (C3VP) field campaigns in the winter of 2006–07, (3) establishing joint ground validation plans with Finland, Canada, and France, and (4) working with the international community to develop a common reference standard for intercalibrations of GPM constellation radiometers, which is key to providing the next-generation global precipitation products for research and applications.

### *Instrument Development and Data Analysis*

Development of lidar technology and application of lidar data for atmospheric measurements are also key areas of research. Systems have been developed to characterize the vertical structure and optical depth of clouds (CPL), atmospheric aerosols (MPLNET, CPL), water vapor (ALVICE, RASL), and winds (GLOW) at fine temporal and/or spatial resolution from ground-based or airborne platforms (CPL, RASL). In addition, the CPL and the Cloud Radar System (CRS), a millimeter-wavelength radar for profiling cloud systems, are instrument simulators and validation tools for CALIPSO and CloudSat, respectively. In June 2007, the CPL and CRS were flown on the ER-2 aircraft in support of the Department of Energy's Atmospheric Radiation Measurement (DoE-ARM) program's Cloud and Land Surface Interaction Campaign (CLASIC) field campaign. Immediately afterward, in July-August 2007, both CPL and CRS were flown on the ER-2 as a critical component of the TC4 mission (see Section 4.2.3). The airborne measurement synergy of the lidar (CPL) and cloud radar (CRS) is an important and unique capability of the Branch.

Development of three instruments funded from the IIP continued. TWiLiTE is an airborne direct detection Doppler lidar to measure wind profiles through the troposphere (0–17 km) using the laser signal backscattered from molecules. HIWRAP is a conical scanning Doppler radar to provide horizontal winds within precipitation and clouds, and ocean surface winds, in addition to more traditional 3-D radar reflectivity and hydrometeor characteristics. Both TWiLiTE and HIWRAP are on schedule for completion in 2008 with test flights in the fall on NASA's WB-57 high-altitude aircraft. Our airborne Raman lidar (RASL) was completed and flown in WAVES\_2007 field campaign (see Section 4.2.4).

GLAS (the Geoscience Laser Altimeter System) was successfully launched aboard the Ice, Cloud and Land Elevation Satellite (ICESat) in early 2003. GLAS is an important part of NASA's Earth Science Enterprise (ESE), which includes a series of satellites to measure Earth's atmosphere, oceans, land, ice, and biosphere for a period of 10 to 15 years. During 2007, GLAS data analysis contributed to two submitted journal publications.

The NASA Micro Pulse Lidar Network (MPLNET) is a federated network of Micro Pulse Lidar (MPL) systems designed to measure aerosol and cloud vertical structure continuously, day and night, over long time periods required to contribute to climate change studies and provide ground validation for models and satellite sensors in the NASA Earth Observing System (EOS). At present, there are fourteen permanent sites worldwide, and four more to be completed soon (see Section 4.3.5). Numerous temporary sites have been deployed in support of various field campaigns since the start of MPLNET in 2000, and three more planned in 2008. Most sites are co-located with sites in the NASA Aerosol Robotic Network (AERONET) to provide both column and vertically resolved aerosol and cloud data. In addition to continuation of expansive network growth during 2007, all MPLNET data have been reprocessed into a new data release, version 2, which includes many new data products. Further information on the MPLNET project, and access to data, may be obtained online at <http://mplnet.gsfc.nasa.gov>.

The Raman lidar group is engaged in a broad range of research involving development and use of technologies for studying atmospheric quantities and processes. There is a substantial effort and collaboration with Howard University (HU). The Raman group taught a lidar techniques course within the HU Physics Department. The WAVES\_2006 and WAVES\_2007 Aura validation field campaigns have been focused at the HU Beltsville campus. The goals of these campaigns were to bring diverse instrumentation to one place for validation of satellite water vapor, ozone and clouds. WAVES\_2007 included the first flights of the Raman group's Raman Airborne Spectroscopic Lidar (RASL) which flew in support of Aura and CALIPSO missions as well as for mesoscale studies and instrument comparisons. About twenty undergraduate and graduate students and many scientists from Howard University, GSFC, Penn State, Univ. of Virginia, Univ. of Colorado, NCAR, Maryland Department of Environment, USDA, NWS, and scientists from Italy, Bolivia, and Brazil have participated in the WAVES experiments. Details of the WAVES experiments, including links to activities, goals, pictures and more can be found at <http://ecotronics.com/lidar-misc/WAVES.htm>.

The Raman group also participated in the second Measurements of Humidity in the Atmosphere Validation Experiments (MOHAVE-II) experiment at JPL's Table Mountain Facility near Pasadena, CA. This deployment supported validation of Aura satellite measurements under the framework of the Network for the Detection of Atmospheric Composition Change (NDACC). MOHAVE-II was the first field deployment of the new ALVICE (Atmospheric Lidar for Validation, Interagency Collaboration and Education) lidar system and demonstrated its capability to profile water vapor throughout the troposphere and into the lower stratosphere. Ms. Felicita Russo received her Ph.D. degree from the University of Maryland, Baltimore County in May 2007, for work on new techniques for quantifying aerosol and cloud properties using lidar. Visiting scientists from Russia, Bolivia, and Brazil have also been recently supported.

### *Numerical Modeling*

The Branch is active in the development, improvement and application of atmospheric modeling systems. Three major development efforts were achieved in the past year. The finite volume General Circulation Model (fvGCM—see also Section 4.5.4) and Goddard Cumulus Ensemble (GCE) model, a cloud-resolving model, were coupled in a multi-scale modeling approach. The use of the fvGCM allows global coverage, and the GCE model provides explicit simulation of cloud processes and their interactions with radiation and surface processes, in contrast with conventional parametric approaches. This modeling system has been applied and tested for two different climate regimes, El Niño (1998) and La Niña (1999). The new, coupled modeling system produced more realistic propagation and intensity of tropical rainfall systems, diurnal variation of rainfall over land and

ocean and intraseasonal oscillations, which are very difficult to forecast using conventional GCMs. A second major effort involved coupling various NASA Goddard physical packages (microphysics, radiation, and land surface models) into a next generation weather forecast model (known as the Weather Research and Forecast model or WRF). The new, coupled modeling system allows better forecasting (or simulation) of convective systems and tropical cyclones. Lastly, an improved GCE modeling system has been developed at Goddard over the last two decades. The GCE model has been recently improved to simulate the impact of atmospheric aerosol concentration on precipitation processes and the impact of land and ocean surface processes on convective systems in different geographic locations. The improved GCE model has also been coupled with the NASA TRMM microwave radiative transfer model and the precipitation radar model to simulate the satellite observed brightness temperature at various frequencies. This new, coupled model system allows us to investigate tropical cloud processes and improves the precipitation data retrieved from NASA satellites.

The same microphysical, long- and shortwave radiative transfer, explicit cloud-radiation, and cloud-surface interactive processes are applied in all three modeling systems. The results from these modeling systems were compared to NASA high-resolution satellite data (e.g., TRMM, CloudSat) in terms of surface rainfall and vertical cloud and precipitation structures. The model results were also compared to NASA and non-NASA field campaigns. The scientific output from the modeling activities was again exceptional with 15 new papers published in 2007.

Branch scientists conducted research in the areas of hurricane formation, structure, and precipitation processes with an emphasis on storms that occurred during special NASA field programs such as CAMEX-4 and the Tropical Cloud Systems and Processes (TCSP) experiment. Halverson et al. (2007) described the TCSP experiment and initial findings related to tropical cyclone formation and intensification. Wu (2007) found a close relationship between trends in hurricane intensity, Sahel rainfall, and Saharan Air Layer activity. Numerical forecast models, such as the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) model, were applied to simulate observed storms at very high grid resolution. The results were compared to field program and satellite (e.g., TRMM) measurements. Analysis of results for Hurricane Erin (CAMEX-4, 2001) led to improved understanding of precipitation organization, storm structure, and their relationship to intensity change and environmental influences (Braun and Wu 2007). Cram et al. (2007), using an MM5 simulation of Hurricane Bonnie from CAMEX-3, examined transport and mixing processes between the eye and eyewall. They found mixing of low-level eye air possessing high thermodynamic energy into the eyewall, which serves to enhance the energy available for convective updrafts in the eyewall and increase the intensity of the storm. A study of the formation of Tropical Storm Gert (TCSP, 2005) is leading to improved knowledge of the processes that contribute to storm formation, particularly the role of deep convective towers. Deep convection tends to spin up cyclonic circulations at low levels while stratiform precipitation enhances mid-level cyclonic rotation. Using the WRF model, we found that, like in many convective systems, deep convection was most active in the earlier stages while stratiform precipitation peaked somewhat later as convective cells decayed. Consequently, the storm's cyclonic circulation developed first at lower levels and then intensified at mid-levels as stratiform precipitation formed. These results suggest more of a bottom-up development as opposed to the more canonical top-down hypotheses of development.

Numerical models and TRMM satellite data are also used to study the organization of precipitation in winter storms and the mechanisms responsible for that organization. We are studying the along-front variations in precipitation structure in a cold front and relating that structure to the synergistic interaction between lower- and upper-tropospheric cold fronts. We are also examining the detailed cloud-to-mesoscale structure of the same cold front and finding that the banding of precipitation within the cold-frontal rainband was related to the possible release of conditional symmetric instability.

## 5.2 Climate and Radiation Branch, Code 613.2

One of the most pressing issues we face is to understand the Earth's climate system and how it is affected by human activities now and in the future. This has been the driving force behind many of the activities in the Climate and Radiation Branch. We have made major scientific contributions in five key areas: hydrologic processes and climate, aerosol–climate interaction, clouds and radiation, model physics improvement, and technology development. Examples of these contributions may be found in the list of refereed articles in Appendix 2 and in the material on the Code 613.2 Branch Web site, <http://climate.gsfc.nasa.gov>.

Key satellite observational efforts from the Branch include MODIS algorithm development and data analysis. The new MODIS “collection 5” processing stream began in April 2006, starting with Aqua MODIS data. This processing stream includes substantial enhancements and updates to the operational cloud and aerosol products developed in the Branch. The availability of MODIS cloud and aerosol products is opening new pathways of research in climate modeling and data assimilation in the Laboratory. MODIS data analysis efforts included the role of 3D radiative effects on aerosol retrievals and a number of studies of 3D and non-plane parallel effects on cloud retrievals.

The MODIS-derived global annual direct aerosol radiative forcing over clear sky oceans was estimated to be  $-5.3 \pm 0.6 \text{ Wm}^{-2}$ . Attempts to quantify aerosol indirect effects on clouds included combining *in situ* cloud microphysics in California marine stratocumulus with TOA broadband CERES observations. An approach to quantifying the indirect effect on precipitation involved continuing analysis of six years of TRMM data which shows the existence of a weekly cycle. Over the continental U.S. in summer, rain intensity and area increase midweek when pollution is at its maximum while the opposite behavior occurs over nearby waters. This finding provides new insight into the influence of human activities on rainfall. The effect of aerosol loading on cloud cover using AERONET ground-based observations showed a positive correlation, in agreement with previous satellite studies.

Efforts to include explicit aerosol nucleation processes in climate models continued. Yogesh Sud led the McRAS (Microphysics of Clouds with Relaxed Arakawa-Schubert Scheme) effort. The new McRAS modules provide an end-to-end aerosol-cloud-radiation and precipitation scheme that explicitly handles CCN/IN activation and cloud formation, wet deposition, and cloud particle size distribution in fractional clouds for radiative calculations. The goal is to develop an aerosol–cloud–radiation interaction scheme that can credibly simulate direct and indirect aerosol effects.

In the applications area, high-resolution MODIS Aerosol Optical Depth (AOD) products (1, 2, and 5 km) are currently under evaluation as part of an on-going 3-dimensional air quality monitoring system project over the U.S. This 3-year effort (2006-2008) is funded by the NASA Application Program (Code YO), with a strong partnership with EPA (data system) and NOAA (air quality forecast). In addition, a 3-year Advanced Monitoring Initiative project (2006-2008) led at Goddard by Allen Chu (GEST/613.2), in support of GEOSS and funded by the EPA Pilot Program using high-resolution MODIS AOD products, is in full swing to study the air quality in the San Joaquin Valley, California. Both projects will incorporate CALIPSO, airborne, and ground-based lidar measurements to study the vertical distribution of aerosol. These two projects will provide insights into the relationship of satellite derived AOD and *in situ* PM<sub>2.5</sub> mass concentration (for particles sizes less than 2.5  $\mu\text{m}$ ).

Branch members continued participation in NASA sponsored field campaigns, including NASA's Tropical Composition, Cloud, and Climate Coupling (TC4) campaign (summer 2007), and the DoE ARM Cloud and Land Surface Interaction Campaign (CLASIC, June 2007).

We continue to serve in key leadership positions on international programs, panels, and committees. Robert Cahalan chaired the Observations Working Group of the Climate Change Science Program (CCSP) Office,

tasked to evaluate and coordinate multi-agency contributions to the U.S. Government climate observing system. Cahalan also chairs the 3-Dimensional Radiative Transfer Working Group of the International Radiation Commission and directs the International Intercomparison of 3-Dimensional Radiation Codes. Warren Wiscombe began his tenure as the DoE Atmospheric Radiation Measurement (ARM) Chief Scientist in October 2005; this appointment includes his half-time residence at Brookhaven National Laboratory. Wiscombe is also the American Geophysical Union (AGU) Atmospheric Sciences Section president.

Branch personnel continue to serve in key project positions. Robert Cahalan serves as project scientist of SOLAR Radiation and Climate Experiment (SORCE) launched on January 25, 2003. SORCE is measuring both Total Solar Irradiance (TSI) and Spectral Solar Irradiance (SSI) with unprecedented accuracy and spectral coverage during a 5-year nominal mission lifetime. Deputy project scientists include Si-Chee Tsay (Terra), Steven Plattnick (Aqua), and Christina Hsu (NPOESS Preparatory Project, starting in November 2006). Associate Branch member Michael D. King is the EOS Senior project scientist.

We continue to make strides in many areas of science leadership, education, and outreach. Thanks to the organizational efforts of the late Yoram Kaufman and the involvement of Lorraine Remer, Charles Ichoku (ES-SIC/613.2) and other Branch members, the popular AeroCenter seminar series has continued into a seventh year. The biweekly seminars attract outside aerosol researchers from NOAA and the University of Maryland on a regular basis. The AeroCenter visitor program continues to reap benefits including joint paper submissions.

The Goddard Sun-Climate Center, like AeroCenter, is a cross-cutting activity within Goddard's Sciences and Exploration Directorate, and is co-hosted by the Climate and Radiation Branch and the Goddard Solar Physics Laboratory. The Center sponsors research on solar system climate, and investigates new opportunities for advancing the understanding of the Sun's forcing of Earth's climate. Visiting scientists from Germany and Japan have joined this effort, and the Center receives advice from an international panel of experts. The Center encourages new collaborations between scientists studying Earth, the Sun, and Earth's moon. See <http://sunclimate.gsfc.nasa.gov>.

The Branch benefits from our close association with the GSFC Earth Sciences Education and Outreach Program, most of whose members (including program manager David Herring, Code 610.3) reside in Branch space and utilize Branch resources. This group produces the Earth Observatory Web site that continues to provide the science community with direct communication gateways to the latest breaking news on NASA Earth Sciences, as well as the more recent NASA Earth Observations (NEO) data set visualization tool.

Finally, we continue with timely updates (often daily) to the Climate and Radiation Branch Web site (<http://climate.gsfc.nasa.gov>). Its "Image of the Week" and "Latest News" items highlight research by Branch members. A search page provides easy access to archived news, images, publications, and other climate information and data. The site supports calendar subscriptions and also has an extensive glossary of Earth science acronyms and a list of links to related sites.

### **5.3 Atmospheric Chemistry and Dynamics Branch, Code 613.3**

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The Atmospheric Chemistry and Dynamics Branch develops computer models and remote sensing instruments and techniques as aids in studies of aerosol, ozone, and other trace gases that affect chemistry, climate, and air quality on Earth. Using satellite, aircraft, balloon, and ground-based measurements, coupled with data analysis and modeling, Branch scientists have played a key role in improving our understanding of how human-made chemicals affect the stratospheric ozone layer.

### *Satellite Data Analysis and Records*

Branch scientists have been active participants in satellite research projects. In the late 1960s, our scientists pioneered development of the Backscattered Ultraviolet (BUV) satellite remote sensing technique. Applying this technique to data taken from NASA and NOAA satellites, Branch scientists have produced a unique long-term record of the Earth's ozone shield. The data record now spans more than three decades, and provides scientists worldwide with valuable information about the complex influences of Sun, climate, and weather on ozone and ultraviolet radiation reaching the ground. We have updated our merged satellite total ozone data set through May of 2007. We have transferred the calibration from the original six satellite instruments to the NOAA 16 and NOAA 17 SBUV/2 instruments. We have further extended this intercalibration to include the OMI instrument on the Aura satellite. We also have a merged profile data set from the SBUV instruments. The data, and information about how they were constructed, can be found at [http://code916.gsfc.nasa.gov/Data\\_services/merged](http://code916.gsfc.nasa.gov/Data_services/merged). It is expected that these data will be useful for trend analyses, for ozone assessments, and for scientific studies in general. For further information, contact Richard Stolarski ([Richard.S.Stolarski@nasa.gov](mailto:Richard.S.Stolarski@nasa.gov)) or Stacey Frith ([smh@code916.gsfc.nasa.gov](mailto:smh@code916.gsfc.nasa.gov)). Branch scientists expect to maintain this venerable record using data from a series of BUV-like instruments that are planned for use on U.S. and international satellites in the next two decades. Branch scientists were also instrumental in developing the UARS project which generates data used by researchers to produce a highly detailed view of the chemistry and dynamics of the stratosphere. Currently, Branch scientists are providing scientific leadership for the EOS Aura satellite, which was launched on July 15, 2004. Aura contains four advanced instruments to study the stratospheric ozone layer, chemistry and climate interactions, and global air quality. Branch scientists are also involved in the design of instruments, algorithms, and data systems for the new generation of ozone sensors on the operational weather satellites (NPP and NPOESS) and are developing state-of-the-art instruments to monitor air quality and tropospheric chemical species from spacecraft located at high vantage points (at distances ranging from 20,000–1,500,000 km from Earth). In addition, they operate a suite of advanced active and passive remote sensing instruments to study the chemical composition of the Earth's atmosphere from ground and aircraft. The Branch has recently developed an advanced instrument and algorithm capability for ground-based validation of OMI satellite aerosol, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub> data.

### *Modeling Activities*

The measurement activities of the Branch are highly coupled with modeling and data analysis activities. The Branch maintains state-of-the-art 2-D and 3-D chemistry models that use meteorological data, produced by the GMAO and other research centers, to interpret global satellite and aircraft measurements of trace gases. Results of these studies are used to produce congressionally-mandated periodic international assessments of the state of the ozone layer, as well as to provide a strategic plan for guidance in developing the next generation of satellite and aircraft missions. A major new thrust of the Branch is to apply the unique synergy between Branch modeling and measurement groups, which proved very successful for the study of stratospheric chemistry, to study chemically and radiatively active tropospheric species, including aerosol, CO<sub>2</sub>, O<sub>3</sub>, CO, NO<sub>x</sub>, and SO<sub>2</sub>, which affect climate, air quality, and human health. The Branch's expertise in modeling atmospheric composition, including aerosols, has generated a new initiative to develop a coupled chemistry-climate model, using the GMAO Global Circulation Model.

The following provides more detailed descriptions of some of the current Branch activities:

#### *3-D Stratospheric Chemistry Model Studies*

The coupled chemistry climate modeling project brings together the atmospheric chemistry and transport modeling of the Atmospheric Chemistry and Dynamics Branch and the General Circulation Model (GCM) development of the GMAO. The initial goal is to understand the role of climate change in determining the future

composition of the atmosphere. We have coupled our stratospheric chemistry and transport into the Goddard Earth Observing System (GEOS) general circulation model and will use this to study the past and future coupling of the stratospheric ozone layer to climate. Our emphasis is on the testing of model processes and model simulations using data from satellites and ground-based measurement platforms. We have run simulations of the past starting in 1950 and have extended them into the future to the year 2100. These simulations led to the discovery that ozone has increased in the middle stratosphere over the Antarctic during summers of the last two decades. The simulation was confirmed by examining data from the SBUV series of satellites. We are now setting up to run the scenarios being defined for the next ozone assessment using the same chemistry coupled into a new version of the general circulation model, GEOS-5. The GEOS-5 version has now been coupled to the combined stratosphere-troposphere chemistry model (COMBO) that has been developed under the Global Modeling Initiative (GMI). The GEOS-5/COMBO version of the CCM is being tested and will be used to attack scientific questions concerning the composition of both the troposphere and stratosphere and their interactions with the climate system.

Co-PIs are Richard Stolarski (Atmospheric Chemistry and Dynamics Branch) and Steven Pawson (Global Modeling and Assimilation Office). For further information, contact Richard Stolarski (Richard.S.Stolarski@nasa.gov), Steven Pawson (Steven.Pawson-1@nasa.gov), or Anne Douglass (Anne.R.Douglass@nasa.gov).

### *Global Modeling Initiative (GMI)*

The goal of GMI is to develop and maintain a state-of-the-art modular 3-D CTM that can be used for assessing the impact of various natural and anthropogenic perturbations on atmospheric composition and chemistry, including the effects of aircraft. The GMI model also serves as a testbed for different process algorithms, emission inventories, parameterizations, and meteorological fields.

The components of the GMI model have been recoded for compliance with the Earth System Modeling Framework. The GMI model is being evaluated through comparison to satellite, aircraft, and ground-based measurements. The combined stratospheric-tropospheric model (COMBO), has been very successful in simulating the temporal and spatial distribution of ozone measured by Aura instruments, both in the stratosphere and upper troposphere. A “tape recorder” effect in CO measurements from MLS is reproduced by the model. This “tape recorder” is driven by the seasonality of biomass burning. The model has also compared well with tropospheric ozone columns derived from OMI and MLS measurements, and with CO from the AIRS instrument. Comparison to OMI tropospheric column of NO<sub>2</sub>, as well as surface ozone measurements over Europe also show good agreement. Comparisons with satellite data, aircraft, and ground-based measurements are ongoing.

The GMI model has participated in the assessment carried out by the Hemispheric Transport of Atmospheric Pollutants (HTAP) international effort. Results from GMI simulations have been incorporated in the HTAP interim report, and will contribute to several scientific publications.

### *OMI Data Analysis*

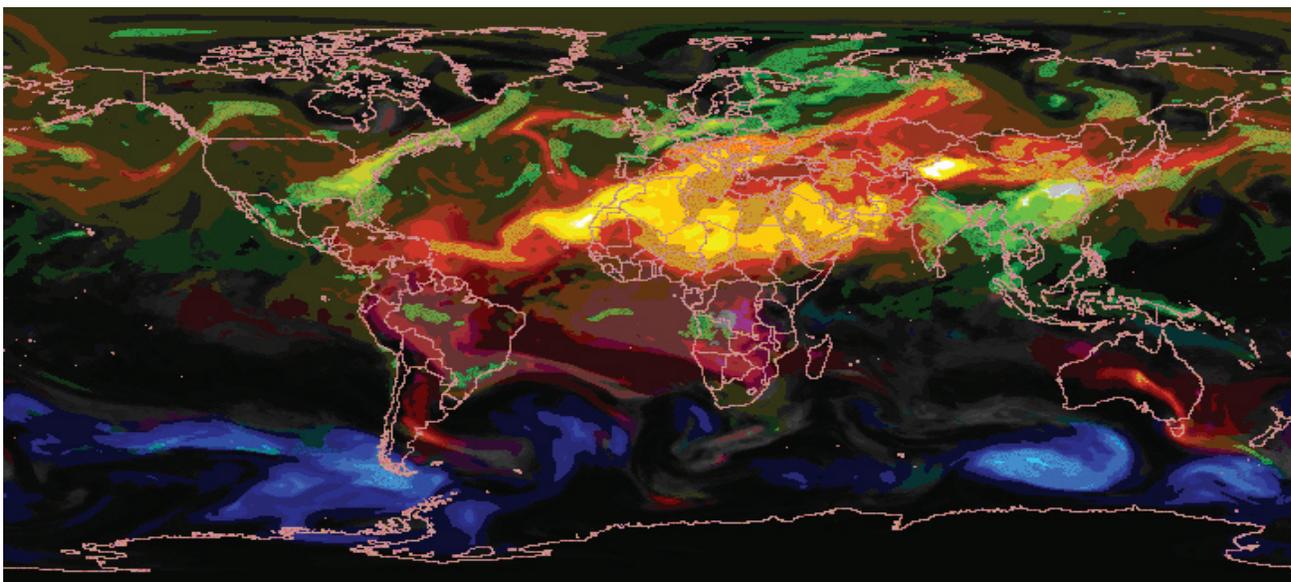
The OMI, built by Dutch/Finnish collaboration, was launched on NASA’s EOS Aura satellite in July 2004. The primary objective of OMI is to continue the long-term record, created by Branch scientists, of total ozone, tropospheric ozone, UVB, aerosols (primarily smoke and desert dust), and volcanic SO<sub>2</sub> using data from NASA’s TOMS instrument series. OMI is also designed to measure several other trace gases important for air quality studies, including NO<sub>2</sub>, anthropogenic SO<sub>2</sub>, HCHO, and BrO, with improved spatial and temporal resolution compared to data from previous instruments, the Global Ozone Monitoring Experiment (GOME) and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), on European satellites. Several Branch scientists are members of a NASA-funded U.S. science team, which is led by Pawan K. Bhartia. In 2005, Branch scientists developed and released several TOMS-like data products from OMI. Several new

products, not previously available from TOMS, have also been produced and are currently being validated. These include cloud parameters such as cloud pressure that are appropriate for use within the OMI trace-gas algorithms. Several scientific papers describing this work were submitted to the special issue on Aura validation in the *Journal of Geophysical Research*. OMI products have been submitted to the data archive.

### *Global Aerosol Studies*

Aerosols affect climate by scattering and absorbing solar radiation and by altering cloud properties and lifetimes. They also exert large influences on weather, air quality, atmospheric chemistry, hydrological cycles, and ecosystems. To understand the roles that aerosols play in the Earth system and to determine the processes that control the aerosol distributions, Branch scientists have developed the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model which simulates major types of atmospheric aerosols and relevant trace gases originating from both anthropogenic and natural sources, such as fossil fuel combustion, biomass burning, desert, ocean, vegetation, and volcanoes. In addition to the original off-line version of the model which is driven by the GEOS-DAS assimilated meteorological fields from the Global Modeling and Assimilation Office (GMAO), the GOCART modules have been implemented into the on-line GEOS-GCM model as well as the Global Modeling Initiative (GMI) modeling framework in the past year by the Branch scientists to further enhance the modeling capability. The GOCART model and GEOS-5 were used to provide onsite forecasts of CO and aerosols during the Tropical Composition, Cloud, and Climate Coupling (TC4) campaign in the summer of 2007, and will be used in the spring and summer of 2008 to support the NASA Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission. Recently, collaborating with NOAA scientists, the GOCART model is being implemented into the regional model WRF-Chem and the NOAA Global Forecasting System (GFS) to expand its applications and serve the larger scientific community.

The modeling activities have been strongly connected to observations. For example, the model has been continuously used to analyze and interpret aerosol observations from satellite instruments of MODIS and MISR and from ground-based sun photometers in the AERONET network; the model output has been integrated into satellite observations to provide the best description of global aerosol distributions; the model vertical profiles of SO<sub>2</sub> and absorbing aerosols are being tested to facilitate OMI retrievals. The model has been a part of the international project AEROCOM (AEROSol Comparisons between Observations and Models) and has been used in the new international activities of Hemispheric Transport of Atmospheric Pollutants and the Atmospheric Chemistry and Climate initiatives. Results from GOCART simulations have been used to determine the contribution to polluted aerosol environments from both local sources and long-range transport.



*Figure 5.1 Simulated global distribution of aerosol optical thickness for July 19 2007, from the GEOS-5 atmospheric general circulation model. The colors represent different aerosol species: blue = sea salt, cyan = carbonaceous, green = sulfate, and orange = dust. Brighter (darker) shading indicates greater (lesser) amounts of aerosol. These results illustrate the GEOS-5 model forecasts run at  $0.5^\circ \times 0.666^\circ$  horizontal resolution in support of the NASA TC4 campaign. Image is generated from the NASA TC4 WMS Viewer (<http://www.map.nasa.gov/cgi-bin/tc4-d5fcst-hwl.cgi>, Jeff de La Beaujardiere, Software Integration and Visualization Office, SIVO).*

### *Measurement and Modeling of Atmospheric Carbon Dioxide*

Recent Laboratory progress in carbon cycle science has come in the areas of atmospheric transport modeling and instrument construction and testing. The atmospheric chemistry and transport model, used for calculating global  $\text{CO}_2$  transport, has incorporated a land-biosphere emissions model and satellite data-constrained biomass burning emissions to produce  $\text{CO}_2$  fields that are closely tied to actual meteorology and emission events. The modeling group is actively participating in an international model intercomparison exercise, TransComC, which is aimed at improving models' ability to utilize upcoming space-based  $\text{CO}_2$  observations, such as the Orbiting Carbon Observatory. We continue collaborating with the GMAO in a new effort to develop a carbon cycle data assimilation system. We are also in a collaborative effort with the Solar System Exploration Division to develop an airborne  $\text{CO}_2$  laser sounder under the IIP. The modeling effort will help to optimize the sounder measurement characteristics through observing system simulation experiments. A partner instrument, the ground-based laser  $\text{CO}_2$  profiler, is also being developed in the Laboratory for Atmospheres. The laser profiler has recently achieved  $\text{CO}_2$  detection in reflection from clouds and has made range-resolved measurements of aerosols at both the online and offline wavelengths. This is the final step in making range-resolved measurements of  $\text{CO}_2$  within the planetary boundary layer. The real-time  $\text{CO}_2$  observations will be compared with modeled distributions to improve our knowledge of the coupling between carbon cycle processes and climate change.

### *Solar Proton Events*

Charles Jackman is using the Whole Atmosphere Community Climate Model (WACCM) to study the influence of solar proton events (SPEs) on the middle atmosphere (stratosphere and mesosphere). He is working on this endeavor with staff at the National Center for Atmospheric Research, where WACCM was developed. This work

has focused on the very largest SPEs in the past 45 years. Comparisons between WACCM predictions and observations are generally reasonable for the SPE-caused production of polar  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) and the associated decrease in ozone during these very large solar events. He plans to continue this work and concentrate next on dynamically induced changes caused by the SPEs.

### *Instrumentation*

Geostationary Spectrograph (GeoSpec) is a dual spectrograph operating in the UV/VIS and VIS/Near-Infrared (NIR) wavelength regions to measure trace gas concentrations of  $\text{O}_3$ ,  $\text{NO}_2$ , and  $\text{SO}_2$ , coastal and ocean pollution events, tidal effects, and aerosol plumes. GeoSpec is intended to support future missions in the combined fields of atmospheres, oceans, and land. The Laboratory prototype, finished in late 2006, was used as a template for future mission studies in response to the NRC decadal survey. GeoSpec activities during the current year included continued testing and calibration such as an intercomparison campaign with the Washington State University MAXDOAS instrument. GeoSpec is a collaboration of our Laboratory, Pennsylvania State University, Washington State University, and Ball Aerospace and Technologies Corporation.

The Airborne Compact Atmospheric Mapper (ACAM) is an aircraft-based measurement program started in 2005. This system combines high resolution photographic imagery of both nadir and forward-looking cloud conditions with nadir UV and VIS spectrographic measurements in order to map trace gas concentrations of  $\text{NO}_2$ ,  $\text{O}_3$ , and aerosols. ACAM activities included planning and redesign for a version to support deployment on a NASA UAV.

The 613.3 Stratospheric Ozone Lidar participated in the SAUNA II Campaign in Sodankylä, Finland during January and February, 2007 (Section 4.2.1). The purpose was to evaluate and quantify the problems that ozone column instruments have in making measurements at high solar zenith angles and high ozone levels. These instruments are important to the validation of satellite measurements at high latitudes. The lidar provided vertical profile, and atmospheric variability information for the interpretation of line of sight column ozone measurements.

## **5.4 Laboratory Research Highlights**

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### **5.4.1 Global Modeling**

One of the strengths of 613.3 is that results from various models can be used to address the same issue. Douglass et al. (2007) uses output from the CGCM, the GMI CTM, the 2-D CTM, and a trajectory model to understand why *in situ* measurements from the ER-2 in the middle- and high- latitude lower stratosphere show that photolysis has broken apart significant fractions of the long-lived chlorofluorocarbons (CFCs) such as  $\text{CF}_2\text{C}_{12}$  and  $\text{CFCl}_3$ , even though the rate of destruction at the altitude of the measurement is insignificant. There is an observed compact relationship between the mean age of a parcel and the parcel fractional release, i.e., the amount of CFC that has been destroyed relative to the amount in the parcel when it crossed the tropical tropopause. This relationship is reproduced by simulations that produce realistic distributions for the mean age, but not by simulations that produce young age distributions as was common for both 2-D and 3-D models during the 1990s. The modern models that reproduce the observed relationships also produce longer lifetimes than the models that produce young ages, e.g., the lifetime for  $\text{CFCl}_3$  that is consistent with the ER-2 observations for mean age and fractional release is about 56 years, significantly longer than the 45 years deduced from ground-based measurements and a simple model. This is important because the 45-year lifetime is used to produce the boundary conditions for assessment calculations (e.g., WMO 2007) or for projections of the recovery of the ozone hole (e.g., Newman et al., 2006).

### 5.4.2 Reversal of Trend of Biomass Burning in the Amazon

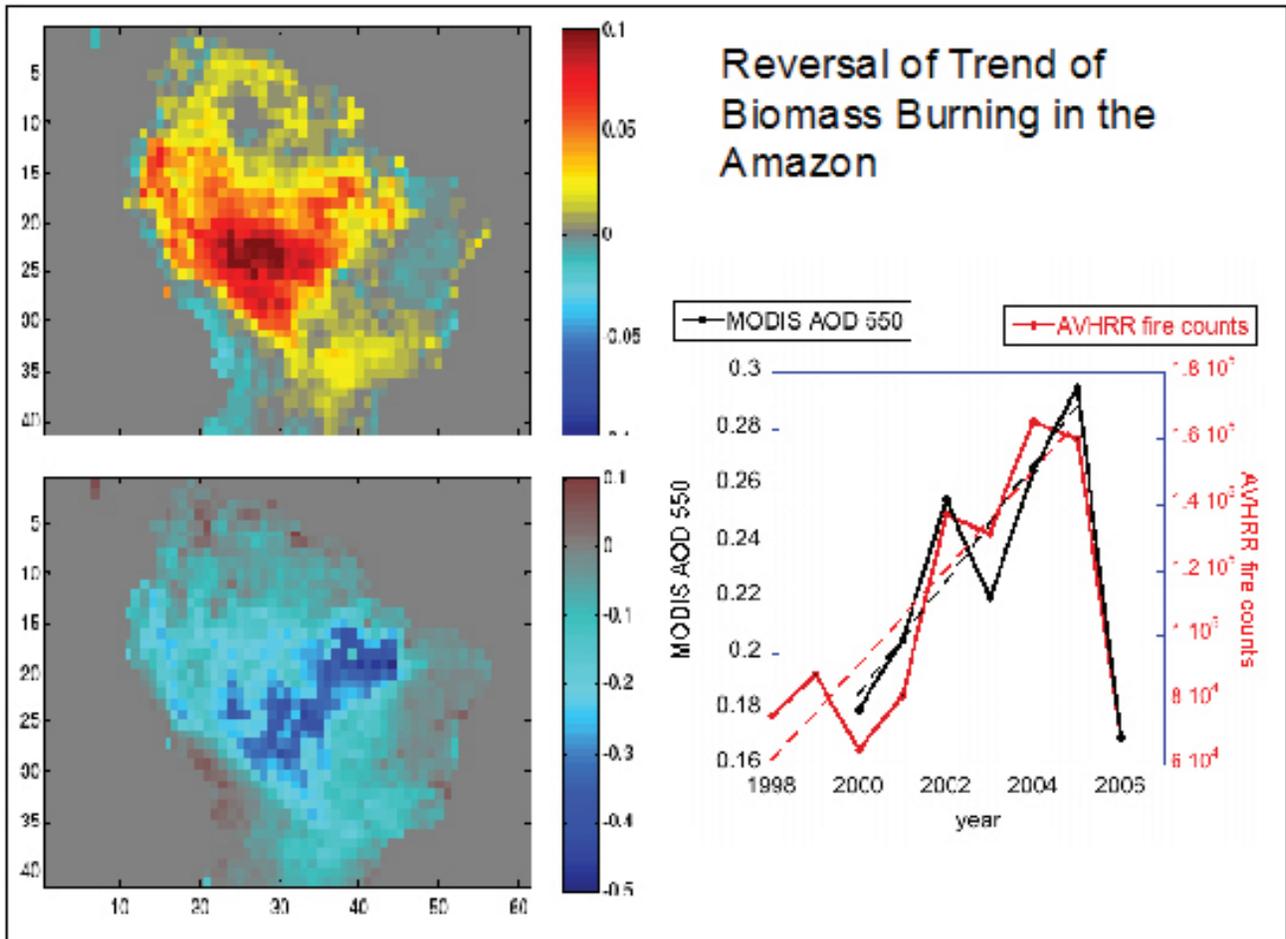


Figure 5.2 Reversal of trend of biomass burning in the Amazon.

Figure 5.2 illustrates the dramatic reversal of an increasing trend in biomass burning in just one year, due to a combination of human effort for change and meteorological factors.

The upper left panel provides the slopes of linear fits through six years of seasonal mean aerosol optical depth (AOD) as observed by the Terra–MODIS satellite sensor. The regressions were calculated independently for each 1-degree square. The biomass burning season is defined as August–November. The time series spans 2000–2005. We see that smoke increased over the entire Amazon Basin during this period. These trends are as high as 0.05 to 0.1 AOD per year, which represents an increase in AOD of 0.30 to 0.60 over the six-year period.

Then, suddenly, in 2006 there was much less smoke. The lower left panel shows the difference in the seasonal mean Terra MODIS AOD between 2005 and 2006. Blues indicate that 2006 had less smoke. The panel on the right shows the interannual variability in MODIS AOD averaged over the entire northern part of South America and also the total number of fire counts summed over the season as observed by AVHRR. We note the tight correlation between total number of fires and seasonal/regional mean AOD. We also note the tightly increasing trends upwards in both data sets until observations in 2006 reverse the trend.

Because the smoke was so alarming in 2005, a concerted effort was made by a coalition of governments, scientists, and civil authorities in 2006 to monitor burning and mitigate smoke production. Also in 2006, the rains came earlier. The result was dramatic. Smoke from biomass burning is a serious environmental hazard, but

unlike earthquakes and severe weather, effective policy can mitigate the severity of the danger to human health, the well-being of the rain forest, and the whole climate system.

As a postscript, the analysis of Koren et al. (2007) ends with the 2006 fire season. In 2007, the Amazon did not benefit from early onset of rain, and perhaps fire mitigation practices were also relaxed, because the 2007 fire season in the Amazon was back at 2005 levels or higher, according to MODIS observations of AOD. For more information see Koren et al. (2007):

Koren, I., L.A. Remer, and K. Longo, 2007: Reversal of trend of biomass burning in the Amazon. *Geophys. Res. Lett.*, **34**, L20404, doi:10.1029/2007GL031530.

### 5.4.3 Tropical Rainfall Variability on Interannual-to-Interdecadal/Longer-Time Scales Derived from the GPCP Monthly Product

Analyzing global and regional variations in precipitation is an important part of understanding both climate variations in general and the possible implications of phenomena such as global warming. Possible changes or variations in precipitation are also important for their impacts on agriculture and water resources. The satellite-based, 27-year (1979–2005) Global Precipitation Climatology Project (GPCP) monthly precipitation data set provides the opportunity to examine part of this climate variation/change puzzle. This product is a community-based analysis of global precipitation under the auspices of the World Climate Research Program (WCRP) that uses information from various satellite measurements and ground-based rain-gauge data. We examined global and large regional precipitation variations and possible long-term changes, with a specific focus on the tropics (25°S–25°N), and found that, while the global linear change of precipitation in the data set is basically negligible during the time period, an increase in tropical rainfall is noted, with a weaker decrease over Northern Hemisphere middle latitudes.

The effects of ENSO and volcanic eruptions on the year-to-year variation of tropical precipitation are first examined. The ENSO events generally do not impact the tropical total rainfall, but induce significant anomalies with opposite signs over tropical land and ocean. Two major volcanic eruptions (El Chichón, March 1982; Pinatubo, June 1991) occurred during the time period. They induced up to a 5% reduction in tropical rainfall over both land and ocean. The derived relations are further applied to the GPCP data to isolate any long-term changes that are present. The increase in tropical total rainfall was especially evident over the oceans. Specifically, the data indicate an upward trend (+0.06 mm day<sup>-1</sup>/decade) and a downward trend (-0.01 mm day<sup>-1</sup>/decade) over tropical ocean and land, respectively (Figure 5.3a). This corresponds to a roughly 5.5% increase (ocean) and 1% decrease (land). After the ENSO and volcano effects are removed from the GPCP data (Figure 5.3b), these changes become more evident, and the (statistical) confidence levels used to estimate whether the change is real increase to higher levels. Furthermore, 2005 has the largest annual tropical total precipitation for the GPCP record. The five highest years are (in descending order) 2005, 2004, 1998, 2003, and 2002. For tropical oceans, the five highest years are 1998, 2004, 2005, 2002, and 2003. The major conclusion here is that the GPCP data set tends to support that tropical ocean precipitation appears to be increasing, possibly in reaction to “global warming”. For further information, contact Robert F. Adler ([Robert.F.Adler@nasa.gov](mailto:Robert.F.Adler@nasa.gov)), and Guojun Gu ([Guojun.Gu-1@nasa.gov](mailto:Guojun.Gu-1@nasa.gov)).

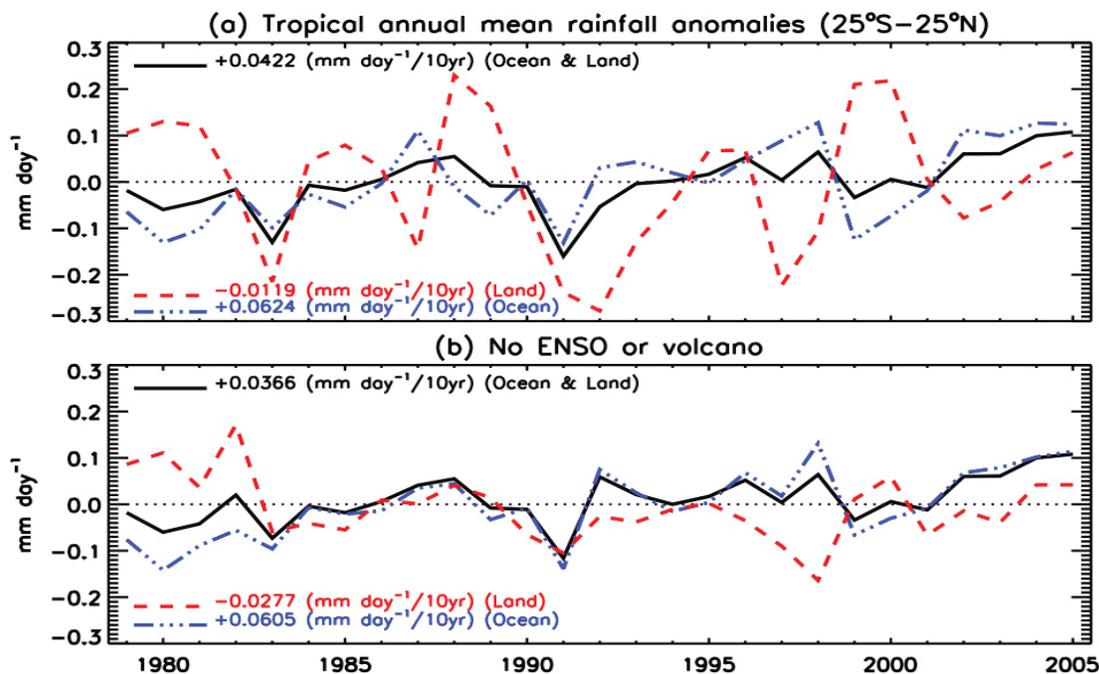


Figure 5.3 Tropical annual mean rainfall anomalies (a) with and (b) without the ENSO and volcano impact.

## 5.5 Instrument Development

The *Laboratory for Atmospheres Instrument Systems Report*, NASA/TP-2005-212783, described the status of instrument development in the Laboratory as of mid-2005. This section describes some of the developments since publication of that report.

### *High-Altitude Imaging Wind and Rain Airborne Profiler*

A dual-wavelength (Ku and Ka band) High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is under development for the NASA Instrument Incubator Program (IIP) for measuring tropospheric winds within precipitation regions and ocean surface winds in rain-free to light-rain regions. This instrument is being designed for operation on high-altitude manned aircraft and the Global Hawk UAV. Proposed lidar-based systems will provide measurements in cloud-free regions globally. Because many of the weather systems are in disturbed regions that contain precipitation and clouds, microwave-based techniques are more suitable in these regions. Airborne radars at NASA and elsewhere have shown the ability to measure winds in precipitation and clouds. These radars have not generally been suitable for deriving the full horizontal wind from above cloud systems (high-altitude or space) that would require conical scan. HIWRAP is a dual-beam, dual-wavelength conical scan radar that uses new technologies that utilize solid state rather than tube-based transmitters (Figure 5.4). Although primarily intended for atmospheric (precipitation) measurements, HIWRAP can serve as a QuikScat simulator with its Ku-band frequency and can provide measurements for GPM algorithm development since it has similar Ku- and Ka-band frequencies. Various subsystems of the radar are near completion and HIWRAP integration and testing will occur during spring 2008. The prototype sensor will be completed and tested on the high-altitude WB-57 aircraft in fall 2008 to demonstrate the system level performance of the instrument. For further information contact Gerry Heymsfield (Gerald.M.Heymsfield@nasa.gov).

## HIWRAP Concept

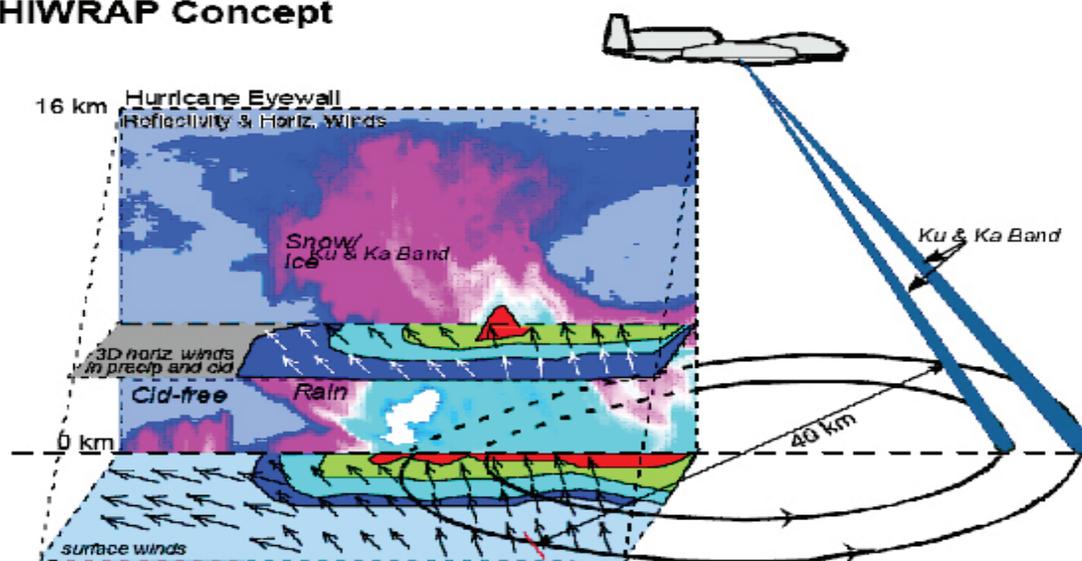


Figure 5.4 HIWRAP Concept

## 5.6 Awards and Special Recognition

### 5.6.1 Individual Awards or Recognition

**Bob Adler** (613) received the William Nordberg award at the Goddard Science Colloquium on November 16, 2007. The William Nordberg Memorial Award for Earth Science is presented annually to a Goddard employee “who best exhibits qualities of broad scientific perspective, enthusiastic programmatic and technical leadership on the national and international levels, wide recognition by peers, and substantial research accomplishments in understanding Earth science processes.” This award recognizes Bob’s outstanding long-term contributions to precipitation science, in particular his dedicated efforts as TRMM project scientist in ensuring the phenomenal success of that mission.

**Thomas McGee** (613.3) received the Alan Berman Research Publication Award from The Department of the Navy and NRL for technical merit and clarity. This award is for the publication entitled, “CHEM2D-OPP: A new Linearized Gas-Phase Ozone Photochemistry Parameterization for High Altitude NWP and Climate Model,” on which he was a coauthor. The lead author was John McCormack of NRL and the publication appeared in *Atmospheric Chemistry and Physics*. The paper used our AROTAL data for comparison with the model results.

**Scott Braun** (613.1) was awarded the NASA Exceptional Scientific Achievement Medal on May 14, 2007, for his research on hurricane formation, structure, and intensification.

**Winston Chao** (613.2) was a NASA Honor Awards Recipient. He was awarded the Exceptional Achievement Medal.

**Anne Douglass** (613.3) and **William Lau** (613) were honored as AGU Fellows at the AGU Honors Ceremony held in conjunction with the AGU Joint Assembly, Acapulco, Mexico, May 22–25. Anne Douglass’s citation reads “for significantly advancing the science of three-dimensional chemical modeling through the use of satellite and ground-based data,” and William Lau’s reads “for his outstanding contributions to the advancement of understanding of the monsoon climate system through original and masterful data analysis and modeling.” The

AGU fellows are awarded annually to scientists who have acknowledged eminence in a field of space or Earth sciences, and are limited to 0.1% of the total AGU membership.

**Paul A. Newman** (613.3) has been selected by the 191 nations of the Montreal Protocol as one of the co-chairs of the Scientific Assessment Panel. The Montreal Protocol is the landmark agreement that regulates gases such as chlorofluorocarbons that deplete the ozone layer. The Panel assesses the status of and other scientific aspects of ozone layer depletion. The four Co-chairs are: Paul A. Newman (USA), A. R. Ravishankara (USA), John Pyle (UK), and Ayite-Lo Ajavon (Togo).

The Scientific Assessment Panel has been a pillar of the ozone protection regime since the very beginning of the implementation of the Montreal Protocol. Through provision of independent, technical and scientific assessments and information, this Panel has helped the world's nations reach informed decisions that have made the Montreal Protocol a world-recognized success. In accordance with the Montreal Protocol, the Panel carries out periodic assessments on the scientific issues of ozone depletion. The first report was published in 1989, and since then, major periodic assessments have been published in 1991, 1994, 1998, 2002, and 2006. The next one, for 2010, is expected to be published in 2011.

**S.K. Satheesh** (613.2/ORAU), an NPP Senior Fellow and Associate Professor with the Indian Institute of Science, currently visiting the Climate and Radiation Branch, has won the Scopus® Award for Earth Sciences. The Second Young Indian Scientist Awards were presented at an event held in New Delhi on December 7, 2007. Scopus® is the largest abstract and citation database of peer-reviewed literature and quality Web sources with smart tools to track, analyze, and visualize research.

### **5.6.2 Goddard Honor Awards**

**Alexander Marshak** (613.2): GSFC Earth Science Achievement  
**N. Christina Hsu** (613.2): Exceptional Achievement—Individual  
**Lorraine Remer** (613.2): Outstanding Leadership

### **5.6.3 Group Achievement Awards**

**Matt McGill** (613.1), **Bill Hart** (613.1/SSAI), **Dennis Hlavka** (613.1/SSAI), and **Steve Palm** (613.1/SSAI) are members of the CALIPSO Team that received a Group Achievement Award at the LaRC 2007 Honor Awards Ceremony on July 13. The citation reads, “For exceptional achievements in the successful development, launch, and operation of the CALIPSO satellite.”

The first Environmental Research Letters Outstanding Article of the Year Award was presented to **Ilan Koren** (613.2/UMBC), **Yoram J. Kaufman** (613.2, Deceased), **Richard Washington**, **Martin C Todd**, **Yinon Rudich**, **J. Vanderlei Martins** (613.2/JCET) and Daniel Rosenfeld for the article “The Bodélé depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest.” In recognition of the outstanding contribution of this paper, each author has earned one-year free publication in ERL for themselves, as well as 6-months free publication for any paper submitted by any member of their institution. All published papers since 30 October 2007 will be considered for next year's award.

**William Lau** (613), **Gerry Heymsfield** (613.1), **Christina Hsu** (613.2), **Si-Chee Tsay** (613.2), and **Oreste Reale** (613/GEST) are members of the NASA African Monsoon Multidisciplinary Analysis (NAMMA) campaign that received an award for outstanding accomplishments in the successful NAMMA field campaign conducted in the Cape Verde Islands.

## 6. EDUCATION AND OUTREACH

### 6.1 Introduction

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NASA's founding legislation directs the Agency to expand human knowledge of Earth and space phenomena and to preserve the role of the United States as a leader in aeronautics, space science, and technology. However, in recent years, undergraduate and graduate enrollment and the number of doctorates awarded in science and engineering have been declining. This trend, along with an aging workforce, places an increasing burden on NASA to maintain its level of achievement in science and technology.

The Laboratory's parent organization, the Earth Sciences Division (Code 610), has established a Committee for Education and Public Outreach, which is charged with coordinating these activities across the Division. Several Laboratory members are also on the ESD committee. Scott Braun, Goran Halusa, Paul Newman, and Lorraine Remer, are all working with David Herring, Program Manager for Education and Outreach, to achieve the Committee's objectives. More information may be found at <http://esdepo.gsfc.nasa.gov/index.php>.

### 6.2 Education

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#### 6.2.1 PUMAS—Practical Uses of Math And Science



Pumas is an online journal, a Web-based collection of brief examples aimed at giving K-12 teachers insights into how the math and science they teach are actually used in everyday life. This site was founded and is edited by **Ralph Kahn** (613.2), who joined the Laboratory in September 2007, coming from JPL. The examples are written primarily by scientists and engineers, and are available to teachers, students, and other interested parties via the PUMAS Web site (<http://pumas.nasa.gov/>). Scientists contribute their expertise by writing the examples, which may be activities, anecdotes, descriptions of “neat ideas,” formal exercises, puzzles, or demonstrations. These examples are widely used by pre-college teachers around the world to enrich their presentation of topics in math and science. PUMAS offers researchers a way to make a substantial contribution to precollege education with a relatively small investment of time and effort, and at the same time, to get a peer-reviewed science education journal article published on the Web. For further information contact Ralph Kahn ([Ralph.Kahn@nasa.gov](mailto:Ralph.Kahn@nasa.gov)).

## 6.2.2 Interaction with Howard University and Other Historically Black Colleges and Universities (HBCUs)

### *Partnerships with Howard University:*

A part of NASA's mission has been to initiate broad-based aerospace research capability by establishing research centers at the Nation's HBCUs. The Center for the Study of Terrestrial and Extraterrestrial Atmospheres (CSTEA) was established in 1992 at Howard University (HU) in Washington, D.C., as part of this initiative. It has been a goal of the Laboratory and the Earth Sciences Division to partner with CSTEA to establish at Howard University a self-supporting facility for the study of terrestrial and extraterrestrial atmospheres, with special emphasis on recruiting and training underrepresented minorities for careers in Earth and space science.

The Laboratory works closely with HU faculty in support of the Howard University Program in Atmospheric Sciences (HUPAS). HUPAS is the first M.S.- and Ph.D.-granting program in atmospheric sciences at an HBCU and the first interdisciplinary academic program at HU. Scientists from our Laboratory have contributed to the HUPAS program as lecturers, advisors to students, and adjunct professors who teach courses. A number of HU students have earned M.S. and Ph.D. degrees in atmospheric sciences.

### *Participation with Howard University on the Beltsville Campus Research Site:*

Howard University has for several years been in the process of building a multi-agency, multi-university field observation research station at the Howard University Research site at Beltsville (HURB). This facility is part of the NOAA-Howard University Center for Atmospheric Science. David Whiteman (613.1), Belay Demoz (613.1, now at Howard University), and others from GSFC are assisting in mentoring students and advising with instrument acquisition for the site. One of the main instruments at the site is a world-class Raman lidar built with heavy involvement from Code 613.1.

During the summer of 2007, students from Howard University participated in the WAVES\_2007 field campaign at the Beltsville site from July 14 to August 8. WAVES is a satellite validation, sonde, and other instrument inter-comparison field campaign centered on the Howard University Research site in Beltsville, Maryland. The main goal of this campaign was to acquire a statistically robust set of measurements of atmospheric water vapor, aerosols and trace gases useful for Aura/Aqua satellite retrieval studies as well as for performing instrument accuracy assessments, and for case studies of regional water vapor and aerosol variability. WAVES was the first major experiment held at HURB and as such required coordination within HU and with NASA GSFC, NOAA/Boulder, NWS/Sterling, and with many universities: UMCP; UMBC; Penn State; Bowie State; Trinity College in DC; Univ. of Virginia; Smith College, MA; Univ. of Wisconsin; and with universities from Brazil, Italy, and Bolivia.



*Figure 6.1 A NASA civil servant and Everett Joseph of Howard University (second from left) training students from Howard University, Trinity College, Smith College, Univ. of Wisconsin, and UMCP on the details of multiple radio sounding launches on a single balloon.*

Previous satellite validation activities have been hosted at sites such as the Department of Energy ARM sites that offer pristine measurement conditions not influenced by pollution sources and away from high population pressure, the Howard University Research site is in Beltsville, MD, a suburb of Washington, DC, and can be subject to periods of high pollution during the summertime. This fact, coupled with the heterogeneous terrain and the high population density makes satellite retrievals of such quantities as water vapor, ozone, and temperature more difficult. However, due to the large affected population and the proximity to the nation's capital, it is very important that satellite retrievals work well in such areas. The WAVES\_2006 and WAVES\_2007 field campaigns were held in July and August 2006 and 2007, to provide a high-quality set of ground-based and balloon-borne measurements to assess the quality of the retrievals from the Aura and Aqua sensors under the “difficult” retrieval conditions that exist in the mid-Atlantic region of the US during the summertime.

WAVES was funded by NASA SMD for two years. The core components of the WAVES funding include proposals awarded to HU, UMBC, and GSFC. For further information see the WAVES Web site, <http://ecotronics.com/lidar-misc/WAVES.htm>, or contact David Whiteman (David.N.Whiteman@nasa.gov).

## 6.3 Summer Programs

### 6.3.1 The Summer Institute in Atmospheric, Hydrospheric, and Terrestrial Sciences

The Summer Institute in Atmospheric, Hydrospheric, and Terrestrial Sciences was held from June 11 to August 17, 2007. The Institute is organized by Per Gloersen (Code 614.1) and is hosted by the Earth Sciences Division (Code 610). It is designed to introduce undergraduate students majoring in all areas of the physical sciences to research opportunities in these areas. After a one-week series of introductory lectures, the students select from a list of research topics and are mentored by a Goddard scientist for a period of nine weeks. At the conclusion of this period, the students give a presentation of their results. Laboratory scientists participating in the Institute, students, and research topics are shown in Table 6.1.

**Table 6.1: Laboratory Scientists Mentoring Students in the 2007 Summer Institute**

Mentor, Code	Student, University	Topic
Yang Hong, 613.1/GEST Bob Adler, 613	Stephanie Hill, Salisbury Univ.	A Study of Rainfall-Triggered Landslides on a Global Scale
Eric Wilcox, 613.2	Cody Fritz, Univ. of Missouri	The Effect of Aerosol on Stratocumulus Clouds in the Eastern-North Pacific
Rob Levy, 613.2/SSAI	Natalia Rodriguez, Universidad de Puerto Rico	Retrieval of Global Aerosol Properties: Validation and Climatology from MODIS
Menglin Jin, 613.2/UMCP Lorraine Remer, 613.2	Krista Romita, Vassar College	A Tale of Two Cities
Charles Ichoku, 613.2/UMCP	Shawn Gindhart, Millersville Univ	Compiling a Climatology of Smoke Plume Injection Heights from Measurements

Stephanie Hill compiled a database of 2007 landslides to compare with algorithm predicted landslides. Floods and associated landslides affect more people than any other type of natural disaster.

Cody Fritz used cloud radar data to investigate the possibility that structural differences between clouds in polluted and clean environments might mitigate the cooling effects of polluted clouds. For the region studied, it appears that liquid water path diminishes in polluted clouds (they're thinner), thus reducing the cooling effect.

Natalia Rodriguez participated in MODIS validation activities over the summer, comparing MODIS aerosol optical depth (AOD) and fine weighting (FW) with AERONET observations over five global regions. AOD correlates well, but FW is basically uncorrelated. These results are used to improve the MODIS retrieval algorithms.

In 'A Tale of Two Cities' (Beijing and New York in this case), Krista Romita presented a study of aerosol effects on radiative transfer and the consequent impact on urban climate systems. Data from AERONET sites in each city, MODIS observations, and radiative transfer models were used in the measurement of aerosol parameters (aerosol optical thickness, single scattering albedo, and asymmetry factor) and in the calculation of heating rates and radiative forcing. This study was aimed at obtaining a better understanding of urban microclimates and city-generated mesoscale circulations.

Shawn Gindhart used several NASA and other resources to locate fires and develop a climatology of smoke plume injection heights. Fire locations were obtained from MODIS, the Earth Observatory, and Google Earth. The heights were from two spaceborne lidars (GLAS and CALIPSO) and the MISR satellite. The resulting injection height climatology can provide estimates of pollutant lifetimes and consequently their range of environmental impacts, and can also be used for comparison with the results of plume rise models.

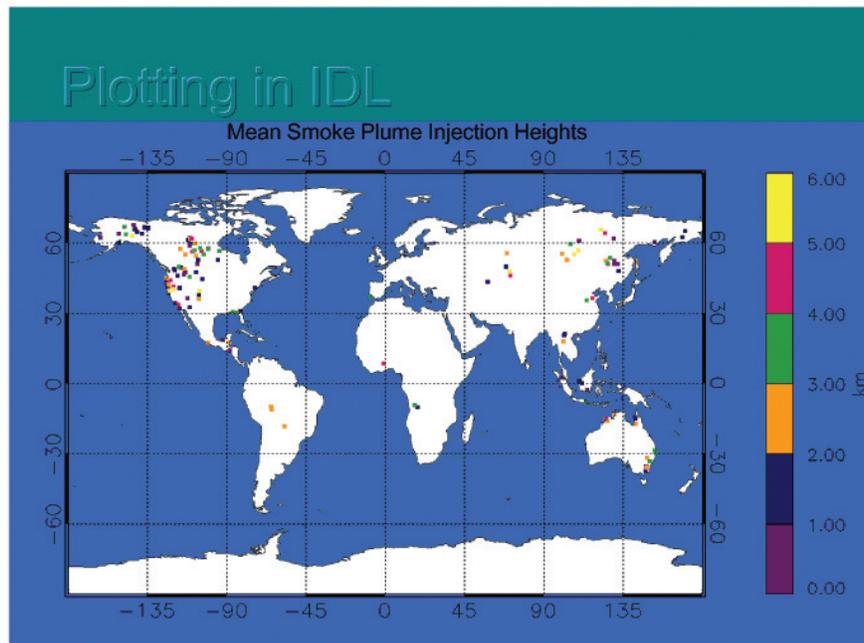


Figure 6.2 Plume injection height climatology (from the Summer Institute presentation of Shawn Gindhart).



Figure 6.3 Participants in the 2007 Summer Institute. Per Gloersen is at the left.

### 6.3.2 Research & Discover: Summer Internship Program in Earth Sciences

Research & Discover is a summer internship program jointly sponsored by the University of New Hampshire (UNH) and GSFC. It is available to students who have completed their junior year of college. Participants receive a stipend, as well as room and board. Following the first summer internship, participants are encouraged to apply for a second summer internship held at the NASA Goddard Space Flight Center. Following this internship, participants will be eligible to receive a two-year fellowship for graduate study at UNH. During summer 2007, Judd Welton of the Mesoscale Atmospheric Processes Branch, advised UNH student Virginia Sawyer on a project that utilized both MPLNET and CALIPSO backscatter lidar data to detect the planetary boundary layer. The results were given on August 9 in a presentation entitled “Automating Detection of the Planetary Boundary Layer in Aerosol Lidar Soundings.”

### 6.3.3 Goddard Earth Sciences and Technology (GEST) Center Graduate Student Summer Program: GEST-GSSP

NASA Goddard Space Flight Center’s Earth Sciences Division, in collaboration with the Goddard Earth Sciences and Technology (GEST) Center of the University of Maryland, Baltimore County, offers a limited number of graduate student research opportunities through its Graduate Student Summer Program (GSSP). This prestigious program is in its eighth year and is designed to stimulate interest in interdisciplinary Earth sciences studies by enabling selected students to carry out an intensive research project at GSFC’s Earth Sciences Division, which can be applied to the student’s graduate thesis.

Positions are available to students interested in any Earth sciences field conducive to the research of NASA GSFC’s Earth Sciences Division. Each student is teamed with a NASA Goddard scientist mentor with parallel scientific interests. NASA mentors can be drawn from any of the participating Earth Sciences Laboratories which include: the Laboratory for Atmospheres, the Hydrospheric and Biospheric Sciences Laboratory, the Global Modeling and Assimilation Office, the Global Change Data Center, and the Software Integration and Visualization Office. During the summer program, there is a lecture series aimed at current popular Earth sciences topics. At the conclusion of the program, students produce final oral and written reports on their summer research activities.

During the summer of 2007, Laboratory personnel acted as mentors for four GEST students. Mentors, students, and their research topics (if available) are given in Table 6.2.

Table 6.2: Laboratory Scientists Mentoring Students in the 2007 GEST-GSSP Program

Mentor, Code	Student, University	Report
William Lau, 613	Andrew Martin, Florida State University	
Wei-Kuo Tao, 613.1	Marcia DeLonge, Univ. of Virginia	Using Goddard Cumulus Ensemble model to investigate precipitation processes associated with African convective systems Using Goddard Cumulus Ensemble model to investigate precipitation processes associated with African convective systems
Bob Adler, 613 Yang Hong, 613.1/GEST	Dalia Bach, Columbia Univ.	
Ali Tokay, 613.1/JCET	Boone Larson	

### 6.3.4 GSFC High School Internship Program (HIP)

HIP is a research intensive program that allows interns to explore “real-time” applications of Science, Technology, Engineering, and Mathematics (STEM) disciplines. By the end of the summer, interns complete eight weeks of research on a project related to NASA’s goals and deliver an oral technical presentation, sharing the results of their research with NASA management, scientists, and fellow interns.

Each HIP student is assigned a NASA scientist or engineer as a mentor and assists the mentor with his or her current project. The interns conduct research and use data for the projects, and the mentors guide the students and help them learn as much as possible from their experience at NASA Goddard.

This year's six-week program ran from June 25 to August 3. Anne Douglass of the Atmospheric Chemistry and Dynamics Branch advised student Xiaoxiao Lin on a study entitled "Comparing Ozone Simulated Data to MLS Aura Data—Finding Locations of Bias." The results were given at the NASA GSFC Summer 2007 Summer Internship Program Final Technical Presentations on August 1.

### 6.3.5 AMS Fellowship Winners' Visit

On June 5, 2007 the Earth Sciences Division hosted a visit to GSFC by a group of AMS Fellowship Winners. The visit was organized by the Laboratory for Atmospheres and consisted of a morning seminar and an afternoon tour of the clean room and other facilities in Building 29. The AMS Fellowship Program, established in 1991, has awarded over 200 fellowships to students entering their first year of graduate study in the atmospheric or related oceanic or hydrologic sciences, with the total dollars awarded reaching nearly \$3.5 million. The program is designed to attract promising young scientists to the AMS-related sciences and provide adequate funding for their first year, allowing the recipients to focus solely on their studies. The AMS is joined by industry leaders and Federal agencies in sponsoring the fellowships, which carry a \$22,000 stipend. The students, their areas of research interest, and universities are listed in Table 6.3.

Table 6.3: 2007 AMS Fellowship Winners Visiting GSFC

Student	University	Research Interest
Zachary Byco	Penn State University	Meteorology
Ariel Cohen	University of Oklahoma	Meteorology, Mesoscale Convective Systems
Gina Eosco	Cornell University	Communication Research
Jessica Fieux	Florida State University	Meteorology
Lauren Hand	University of Georgia	Concentration Factor Analysis to Relate Meteorological Parameters
Kimberly Klockow	University of Oklahoma	Meteorology
David Knight	University of Virginia	Environmental Sciences
Rebekah LaBar	University of Oklahoma	Meteorology, Mesoscale Convective Systems
Christopher McKinney	Texas A&M University	Atmospheric Sciences
Stephen Munchak	Colorado State University	Remote Sensing of Precipitation
Maryann Racine	Harvard University	Atmospheric Chemistry
Carlos Szembek	Yale University	Atmospheric, Ocean, and Climate Dynamics
John Williams	M.I.T.	Hurricane Research

During the morning seminar, presentations were given by scientists from the Laboratory for Atmospheres (Code 613), the Hydrospheric and Biospheric Sciences Laboratory (Code 614), and the Global Modeling and Assimilation Office (GMAO, Code 610.1). The agenda consisted of the following:

- 9:15–9:30: **William Lau**, Chief, Laboratory for Atmospheres (613)  
Welcome and opening remarks.
- 9:30–10:00: **Ron Gelaro**, Global Modeling and Assimilation Office (610.1).  
"Assessing the Impact of Observations on Numerical Weather Forecasts"

## EDUCATION AND OUTREACH

10:00–10:30: **Lorraine Remer**, Climate and Radiation Branch (613.2).  
“Can Aerosols Save Us From Global Warming”

10:30–10:45: Break

10:45–11:15: **Lahouari Bounova**, Biospheric Sciences Branch (614.4).  
“Combining Satellite Data and Models to Study Climate”



*Figure 6.4 Lorraine Remer of the Climate and Radiation Branch (Code 613.2) addresses the AMS fellowship winners during their visit to GSFC.*

During the afternoon, the AMS students toured facilities at Building 29, guided by Barbara Lambert, flight hardware photographer with SGT Corp.



Figure 6.5 Barbara Lambert, third from right in the black sweater, and AMS Fellowship Winners view the Hubble Space Telescope clean room in Building 29. A mockup of a shuttle control panel is at the left in this photo.

## 6.4 University Education

Laboratory members are active in supporting university education through teaching courses and advising graduate students. Table 6.4 lists instructors and courses taught.

Table 6.4: Courses Taught in 2007

University	Course	Instructor, Code
UMBC	PHYS 440/640, Computational Physics	David Lary, 613.3/UMBC
UMBC	Physics 602, Statistical Mechanics	Prasun Kundu, 613.2/JCET
Johns Hopkins Univ.	Physics 615.415.31, Statistical Mechanics and Thermodynamics	Prasun Kundu, 613.2/JCET

The following, Table 6.5, lists Laboratory members serving as graduate student advisors and/or on student Ph.D. committees. Committee members are indicated by an asterisk after the member’s name and code. The actual or anticipated date of the student’s dissertation defense, if available, is shown after the student name.

Table 6.5: Graduate Student Advising by Laboratory for Atmospheres Members

Member, Code	Student	Degree	Institution	Thesis Topic or Area
Oreste Reale, 613/ GEST	Marangelly Fuentes	Ph.D.	Howard University	Comparison of tropical cyclo- genetic processes in current global models
David Starr, 613.1	Tamara Singleton	Ph.D.	UMCP	Influence of Gravity Waves on Cirrus Clouds
Eyal Amitai, 613.1/ GMU	Xavier Llord	Ph.D.	UPC, Barcelona, Spain	Radar Meteorology
Gerald Heymsfield, 613.1	Steven Guimond	Ph.D.	Florida State Uni- versity	Hurricane Hot Towers with Aircraft and Satellite Obser- vations
David Whiteman, 613.1	Rasheen Connell	Ph.D.	Howard University	A Numerical Model Charac- terizing the Performance of the Howard University Raman Lidar System
Wei-Kuo Tao, 613.1*	Jiwen Fan, August 2007	Ph.D.	Texas A&M Univ.	Cloud-Chemistry-Aerosol In- teractions
Wei-Kuo Tao, 613.1*	Thomas L. O'Halloran, Sum- mer 2007	Ph.D.	Univ. of Virginia	Cloud-Land-Vegetation Inter- actions
Steven Platnick, 613.2*	Joonsuk Lee, Spring 2007	Ph.D.	Texas A&M Univ.	Assessing Subvisual Cirrus with MODIS
Steven Platnick, 613.2	Brent Maddox	Ph.D.	Univ. of Wisconsin, Madison	Analysis of MODIS gridded cloud products
Charles Gatebe, 613.2	Juliao J. Cumbane	Ph.D.	Univ. of Johannes- burg, South Africa	Investigations of Clean Air Slots over Southern Africa from Multiangular Measure- ments
Tamas Varnai, 613.2/ UMBC	Philippe Chambon	Masters	Ecole Normale Su- périeure Lyon, Fr.	Influence of horizontal cloud variability on satellite retriev- als of cloud optical thickness
Kenneth Pickering, 613.3	Amanda Hansen	Ph.D.	Florida State Uni- versity	Development of a Lightning NO <sub>x</sub> Parameterization for the WRF-Chem Model

Laboratory members participate with faculty at several joint centers identifying students whose research interests are shared by a faculty member and a Laboratory scientist. Students are encouraged to visit Goddard and it is anticipated that the Laboratory member will serve on the student's thesis committee. Table 6.6 lists students currently supported.

Table 6.6: Graduate Students Supported at the Joint Centers

Student	University	Topic	Advisor and/or Sponsor
Oleg Aulov	UMBC	Enabling Model Interactions in Sensor Webs	David Lary, 613.3/UMBC
Andrew Rickert	UMBC	Enabling Model Interactions in Sensor Webs	David Lary, 613.3/UMBC
Brittany McClure*	UMCP	OMI SO <sub>2</sub> data validation with aircraft <i>in situ</i> data	Russell Dickerson, UMCP; Nickolay Krotkov, 613.3/GEST
Ravi Siddani**	UMBC	Space-time Statistics of Precipitation	Prasun Kundu, 613.2/JCET
Tabitha Huntemann	UMCP	Cloud-model Simulations of NO <sub>x</sub> from Lightning	Kenneth Pickering 613.3

\*Graduated in August 2007 from the Chemistry Department with a Masters degree.

\*\* Received Ph.D. in December 2007.

## 6.5 Open Lecture Series

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### *Distinguished Lecturer Seminar Series*

One aspect of the Laboratory's public outreach is a Distinguished Lecturer Seminar Series, which is held each year and is announced to all our colleagues in the area. Most of the lecturers are from outside NASA and this series gives them a chance to visit with our scientists and discuss the latest ideas from experts. The following were the lectures presented in 2007.

January 25

**Eric Smith**, Mesoscale Atmospheric Processes Branch, NASA GSFC

“Advanced Technologies for Measurement of Precipitation from LEO and GEO Satellite Platforms”

February 15

**Jose Rodriguez**, Head, Atmospheric Chemistry and Dynamics Branch, NASA GSFC

“Understanding Processes and Uncertainties in Atmospheric Models: The Global Modeling Initiative”

March 16

**Lorraine Remer**, Climate and Radiation Branch, NASA GSFC

“Trends, Absorption, Aerosols and Clouds”

April 5

**Robert Wilhelmson**, National Center for Supercomputing Applications

“Storm Research and Education in the Context of Evolving Cyberinfrastructure and Petascale Computing”

April 19

**Graeme Stephens**, Colorado State University

“Early Science from CloudSat and the A-Train”

April 26

**Robert Cahalan**, Head of Climate and Radiation Branch, NASA GSFC  
“The Sun, The Moon, and Central America”

May 17

**Anthony Del Genio**, NASA Goddard Institute for Space Studies  
“Convective Cluster Lifecycles and Intensities”

June 12

**Greg Holland**, National Center for Atmospheric Research  
“Anthropogenic Influences on Hurricanes in the North Atlantic”

August 15

**Hui Su**, Jet Propulsion Laboratory, California Institute of Technology  
“Variation of Tropical Upper Tropospheric Clouds With Sea Surface Temperature and Associated Radiative Effects”

September 19, 2007

**Stephen A. Klein**, Lawrence Livermore National Laboratory  
“What Does Weather-forecasting Offer Climate Models?”

## **6.6 Public Outreach**

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In addition to teaching and committee work, Laboratory members give seminars to university and other student groups and to public audiences.

January 9

**Charles Jackman** (613.3) presented a talk entitled “Has the Ozone Layer Changed?” to the Goddard Retirees and Alumni Association.

January 16

**Andrew Negri** (613.1/Emeritus) judged a science fair at Bladensburg Elementary.

February 20

**Andrew Negri** (613.1/Emeritus), judged a science fair at Eleanor Roosevelt HS.

March 23

As a committee member, **Ali Tokay** (613.1/JCET) attended the masters thesis defense of C. Malakpet of the University of Louisiana-Lafayette.

March 29

**Ali Tokay** (613.1/JCET) gave a seminar at the Interdisciplinary Remote Imaging and Sensing (IRIS) Research Center, Catholic University on March 29, 2007.

April 9

At the DoE/ARM Science Team Meeting, held March 26–30 in Monterey, CA, Felicity Russo, a Ph.D. graduate student at UMBC, presented a poster entitled “Measurements of Liquid Water Content with the ARM Raman Lidar at SGP.” Profile measurements of cloud liquid water content, cloud droplet radius, and cloud droplet number density based on new measurement capability installed in the ARM Raman lidar were presented. Retrievals of sub-cloud aerosol extinction from the same Raman lidar data have also been performed permitting the aerosol indirect effect parameter, IE as defined by Graham Feingold, to be evaluated. The results indicate that

changes in cloud droplet size are anti-correlated with changes in sub-cloud extinction for extinctions measured as much as 100 meters below the cloud but that the correlation decreases with increasing distance below the cloud. These measurements constitute what we believe to be the first remote sensing of the aerosol indirect effect using lidar. **David Whiteman** (613.1) is Ms. Russo's research advisor. **Belay Demoz** (613.1) is a member of her Ph.D. committee.

April 13

As a committee member, **Richard Stewart** (613) attended the Ph.D. thesis defense of Michelle Hawkins at Howard University. The thesis title was "Investigations of Ozone Concentrations in the Tropical Marine Boundary Layer during Saharan Dust and Biomass Burning Events." Ms. Hawkins passed the defense, subject to revisions in her thesis. She was the latest of a number of students awarded recent Ph.D.s in Atmospheric Sciences who started their graduate careers at Howard University in programs funded by NASA.

**Eyal Amitai** (613.1/GMU) gave an invited seminar on "Studying Rain Rate from Space, Ground and Underwater Observations: Present and Future" at the Italian National Research Council's Institute of Atmospheric Sciences and Climate (ISAC-CNR) in Bologna, Italy.

April 24

**Paul A. Newman** (613.3) gave a talk at the "Space and the Polar Regions" international seminar that was organized by the Embassy of France and George Mason University's Center for Aerospace Policy. Paul Newman's talk was "Polar ozone depletion: a satellite view." The meeting was held at George Mason University April 24-25.

May 2

**David Whiteman and Belay Demoz** (613.1) are members of the dissertation committee of Rasheen Connell, a graduate student in the Physics and Astronomy department of Howard University. Mr. Connell was admitted to Ph.D. candidacy by his committee after a successful presentation on May 2 of a research proposal entitled "A Numerical Model Characterizing the Performance of the Howard University Raman Lidar System."

May 9

**Richard Stewart** (613) served as a member of the GSFC High School Internship Program (HIP) selection committee. Of roughly 115 applicants 12 were selected for this program. HIP is a research-intensive, 8-week summer program that allows interns to explore applications of Science, Technology, Engineering, and Mathematics (STEM) disciplines to Goddard research.

**Belay B. Demoz** (613.1) attended the first meeting of the NASA Student Collaboration Program Definition Team. The 13-member SCPDT is charged to "develop a white paper capturing best practices in project-based learning exemplifying the nature of NASA's scientific exploration, explore additional learning opportunities of a similar character that is not part of a flight mission, and provide opportunities for community input, including conducting an open workshop." The SMD will publish the final report for wide distribution.

May 14

As a committee member, **Wei-Kuo Tao** (613.1) attended the Ph.D. thesis defense of Jiwen Fan at Texas A&M University. The thesis title was "Effects of Aerosols on Deep Convective Cumulus Clouds." Ms. Fan passed the defense. Jiwen Fan was a recipient of the NASA Earth Science Fellowship.

May 20

Khrystle C. Roberts from Trinidad and Tobago graduated from Trinity University in Washington, DC on May 20 with a double major in Chemistry and Environmental Science and as a recently elected member of Phi Beta Kappa. Her senior project was entitled "Comparing Chemical Reactions for Measuring Ground-level Ozone in the Atmosphere" and was derived from NASA-sponsored work that occurred during the WAVES\_2006 field

campaign that was hosted at the Howard University research site in Beltsville, MD. **David Whiteman** and **Belay Demoz** (613.1) were the NASA leads of WAVES\_2006.

June 6

**Charles Jackman** (613.3) gave a SESI talk titled “Has the Ozone Layer Changed?”

June 16

**Scott Braun** (613.1) participated in an “Ask An Expert” session at the Maryland Science Center in Baltimore, MD, on June 16. After the premiere of “Hurricane on the Bayou,” a new IMAX movie about Hurricane Katrina, Braun answered questions from movie viewers and other science center guests about hurricanes.

June 19

**Charles Gatebe** (613.2/GEST) gave a talk at the meeting of Oklahoma’s Ponca City Aviation Booster/Northern Oklahoma Flight Academy entitled “Understanding the Climate System through Observational data: CLASIC/CHAPS field experiment.”

June 26

**Scott Braun** (613.1) gave a talk on “NASA Hurricane Research” to middle school teachers involved in the NASA/Anne Arundel County Public Schools Summer Science Academy.

June 27

**George Huffman** (613.1/SSAI) and **David Bolvin** (613.1/SSAI) each hosted a teacher “job shadowing” as part of the Anne Arundel Public Schools summer teacher institute.

July 2

During June, **Bob Cahalan** (613.2) visited a rural primary school in El Silencio, Costa Rica that has participated in a pilot program of One Laptop Per Child. He discussed with them several programs that the children had developed to simulate space travel, and answered their questions about a variety of NASA activities. These included goals of the aircraft flights of several NASA aircraft over Costa Rica in July–August 2007, as part of the Tropical Composition, Cloud, and Climate Coupling (TC4) field deployment, in which scientists from Goddard will participate. The children asked him whether he planned to fly into space, and he answered that he and his science colleagues are now rather busy flying, and studying the many changes on Earth.

July 10

*Public Lecture on Earth Science Research*

Climate and Radiation Branch scientist, **Eric Wilcox** (613.2), gave a public lecture on Earth science research at NASA and the application of satellite technology to the study of Earth and the environment at the Squaw Valley resort near Lake Tahoe, California. This invited lecture was sponsored by the Squaw Valley Institute, a non-profit organization dedicated to hosting cultural events in the Squaw Valley, North Lake Tahoe community. Squaw Valley is a world-famous ski resort and site of the 1960 Winter Olympics.

July 31

**Rich Stolarski** (613.3) gave a talk entitled “Ozone—The Good: Stratosphere; The Bad: Troposphere” to a group of visitors from Howard University. The group consisted of Howard faculty, graduate students, and teachers from local schools. The interests of this group included chemistry, physics, biology, and genetics. The group was led by Greg Jenkins, Director of the Howard University Program in Atmospheric Sciences (HUPAS).

August 2

**Scott Braun** (613.1) and **Jeff Halverson** (613.1/UMBC) presented programmatic and research highlights related to hurricanes at the “About Goddard” event. Their presentations covered topics ranging from satellite applications to field experiments to numerical modeling and to new sensor development.

August 9

**Charles Ichoku** (613.2/UMCP) presented a public lecture entitled “How wildfires affect us all, far and near” to vacationers aboard a Royal Caribbean cruise ship, the Explorer of the Seas, while cruising the Caribbean and Bermuda.

September 16

On Sunday, September 16, 2007, **Richard Stolarski** (613.3) participated in panel discussions that were part of a science seminar held to celebrate the 20th Anniversary of the Montreal Protocol to limit ozone depleting substances in the atmosphere. The seminar was in Montreal, Canada as part of the 19th meeting of the parties. The parties consisted of delegations from the 191 countries that had signed the protocol, plus representatives from industry and non-government organizations. The meeting of the parties continued through the week of September 17–21. They are considering the possibility of expanding the protocol to include a faster phase-out of the HCFC compounds. The claim is that this would do more to mitigate global warming than the binding parts of the Kyoto Protocol.

September 18

**Thomas Bell** (613.2) gave an invited seminar at Texas A&M University titled, “The ‘Weekend Effect’ for Precipitation over Eastern U.S.: Evidence for Midweek Storm Intensification by Pollution” on September 18, 2007.

September 21

**William Lau** (613) was among five expert panelists who presented lectures at a public forum on “Hurricanes and Climate Change: What Have We Learned in the Past Two Years” at the Dirksen Senate Office Building, Capital Hill. The forum was hosted by the American Meteorological Society for the purpose of educating the public and Congress on important earth science issues affecting our society. Attendees include congressional staffers, representatives from Government agencies, journalists, science writers, and stake holders from industry. His lecture was entitled “Rainfall extremes, Saharan dust, tropical cyclones and climate change,” where he presented latest results from TRMM and MODIS, showing that tropical cyclones are increasingly feeding into extreme rainfall events, and that Saharan dust may be important in modulating hurricane statistics and seasonal hurricane predictions.

September 26

**Scott Braun** (613.1) participated in the Ph.D. thesis defense of Joseph Olson of State University of New York, Stony Brook University, on September 26, 2007. Olson’s thesis was “Structure and Dynamics of Barrier Jets along the Southeast Alaskan Coast.” Braun was invited to serve on Olson’s committee in 2004 because of his research, published in 1999, on idealized modeling of the effects of broad mountain barriers on upstream flow and on propagating cold fronts.

September 27

**Kenneth Pickering** (613.3) presented a lecture entitled, “Air Quality Science at NASA,” at the Goddard Visitor’s Center to a group of 11th grade students from Wakefield High School in Arlington, VA.

October 10

**Charles Ichoku** (613.2/UMCP) was an invited guest lecturer at a University of Maryland, College Park, undergraduate Honors Course (238-O) and delivered a lecture entitled, “The African Atmospheric Environment in the Age of Satellite Remote Sensing.”

October 18

**Wei-Kuo Tao** (613.1) presented an invited lecture on “Cloud-Resolving Models and their Applications on Precipitation Processes” to the graduate students of the Department of Meteorology at the University of Maryland.

October 30

**Charles Ichoku** (613.2/UMCP) was an invited guest lecturer at a University of Maryland, College Park graduate Honors Course on remote sensing, and delivered a lecture entitled, “Remote Sensing Provides the Ideal Tool for Measurement of Wildfires and Smoke Emissions.”

November 28

**Scott Braun** (613.1) presented an overview of NASA hurricane research to visitors from the Discovery Channel.

November 30

**Scott Braun** (613.1) was interviewed by John Hamilton of National Public Radio for a story on the 2007 hurricane season.

December 31

**Eyal Amitai** (613.1/GMU) gave an invited seminar at Tel Aviv University titled “Surface Rainfall Intensities from Satellite, Ground, and Underwater Observations.”

Undated

**Chuck Cote** (613/Retired) held discussions with Etienne Benson, a Ph.D. candidate from MIT, who is pursuing a degree in Wildlife/Biology and is doing research on the history of animal tracking. These discussions concerned a series of experiments with the Smithsonian Institution and the University of Wyoming that took place in the early 1970s using the Nimbus 3 and 4 IRLS (Interrogation, Location and Recording System) to track Elk in Wyoming and Montana. Etienne has completed a considerable amount of document research through the archives at the Smithsonian Institution on the subject but was missing some key facts and information. Cote was able to provide information, data, and photographs that Etienne needed to complete his dissertation in December. Cote agreed to be a reviewer of the draft dissertation.

## 6.7 Project Outreach

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Funded projects in which Laboratory members participate contain elements of both education and public outreach that are described on the project Web sites. Some of these outreach efforts are summarized in the following sections.

### TERRA

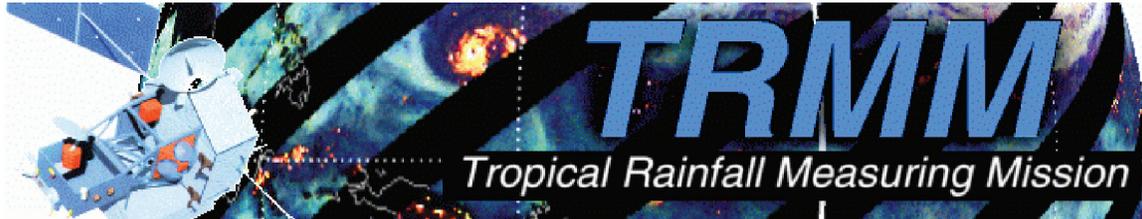


The EOS Terra outreach effort is a coordinated effort to foster greater cooperation and synergy among the various outreach groups within the EOS community. The Terra mission is designed to improve understanding of the movements of carbon and energy throughout Earth’s climate system.

The “About Terra” link on the Terra home page (<http://terra.nasa.gov>) contains links to five tutorials designed to inform the public about the importance of the physical parameters observed by the instruments aboard the Terra spacecraft. These tutorials deal with the properties of aerosols, changes in cloud cover and land surface, the Earth’s energy balance, and the role of the oceans in climate change. The home page also contains 14 direct

links to topics maintained by the Earth Observatory, an outreach site of the Committee for Education and Public Outreach. These links discuss a wide range of topics including Antarctica, flood plains, glaciers, air pollution, and volcanoes discussing each in the context of Terra observations and why such observations are important. The Terra Web site also contains a number of links under ‘Features’ to tutorials on topics of interest such as hurricanes and the cost of natural hazards. These tutorials are part of the NASA Earth Observatory Web site.

## TRMM



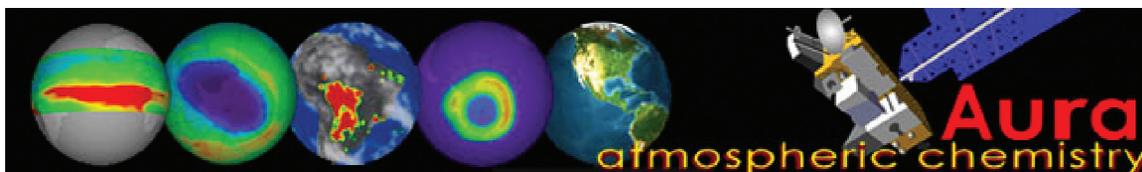
TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. TRMM continues its comprehensive Education/Outreach program, in which Laboratory personnel promote TRMM science and technology to the public under the leadership of TRMM Project Scientist Robert Adler (Code 613, Emeritus). TRMM has also included the development of broadcast visuals and educational curriculum in its outreach activities. The Educational Resources link on the TRMM home page leads to five problem-based classroom modules in PDF format. These manuals are titled ‘Investigating the Climate System’ and consist of tutorials on clouds, winds, precipitation, weather, and energy. The first four are appropriate for students in grades 5–8, the last is directed at students in grades 9–12. These packages are available on the TRMM Web site (<http://trmm.gsfc.nasa.gov/>) and have been reviewed as a part of the Earth Science Enterprise (ESE) Education product review. There are also 11 educational videos that give brief tutorials on various aspects of the TRMM project and on the atmosphere’s water and energy cycles.

## Global Precipitation Measurement (GPM)



The GPM is a follow-on, and expanded, mission of the current ongoing TRMM. GPM is one of the Earth Observing System programs, mainly initiated by JAXA, the National Institute of Information and Communications Technology (NICT), and NASA. Both the ‘Science’ and ‘Public Outreach’ links on the GPM Web site (<http://gpm.gsfc.nasa.gov/index.html>) contain a wealth of educational materials. The ‘Science features’ section on either page has links to numerous additional discussions of the satellite, its instruments, and what will be measured.

## EOS Aura



The Aura satellite was launched from Vandenberg AFB on July 15, 2004. The Laboratory for Atmospheres has responsibility for conducting the Education and Public Outreach program for the EOS Aura mission. Aura's Education and Public Outreach program has four objectives:

- (1) Educate students about the role of atmospheric chemistry in geophysics and the biosphere;
- (2) Enlighten the public about atmospheric chemistry and its relevance to the environment and their lives;
- (3) Inform geophysics investigators of Aura science, and thus enable interdisciplinary research; and
- (4) Inform industry and environmental agencies of the ways Aura data will benefit the economy and contribute to answering critical policy questions regarding ozone depletion, climate change, and air quality.

To attain these objectives, the Aura project supports a strong educational and public outreach effort through formal and informal education partnerships with organizations that are leaders in science education and communication. Partners include the Smithsonian Institution's National Museum of Natural History (NMNH), the American Chemical Society (ACS), and the Global Learning and Observations to Benefit the Environment (GLOBE) Program. Our goals are to educate students and the public and inform industry and policy makers how Aura will lead to a better understanding of the global environment.

NMNH, working with Aura scientists, will design and create an interactive exhibit on atmospheric chemistry as part of its Forces of Change program. NMNH will convey the role that atmospheric chemistry plays in people's lives through the use of remote sensing visualizations and museum objects.

The ACS has produced special issues of the publication ChemMatters. These issues focus on the chemistry of the atmosphere and various aspects of the EOS Aura mission. The special editions of ChemMatters will reach approximately 30,000 U.S. high school chemistry teachers and their students.

The Globe Program is a worldwide network of students, teachers (10,000 schools in over 95 countries), and scientists working together to study and understand the global environment. Drexel University's (Philadelphia, PA) ground-based instruments will measure ultraviolet-A (UV-A) radiation and aerosols to support measurements taken from the Aura spacecraft. A tropospheric ozone measurement developed by Langley Research Center is also a GLOBE protocol.

Aura's Education and Project Outreach program will also be present at science and environmental fairs and science and technology conferences to demonstrate how Aura fits into NASA's program to study the Earth's environment. The Aura Web site is <http://aura.gsfc.nasa.gov/>.

## TOMS



The Atmospheric Chemistry and Dynamics Branch is committed to quality scientific education for students of all ages and levels. The TOMS Web site contains resource materials for science educators at <http://toms.gsfc.nasa.gov/teacher/teacher.html>. Three lessons that make use of TOMS data and that study the uses of Earth-orbiting satellites are presented at this site. One of these is directed at students in grades 5–8, others are directed to those in grades 9–12. There is also a link to five projects for independent research, which allow advanced students to learn more about atmospheric chemistry and dynamics.

There is also an online textbook at [http://www.ccpo.odu.edu/SEES/ozone/oz\\_class.htm](http://www.ccpo.odu.edu/SEES/ozone/oz_class.htm) written by Branch scientists. This textbook was designed as an educational resource for the general public, as well as for students and educators. It contains 12 chapters covering all aspects of the science of stratospheric ozone. Each chapter has numerous low- and high-resolution figures, and ends with a set of review questions.



## 7. ACRONYMS

Acronyms defined and used only once in the text may not be included in this list. Two acronyms, NPP and GMI, have dual definitions. The meaning will be clear from context in this report.

ACAM	Airborne Compact Atmospheric Mapper
ACRM	ARM Climate Research Facility
ACS	American Chemical Society
ADEOS	ADvanced Earth Observing Satellite
AEROCOM	AEROSol Comparisons between Observations and Models
AERONET	Aerosol Robotic Network
AEWs	African Easterly Wave(s)
AFB	Air Force Base
AGU	American Geophysical Union
AI	Aerosol Index
AIAA	American Institute of Aeronautics and Astronautics, Inc.
AIM	Aeronomy of Ice in the Mesosphere
AIRS	Atmospheric Infrared Sounder
ALVICE	Atmospheric Lidar for Validation, Interagency Collaboration and Education
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	AMSR Earth Observing System (EOS)
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
APSATS	Asia Pacific Satellite Training Seminar
ARCTAS	Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
ARM	Atmospheric Radiation Measurement (Program)
ARM CART	ARM Cloud and Radiation Test Bed
AROTAL	Airborne Raman Ozone, Temperature, and Aerosol Lidar
ASP/DoE	Atmospheric Sciences Program/Department of Energy
ATL	Aerosol and Temperature Lidar
ATMS	Advanced Technology Microwave Sounder
AVE	Aura Validation Experiment
AVHRR	Advanced Very High Resolution Radiometer
BASE-ASIA	Biomass-burning Aerosols in South East-Asia: Smoke Impact Assessment
BUV	Backscatter Ultraviolet
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection And Moisture EXperiment
CAR	Cloud Absorption Radiometer
CCM	Chemistry Climate Model
CCN	Cloud Condensation Nuclei
CCSP	Climate Change Science Program
CC-VEx	CALIPSO-CloudSat Validation Experiment
CDE	Cosmic Dust Experiment
CERES	Clouds and the Earth's Radiant Energy System
CFCs	Chlorofluorocarbons

## ACRONYMS

CGCM	Chemistry and General Circulation Model
CHAPS	Cumulus Humilis Aerosol Processing Study
CIMSS	Cooperative Institute of Meteorological Satellite Studies
CIPS	Cloud Imaging and Particle Size experiment
CLASIC	Cloud and Land Surface Interaction Campaign
CLIVAR	Climate Variability and Predictability Programme
CMOS	Complementary metal–oxide–semiconductor
COMBO	Combined Stratospheric-Tropospheric Model
COMMIT	Chemical, Optical, and Microphysical Measurements of <i>In situ</i> Troposphere
CoSSIR	Compact Scanning Submillimeterwave Imaging Radiometer
COVIR	Compact Visible and Infrared Radiometer
CP	Convective Parameterization
CPL	Cloud Physics Lidar
CR-AVE	Costa Rica AVE
CrIS	Crosstrack Infrared Sounder
CRS	Cloud Radar System
CSTEA	Center for the Study of Terrestrial and Extraterrestrial Atmospheres
CTM	Chemical Transport Model
DAAC	Distributed Active Archive Center
DFRC	Dryden Flight Research Center
DOAS	Differential Optical Absorption Spectroscopy
DoE	Department of Energy
DPR	Dual-frequency Precipitation Radar
DSCOVER	Deep Space Climate Observatory (formerly Triana)
DU	Dobson Unit
EAST-AIRE	East Asian Study of Tropospheric Aerosols: an International Regional Experiment
ECMWF	European Centre for Medium-Range Weather Forecasts
EDOP	ER-2 Doppler Radar
ELF	Elastic Lidar Facility
ENSO	El Niño Southern Oscillation
EnviSat	Environmental Satellite
EOS	Earth Observing System
EPA	Environmental Protection Agency
EPIC	Earth Polychromatic Imaging Camera
EP-TOMS	Earth Probe TOMS
ESE	Earth Science Enterprise
ERBE	Earth Radiation Budget Experiment
ESD	Earth Sciences Division
ESMF	Earth System Modeling Framework
ESRL	Earth System Research Laboratory (NOAA)
ESSIC	Earth System Science Interdisciplinary Center
ESTO	Earth Science Technology Office
EU	European Union
FMI-ARC	Finnish Meteorological Institute—Arctic Research Center
FOV	Field of View
fvGCM	Finite volume GCM

GCE	Goddard Cumulus Ensemble model
GCM	General Circulation Model
GEOS	Goddard Earth Observing System
GeoSpec	Geostationary Spectrograph
GEOSS	Global Earth Observation System of Systems
GES DISC	Goddard Earth Sciences Data and Information Services Center
GEST	Goddard Earth Sciences and Technology Center
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecasting System
GISS	Goddard Institute for Space Studies
GLAS	Geoscience Laser Altimeter System
GLOBE	Global Learning and Observations to Benefit the Environment
GLOW	Goddard Lidar Observatory for Winds
GMAO	Global Modeling and Assimilation Office
GMI	GPM Microwave Imager
GMI	Global Modeling Initiative
GMT	Greenwich Mean Time
GMU	George Mason University
GOCART	Goddard Chemistry Aerosol Radiation and Transport
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GSSP	Graduate Student Summer Program
GSWP	Global Soil Wetness Project
GV	Ground Validation
GVP	Ground Validation Program
HARLIE	Holographic Airborne Rotating Lidar Instrument Experiment
HBCUs	Historically Black Colleges and Universities
HIP	High school Internship Program
HIRDLS	High Resolution Dynamics Limb Sounder
HIRS	High Resolution Infrared Sounder
HIWRAP	High-Altitude Imaging Wind and Rain Airborne Profiler
HSB	Humidity Sounder Brazil
HTAP	Hemispheric Transport of Atmospheric Pollutants
HU	Howard University
HUPAS	Howard University Program in Atmospheric Sciences
HURB	Howard University Research site at Beltsville
HY-SiB	Hydrology and Simple Biosphere
ICESat	Ice, Cloud, and Land Elevation Satellite
IIP	Instrument Incubator Program
INTEX-B	Intercontinental Chemical Transport Experiment—Part B
IORD	Integrated Operational Requirements Document
IPCC	Intergovernmental Panel on Climate Change

## ACRONYMS

IPO	Integrated Program Office
IRIS	Interdisciplinary Remote Imaging and Sensing
ISAS	Institute of Space and Aeronautical Science (Japan)
JAXA	Japan Aerospace Exploration Agency
JAMEX	Joint Aerosol Monsoon Experiment
JCET	Joint Center for Earth Systems Technology
JCOSS	Joint Center for Observation System Science
JCSDA	Joint Center for Satellite Data Assimilation
JGR	Journal of Geophysical Research
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KILT	Kiritimati Island Lidar Trailer
L2-SVIP	Lagrange-2 Solar Viewing Interferometer Prototype
LaRC	Langley Research Center
LIDAR	Light Detection and Ranging
LIS	Land Information System
LRR	Lightweight Rainfall Radiometer
LRR-X	LRR-X band
MAPB	Mesoscale Atmospheric Processes Branch
MAS	MODIS Airborne Simulator
MAXDOAS	Multi-Axis Differential Optical Absorption Spectroscopy
McRAS	Microphysics of Clouds with the Relaxed Arakawa-Schubert Scheme
MDE	Maryland Department of the Environment
MF-DOAS	Multi-Function Differential Optical Absorption Spectrometer
MFRSR	Multi-filter Rotating Shadowband Radiometer
MILAGRO	Megacity Initiative: Local And Global Research Observations
MISR	Multi-Angle Imaging Spectroradiometer
MIT	Massachusetts Institute of Technology
MLS	Microwave Limb Sounder
MM5	Mesoscale Model 5
MMF	Multi-Model Framework
MODIS	Moderate Resolution Imaging Spectroradiometer
MOHAVE	Measurements Of Humidity in the Atmosphere and Validation Experiment
MOPITT	Measurement of Pollution in the Troposphere
MPL	Micro-Pulse Lidar
MPLNET	Micro-Pulse Lidar Network
MSL	Mean Sea Level
MSU	Microwave Sounding Unit
NAMMA	NASA African Monsoon Multidisciplinary Analysis
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NATIVE	Nittany Atmospheric Trailer and Integrated Validation Experiment
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NEO	NASA Earth Observations

NESDIS	National Environmental Satellite Data and Information Service
NICT	National Institute of Information and Communications Technology
NIIEM	Russian Scientific Research Institute of Electromechanics
NIR	Near Infrared
NIST	National Institute of Standards and Technology
NISTAR	National Institute of Standards and Technology Advanced Radiometer
NIVR	Netherlands's Agency for Aerospace Programs
NMNH	National Museum of Natural History
NMS	Neutral Mass Spectrometer
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar Orbiting Environmental Satellite System
NPP	NASA Postdoctoral Program
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
ORAU	Oak Ridge Associated Universities
OGO	Orbiting Geophysical Observatory
OLR	Outgoing Longwave Radiation
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OOAT	Ozone Operational Algorithm Team
PAVE	Polar Aura Validation Experiment
PBL	Planetary Boundary Layer
PI	Principal Investigator
PM2.5	Particulate Matter, diameter < 2.5 $\mu\text{m}$
PMC	Polar Mesospheric Clouds
POES	Polar Orbiting Environmental Satellite
PUMAS	Practical Uses of Math and Science
QuikSCAT	(NASA's) Quick Scatterometer satellite
RASL	Raman Airborne Spectroscopic Lidar
RCDF	Radiometric Calibration and Development Facility
RFP	Request for Proposal
RMS	Root Mean Squared
RRS	Radiosonde Replacement System
SAGE	Stratospheric Aerosol and Gas Experiment
SBIR	Small Business Innovative Research
SAL	Saharan Air Layer
SAIC	Science Applications International Corporation
SAOZ	Système d'Analyse par Observation Zénithal
SAP	Scientific Assessment Panel
SAUNA	Sodankylä Total Column Ozone Intercomparison
SBUV	Solar Backscatter Ultraviolet

## ACRONYMS

SBUV/2	Solar Backscatter Ultraviolet/version 2
SDS	Scientific Data Set
SEB	Source Evaluation Board
SESI	Scientific and Engineering Student Internship program
SGP	Southern Great Plains
SGT	Stinger Ghaffarian Technologies
ShADOE	Shared Aperture Diffractive Optical Element (telescope)
SHADOZ	Southern Hemisphere ADDitional OZonesondes
SIVO	Software Integration and Visualization Office
SMART	Surface-sensing Measurements for Atmospheric Radiative Transfer
SMD	Science Mission Directorate
SOAT	Sounder Operational Algorithm Team
SOLSE/LORE	Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment
SOLVE	SAGE III Ozone Loss and Validation Experiment
SOFIE	Solar Occultation for Ice Experiment
SORCE	Solar Radiation and Climate Experiment
SPE	Solar Proton Event
SRL	Scanning Raman Lidar
SSI	Spectral Solar Irradiance
SSM/I	Special Sensor Microwave Imager
SSAI	Science Systems and Applications, Inc.
SSU	Spectral Sensor Unit
STEM	Science, Technology, Engineering, and Mathematics
STROZ LITE	Stratospheric Ozone Lidar Trailer Experiment
STS	Space Transportation System
SVIP	Solar Viewing Interferometer Prototype
TCSP	Tropical Cloud Systems and Processes
TES	Tropospheric Emission Spectrometer
THOR	cloud THickness from Offbeam Returns
TIROS	Television Infrared Observation Satellite
TMF	Table Mountain facility
TMPA	TRMM Multi-satellite Precipitation Analysis
TOA	Top Of Atmosphere
TOGA– COARE	Tropical Ocean Global Atmosphere– Coupled Ocean Atmosphere Response Experiment
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
TSI	Total Solar Irradiance
TTL	Tropical Tropopause Transition Layer
TWiLiTE	Tropospheric Wind Lidar Technology Experiment
TWP-ICE	Tropical Warm Pool International Cloud Experiment
UAE2	United Arab Emirates Unified Aerosol Experiment
UARS	Upper Atmosphere Research Satellite
UAV	Unmanned Aerial Vehicle
UMBC	University of Maryland, Baltimore County
UMCP	University of Maryland, College Park

UNH	University of New Hampshire
URAD	UAV Radar
USDA	United States Department of Agriculture
UTC	Universal Coordinated Time
UV	Ultraviolet
UV-B	Ultraviolet-B radiation
UV-MFRSR	Ultraviolet Multifilter Rotating Shadowband Radiometer
VIIRS	Visible/Infrared Imager/Radiometer Suite
VINTERSOL	Validation of International Satellites and study of Ozone Loss
VIS	Visible
WACCM	Whole Atmosphere Community Climate Model
WAVES	Water Vapor Validation Experiment – Satellite/Sondes
WCRP	World Climate Research Program
WMI	Weather Modification Inc.
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting



## APPENDIX 1: THE LABORATORY IN THE NEWS

The following pages contain news articles and press releases that describe some of the Laboratory's activities during 2007.

## METEOROLOGY

## A Dose of Dust That Quieted An Entire Hurricane Season?

The 2006 hurricane season was looking grim. Three hurricanes had ripped across Florida during the 2004 season. Four hurricanes, including Katrina, had ravaged the Gulf Coast in 2005. Now meteorological signs were unanimous in foretelling yet another hyperactive hurricane season, the eighth in 10 years. But the forecasts were far off the mark. The 2006 season was normal, and no hurricanes came anywhere near the United States or the Caribbean.

Now two climatologists are suggesting that dust blown across the Atlantic from the Sahara was pivotal in the busted forecasts. The dust seems to have suppressed storm activity over the southwestern North Atlantic and Caribbean by blocking some energizing sunlight, they say. "I think they're on to something," says hurricane researcher Kerry Emanuel of the Massachusetts Institute of Technology in Cambridge. Dust "might play a big role" in year-to-year fluctuations in hurricane activity.

As the 2006 season approached, conditions looked propitious for another blustery hurricane season. In particular, there was no sign of El Niño, whose Pacific warming can reach out to the Atlantic and alter atmospheric circulation to suppress hurricanes there. But, unremarked by forecasters, an unusually heavy surge of dust began blowing off North Africa and into the western Atlantic at the 1 June beginning of the official hurricane season. Two weeks later, the surface waters of the western Atlantic began to cool compared with temperatures in the previous season.

Climatologists William Lau of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and Kyu-Myong Kim of the University of Maryland, Baltimore County, in Baltimore argue in the 27 February issue of *Eos* that the arrival of the thick dust and the subsequent cooling were no coincidence. The dust blocked some sunlight and cooled the surface, they say. That cooling went on to trigger a shift toward less favorable conditions for the formation and intensification of storms in the western Atlantic, they argue. As a result, no storm tracks crossed where nine had passed the previous season.

Lau and Kim find that historically,

El Niño's influence on Atlantic storms has in fact prevailed in the eastern tropical Atlantic, as it may have done last year when it put in a surprise appearance beginning in August. But in the west, near the Caribbean and the United States, dust has been the dominant external influence, they found. "We're not denying El Niño had an impact," says Lau, but "maybe



**Storm killer?** Dust blown off West Africa may suppress hurricanes in the western Atlantic.

we have neglected an equally important factor, if not a more important factor."

Many hurricane researchers are intrigued but cautious. "The authors have an intriguing hypothesis," says Christopher Landsea of the National Hurricane Center in Miami, Florida, but "there's not much evidence that there is a direct cause and effect going on here." And if dust were involved, it would have been more complicated than a simple cooling, says Jason Dunion of the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory in Miami. The dust comes in a layer of air whose extreme dryness and high winds are thought to discourage storm development and intensification as well.

If dust is a major factor in the Atlantic, it will only complicate forecasting the severity of hurricane seasons. Anticipating the arrival of El Niño is proving tricky enough. Predicting far-traveled Saharan dust months ahead—both the necessary North African dryness and the dust-carrying winds—could be formidable.

—RICHARD A. KERR

## SCIENCE SCOPE

### Broad Institute Given \$100 Million

The already well-heeled Broad Institute in Cambridge, Massachusetts, this week announced a \$100 million gift from a wealthy direct marketer to conduct research on severe mental illnesses such as bipolar disorder and schizophrenia. The funding from the Stanley Medical Research Institute will allow the Broad—a joint venture between the Massachusetts Institute of Technology and Harvard University—to create an interdisciplinary center that will draw on the universities' expertise in neuroscience and genomics. That center, located within the Broad Institute, will be led by Edward Scolnick, a former National Institutes of Health researcher and president of Merck Research Laboratories. The money from the Stanley Institute, founded by the family of Theodore and Vada Stanley, will help Broad researchers apply "the most advanced genomic tools" to the biology of mental illness, says Harvard Provost Steven Hyman.

—ANDREW LAWLER

### Ganging Up on Jupiter

A NASA probe heading to Pluto and a European Space Agency (ESA) spacecraft on its way to a comet will team up in coming weeks in an unusual effort to observe Jupiter. ESA's Rosetta, launched in 2004 and currently in the neighborhood of Mars, will examine the ring of electrically charged particles around the gas giant planet that may stem from volcanic eruptions on its moon Io. Meanwhile, NASA's New Horizons mission (below) sped past Jupiter last week after leaving Earth in January 2006. As the probe uses the planet's gravity to slingshot its way to Pluto, the onboard instruments are monitoring the Jupiter system.

The roughly simultaneous observations from the two probes could provide a unique set of data on the planet. "We couldn't pass up this opportunity to study Jupiter's meteorology,



rings, aurorae, satellites, and magnetosphere," says New Horizons principal investigator S. Alan Stern of Southwest Research Institute in Boulder, Colorado. The joint effort augurs well for future international cooperation in space science: Stern takes over as NASA's science chief next month.

—ANDREW LAWLER

Downloaded from www.sciencemag.org on March 9, 2007

CREDIT: SEAN WIFE/PROJECT NISARGSFC, NASA

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Article published Mar 9, 2007

## African dust casts big damper

*Its impact on storms is more far-ranging than suspected*

By CATHY ZOLLO  
H-T SCIENCE WRITER  
[cathy.zollo@heraldtribune.com](mailto:cathy.zollo@heraldtribune.com)

Something so remote as drought in Africa, the cause of suffering for millions, could stifle hurricanes in the Atlantic in more ways than scientists first thought.

The recent findings will likely change the way forecasters look at whole seasons and individual storms.

Scientists have known for a few years that the dust, driven skyward by desert heat and blown to the Atlantic, chokes storms that are building off the African coast.

Now, they have discovered that the dust has a much wider effect on storms, smothering the development of storms as far away as the Caribbean.

The findings, reported in a recent issue of *Eos*, a publication of the American Geophysical Union, showed that the dust creates a cooling effect on western Atlantic waters.

The dust starts what scientists call a feedback loop, first cooling the Atlantic by shielding it from the sun.

The cooler water then cools the air above, causing it to sink, creating wind at the surface. That wind amplifies the cooling effect through evaporation and by causing water at the surface to mix with deeper, even cooler water.

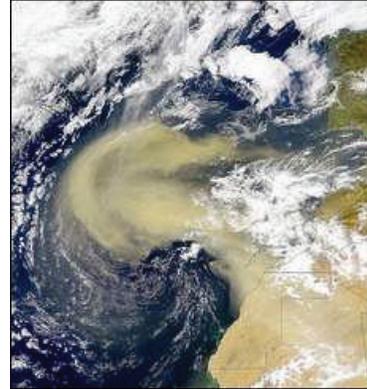
The effect, which scientists called dramatic, is greatest in the western Atlantic and Caribbean.

William Lau, chief of the Laboratory of the Atmospheres at NASA's Goddard Space Flight Center in Greenbelt, Md., and Kyu-Myong Kim, of Goddard's Earth Sciences and Technology Center at the University of Maryland, made the discovery.

Looking back 25 years, they found that the effect of the dust is stronger than that of El Niño for keeping storms down in the western Atlantic and Caribbean.

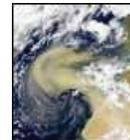
"When we move to the eastern Atlantic, the effect is comparable," Lau said.

The sinking air that the cooler water creates has its own storm-dampening effect. Building tropical storms need rising air to grow. Sinking cold air: another wet blanket.



SEAWIFS PROJECT / NASA  
Satellite image provided by NASA of a massive sand storm blowing off the northwest African desert has blanketed hundreds of thousands of square miles of the eastern Atlantic ocean.

### More photos



NASA / 2000  
A satellite image shows a sandstorm from northwest Africa in 2000 blanketing hundreds of thousands of square miles of the Atlantic.

Though the African dust invasion of the Atlantic is an annual event in June, July and August, its intensity varies year to year, depending on drought conditions in Africa.

Rains in Africa's Sahel, south of the Sahara, determine how much plant cover there will be for the coming year.

It also reveals how much dust might get kicked up in the atmosphere the following year and ride easterly winds to the Atlantic.

Amato Evan, a climate scientist at the University of Wisconsin at Madison, also looked at decades of dust data and found that years with more dust tend to mean fewer hurricanes.

His work partially answered questions about why long-range forecasters were fooled by the 2006 season. They called for an above-average season, and it was average in number and a relief for Florida, with no hurricane making landfall here or on any U.S. coast.

"There might be kind of a threshold where you pump enough dust over the ocean and you are really going to kill the hurricanes," Evan said.

Scientists don't yet have a good idea how much dust will roll off Africa during the 2007 season, but Phil Klotzbach, lead author of the seasonal hurricane forecast put out by the William Gray team at Colorado State University, said he is already considering the dust and its effects for the team's forecast that is updated in April.

So far, they are calling for an active season with 14 named storms, seven hurricanes, three of them intense, with winds greater than 110 mph.

About half of the systems that become tropical storms in any season begin as easterly waves. Those are areas of unstable air that literally weave north and south as they move from Africa to the Atlantic.

A little bit farther west, the waves enter a massive mid-Atlantic pool of warm water that forecasters call the tropical storm genesis zone. This is where each year a handful out of about a hundred waves find the conditions to become hurricanes.

The other half of the storms that form in a given year grow up in the western Atlantic, Caribbean and Gulf of Mexico.

In years when there is a lot of dust, fewer hurricane form in both places.

Though scientists don't yet know whether global warming or deforestation add to a dust cycle, they say the dust seems to increase or decrease for decades at a time and could point to another reason for decades- long cycles of warmer and cooler Atlantic waters.

Published online: 24 April 2007; | doi:10.1038/news070423-6

## Every cloud has an invisible halo

Unseen particles may confuse climate models.

**Philip Ball**

Clouds are bigger than they look, according to new measurements by atmospheric scientists in Israel and the United States. They say that clouds are surrounded by a 'twilight zone' of diffuse particles, invisible to the naked eye, extending for tens of kilometres around the cloud's visible portion.

These vast, sparse haloes of droplets may have been overlooked in atmospheric studies, the researchers say. And they think that this could have skewed attempts to understand how clouds influence climate.

Clouds are one of the biggest sources of uncertainty in efforts to measure and predict global warming. They have two opposite effects: increasing warming by absorbing heat radiated from the planet's surface (which is why cloudy nights are warmer), while offsetting this by reflecting sunlight back into space from cloud tops.

Most atmospheric scientists now think that clouds have an overall global cooling effect. Measurements of warming trends therefore have to take into account whether the skies are cloudy or not, and model forecasts of future warming may hinge on whether they predict more or less cloudiness.



Clouds have unseen portions that stretch for many kilometres.

*AddStyle*

### Cloudy distinction

Such modelling studies typically try to distinguish between cloudy and cloud-free regions of the atmosphere. But the new results show that this distinction is less clear-cut than has been thought, say Ilan Koren of the Weizmann Institute of Science in Rehovot, Israel, and his colleagues, who publish their discovery in *Geophysical Research Letters*<sup>1</sup>.

“ Right now there is a discrepancy between what global models predict for aerosol effects and what satellites measure. ”

Lorraine Remer  
NASA Goddard Space  
Flight Center

Clouds are formed when floating solid particles called aerosols — dust, for example — act as 'seeds' on which water droplets grow. Aerosols reflect light, and do so more strongly as they grow by accumulating water. The large droplets in clouds reflect most visible light, which is what makes clouds look white and opaque.

Koren and his colleagues first demonstrated that it is relatively easy to see from digital photographs that clouds are surrounded by an invisible haze, made up of these water-coated, or humidified, aerosols. If the parts of the photo containing visible white stuff are masked out, the surrounding haze comes into view.

This haze extends far further than anyone has ever imagined. "People may have seen these extended haloes anecdotally," says Koren's colleague Lorraine Remer of the NASA Goddard Space Flight Center in Greenbelt, Maryland. "But thanks to a new generation of instruments, the satellite observations have got much better, and we can look on larger scales, with more sensitivity and at finer resolution."

Satellite images of clouds over the Atlantic Ocean show that the sky's reflectance — a measure of how much humidified aerosol it contains — falls very gradually with increasing distance from the edge of a cloud, and is still declining at least 20-30 kilometres away, Koren's team says.

### Into the twilight zone

To study these twilight zones further, the researchers studied several years' worth of images collected by a global network of ground-based lightmeters called AERONET, usually used to monitor the brightness of the Sun.

Sudden dips in the light detected by these instruments are automatically logged as indicating the passage of a cloud. Koren and colleagues discovered that it can take well over an hour for light levels to recover fully after a cloud has passed, indicating that their haloes are very broad.

Not all clouds will have a big twilight zone, the researchers say. For example, the halo might be tightly reined in around the sharp-edged white cumulus clouds that form when moist, warm air rises and cools. But they estimate that for typical global cloud coverage, the halo could encompass as much as two-thirds of the sky usually classed as cloud-free.

Remer says that some climate models might already include these extended cloud haloes — they should 'grow' them automatically if they do a good job of capturing the humidity variations of the air. But other, simpler, models might neglect the effect.

As a result, Remer suspects that the overall cooling effect of aerosols may have been underestimated. But she admits that it is too early to say whether that is really the case, or how significant an impact it might have on climate predictions.

"Right now there is a discrepancy between what global models predict for aerosol effects and what satellites measure," she says. "This might be part of the reason for that."

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Story from [news@nature.com](mailto:news@nature.com):  
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Tabatha Thompson  
Headquarters, Washington  
202-358-3895

Jim Scott  
University of Colorado, Boulder  
303-492-3114

MEDIA ADVISORY: M07-68

NASA MEDIA TELECONFERENCE ON UPCOMING CLIMATE, OZONE EXPEDITION

WASHINGTON -- Scientists planning NASA's largest Earth science expedition of the year will hold a media teleconference on Wednesday, June 27, at 2 p.m. EDT to discuss the upcoming Tropical Composition, Cloud and Climate Coupling (TC4) field campaign.

The TC4 study will tackle challenging questions about Earth's ozone layer and climate using coordinated observations from satellites and high-flying NASA airplanes. Researchers will study how chemical compounds in the air are transported to the stratosphere, the area of the atmosphere that contains most of Earth's ozone. They will investigate how this vertical transport of water and chemicals affects climate-influencing cirrus clouds, and the chemistry of the upper atmosphere, of which ozone is an important component. The campaign will be based out of San Jose, Costa Rica, starting in mid-July.

Briefing participants are:

- Michael Kurylo, TC4 program scientist, NASA Headquarters, Washington
- Hal Maring, TC4 program scientist, NASA Headquarters
- **David Starr**, TC4 mission scientist, NASA Goddard Space Flight Center, Greenbelt, Md.
- Brian Toon, TC4 mission scientist, University of Colorado, Boulder

washingtonpost.com

Friday, August 10, 2007

### **Does African Dust Affect Atlantic Hurricanes?**

Storm scientists are taking a closer look at whether giant dust clouds from the Sahara could join the El Niño phenomenon as a leading indicator of the ferocity of Atlantic hurricane seasons.

Scientists are intrigued by preliminary research showing a direct correlation between the sandy plumes and tropical cyclones.

"What we've seen is: more dust, fewer hurricanes," said **William Lau**, chief of the Laboratory for Atmospheres at NASA's Goddard Space Flight Center.

The busy and damaging hurricane seasons of 2004 and 2005, which rattled global energy and insurance markets, have heightened interest in storm forecasting and in research on factors that make tropical cyclones either spin into monster storms or wither and die at sea.

El Niño, a warming of eastern Pacific waters, has become a dominant storm indicator because it can flatten an Atlantic hurricane season by increasing the wind shear that can rip apart cyclones.



FEATURE

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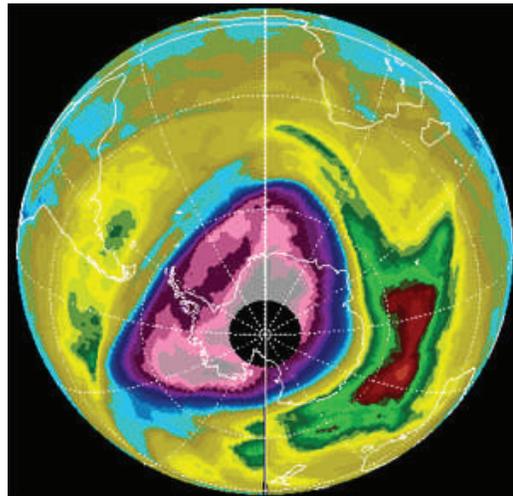
**R.I.P. TOMS: NASA Ozone Instrument Laid to Rest After Three Decades**

08.15.07

During its almost 30-year lifespan, the Total Ozone Mapping Spectrometer (TOMS) program provided unique and valuable information that shaped public policy and international perspectives on the environment. The instrument was important because its data established the geographical extent of the "ozone hole" over the Antarctic, and monitored its year-to-year evolution.

With the recent decommissioning of the last of the three TOMS instruments, Earth Probe TOMS, the TOMS program closed on May 30, 2007. The legacy TOMS leaves behind will not be forgotten.

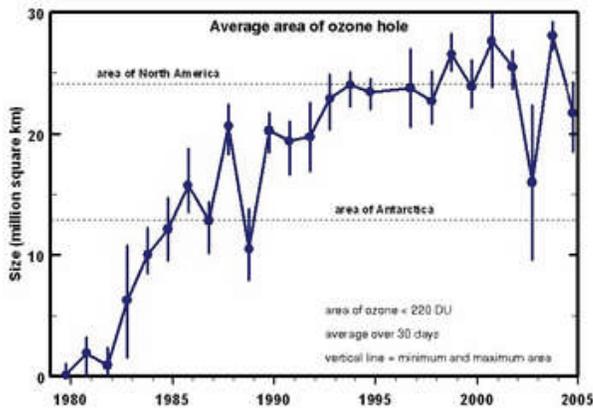
**Image right:** The ozone hole over the arctic in the year 2000, as seen by Earth Probe TOMS. *Click image to enlarge.* **Credit:** NASA



The TOMS program began with the launch of TOMS Flight Model No. 1 on the Nimbus-7 spacecraft on October 24, 1978. NASA scientists originally designed the instrument to study weather patterns by mapping global ozone. They quickly realized that some of the data collected by TOMS was much more significant than they initially had imagined.

The instrument gave scientists a tool for studying ozone in the upper and lower atmosphere in a way that had never been done before, more frequently and with far greater detail. The TOMS instrument captured a vast number of images of the ozone daily, which allowed scientists to constantly monitor changes in the ozone. The capability to measure long-term trends with the TOMS instrument series has been critical to international ozone assessment activities.

Ozone that surrounds the Earth in the upper atmosphere acts as protection from the sun's harmful ultraviolet rays. A thinning of the upper ozone layer would put people at greater risk for skin cancer, cataracts and impaired immune systems. Ozone in the lower atmosphere, close to Earth's surface, is a pollutant that causes damage to lung tissue and plants.



**Image left:** A graph of the size of the ozone hole from 1979 to 2004. *Click image to enlarge.* **Credit:** NASA

TOMS measured the Earth's ozone levels by calculating the amount of ultraviolet light scattered from the Earth's surface and atmosphere back into space. Since the ozone layer absorbs ultraviolet light, areas in which less ultraviolet light was recorded indicated the presence of more ozone.

"TOMS was unique because it was a total ozone mapper. It measured ozone on every spot on the Earth every day. That is why it was so valuable, it saw everything," said Richard McPeters, the principal investigator for Earth Probe TOMS, at NASA's Goddard Space Flight Center, Greenbelt, Md. McPeters worked on TOMS from the earliest days of the program.

The data from the TOMS instrument were critical to the detection of long-term damage to the ozone layer over long periods of time, including above heavily populated areas.

These discoveries led to the passage of the Montreal Protocol in 1987, an international agreement restricting the production of ozone-depleting chemicals.

**Image right:** The Earth Probe TOMS instrument before its launch in 1996. **Credit:** NASA

TOMS data were also key in confirming the destruction of the ozone at the South Pole each year, the "ozone hole," which is now an annual occurrence.

A new TOMS instrument on the Russian spacecraft Meteor-3 replaced TOMS/Nimbus-7 after 14 years of service. TOMS/Meteor-3 was the first significant U.S. instrument to fly aboard a Russian spacecraft and provided a main source of ozone data until it stopped working in 1994.

The final leg of the TOMS program was launched in July of 1996. This TOMS instrument, aboard the Earth Probe spacecraft, was placed at a lower altitude than its predecessors. The lower orbit allowed Earth Probe TOMS to provide better resolution for viewing smaller phenomena, like volcanoes, forest fires and sources of pollution. This instrument took almost



NASA - R.I.P. TOMS: NASA Ozone Instrument Laid to Rest After Th... [http://www.nasa.gov/centers/goddard/news/topstory/2007/toms\\_end\\_pr...](http://www.nasa.gov/centers/goddard/news/topstory/2007/toms_end_pr...)

200,000 measurements daily, covering nearly the entire planet.



**Image left:** The official Earth Probe TOMS mission patch. **Credit:** NASA



Earth Probe TOMS also kicked off collaboration between Goddard and Capitol College of Laurel, Md. Students from Capitol College's Space Operations Institute worked with the TOMS Flight Operations Team at Goddard to redesign the Earth Probe TOMS ground control system. A few years later, the TOMS control center was moved to the Capitol College campus and the students took over the full operation of the instrument with periodic supervision by the team at Goddard.

Edward Chang, the contracting officer's technical representative from Goddard, says that even though the TOMS mission has ended, the collaboration between NASA and Capitol College continues. The college took the lead in decommissioning Earth Probe TOMS on May 30, 2007.

**Image right:** The Nimbus-7 spacecraft, which carried the first TOMS instrument, before its launch in 1978. *Click image to enlarge.* **Credit:** NASA



Following failure of the transmitter in late 2006, TOMS was no longer able to send its data back to the scientists on the ground, so continuing to operate the instrument was useless. The spacecraft will remain in its current orbit, but with all fuel and other energy sources cut off. It will take 37 years for the spacecraft to re-enter the atmosphere.

The Ozone Monitoring Instrument, a more advanced spectrometer that flies on the Aura satellite, has taken over the work done by the TOMS program. Launched in 2004, this instrument was created through collaboration between Goddard and the Netherlands Agency for Aerospace Programs working with the Finnish Meteorological Institute. Like TOMS, the Ozone Monitoring Instrument records total ozone and other atmospheric data related to ozone chemistry and climate.

TOMS delivered some of the most critical and influential environmental data ever recorded, documenting the long-term decline of global ozone levels and the emergence and development of the Antarctic ozone hole. It allowed the world to view and understand ozone in a new way, helping to shape international environmental perspectives and policy.

The program's legacy, according to McPeters, lies in the incredibly detailed information TOMS provided for examining changes in the ozone layer. "People got used to being able to view the Earth the way TOMS viewed it, seeing a global image of the ozone in high resolution every day. At this point, as a result of TOMS, that view is now considered a necessity."

Related Links:

- + [The TOMS Program](#)
- + [AURA's Ozone Monitoring Instrument](#)
- + [NASA's Ozone Hole Watch](#)

**Laura Spector**  
Goddard Space Flight Center

Find this article at:  
[http://www.nasa.gov/centers/goddard/news/topstory/2007/toms\\_end.html](http://www.nasa.gov/centers/goddard/news/topstory/2007/toms_end.html)

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Grey Hautaluoma  
Headquarters, Washington  
202-358-0668  
grey.hautaluoma-1@nasa.gov

Lynn Chandler  
Goddard Space Flight Center, Greenbelt, Md.  
301-286-2806  
lynn.chandler-1@nasa.gov

RELEASE: 07-181

#### SCIENTISTS SEE FIRST SIGNS OF LONG-TERM CHANGES IN TROPICAL RAINFALL

WASHINGTON - NASA scientists have detected the first signs that tropical rainfall is on the rise, using the longest and most complete data record available.

The international scientific community assembled a 27-year global record of rainfall from satellite and ground-based instruments. The researchers found the rainiest years between 1979 and 2005 occurred primarily after 2001. The wettest year was 2005, followed by 2004, 2003, 2002 and 1998. The study appeared in the August 1 issue of the American Meteorological Society's Journal of Climate. The rainfall increase was concentrated over tropical oceans, with a slight decline over land.

"When we look at the whole planet over almost three decades, the total amount of rain falling has changed very little. But in the tropics, where nearly two-thirds of all rain falls, there has been an increase of 5 percent," said lead author **Guojun Gu**, a research scientist at NASA's Goddard Space Flight Center in Greenbelt, Md.

Climate scientists predict that a warming trend in Earth's atmosphere and surface temperatures would produce an accelerated recycling of water between land, sea and air. Warmer temperatures increase the evaporation of water from the ocean and land and allow air to hold more moisture. Eventually, clouds form that produce rain and snow.

"A warming climate is the most plausible cause of this observed trend in tropical rainfall," said co-author **Robert F. Adler**, senior scientist at Goddard's Laboratory for Atmospheres. Adler and Gu are now working on a detailed study of the relationship between surface temperatures and rainfall patterns to investigate the possible link further.

Obtaining a global view of our planet's rainfall patterns is a challenge. Only since the satellite era have regular estimates of rainfall over oceans been available to supplement the long-term, but land-limited record from rain gauges. Recently, the many different land- and space-based data have been merged into a global record: the Global Precipitation Climatology Project, organized under the World Climate Research Program.

Using this global record, the scientists identified a small upward trend in overall tropical rainfall since 1979. To assess whether this pattern was a long-term trend rather than natural year-to-year variability, they removed the effects of the two natural phenomena that change rainfall: the El Niño -Southern Oscillation and large volcanic eruptions.

El Niño is a cyclical warming of the ocean waters in the central and eastern tropical Pacific that generally occurs every three to seven years and alters weather patterns worldwide. Volcanoes that loft debris into the upper troposphere and stratosphere create globe-circling bands of aerosol particles that slow the formation of precipitation by increasing the number of small cloud drops and temporarily shielding the planet from sunlight. The result lowers surface temperatures and evaporation that fuels rainfall. Two such eruptions - El Chicon in Mexico and Mount Pinatubo in the Philippines - occurred during the 27-year period.

The scientists found that during El Niño years, total tropical rainfall did not change significantly, but more rain fell over oceans than usual. During the two years following each volcanic eruption, overall tropical rainfall was reduced by about 5 percent. With these effects removed from the rainfall record, the long-term trend appears more clearly in the rainfall data both over land and over the ocean.

According to Adler, evidence for the rainfall trend is holding as more data come in. The latest numbers for 2006 show another record-high year for tropical rainfall, tying 2005 as the rainiest year. Adler's research group at NASA produces the Global Precipitation Climatology Project's monthly rainfall updates.

"The next step toward firmly establishing this initial indication of a long-term tropical rainfall trend is to continue to lengthen and improve our data record," said Adler, who is project scientist of the Tropical Rainfall Measuring Mission (TRMM), a joint effort between NASA and the Japan Aerospace Exploration Agency. The satellite's three primary instruments are providing the most detailed view of rainfall ever provided from space. Since 1997, Adler's group has been incorporating the mission's rainfall data into the global rainfall record.

NASA plans to extend the success of monitoring rainfall over the tropics to the entire globe with the Global Precipitation Measurement mission, scheduled for launch in 2013. This international project will measure both rain and snow around the world.

Sept. 13, 2007

Tabatha Thompson  
Headquarters, Washington  
202-358-3895  
tabatha.thompson-1@nasa.gov

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## NASA KEEPS EYE ON OZONE LAYER AMID MONTREAL PROTOCOL'S SUCCESS

WASHINGTON - NASA scientists will join researchers from around the world to celebrate the 20th anniversary of the Montreal Protocol, an international treaty designed to reduce the hole in Earth's protective ozone layer. The United Nations Environment Programme will host the meeting from Sept. 23 to 26 in Athens, Greece. NASA scientists study climate change and research the timing of the recovery of the ozone layer.

"The Montreal Protocol has been a resounding success," said **Richard Stolarski**, a speaker at the symposium from NASA's Goddard Space Flight Center, Greenbelt, Md. "The effect can be seen in the leveling off of chlorine compounds in the atmosphere and the beginning of their decline."

Since the Montreal Protocol was signed on Sept. 16, 1987, more than 100 nations have agreed to limit the production and release of compounds, notably human-produced chlorofluorocarbons, known as CFCs. CFCs and a list of other compounds are known to degrade the layer of ozone in the stratosphere that shields life from the sun's ultraviolet radiation. That process gives rise to the ozone hole above Antarctica.

Today, space-based instruments aboard NASA's Aura satellite monitor the chemical make-up of the atmosphere and collect data that will help researchers better understand ozone chemistry through computer models. While the data show that average chlorine levels are beginning to decline, springtime ozone depletion in the polar regions continues to be a prominent atmospheric feature.

"The goal now is to ensure that CFCs and other emissions continue to fall to below the levels that produce an ozone hole," said Goddard's **Anne Douglass**, the deputy project scientist for Aura. "This won't happen until about 2070."

NASA and National Oceanic and Atmospheric Administration scientists announced in 2006 that the hole was the largest ever observed, at 10.6 million square miles. The size of the hole will approach its annual peak in late September. Researchers at the symposium will discuss 20 years of scientific progress, as well as how best to monitor the atmosphere to ensure the goals of the treaty are realized.

In addition to the current satellite measurements, NASA research efforts use data collected on the ground, in the air and from previous missions.

Data from past satellite observations have been essential to understanding ozone depletion. NASA's Total Ozone Mapping Spectrometer, or TOMS, was one of NASA's signature ozone research achievements. TOMS launched in 1978 and was decommissioned in May 2007.

"The TOMS images of the Antarctic ozone hole caused worldwide alarm and thus played a key role in the Montreal Protocol and other international agreements to phase out the offending chemicals from our environment," said Goddard's **Pawan Bhartiya**, project scientist for the mission. In addition, measurements from the Stratospheric Aerosol and Gas Experiment, along with the Microwave Limb Sounder and the Halogen Occultation Experiment aboard the Upper Atmospheric Research Satellite, were important to scientists' understanding of ozone.

Scientists collect atmospheric composition data from ground-based monitoring stations around the world. Researchers have collected measurements since 1978 for nearly all compounds identified in the Montreal Protocol. The data come from coastal monitoring stations used in previous missions and as part of the NASA-sponsored Advanced Global Atmospheric Gases Experiment.

Airborne instruments have been a critical piece of the scientific search to find the cause of ozone depletion, and they remain central to NASA's research efforts today.

Data from NASA's Airborne Antarctic Ozone Experiment in 1987 "provided the smoking gun measurements that nailed down the cause of the ozone hole being the increase of CFCs combined with the unique meteorology of the

Antarctic," Stolarski said. Since then, NASA has sponsored several airborne field campaigns that have furthered understanding of the chemical processes controlling ozone.

These measurements are key for researchers working to predict the future of the global ozone layer. The differences between loss and recovery of ozone at the poles and in non-polar regions are complex. "Such complexity has led to heated debates over the timing and extent of recovery," said Ross Salawitch, an atmospheric chemist at the Jet Propulsion Laboratory, Pasadena, Calif.

The modern focus in ozone research also has shifted to include the effects of climate change. "Twenty years ago we went out of our way to separate ozone depletion from climate change," Salawitch said. "After a decade of looking at data, the community realizes they are linked in subtle but profoundly important ways."

From The Oregonian, September 19, 2007

## Clouds of mystery

**Scientists suspect glowing wisps show that global warming is changing Earth's atmosphere** Wednesday, September 19, 2007

MICHAEL MILSTEIN

**The Oregonian Staff**

Relaxing in the hot tub behind his Warrenton home one evening in June, Brad Hill spotted a strange wiry cloud unlike any he had ever seen.

It glowed electric blue. As the sun fell below the horizon, the tendril grew brighter and brighter.

Scientists strongly suspect that such curious clouds, now expanding around the planet and growing brighter, are one of the most visible signs yet that global warming is altering Earth's atmosphere.

They're known as noctilucent, or night-shining, clouds. They resemble normal cirrus clouds but build mysteriously in summer about 50 miles higher in the sky. They were first reported in the late 1800s and seem to be proliferating with the rise of greenhouse gases.

Sky watchers used to see noctilucent clouds only at northern latitudes such as in Canada and Scandinavia but now spot them more often as far south as Oregon. Oregonians from Bend to the coast reported the clouds this summer, when they appeared especially bright.

The clouds are too wispy to see during the day. They show up only after dusk, when the sun has set but sunlight from over the horizon still illuminates the upper atmosphere, where the clouds hover near the edge of space.

"It's really not a normal sunset color at all," said Hill, a paragliding instructor who watches the sky constantly. He was so captivated it took him 10 minutes to realize that he should snap photos of the cloud he saw in June.

Many researchers suspect the clouds are spreading because, though greenhouse gases hold more heat in the lower atmosphere, they deflect more heat away from the highest reaches of the atmosphere. That causes it to cool and helps ice crystals coalesce into the clouds. The same greenhouse gases may also move extra water into the atmosphere's upper fringe, adding to the luminous wisps.

The clouds have attracted so much attention that NASA launched a new satellite last spring to probe them and the mesosphere, the little-studied layer of atmosphere where the clouds form.

"If indeed we're doing something to change the atmosphere so far above Earth, then we need to understand what it is," said James Russell, a professor at Hampton University in Virginia. He is the lead scientist for the satellite mission, called Aeronomy of Ice in the Mesosphere, or AIM.

The satellite carries newly designed equipment to look into the mesosphere, which is too high for planes or weather balloons to reach but too low for most satellites, which begin to burn up as they drop into it.

Last month, the satellite looked down onto a flotilla of the clouds as huge radar dishes in Greenland and Alaska looked up, collecting some of the most detailed data yet. Researchers are analyzing the data for clues about what's behind the clouds' formation.

They know the clouds require three key ingredients: water vapor to form the ice that makes the clouds; seed particles such as dust for the ice to build upon; and cold temperatures to drive the formation of ice.

"They're increasing in number, and they're occurring at lower latitudes," said Scott Bailey, a Virginia Tech professor who is deputy lead scientist for AIM. "The fact that they were not here at all 120 years ago, and now they are is itself a sign something is changing up there."

The upper atmosphere where the clouds build is usually very dry, because water gets caught by an extremely cold underlying layer of air called the tropopause. But methane, a potent greenhouse gas that has doubled in concentration since the Industrial Revolution, can make it through -- with water hitching a ride.

Once the methane passes into the upper atmosphere, sunlight helps break it down into water molecules, moistening the otherwise dry environment and contributing to the clouds, researchers say.

About 60 percent of methane emissions come from human sources, but concentrations in the atmosphere appear to have leveled off in recent years.

Exhaust from rockets, such as those that loft the space shuttle, also add water to the upper atmosphere. That helps create noctilucent clouds shortly after launches. But those clouds last only about a day, so that wouldn't explain the clouds appearing at other times, Bailey said.

At the same time, colder temperatures may help freeze more of the water to make clouds. The upper atmosphere appears to be cooling a few degrees per decade. That's because

carbon dioxide, the greenhouse gas that catches and holds heat near the Earth, does the opposite in the upper atmosphere -- catching the heat and releasing it into space.

That lowers temperatures, making it easier to form bigger ice particles that make the clouds appear brighter.

Levels of carbon dioxide, released by burning fossil fuels, are at their highest point in the atmosphere in hundreds of thousands of years.

Solar cycles also shrink or expand the clouds by alternately cooling and heating the upper atmosphere as energy from the sun rises and falls every 11 years. That may have amplified this summer's display.

But the clouds are growing still brighter and more widespread over and above those cycles, said Jeffrey Thayer, a professor of aerospace engineering at the University of Colorado, Boulder.

Researchers differ on how clear the evidence is for increasing amounts of water or lower temperatures in the upper atmosphere, but almost all agree the clouds are spreading.

### **Occurring more often**

Data from past satellites that tracked the clouds show they occur 50 to 60 percent more often now than 28 years ago, said **Matthew DeLand**, a scientist at Science Systems and Applications Inc. who works with NASA. "We definitely see increasing trends at all latitudes. There are places that 20 years ago you didn't have people seeing the clouds where now they do."

Ice in the clouds forms around tiny dust particles. It's unclear where they come from, but they may be the leftovers of dust particles arriving from space.

Noctilucent clouds were first recorded in 1885, just after the massive volcanic eruption of Krakatoa in Indonesia in 1883. Some scientists suspect the blast shot extra water, and possibly dust particles, into the upper atmosphere, briefly accelerating the clouds' emergence as rising levels of methane and carbon dioxide took hold over the longer term.

Common clouds in the lower atmosphere can help offset global warming by reflecting sunlight away from Earth. Noctilucent clouds remain much too thin and wispy to have a similar effect, with particles more than 1,000 times smaller than usual cirrus clouds, Thayer said.

But if the strangely glowing clouds continue to brighten and expand, they might begin to have a broader influence.

# Hill Heat

Science Policy Legislation Action

## Hurricanes and Climate Change: What's Resolved and What Remains To Be Resolved? on Friday, September 21, 2007

Is there a scientific basis for anticipating that human-induced climate warming does and/or will affect hurricanes in some way, over and above natural climate variability? Do observations and model simulations support that expectation, or are there issues with data and observations that make the task of sorting out linkages more difficult? If the latter, what are the observational and data issues that continue to make this a challenging scientific problem? What do we know now that we did not know two years ago? What role do model simulations play in helping to sort out linkages, if any, between global warming and hurricanes, in the absence of data/observation or the presence of unreliable data/observations? How can we best develop a coordinated national effort to provide urgently required information for planning, community response and infrastructure development.

### Moderator

- Dr. Anthony Socci, Senior Science Fellow, American Meteorological Society

### Speakers

- Dr. Kerry Emanuel, Professor of Atmospheric Science, Massachusetts Institute of Technology, Cambridge, MA
- Dr. William K. M. Lau, Chief, Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, MD
- Dr. Greg Holland, Director, Mesoscale and Microscale Meteorology Division, Earth and Sun Systems Laboratory, National Center for Atmospheric Research, Boulder, CO
- Dr. Gabriel Vecchi, Research Oceanographer, Climate diagnostics Group, Geophysical Fluid Dynamics Lab/NOAA, Princeton, NJ.
- Thomas R. Knutson, Research Meteorologist, Climate Dynamics and Prediction Group, Geophysical Fluid Dynamics Lab/NOAA, Princeton, NJ.

### Overview of Hurricanes and Climate Change (a.k.a. global warming)

The understanding of climate change, including its effects on hurricanes, rests on three essential scientific techniques: theory, observation, and computational modeling. Each of these three approaches has unique strengths and limitations. In this talk, I will discuss the application of each of these to understanding the effect of climate change on hurricane activity and demonstrate that while each approach is compromised by uncertainties, taken together they present a persuasive picture of increasing hurricane risk as the climate warms.

### Notes:

*The science of hurricanes and climate rests on all three of observations, theory, and computer models.*

*There's no significant trend in the number of storms recorded per year, nor do we know what determines that number.*

*Tropical cyclone power dissipation. There's a strong correlation between cyclonic power dissipation and sea-surface temperature before 1987, then the record is highly variable.*

*We no longer fly planes into storms in the western Pacific. We can't do everything with satellites.*

*Good correlation in the Atlantic. Since the 1980s Atlantic hurricane strength has doubled.*

*Paleotempestology: Jeff Donnelley, Jon Woodruff, Phil Lane, WHOI. May be able to show longer record of changing hurricane activity.*

*We have the theory of potential intensity. Observed potential intensity has gone up dramatically since 1990.*

*What is causing SST changes in the northern hemisphere? The tropical Atlantic's SST changes are consistent with the entire northern hemisphere SST.*

*You can explain a lot of the difference between Atlantic SST and global mean temperatures by aerosol forcing.*

*There are beginnings of downscaling techniques to seed GCMs with fledgling cyclonic storms. Their preliminary results show decreases overall, some increases. Decrease in frequency but increase in intensity and rainfall. But they predict less change than we have already observed over the past 50 years.*

### Rainfall Extremes, Saharan Dust, Tropical Cyclones and Climate Change

Trends in tropical rainfall are more readily detectable in the form of changes in rainfall characteristics, rather than in rainfall total. From satellite data, we find that in the tropics there is a strong positive trend in extreme heavy and very light rains, coupled to a negative trend in moderate rain. Climatologically over tropical oceans, a large portion (over 60%) of most extreme heavy rainfall (top 5%) can be identified with those coming from tropical cyclones. Over the Atlantic, the contribution of tropical cyclones to heavy rain events has almost doubled in the last quarter century. Over the Pacific basin, the increase is lesser at about 10%. The differences in the basin may be related to the percentage change in the warm pool (SST > 28 °C) areas in both oceans. Overall, tropical cyclones appear to be feeding more extreme rainfall events in the tropics in recent decades.

Saharan dust can affect tropical cyclones development, and may be a factor contributing to long-term hurricane statistics and possibly in seasonal hurricane forecasts. The Saharan Air Layer (SAL) can suppress tropical cyclogenesis through entrainment of hot, dry air into a developing cyclone, increasing stability and denying the developing system of its moisture supply. Saharan dust may also pre-condition the Atlantic, cooling the ocean surface through attenuation of solar radiation, during the early hurricane season. Additionally, differential radiative heating of the atmosphere by Saharan dust may induce changes in the large-scale circulation over the West Africa and Atlantic region. All these effects may provide a feedback on the coupled ocean-atmosphere system over the Atlantic, modulating the seasonal statistics of hurricanes. Analyses of satellite data and historical records show a more (less) active hurricane season is generally associated with less (more) Saharan dust over the Atlantic.

### Global Warming and Hurricane Activity

The past century has seen North Atlantic hurricanes occurring in three periods of relatively stable frequency separated by sharp upward transitions. Each period has experienced 50% more hurricanes than the previous one and each was associated with a distinct change in eastern Atlantic sea surface temperatures (SSTs). After taking account of missing cyclones in earlier periods due to poor observing systems, we have experienced an 80-100% increase in hurricane frequency over since the early 1900s. Natural variability has contributed to some of the observed changes, but the compelling conclusion is that the overall increase has been substantially influenced by greenhouse warming. Superimposed on this increasing hurricane frequency is a completely independent oscillation in the proportions of major and minor hurricanes (compared to all storms). This oscillation has no distinguishable net trend and may arise largely from internal oscillations of the climate system. The period of enhanced major hurricane activity during 1945-1964 arose entirely from this oscillation. Unfortunately, the period since 1995 has experienced a double-whammy of a sharp increase in both numbers of hurricanes and the proportion of major hurricanes.

This heightened hurricane activity is unlikely to decrease in the future and we may see further increases. If so, current planning, building and coastal levee systems may prove to be inadequate, leading to more New Orleans-type disasters. The National Hurricane Research Initiative is designed to provide us with the tools to assess this future threat, to develop improved forecast and community response approaches, and to establish coastal planning approach to minimize the potential for future disasters. It is an initiative of critical national importance, which deserves

strong and urgent support.

#### Long-term changes in Tropical Cyclone Activity: Looking Forward and Looking Back

To understand how human-induced climate change influences global and Atlantic tropical cyclone activity it is essential to have accurate records of past tropical cyclone variations and to model future climate conditions. The ways that tropical cyclones are measured have evolved over time, thereby influencing the homogeneity of the record. Statistical techniques can help, however, to estimate these deficiencies in the century-scale record. To project future conditions, global climate models (GCMs) – though not perfect – are our best tools. Although current computing power prevents GCMs from explicitly representing tropical cyclones, GCMs do indicate robust changes in many of the large-scale environmental conditions that are known to influence tropical cyclone activity, such as the thermodynamic structure of the atmosphere and vertical wind shear. Analyses of climate models and reconstructions of past tropical cyclone records indicate:

- Observational evidence for century-scale changes in tropical cyclone activity is mixed, depending on the metric chosen, on the statistical correction applied to the data and on the time interval being examined.
- Climate model projections of the Atlantic and East Pacific response to global warming exhibit mixed changes in cyclone-relevant parameters, with both an increase in thermodynamic potential intensity of tropical cyclones and an increase in vertical wind shear. More refined methods are needed to understand the detailed response of tropical cyclones to these environmental changes.
- Outside of the Atlantic and East Pacific, projected changes to both the thermodynamic potential and the wind shear indicate conditions more favorable to tropical cyclone activity under global warming.
- Although questions remain about the detailed response of tropical cyclone activity to human-induced climate change, we have relatively much greater confidence in the projected response of other large-scale climate conditions to increasing greenhouse gases (e.g., global warming, surface temperatures over land warm faster than over ocean, Arctic sea ice reduction, increase in ocean heat content, etc.).

*Estimating how many tropical storms we missed before satellite observations, based on ship tracks. We have real observation gaps during WWI and WWII.*

*Model results show temperatures and wind shear increasing in most areas, not pointing in a clear direction for potential intensity. In the West Pacific and Indian Ocean, however, the trends all point toward increased cyclonic frequency.*

#### Modeling the Response of Atlantic Hurricanes to Climate Variability and Change

A pressing question concerning ongoing global warming is whether human-caused warming of the planet has had any discernible impact on Atlantic hurricane activity. Confidence in any such a link is currently hampered by both data quality issues for the hurricane observational record and by limited work specifically targeting this question from a modeling perspective. Based on existing studies to date:

- Observed data, including consideration of data problems, give conflicting indications on whether there have been significant increases in Atlantic tropical storm and hurricane numbers. U.S. land-falling numbers have not increased. Models have not yet reproduced some reported long-term (~100 yr) increasing trends in basin-wide numbers.
- High resolution models consistently project increasing hurricane intensities and rainfall rates for the late 21st century, but whether there will be more or fewer hurricanes remains uncertain.
- A new modeling approach reproduces many important aspects of Atlantic hurricane activity observed since 1980, and thus shows promise as a tool for both understanding past variations and for making more reliable projections of future hurricane activity.

**Biographies** Dr. Kerry Emanuel is a professor of atmospheric science at the Massachusetts Institute of Technology, where he has been on the faculty since 1981, after spending three years as a faculty member at UCLA. Professor Emanuel's research interests focus on tropical meteorology and climate, with a specialty in hurricane physics. His interests also include cumulus convection, and advanced methods of sampling the atmosphere in aid of numerical weather prediction. He is the author or co-author of over 100 peer-reviewed scientific papers, and three books, including *Divine Wind: The History and Science of Hurricanes*, recently released by Oxford University Press and aimed at a general audience, and *What We Know about Climate Change*, published by the MIT Press.

Dr. William Lau is currently the Chief of the Laboratory for Atmospheres at NASA, Goddard Space Flight Center, and Adjunct Professor at Department of Meteorology U. of Maryland. His research work spans three decades and covers a wide range of topics including climate dynamics, tropical and monsoon meteorology, ocean-atmosphere interaction, and climate variability and change.

Dr. Lau has received numerous awards for his research and his scientific leadership, including among others, the AMS Meisinger Award in 1997; the John Lindsay Award, 1998; the NASA Exceptional Science Achievement Award, 1991; the William Nordberg Award (GSFC highest award in Earth Sciences), 2002. He is a Goddard Senior Fellow, a fellow of the American Meteorological Society since 1988, and a fellow of the American Geophysical Union, 2007. Dr. Lau has published over 190 refereed papers, book Chapters in refereed journals. He is the principal author of a book "Intraseasonal Variability in the Tropical Ocean-Atmosphere System", published in 2006. Dr. Lau received his B. Sc. in Physics and Mathematics from the University of Hong Kong, and his Ph.D. in Atmospheric Sciences from the University of Washington, Seattle.

Dr. Greg Holland is currently Director of the Mesoscale and Microscale Meteorology Division at the National Center for Atmospheric Research in Boulder, where he is involved scientifically with hurricane landfall, genesis and climate related work. He is a fellow of the American Meteorological Society as well as the Australian Meteorological and Oceanographic Society. Dr. Holland has several areas of research interests which have carried through to applications and include improved forecasting of tropical cyclone motion, scale interactions associated with cyclogenesis, establishment of field facilities, establishment of programs on coastal impacts of tropical cyclones and the development of Unmanned Aerial Vehicles (UAVs).

Dr. Holland has authored or co-authored more than 120 peer-reviewed scientific journal articles and book chapters, as well as dozens of planning documents, scientific prospectuses and workshop papers. He has given several hundred invited talks worldwide, as well as many contributed presentations at national and international conferences on hurricanes and related. He has also convened several national and international workshops, and served on several national and international committees and science-planning initiatives.

Dr. Gabriel Vecchi is a Research Oceanographer at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, where he has been working since 2003. GFDL, which is part of the National Oceanic and Atmospheric Administration (NOAA), is one of the world's leading climate modeling centers. Dr. Vecchi received a B.A. in Mathematics from Rutgers University, and an M.S. in Oceanography, an M.S. in Applied Mathematics and a Ph.D. in Oceanography from the University of Washington. His scientific research focuses on the interactions between the atmosphere and oceans on timescales from weeks to centuries. His recent research has focused on understanding long-term changes to tropical circulation and variability, including characterizing changes relevant to the possible impact of climate change on hurricanes.

Dr. Vecchi currently serves on the Climate Variability and Predictability (CLIVAR) Indian Ocean Panel, and is an Associate Editor of the *Journal of the Atmospheric Sciences*. His awards include the Presidential Early Career Award for Scientists and Engineers (PECASE), the American Geophysical Union's Editor's Citation for Excellence in Refereeing for *Geophysical Research Letters*, and the Cook College, Rutgers University Marine Sciences Student of the Year. He has over 30 publications in peer-reviewed science journals or book chapters.

Thomas R. Knutson has been a Research Meteorologist at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey since 1990. GFDL, which is part of the National Oceanic and Atmospheric Administration, is one of the world's leading climate modeling centers. Mr. Knutson has authored several modeling studies in major scientific journals on the potential impact of climate change on hurricanes. He now leads a project at GFDL aimed at simulating past and future Atlantic hurricane activity using regional high-resolution models.

He currently serves on the World Meteorological Organization (WMO) Expert Team on Climate Impacts on Tropical Cyclones, and was a major contributor to the December 2006 WMO "Statement on Tropical Cyclones and Climate Change". He is a member of a U.S. Climate Change Science Program (CCSP) committee developing an assessment report on "Weather and Climate Extremes in a Changing Climate," the AMS Climate Variability and Change Committee, and is an Associate Editor of the *Journal of Climate*. Mr. Knutson has over 30 publications in peer-reviewed science journals or book chapters.

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[http://www.nasa.gov/centers/goddard/news/topstory/2007/newman\\_montreal.html](http://www.nasa.gov/centers/goddard/news/topstory/2007/newman_montreal.html)

**FEATURE**

Montreal Protocol Selects Goddard's Paul Newman as  
Scientific Assessment Panel Co-Chair

10.25.07

The 191 nations of the Montreal Protocol have selected Dr. Paul A. Newman, an atmospheric physicist in the Atmospheric Chemistry and Dynamics Branch at Goddard Space Flight Center, as co-chair of their Scientific Assessment Panel. The Montreal Protocol is the historic international agreement that protects the Earth's ozone layer.

**Image right:** Dr. Paul A. Newman **Image**  
**Courtesy:** Ilias Anagnostopoulos

The 1987 Montreal Protocol established three panels to periodically provide updates on matters related to the ozone layer. As co-chair of the Scientific Assessment Panel, Newman is specifically charged with providing assessments of the science related to the ozone layer, ozone-depleting substances, climate and ozone interactions, and ultraviolet radiation at the Earth's surface.



“I’m really honored by my selection,” said Newman. “First, it’s still a very important task as ozone begins to show the first signs of recovery, and second, because my colleagues have entrusted me with the continuations of this work.”

Newman’s background and experience has more than prepared and him for this prestigious position. He graduated from Seattle University with a bachelor of science in physics and a minor in mathematics. He completed his doctorate in physics at Iowa State University.

For 17 years Newman has been with NASA, where his principal area of research has been stratospheric dynamics and chemistry. Newman has participated in and led more than 15 NASA aircraft field campaigns, including trips to Costa Rica, Sweden, Norway, and Alaska. During the SAGE III Ozone Loss and Validation Experiment (SOLVE) in 2000, Newman directed the first flight of the NASA ER-2, a civilian version of the U-2 spy plane, over Russia since the famous shoot-down of Gary Powers in May 1960 at the height of the Cold War.

Newman has also spent time researching the Antarctic ozone hole during his career with NASA. In the summer of 2006, he published a new prediction of the recovery of the Antarctica ozone hole.

In addition to Newman, the committee includes Ayité-Lô Nohende Ajavon of Université de Lomé in Togo, John Pyle of Cambridge University, U.K., and A.R. Ravishankara of the U.S. NOAA Earth Sciences Research Laboratory.

**Lynn Chandler**  
**Goddard Space Flight Center**



National Aeronautics  
and Space Administration

FEATURE

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## Local Sources Major Cause of U.S. Near-Ground Aerosol Pollution

11.16.07

A new NASA study estimates that most ground-level particulate pollution in the United States stems from regional sources in North America and only a small amount is brought to the country from other parts of the world.

**Image right:** A cloud of pollution hangs over the Eastern United States in this image captured in July 2002 by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). The majority of such haze originates locally in North America, and only a small amount is imported from other continents, new research suggests. [+ Larger image](#) Credit: Jacques Desclotres, MODIS Land Rapid Response Team, NASA/GSFC

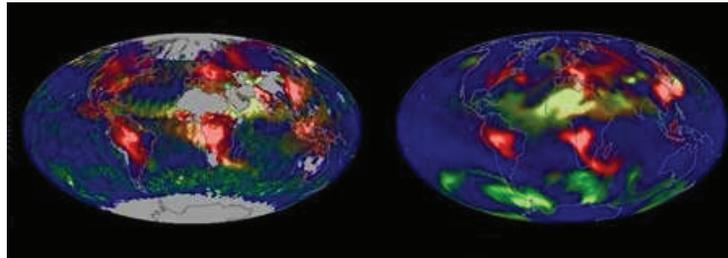


Researchers using an innovative global aerosol tracking model have for the first time produced a global estimate of sources and movements of aerosols near the ground where they can affect human health and run afoul of environmental regulations. Previously, researchers studying aerosols moving between continents focused primarily on tracking a single type of aerosol, such as dust or black carbon, or measuring their quantities throughout the atmosphere. This left gaps in understanding where ground-level particulate pollution comes from.

"This is the first study to comprehensively consider the origin, composition and type of fine particles over the United States and connect them to both domestic and foreign sources," said Mian Chin, an atmospheric scientist at NASA's Goddard Space Flight Center, Greenbelt, Md., and lead author of the study.

Aerosols are airborne particles that arise from both human sources such as burning fossil fuels, and natural sources such as fires, dust and volcanoes. They are also a major source of near-ground pollution. Since 1970, particulate matter has been regulated in the United States by the Clean Air Act. A more recent concern has been aerosols that arrive here from distant shores carried by the wind.

Chin and colleagues set out to investigate how much and what type of aerosols made the intercontinental journey in 2001. The team employed the help of a computer model using known air chemistry and wind patterns to trace a region's aerosols – everything from fossil fuel and biofuel combustion, biomass burning, and volcanic sources, desert dust and sea salt – back to their sources.



**Image left:** Aerosols in Earth's atmosphere can be a major source of pollution worldwide, and include fine aerosols such as pollution and smoke (red) and coarse aerosols such as dust and sea-salt (green). The left image shows aerosol levels on April 13, 2001 as seen by a NASA satellite. The map at right is a computer simulation of the same day showing that the model accurately estimates the transport of aerosols between continents. [+ Larger image](#) Credit: NASA

"Using the model, we followed the path of aerosols to find out how much is local and how much is from outside a region," Chin says.

Chin and colleagues estimate that between 65-70 percent of surface particulate matter in the eastern U.S. originates from regional pollution aerosols from fuel combustion in North America. The report was in the Nov. 1 edition of the European Geosciences Union's Atmospheric Chemistry and Physics.

They also found that 30-40 percent of fine particulates in the western U.S. come from local pollution sources. The model results estimated that just 2-6 percent of U.S. surface fine particulates come from fuel combustion particles emitted outside of North America, including Asia and Europe. About 50 percent of surface fine particulate matter in the western U.S. stems from a natural source: dust transported from Asia or from local deserts and organic aerosols from vegetation.

"Our results indicate that controlling regional pollution emissions will be the most effective and most responsible way to manage U.S. air

NASA - Local Sources Major Cause of U.S. Near-Ground Aerosol Poll..[http://www.nasa.gov/vision/earth/environment/particulate\\_pollution\\_prt.htm](http://www.nasa.gov/vision/earth/environment/particulate_pollution_prt.htm)

quality," Chin says.

**Kathryn Hansen**  
Goddard Space Flight Center

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## APPENDIX 2. REFEREED ARTICLES

Asterisks indicate articles highlighted in Appendix 3.

Laboratory members' names are in boldface

### 613 Senior Staff and Senior Scientists

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## APPENDIX 3. HIGHLIGHTED ARTICLES PUBLISHED IN 2007



GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L23811, doi:10.1029/2007GL031538, 2007

## Cooling of the Atlantic by Saharan dust

K. M. Lau<sup>1</sup> and K. M. Kim<sup>2</sup>

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[1] Using aerosol optical depth, sea surface temperature, top-of-the-atmosphere solar radiation flux, and oceanic mixed-layer depth from diverse data sources that include NASA satellites, NCEP reanalysis, *in situ* observations, as well as long-term dust records from Barbados, we examine the possible relationships between Saharan dust and Atlantic sea surface temperature. Results show that the estimated anomalous cooling pattern of the Atlantic during June 2006 relative to June 2005 due to attenuation of surface solar radiation by Saharan dust remarkably resemble observations, accounting for approximately 30–40% of the observed change in sea surface temperature. Historical data analysis show that there is a robust negative correlation between atmospheric dust loading and Atlantic SST consistent with the notion that increased (decreased) Saharan dust is associated with cooling (warming) of the Atlantic during the early hurricane season (July–August–September). **Citation:** Lau, K. M., and K. M. Kim (2007), Cooling of the Atlantic by Saharan dust, *Geophys. Res. Lett.*, *34*, L23811, doi:10.1029/2007GL031538.

### 1. Introduction

[2] An estimated amount of 60–200 million tons of dust particles are lifted annually from the Saharan desert surface and transported westward by the easterly winds over the Atlantic Ocean [Prospero and Lamb, 2003]. During the peak season of June through August, airborne dust particles reach the western Atlantic and Caribbean, and can be detected as far west as Florida, and the Gulf of Mexico [Colarco *et al.*, 2003; Wong *et al.*, 2006]. Saharan dusts have been shown to affect the development of clouds and precipitation over oceanic areas across the Atlantic, as well as modulating thunderstorm activities over the Caribbean, and the southeast US [Kaufman *et al.*, 2005; Sassen *et al.*, 2003]. Hot dry air, known as the Saharan Air Layer (SAL), which often accompanies Saharan dust outbreaks, can suppress tropical cyclogenesis and inhibit Atlantic hurricane formation [Dunion and Velden, 2004; Wu, 2007]. Studies have also found significant positive correlation between dust cover and Atlantic tropical cyclone days [Evan *et al.*, 2006].

[3] Recently Lau and Kim [2007a] found significant increase in Saharan dust and reduction of sea surface temperature (SST) over the West Atlantic and Caribbean region during the hurricane season, June through November, of

2006 compared to 2005. They argued that the attenuation of solar radiation reaching the ocean surface by excessive Saharan dust in June–July, 2006 (relative to 2005) may have been instrumental in initiating the rapid cooling of the entire Atlantic Ocean. The cooling subsequent metastasized through atmospheric-oceanic coupled feedback to become a part of an altered climate state in the North Atlantic and West Africa regions unfavorable for hurricane formation. In a subsequent exchange [Evan, 2007; Lau and Kim, 2007b], issues were raised regarding the magnitude of the difference in atmospheric dust loading, and the degree to which solar attenuation effect by dust could lower Atlantic SST. In this paper, we present observation-based estimates of possible large-scale cooling of the Atlantic by Saharan dust attenuation effect for 2006 relative to 2005, and examine statistical dust-SST relationships based on long-term historical records.

[4] The data used for this study are drawn from a wide range of independent sources, including daily Aerosol-Index (AI) [Hsu *et al.*, 1999] for absorbing aerosols (dust and black carbon) from the Ozone Monitoring Instrument (OMI), aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) [Remer *et al.*, 2005], daily sea surface temperature from Tropical Rainfall Measuring Mission Microwave Imager (TMI), top-of-the atmosphere solar radiation from the National Center for Environmental Prediction (NCEP) reanalysis data, and climatological oceanic mixed layer depth from the Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN). Also used for the historical data analysis are long-term data from the Barbados dust record [Prospero and Nees, 1986], and the SST record from the Hadley Center [Rayner *et al.*, 2003].

### 2. Results

#### 2.1. Dust and SST Variation During 2005–2006

[5] From the daily variation (smoothed by a 5-day running mean) of dust loading (OMI-AI) and SST over the Western Atlantic/Caribbean region (70°W–40°W, 15°N–30°N) in 2006, (shown as the deviation from 2005 in Figure 1), dust loading is clearly higher for most of the year in 2006 compared to 2005 (Figure 1a). The dust loading shows large fluctuations from June through September, reflecting the dynamical nature of the dust outbreak and transport processes. This region experienced episodic cooling in SST throughout 2006 (Figure 1b), with two significant episodes in mid-March through May, which seemed to follow two dust events (Figure 1a) during the same period. The most pronounced cooling occurred in mid-June, about one-to-two weeks after the major dust event in June. The cooling rapidly reached its maximum in late June and mid-July, and lasted through the end of September. Given that dust outbreaks and loadings are highly dependent on fast atmospheric processes, and SST on relatively slow ocean processes, any relationship

<sup>1</sup>Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Goddard Earth Science and Technology Center, University of Maryland Baltimore County, Baltimore, Maryland, USA.

## A Numerical Study of Hurricane Erin (2001). Part II: Shear and the Organization of Eyewall Vertical Motion

SCOTT A. BRAUN

*Mesoscale Atmospheric Processes Branch, Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland*

LIGUANG WU

*Goddard Earth Science and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland*

(Manuscript received 11 January 2006, in final form 19 June 2006)

### ABSTRACT

A high-resolution numerical simulation of Hurricane Erin (2001) is used to examine the organization of vertical motion in the eyewall and how that organization responds to a large and rapid increase in the environmental vertical wind shear and subsequent decrease in shear. During the early intensification period, prior to the onset of significant shear, the upward motion in the eyewall was concentrated in small-scale convective updrafts that formed in association with regions of concentrated vorticity (herein termed mesovortices) with no preferred formation region around the eyewall. Asymmetric flow within the eye was weak. As the shear increased, an azimuthal wavenumber-1 asymmetry in storm structure developed with updrafts tending to occur on the downshear to downshear-left side of the eyewall. Continued intensification of the shear led to increasing wavenumber-1 asymmetry, large vortex tilt, and a change in eyewall structure and vertical motion organization. During this time, the eyewall structure was dominated by a vortex couplet with a cyclonic (anticyclonic) vortex on the downtilt-left (downtilt-right) side of the eyewall and strong asymmetric flow across the eye that led to strong mixing of eyewall vorticity into the eye. Upward motion was concentrated over an azimuthally broader region on the downtilt side of the eyewall, upstream of the cyclonic vortex, where low-level environmental inflow converged with the asymmetric outflow from the eye. As the shear diminished, the vortex tilt and wavenumber-1 asymmetry decreased, while the organization of updrafts trended back toward that seen during the weak shear period. Based upon the results for the Erin case, as well as that for a similar simulation of Hurricane Bonnie (1998), a conceptual model is developed for the organization of vertical motion in the eyewall as a function of the strength of the vertical wind shear. In weak to moderate shear, higher wavenumber asymmetries associated with eyewall mesovortices dominate the wavenumber-1 asymmetry associated with the shear so that convective-scale updrafts form when the mesovortices move into the downtilt side of the eyewall and dissipate on the uptilt side. Under strong shear conditions, the wavenumber-1 asymmetry, characterized by a prominent vortex couplet in the eyewall, dominates the vertical motion organization so that mesoscale ascent (with embedded convection) occurs over an azimuthally broader region on the downtilt side of the eyewall. Further research is needed to determine if these results apply more generally.

### 1. Introduction

The National Aeronautics and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) satellite has proven to be a valuable tool for the study of precipitation in hurricanes. Lonfat et al. (2004) used rainfall estimates from the TRMM Micro-

wave Imager (TMI) to examine the climatological rainfall characteristics of hurricanes with emphases on the variations with respect to storm intensity and location (different ocean basins) and on asymmetries in rainfall structure. Cecil et al. (2002) and Cecil and Zipser (2002) examined TRMM radar, TMI, and lightning data in hurricanes and found that the precipitation characteristics were very similar to nonhurricane tropical oceanic precipitation. The hurricane outer rainbands produced more lightning per unit area than the eyewall and inner rainbands, as well as other tropical oceanic convection, and were proposed to be a pre-

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*Corresponding author address:* Dr. Scott Braun, Mesoscale Atmospheric Processes Branch, NASA GSFC, Code 613.1, Greenbelt, MD 20771.  
E-mail: scott.a.braun@nasa.gov

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MWR3336

## Tropical Rainfall Variability on Interannual-to-Interdecadal and Longer Time Scales Derived from the GPCP Monthly Product

GUOJUN GU

*Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, and  
Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland*

ROBERT F. ADLER

*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland*

GEORGE J. HUFFMAN

*Science Systems and Applications Inc., and Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland*

SCOTT CURTIS

*Department of Geography, East Carolina University, Greenville, North Carolina*

(Manuscript received 15 March 2006, in final form 6 December 2006)

### ABSTRACT

Global and large regional rainfall variations and possible long-term changes are examined using the 27-yr (1979–2005) Global Precipitation Climatology Project (GPCP) monthly dataset. Emphasis is placed on discriminating among variations due to ENSO, volcanic events, and possible long-term climate changes in the Tropics. Although the global linear change of precipitation in the dataset is near zero during the time period, an increase in tropical rainfall is noted in the dataset, with a weaker decrease over Northern Hemisphere middle latitudes. Focusing on the Tropics (25°S–25°N), the dataset indicates an upward linear change ( $0.06 \text{ mm day}^{-1} \text{ decade}^{-1}$ ) and a downward linear change ( $-0.01 \text{ mm day}^{-1} \text{ decade}^{-1}$ ) over tropical ocean and land, respectively. This corresponds to an about 5.5% increase (ocean) and 1% decrease (land) during the entire 27-yr time period. The year 2005 has the largest annual tropical total precipitation (land plus ocean) for the GPCP record. The five highest years are (in descending order) 2005, 2004, 1998, 2003, and 2002. For tropical ocean the five highest years are 1998, 2004, 2005, 2002, and 2003.

Techniques are applied to isolate and quantify variations due to ENSO and two major volcanic eruptions during the time period (El Chichón, March 1982; Mount Pinatubo, June 1991) in order to examine longer-time-scale changes. The ENSO events generally do not impact the tropical total rainfall, but rather induce significant anomalies with opposite signs over tropical land and ocean. The impact of the two volcanic eruptions is estimated to be about a 5% reduction in tropical rainfall over both land and ocean. A modified dataset (with ENSO and volcano effects removed) retains the same approximate linear change slopes, but with reduced variances, thereby increasing the statistical significance levels associated with the long-term rainfall changes in the Tropics. However, although care has been taken to ensure that this dataset is as homogeneous as possible, firm establishment of the existence of the discussed changes as long-term trends may require continued analysis of the input datasets and a lengthening of the observation period.

### 1. Introduction

Exploring global climate variability and change has an immense environmental and societal significance

(e.g., Kumar et al. 2004). Previous studies showed interannual variability and interdecadal/longer-term changes in various climate components, for example, surface air temperature, sea surface temperature (SST), land rainfall, etc., specifically during recent decades (e.g., Cane et al. 1997; Chen et al. 2002; Simmons et al. 2004). The El Niño–Southern Oscillation (ENSO) generally dominates the global variability on interannual

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*Corresponding author address:* Guojun Gu, NASA GSFC, Code 613.1, Greenbelt, MD 20771.  
E-mail: ggu@agnes.gsfc.nasa.gov

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# NASA'S TROPICAL CLOUD SYSTEMS AND PROCESSES EXPERIMENT

## Investigating Tropical Cyclogenesis and Hurricane Intensity Change

BY J. HALVERSON, M. BLACK, S. BRAUN, D. CECIL, M. GOODMAN, A. HEYMSFIELD, G. HEYMSFIELD,  
R. HOOD, T. KRISHNAMURTI, G. MCFARQUHAR, M. J. MAHONEY, J. MOLINARI, R. ROGERS, J. TURK,  
C. VELDEN, D.-L. ZHANG, E. ZIPSER, AND R. KAKAR

High altitude research flights during the active 2005 Atlantic and eastern Pacific hurricane season yielded interesting and surprising observations, both within and above the clouds.

**B** **ACKGROUND AND MOTIVATION FOR TCSP.** A key mandate of the National Aeronautics and Space Administration's (NASA's) Weather Focus Area is to investigate high-impact weather events, such as tropical cyclones, through a combination of new and improved space-based observations, high-altitude research aircraft, and sophisticated numerical models to improve the understanding

and predictability of weather, climate, and natural hazards. One of the areas of tropical meteorology that remains elusive to both understanding and prediction is the genesis and intensification of tropical cyclones. The processes by which tropical disturbances develop into depressions, storms, or hurricanes (termed tropical cyclogenesis) remain one of the outstanding and fascinating research topics in meteorology. The

**AFFILIATIONS:** HALVERSON—Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland; BLACK AND ROGERS—NOAA/Hurricane Research Division, Miami, Florida; BRAUN AND G. HEYMSFIELD—NASA Goddard Space Flight Center, Greenbelt, Maryland; CECIL—Earth System Science Center, University of Alabama, Huntsville, Huntsville, Alabama; GOODMAN AND HOOD—NASA Marshall Space Flight Center, Huntsville, Alabama; A. HEYMSFIELD—University Center for Atmospheric Research, Boulder, Colorado; KRISHNAMURTI—The Florida State University, Tallahassee, Florida; MCFARQUHAR—University of Illinois at Urbana—Champaign, Urbana, Illinois; MAHONEY—Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California; MOLINARI—University at Albany, State University of New York, Albany, New York; TURK—Naval Research Laboratory, Washington, DC; VELDEN—University of Wisconsin—Madison—

Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin; ZHANG—University of Maryland, College Park, College Park, Maryland; ZIPSER—University of Utah, Salt Lake City, Utah; KAKAR—NASA Headquarters Science Mission Directorate, Washington, DC.

**CORRESPONDING AUTHOR:** Dr. Jeffrey B. Halverson, JCET/UMBC, 5523 Research Park Dr., Suite 320, Baltimore, MD 21228  
E-mail: jeffhalv@umbc.edu

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## A first approach to global runoff simulation using satellite rainfall estimation

Yang Hong,<sup>1,2,3</sup> Robert F. Adler,<sup>1</sup> Faisal Hossain,<sup>4</sup> Scott Curtis,<sup>5</sup> and George J. Huffman<sup>1,6</sup>

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[1] Motivated by the recent increasing availability of global remote sensing data for estimating precipitation and describing land surface characteristics, this note reports an approximate assessment of quasi-global runoff computed by incorporating satellite rainfall data and other remote sensing products in a relatively simple rainfall-runoff simulation approach: the Natural Resources Conservation Service (NRCS) runoff curve number (CN) method. Using an antecedent precipitation index (API) as a proxy of antecedent moisture conditions, this note estimates time-varying NRCS-CN values determined by the 5-day normalized API. Driven by a multiyear (1998–2006) Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis, quasi-global runoff was retrospectively simulated with the NRCS-CN method and compared to Global Runoff Data Centre data at global and catchment scales. Results demonstrated the potential for using this simple method when diagnosing runoff values from satellite rainfall for the globe and for medium to large river basins. This work was done with the simple NRCS-CN method as a first-cut approach to understanding the challenges that lie ahead in advancing the satellite-based inference of global runoff. We expect that the successes and limitations revealed in this study will lay the basis for applying more advanced methods to capture the dynamic variability of the global hydrologic process for global runoff monitoring in real time. The essential ingredient in this work is the use of global satellite-based rainfall estimation.

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### 1. Introduction

[2] Many hydrological models have been introduced in the hydrological literature to predict runoff [Singh, 1995], but few of these have become common planning or decision-making tools [Choi *et al.*, 2002], either because the data requirements are substantial or because the modeling processes are too complicated for operational application. On the other hand, progress in regional or global rainfall-runoff simulation has been constrained by the difficulty of measuring spatiotemporal variability of the primary causative factor, i.e., rainfall fluxes, continuously over space and time. Building on progress in remote sensing technology, researchers have improved the accuracy, coverage, and resolution of rainfall estimates by combining imagery from infrared, passive microwave, and space-borne radar sensors

[Adler *et al.*, 2003]. Today remote sensing imagery acquired and processed in real time can provide near-real-time rainfall at hydrologically relevant spatiotemporal scales (tens of kilometers and subdaily [Hong *et al.*, 2005; Huffman *et al.*, 2007; Joyce *et al.*, 2004; Sorooshian *et al.*, 2000; Turk and Miller, 2005]). Over much of the globe, remote sensing precipitation estimates are the only available source of rainfall information, particularly in real time. Correspondingly, remote sensing has increasingly become a viable data source to augment the conventional hydrological rainfall-runoff simulation, especially for inaccessible regions or complex terrains, because remotely sensed imageries are able to monitor precipitation and identify land surface characteristics such as topography, stream network, land cover, vegetation, etc. Artan *et al.* [2007] demonstrated the improved performance of remotely sensed precipitation data in hydrologic modeling when the hydrologic model was recalibrated with satellite data rather than gauge rainfall over four subbasins of the Nile and Mekong rivers.

[3] Motivated by the recent increasing availability of global remote sensing data for estimating precipitation and describing land surface characteristics, this note attempts to obtain a ballpark assessment of global runoff by incorporating satellite rainfall data and other remote sensing products through a relatively simple rainfall-runoff simulation approach: the United States Natural Resources Conservation Service (NRCS) runoff curve number (CN) method [Natural Resources Conservation Service (NRCS), 1986; Burges *et al.*, 1998]. Its simplicity is especially critical for

<sup>1</sup>Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Now at School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, Oklahoma, USA.

<sup>3</sup>Formerly at Goddard Earth Science Technology Center, University of Maryland Baltimore County, Baltimore, Maryland, USA.

<sup>4</sup>Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, Tennessee, USA.

<sup>5</sup>Department of Geography, East Carolina University, Greenville, North Carolina, USA.

<sup>6</sup>Science Systems and Applications, Inc., Lanham, Maryland, USA.

## The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales

GEORGE J. HUFFMAN,<sup>\*,+</sup> ROBERT F. ADLER,<sup>\*</sup> DAVID T. BOLVIN,<sup>\*,+</sup> GUOJUN GU,<sup>\*,#</sup> ERIC J. NELKIN,<sup>\*,+</sup> KENNETH P. BOWMAN,<sup>@</sup> YANG HONG,<sup>\*,#</sup> ERICH F. STOCKER,<sup>&</sup> AND DAVID B. WOLFF<sup>\*,+</sup>

<sup>\*</sup>Laboratory for Atmospheres, NASA GSFC, Greenbelt, Maryland

<sup>+</sup>Science Systems and Applications, Inc., Lanham, Maryland

<sup>#</sup>Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland

<sup>@</sup>Texas A&M University, College Station, Texas

<sup>&</sup>Global Change Data Center, NASA GSFC, Greenbelt, Maryland

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### ABSTRACT

The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales ( $0.25^\circ \times 0.25^\circ$  and 3 hourly). TMPA is available both after and in real time, based on calibration by the TRMM Combined Instrument and TRMM Microwave Imager precipitation products, respectively. Only the after-real-time product incorporates gauge data at the present. The dataset covers the latitude band  $50^\circ\text{N}$ – $50^\circ\text{S}$  for the period from 1998 to the delayed present. Early validation results are as follows: the TMPA provides reasonable performance at monthly scales, although it is shown to have precipitation rate-dependent low bias due to lack of sensitivity to low precipitation rates over ocean in one of the input products [based on Advanced Microwave Sounding Unit-B (AMSU-B)]. At finer scales the TMPA is successful at approximately reproducing the surface observation-based histogram of precipitation, as well as reasonably detecting large daily events. The TMPA, however, has lower skill in correctly specifying moderate and light event amounts on short time intervals, in common with other finescale estimators. Examples are provided of a flood event and diurnal cycle determination.

### 1. Introduction

Precipitation displays small-scale variability and highly nonnormal statistical behavior that requires frequent, closely spaced observations for adequate representation. Such observations are not possible through surface-based measurements over much of the globe, particularly in oceanic, remote, or developing regions. Consequently, researchers have come to depend on suites of sensors flying on a variety of satellites over the last 25+ years for the majority of the information used to estimate precipitation on a global basis. While it is possible to create such estimates solely from one type of sensor, researchers have increasingly moved to using combinations of sensors in an attempt to improve accuracy, coverage, and resolution. The first such combi-

nations were performed at a relatively coarse scale to ensure reasonable error characteristics. For example, the Global Precipitation Climatology Project (GPCP) satellite–gauge (SG) combination is computed on a monthly  $2.5^\circ \times 2.5^\circ$  latitude–longitude grid (Huffman et al. 1997; Adler et al. 2003). Subsequently, the scientific community requested that the estimates be made available at finer scale, even at the cost of higher uncertainties. Finer-scale products initiated by the GPCP include the Pentad (Xie et al. 2003) and One-Degree Daily (Huffman et al. 2001) combination estimates of precipitation. Other research groups have introduced a number of finescale estimates in the past several years that are now in quasi-operational production (see Huffman 2005), including the Climate Prediction Center (CFC) morphing algorithm (CMORPH; Joyce et al. 2004), the Naval Research Laboratory Global Blended-Statistical Precipitation Analysis (NRLgeo; Turk and Miller 2005), the Passive Microwave-Calibrated Infrared algorithm (PMIR; Kidd et al. 2003), and the Precipitation Estimation from Remotely Sensed Informa-

Corresponding author address: George J. Huffman, NASA GSFC, Code 613.1, Greenbelt, MD 20771.  
E-mail: huffman@agnes.gsfc.nasa.gov

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## Improving Simulations of Convective Systems from TRMM LBA: Easterly and Westerly Regimes

S. LANG,\* W.-K. TAO,+ R. CIFELLI,# W. OLSON,@ J. HALVERSON,@ S. RUTLEDGE,#  
AND J. SIMPSON+

\*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and Science Systems and Applications, Inc.,  
Lanham, Maryland

+Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland

#Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

@Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and Joint Center for Earth Systems Technology,  
University of Maryland, Baltimore County, Baltimore, Maryland

(Manuscript received 18 November 2005, in final form 13 July 2006)

### ABSTRACT

The 3D Goddard Cumulus Ensemble model is used to simulate two convective events observed during the Tropical Rainfall Measuring Mission Large-Scale Biosphere–Atmosphere (TRMM LBA) experiment in Brazil. These two events epitomized the type of convective systems that formed in two distinctly different environments observed during TRMM LBA. The 26 January 1999 squall line formed within a sheared low-level easterly wind flow. On 23 February 1999, convection developed in weak low-level westerly flow, resulting in weakly organized, less intense convection. Initial simulations captured the basic organization and intensity of each event. However, improvements to the model resolution and microphysics produced better simulations as compared to observations. More realistic diurnal convective growth was achieved by lowering the horizontal grid spacing from 1000 to 250 m. This produced a gradual transition from shallow to deep convection that occurred over a span of hours as opposed to an abrupt appearance of deep convection. Eliminating the dry growth of graupel in the bulk microphysics scheme effectively removed the unrealistic presence of high-density ice in the simulated anvil. However, comparisons with radar reflectivity data using contoured-frequency-with-altitude diagrams (CFADs) revealed that the resulting snow contents were too large. The excessive snow was reduced primarily by lowering the collection efficiency of cloud water by snow and resulted in further agreement with the radar observations. The transfer of cloud-sized particles to precipitation-sized ice appears to be too efficient in the original scheme. Overall, these changes to the microphysics lead to more realistic precipitation ice contents in the model. However, artifacts due to the inability of the one-moment scheme to allow for size sorting, such as excessive low-level rain evaporation, were also found but could not be resolved without moving to a two-moment or bin scheme. As a result, model rainfall histograms underestimated the occurrence of high rain rates compared to radar-based histograms. Nevertheless, the improved precipitation-sized ice signature in the model simulations should lead to better latent heating retrievals as a result of both better convective–stratiform separation within the model as well as more physically realistic hydrometeor structures for radiance calculations.

### 1. Introduction

Cloud models serve as a valuable tool for inferring information about clouds that cannot be directly measured such as latent heating (Tao et al. 1990, 1993b, 2000, 2001; Olson et al. 1999; Yang and Smith 1999a,b, 2000; Shige et al. 2004), budget sensitivities (Tao et al. 1993a), cloud–radiation interaction (Tao et al. 1996),

and remote sensing of precipitation (Szejwach et al. 1986; Mugnai et al. 1990, 1993; Adler et al. 1991; Smith et al. 1992, 1994; Kummerow et al. 1996; Panegrossi et al. 1998; Olson et al. 2006). Furthermore, these models provide a means to improve deficiencies in larger-scale models. A central objective of the Global Energy and Water-Cycle Experiment (GEWEX) Cloud System Study (GCSS) is to improve the parameterization of cloud systems in large-scale models by improving our understanding of cloud system processes using cloud-resolving models (CRMs; Moncrieff et al. 1997). It is imperative therefore that CRM results are carefully verified with observational data to ensure that the in-

Corresponding author address: Mr. Stephen Lang, Mesoscale Atmospheric Processes Branch, Code 613.1, NASA Goddard Space Flight Center, Greenbelt, MD 20771.  
E-mail: lang@agnes.gsfc.nasa.gov

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## Airborne validation of spatial properties measured by the CALIPSO lidar

Matthew J. McGill,<sup>1</sup> Mark A. Vaughan,<sup>2</sup> Charles R. Trepte,<sup>3</sup> William D. Hart,<sup>4</sup> Dennis L. Hlavka,<sup>4</sup> David M. Winker,<sup>3</sup> and Ralph Kuehn<sup>2</sup>

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[1] The Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite provides a new and exciting opportunity to study clouds and aerosols in the Earth's atmosphere using range-resolved laser remote sensing. Following the successful launch of the CALIPSO satellite, validation flights were conducted using the long-established Cloud Physics Lidar (CPL) to verify CALIPSO's calibration and validate various CALIPSO data products. This paper presents results of the initial comparisons made between the spaceborne CALIPSO lidar and the airborne CPL. Results are presented to validate measurement sensitivity and the spatial properties reported in the CALIPSO data products. Cloud layer top determinations from CALIPSO are found to be in good agreement with those from CPL. Determinations of minimum detectable backscatter are in excellent agreement with theoretical values predicted prior to launch.

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### 1. Introduction

[2] The successful launch of the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite in April 2006 ushered in a new era in satellite-based remote sensing [Winker *et al.*, 2003, 2007]. The primary payload aboard CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a dual wavelength, polarization-sensitive backscatter lidar that measures vertical profiles of the spatial and optical characteristics of clouds and aerosols in the Earth's atmosphere.

[3] The CALIPSO satellite is an important component of NASA's "A-train" constellation, which is a group of five formation-flying remote sensing satellites. The instruments in the A-Train were chosen to provide a comprehensive suite of measurements, both passive and active, to enable improved understanding of the Earth's atmosphere. The A-Train is named for the Aqua satellite [Parkinson, 2003] which leads the procession. Closely following Aqua are the CloudSat [Stephens *et al.*, 2002], CALIPSO, PARASOL [Steinmetz *et al.*, 2005], and Aura [Schoeberl *et al.*, 2006] satellites. The A-Train satellites fly in a 705-km Sun-synchronous orbit with a 1330 local time equatorial crossing time. With the simultaneous addition of CALIPSO and CloudSat, A-Train researchers will for the first time have access to a global suite of collocated vertical profile

measurements to augment the horizontal plane data acquired by existing passive sensors.

[4] The CALIPSO satellite became operational on 7 June 2006. While CALIPSO data will be a valuable source of research data, it is important that the CALIPSO measurements be validated so that the research community can use CALIPSO data with confidence. Accordingly, after initial data verification, aircraft flights were conducted to verify CALIPSO calibration and to validate the level 1 data products.

### 2. CALIPSO-CloudSat Validation Experiment (CC-VEX)

[5] During the period 26 July to 14 August 2006, the ER-2 Cloud Physics Lidar (CPL) [McGill *et al.*, 2002, 2003] was used for validation of the CALIPSO satellite lidar. The CPL provides high-resolution profiling of clouds and aerosol layers for use in cloud and radiation studies. The CPL is a state-of-the-art system operating at 1064 nm, 532 nm, and 355 nm, with linear depolarization measured using the 1064 nm channel. Measuring the backscattered signal at multiple wavelengths provides information about cloud and aerosol optical properties and the depolarization measurement can be used to determine the ice-water phase of clouds. The CPL provides data products similar to those of the CALIPSO satellite lidar and as such is an excellent CALIPSO simulator and validation tool.

[6] The high-altitude NASA ER-2 aircraft was used for the validation flights owing to its ability to fly above 20 km altitude and thereby provide "satellite-like" measurements. The flights were meant to simultaneously validate multiple aspects of the NASA A-Train of satellites, including the CloudSat radar. The payload for the CC-VEX mission included the CPL, the Cloud Radar System (CRS) [Li *et*

<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Science Systems and Applications, Inc., Hampton, Virginia, USA.

<sup>3</sup>NASA Langley Research Center, Hampton, Virginia, USA.

<sup>4</sup>Science Systems and Applications, Inc., Greenbelt, Maryland, USA.

## Cloud Resolving Modeling

Wei-Kuo TAO

*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.*

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### Abstract

One of the most promising methods to test the representation of cloud processes used in climate models is to use observations together with cloud resolving models (CRMs). CRMs use more sophisticated and realistic representations of cloud microphysical processes, and they can reasonably well resolve the time evolution, structure, and life cycles of clouds and cloud systems (with sizes ranging from about 2–200 km). CRMs also allow for explicit interaction between clouds, outgoing longwave (cooling) and incoming solar (heating) radiation, and ocean and land surface processes. Observations are required to initialize CRMs and to validate their results.

This paper provides a brief discussion and review of the main characteristics of CRMs as well as some of their major applications. These include the use of CRMs to improve our understanding of: (1) convective organization, (2) cloud temperature and water vapor budgets, and convective momentum transport, (3) diurnal variation of precipitation processes, (4) radiative-convective quasi-equilibrium states, (5) cloud-chemistry interaction, (6) aerosol-precipitation interaction, and (7) improving moist processes in large-scale models. In addition, current and future developments and applications of CRMs will be presented.

### 1. Introduction

Understanding the hydrological cycle is crucial in climate modeling and climate change. The hydrological cycle distinguishes the Earth from the other planets. A key link in the hydrological cycle is the rain that falls from clouds and cloud systems in the Tropics, which amounts to about two-thirds of the global precipitation. The vertical distribution of latent heat release by these clouds/convective systems can also modulate the large-scale tropical circulation (Hartmann et al. 1984; Sui and Lau 1989; and others), which, in turn, impacts midlatitude weather through teleconnection patterns such as those associated with El Niño. Furthermore, changes in the moisture distribution at

middle and upper levels of the troposphere as well as the radiative responses of cloud hydrometeors to outgoing longwave and incoming shortwave radiation are a major factor in determining whether the earth system will warm or cool as the cloud systems respond to changes in their environment (Ramanathan and Collins 1991; Lindzen 1990a, b; Betts 1990; Lau et al. 1993).

Cloud resolving models have been used to improve our understanding of cloud and precipitation processes and phenomena from micro-scale to cloud-scale and mesoscale as well as their interactions with radiation and surface processes. For example, cloud models have been used to study the mechanisms associated with cloud-cloud interactions and mergers (see Tao 2003 for a review), ice processes and their role in stratiform rain formation and their effect on cloud system mass, temperature and water vapor budgets (see Tao and Moncrieff 2003 for a review), precipitation efficiency (see Tao et

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Corresponding author: Wei-Kuo Tao, Code 613.1, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

E-mail: tao@agnes.gsfc.nasa.gov

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## Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations

Wei-Kuo Tao,<sup>1</sup> Xiaowen Li,<sup>1,2</sup> Alexander Khain,<sup>3</sup> Toshihisa Matsui,<sup>1,2</sup> Stephen Lang,<sup>4</sup> and Joanne Simpson<sup>1</sup>

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[1] A two-dimensional cloud-resolving model with detailed spectral bin microphysics is used to examine the effect of aerosols on three different deep convective cloud systems that developed in different geographic locations: south Florida, Oklahoma, and the central Pacific. A pair of model simulations, one with an idealized low cloud condensation nuclei (CCN) (clean) and one with an idealized high CCN (dirty environment), is conducted for each case. In all three cases, rain reaches the ground earlier for the low-CCN case. Rain suppression is also evident in all three cases with high CCN. However, this suppression only occurs during the early stages of the simulations. During the mature stages of the simulations the effects of increasing aerosol concentration range from rain suppression in the Oklahoma case to almost no effect in the Florida case to rain enhancement in the Pacific case. The model results suggest that evaporative cooling in the lower troposphere is a key process in determining whether high CCN reduces or enhances precipitation. Stronger evaporative cooling can produce a stronger cold pool and thus stronger low-level convergence through interactions with the low-level wind shear. Consequently, precipitation processes can be more vigorous. For example, the evaporative cooling is more than two times stronger in the lower troposphere with high CCN for the Pacific case. Sensitivity tests also suggest that ice processes are crucial for suppressing precipitation in the Oklahoma case with high CCN. A comparison and review of other modeling studies are also presented.

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### 1. Introduction

[2] Aerosols and especially their effect on clouds are one of the key components of the climate system and the hydrological cycle [Ramanathan *et al.*, 2001]. Yet, the aerosol effect on clouds remains largely unknown and the processes involved not well understood. A recent report published by the National Academy of Science states “The greatest uncertainty about the aerosol climate forcing—indeed, the largest of all the uncertainties about global climate forcing—is probably the indirect effect of aerosols on clouds” [National Research Council, 2005, p. 29]. The aerosol effect on clouds is often categorized into the traditional “first indirect (i.e., Twomey)” effect on the cloud droplet sizes for a constant liquid water

path [Twomey, 1977] and the “semidirect” effect on cloud coverage [e.g., Ackerman *et al.*, 2000]. Enhanced aerosol concentrations can also suppress warm rain processes by producing a narrow droplet spectrum that inhibits collision and coalescence processes [e.g., Squires and Twomey, 1960; Warner and Twomey, 1967; Warner, 1968; Rosenfeld, 1999].

[3] The aerosol effect on precipitation processes, also known as the second type of aerosol indirect effect [Albrecht, 1989], is even more complex, especially for mixed-phase convective clouds. A combination of cloud top temperature and effective droplet sizes, estimated from the Advanced Very High Resolution Radiometer (AVHRR), has been used to infer the suppression of coalescence and precipitation processes for smoke [Rosenfeld and Lensky, 1998] and desert dust [Rosenfeld *et al.*, 2001]. Multisensor (passive/active microwave and visible and infrared sensors) satellite observations from the Tropical Rainfall Measuring Mission (TRMM) have been used to infer the presence of nonprecipitating supercooled liquid water near the cloud top due to overseeding from both smoke over Indonesia [Rosenfeld, 1999] and urban pollution over Australia [Rosenfeld, 2000]. In addition, aircraft measurements have provided evidence of sustained supercooled liquid

<sup>1</sup>Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

<sup>3</sup>Department of Atmospheric Science, Hebrew University of Jerusalem, Jerusalem, Israel.

<sup>4</sup>Science Systems and Applications, Inc., Lanham, Maryland, USA.



## Properties of light stratiform rain derived from 10- and 94-GHz airborne Doppler radars measurements

Lin Tian,<sup>1,2</sup> Gerald M. Heymsfield,<sup>2</sup> Lihua Li,<sup>1,2</sup> and Ramesh C. Srivastava<sup>3</sup>

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[1] This paper presents an initial investigation of using airborne Doppler radar operating at 10 and 94 GHz to measure the light stratiform rain ( $\leq 5 \text{ mm hr}^{-1}$ ). It has been shown that the combination of 10 and 94 GHz is more sensitive to resolve the raindrop size distribution (RSD) in light rain than that of 14 and 35 GHz. A case of light stratiform rain over southern Florida is examined in detail in this study. Techniques for retrieving the profiles of a Gamma raindrop size distribution (RSD), vertical air velocity, and attenuation by precipitation and water vapor are presented. This approach uses the difference of the Doppler velocity at two frequencies and yields both RSD and the vertical air motion. The approach is primarily applicable to rain rates less than  $5 \text{ mm hr}^{-1}$ . The magnitudes of the retrieved RSD are similar to those found in ground-based observations of light stratiform rain. The retrieved vertical winds with downdrafts below about 3 km and weak updraft above are similar to what has been observed in widespread stratiform rain with melting band. The sensitivities of the retrieval to Gamma shape parameter are discussed.

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### 1. Introduction

[2] The vertical profiles of raindrop size distribution (RSD), vertical air velocity, precipitation, and water vapor distribution are important for studying the latent heating/cooling profile of precipitation yet are difficult to measure. Over the past several years, the Tropical Rainfall Measuring Mission (TRMM) [Kummerow *et al.*, 2000] has provided data for improving weather prediction and understanding precipitation structure and formation. Measurements by the single-wavelength TRMM precipitation radar (PR) have been used to estimate attenuation-corrected reflectivity and, from that, the rainfall rate [Iguchi *et al.*, 2000]. The data have also been used in conjunction with numerical cloud models to estimate latent heating/cooling [Tao *et al.*, 2000].

[3] One of the main uncertainties in estimating rainfall rate from the TRMM single-wavelength PR is the variability in the raindrop size distribution (RSD). A dual-wavelength radar, with a carefully selected frequency pair, can help to reduce this uncertainty. The upcoming Global Precipitation Measurement (GPM) dual-frequency radar (14 and 35 GHz) can provide RSD information and hence improve the accuracy of rainfall estimation. Many dual-frequency rain-profiling algorithms have been proposed to

date, starting with those developed by Eccles and Muller [1971], Fujita [1983], Meneghini *et al.* [1992], and Marzoug and Amayenc [1994]. These approaches start by assuming a two-parameter analytic RSD and proceed to develop a procedure to retrieve the parameters given the reflectivity profiles at the two frequencies. Doppler velocities are not considered in those approaches. At vertical incidence, the Doppler velocity is essentially due to the vertical air velocity and the fall velocity of the scattering particles. A number of investigators have shown that, under certain assumptions, the vertical air velocity and raindrop size distribution can be deduced from the mean Doppler velocity and reflectivity [e.g., Atlas and Matejka, 1985; Ulbrich, 1991]. Basic limitations of these methods are the errors incurred because of errors in deduced vertical winds and the effect of the turbulence. Meneghini *et al.* [2003] has explored the possibility of using the difference of Doppler velocities at 13.6 and 35 GHz, which is not affected by the vertical air motion, to improve the RSD estimation.

[4] In this study, we use a dual-frequency Doppler radar system operating at 10 and 94 GHz. In light rain, this system may resolve the RSD better than the GPM frequency pair because the difference in reflectivities at 14 and 35 GHz is small [Haddad *et al.*, 2006] compared to that at 10 and 94 GHz. Moreover, Doppler velocities measured by our system help to further resolve the RSD at vertical incidence. A disadvantage of the 94-GHz frequency is that it suffers greater attenuation than the GPM frequencies. This limits the 94 GHz system to light rain of intensity  $\leq 5 \text{ mm hr}^{-1}$ , but it would be capable of detecting much lighter rain (and high level ice clouds) than either the GPM or the TRMM radars. Moreover, light rain may have a greater impact on

<sup>1</sup>Goddard Earth Science and Technology Center, University of Maryland, Baltimore County, Maryland, USA.

<sup>2</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>3</sup>Department of the Geophysical Sciences, The University of Chicago, Chicago, Illinois, USA.

# Cloud Optical Depth Retrievals From Solar Background “Signals” of Micropulse Lidars

J. Christine Chiu, Alexander Marshak, Warren J. Wiscombe, Sandra C. Valencia, and E. Judd Welton

**Abstract**—Pulsed lidars are commonly used to retrieve vertical distributions of cloud and aerosol layers. It is widely believed that lidar cloud retrievals (other than cloud base altitude) are limited to optically thin clouds. Here, we demonstrate that lidars can retrieve optical depths of thick clouds using solar background light as a signal, rather than (as now) merely a noise to be subtracted. Validations against other instruments show that retrieved cloud optical depths agree within 10%–15% for overcast stratus and broken clouds. In fact, for broken cloud situations, one can retrieve not only the aerosol properties in clear-sky periods using lidar signals, but also the optical depth of thick clouds in cloudy periods using solar background signals. This indicates that, in general, it may be possible to retrieve both aerosol and cloud properties using a single lidar. Thus, lidar observations have great untapped potential to study interactions between clouds and aerosols.

**Index Terms**—Cloud, cloud–aerosol interactions, lidar, remote sensing, zenith radiance.

## I. INTRODUCTION

MICROPULSE lidar (MPLs) systems, developed in 1992 [1], are now widely used to retrieve heights of cloud layers and vertical distributions of aerosols layers [2], [3]. The MPL time-dependent returned signal is proportional to the amount of light backscattered by atmospheric molecules, aerosols, and clouds. However, measured photon counts must be converted to attenuated backscatter profiles, and during the process a number of noise sources need to be accounted for [4] and [5].

One source of noise is solar background light, which is measured by the MPL detector in addition to backscattered laser light. The MPL has a narrow field of view and filter bandwidth to reduce solar noise, but the contribution remains significant near solar noon or when a bright cloud is overhead. Fortunately, this noise can be estimated. Due to a time interval of 400  $\mu$ s between consecutive pulses, data can be retrieved up to a range of 60 km. However, there is no discernible

backscatter beyond 30 km. Therefore, we can estimate solar background light using sample bins between 45 and 55 km.

One man’s noise is another man’s signal. When lidars point straight up, the solar background noise is the solar zenith radiance, which can be used to retrieve cloud optical properties [6], [7]. We are unaware of any retrieval algorithm that uses the solar background light observed by lidars as a signal. This letter aims to address this issue by providing a proof-of-concept for using solar background “signal” from MPL to retrieve cloud optical depth. We will also evaluate results against those retrieved from other methods, and discuss the potential of our method to shed light on aerosol–cloud interactions.

## II. APPROACH

Solar background signal is estimated from lidar bins beyond 30 km in units of photon counts. For retrieval purposes, photon counts must be converted to actual radiance. This conversion is instrument-dependent. [8] described a laboratory calibration procedure capable of converting raw detector counts to calibrated radiance. The authors demonstrated that the calibrated MPL solar background radiance agreed with zenith radiance measurements from principal plane observations using a collocated AERONET sunphotometer [9]. Thus, it is possible to calibrate MPL systems using the collocated AERONET sunphotometers instead of the more time-consuming laboratory calibration. The sunphotometer calibration method would also account for MPL calibration drifts during the period of MPL deployment (due to filter degradation and window cleanliness). In this letter, we followed their method and derived MPL calibration coefficients using AERONET data when available.

MPLs of the atmospheric radiation measurement (ARM) program and of the NASA MPL Network (MPLNET [10]) both operate at a 523-nm wavelength. The general relationship between zenith radiance and cloud optical depth at this wavelength is depicted in Fig. 1, based on 1-D plane-parallel radiative transfer. Clearly, this relationship is not a one-to-one function. There are two cloud optical depths that give the same zenith radiance: one corresponds to thinner clouds and the other to thicker clouds. Thus, it is impossible to unambiguously retrieve cloud optical depth from solar background signal of a one-channel MPL. To remove this ambiguity, a criterion is needed to distinguish thick clouds from thin clouds or no clouds. A simple criterion adapted here assumes that if a lidar beam is completely attenuated, the detected clouds correspond to the larger optical depth.

Retrievals from MPL solar background signal are intercompared with those from three other instruments. The first instrument is the ARM multifilter rotating shadowband radiometer

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J. C. Chiu is with the Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD 21250 USA (e-mail: cchiu@climate.gsfc.nasa.gov).

A. Marshak, W. J. Wiscombe, and E. J. Welton are with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: Alexander.Marshak@nasa.gov; Warren.J.Wiscombe@nasa.gov; Ellsworth.J.Welton@nasa.gov).

S. C. Valencia was with Science, Systems, and Applications, Inc., Lanham, MD 20706 USA, and the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA. She is now with the London School of Economics and Political Science, WC2A 2AE London, U.K. (e-mail: s.c.valencia@lse.ac.uk).

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## Satellite-derived aerosol optical depth over dark water from MISR and MODIS: Comparisons with AERONET and implications for climatological studies

Ralph A. Kahn,<sup>1</sup> Michael J. Garay,<sup>1</sup> David L. Nelson,<sup>1</sup> Kevin K. Yau,<sup>1</sup> Michael A. Bull,<sup>1</sup> Barbara J. Gaitley,<sup>1</sup> John V. Martonchik,<sup>1</sup> and Robert C. Levy<sup>2</sup>

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[1] Although the current Multiangle Imaging Spectroradiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite passive remote sensing midvisible aerosol optical thickness (AOT) products are accurate overall to about 0.05 or 20%, they differ systematically on a global, monthly average basis, by about 0.03 to 0.05. Some key climate change and other applications require accuracies of 0.03 or better. The instruments are sufficiently stable and well characterized, and have adequate signal-to-noise, to realize such precision. However, assumptions made in the current standard aerosol retrieval algorithms produce AOT biases that must be addressed first. We identify the causes of AOT discrepancies over dark water under typical, relatively low AOT conditions and quantify their magnitudes on the basis of detailed analysis. Examples were selected to highlight key issues for which there are coincident MISR, MODIS, and Aerosol Robotic Network (AERONET) observations. Instrument calibration and sampling differences, assumptions made in the MISR and MODIS standard algorithms about ocean surface boundary conditions, missing particle property or mixture options, and the way reflectances used in the retrievals are selected each contribute significantly to the observed differences under some circumstances. Cloud screening is also identified as a factor, though not fully examined here, as are the relatively rare high-AOT cases over ocean. Specific algorithm upgrades and further studies indicated by these findings are discussed, along with recommendations for effectively using the currently available products for regional and global applications.

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### 1. Introduction

[2] The Multiangle Imaging Spectroradiometer (MISR) [Diner *et al.*, 1998] began taking data in late February 2000. Since then, numerous studies have compared aerosol optical thickness (AOT) retrieved from the instrument's 36 spectral angular channels with similar quantities derived from the Aerosol Robotic Network (AERONET) [Holben *et al.*, 1998] Sun photometer network, the Moderate Resolution Imaging Spectroradiometer (MODIS) [Barnes *et al.*, 1998; Salomonson *et al.*, 1989] that flies aboard the Terra satellite with MISR, and other regional and global observations [e.g., Abdou *et al.*, 2005; Christopher and Wang, 2004; Diner *et al.*, 2001; Kahn *et al.*, 2005a, 2005b; Liu *et al.*, 2004; Martonchik *et al.*, 2004; Myhre *et al.*, 2005; Redemann *et al.*, 2005; Schmid *et al.*, 2003; Yu *et al.*, 2006].

That work demonstrates the MISR Standard Aerosol Retrieval algorithm (V16 or lower) retrieves AOT over land and water, with overall statistical accuracy better than 0.05 or 20%, whichever is larger, and with greater accuracy over some surfaces such as dark water. Similar results are reported for MODIS-AERONET AOT comparisons [Remer *et al.*, 2005; Levy *et al.*, 2003, 2005; Chu *et al.*, 2002; L. A. Remer *et al.*, 2006, Algorithm for remote sensing of tropospheric aerosol from MODIS: Collection 5, available at [http://modis-atmos.gsfc.nasa.gov/reference\\_atbd.php](http://modis-atmos.gsfc.nasa.gov/reference_atbd.php); hereinafter referred to as Remer *et al.*, 2006].

[3] However, some blunders occur, often because of inadequate cloud screening or inaccurate surface property assumptions, and persistent small but systematic differences between MISR and MODIS AOT values can be significant when large aggregates of measurements from the two instruments are compared. MODIS produces generally higher midvisible AOT than MISR and AERONET over land, whereas MISR AOT is generally higher than MODIS over water [e.g., Abdou *et al.*, 2005; Myhre *et al.*, 2005]. Recent improvements in MISR band-to-band and camera-to-camera calibration have reduced average MISR-

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

<sup>2</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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## Remote sensing the vertical profile of cloud droplet effective radius, thermodynamic phase, and temperature

J. Vanderlei Martins<sup>1,2</sup>, A. Marshak<sup>2</sup>, L. A. Remer<sup>2</sup>, D. Rosenfeld<sup>3</sup>,  
Y. J. Kaufman<sup>2</sup>, R. Fernandez-Borda<sup>4</sup>, I. Koren<sup>5</sup>, V. Zubko<sup>6</sup>, and P. Artaxo<sup>7</sup>

<sup>1</sup>Department of Physics, and Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD, USA

<sup>2</sup>Climate and Radiation Branch, NASA – Goddard Space Flight Center, Greenbelt, MD, USA

<sup>3</sup>Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel

<sup>4</sup>Catholic University, Washington DC, USA

<sup>5</sup>Department of Environmental Sciences, Weizmann Institute, Rehovot, Israel

<sup>6</sup>Advanced Computation Technologies, Inc., Lanham, MD, USA

<sup>7</sup>Institute of Physics, University of Sao Paulo, Brazil

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Correspondence to: J. Vanderlei Martins (martins@climate.gsfc.nasa.gov)

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### Abstract

Cloud-aerosol interaction is no longer simply a radiative problem, but one affecting the water cycle, the weather, and the total energy balance including the spatial and temporal distribution of latent heat release. Information on the vertical distribution of cloud droplet microphysics and thermodynamic phase as a function of temperature or height, can be correlated with details of the aerosol field to provide insight on how these particles are affecting cloud properties and its consequences to cloud lifetime, precipitation, water cycle, and general energy balance. Unfortunately, today's experimental methods still lack the observational tools that can characterize the true evolution of the cloud microphysical, spatial and temporal structure in the cloud droplet scale, and then link these characteristics to environmental factors and properties of the cloud condensation nuclei.

Here we propose and demonstrate a new experimental approach (the cloud scanner instrument) that provides the microphysical information missed in current experiments and remote sensing options. Cloud scanner measurements can be performed from aircraft, ground, or satellite by scanning the side of the clouds from the base to the top, providing us with the unique opportunity of obtaining snapshots of the cloud droplet microphysical and thermodynamic states as a function of height and brightness temperature in clouds at several development stages. The brightness temperature profile of the cloud side can be directly associated with the thermodynamic phase of the droplets to provide information on the glaciation temperature as a function of different ambient conditions, aerosol concentration, and type. An aircraft prototype of the cloud scanner was built and flew in a field campaign in Brazil.

The CLAIM-3D (3-Dimensional Cloud Aerosol Interaction Mission) satellite concept proposed here combines several techniques to simultaneously measure the vertical profile of cloud microphysics, thermodynamic phase, brightness temperature, and aerosol amount and type in the neighborhood of the clouds. The wide wavelength range, and the use of multi-angle polarization measurements proposed for this mis-

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## The Plane-Parallel Albedo Bias of Liquid Clouds from MODIS Observations

LAZAROS OREOPOULOS

*Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, and Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland*

ROBERT F. CAHALAN AND STEVEN PLATNICK

*Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland*

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### ABSTRACT

The authors present the global plane-parallel shortwave albedo bias of liquid clouds for two months, July 2003 and January 2004. The cloud optical properties necessary to perform the bias calculations come from the operational Moderate Resolution Imaging Spectroradiometer (MODIS) *Terra* and MODIS *Aqua* level-3 datasets. These data, along with ancillary surface albedo and atmospheric information consistent with the MODIS retrievals, are inserted into a broadband shortwave radiative transfer model to calculate the fluxes at the atmospheric column boundaries. The plane-parallel homogeneous (PPH) calculations are based on the mean cloud properties, while independent column approximation (ICA) calculations are based either on 1D histograms of optical thickness or joint 2D histograms of optical thickness and effective radius. The (positive) PPH albedo bias is simply the difference between PPH and ICA albedo calculations. Two types of biases are therefore examined: 1) the bias due to the horizontal inhomogeneity of optical thickness alone (the effective radius is set to the grid mean value) and 2) the bias due to simultaneous variations of optical thickness and effective radius as derived from their joint histograms. The authors find that the global bias of albedo (liquid cloud portion of the grid boxes only) is  $\sim +0.03$ , which corresponds to roughly 8% of the global liquid cloud albedo and is only modestly sensitive to the inclusion of horizontal effective radius variability and time of day, but depends strongly on season and latitude. This albedo bias translates to  $\sim -3$ – $-3.5$   $\text{W m}^{-2}$  of bias (stronger negative values) in the diurnally averaged global shortwave cloud radiative forcing, assuming homogeneous conditions for the fraction of the grid box not covered by liquid clouds; zonal values can be as high as  $8 \text{ W m}^{-2}$ . Finally, the (positive) broadband atmospheric absorptance bias is about an order of magnitude smaller than the albedo bias. The substantial magnitude of the PPH bias underlines the importance of predicting subgrid variability in GCMs and accounting for its effects on cloud–radiation interactions.

### 1. Introduction

The bias in solar radiative fluxes within a model or other large-scale grid due to the assumption of horizontal homogeneity in cloud optical thickness  $\tau$  [plane-parallel homogeneous (PPH) bias] received a great amount of attention following the publication of the study by Cahalan et al. (1994), but its existence and potential importance had already emerged in earlier publications (Harshvardhan and Randall 1985; Stephens 1988). Cahalan et al. provided a theoretical framework

for studying the PPH bias by using a fractal cloud model but restricted the quantitative analysis of cloud inhomogeneity on marine stratocumulus clouds with properties derived from surface microwave radiometer observations. Cloud microphysics (i.e., droplet effective radius  $r_e$ ) was assumed constant ( $r_e = 10 \mu\text{m}$ ), surface and atmospheric effects were neglected, and the radiative transfer did not extend beyond monochromatic calculations. For typical marine stratocumulus observed during the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE), Cahalan et al. found a value of  $\sim +0.09$  as representative of the PPH albedo bias at visible wavelengths. Subsequent observationally based work (Barker 1996; Oreopoulos and Davies 1998; Pincus et al. 1999; Ros-

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*Corresponding author address:* Lazaros Oreopoulos, NASA Goddard Space Flight Center, Code 613.2, Greenbelt, MD 20771.  
E-mail: lazarus@climate.gsfc.nasa.gov



## Potential for airborne offbeam lidar measurements of snow and sea ice thickness

Tamás Várnai<sup>1</sup> and Robert F. Cahalan<sup>2</sup>

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[1] This article discusses the capabilities and limitations of a new approach to airborne measurements of snow and sea ice thickness. Such measurements can help better understand snow and sea ice processes and can also contribute to the validation of satellite measurements. The approach discussed here determines physical snow and sea ice thickness by observing the horizontal spread of lidar pulses: The bright halo observed around an illuminated spot extends farther out in thicker layers because photons can travel longer without escaping through the bottom. Since earlier studies suggested the possibility of such sea ice retrievals, this article presents a theoretical analysis of additional uncertainties that arise in airborne observations of snow and sea ice. Snow and sea ice retrievals pose somewhat different challenges because while sea ice is usually much thicker, snow contains a much higher concentration of scatterers. As a result, sea ice halos are larger, but snow halos are brighter. The results indicate that airborne sea ice retrievals are possible at night and that snow retrievals are possible during both night and day. For snow thicknesses less than about 50 cm, observational issues, such as calibration uncertainty, can cause retrieval uncertainties on the order of 10% in 1-km-resolution retrievals. For moderate snow and sea ice thicknesses (<30 cm and 3 m, respectively), these issues cause similar (~10%) uncertainties in sea ice thickness retrievals as well. These results indicate that offbeam lidars have the potential to become an important component of future snow and sea ice observing systems.

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### 1. Introduction

[2] Snow and sea ice thicknesses are not only indicators of the growth and melt of snow cover and sea ice, but they also influence surface fluxes of heat, radiation, and momentum. Yet, snow and sea ice thicknesses are among the least known parameters of the cryosphere. The pressing need for large-scale measurements of these parameters spurred the development of a variety of remote sensing methods. For example, sea ice thickness is often estimated using freeboard altimetry based on lidar or radar observations [e.g., Comiso *et al.*, 1991; Wadhams *et al.*, 1991; Laxon *et al.*, 2003] or using ice classification based on synthetic aperture radar (SAR) data [e.g., Steffen and Heinrichs, 2001; Kwok and Cunningham, 2002], whereas snow thickness is often estimated from passive microwave observations [e.g., Markus and Cavalieri, 1998; Kelly *et al.*, 2003]. These measurements provided numerous important insights but remain affected by substantial uncertainties. For example, freeboard sea ice measurements suffer from the lack of

direct information on snow thickness and from uncertainties in sea level and instrument altitude, whereas microwave snow measurements are affected by calibration uncertainties and surface roughness [e.g., Kwok *et al.*, 2004; Powell *et al.*, 2006; Stroeve *et al.*, 2006]. This article examines the feasibility of a new approach that uses offbeam lidar data for simultaneous measurements of snow and sea ice thickness.

[3] As illustrated in Figure 1, offbeam lidars detect diffuse return signals from several annular rings. These instruments determine the thickness of highly opaque media by observing the horizontal spread of lidar pulses: The bright halo observed around the illuminated spot extends farther out in thicker layers, because photons can travel farther without escaping through the bottom [e.g., Voss and Schoonmaker, 1992; Davis *et al.*, 1997; Davis and Marshak, 2002] (Figure 2). This measurement approach was used in several disciplines, providing thickness measurements for media as diverse as tooth enamel and thick clouds [e.g., Groenhius *et al.*, 1983; Cahalan *et al.*, 2005a; Polonsky *et al.*, 2005]. Moreover, results from ground-based experiments of Haines *et al.* [1997, Table 1] suggest to us that this approach can provide accurate thickness measurements for sea ice as well. (In these ground-based experiments ice thickness and extinction coefficient were obtained using data from a light detector that moved around a lamp illuminating the ice at a single point.) This article examines

<sup>1</sup>Joint Center for Earth System Technology, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

<sup>2</sup>Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.



### 3-D aerosol-cloud radiative interaction observed in collocated MODIS and ASTER images of cumulus cloud fields

Guoyong Wen,<sup>1,2</sup> Alexander Marshak,<sup>1</sup> Robert F. Cahalan,<sup>1</sup> Lorraine A. Remer,<sup>1</sup> and Richard G. Kleidman<sup>3</sup>

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[1] Three-dimensional (3-D) aerosol-cloud interaction is examined by analyzing two images containing cumulus clouds in biomass-burning regions in Brazil. The research consists of two parts. The first part focuses on identifying 3-D cloud impacts on reflectances for the pixels selected for the MODIS aerosol retrieval based purely on observations. The second part of the research combines the observations with radiative transfer computations to identify key parameters in the 3-D aerosol-cloud interaction. We find that 3-D cloud-induced enhancement depends on the optical properties of nearby clouds as well as on wavelength. The enhancement is too large to be ignored. Associated bias error in one-dimensional (1-D) aerosol optical thickness retrieval ranges from 50 to 140% depending on wavelength and the optical depth of nearby clouds, as well as aerosol optical thickness. We caution the community to be prudent when applying 1-D approximations in computing solar radiation in clear regions adjacent to clouds or when using traditional retrieved aerosol optical thickness in aerosol indirect effect research.

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#### 1. Introduction

[2] Aerosols play a critical role in the process of cloud formation. A change in aerosol properties may directly impact atmospheric radiation and also lead to a change in the microphysical and radiative properties of clouds and thus directly and indirectly influence the Earth's climate. Analyzing AERONET [see Holben *et al.*, 1998] ground-based network data, Kaufman and Koren [2006] recently found that absorbing and nonabsorbing aerosols affect cloud cover differently. While absorbing aerosols prevent clouds from forming, nonabsorbing aerosols extend cloud life times and are associated with enhanced cloud cover. This complements the fundamental theory of Twomey [1977] that ties an increase of anthropogenic aerosol to possible consequences to global climate change. An example of an application of this theory is the modification of cloud properties through a change in cloud condensation nuclei (CCN) in ship tracks observed from space [Platnick *et al.*, 2000; Coakley *et al.*, 1987]. However, assessing and quantifying the indirect effect of aerosol on cloud properties and climate on global scale still remains a great challenge. The

radiative forcing of aerosol indirect effect on climate has been identified as the most uncertain among other radiative forcing factors [Intergovernmental Panel on Climate Change, 2001]. For example, the effect of aerosols on cloud albedo has a large range of uncertainties estimated as cooling between  $-2$  and  $0$  W/m<sup>2</sup>. The level of scientific understanding of aerosol indirect effect is categorized as "very low." Global observation of aerosol and cloud properties from satellite is one way to advance our understanding of aerosol indirect effect on the Earth's climate and to reduce its uncertainties.

[3] However, aerosol and cloud properties inferred from satellite observations are subject to uncertainties. This is partly because cloud and aerosol properties are derived from the satellite-observed reflected solar radiation on the basis of various assumptions about the Earth's surface, atmosphere, aerosols, and clouds. For operational purpose, the atmosphere, aerosols, and clouds are usually assumed to be horizontally homogeneous and plane parallel, which is called the 1-D approximation or plane-parallel approximation (PPA). In this approximation, it is assumed that radiative properties of an individual pixel are independent of its neighbors. Many studies have shown that 3-D cloud structure has a complicated impact on the retrievals of cloud properties [e.g., Chambers *et al.*, 1997; Várnai and Marshak, 2002; Iwabuchi and Hayasaka, 2003; Horváth and Davies, 2004; Marshak *et al.*, 2006]. In this study, we focus on how 3-D cloud structure affects reflectance in the clear region near clouds and what are the consequences of this enhanced reflectance on aerosol retrievals.

<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore County, Maryland, USA.

<sup>3</sup>Science Systems and Applications, Inc., Lanham, Maryland, USA.

## The Frequency of Extreme Rain Events in Satellite Rain-Rate Estimates and an Atmospheric General Circulation Model

ERIC M. WILCOX\*

*Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey*

LEO J. DONNER

*NOAA/Geophysical Fluid Dynamics Laboratory, Princeton University, Princeton, New Jersey*

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### ABSTRACT

The frequency distributions of surface rain rate are evaluated in the Tropical Rainfall Measuring Mission (TRMM) and Special Sensor Microwave/Imager (SSM/I) satellite observations and the NOAA/GFDL global atmosphere model version 2 (AM2). Instantaneous satellite rain-rate observations averaged over the  $2.5^\circ$  latitude  $\times$   $2^\circ$  longitude model grid are shown to be representative of the half-hour rain rate from single time steps simulated by the model. Rain-rate events exceeding  $10 \text{ mm h}^{-1}$  are observed by satellites in most regions, with  $1 \text{ mm h}^{-1}$  events occurring more than two orders of magnitude more frequently than  $10 \text{ mm h}^{-1}$  events. A model simulation using the relaxed Arakawa-Schubert (RAS) formulation of cumulus convection exhibits a strong bias toward many more light rain events compared to the observations and far too few heavy rain events. A simulation using an alternative convection scheme, which includes an explicit representation of mesoscale circulations and an alternative formulation of the closure, exhibits, among other differences, an order of magnitude more tropical rain events above the  $5 \text{ mm h}^{-1}$  rate compared to the RAS simulation. This simulation demonstrates that global atmospheric models can be made to produce heavy rain events, in some cases even exceeding the observed frequency of such events. Additional simulations reveal that the frequency distribution of the surface rain rate in the GCM is shaped by a variety of components within the convection parameterization, including the closure, convective triggers, the spectrum of convective and mesoscale clouds, and other parameters whose physical basis is currently only understood to a limited extent. Furthermore, these components interact nonlinearly such that the sensitivity of the rain-rate distribution to the formulation of one component may depend on the formulation of the others. Two simulations using different convection parameterizations are performed using perturbed sea surface temperatures as a surrogate for greenhouse gas-forced climate warming. Changes in the frequency of rain events greater than  $2 \text{ mm h}^{-1}$  associated with changing the convection scheme in the model are greater than the changes in the frequency of heavy rain events associated with a 2-K warming using either model. Thus, uncertainty persists with respect to simulating intensity distributions for precipitation and projecting their future changes. Improving the representation of the frequency distribution of rain rates will rely on refinements in the formulation of cumulus closure and the other components of convection schemes, and greater certainty in predictions of future changes in both total rainfall and in rain-rate distributions will require additional refinements in those parameterizations that determine the cloud and water vapor feedbacks.

### 1. Introduction

An increase in the frequency of heavy rain events is one expected consequence of climate change associated

with increasing greenhouse gas concentrations in the atmosphere. Such a change may be expected based on simple theoretical arguments, which are now being tested in global climate model simulations of increasing greenhouse gas concentration scenarios. Many of the processes leading to precipitation, however, are not well resolved in coarse-resolution models used for global climate change prediction. As a result, the intensity of simulated rainfall events may depend strongly on the formulation of various parameterizations designed to estimate the bulk effects of subgrid-scale processes on

\* Current affiliation: NASA Goddard Space Flight Center, Greenbelt, Maryland.

Corresponding author address: Eric Wilcox, NASA Goddard Space Flight Center, Code 613.2, Greenbelt, MD 20771.  
E-mail: eric.m.wilcox@nasa.gov

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## Use of High-Resolution Satellite Observations to Evaluate Cloud and Precipitation Statistics from Cloud-Resolving Model Simulations. Part I: South China Sea Monsoon Experiment

Y. P. ZHOU,\* W.-K. TAO,<sup>+</sup> A. Y. HOU,<sup>+</sup> W. S. OLSON,<sup>#</sup> C.-L. SHIE,\* K.-M. LAU,<sup>+</sup> M.-D. CHOU,<sup>@</sup>  
X. LIN,\* AND M. GRECU\*

\*Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland

<sup>+</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland

<sup>#</sup>Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, Maryland

<sup>@</sup>National Taiwan University, Taipei, Taiwan

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### ABSTRACT

Cloud and precipitation simulated using the three-dimensional (3D) Goddard Cumulus Ensemble (GCE) model are compared to Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Precipitation Radar (PR) rainfall measurements and Clouds and the Earth's Radiant Energy System (CERES) single scanner footprint (SSF) radiation and cloud retrievals. Both the model simulation and retrieved parameters are based upon observations made during the South China Sea Monsoon Experiment (SCSMEX) field campaign. The model-simulated cloud and rain systems are evaluated by systematically examining important parameters such as the surface rain rate, convective/stratiform percentage, rain profiles, cloud properties, and precipitation efficiency.

It is demonstrated that the GCE model is capable of simulating major convective system development and reproduces the total surface rainfall amount as compared to rainfall estimated from the SCSMEX sounding network. The model yields a slightly higher total convective rain/stratiform rain ratio than the TMI and PR observations. The GCE rainfall spectrum exhibits a greater contribution from heavy rains than those estimated from PR or TMI observations. In addition, the GCE simulation produces much greater amounts of snow and graupel than the TRMM retrievals. The model's precipitation efficiency of convective rain is close to the observations, but the precipitation efficiency of stratiform rain is much lower than the observations because of large amounts of slowly falling simulated snow and graupel. Compared to observations, the GCE produces more compact areas of intense convection and less anvil cloud, which are consistent with a smaller total cloud fraction and larger domain-averaged outgoing longwave radiation.

### 1. Introduction

Clouds and precipitation play key roles in linking the earth's energy cycle and water cycles. Clouds modulate the incoming solar radiation through reflection and the outgoing longwave radiation by altering the effective emitting temperature. Cloud itself is an important component of the hydrological cycle. Precipitation starts with cloud formation and through condensation and latent heat release it connects both the energy and water cycles. The sensitivity of deep convective cloud systems and their associated precipitation efficiency in re-

sponse to climate change are key factors in predicting the future climate.

Components of the space-based Earth Observing System (EOS), such as the National Aeronautics and Space Administration's (NASA) Clouds and the Earth's Radiant Energy System (CERES) experiment (Wielicki et al. 1996) and the Tropical Rainfall Measuring Mission (TRMM; Simpson et al. 1988, 1996) are designed to provide crucial cloud and precipitation measurements for advancing our understanding of the role of clouds and precipitation in the global energy and water cycles, and for improving their representation in general circulation and climate models. The CERES products include broadband shortwave and longwave radiation from the top of the atmosphere, as well as simultaneous cloud properties retrieved from the other

Corresponding author address: Dr. Yaping Zhou, NASA Goddard Space Flight Center, Mail Code 613.2, Greenbelt, MD 20771.  
E-mail: yaping.zhou-1@nasa.gov



## Sulfur dioxide emissions from Peruvian copper smelters detected by the Ozone Monitoring Instrument

S. A. Carn,<sup>1</sup> A. J. Krueger,<sup>1</sup> N. A. Krotkov,<sup>2</sup> K. Yang,<sup>2</sup> and P. F. Levelt<sup>3</sup>

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[1] We report the first daily observations of sulfur dioxide (SO<sub>2</sub>) emissions from copper smelters by a satellite-borne sensor - the Ozone Monitoring Instrument (OMI) on NASA's EOS/Aura spacecraft. Emissions from two Peruvian smelters (La Oroya and Ilo) were detected in up to 80% of OMI overpasses between September 2004 and June 2005. SO<sub>2</sub> production by each smelter in this period is assessed and compared with contemporaneous emissions from active volcanoes in Ecuador and southern Colombia. Annual SO<sub>2</sub> discharge from the Ilo smelter, La Oroya smelter, and volcanoes in 2004–2005 is estimated and amounts to  $0.3^{+0.2}_{-0.1}$ ,  $0.07 \pm 0.03$ , and  $1.2 \pm 0.5$  Tg, respectively. This study confirms OMI's potential as an effective tool for evaluation of anthropogenic and natural SO<sub>2</sub> emissions. Smelter plumes transport an array of toxic metals in addition to SO<sub>2</sub> and continued monitoring to mitigate health and environmental impacts is recommended.

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### 1. Introduction

[2] Anthropogenic activities over the last century (mainly fossil fuel burning and metal smelting) have raised atmospheric SO<sub>2</sub> concentrations by up to 3 orders of magnitude [Pham *et al.*, 1996]. Of potentially greater significance is the concomitant increase in production of derived sulfate aerosol, which indirectly affects the climate system and water cycle by supplying cloud condensation nuclei, enhancing cloud albedo, and suppressing precipitation [Twomey, 1977; Charlson *et al.*, 1992; Rosenfeld, 2000]. An inventory of anthropogenic SO<sub>2</sub> source strengths is therefore a crucial component of global atmospheric models, but to date emissions from major source regions such as East Asia have typically been estimated using complex algorithms that rely on large input datasets, enumerating parameters such as fuel use and the removal efficiency of emission abatement systems [e.g., Streets *et al.*, 2003].

[3] As a viable alternative to these “bottom-up” estimates of emissions, the ultraviolet (UV) GOME and SCIAMACHY satellite sensors have demonstrated that anthropogenic SO<sub>2</sub> emissions can be detected from space

[e.g., Eisinger and Burrows, 1998]. However, the efficacy of GOME and SCIAMACHY data for detailed studies of SO<sub>2</sub> emissions is restricted by poor spatial or temporal sampling. On July 15, 2004, NASA launched the Ozone Monitoring Instrument (OMI) as part of the EOS-Aura mission (<http://aura.gsfc.nasa.gov>). OMI has a unique combination of footprint size ( $13 \times 24$  km at nadir), spectral resolution (0.45 nm) and global contiguous coverage for space-based UV measurements of SO<sub>2</sub>, surpassing the sensitivity of the Earth Probe Total Ozone Mapping Spectrometer (EP-TOMS), which could only detect anthropogenic SO<sub>2</sub> emissions when atmospheric loadings were exceptional [Carn *et al.*, 2004]. Using algorithms developed for retrieval of SO<sub>2</sub> from OMI, the noise level of SO<sub>2</sub> measurements has been reduced by an order of magnitude compared to the TOMS instruments [Krotkov *et al.*, 2006]. As we demonstrate here, these improvements permit detection of SO<sub>2</sub> discharge from specific industrial sources on a daily basis.

### 2. OMI Instrument and SO<sub>2</sub> Algorithm

[4] OMI is a hyperspectral UV/Visible spectrometer with a 2600 km swath for daily, contiguous global mapping of ozone and trace gases including SO<sub>2</sub>, NO<sub>2</sub> and BrO. It was contributed to the 6-year Aura mission by the Royal Netherlands Meteorological Institute (KNMI) and the Netherlands Agency for Aerospace Programs (NIVR), in collaboration with the Finnish Meteorological Institute (FMI). Operational data flow from OMI began in September 2004. The Aura spacecraft is in a sun-synchronous orbit at 705 km altitude and crosses the equator at 1:45 pm  $\pm$  15 minutes local time each day (ascending node).

[5] Most OMI data products are currently produced using radiances at a subset of UV wavelengths calibrated with post-launch data. We have developed a scheme termed the Band Residual Difference (BRD) algorithm, which retrieves total column SO<sub>2</sub> using four OMI wavelengths situated at SO<sub>2</sub> band extrema between 310.8 and 314.4 nm [Krotkov *et al.*, 2006]. As described above, the BRD retrieval noise is an order of magnitude lower than achieved with EP-TOMS, permitting detection of weaker SO<sub>2</sub> sources and smaller SO<sub>2</sub> clouds with OMI. We have also developed time-averaging techniques which further improve the signal to noise ratio. All SO<sub>2</sub> data in this paper were produced using the BRD algorithm, the derivation of which is described by Krotkov *et al.* [2006].

[6] We caution that OMI SO<sub>2</sub> algorithms are subject to ongoing development and refinement, and that OMI SO<sub>2</sub> data have not yet been rigorously validated using correlative measurements. Retrieval of anthropogenic SO<sub>2</sub> in the planetary boundary layer (PBL) is particularly challenging due

<sup>1</sup>Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, Maryland, USA.

<sup>2</sup>Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore, Maryland, USA.

<sup>3</sup>Royal Netherlands Meteorological Institute, De Bilt, Netherlands.



## Effects of the 2004 El Niño on tropospheric ozone and water vapor

S. Chandra,<sup>1,2</sup> J. R. Ziemke,<sup>1,2</sup> M. R. Schoeberl,<sup>3</sup> L. Froidevaux,<sup>4</sup> W. G. Read,<sup>4</sup> P. F. Levelt,<sup>5</sup> and P. K. Bhartia<sup>3</sup>

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[1] The global effects of the 2004 El Niño on tropospheric ozone and H<sub>2</sub>O based on Aura OMI and MLS measurements are analyzed. Although it was a weak El Niño from a historical perspective, it produced significant changes in these parameters in tropical latitudes. Tropospheric ozone increased by 10–20% over most of the western Pacific region and decreased by about the same amount over the eastern Pacific region. H<sub>2</sub>O in the upper troposphere showed similar changes but with opposite sign. These zonal changes in tropospheric ozone and H<sub>2</sub>O are caused by the eastward shift in the Walker circulation in the tropical Pacific region during El Niño. During the 2004 El Niño, biomass burning did not have a significant effect on the ozone budget in the troposphere, unlike the 1997 El Niño. Zonally averaged tropospheric column ozone did not change significantly either globally or over tropical latitudes. **Citation:** Chandra, S., J. R. Ziemke, M. R. Schoeberl, L. Froidevaux, W. G. Read, P. F. Levelt, and P. K. Bhartia (2007), Effects of the 2004 El Niño on tropospheric ozone and water vapor, *Geophys. Res. Lett.*, *34*, L06802, doi:10.1029/2006GL028779.

### 1. Introduction

[2] Ziemke and Chandra [2003] have shown that El Niño and La Niña events are major sources of decadal variability in tropospheric O<sub>3</sub> in the tropical atmosphere. These events produce changes in the convection pattern and large-scale circulation in the tropical Pacific region causing tropospheric column ozone (TCO) to vary from the western to the eastern Pacific with a sign change near the dateline. During El Niño, TCO is enhanced over the Indonesian region and reduced over the eastern Pacific. La Niña generally produces the opposite effect. One of the most intense El Niño events on record occurred during 1997 which caused a major perturbation in the ocean-atmosphere system including a drought and large-scale forest fires in the Indonesian region. The effects of the 1997 El Niño on tropospheric O<sub>3</sub> in the tropics have been extensively studied from both satellite and ground based measurements [e.g., Chandra *et al.*, 1998, 2002; Fujiwara *et al.*, 1999; Thompson *et al.*, 2001] and are, generally, well simulated by global models of

atmospheric chemistry and transport [e.g., Sudo and Takahashi, 2001; Chandra *et al.*, 2002; Peters *et al.*, 2001, Zeng and Pyle, 2005, Doherty *et al.*, 2006]. The study of El Niño and La Niña related changes in tropospheric O<sub>3</sub> has been generally limited to the tropical region because global measurements of tropospheric O<sub>3</sub> outside the tropics were not available. A number of studies have suggested that El Niño has significant influence on the inter-annual variation of stratosphere-troposphere exchange (STE) which affects tropospheric O<sub>3</sub> outside the tropics [Langford *et al.*, 1998; James *et al.*, 2003; Zeng and Pyle, 2005].

[3] Recently, Ziemke *et al.* [2006] produced global maps of TCO from the Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) measurements beginning August 2004. TCO is determined using the tropospheric O<sub>3</sub> residual method which involves subtracting stratospheric column ozone (SCO) from total column ozone measured from MLS and OMI instruments. There was an El Niño event during the latter part of 2004. Even though this event was weak by historical standards, it provides an opportunity to study the possible effects of El Niño on tropospheric O<sub>3</sub> outside the tropical region. The purpose of this paper is to study global effects of the 2004 El Niño on tropospheric O<sub>3</sub> derived from the OMI/MLS instruments on the Aura Satellite. This study combines tropospheric O<sub>3</sub> measurements with H<sub>2</sub>O measurements from the MLS instrument on the same satellite. Like O<sub>3</sub>, H<sub>2</sub>O is affected by deep tropical convection and large-scale transport processes. During 1997, El Niño-related changes in tropospheric O<sub>3</sub> and upper troposphere (UT) H<sub>2</sub>O were anti-correlated over most of the tropical region [Chandra *et al.*, 1998].

### 2. The 2004 El Niño Event

[4] According to the World Meteorological Organization (WMO) criterion (available at <http://www.nws.noaa.gov/ost/climate/STIP/ElNinoDef.htm>), an El Niño event occurs when the sea surface temperature (SST) in the Niño 3.4 region (a rectangular region covering longitudes 120°W–170°W and latitudes 5°S–5°N) is at least 0.5°C above normal when averaged over three consecutive months. Using this criterion, the last six months of 2004 may be categorized as El Niño months. The mean values of SST in these months were 0.7°C to 0.9°C higher with respect to 1971–2000 base periods (available at [http://www.cpc.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml)). The SST values are lower compared to the 2002 El Niño and significantly lower compared to the 1997 El Niño. For example, the mean SST anomalies ( $\Delta$ SST) for November and December 2004 were respectively 0.9°C and 0.8°C. For the same two months,  $\Delta$ SST were 1.5°C for the 2002 El Niño, and 2.5°C for the 1997 El Niño. In all cases, the mean represents a three-month

<sup>1</sup>Goddard Earth Sciences and Technology, University of Maryland Baltimore County, Baltimore, Maryland, USA.

<sup>2</sup>Also at NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>3</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>4</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

<sup>5</sup>Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

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## Intercontinental transport of pollution and dust aerosols: implications for regional air quality

Mian Chin<sup>1</sup>, T. Diehl<sup>2</sup>, P. Ginoux<sup>3</sup>, and W. Malm<sup>4</sup>

<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, MD, USA

<sup>2</sup>University of Maryland Baltimore County, Baltimore, MD, USA

<sup>3</sup>NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

<sup>4</sup>National Park Service, CIRA, Colorado State University, Fort Collins, CO, USA

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**Abstract.** We use the global model GOCART to examine the impact of pollution and dust aerosols emitted from their major sources on surface fine particulate matter concentrations at regional and hemispheric scales. Focusing on the North America region in 2001, we use measurements from the IMPROVE network in the United States to evaluate the model-simulated surface concentrations of the “reconstructed fine mass” (RCFM) and its components of ammonium sulfate, black carbon (BC), organic matter (OM), and fine mode dust. We then quantify the RCFM budget in terms of the RCFM chemical composition, source type, and region of origin to find that in the eastern U.S., ammonium sulfate is the dominant RCFM component (~60%) whereas in the western U.S., dust and OM are just as important as sulfate but have considerable seasonal variations, especially in the NW. On an annual average, pollution aerosol (defined as aerosols from fuel combustion for industrial and transportation uses) from North America accounts for 65–70% of the surface RCFM in the eastern U.S. and for a lower proportion of 30–40% in the western U.S.; by contrast, pollution from outside of North America contributes to just 2–6% ( $\sim 0.2 \mu\text{g m}^{-3}$ ) of the total RCFM over the U.S. In comparison, long-range transport of dust brings 3 to 4 times more fine particles than the transport of pollution to the U.S. ( $0.5\text{--}0.8 \mu\text{g m}^{-3}$  on an annual average) with a maximum influence in spring and over the NW. Of the major pollution regions, Europe has the largest potential to affect the surface aerosol concentrations in other continents due to its shorter distance from receptor continents and its larger fraction of sulfate-producing precursor gas in the outflow. With the IPCC emission scenario for the year 2000, we find that European emissions increase levels of ammonium sulfate by  $1\text{--}5 \mu\text{g m}^{-3}$  over the surface of northern Africa and western Asia, and its contribution to eastern Asia

( $\geq 0.2 \mu\text{g m}^{-3}$ ) is twice as much as the Asian contribution to North America. Asia and North America pollution emissions exert strong impacts on their neighboring oceans, but their influences over other continents are relatively small ( $\leq 10\%$ ) due to long traveling distances across the oceans and efficient removal during transport. Among the major dust source regions, Asia displays a significant influence over large areas in the northern hemisphere except over the North Atlantic and the tropics, where African dust dominates. We also notice that the African dust and European pollution can travel eastward through a pathway spanning across Asia and North Pacific to western North America; such a pathway is difficult to detect because these aerosols usually merge and travel together with Asian dust and pollution labeled as “Asian outflow”.

### 1 Introduction

Aerosol, also known as particulate matter (PM), is one of the major air pollutants determining ambient air quality. Airborne particle sizes vary widely from a few nm ( $10^{-9}$  m) to a few hundred  $\mu\text{m}$  in diameter; those with diameters smaller than  $10 \mu\text{m}$  ( $\text{PM}_{10}$ ) are of health concern because they can penetrate into the lungs, and those smaller than  $2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ) pose the most serious risks to human health, being linked to respiratory or cardiovascular diseases and even deaths (Ostro et al., 1999, 2000; World Health Organization, 2002; Pope, 2002). Aerosol is also known to cause regional haze, which leads to discoloration, loss of texture, and deterioration of visual range in national parks and wilderness areas (Malm et al., 2000). Sources of PM include both direct emissions and chemical transformations of precursor gases emitted from power plants, automobiles, wood

Correspondence to: Mian Chin  
 (mian.chin@nasa.gov)

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## Global budget of CO, 1988–1997: Source estimates and validation with a global model

B. N. Duncan,<sup>1,2,3</sup> J. A. Logan,<sup>1</sup> I. Bey,<sup>1,4</sup> I. A. Megretskaya,<sup>1</sup> R. M. Yantosca,<sup>1</sup> P. C. Novelli,<sup>5</sup> N. B. Jones,<sup>6,7</sup> and C. P. Rinsland<sup>8</sup>

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[1] We present a model study of carbon monoxide for 1988–1997 using the GEOS-Chem 3-D model driven by assimilated meteorological data, with time-varying emissions from biomass burning and from fossil fuel and industry, overhead ozone columns, and methane. The hydroxyl radical is calculated interactively using a chemical parameterization to capture chemical feedbacks. We document the inventory for fossil fuels/industry and discuss major uncertainties and the causes of differences with other inventories that give significantly lower emissions. We find that emissions hardly change from 1988 to 1997, as increases in Asia are offset by decreases elsewhere. The model reproduces the 20% decrease in CO at high northern latitudes and the 10% decrease in the North Pacific, caused primarily by the decrease in European emissions. The model compares well with observations at sites impacted by fossil fuel emissions from North America, Europe, and east Asia suggesting that the emissions from this source are reliable to 25%, and we argue that bottom-up emission estimates are likely to be too low rather than too high. The model is too low at the seasonal maximum in spring in the southern tropics, except for locations in the Atlantic Ocean. This problem may be caused by an overestimate of the frequency of tropical deep convection, a common problem in models that use assimilated meteorological data. We argue that the yield of CO from methane oxidation is near unity, contrary to some other studies, based on removal rates of intermediate species.

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[2] Carbon monoxide plays important roles in atmospheric chemistry. Reaction with carbon monoxide (CO) provides the dominant sink for the hydroxyl radical (OH), the main tropospheric oxidant, and oxidation of CO provides a source or a sink for ozone, depending on levels of nitrogen oxides (NO<sub>x</sub>) [e.g., Levy, 1971; Crutzen, 1973; Logan *et al.*, 1981]. Changes in emissions of CO have the potential to influence climate by affecting methane and other radiatively important gases that are removed by OH, and by affecting tropospheric ozone itself [e.g., Daniel and Solomon, 1988; Mickley *et al.*, 1999].

[3] Carbon monoxide increased in the Northern Hemisphere (NH) from the 1950s until the 1980s and decreased from the late 1980s until mid-1997 [Zander *et al.*, 1989;

Khalil and Rasmussen, 1994; Novelli *et al.*, 1994, 1998, 2003]. There were large increases in CO in the NH associated with anomalously large forest fires in 1998, 2002, and 2003; however, levels in 2000 and 2001 were similar to those in 1997 [Novelli *et al.*, 2003; Yurganov *et al.*, 2004, 2005]. Part of the downward trend in CO in the early 1990s has been attributed to the effects of the Mount Pinatubo eruption in June 1991, when ozone levels in the lower stratosphere were reduced and tropospheric OH was enhanced [Bekki *et al.*, 1994; Novelli *et al.*, 1994; Dlugokencky *et al.*, 1996].

[4] The temporal behavior of CO is best documented by surface measurements from the NOAA Earth System Research Laboratory, Global Monitoring Division (GMD) that started in 1988 [Novelli *et al.*, 1994, 1998, 2003], and by column measurements at a few locations [e.g., Mahieu *et*

<sup>1</sup>School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA.

<sup>2</sup>Now at Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland, USA.

<sup>3</sup>Also at NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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<sup>4</sup>Now at Laboratoire de Modélisation de Chimie Atmosphérique, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

<sup>5</sup>Global Monitoring Division, Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.

<sup>6</sup>National Institute of Water and Atmospheric Research, Lauder, New Zealand.

<sup>7</sup>Now at Department of Chemistry, University of Wollongong, Wollongong, New South Wales, Australia.

<sup>8</sup>NASA Langley Research Center, Hampton, Virginia, USA.



## Mesospheric dynamical changes induced by the solar proton events in October–November 2003

Charles H. Jackman,<sup>1</sup> Raymond G. Roble,<sup>2</sup> and Eric L. Fleming<sup>1,3</sup>

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[1] The Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIME-GCM) was used to study the atmospheric dynamical influence of the solar protons that occurred in Oct–Nov 2003, the fourth largest period of solar proton events (SPEs) measured in the past 40 years. The highly energetic solar protons produced odd hydrogen (HO<sub>x</sub>) and odd nitrogen (NO<sub>y</sub>). Significant short-lived ozone decreases (10–70%) followed these enhancements of HO<sub>x</sub> and NO<sub>y</sub> and led to a cooling of most of the lower mesosphere. Temperature changes up to ±2.6 K were computed as well as wind (zonal, meridional, vertical) perturbations up to 20–25% of the background winds as a result of the solar protons. The solar proton-induced mesospheric temperature and wind perturbations diminished over a period of 4–6 weeks after the SPEs. The Joule heating in the mesosphere, induced by the solar protons, was computed to be relatively insignificant for these solar storms. **Citation:** Jackman, C. H., R. G. Roble, and E. L. Fleming (2007), Mesospheric dynamical changes induced by the solar proton events in October–November 2003, *Geophys. Res. Lett.*, 34, L04812, doi:10.1029/2006GL028328.

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[2] Several very large solar eruptive events in late October and early November 2003 resulted in huge fluxes of charged particles at the Earth [Mewaldt *et al.*, 2005]. Much of the energy was carried by solar protons, which impacted the middle atmosphere (stratosphere and mesosphere) leading to ionizations, dissociations, dissociative ionizations, and excitations. The proton-induced atmospheric interactions resulted in the production of odd hydrogen, HO<sub>x</sub> (H, OH, HO<sub>2</sub>), and odd nitrogen, NO<sub>y</sub> (N, NO, NO<sub>2</sub>, NO<sub>3</sub>, N<sub>2</sub>O<sub>5</sub>, HNO<sub>3</sub>, HO<sub>2</sub>NO<sub>2</sub>, HONO, ClONO<sub>2</sub>, ClNO<sub>2</sub>, BrONO<sub>2</sub>) constituents either directly or through a photochemical sequence [e.g., Swider and Keneshea, 1973; Crutzen *et al.*, 1975]. There were a few periods from 26 Oct.–7 Nov., 2003, when the proton fluxes increased dramatically beyond background levels for 1–3 days. These periods are known as solar proton events (SPEs) and some of the middle atmospheric constituent influences during these SPEs have been discussed before [e.g., Jackman *et al.*, 2005a; Verronen *et al.*, 2005]. These Oct./Nov. 2003 SPEs were very intense

and were computed to be the fourth largest SPE period in the past 40 years [Jackman *et al.*, 2005b].

[3] We are not aware of any measured atmospheric dynamical changes during these very significant atmospheric perturbations, however, past studies [Banks, 1979; Reagan *et al.*, 1981; Jackman and McPeters, 1985; Roble *et al.*, 1987; Reid *et al.*, 1991; Zadorozhny *et al.*, 1994; Jackman *et al.*, 1995; Krivolutsky *et al.*, 2006] have suggested that very large SPEs can lead to temperature changes through ozone depletion and/or Joule heating.

[4] In this paper, we used the latest version of the TIME-GCM (Thermosphere Ionosphere Mesosphere Electrodynamic – General Circulation Model) [Roble, 2000], which contains both ozone photochemistry and auroral particle and Joule heating, to study the influence of the very large proton fluxes during Oct./Nov. 2003 on the temperature and winds of the middle atmosphere. The TIME-GCM allowed us the opportunity to compare and contrast the different atmospheric perturbations during SPEs that lead to temperature and wind changes. We will focus on a snap-shot output from the model for one day, 30 October 2003, at 0:00 UT near a period of maximum solar proton flux to investigate these effects.

### 2. Model Description and Solar Proton Caused Constituent Change

[5] The TIME-GCM was first described by Roble and Ridley [1994]. This model has an effective 5° latitude × 5° longitude grid with 45 constant pressure surfaces in the vertical between approximately 30 and 500 km altitude with a vertical resolution of 2 grid points per scale height and a model time step of 5 minutes. The TIME-GCM has a comprehensive set of physical, chemical, and dynamical processes included to simulate the upper atmosphere and ionosphere. A detailed description of the model and its components is given by Roble [2000].

[6] The model is forced at its lower boundary of 10 hPa by global geopotential height and temperature distributions from NCEP (National Centers of Environmental Prediction) analysis. This feature provides the ability to simulate particular periods of interest, such as 27 October through 11 December 2003 for this specific study [e.g., Liu and Roble, 2005].

[7] We use the proton flux data provided by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) for the NOAA Geostationary Operational Environmental Satellites (GOES) (see <http://sec.noaa.gov/Data/goes.html>). The GOES 11 data are considered to be the most reliable of the current GOES datasets for the proton fluxes depositing energy into polar latitudes and were used as the source of protons in several

<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA.

<sup>3</sup>Also at Science Systems and Applications, Inc., Lanham, Maryland, USA.



## Effects of data selection and error specification on the assimilation of AIRS data<sup>†</sup>

J. Joiner,<sup>1\*</sup> E. Brin,<sup>2</sup> R. Treadon,<sup>3</sup> J. Derber,<sup>3</sup> P. Van Delst,<sup>3</sup> A. Da Silva,<sup>4</sup> J. Le Marshall,<sup>3</sup> P. Poli,<sup>5</sup> R. Atlas,<sup>6</sup> D. Bungato<sup>2</sup> and C. Cruz<sup>7</sup>

<sup>1</sup> NASA Goddard Space Flight Center Laboratory for Atmospheres, USA

<sup>2</sup> Science Applications International Corporation, USA

<sup>3</sup> Joint Center for Satellite Data Assimilation, USA

<sup>4</sup> NASA Goddard Space Flight Center Global Modeling and Assimilation Office, USA

<sup>5</sup> Centre National de Recherches Météorologiques, Météo France, Toulouse, France

<sup>6</sup> NOAA Atlantic Oceanographic and Meteorological Laboratory, USA

<sup>7</sup> NGITI, USA

**ABSTRACT:** The Atmospheric InfraRed Sounder (AIRS), flying aboard NASA's Aqua satellite with the Advanced Microwave Sounding Unit-A (AMSU-A) and four other instruments, has been providing data for use in numerical weather prediction and data assimilation systems for over three years. The full AIRS data set is currently not transmitted in near-real-time to the prediction/assimilation centres. Instead, data sets with reduced spatial and spectral information are produced and made available within three hours of the observation time. In this paper, we evaluate the use of different channel selections and error specifications. We achieve significant positive impact from the Aqua AIRS/AMSU-A combination during our experimental time period of January 2003. The best results are obtained using a set of 156 channels that do not include any in the H<sub>2</sub>O band between 1080 and 2100 cm<sup>-1</sup>. The H<sub>2</sub>O band channels have a large influence on both temperature and humidity analyses. If observation and background errors are not properly specified, the partitioning of temperature and humidity information from these channels will not be correct, and this can lead to a degradation in forecast skill. Therefore, we suggest that it is important to focus on background error specification in order to maximize the impact from AIRS and similar instruments. In addition, we find that changing the specified channel errors has a significant effect on the amount of data that enters the analysis as a result of quality control thresholds that are related to the errors. However, moderate changes to the channel errors do not significantly impact forecast skill with the 156 channel set. We also examine the effects of different types of spatial data reduction on assimilated data sets and NWP forecast skill. Whether we pick the centre or the warmest AIRS pixel in a 3×3 array affects the amount of data ingested by the analysis but does not have a statistically significant impact on the forecast skill. Published in 2007 by John Wiley & Sons, Ltd.

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### 1. Introduction

The Atmospheric Infra-Red Sounder (AIRS) (Aumann *et al.*, 2003) is the first of several advanced high-spectral-resolution nadir-viewing passive infrared sounders to be used for climate applications and operational numerical weather prediction (NWP). AIRS is a grating spectrometer that has been flying on the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) polar-orbiting Aqua platform since May 2002 along with the Advanced Microwave Sounding Unit - A (AMSU-A) and four other instruments. Over the next few years, additional kilochannel interferometers will fly in Low Earth Orbit. These include the Infrared Atmospheric

Sounding Interferometer (IASI) on the EUMETSAT MetOp platform and the Cross-Track Infrared Sounder (CrIS) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) series of satellites as well as the NASA/National Oceanic and Atmospheric Administration (NOAA)/(US) Department of Defense (DoD) NPOESS Preparatory Project (NPP).

In order to facilitate near-real-time (NRT) transmission of the voluminous AIRS data, the complete AIRS data set must be reduced. There are several possible methods of data reduction. These include channel and/or pixel subsetting and methods such as principle component analysis that represent only the most important modes of the spectral information content. Before launch, the NOAA National Environmental Satellite Data and Information Service (NESDIS) set up a special processing system to provide several different data sets to the NWP and data assimilation community (Goldberg *et al.*, 2003).

\* Correspondence to: J. Joiner, NASA Goddard Space Flight Center, Code 613.3, Greenbelt, MD, 20771, USA.  
 E-mail: Joanna.Joiner@nasa.gov

<sup>†</sup> This article is a US Government work and is in the public domain in the USA.



## Variations in stratospheric inorganic chlorine between 1991 and 2006

D. J. Lary,<sup>1,2</sup> D. W. Waugh,<sup>3</sup> A. R. Douglass,<sup>2</sup> R. S. Stolarski,<sup>2</sup> P. A. Newman,<sup>2</sup> and H. Mussa<sup>4</sup>

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[1] A consistent time series of stratospheric inorganic chlorine  $\text{Cl}_y$  from 1991 to present is formed using spaceborne observations together with neural networks. A neural network is first used to account for inter-instrument biases in HCl observations. A second neural network is used to learn the abundance of  $\text{Cl}_y$  as a function of HCl and  $\text{CH}_4$ , and to form a time series using available HCl and  $\text{CH}_4$  measurements. The estimates of  $\text{Cl}_y$  are broadly consistent with calculations based on tracer fractional releases and previous estimates of stratospheric age of air. These new estimates of  $\text{Cl}_y$  provide a critical test for global models, which exhibit significant differences in predicted  $\text{Cl}_y$  and ozone recovery. **Citation:** Lary, D. J., D. W. Waugh, A. R. Douglass, R. S. Stolarski, P. A. Newman, and H. Mussa (2007), Variations in stratospheric inorganic chlorine between 1991 and 2006, *Geophys. Res. Lett.*, *34*, L21811, doi:10.1029/2007GL030053.

### 1. Introduction

[2] Knowledge of the distribution of inorganic chlorine  $\text{Cl}_y$  in the stratosphere is needed to attribute changes in stratospheric ozone to changes in halogens, and to assess the realism of chemistry-climate models [Eyring *et al.*, 2006; Eyring *et al.*, 2007]. However, there are limited direct observations of  $\text{Cl}_y$ . Simultaneous measurements of the major inorganic chlorine species are rare [Zander *et al.*, 1992; Gunson *et al.*, 1994; Bonne *et al.*, 2000; Nassar *et al.*, 2006]. In the upper stratosphere,  $\text{Cl}_y$  can be inferred from HCl alone [e.g., Anderson *et al.*, 2000; Froidevaux *et al.*, 2006b].

[3] Here we combine observations from several spaceborne instruments using neural networks [Lary and Mussa, 2004] to produce a time series for  $\text{Cl}_y$ . A neural network is used to characterize differences among various HCl measurements, and to perform an inter-instrument bias correction. Measurements from several different instruments are used in this analysis. These instruments, together with temporal coverage and measurement uncertainties, are listed in Table 1. The HALOE uncertainties are only estimates of random error and do not include any indications of overall accuracy. All instruments provide measurements through the depth of the stratosphere. A second neural network is

used to infer  $\text{Cl}_y$  from these corrected HCl measurements and measurements of  $\text{CH}_4$ .

[4] Sections 2 and 3 describe the HCl and  $\text{Cl}_y$  intercomparisons. Section 4 presents a summary.

### 2. HCl Intercomparison

[5] We first compare measurements of HCl from the different instruments listed in Table 1. Comparisons are made in equivalent PV latitude - potential temperature coordinates [Schoeberl *et al.*, 1989; Proffitt *et al.*, 1989; Lait *et al.*, 1990; Douglass *et al.*, 1990; Lary *et al.*, 1995; Schoeberl *et al.*, 2000] to extend the effective latitudinal coverage of the measurements and identify contemporaneous measurements in similar air masses.

[6] The Halogen Occultation Experiment (HALOE) provides the longest record of space based HCl observations. Figure 1 compares HALOE HCl with HCl observations from (1) the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS), (2) the Atmospheric Chemistry Experiment (ACE), and (3) the Microwave Limb Sounder (MLS). In these plots each point is the median HCl observation made by the instrument during each month for 30 equivalent latitude bins from pole to pole and 25 potential temperature bins from the 300–2500 K potential temperature surfaces.

[7] For each of these bins we only use data in the range where the supplied quality flags show it suitable for scientific use. For each bin, we characterize the median observation uncertainty and the representativeness uncertainty. The representativeness is a measure of the spatial variability over the bin, in our case characterized by the average deviation of the observations in the bin. The average deviation is a measure of the width of the probability distribution of observations. Unlike the standard deviation, the average deviation is not strongly influenced by a few outliers. Each of these uncertainties are used later in Figures 2 and 3.

[8] A consistent picture is seen in these plots: HALOE HCl measurements are lower than those from the other instruments. The slopes of the linear fits (relative scaling) are 1.05 for the HALOE-ATMOS comparison, 1.09 for the HALOE-MLS, and 1.18 for the HALOE-ACE. The offsets are apparent at the 525 K isentropic surface and above. Previous comparisons among HCl datasets reveal a similar bias for HALOE [Russell *et al.*, 1996; McHugh *et al.*, 2005; Froidevaux *et al.*, 2006a]. ACE and MLS HCl measurements are in much better agreement (Figure 1d). Note, all measurements agree within the stated observational uncertainties summarized in Table 1.

[9] To combine the above HCl measurements to form a continuous time series of HCl (and then  $\text{Cl}_y$ ) from 1991 to 2006 it is necessary to account for the biases between data

<sup>1</sup>Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore, Maryland, USA.

<sup>2</sup>Atmospheric Chemistry and Dynamics Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>3</sup>Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland, USA.

<sup>4</sup>Department of Chemistry, University of Cambridge, Cambridge, UK.

## The QBO as potential amplifier and conduit to lower altitudes of solar cycle influence

H. G. Mayr<sup>1</sup>, J. G. Mengel<sup>2</sup>, C. L. Wolff<sup>1</sup>, F. T. Huang<sup>3</sup>, and H. S. Porter<sup>4</sup>

<sup>1</sup>Goddard Space Flight Center, Greenbelt, MD, USA

<sup>2</sup>Science Systems & Applications, Lanham, MD, USA

<sup>3</sup>Creative Computing Solutions Inc. Rockville, MD, USA

<sup>4</sup>Furman University, Greenville, SC, USA

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**Abstract.** In several papers, the solar cycle (SC) effect in the lower atmosphere has been linked observationally to the Quasi-biennial Oscillation (QBO) of the zonal circulation. Salby and Callaghan (2000) in particular analyzed the QBO wind measurements, covering more than 40 years, and discovered that they contain a large SC signature at 20 km. We present here the results from a study with our 3-D Numerical Spectral Model (NSM), which relies primarily on parameterized gravity waves (GW) to describe the QBO. In our model, the period of the SC is taken to be 10 years, and the relative amplitude of radiative forcing varies exponentially with height, i.e., 0.2% at the surface, 2% at 50 km, and 20% at 100 km and above. Applying spectral analysis to identify the SC signature, the model generates a relatively large modulation of the QBO, which reproduces the observations qualitatively. The numerical results demonstrate that the QBO modulation, closely tracking the phase of the SC, is robust and persists at least for 70 years. The question is what causes the SC effect, and our analysis shows that four interlocking processes are involved: (1) In the mesosphere at around 60 km, the solar UV variations generate in the zonal winds a SC modulation of the 12-month annual oscillation, which is hemispherically symmetric and confined to equatorial latitudes like the QBO. (2) Although the amplitude of this equatorial annual oscillation (EAO) is relatively small, its SC modulation is large and extends into the lower stratosphere under the influence of, and amplified by, wave forcing. (3) The amplitude modulations of both EAO and QBO are essentially in phase with the imposed SC heating for the entire time span of the model simulation. This indicates that, due to positive feedback in the wave mechanism, the EAO apparently provides the pathway and pacemaker for the SC modulation of the QBO. (4) Our analysis demonstrates that the SC modulations of the QBO and EAO are ampli-

fied by tapping the momentum from the upward propagating gravity waves. Influenced and amplified by wave processes, the QBO thus acts as conduit to transfer to lower altitudes the larger SC variations in the UV absorbed in the mesosphere. Our model produces in the temperature variations of the QBO and EAO measurable SC modulations at polar latitudes near the tropopause. The effects are apparently generated by the meridional circulation, and planetary waves presumably, which redistribute the energy from the equatorial region where the waves are very effective in amplifying the SC influence.

**Keywords.** Meteorology and atmospheric dynamics (General circulation; Middle atmosphere dynamics; Waves and tides)

### 1 Introduction

The Quasi-biennial Oscillation (QBO) of the zonal circulation at equatorial latitudes has been linked observationally to solar cycle (SC) effects in the stratosphere at northern polar latitudes. Following a study by Holton and Tan (1980), Labitzke (1982, 1987) and Labitzke and van Loon (1988, 1992) discovered that the temperatures at northern polar latitudes in winter are positively and negatively correlated with the SC when the QBO is respectively in its negative and positive phase. And at mid-latitudes they observed opposite correlations. In the northern stratosphere, Dunkerton and Baldwin (1992) and Baldwin and Dunkerton (1998) also found evidence of a correlation between the SC and the phase of the QBO.

The SC influence on the QBO connection with the polar region has been simulated successfully in recent modeling studies. Matthes et al. (2004) inserted rocketsonde data into their GCM to produce realistic QBO wind fields around the equator. Carrying out model runs with fixed eastward and

Correspondence to: H. G. Mayr  
(hmayr2@verizon.net)



## Ozone climatological profiles for satellite retrieval algorithms

Richard D. McPeters,<sup>1</sup> Gordon J. Labow,<sup>2</sup> and Jennifer A. Logan<sup>3</sup>

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[1] A new altitude-dependent ozone climatology has been produced for use with the version 8 Total Ozone Mapping Spectrometer (TOMS) and Solar Backscatter Ultraviolet retrieval algorithms. The climatology consists of monthly average ozone profiles for 10° latitude zones covering altitudes from 0 to 60 km (in  $Z^*$  pressure altitude coordinates). The climatology was formed by combining data from Stratospheric Aerosol and Gas Experiment II (SAGE II; 1988–2001) or Microwave Limb Sounder (MLS; 1991–1999) with data from balloon sondes (1988–2002). Ozone below 10 km is based on balloon sondes, whereas ozone at 19 km and above is based on SAGE II measurements. When SAGE data are not available (at high latitudes), MLS data are used. The ozone climatology in the southern hemisphere and tropics has been greatly improved in recent years by the addition of a large number of balloon sonde measurements made under the Southern Hemisphere Additional Ozonesondes program. The new climatology better represents the seasonal behavior of ozone in the troposphere, including the known hemispheric asymmetry, and in the upper stratosphere. A modification of this climatology was used for the TOMS version 8 retrieval that includes total ozone dependence, which is important in the lower stratosphere. Comparisons of TOMS ozone with ground stations show improved accuracy over previous TOMS retrievals due in part to the new climatology.

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[2] Ozone climatologies are used for many purposes, and no single climatology will be optimum for all uses. A climatology developed by *Fortuin and Kelder* [1998] based on a combination of balloon and Solar Backscatter Ultraviolet (SBUV) data was, they note, intended mainly for climate simulations with general circulation models. *McPeters et al.* [1997] developed a climatology using SBUV data specifically for estimating the amount of ozone above balloon burst altitude so that total column ozone could be calculated from electrochemical concentration cell sonde measurements. Recently, *Lamsal et al.* [2004] developed a climatology to be used as an a priori for the Sciamachy optimal retrieval algorithm that has also been used in differential optical absorption spectroscopy retrievals. This climatology uses total column ozone to parameterize the profile shape.

[3] Satellite retrieval algorithms for backscattered ultraviolet (BUV) measurements have in the past used a relatively simple ozone climatology. The Total Ozone Mapping Spectrometer (TOMS) retrievals in version 7 used a total

ozone-dependent climatology consisting of 26 profiles with ozone in Umkehr layers (~5 km) covering low-latitude, midlatitude, and high-latitude zones. That climatology and results of a study of the errors due to profile shape at high latitudes are discussed by *Wellemeyer et al.* [1997]. While such a climatology is adequate for accounting for stratospheric ozone profile shape changes, it has a relatively fixed tropospheric ozone climatology since tropospheric ozone does not correlate well with total column ozone. This has become a limitation on accuracy since tropospheric ozone variability has proven to be one of the largest sources of error in the current algorithms. These errors are discussed by *Bhartia* [2002] in the OMI Algorithm Theoretical Basis Document (ATBD).

[4] Ozone retrieval algorithms based on the optimal retrieval method [*Rodgers*, 2000] benefit from an accurate climatology in altitude regions where the measurement loses sensitivity, for example, in the lowest 10 km of the atmosphere for a TOMS total column ozone retrieval. The climatology also supplies information to such retrievals in the form of higher vertical resolution information than the retrieval itself can achieve. An SBUV retrieval derives a fairly accurate measure of the total amount of ozone between the ground and about 20 km, but has little information on how it is distributed. The climatology determines the distribution of ozone within this region in an SBUV retrieval.

[5] A good climatology can also be used when detailed day-to-day information is not necessary, such as in the

<sup>1</sup>Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Science Systems and Applications Inc., Lanham, Maryland, USA.

<sup>3</sup>Division of Engineering and Applied Science, Harvard University, Cambridge, Massachusetts, USA.

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## Observationally derived transport diagnostics for the lowermost stratosphere and their application to the GMI chemistry and transport model

S. E. Strahan<sup>1</sup>, B. N. Duncan<sup>1</sup>, and P. Hoor<sup>2</sup>

<sup>1</sup>Goddard Earth Science and Technology Center, University of Maryland, Baltimore County, Baltimore, MD 21250, USA

<sup>2</sup>Max Planck Institute for Chemistry, Air Chemistry, Mainz, Germany

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**Abstract.** Transport from the surface to the lowermost stratosphere (LMS) can occur on timescales of a few months or less, making it possible for short-lived tropospheric pollutants to influence stratospheric composition and chemistry. Models used to study this influence must demonstrate the credibility of their chemistry and transport in the upper troposphere and lower stratosphere (UT/LS). Data sets from satellite and aircraft instruments measuring CO, O<sub>3</sub>, N<sub>2</sub>O, and CO<sub>2</sub> in the UT/LS are used to create a suite of diagnostics for the seasonally-varying transport into and within the lowermost stratosphere, and of the coupling between the troposphere and stratosphere in the extratropics. The diagnostics are used to evaluate a version of the Global Modeling Initiative (GMI) Chemistry and Transport Model (CTM) that uses a combined tropospheric and stratospheric chemical mechanism and meteorological fields from the GEOS-4 general circulation model. The diagnostics derived from N<sub>2</sub>O and O<sub>3</sub> show that the model lowermost stratosphere has realistic input from the overlying high latitude stratosphere in all seasons. Diagnostics for the LMS show two distinct layers. The upper layer begins ~30 K potential temperature above the tropopause and has a strong annual cycle in its composition. The lower layer is a mixed region ~30 K thick near the tropopause that shows no clear seasonal variation in the degree of tropospheric coupling. Diagnostics applied to the GMI CTM show credible seasonally-varying transport in the LMS and a tropopause layer that is realistically coupled to the UT in all seasons. The vertical resolution of the GMI CTM in the UT/LS, ~1 km, is sufficient to realistically represent the extratropical tropopause layer. This study demonstrates that the GMI CTM has the transport credibility required to study the impact of tropospheric emissions on the stratosphere.

Correspondence to: S. E. Strahan  
 (sstrahan@pop600.gsfc.nasa.gov)

### 1 Introduction

Evaluation of transport between the upper troposphere (UT) and lower stratosphere (LS) is important because of the potential for tropospheric pollutants to impact stratospheric composition and chemistry. A decade ago, Ko et al. (1997) proposed that Br<sub>y</sub> produced from short-lived species in the tropical UT may contribute to stratospheric halogen loading, and a recent study using BrO measurements and photochemical models supports this hypothesis (Salawitch et al., 2005). More recently, a “tape recorder” of CO forced by seasonal variations in biomass burning was identified in the tropical UT/LS using satellite CO measurements (Schoeberl et al., 2006). Tropospheric pollutants with lifetimes of only a few months can affect the composition of the lowest portions of the stratosphere.

There are two major transport pathways to the stratosphere (Holton et al., 1995; Dessler et al., 1995). In the tropics, convection brings boundary layer air up to ~12 km (~345 K), the base of the tropical tropopause layer (TTL) (Folkins, 2002). The TTL begins where convective mass flux falls off rapidly and extends to the cold point tropopause at 17–18 km (370–380 K) (Gettelman and Forster, 2002). Net heating rates become positive at about 16 km (~360 K) in the TTL and ascent by the Brewer-Dobson circulation slowly lifts air up to and across the tropical tropopause and into the stratosphere. A second pathway involves quasi-horizontal transport of air in the TTL to the extratropical lowermost stratosphere (LMS). This pathway is aided by monsoon anticyclones in the summer hemisphere (Chen, 1995), with poleward transport of tropospheric air on the west side and equatorward transport of stratospheric air on the east side of the monsoonal circulation.

The lowermost stratosphere is defined as the region between the extratropical tropopause, where isentropes connect the stratosphere and troposphere, and the stratospheric

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