

TABLE OF CONTENTS

	<u>Page</u>
LIST OF ILLUSTRATIONS	i
ABSTRACT	ii
LIST OF ACRONYMS	ii
1. RESULTS FROM PRIOR RESEARCH	1
2. PROPOSED RESEARCH (STATEMENT OF WORK)	2
2.1 Rationale and Overall Goals	2
2.2 Relationship of the Proposed Research to Other Proposed Measurements and Analyses	3
2.3 ACE-Asia Goals, Overall Approach, and the 2001 Intensive Field Study	3
2.4 Satellite Measurements and Retrievals Relevant to ACE-Asia and the Proposed Research	5
2.5 Expected Role of Airborne Sunphotometry in ACE-Asia	6
2.6. Proposed Tasks	10
2.6.1 Year One	10
2.6.2 Years Two and Three	11
2.7. Schedule	13
2.8. References	13
3. BUDGET	17
4. STAFFING, RESPONSIBILITIES, AND VITAE	19
5. CURRENT AND PENDING SUPPORT	28

ILLUSTRATIONS

1 Aerosol-induced change in net shortwave flux at tropopause calculated from satellite maps of aerosol optical depth and aerosol intensive properties from TARFOX.	F1
2 Channel wavelengths of Ames Airborne Tracking Sunphotometers (AATS-6 and AATS-14) in relation to atmospheric spectra.	F2
3 Latitude transects of aerosol optical depth and Ångström exponent derived from the AATS-6 sunphotometer aboard the UW C-131A, from ATSR-2, and from AVHRR.	F3
4 Aerosol optical thickness measured by sunphotometer (AATS-6) aboard the C-131A aircraft and derived from MAS data as a function of wavelength.	F4
5 Scatter plot and spectra of aerosol optical depths obtained in ACE-2 by AATS-6 on the R/V Vodyanitskiy, AATS-14 on the Pelican aircraft, and AVHRR on the NOAA-14 Satellite.	F5
6 Profiles of aerosol optical depth and extinction at selected AATS-14 wavelengths (380, 500, 864 and 1558 nm) measured in ACE-2.	F6
7 Comparison of aerosol optical depth spectra for the marine boundary layer during a Pelican flight in ACE-2.	F7
8 Marine boundary layer aerosol size distributions from in situ measurements and inverted from AATS-14 extinction spectra measured on Pelican flight tf15 in ACE-2.	F8
9 Profiles of the columnar water vapor and water vapor density measured in ACE-2 by AATS-14 and in situ sensor.	F9
10 Scatter diagram of columnar water vapor calculated from radiosonde measurements and from AATS-6 measurements during ACE-2.	F10
11 Aerosol single-scattering albedo profiles determined for TARFOX flight 1728 (July 17, 1996) by two techniques.	F11
12 Comparison between aerosol-induced change in solar flux derived from C-130 pyranometer measurements (data points) and calculations (curves).	F12

ACE-Asia Aerosol Radiative Effect Studies Using Airborne Sunphotometer, Satellite and In-Situ Measurements

Principal Investigator: Philip B. Russell, NASA Ames Research Center
Proposed Cost: \$499,000, April 1, 2000-March 31, 2003

ABSTRACT

We propose to study the radiative effects of aerosols in the Asia-Pacific region by making airborne sunphotometer measurements in the ACE-Asia 2001 intensive field study and by conducting closure analyses and integrated assessments that combine satellite and suborbital measurements. Research in FY 2000 will focus on preparing for the 2001 intensive experiment by (a) developing analysis techniques for mixed aerosols in the polluted and clean boundary layer and in elevated desert dust layers, (b) investigating the sensitivity of satellite optical depth retrieval techniques and predictions of aerosol-induced radiative forcing to the properties of aerosols likely to be seen over the Western Pacific and Asia, and (c) providing information about the location and frequency of occurrence of the Asian aerosol plume to the ACE-Asia planning process. The FY 2000 research will build on results for American, European and African aerosols obtained in TARFOX and ACE-2. Research in FY 2001-02 will include: (a) measuring aerosol optical depth and extinction spectra along with water vapor column contents using an Ames Airborne Tracking Sunphotometer in coordination with satellite, in situ, and other remote measurements during the Intensive Observation Period (IOP, late March-April 2001), (b) assessing the quality of the combined ACE-Asia in situ and remote measurements and analysis models by conducting closure studies, and (c) providing an initial assessment of the radiative effects of aerosols over the Western Pacific and Asia by applying and extending the techniques developed in FY 2000.

We envision the research proposed here to NOAA as part of a larger ACE-Asia effort by the Ames airborne sunphotometer/satellite team. We are seeking NASA and Navy support for the other components of this overall effort. Specifically, this proposal requests support for measurements by the 6-channel Ames Airborne Tracking Sunphotometer (AATS-6) on the NCAR C-130. Separately, we are seeking NASA and Navy support for measurements by our 14-channel unit (AATS-14) on the CIRPAS Twin Otter. In addition, we have requested NASA support for modeling and enhanced analyses using ACE-Asia and other data. Recognizing that both funding and platform participation in ACE-Asia are uncertain, we are currently maintaining the flexibility to assemble a research approach that is most productive given the final levels of funding and participation by others. If, for example, the NCAR C-130 does not participate in ACE-Asia (because of aerosol inlet problems or funding limitations), we propose that the funding requested here be applied to either (a) AATS-6 measurements on an ACE-Asia ship (as we did in ACE-2) or (b) AATS-14 measurements on the Twin Otter. Regardless of the measurement configuration ultimately chosen, we will pursue our overall goal of assessing the radiative effects of aerosols in the Asia-Pacific region to the extent possible with the suborbital and satellite measurement data sets and the analysis funding available.

ACRONYMS

AA-SEC	ACE-Asia Survey and Evolution Component (ACE-Asia 2001 Intensive Field Study)
AATS-6	6-channel Ames Airborne Tracking Sunphotometer
AATS-14	14-channel Ames Airborne Tracking Sunphotometer
ACE	Aerosol Characterization Experiment
ADEOS	Advanced Earth Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BOREAS	Boreal Ecosystem-Atmosphere Study
CERES	Clouds and the Earth's Radiant Energy System
CIRPAS	Center for Interdisciplinary Remotely Piloted Aircraft Studies
EOS	Earth Observing System
ERBE	Earth Radiation Budget Experiment
FIFE	First ISLSCP Field Experiment
GACP	Global Aerosol Climatology Program

GLI	Global Imager
GOES	Geostationary Operational Environmental Satellite
HAPEX-Sahel	Hydrologic-Atmospheric Pilot Experiment in the Sahel
IGAC	International Global Atmospheric Chemistry Program
INDOEX	Indian Ocean Experiment
IOP	Intensive Observation Period
ISLSCP	International Satellite Land Surface Climatology Project
LITE	Lidar In-space Technology Experiment
OES	Office of Earth Science
MAS	MODIS Airborne Simulator
MDAR	Modeling and Data Analysis Research Program
MISR	Multi-angle Imaging Spectro-Radiometer
MODIS	Moderate-resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
NCAR	National Center for Atmospheric Research
PATMOS	Pathfinder Atmospheric Data Sets [from AVHRR]
PICASSO-CENA	Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations – Climatologie Etendue des Nuages et des Aerosols
POLDER	Polarization and Directionality of the Earth's Reflectances
SAFARI	Southern African Fire-Atmosphere Regional Science Initiative
SAGE	Stratospheric Aerosol and Gas Experiment
SCAR-B	Smoke, Clouds And Radiation experiment in Brazil
SeaWiFS	Sea-viewing Wide-Field-of-view Sensor
SEC	Survey and Evolution Component [of ACE-Asia]
SSFR	Spectral Solar Flux Radiometer
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TOMS	Total Ozone Mapping Spectrometer
TRACE-A	Transport and Chemistry Near the Equator-Atlantic
TRACE-P	Transport and Chemical Evolution over the Pacific
TRMM	Tropical Rainfall Measurement Mission
UNOLS	University-National Oceanographic Laboratory Systems

ACE-Asia Aerosol Radiative Effect Studies Using Airborne Sunphotometer, Satellite and In-Situ Measurements

1. RESULTS FROM PRIOR RESEARCH

As required by the guidelines in the Program Announcement, this section briefly summarizes results of related projects supported by NOAA and other agencies. More extensive descriptions of selected results and their relevance to the proposed research are given in Sections 2.4 and 2.5. As requested, each paragraph head gives award title, funding agency, award number (if available), period of award, and total award.

Improved Exploitation of Field Data Sets to Address Aerosol Radiative-Climatic Effects and Development of a Global Aerosol Climatology, NASA RTOP #622-44-75-10, 10/98-9/01, \$525,000. This ongoing award supports tasks on (a) Airborne Sunphotometer Optical Depth Data Quality Checks, (b) Mixed Aerosol Optical Modeling, (c) Automated Size Distribution Retrievals, (d) Size Distribution Comparisons and Closure Studies, (e) Water Vapor/Aerosol Interactions and Satellite Retrievals, and (f) Flux Change/Radiative Forcing Studies. Vertical profiles of derived single scattering albedos and flux changes for TARFOX aerosols have been described in a journal paper by Redemann et al. (2000b); an example of the single scattering albedo results is in Section 2.5. Other results include calculations of the humidity dependence of single scattering albedo of sulfate-coated soot particles and a comparison of aerosol single scattering albedos determined in TARFOX and ACE-2 by a variety of techniques. These results and the remainder of this research are in the prepublication stage, but early results have been presented at several conferences.

ACE-2 Ship Sunphotometry and Integrated Analyses, NOAA Office of Global Programs, Order No. NA97AANAG0163, 5/97-4/00, \$265,000. This award supported (a) ACE-2 CLEARCOLUMN coordination by Dr. Russell, (b) Measurements by the 6-channel Ames Airborne Tracking Sunphotometer (AATS-6) on the ACE-2 ship, (c) Special AATS-6 calibrations and intercomparisons, and (d) Analyses combining the AATS-6 data with satellite and other suborbital data. Results are described in four journal publications led by our team (Bergstrom and Russell, 1999; Livingston et al., 2000; Russell and Heintzenberg, 2000; Schmid et al., 1999), plus several others we coauthored (e.g., Durkee et al., 2000; Pilewski et al., 2000). Selected results are summarized in Sections 2.4 and 2.5 of this proposal.

ACE-2 Airborne Sunphotometer Measurements, Naval Postgraduate School, 11/96-10/97, \$129,000. This award supported preparation and calibration of the 14-channel Ames Airborne Tracking Sunphotometer (AATS-14) and measurements by AATS-14 on the Pelican aircraft in ACE-2. Twenty-one flights were made, including four Langley-plot calibration flights. Data were analyzed using the award listed below; selected results are shown in Section 2.5.

TARFOX and ACE-2 Integrated Analyses, NASA RTOP #622-44-10-10, 10/96-9/99, \$450,000. This award supported (a) TARFOX analysis coordination by Dr. Russell, (b) TARFOX airborne sunphotometer integrated analyses, (c) Analyses of AATS-14 measurements on ACE-2 Pelican flights, and (d) Related ACE-2 integrated analyses. Results are described in four journal publications led by our team (Russell et al., 1999a,b; Redemann et al., 2000a, Schmid et al., 2000), a PhD thesis (Redemann, 1999), and several journal papers we coauthored (e.g., Tanre et al., 1999; Veeffkind et al., 1999; Ferrare et al., 2000a,b; Collins et al., 2000; Gasso et al., 2000; Welton et al., 2000). Selected results are summarized in Section 2.5 of this proposal.

TARFOX Airborne Sunphotometry, NASA RTOP #460-43-46-10, 5/95-9/96, \$61,000. Results: Optical depth spectra were measured with AATS-6 on 18 flights of the UW C-131A, and demonstration measurements were made with AATS-14 on 5 flights of the Pelican. Flights were coordinated with overpasses by four satellites, flights by ER-2 and C-130 aircraft, and surface lidar and radiometer measurements. Results of early closure analyses were described by Hegg et al. (1997). A new expression was derived for computing aerosol-induced flux changes (i.e. radiative forcing) as a function of solar zenith angle. Results of the new expression were compared to two-stream and adding-doubling results, and all three techniques were used to estimate flux changes expected in column closure experiments. This local radiative forcing was shown to be 15-100 times as large as global-average results (Russell et al., 1997).

2. PROPOSED RESEARCH (STATEMENT OF WORK)

2.1 Rationale and Overall Goals

Aerosol effects on atmospheric radiation remain a major uncertainty in understanding past and present climates and in predicting the future climate. Recent experiments designed to reduce this uncertainty (e.g., TARFOX, ACE-2, and INDOEX) have produced important advances but in the process have emphasized remaining questions that must be answered (Russell et al., 1999a; Raes et al., 2000; Russell and Heintzenberg, 2000; Ramanathan, 1999). For example, there is now a renewed appreciation for the variety and complexity of actual aerosols and for the importance of capturing the salient features of this complexity when, for example, relating predictions of global aerosol chemical transport models (CTMs) to satellite-derived optical depths and radiative forcings. There is also an increased appreciation for the effect of absorbing aerosols on the vertical thermal structure of the atmosphere, and hence on convection, cloud formation and persistence, and surface evaporation (e.g., Russell et al., 1999b; Ramanathan, 1999). This is in contrast to the emphasis of several years ago on the effect of nonabsorbing aerosols on top-of-atmosphere or top-of-troposphere radiation budgets.

The results of recent experiments have not only emphasized the complexity of the problem but have also demonstrated, via measurements and models, that the effects of aerosols are too large to be ignored. For example, results from TARFOX, ACE-2, and INDOEX have demonstrated that aerosols in persistent plumes from America, Europe, Africa, and India produce seasonal top-of-atmosphere radiative flux changes that exceed those of anthropogenic greenhouse gases (several $W m^{-2}$) and daily surface radiative flux changes that are larger still (several tens of $W m^{-2}$) (Bergstrom and Russell, 1999; Russell et al., 1999b; Meywerk and Ramanathan, 1999; Ramanathan, 1999; Satheesh et al., 1999). These surface flux changes affect not only convection and clouds but also sea-surface evaporation rates and probably regional hydrology (e.g., Huebert et al., 1999a,b; Ramanathan, 1999).

The aerosol plume emanating from eastern Asia over the Pacific is already one of the world's major aerosol plumes, and it is expected to increase rapidly over the next several decades as a result of Asian economic development. It differs in several important ways (see below) from the American, European, African, and Indian plumes studied in TARFOX, ACE-2, and INDOEX. Hence, it is probably the most important continental aerosol plume to study now (Huebert et al., 1999a,b).

The overall goal of the proposed research is to assess the radiative effects of the aerosols in this Asia-Pacific regional plume. The approach will be to make airborne sunphotometer measurements in the ACE-Asia 2001 Intensive Observation Period (IOP, late March-April) in coordination with satellite and other suborbital measurements and to conduct closure analyses and integrated assessments that combine the satellite and suborbital measurements. In FY 2000 our research will focus on preparing for the 2001 IOP by:

- (a) Developing analysis techniques for mixed aerosols in the polluted and clean boundary layer and in elevated desert dust layers,
- (b) Investigating the sensitivity of satellite optical depth retrieval techniques and predictions of aerosol-induced radiative forcing to the properties of aerosols likely to be seen over the Western Pacific and Asia, and
- (c) Providing information about the location and frequency of occurrence of the Asian aerosol plume to the ACE-Asia planning process.

Our FY 2000 research will build on results for American, European and African aerosols obtained in TARFOX and ACE-2. Research in FY 2001-02 will include:

- (a) Measuring aerosol optical depth and extinction spectra along with water vapor column contents using an Ames Airborne Tracking Sunphotometer in coordination with satellite, in situ, and other remote measurements during the IOP (March-April 2001),
- (b) Assessing the quality of the combined ACE-Asia measurements and analysis models by conducting extensive closure studies, and

(c) Providing an initial assessment of the radiative effects of aerosols over the Western Pacific and Asia by applying and extending the techniques developed in FY 2000.

2.2 Relationship of the Proposed Research to Other Proposed Measurements and Analyses

This proposal requests support for measurements with the 6-channel Ames Airborne Tracking Sunphotometer (AATS-6) on the NCAR C-130 in the 2001 intensive field study, plus certain limited analyses, as summarized above and specified in Sections 2.4-2.6. We envision the research proposed here to NOAA as part of a larger ACE-Asia effort by the Ames airborne sunphotometer/satellite team. Separately, we are seeking NASA and Navy support for the other components of this overall effort, including measurements by our 14-channel unit (AATS-14) on the CIRPAS Twin Otter. Recognizing that both funding and platform participation in ACE-Asia are uncertain, we are currently maintaining the flexibility to assemble a research approach that is most productive given the final levels of funding and participation by others. If, for example, the NCAR C-130 does not participate in ACE-Asia (because of aerosol inlet problems or funding limitations), we propose that the measurement funding requested here be applied to either (a) AATS-6 measurements on an ACE-Asia ship (as we did in ACE-2) or (b) AATS-14 measurements on the Twin Otter.

We have also submitted a proposal, "Satellite-Sunphotometer Studies of Aerosol, Water Vapor and Ozone Roles in Climate-Chemistry-Biosphere Interactions", to the NASA Modeling and Data Analysis Research (MDAR) Program. That proposal includes no funds for measurements, instead requesting funding for modeling and analysis of data acquired in field experiments such as SAFARI-2000 and ACE-Asia. The specific tasks proposed to NASA MDAR are: (1.1) Optical Modeling of Smokes and Other Aerosols Expected in SAFARI 2000, (1.2) Ozone-Aerosol Separation Algorithm Refinement and Simulations, (1.3) Water Vapor Retrieval Refinement, (1.4) Aerosol Column Size Distribution and Mass Retrieval Algorithm Development, (1.5) Quick-Look Analyses and Comparisons to Satellite Data, (1.6) Preliminary Aerosol Radiative Effect Calculations, (2.1) Satellite Validation Studies, (2.2) Update of Aerosol Optical Models, Including Mineral Dusts, (2.3) Aerosol Evolution and Budget Studies, (2.4) Aerosol Chemical-Physical-Optical Closure Studies, (2.5) Aerosol Radiative Effect Calculations, and (2.6) Integrated Analyses and Assessments. Funding requested from NASA MDAR is \$225K, \$267K, and \$309K in FY00, FY01, and FY02, respectively; to date the proposal has not been selected for funding.

In an effort to limit the cost of the current proposal (which includes both measurements and analyses) the analyses proposed here are very limited compared to the MDAR list above. If the MDAR proposal is funded, the analyses proposed here will benefit from the MDAR analyses. If the MDAR proposal is not funded, the analyses proposed here can still produce a published research product, especially from the combined analysis efforts in FY2000 and FY2002. Efforts in FY2001 will be limited primarily to measurements (including preparations) and initial data reduction and quality checks (including preliminary closure comparisons).

Regardless of the sunphotometer/aircraft measurement configuration ultimately chosen, we will pursue our overall goal of assessing the radiative effects of aerosols in the Asia-Pacific region to the extent possible with the suborbital and satellite measurement data sets and the analysis funding available.

Sections 2.3-2.5 summarize ACE-Asia's goals and overall approach, as well as the expected role of satellite and sunphotometer measurements in relation to in situ and other remote measurements. Section 2.6 describes the proposed research tasks.

2.3 ACE-Asia Goals, Overall Approach, and the 2001 Intensive Field Study

The Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) is the fourth in a series of aerosol characterization experiments organized by the International Global Atmospheric Chemistry Program (IGAC). Each ACE is designed to integrate suborbital and satellite measurements and models so as to reduce the uncertainty in calculations of the climate forcing due to aerosol particles (Huebert et al., 1999b). ACE-Asia focuses on aerosol outflow from Asia to the Pacific basin because (1) Asian anthropogenic emissions and mineral dust are very different from the environments of previous ACE experiments, and (2) Expected increases in Asian emissions have the potential to cause large changes in radiation budgets, cloud microphysics, and hydrological output over the coming decades.

The goals of ACE-Asia are to determine and understand the properties and controlling factors of the aerosol in the anthropogenically modified atmosphere of Eastern Asia and the Northwest Pacific and to assess their relevance for radiative forcing of climate (Huebert et al., 1999b). Subsidiary objectives are to:

1. Determine the physical, chemical, and radiative properties of the major aerosol types in the Asian Pacific region, determine their state of mixing, and investigate the relationships among these properties.
2. Quantify the physical and chemical processes controlling the evolution of aerosols in the Asian Pacific region and in particular their physical, chemical, and radiative properties.
3. Develop procedures to extrapolate aerosol properties and processes from local to regional and global scales, and assess the regional direct and indirect radiative forcing by aerosols in the Eastern Asia and Northwest Pacific region.

ACE-Asia will include a network of ground stations operated over the 2000-2004 timeframe, with intensive, multiplatform field studies to focus on specific objectives. The first intensive field study (previously called the Survey and Evolution Component, AA-SEC) is described in the overview by Huebert et al. (1999a). Planned for March-April 2001, it has the following goals (Huebert et al., 1999b):

- determine the physical, chemical and radiative properties of the aerosol in the ACE-Asia region and assess the vertical, regional and temporal (diurnal to multi-day) variability of these properties,
- assess the major processes controlling the oxidation mechanisms of aerosol precursor gases and the formation, evolution and deposition of aerosol particles,
- quantify the direct radiative effect of the combined natural and anthropogenic aerosol in the ACE-Asia study area,
- refine satellite aerosol retrievals in the ACE-Asia region so that satellite observations can be used to obtain a high temporally and spatially resolved assessment of the clear-sky direct effect of aerosols on radiative transfer,
- improve the parameterizations used in chemical transport models in order to obtain more accurate regional distributions of aerosol properties, and
- test and refine radiative transfer models used with chemical transport models to calculate direct radiative forcing by aerosol particles.

To address these goals flight plans and ship operations will be directed to sample regional aerosol features (e.g. dust layers, urban and industrial plumes) under different synoptic meteorological patterns and at various distances from shore. Quantifying aerosol direct radiative forcing will require the integration of multiple measurement and modeling approaches. Radiative transfer models, coupled with chemical transport models, will be used to partition the radiative effects of aerosols between the natural and anthropogenic components and thus quantify aerosol direct radiative forcing. These models must rely on accurate parameterizations of aerosol properties. Satellites will be used to assess the temporal and spatial variability in aerosol columnar extinction. These observations can be used to assess the direct radiative effect of the combined natural and anthropogenic aerosol. However, the algorithms used for these retrievals must again rely on accurate parameterizations of aerosol properties. In-situ measurements of aerosol chemical, physical, and radiative properties and radiative fluxes throughout the vertical column can be used to directly quantify the radiative effect of the combined natural and anthropogenic aerosol and provide the parameterizations needed for satellite retrievals and models. The combination of in-situ measurements, columnar extinction measurements (surface-based, air and space-borne radiometers), radiative flux measurements and models will produce an overdetermined data set that can be used to evaluate the combined uncertainty of the models and measurements used to assess the direct radiative forcing of aerosols in the ACE-Asia study area.

The AA-SEC omnibus proposal to NSF (Huebert et al., 1999a) describes a plan to address these questions using three US mobile platforms (the NCAR C-130, the CIRPAS Twin Otter, and a NOAA or UNOLS ship) plus 1-2 enhanced ground stations working in coordination with ships, aircraft, lidars, and surface sites from a variety of nations (e.g., Japan, Korea, China, and Taiwan). The operations base is tentatively chosen as Iwakuni Marine Base, near Hiroshima in southern Japan. Efforts will be made to coordinate some AA-SEC flights with the NASA TRACE-P program, which will be focusing on photochemistry in Asian outflow at about the same time, using measurements on the NASA DC-8 and P-3. If possible AA-SEC will coordinate some observations with an airborne simulator for the PICASSO-CENA spaceborne lidar.

As in previous ACEs, satellite data products will be used by ACE-Asia both in realtime to plan and direct flights and for post-campaign analyses. For example, ACE-Asia flights that study the plumes of desert dust emanating from Asia will be guided by satellite observations that identify locations of maximum dust concentrations and areas where concentration gradients can most easily be studied. In flights designed to study aerosol evolution, satellite observations of the decay of backscatter by the continental plume will be used to identify regions where removal mechanisms seem especially effective. As amplified in the following section, our proposed research will use satellite data in exploratory studies before the 2001 intensive and in more complete studies during and after the intensive, and it will also contribute to the validation and refinement of satellite retrievals.

2.4 Satellite Measurements and Retrievals Relevant to ACE-Asia and the Proposed Research

Satellite measurements of Earth-reflected radiance have been used to derive both aerosol optical depths and aerosol effects on radiative fluxes. As recently summarized by King et al. (1999), several approaches have been used to retrieve aerosol optical depth (AOD) from radiances or reflectances measured by a wide range of satellite sensors (e.g., AVHRR on NOAA-7, -9, -11, -14, POLDER and OCTS on ADEOS, ATSR-2 on ERS-2, SeaWiFS on OrbView-2). Mishchenko et al. (1999) have shown that these optical depth retrievals depend strongly on cloud screening methods and radiometer calibration, and, to a lesser extent, on models of aerosol single scattering albedo ω , scattering phase function P_a , and surface reflectance. Although a complete treatment requires numerical multiple scattering techniques (e.g., Mishchenko et al., 1999), the dependence on ω and P_a can be illustrated by using the linearized single scattering approximation (e.g., Stowe et al., 1997; King et al., 1999),

$$AOD_{SAT} = 4\mu_0\mu_v \frac{L_a}{\omega P_a(\Psi)}, \quad (1)$$

in which L_a is the aerosol contribution to the satellite-measured radiance, μ_0 and μ_v are sun and view zenith cosines, and Ψ is scattering angle.

Aerosol effects on radiative fluxes and budgets can also be derived from satellite measurements in several ways. One approach is to use satellite flux products, which are obtained by using directional and spectral models to convert the radiance(s) at the satellite viewing angle and wavelength band(s) to directionally and spectrally integrated fluxes (e.g., Ramanathan et al., 1989). For example, Minnis et al. (1993) used monthly-averaged ERBE-retrieved fluxes to show that, in August 1991, the Pinatubo volcanic aerosol increased upwelling fluxes by 10 W m^{-2} in the 5°N to 5°S band and 4 W m^{-2} in the 40°N to 40°S band. More recently, Ramanathan (1999) and Satheesh and Ramanathan (1999) used CERES data from the TRMM satellite to show that the tropospheric aerosol observed in INDOEX increased diurnal mean upwelling fluxes by $\sim 10 \text{ W m}^{-2}$ or more.

Another approach to obtaining aerosol-induced flux changes from satellite data is to combine satellite-retrieved AOD with other aerosol and surface properties in a radiative transfer calculation. For example, Figure 1 shows the aerosol-induced change in net shortwave flux at the tropopause obtained in this way by Bergstrom and Russell (1999). They used the AVHRR/NOAA AODs reported by Husar et al. (1997) for the period July 1989-June 1991 in combination with aerosol intensive properties determined primarily in TARFOX. Those intensive properties, which included optical depth wavelength dependence and spectra of single scattering albedo and scattering asymmetry parameter across the solar wavelength range (0.3 to $4 \mu\text{m}$), were also checked against initial properties from ACE-2. Comparing frames e and f of Figure 1 shows that changing ω from 0.9 to 1.0, while keeping AOD and all other properties unchanged, increased the computed annual regional average flux change by 37% (from -3.5 to -4.8 W m^{-2}). However, Eq. (1) shows that, when starting with a given satellite radiance L_a , changing ω (or P_a) also changes retrieved AOD. Hence, a fully consistent treatment starting with satellite radiance L (rather than, e.g., the Husar et al. AOD values used by Bergstrom and Russell) must take this dependence into account. The resulting dependences are best calculated with a multiple scattering code but can be illustrated using the diurnal average flux-change approximation of Haywood and Shine (1995), Chylek and Wong (1995), and Russell et al. (1997),

$$\Delta_a F \hat{=} \frac{1}{2} F_T T^2 (1 - A_c) \{ \omega \overline{\beta_a} (1 - \overline{R_s})^2 - 2(1 - \omega) \overline{R_s} \} AOD, \quad (2)$$

in which $\Delta_a F \hat{=}$ is the aerosol-induced change in upwelling flux at the top of atmosphere, F_T is the solar constant, T is atmospheric transmission, A_c is cloud fraction, β_a is the aerosol upscatter fraction, and R_s is surface albedo. Substituting (1) in (2) yields

$$\Delta_a F \uparrow = 2F_0 T^2 (1 - A_c) \{ \omega \bar{\beta}_a (1 - \bar{R}_s)^2 - 2(1 - \omega) \bar{R}_s \} \mu_0 \mu_v \frac{L_a}{\omega P_a(\Psi)} \quad (3)$$

Changing aerosol complex refractive index m to change ω can produce even larger changes in $P_a(\Psi)$ at satellite view angles. For example, Stowe et al. (1997) report that increasing m_i from 0 to 0.01 in the model of Ignatov et al. (1995) decreased ω by only 10% while simultaneously decreasing $P_a(\Psi)$ by ~30%, thus decreasing their product by ~37% and increasing AOD_{SAT} by ~59% (cf. Eq. (1)).

In the proposed research we will start with the approach of Bergstrom and Russell (1999) and then explore more advanced and self-consistent ways of deriving effects of the Asia-Pacific regional aerosol on radiative fluxes. That is, we will start in FY2000 with satellite-retrieved AOD data sets and retrieval algorithms that already exist or are being developed. Examples include the 1989-91 AVHRR retrievals of Husar et al. (1997), other AVHRR retrievals by Durkee et al. (2000) and Nakajima and Higurashi (1998), 1996-97 results from OCTS and POLDER on ADEOS, 1994-99 AVHRR data available in PATMOS data sets, or the 1985-88 AVHRR/NOAA 9 preliminary aerosol climatology of Mishchenko and Geogdzhayev (1999), developed as part of the Global Aerosol Climatology Program. To the extent possible we will ascertain the aerosol models used in deriving those AODs. We will then use those aerosol models together with the derived AODs in radiative transfer calculations of aerosol-induced flux changes $\Delta_a F$ at various altitudes (e.g., top of atmosphere, tropopause, surface). The calculations will use the generalized two-stream model used by Bergstrom and Russell (1999), the Fu-Liou broadband radiative transfer model (Fu and Liou, 1992; 1993) used by Redemann et al. (2000b), and/or the radiative perturbation approach (Box and Trautman, 1994; Sendra and Box, 1999) pioneered by the group of Co-I Michael Box. Next we will investigate the effect, on both retrieved AOD and calculated $\Delta_a F$, of realistic changes in the aerosol models. The changed aerosol models will be based both on published results for aerosols expected in the ACE-Asia area and on measurements during ACE-Asia. An analogous approach for Indian Ocean aerosols has been used by Rajeev et al. (2000). Our goal is to derive by 2002 a self-consistent set of satellite-based AOD and $\Delta_a F$ fields that reflect aerosol measurements made in ACE-Asia. We will also examine ERBE and CERES flux data products (analogous to the approaches of Minnis et al. and Ramanathan [see above]) for aerosol effects, and we will compare them to our results obtained from satellite AOD data.

We will study aerosol radiative effects over both land and ocean. Data from the new EOS Terra platform, launched December 18, 1999, will aid in this regard. Terra carries the sensors MODIS, MISR, MOPITT, ASTER, and a new CERES system to complement that already flying on TRMM. The multi-angle measurements of MISR, and the improved spectral resolution of both MODIS and MISR, will increase chances of accurate AOD retrievals over land. TOMS and TOMS-like sensors on several platforms (e.g., Earth Probes, and the new GLI on ADEOS II) will provide regional maps of both column ozone and aerosol index over land and water. POLDER on ADEOS II will provide aerosol measurements that benefit from its polarization sensing capability, helping to extend retrievals over land. SeaWiFS and MODIS data products will also include aerosols in regions impacted by Asian continental outflow over both the Pacific and Indian Oceans.

All these satellite products will require validation over a wide range of conditions. Although validation studies for the sensors listed above will be conducted prior to the ACE-Asia 2001 intensive (e.g., in SAFARI-2000 in southern Africa), the intensive will provide new conditions and data sets with which to extend those validation studies. For example, the yellowish soil dust aerosol layers emanating from Asia are known to have different spectral absorption characteristics than the red-brown Sahara dust (e.g., Nakajima et al., 1989); however, these differences are not well quantified. ACE-Asia measurements during yellow dust plume events should provide important new validation data sets for EOS Terra and TOMS aerosol and ozone products, and for water-leaving radiance products from SeaWiFS as well as MODIS. The ACE-Asia suborbital measurements will also be essential in extending data outside the satellite overpass times and locations.

2.5 Expected Role of Airborne Sunphotometry in ACE-Asia

The AA-SEC Science and Implementation Plan (Huebert et al., 1999a) specifies aerosol optical depth measurements as part of the minimum requirement for both surface and airborne platforms, and it includes an Ames tracking sunphotometer as part of the "Highest Priority – Essential" payload for the NCAR C-130 and part of the recommended payload for the CIRPAS Twin Otter. Some of the reasons for these inclusions are summarized below. The AA-SEC Plan (Huebert et al., 1999a) also includes a variety of schematic C-130 and Twin Otter flight plans, each designed to address specific questions. For example, they include flights at

several altitudes across the edges of elevated dust layers and upwind and downwind of urban-industrial plumes. Some flight patterns include legs with the Twin Otter flying near the surface under a plume while the C-130 overflies the plume with a downward-looking lidar. In this section we outline how airborne sunphotometer measurements and analyses could contribute to such flights and their analyses, using examples from recent studies with AATS-6 and -14 data. For reference, Figure 2 shows AATS-6 and -14 channel wavelengths in relation to atmospheric spectra.

As noted above, satellite validation is an essential element of ACE-Asia, because of the expected major role of satellite measurements in assessing regional, seasonal, and interannual aerosol effects. Airborne sunphotometer measurements flown along transects near the land or ocean surface in ACE-Asia can provide aerosol optical depth spectra useful for validating products from simultaneous satellite overflights. This is illustrated in Figure 3, which shows a comparison of airborne sunphotometer (AATS-6), AVHRR, and ATSR-2 data acquired in TARFOX over the Atlantic Ocean when the UW C-131A flew across a gradient of aerosol optical depth between latitudes 37-39 N (Veefkind et al., 1999). The flight path was chosen using half-hourly GOES images to locate the aerosol gradient. Comparing Figures 3a and 3b shows that the ATSR-2 retrieval reproduces the sunphotometer-measured optical depth gradient better than the AVHRR retrieval. Comparing 3c and 3d shows how the ATSR-2 retrieval also matches the sunphotometer-determined Angstrom exponent better than AVHRR. In the ACE-Asia 2001 intensive GOES or other realtime satellite imagery could be used to design flight legs across the gradient from plume core to edge during a subsequent satellite overpass (by, e.g., EOS Terra carrying MODIS, MISR, and CERES). AATS optical depth spectra on legs flown near the surface would provide validation data for comparisons such as those in Figure 3.

Figure 4 shows other comparisons from TARFOX, when AATS-6 on the UW C-131A underflew the MODIS Airborne Simulator (MAS) on the NASA ER-2 (Tanre et al., 1999). These comparisons focus on the wavelength dependence of optical depth and illustrate how the magnitude of optical depth affects the success of the MAS retrieval. Specifically, the good agreement in wavelength dependence and magnitude obtained when optical depth is relatively large (>0.2 for $\lambda < 1 \mu\text{m}$) degraded when optical depth decreased below ~ 0.05 (causing MAS-measured radiance from the aerosol to decrease relative to radiance from the ocean surface). Establishing such limits and uncertainties is a major reason for validation studies. In the ACE-Asia 2001 intensive they could be conducted for a variety of aerosol types and conditions, over different types of land surfaces (e.g., densely vs. sparsely vegetated), the ocean, and on transects spanning land and ocean.

Figure 5 illustrates how a change in aerosol type can affect the validity of satellite retrievals. The scatter diagram in Figure 5a (Durkee et al., 2000) compares AVHRR-retrieved aerosol optical depth (AOD) at 630 and 860 nm with AOD measured in ACE-2 by a variety of sunphotometers on land, ship, and aircraft. Data points with $\text{AOD} > 0.25$ are cases where an elevated layer of Sahara dust was present; those with $\text{AOD} < 0.25$ had no Sahara dust. For all 23 cases shown the AVHRR standard error of estimate is 0.025 for 630 nm wavelength and 0.023 for 860 nm. Note that in the dust-containing cases ($\text{AOD} > 0.25$), the AVHRR-retrieved AODs are biased low compared to sunphotometer optical depths (by amounts ranging from 0.01 to 0.08) whereas in the dust-free cases AVHRR-retrieved values are biased slightly high. Figure 5b compares AOD spectra for a case from Figure 5a where dust was present; Figure 5c is the analogous comparison for a dust-free case (Livingston et al., 2000; Schmid et al., 2000). These cases show clearly the change in bias of the AVHRR retrieved values between dust-free and dust-containing cases, especially at 860 nm. Possible reasons for this change include differences between the wavelength-dependent single scattering albedos and phase functions of the Sahara dust and those assumed in the AVHRR retrieval (Durkee et al., 2000), plus the height of the absorbing dust aerosols (e.g., Quijano et al., 1999). In the ACE-Asia 2001 intensive field study, sunphotometer underflights of different types of aerosol (e.g., desert dust vs. industrial emissions) could provide analogous tests of the validity of satellite products as a function of aerosol type. Vertical profile flights by the sunphotometer aircraft would provide simultaneous in situ data on aerosol physicochemical properties, helping to complete the picture.

In comparisons like those in Figures 4 and 5 it is important to understand all significant error sources for each measurement technique and to quantify their combined effect in realistic error bars. The error bars on the AATS data result from a comprehensive error analysis (Russell et al., 1993) and include contributions from uncertainties in calibration, signal measurement, Rayleigh scattering, absorbing gases (O_3 , O_4 , H_2O , NO_2), air mass, and diffuse light. They are produced routinely in our analyses and will be in the proposed work.

AA-SEC flight plans (Huebert et al., 1999a) also call for the C-130 and Twin Otter to ascend from near the surface through the aerosol layers aloft while collecting in situ data on aerosol size distribution, chemistry, light scattering and absorption. Figure 6 illustrates the ability of the airborne sunphotometers to measure vertical profiles of multiwavelength aerosol optical depth and extinction during such aircraft profiles (Schmid et al., 2000). The case shown, obtained in ACE-2, documents an elevated layer of Sahara dust (~2-3.5 km asl) overlying a very clean layer (~1-2 km asl) and a moderately polluted marine boundary layer (<~1 km asl). Note that the wavelength dependence of extinction is very different in the marine and Sahara layers, with extinction nearly independent of wavelength between 380 and 864 nm in the Sahara layer, owing to the relatively large particles there. The ACE-Asia 2001 intensive is expected to reveal many occurrences of analogous layering, with different layers often having different sources and characteristics. Airborne sunphotometry combined with simultaneous in situ physicochemical-optical measurements will provide a rich data set for modeling such diverse, vertically structured aerosols and understanding their impact on satellite retrievals.

Closure studies that examine the degree of consistency between sunphotometer measurements, in situ measurements, and the models that link them are an important source of information on the strengths and weaknesses of the examined measurement and modeling techniques. A typical result from such a closure study is shown in Figure 7 (Schmid et al., 2000). The data were obtained in ACE-2 when the Pelican aircraft ascended through a marine boundary layer, carrying AATS-14 and a variety of in situ samplers. The optical depth spectrum labeled "Caltech OPC" was obtained by combining in situ size spectra with refractive index models obtained from size-resolved chemical composition measurements at a nearby surface site (which were consistent with size-integrated chemistry measured on the aircraft). The optical depths labeled "Neph+PSAP" were obtained by combining nephelometer measurements of aerosol light scattering (at 1 or 3 wavelengths) with absorption measurements from an absorption photometer.

The result in Figure 7 is typical in that the optical depth spectrum measured by sunphotometer (AATS-14) exceeds that calculated from the in situ measurements. Although some of the error bars overlap (e.g., the OPC-derived optical depth bars with the others), the fact that sunphotometer-measured optical depths nearly always exceed in situ derived optical depths in ACE-2, TARFOX, and other comparisons (e.g., Clarke et al., 1996; Hegg et al., 1997; Hartley et al. 2000; Kato et al., 1999; Remer et al., 1997) points to a systematic phenomenon that bears explaining. Possible reasons include (1) loss of semivolatile aerosol material (e.g., organics) during in situ sampling that is not accounted for in the in situ analyses (e.g., Eatough et al., 1996), and (2) light absorption by a gas along the sunphotometer viewing path that is not accounted for in the sunphotometer analyses (e.g., Halthore et al., 1998). Explaining this persistent difference could have fundamental implications for our understanding of aerosol properties and/or radiative transfer. The ACE-Asia 2001 intensive could present excellent opportunities for studying this question, if one or more aircraft carry enhanced instrumentation for measuring organic aerosols and spectral flux radiometers (Pilewskie et al., 1998) that can help to distinguish aerosol absorption from gas absorption (see below).

At the same time the AATS data could provide a test of the backscatter-to-extinction ratios and other assumptions used to derive optical depths from the C-130 lidar. Such comparisons could be a valuable precursor to validation flights for PICASSO-CENA conducted after its launch (scheduled for 2003). This would yield AATS vertical profiles of multiwavelength extinction (as in Figure 6) for comparison to lidar profiles (as was done, e.g., in ACE-2 by Schmid et al., 2000; and Welton et al., 2000). Comparisons of the profiles of sunphotometer extinction, lidar backscatter, and in situ size distribution can yield best-fit values of complex refractive index and single-scattering albedo for each sampled layer, as demonstrated by Redemann et al. (1998, 2000a,b) with PEM-West and TARFOX measurements (see Figure 11). These values could be compared to single scattering albedos from the in situ scattering and absorption measurements (see below) and to complex refractive indices from the in situ chemistry measurements, taking into account the local humidity and effects of aerosol hygroscopicity.

Another type of closure study relating in situ and sunphotometer measurements compares in situ size distributions with those retrieved from sunphotometer optical depth spectra. Such a comparison is shown in Figure 8 (Schmid et al., 2000). Within the optically effective diameter range (~0.22 to 8 μm) the AATS-14 retrieved distribution replicates the main features of the in situ distribution, although for some diameters (~0.7 to 3 μm) the AATS-14 retrieved distribution exceeds the in situ values. This exceedence is in accord with the systematic difference between sunphotometer and in situ optical depth spectra noted above.

The size distribution retrieval in Figure 8 used the constrained linear inversion program of King et al. (1978) and a refractive index model for the polluted marine boundary layer aerosol recommended by Tanre et al. (1997). In the proposed research new aerosol optical models appropriate to the ACE-Asia aerosols will be developed and used both in the King inversion procedure and in a new procedure based on the recent results of Remer et al. (1998) regarding persistent features of multimodal aerosols. Sunphotometer optical depth spectra will also be provided to Co-Investigator Dr. Michael Box, whose group will analyze them to extract aerosol size information. Techniques they have developed for this purpose include table look-up, analytic inversion in the anomalous diffraction approximation, singular function theory, and analytic eigenfunction theory (e.g., Box et al., 1992; Viera and Box, 1987). They have recently developed a covariance matrix method to accurately separate the aerosol contribution in trace gas channels. This same technique is currently being extended to develop better techniques to obtain aerosol size information, as well as the direct extraction of aerosol surface area and volume.

Sunphotometer-derived column or layer size distributions could be validated by comparisons to in situ data from profile flights (as, e.g., in Figure 8), and used when underflying plumes to document changes in overlying aerosol effective radius, surface area, and mass. This information should be valuable in aerosol evolution studies (e.g., to see whether sedimentation modifies the dust size-distribution in a predictable way) and reduce the need for aircraft profiles, which take flight time away from horizontal legs. However, deriving accurate information on aerosol size, surface area, and mass from sunphotometer optical depth spectra requires algorithms that incorporate size-dependent effective refractive indices that are appropriate to the aerosol on the sunphotometer viewing path. Incorporation of simultaneous AATS data on water vapor will be investigated as a means of accounting for possible humidification effects on refractive index (which will be different in sulfate layers and dust layers, for example).

Water in both vapor and condensed phases has a strong influence on radiative transfer and on aerosol size and composition. Given the horizontal contrast in water vapor sources among continental and marine parts of air mass trajectories, one can expect important variations in water vapor and associated aerosol changes in ACE-Asia. AATS-6 and AATS-14 measure water vapor transmission in the 940-nm band (cf. Figure 2), thus permitting simultaneous retrievals of water vapor column contents and aerosol optical depth spectra. This ability to measure water vapor and aerosols on a common viewing path should be useful in studying aerosol-water vapor interactions. The water vapor sensing ability is illustrated in Figure 9, which compares an AATS-14 water vapor profile to simultaneous in situ measurements (Schmid et al., 2000). Figure 10 shows a scatter plot comparing AATS-6 water vapor columns with those obtained by integrating radiosonde profiles in ACE-2 (Livingston et al., 2000). The rms difference, 0.10 g cm^{-2} over a range of 1.5 to 3.3 g cm^{-2} , is typical of other comparisons we have made. For example, in the fall 1997 Water Vapor Intensive Observation Period (IOP) of the Atmospheric Radiation Measurement (ARM) program, AATS-6 water vapor column retrievals agreed within 0.11 g cm^{-2} with results from the Global Positioning System (2 locations), 3 microwave radiometers, radiosondes, and two other sunphotometers. The range of water vapor column amounts during the IOP was 1 to 5 g cm^{-2} .

ACE-Asia planning documents stress the importance of realtime or quick-turnaround data analyses and open data access as means of maximizing the scientific return from the measurements. Both AATS-6 and AATS-14 have demonstrated this in previous campaigns like TARFOX and ACE-2, where they produced realtime color plots of aerosol optical depth spectra that were used in flight direction and planning, as well as in daily science team meetings (which included comparisons to satellite products). With adequate preparation, this capability could be extended in the ACE-Asia 2001 intensive to include realtime or quick-turnaround displays of water vapor and ozone overburdens, as well as of the effective radius, volume, and/or mass of the overlying aerosol column. The latter would be useful for observing the evolution of aerosol size when, for example, following a plume downwind, or for mapping cross-plume column masses. Acquiring analogous plume-integrated sizes and masses with in situ sensors would require time-consuming vertical profiling (thus reducing time available for horizontal surveys) and would subject the aerosols to the sampling challenges that are especially difficult on a vertically profiling aircraft. Providing the above-described realtime displays requires the development and testing of algorithms before the campaign, as described in the proposal to NASA MDAR mentioned in Section 2.2.

The AA-SEC Plan (Huebert et al., 1999a) also includes a variety of schematic C-130 and Twin Otter flight plans, each designed to address specific questions from the list above. For example, they include flights at several altitudes across the edges of elevated dust layers and upwind and downwind of urban-industrial

plumes. Some flight patterns include legs with the Twin Otter flying near the surface under a plume while the C-130 overflies the plume with a downward-looking lidar. This will permit comparisons between AATS-14 extinction profiles (like those shown in Figure 6) and backscatter and/or extinction profiles from the lidar. Both AATS-6 and AATS-14 have participated in such comparisons previously. In ACE-2, for example, Schmid et al. (2000) and Welton et al. (2000) compared lidar and airborne sunphotometer profiles in a Sahara dust layer over the Izana observatory in the Canary Islands. They got good agreement when the lidar analysis used a backscatter-to-extinction ratio derived from simultaneous ground-based sunphotometry. In TARFOX, Redemann et al. (2000a) derived best-fit complex refractive indices in aerosol layers by comparing simultaneous profiles of backscatter from an ER-2 lidar profile with profiles of extinction and relative size distribution from AATS-6 and optical particle counters on the UW C-131A. By combining the best-fit complex refractive indices with the relative size distribution profiles, Redemann et al. (2000b) then produced profiles of aerosol single scattering albedo (SSA). Figure 11 shows an example result, compared to the SSA profile obtained by Hartley et al. (2000) using simultaneous measurements of aerosol scattering, absorption, and scattering humidification factor.

Combining airborne sunphotometer optical depth profiles with radiative flux profiles is a potentially powerful way to determine the absorption properties (hence SSA) of the ambient aerosol, unperturbed by sampling processes. This is illustrated by the TARFOX results shown Figure 12 (Russell et al., 1999b). The data points show the aerosol-induced decrease in downwelling solar flux measured by pyranometers on the UK C-130 during two descents into aerosol layers over the Atlantic Ocean, plotted versus broadband aerosol optical depth derived from occulted pyranometer measurements (Hignett et al., 1999). (The absorbing gas and Rayleigh components have been removed from both the flux change and the optical depth using, e.g., concurrent water vapor measurements.) The curves show calculations of the expected flux change, based on aerosol size distributions retrieved from AATS-6 sunphotometer measurements on the UW C-131A, a real refractive index spectrum for aqueous sulfate, and a range of imaginary refractive indices giving the midvisible single-scattering albedos $\omega(550 \text{ nm})$ shown. Comparing the data points and curves shows that the best-fit value of $\omega(550 \text{ nm})$ is ~ 0.9 ; chi-square analyses using the error bars on the pyranometer optical depths and flux changes (the cross in Figure 12) yield $\omega(550 \text{ nm}) = 0.895 \pm 0.025$ and 0.905 ± 0.045 for July 25 and 27, respectively.

In the ACE-Asia 2001 intensive field study careful measurements by well calibrated and controlled flux radiometers on the same aircraft as AATS-6 or AATS-14 could permit analogous flux-change studies. For example, Dr. Peter Pilewskie of NASA Ames is proposing to put his Solar Spectral Flux Radiometers (SSFR, Pilewskie et al., 1998) on the C-130 and/or Twin Otter. Combining such spectral flux measurements with AATS optical depth measurements would permit much improved flux change studies. The spectral resolution of SSFR and AATS-6 or -14 will permit the type of flux change analysis shown in Figure 12 to be accomplished in a wide range of narrow (5 nm) spectral bands. This will permit, for example, solving for SSA as a function of wavelength. It will also aid in identifying absorption features that might be due to unknown gas spectroscopy, rather than aerosols. And it will help to identify artifacts that might be caused by cloud fragments or surface albedo effects. The measurements in Figure 12 were made over the ocean during a cloud-free period to minimize such effects. This will be done in ACE-Asia also; however, the fine spectral resolution in the SSFR flux measurements may allow the measurements to be extended over a uniform land surface, and may also allow some relaxation in the cloud-free criterion. This will be investigated. These types of measurements will also be carried out when an absorbing aerosol is carried over a uniform stratus deck; the underlying cloud reflectivity maximizes aerosol absorption in such a case. Asian dust outflow over coastal stratus in ACE-Asia could provide such an opportunity.

2.6. Proposed Tasks

For the funding requested in Section 3 we will provide the necessary personnel, equipment, and facilities, and will perform the following tasks.

2.6.1 Year One

2.6.1.1 Task 1.1: Satellite Data Acquisition. Acquire a representative suite of satellite data on aerosol optical depths in the ACE-Asia area. Consider results derived from AVHRR by several techniques (e.g., Husar et al., 1997; Durkee et al., 2000; Nakajima and Higurashi, 1998) and also results from OCTS and POLDER on the ADEOS satellite, SeaWiFS on the OrbView-2 satellite, and ATSR-2 on the ERS-2 satellite.

Coordinate with the investigators who are performing the satellite retrieval intercomparison for GACP. Investigate the TOMS absorbing and nonabsorbing aerosol data products for applicability.

2.6.1.2 Task 1.2: Preliminary Aerosol Optical Modeling. Survey existing optical models of aerosols in the polluted and clean marine boundary layer and in elevated dust layers; select those that seem most applicable to Asian outflow aerosols. Use previous (e.g., ACE-2, TARFOX) results for single scattering albedo, size distribution, and optical depth wavelength dependence determined by several techniques. Check results for consistency with size-resolved chemical composition and hygroscopicity measurements, and use trajectory analysis to help estimate soil dust chemical composition. Use shell-and-core calculations to investigate the dependence of aerosol absorption on relative humidity. For each aerosol type, provide spectra of extinction, single scattering albedo, scattering asymmetry parameter, and scattering phase function at satellite measuring angles. For soil dust aerosols, extend these spectra into the terrestrial infrared (wavelength > 4 microns).

2.6.1.3 Task 1.3: Satellite Sensitivity Studies. Compare the phase functions and single scattering albedos obtained in Task 1.2 with those assumed in the satellite retrievals used in Task 1.1. Provide a preliminary estimate of how using the more realistic properties would change the retrieved optical depths.

2.6.1.4 Task 1.4: Preliminary Estimates of Aerosol-Induced Radiative Flux Changes. Combine the intensive optical properties from Task 1.2 with the optical depths from Tasks 1.1 and 1.3 to estimate radiative flux changes caused by Asian aerosols over the Pacific. Include flux changes at top of atmosphere, tropopause, and surface. For soil dust aerosols include shortwave and longwave effects.

2.6.1.5 Task 1.5: Estimates of the location and frequency of occurrence of the Asian aerosol plume. From the data obtained in Task 1.1 and results of Tasks 1.3 estimate the year-to-year variation in the location and frequency of occurrence of the Asian plume in the ACE-ASIA measurement area. Provide the information to the ACE-ASIA science team for planning purposes.

2.6.2 Years Two and Three

2.6.2.1 Task 2.1: AATS-6 Integration and Test Flights on the NCAR C-130. We will work with NCAR personnel to integrate AATS-6 on the C-130 and will demonstrate science data acquisition on test flights.

2.6.2.2 Task 2.2: Pre- and Post-mission Calibrations. We will conduct pre- and post-mission calibrations of the water vapor and aerosol channels of AATS-6 at a mountaintop site (e.g., Mauna Loa Observatory) in ~February and ~May 2001. Efforts will be made to conduct the calibrations with other ACE-Asia sunphotometers, to permit intercomparisons.

2.6.2.3 Task 2.3: Airborne Sunphotometer Measurements. We will make measurements of aerosol optical depth and water vapor columns using AATS-6 on the NCAR C-130 during the ACE-Asia intensive in March-April 2001. We will provide quick-look data products (plots, electronic files) to the Science Team within 24 hours after each flight. We will provide calibrated, reanalyzed data products within nine months following the post-mission calibration.

2.6.2.4 Task 2.4: Intercomparisons, Validations, and Integrated Closure Analyses. Depending on our level of funding, we will perform selected intercomparisons and closure analyses of the type described in Sections 2.4 and 2.5. Data will be exchanged, archived, and released to the scientific community according to ACE-Asia protocols (Huebert et al., 1999b) and formats.

Satellite Validation Studies. Comparisons of the type shown in Figures 3-5 will be made between satellite data products and airborne sunphotometer aerosol optical depth spectra, wavelength dependence parameters (e.g., the Angstrom exponent), and water vapor column contents. The degree of agreement or disagreement found will be quantified in terms of root-mean-square differences and mean biases, all as functions of wavelength, aerosol type, and viewing condition (including surface type and solar and satellite angles). The airborne sunphotometer data can be used to assess the degree of variability within satellite pixels (including variations between surface sunphotometer sites), which may be particularly important near localized sources or plume edges or for measurements in broken cloud fields. Aerosol models assumed in the satellite retrievals will be compared to the aerosol models used or developed in Task 1.2, and also to aerosol properties determined from in situ measurements in ACE-Asia. Where significant differences in assumed and actual

aerosol properties are found, examples of adjusted satellite products can be produced, using the single scattering albedo and phase function of the actual aerosols. Possible shape effects for soil dust and sea salt aerosols can be investigated (e.g., Mishchenko et al., 1997; Kahn et al., 1997), as well as effects of the vertical distribution of absorbing and nonabsorbing aerosols (e.g., Clark et al., 1997; Quijano et al., 1999).

Update of Aerosol Optical Models, Including Mineral Dusts. The aerosol optical models used or developed in Task 1.2 will be updated using the suborbital measurements (e.g., in situ chemical, physical and optical, airborne sunphotometer, ground Sun/sky radiometer, and air and ground lidar). Areas of emphasis can include quantifying characteristic differences between African (reddish-brown) and Asian (yellowish) soil dust aerosols (e.g., Sokolik and Toon, 1999; Sokolik, 1999) and capturing changes that occur during downwind evolution of various aerosols (including dusts and smokes) as a result of agglomeration of different particles (e.g., soot, sulfates, nitrates), condensation of water and/or organic vapors, and photochemical reactions outside and inside of clouds. Particular emphasis will be placed on quantifying the wavelength- and humidity-dependent single scattering albedo of realistic multicomponent aerosols, since this parameter is so important in determining both AOD_{SAT} and aerosol radiative impacts on climate (including top-of-atmosphere forcing, surface forcing, stability changes, and cloud changes).

Aerosol Evolution and Budget Studies. If our proposal to NASA MDAR (see Section 2.2) is funded we will combine the algorithms developed in that work with airborne sunphotometer data acquired while underflying plumes and hazes in downwind and crosswind transects to study how aerosol sizes and masses evolve during downwind transport, and how various sources contribute to regional mass budgets. Efforts will be made to use the airborne sunphotometer water vapor measurements to estimate the condensed water content of overlying aerosols and thereby choose the most appropriate aerosol optical property models to use in the algorithms that retrieve size distribution and mass from optical depth spectra.

Aerosol Chemical-Physical-Optical Closure Studies. In addition to the satellite validation studies described above we plan to conduct closure studies that evaluate the mutual consistency of the sunphotometer data products, other remote, radiometric, and in situ measurements, and the models that link them. Examples include:

- Comparisons (as in Figure 7) between optical depth spectra measured by airborne sunphotometer and calculated from in situ measurements of size distribution, chemical composition (including condensed water), light scattering, and absorption on the same aircraft profile,
- Comparisons (as in Figure 8) between size distributions retrieved from airborne sunphotometer extinction or optical depth spectra and obtained from in situ measurements (after correcting for such sampling effects as evaporation, inlet size cutoffs, and composition-dependent calibration factors),
- Comparisons between sunphotometer optical depths and those obtained from lidar profiles using the backscatter-to-extinction values assumed in the lidar analyses. These backscatter-to-extinction ratios will also be compared to those derived from in situ measurements and the aerosol models developed in Tasks 1.1 and 2.2. Effects of nonsphericity in soil dust and seasalt aerosols will be considered, since lidar backscatter is sensitive to nonsphericity.
- (If the ACE-Asia proposal by Dr. Pilewskie is funded) Comparisons between radiative flux changes measured by SSFRs (Pilewskie et al., 1998) and calculated from simultaneously measured aerosol and gas properties. These comparisons will be analogous to those in Figure 12, with the advantage that both the flux changes (from SSFR) and the optical depths (from AATS-6 or -14) will be available in narrow wavelength bands. Hence best-fit aerosol single scattering albedos derived from analyses like those in Figure 12 will also be available as a function of wavelength.
- Comparisons of aerosol single scattering albedos derived by a variety of techniques, including (1) comparing lidar backscatter, sunphotometer extinction, and in situ size distribution profiles (e.g., Redemann et al., 2000a), (2) combining in situ measurements of aerosol light scattering, absorption, and hygroscopicity (e.g., Hegg et al., 1997; Hartley et al., 2000), (3) flux-change comparisons (e.g., Russell et al., 1999b), and (4) the optical modeling in Tasks 1.2 and this task. A comparison of results from techniques (1) and (2) is illustrated in Figure 11.

The above examples are only illustrative. Our experience has been that participation in multiplatform, multiagency campaigns like ACE-Asia presents many opportunities for comparisons and closure studies, some of which, though very important, were not anticipated in advance. These closure studies, which typically entail collaborations among several groups using disparate measurement and modeling techniques,

germinate during pre- and post-campaign science team meetings as well as during the campaigns. We expect that this will be the case during the proposed research.

2.6.2.5 Task 2.5: Aerosol Radiative Effect Calculations. We will expand on the radiative transfer modeling carried out in Task 1.4. by incorporating the aerosol fields actually observed by satellite during ACE-Asia. In addition, aerosol parameters obtained from the multi-instrument closure studies in Task 2.4 and those derived from the advanced mixed aerosol optical models outlined in Tasks 1.2 and 2.4 will be used to drive the radiative transfer codes. Our goal is to derive by 2002 a self-consistent set of satellite-based AOD and ΔF fields that reflect aerosol measurements made in ACE-Asia. We will also examine ERBE and CERES flux data products (analogous to the approaches of Minnis et al. and Ramanathan [see above]) for aerosol effects, and we will compare them to our results obtained from satellite AOD data.

2.7. Schedule

- 2000 C-130/AATS-6 integration planning, Boulder, CO (~May)
Acquire suite of Asia-Pacific satellite optical depth data (May-Sep)
Choose & develop Asia-Pacific aerosol optical models (May-Dec)
Western Pacific Geophysics Meeting, Tokyo (27-30 Jun)
IGARSS 2000, Honolulu, HI (24-28 Jul)
Investigate effect of model aerosol properties on satellite optical depths (Jul-Nov)
Estimate radiative flux changes (Jul-Dec)
ACE-Asia Science Team Meeting, Hawaii (Fall)
2001 Intensive Field Study Planning Meeting, Iwakuni Marine Base, Japan (~Sep/Oct)
- 2001 C-130/AATS-6 integration & test flights, Boulder, CO (~Jan)
Pre-mission sunphotometer aerosol/water vapor calibration, Mauna Loa Observatory, HI (Feb)
ACE-Asia intensive deployment, Iwakuni Marine Base, Japan (25 Mar-30 Apr)
Post-mission sunphotometer aerosol/water vapor calibration, Mauna Loa Observatory, HI (May)
Data reduction and initial closure tests (May-Dec)
ACE-Asia Science Team Meeting and Data Workshop (~Oct?)
ACE-Asia Special Session at Scientific Conference (primarily individual analyses; ~Dec?)
- 2002 Update optical models using ACE-Asia results (Jan-Aug)
Continuing closure studies (Jan-Dec)
Radiative flux change studies (Jan-Dec)
ACE-Asia Special Session at Scientific Conference (including integrated analyses; ~May?)
ACE-Asia Science Team Meeting and Data Workshop (~Sep?)
- 2003 ACE-Asia Special Journal Issues

2.8. References

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Welton, E.J., K.J. Voss, H.R. Gordon, H. Maring, A. Smirnov, B. Holben, B. Schmid, J.M. Livingston, P.B. Russell, P.A. Durkee, P. Formenti, M.O. Andrea, and O. Dobovik, Ground-based lidar measurements of aerosols during ACE-2: Instrument description, results, and comparisons with other ground based and airborne measurements, *Tellus*, in press, 2000.

3. BUDGET

4. STAFFING, RESPONSIBILITIES, AND VITAE

Dr. Philip Russell will be Principal Investigator. As such, he will supervise the work, lead the planning, and participate in the measurements and analyses, as well as selected presentations and publications. He will be responsible for the completion of the work within budget and schedule. Mr. John Livingston and Drs. Beat Schmid and Jens Redemann will use AATS-6 in the proposed measurements and participate in its preparation. They and Dr. Robert Bergstrom will participate in the development and use of algorithms and models and will lead and/or participate in specified data analyses, presentations, and publications. Ames will furnish additional engineering and technical personnel necessary to maintain, operate, and repair the instrumentation before, during, and after the calibrations and field measurements.

Dr. Michael Box of the University of New South Wales (UNSW) in Australia, along with selected members of his group (including Dr. Gail Box), will analyze AATS optical depth and extinction spectra using their innovative algorithms, with the goal of deriving particle size information, surface area and volume, from which radiative forcing calculations will also be performed. Dr. Box is seeking Australian support for this collaborative research, and no support for the UNSW effort is requested in this proposal.

(a) Philip B. Russell Abbreviated Curriculum Vitae

B.A., Physics, Wesleyan University (1965, Magna cum Laude; Highest Honors). M.S. and Ph.D., Physics, Stanford University (1967 and 1971, Atomic Energy Commission Fellow). M.S., Management, Stanford University (1990, NASA Sloan Fellow).

Postdoctoral Appointee, National Center for Atmospheric Research (1971-72, at University of Chicago and NCAR). Physicist to Senior Physicist, Atmospheric Science Center, SRI International (1972-82). Chief, Atmospheric Experiments Branch (1982-89), Acting Chief and Acting Deputy Chief, Earth System Science Division (1988-89), Chief, Atmospheric Chemistry and Dynamics Branch (1989-95), Research Scientist (1995-present), NASA Ames Research Center.

Currently, Member, Science Team for Global Aerosol Climatology Project (GACP; Investigation Title: Improved Exploitation of Field Data Sets to Address Aerosol Radiative-Climatic Effects and Development of a Global Aerosol Climatology). Member, Science Teams for SAGE II and SAGE III (satellite sensors of stratospheric aerosols, ozone, nitrogen dioxide, and water vapor). Primary responsibilities: analyses of volcanic aerosol properties and effects, development of the SAGE III Aerosol Algorithm Theoretical Basis Document (ATBD), and experiment design and data analyses to validate the satellite measurements.

Previously, NASA Ames Associate Fellow (1995-96, awarded for excellence in atmospheric research).

Previously, Co-coordinator for the CLEARCOLUMN component of the Second Aerosol Characterization Experiment (ACE-2) of the International Global Atmospheric Chemistry (IGAC) Project. Coordinator for IGAC's Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX). Convenor of TARFOX Special Sessions, Spring 1997 Meeting, American Geophysical Union (AGU). Coordinator, TARFOX special issues of *Journal of Geophysical Research* (1998-99). Program Co-Chair, International Specialty Conference on Visual Air Quality, Aerosols, and the Global Radiation Balance (Bartlett, New Hampshire, 10/1997). Member, Direct Aerosol Radiative Forcing Committee of IGAC Focus 8: Atmospheric Aerosols (1996-98).

Previously, Editor (1993, 1996) and Editor-in-Chief (1994-95), *Geophysical Research Letters*; Member, Board of Editors and Atmospheric Science Executive Committee, American Geophysical Union. Guest Editor, *Journal of Geophysical Research* Special Issues on "Midlatitude Stratospheric Dynamics and Cross-Tropopause Exchange," "Tropical Stratosphere-Troposphere Exchange," and "SAGE II Aerosol and Ozone Data Validation and Initial Data Use" (1988-93). Convenor, Sessions on the Atmospheric Effects of 1991 Pinatubo Eruption, AGU Fall Meeting (1992). Organizer and/or report editor, Workshops on "Requirements for a Very-High-Altitude Aircraft for Atmospheric Research," "Scientific Application of Remotely Piloted Aircraft Measurements of Radiation, Water Vapor, and Trace Gases to Climate Studies," and "Mission Measurement Strategies for the Subsonic Assessment Program" (1989-94). Member, Interagency Task Group on Airborne Geoscience (1987-89), Member, American Institute of Aeronautics and Astronautics (AIAA) Losey Atmospheric Sciences Award Selection Committee, (1986-87), Member, AIAA

Atmospheric Environment Technical Committee (1984-90), Invited Participant, World Meteorological Organization Experts Meeting on Aerosols and their Climatic Effects (1983), Invited Participant, NOAA Workshop on Global Large Aerosols (1982), Chair, American Meteorological Society International Committee on Laser Atmospheric Studies (1979-82, Member, 1978-82), Member, National Research Council Committee on Army Basic Research (1979-81), Member, American Meteorological Society Committee on Radiation Energy (1979-81).

Previously, Project Scientist, Small High-Altitude Science Aircraft (SHASA) Project to develop the Perseus A Remotely Piloted Aircraft (RPA, 1992-94), Member, Science/Aeronautics Seam Team of NASA Ames Reorganization Team (1994), Member, Ad Hoc Committee on the NASA Environmental Research Aircraft and Sensor Technology (ERAST) Program (1993-4), Member, NASA Red Team on Remote Sensing and Environmental Monitoring of Planet Earth (1992-3), Leader, NASA Ames Earth Science Advanced Aircraft (ESAA) Team (1990-94), Member, National Aero-Space Plane (NASP) Committee on Natural Environment (1988-94), Member, NASA Ames Strategy and Tactics Committee (1986-87), Chair, NASA Ames Atmospheric Science Strategy Review Team (1986-87), Manager, NASA Stratosphere-Troposphere Exchange Project (STEP, 1983-93), Member, NASA Solar-Terrestrial Observatory Science Study Group (1979-80), Member, NASA Atmospheric Lidar Working Group (1977-79), Member, NASA Spacelab 2 Investigations Review Panel (1977).

NASA Exceptional Service Medal (1988, for managing Stratosphere-Troposphere Exchange Project), NASA Space Act Award (1989, for invention of Airborne Autotracking Sunphotometer), and NASA Group Achievement Awards (1994, for Stratospheric Photochemistry, Aerosols and Dynamics Expedition; 1991, for Airborne Arctic Stratospheric Expedition; and 1989, for Airborne Antarctic Ozone Experiment). Graham Prize (1965, outstanding undergraduate in natural science, Wesleyan University). Member, Phi Beta Kappa and Sigma Xi.

Patent, "Airborne Tracking Sunphotometer Apparatus and System" (U.S. Pat. No. 4,710,618, awarded 1987)

PUBLICATIONS

(as specified in the Program Announcement, all publications in the past three years, with up to five other relevant papers)

2000:

Collins, D. R., et al. (with P. B. Russell), In situ aerosol size distributions and clear column radiative closure during ACE-2. *Tellus B*, in press, 2000.

Durkee, P. A., et al. (with P. B. Russell), Regional aerosol properties from satellite observation: ACE-1, TARFOX and ACE-2 results. *Tellus B*, in press, 2000.

Ferrare, R., et al. (with P. B. Russell), Comparisons of aerosol optical properties and water vapor among ground and airborne lidars and sun photometers during TARFOX, *J. Geophys. Res.*, in press, 2000a.

Ferrare, R., et al. (with P. B. Russell), Comparisons of LASE, aircraft, and satellite measurements of aerosol optical properties and water vapor during TARFOX, *J. Geophys. Res.*, in press, 2000b.

Gassó, S., et al. (with P. B. Russell), Influence of humidity on the aerosol scattering coefficient and its effect on the upwelling radiance during ACE-2. *Tellus B*, in press, 2000.

Hartley, W. S., P. V. Hobbs, J. L. Ross, P. B. Russell and J. M. Livingston, Properties of aerosols aloft relevant to direct radiative forcing off the mid-Atlantic coast of the United States, *J. Geophys. Res.* (2nd Special Issue on TARFOX), in press, 2000.

Ismail, S., E.V. Browell, R. Ferrare, S. A. Kooi, M. Clayton, V. Brackett, P.B. Russell, LASE measurement of aerosol and water vapor profiles measured during TARFOX, *J. Geophys. Res.* (2nd Special Issue on TARFOX), in press, 2000.

Pilewskie, P., M. Rabette, R. Bergstrom, J. Marquez, B. Schmid, and P. B. Russell, The discrepancy between measured and modeled downwelling solar irradiance at the ground: Dependence on water vapor, *Geophys. Res. Lett.*, 27, 137-140, 2000.

Russell, P. B., and J. Heintzenberg, An overview of the ACE-2 Clear Sky Column Closure Experiment (CLEARCOLUMN), *Tellus B*, in press, 2000.

Welton, E. J., et al. (with P. B. Russell), Ground-based lidar measurements of aerosols during ACE-2: Instrument description, results, and comparisons with other ground-based and airborne measurements. *Tellus B*, in press, 2000.

[See 2 *Tellus B* papers led by Livingston and Schmid in their CVs.]

[See 2 *J. Geophys. Res.* papers led by Redemann in his CV.]

1999:

Bergstrom, R. W., and P. B. Russell, Estimation of aerosol radiative effects over the mid-latitude North Atlantic region from satellite and in situ measurements. *Geophys. Res. Lett.*, 26, 1731-1734, 1999.

Russell, P. B., P. V. Hobbs, and L. L. Stowe, Aerosol properties and radiative effects in the United States Mid-Atlantic haze plume: An overview of the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), *J. Geophys. Res.*, 104, 2213-2222, 1999a.

Russell, P. B., J. M. Livingston, P. Hignett, S. Kinne, J. Wong, and P. V. Hobbs, Aerosol-induced radiative flux changes off the United States Mid-Atlantic coast: Comparison of values calculated from sunphotometer and in situ data with those measured by airborne pyranometer, *J. Geophys. Res.*, 104, 2289-2307, 1999b.

Tanre, D., L. A. Remer, Y. J. Kaufman, S. Mattoo, P. V. Hobbs, J. M. Livingston, P. B. Russell, and A. Smirnov, Retrieval of aerosol optical thickness and size distribution over ocean from the MODIS airborne simulator during TARFOX, *J. Geophys. Res.*, *104*, 2261-2278, 1999.

Veefkind, J. P., G. de Leeuw, P. A. Durkee, P. B. Russell, P. V. Hobbs, and J. M. Livingston, Aerosol optical depth retrieval using ATSR-2 and AVHRR data during TARFOX, *J. Geophys. Res.*, *104*, 2253-2260, 1999.

[See *Geophys. Res. Lett.* paper led by Schmid in his CV.]

1998:

Boucher, O. et al. (with P. B. Russell), Intercomparison of models representing direct shortwave radiative forcing by sulfate aerosols, *J. Geophys. Res.*, *103*, 16,979-16,998, 1998.

[6 2-page peer-reviewed extended abstracts in *J. Aerosol. Sci.* describing TARFOX and ACE-2 results.]

1997:

Hamill, P., E. J. Jensen, P. B. Russell, and J. J. Bauman, "The Life Cycle of Stratospheric Aerosol Particles", *Bull. Am. Meteor. Soc.*, *78*, 1395-1410, 1997.

Hansen, J., et al. (with P. Russell), "Forcings and Chaos in Interannual to Decadal Climate Change." *J. Geophys. Res.* *102*, 25,679-25,720, 1997.

Hegg, D. A., J. Livingston, P. V. Hobbs, T. Novakov, and P. B. Russell, "Chemical Apportionment of Aerosol Column Optical Depth Off the Mid-Atlantic Coast of the United States," *J. Geophys. Res.*, *102*, 25,293-25,303, 1997.

Russell, P. B., S. Kinne and R. Bergstrom, "Aerosol Climate Effects: Local Radiative Forcing and Column Closure Experiments," *J. Geophys. Res.*, *102*, 9397-9407, 1997.

Five Other Relevant Papers:

Russell, P. B., J. M. Livingston, R. F. Pueschel, J. J. Bauman, J. B. Pollack, S. L. Brooks, P. Hamill, L. W. Thomason, L. L. Stowe, T. Deshler, E. G. Dutton, and R. W. Bergstrom. "Global to Microscale Evolution of the Pinatubo Volcanic Aerosol, Derived from Diverse Measurements and Analyses." *J. Geophys. Res.*, *101*, 18,745-18,763, 1996a.

Russell, P.B., J. M. Livingston, R. F. Pueschel, J. A. Reagan, E.V. Browell, G. C. Toon, P.A. Newman, M.R. Schoeberl, L.R. Lait, L. Pfister, Q. Gao, and B. M. Herman. "Post-Pinatubo Optical Depth Spectra vs. Latitude and Vortex Structure: Airborne Tracking Sunphotometer Measurements in AASE II." *Geophys. Res. Lett.*, *20*, 2571-2574, 1993.

Russell, P.B., and M.P. McCormick. "SAGE II Aerosol Data Validation and Initial Data Use: An Introduction and Overview." *J. Geophys. Res.*, *94*, 8335-8338, 1989.

Russell, P.B., T.J. Swissler, M.P. McCormick, W.P. Chu, J.M. Livingston, and T.J. Pepin. "Satellite and Correlative Measurements of the Stratospheric Aerosol: I. An Optical Model for Data Conversions." *J. Atmos. Sci.*, *38*, 1270-1294, 1981.

Russell, P.B., J.M. Livingston, and E.E. Uthe. "Aerosol-Induced Albedo Change: Measurement and Modeling of an Incident." *J. Atmos. Sci.*, *36*, 1587-1608, 1979.

(b) Beat Schmid
Abbreviated Curriculum Vitae

Bay Area Environmental Research Institute
3430 Noriega Street
San Francisco, CA 94122

Education

M.S. (Lizentiat)	1991	Institute of Applied Physics, University of Bern, Switzerland
Ph.D.	1995	Institute of Applied Physics, University of Bern, Switzerland
Postdoctoral Fellowship	1995-97	Institute of Applied Physics, University of Bern, Switzerland

Professional Experience

Bay Area Environmental Research Institute, San Francisco, CA (1997-Present)

-Senior Research Scientist

University of Arizona, Tucson, AZ (Oct. 1995 -Jan. 1996)

-Visiting Scientist

University of Bern, Switzerland (1989-1997)

-Research Assistant (1989-1995)

-Postdoctoral Researcher (1995-1997)

Scientific Contributions

- 7 years of leading studies in ground-based and airborne sun photometry: instrument design and calibration, development and validation of algorithms to retrieve aerosol optical depth and size distribution, H₂O and O₃.
- Participate with the NASA Ames Airborne Sun photometers in ACE-2 (North Atlantic Regional Aerosol Characterization Experiment, 1997, Tenerife). Extensive comparison of results (closure studies) with other techniques: lidar, optical particle counters, nephelometers, and satellites.

- Participate with the NASA Ames Airborne Sun photometers in the Dep. of Energy, Atmospheric Radiation Measurement (ARM) program integrated fall 1997 intensive observation period (IOP) in Oklahoma. Appointed to lead sun photometer intercomparison. Extensive comparison of water vapor results with radiosondes, microwave radiometers, lidar, and Global Positioning System.
- Test of candidate methods for SAGE 3 satellite ozone/aerosol separation using airborne sunphotometer data.
- Application of NOAA/AVHRR satellite data to monitor vegetation growth in Switzerland

Scientific Societies/Committees

-American Geophysical Union

Publications

(As specified in Program Announcement, all publication in 1997-2000 with up to five other relevant papers)

2000:

- Schmid, B.**, J. M. Livingston, P. B. Russell, P. A. Durkee, H. H. Jonsson, D. R. Collins, R. C. Flagan, J. H. Seinfeld, S. Gassó, D. A. Hegg, E. Öström, K. J. Noone, E. J. Welton, K. J. Voss, H. R. Gordon, P. Formenti, and M. O. Andreae, Clear sky closure studies of lower tropospheric aerosol and water vapor during ACE-2 using airborne sunphotometer, airborne in-situ, spaceborne, and ground-based measurements, *Tellus*, in press, 2000.
- Collins, D. R., Jonsson, H. H., Seinfeld, J. H., Flagan, R. C., Gassó, S., Hegg, D. A., **Schmid, B.**, Russell, P. B., Livingston, J. M., Öström, E., Noone, K. J., Russell, L. M. and Putaud, J. P. In situ aerosol size distributions and clear column radiative closure during ACE-2. *Tellus*, in press, 2000.
- Durkee, P. A., Nielsen, K. E., Smith, P. J., Russell, P. B., **Schmid, B.**, Livingston, J. M., Holben, B. N., Collins, D. R., Flagan, R. C., Seinfeld, J. H., Noone, K. J., Öström, E., Gassó, S., Hegg, D., Russell, L. M., Bates, T. S. and Quinn, P. K. Regional aerosol properties from satellite observations: ACE-1, TARFOX and ACE-2 results. *Tellus*, in press, 2000.
- Gassó, S., Hegg, D. A., Noone, K. J., Covert, D. S., **Schmid, B.**, Russell, P. B., Livingston, J. M., Durkee, P.A. and Jonsson, H. H. Influence of humidity on the aerosol scattering coefficient and its effect on the upwelling radiance during ACE2. *Tellus*, in press, 2000.
- Livingston, J. M., V. Kapustin, **B. Schmid**, P. B. Russell, P. K. Quinn, T. S. Bates, P. A. Durkee, P. J. Smith, V. Freudenthaler, D. S. Covert, S. Gasso, D. Hegg, D. R. Collins, R. C. Flagan, J. H. Seinfeld, V. Vitale, and C. Tomasi, Shipboard sunphotometer measurements of aerosol optical depth spectra and columnar water vapor during ACE-2 and comparison to selected land, ship, aircraft, and satellite measurements. *Tellus*, in press, 2000.
- Welton, E. J., Voss, K. J., Gordon, H. R., Maring, H., Smirnov, A., Holben, B. N., **Schmid, B.**, Livingston, J. M., Russell, P. B., Durkee, P. A., Formenti, P., Andreae, M. O. and Dubovik, O. Ground-based lidar measurements of aerosols during ACE-2: lidar description, results, and comparisons with other ground-based and airborne measurements. *Tellus*, in press, 2000.
- Redemann, J., R.P. Turco, K.N. Liou, P.B. Russell, R.W. Bergstrom, **B. Schmid**, J.M. Livingston, P.V. Hobbs, W.S. Hartley, S. Ismail, R.A. Ferrare, E.V. Browell. Retrieving the Vertical Structure of the Effective Aerosol Complex Index of Refraction From a Combination of Aerosol In Situ and Remote Sensing Measurements During TARFOX. *Journal of Geophysical Research*, in press, 2000.
- Ferrare, R., S. Ismail, E. Browell, V. Brackett, M. Clayton, S. Kooi, S. H. Melfi, D. Whiteman, G. Schwemmer, K. Evans, P. Russell, J. Livingston, **B. Schmid**, B. Holben, L. Remer, A. Smirnov, P. Hobbs. Comparisons of aerosol optical properties and water vapor among ground and airborne lidars and sun photometers during TARFOX. *Journal of Geophysical Research*, in press, 2000.
- Pilewskie, P., M. Rabette, R. Bergstrom, J. Marquez, **B. Schmid**, and P. B. Russell. The discrepancy between measured and modeled downwelling solar irradiance at the ground: Dependence on water vapor, *Geophys. Res. Lett.*, 27, 137-140, 2000.

1999:

- Schmid B.**, J. Michalsky, R. Halthore, M. Beauharnois, L. Harrison, J. Livingston, P. Russell, B. Holben, T. Eck, and A. Smirnov, Comparison of Aerosol Optical Depth from Four Solar Radiometers During the Fall 1997 ARM Intensive Observation Period, *Geophys. Res. Lett.*, Vol. 26, No. 17, 2725-2728, 1999.

1998:

- Schmid, B.**, P.R. Spyak, S.F. Biggar, Ch. Wehrli, J. Sekler, T. Ingold, C. Mätzler, and N. Kämpfer, "Evaluation of the applicability of solar and lamp radiometric calibrations of a precision Sun photometer operating between 300 and 1025 nm." *Applied Optics*, Vol. 37, No. 18, 3923-3941, 1998.

[5 2-page peer-reviewed extended abstracts describing TARFOX and ACE-2 results in *J. Aerosol Sci.*, Vol. 29, Suppl. 1 and 2.]

1997:

- Schmid, B.**, C. Mätzler, A. Heimo, and N. Kämpfer, Retrieval of Optical Depth and Size Distribution of Tropospheric and Stratospheric Aerosols by Means of Sun Photometry. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 35, No. 1, 172-182, 1997.

Two other relevant papers:

- Schmid, B.**, K. J. Thome, P. Demoulin, R. Peter, C. Mätzler, and J. Sekler, Comparison of Modeled and Empirical Approaches for Retrieving Columnar Water Vapor from Solar Transmittance Measurements in the 0.94 Micron Region. *Journal of Geophysical Research*, Vol. 101, No. D5, 9345-9358, 1996.
- Schmid, B.**, and C. Wehrli, Comparison of Sun Photometer Calibration by Langley Technique and Standard Lamp. *Applied Optics*, Vol. 34, No. 21, 4500-4512, 1995.

(c) Jens Redemann
Abbreviated Curriculum Vitae

Research Scientist, Bay Area Environmental Research Institute
MS-245, NASA Ames Research Center, Moffett Field, CA 94035-1000
Phone: (650) 604-6259 Fax: (650) 604-3625, email: jredemann@mail.arc.nasa.gov

PROFESSIONAL EXPERIENCE

Research Scientist Bay Area Environmental Research Institute, San Francisco.	April 1999 to present
Research Assistant University of California, Los Angeles, Department of Atmospheric Sciences.	May 1995 to March 1999
Lecturer University of California, Los Angeles, Department of Atmospheric Sciences.	Jan. 1999 to March 1999
Tutor Ivy West Educational Services, Marina Del Rey, CA.	1997 to 1998
Research Assistant Free University of Berlin, Germany. Department of Physics.	June 1994 to April 1995

EDUCATION

Ph.D. in Atmospheric Sciences. University of California, Los Angeles. Specialization: atmospheric physics and chemistry.	1999
M.S. in Atmospheric Sciences. University of California, Los Angeles. Specialization: atmospheric physics and chemistry.	1997
M.S. in Physics. Free University of Berlin, Germany. Specialization in experimental physics and mathematics.	1995

RELEVANT RESEARCH EXPERIENCE

- Developed inversion algorithms (C and IDL) and data analysis tools for aircraft-based lidar and sunphotometer measurements during field experiments (PEM, TARFOX).
- Compared remotely sensed data to aerosol in situ measurements and devised techniques to retrieve the vertical structure of aerosol optical properties and radiative effects.
- Involved in the development of a multi-wavelength, ground-based lidar system at the Free University of Berlin, Germany.
- Provided solutions to scientific and numerical problems pertaining to aerosol physics and performed validation measurements relevant to Clean Room Technology for the computer chip industry.
- Specialized course work in atmospheric sciences, geophysical fluid dynamics, cloud physics, radiative transfer and remote sensing.

HONORS

Invited Speaker at the Atmospheric Chemistry Colloquium for Emerging Senior Scientists (ACCESS V).	June 1999
Outstanding Student Paper Award, American Geophysical Union - fall meeting.	1998
NASA Global Change Research Fellowship Awards.	1996-1998
UCLA Neiburger Award for excellence in the teaching of the atmospheric sciences.	1997

ORGANIZATIONS

American Association for Aerosol Research, American Geophysical Union, Co-president of the UCLA - Atmospheric Sciences Graduate Student Group.

RELEVANT PUBLICATIONS

2000:

Redemann, J., R.P. Turco, K.N. Liou, P.B. Russell, R.W. Bergstrom, B. Schmid, J.M. Livingston, P.V. Hobbs, S. Ismail, E.V. Browell. Retrieving the Vertical Structure of the Effective Aerosol Complex Index of Refraction From Aerosol In Situ and Remote Sensing Methods During TARFOX, *J. Geophys. Res.*, in press.

Redemann, J., R.P. Turco, K.N. Liou, P.B. Russell, R.W. Bergstrom, P.V. Hobbs, E.V. Browell. Case Studies of the Vertical Structure of the Aerosol Radiative Forcing During TARFOX, *J. Geophys. Res.*, in press.

1999:

Redemann, J., P.B. Russell, P. Hamill. Measurements and Modeling of Aerosol Absorption and Single Scattering Albedo at Ambient Relative Humidity, Presented at the AGU 1999 Fall Meeting, Dec. 13-17, San Francisco, CA, 1999.

1998:

Redemann, J., R.P. Turco, R.F. Pueschel, M.A. Fenn, E.V. Browell and W.B. Grant. A Multi-Instrument Approach for Characterizing the Vertical Structure of Aerosol Properties: Case Studies in the Pacific Basin Troposphere, *J. Geophys. Res.*, 103, 23,287 - 23,298, 1998.

Redemann, J., R.P. Turco, R.F. Pueschel, E.V. Browell, W.B. Grant. Combining Data From Lidar and In Situ Instruments to Characterize the Vertical Structure of Aerosol Optical Properties, Presented at the Nineteenth International Laser Radar Conference, Annapolis, MD, July 6-10, 1998, *NASA/CP-1998-207671/PTL*, pp.95-99, 1998.

Before 1997:

Redemann, J., R.P. Turco, R.F. Pueschel, E.V. Browell, W.B. Grant. Comparison of Aerosol Measurements by Lidar and In Situ Methods in the Pacific Basin Troposphere, in '*Advances in Atmospheric Remote Sensing with Lidar*', A. Ansmann, R. Neuber, P. Rairoux, U. Wandinger (eds.), pp.55-58, Springer, Berlin, 1996.

Pueschel, R.F.; D.A. Allen, C. Black, S. Faisant, G.V. Ferry, S.D. Howard, J.M. Livingston, J. Redemann, C.E. Sorensen, S. Verma. Condensed Water in Tropical Cyclone "Oliver", 8 February 1993, *Atmospheric Research*, 38, pp.297-313, 1995.

**(d) John Livingston
Abbreviated Curriculum Vitae**

Senior Research Meteorologist, Applied Physical Sciences Laboratory,
SRI International, Menlo Park, CA 94025

Specialized Professional Competence

Atmospheric physics and meteorology; atmospheric radiometry; computer simulation of atmospheric remote sensing systems; numerical analysis and inversion of in-situ and remotely sensed atmospheric data

Representative Research Assignments at SRI (Since 1978)

Acquisition and analysis of ground-based, airborne, and shipboard sunphotometer measurements
Validation of satellite particulate extinction measurements (SAM II, SAGE I, and SAGE II), and corresponding studies of the global distribution of stratospheric aerosols
Analysis of *in situ* measurements of stratospheric and tropospheric aerosols
Acquisition, modeling and analysis of Differential Absorption Lidar measurements of tropospheric ozone
Simulation of passive sensor radiance measurements to infer range to an absorbing gas
Experimental study of aerosol effects on solar radiation using remote sensors
Error analysis and simulation of lidar aerosol measurements
Analysis of lidar propagation through fog, military smoke, and dust clouds
Evaluation of the lidar opacity method for enforcement of stationary source emission standards
Weather forecasting for large-scale air pollution field study
Testing and evaluation of an offshore coastal dispersion computer model
Application of objective wind field and trajectory models to meteorological measurements

Professional Experience

Research Meteorologist to Senior Research Meteorologist, SRI International (1978-present)
Research assistant, University of Arizona Institute of Atmospheric Physics (1974-1977)
NASA Kennedy Space Center (1975-1976): participant in thunderstorm electrification studies

Academic Background

University of Notre Dame Year-in-Japan Program (1971-1972), Sophia University, Tokyo, Japan
B.S. summa cum laude in earth sciences (1974), University of Notre Dame, Notre Dame, IN
M.S. in atmospheric sciences (1977), University of Arizona, Tucson, AZ
M.B.A. with highest honors (1992), Santa Clara University, Santa Clara, CA

Honors

NASA Ames Research Center Contractor of the Year (1997), NASA Certificate of Recognition (1992) for co-authored technical paper, NASA Group Achievement Award (1989) for Airborne Antarctic Ozone Experiment

Professional Associations

American Geophysical Union

PUBLICATIONS

2000:

- Collins, D. R., et al. (with J. M. Livingston), In situ aerosol size distributions and clear column radiative closure during ACE-2. *Tellus B*, in press, 2000.
- Durkee, P. A., et al. (with J. M. Livingston), Regional aerosol properties from satellite observation: ACE-1, TARFOX and ACE-2 results. *Tellus B*, in press, 2000.
- Ferrare, R., et al. (with J. M. Livingston), Comparisons of aerosol optical properties and water vapor among ground and airborne lidars and sun photometers during TARFOX, *J. Geophys. Res.*, in press, 2000a.
- Ferrare, R., et al. (with J. M. Livingston), Comparisons of LASE, aircraft, and satellite measurements of aerosol optical properties and water vapor during TARFOX, *J. Geophys. Res.*, in press, 2000b.
- Gassó, S., et al. (with J. M. Livingston), Influence of humidity on the aerosol scattering coefficient and its effect on the upwelling radiance during ACE-2. *Tellus B*, in press, 2000.
- Hartley, W. S., P. V. Hobbs, J. L. Ross, P. B. Russell and J. M. Livingston, Properties of aerosols aloft relevant to direct radiative forcing off the mid-Atlantic coast of the United States, *J. Geophys. Res.* (2nd Special Issue on TARFOX), in press, 2000.
- Livingston, J. M., V. N. Kapustin, B. Schmid, P. B. Russell, P. K. Quinn, T. S. Bates, P. A. Durkee, P. J. Smith, V. Freudenthaler, M. Wiegner, D. S. Covert, S. Gassó, D. Hegg, D. R. Collins, R. C. Flagan, J. H. Seinfeld, V. Vitale and C. Tomasi, Shipboard sunphotometer measurements of aerosol optical depth spectra and columnar water vapor during ACE-2 and comparison with selected land, ship, aircraft, and satellite measurements. *Tellus B*, in press, 2000.
- Redemann, J., et al. (with J. M. Livingston), Retrieving the Vertical Structure of the Aerosol Complex Index of Refraction From Aerosol In Situ and Remote Sensing Methods During TARFOX. *J. Geophys. Res.* 2nd TARFOX special issue, in press, 2000.
- Schmid, B., et al. (with J. M. Livingston), Clear sky closure studies of lower tropospheric aerosol and water vapor during ACE-2 using airborne sunphotometer, airborne in-situ, space-borne, and ground-based measurements. *Tellus B*, in press, 2000.
- Welton, E. J., et al. (with J. M. Livingston), Ground-based lidar measurements of aerosols during ACE-2: Instrument description, results, and comparisons with other ground-based and airborne measurements. *Tellus B*, in press, 2000.

1999:

- Russell, P. B., J. M. Livingston, P. Hignett, S. Kinne, J. Wong, and P. V. Hobbs, Aerosol-induced radiative flux changes off the United States Mid-Atlantic coast: Comparison of values calculated from sunphotometer and in situ data with those measured by airborne pyranometer, *J. Geophys. Res.*, 104, 2289-2307, 1999.
- Tanre, D., L. A. Remer, Y. J. Kaufman, S. Mattoo, P. V. Hobbs, J. M. Livingston, P. B. Russell, and A. Smirnov, Retrieval of aerosol optical thickness and size distribution over ocean from the MODIS airborne simulator during TARFOX, *J. Geophys. Res.*, 104, 2261-2278, 1999.
- Veefkind, J. P., G. de Leeuw, P. A. Durkee, P. B. Russell, P. V. Hobbs, and J. M. Livingston, Aerosol optical depth retrieval using ATSR-2 and AVHRR data during TARFOX, *J. Geophys. Res.*, 104, 2253-2260, 1999.
- Schmid, B., J. Michalsky, R. Halthore, M. Beauharnois, L. Harrison, J. Livingston, P. Russell, B. Holben, T. Eck, and A. Smirnov, Comparison of aerosol optical depth from four solar radiometers during the Fall 1997 ARM Intensive Observation Period, *Geophys. Res. Lett.*, 104, 2261-2278, 1999.

1998:

[6 2-page peer-reviewed extended abstracts in *J. Aerosol. Sci.* describing TARFOX and ACE-2 results.]

1997:

- Hegg, D. A., J. Livingston, P. V. Hobbs, T. Novakov, and P. B. Russell, Chemical Apportionment of Aerosol Column Optical Depth Off the Mid-Atlantic Coast of the United States. *J. Geophys. Res.*, 102, 25,293-25,303, 1997.

Five Other Relevant Papers:

- Livingston, J.M., and P. B. Russell, Retrieval of aerosol size distribution moments from multiwavelength particulate extinction measurements. *J. Geophys. Res.*, 94, 8425-8433, 1989.
- Pueschel, R.F., J. M. Livingston, G. V. Ferry, and T. E. DeFelice, Aerosol abundances and optical characteristics in the Pacific basin free troposphere. *Atmos. Environ.*, 28, 951-960, 1993.
- Pueschel, R.F., J. M. Livingston, P. B. Russell, and S. Verma, Physical and optical properties of the Pinatubo volcanic aerosol: aircraft observations with impactors and a Sun-tracking photometer. *J. Geophys. Res.*, 99, 12,915-12,922, 1994.
- Russell, P. B., J. M. Livingston, R. F. Pueschel, J. J. Bauman, J. B. Pollack, S. L. Brooks, P. Hamill, L. W. Thomason, L. L. Stowe, T. Deshler, E. G. Dutton, and R. W. Bergstrom, Global to Microscale Evolution of the Pinatubo Volcanic Aerosol, Derived from Diverse Measurements and Analyses. *J. Geophys. Res.*, 101, 18,745-18,763, 1996.
- Russell, P.B., J.M. Livingston, and E.E. Uthe, Aerosol-Induced Albedo Change: Measurement and Modeling of an Incident. *J. Atmos. Sci.*, 36, 1587-1608, 1979.

**(e) Robert W. Bergstrom
Vita**

B.S., Mechanical Engineering, Oregon State University (1968). M.S. and Ph.D., Mechanical Engineering, Purdue University (1969 and 1972). J.D., Law, Stanford University (1983). Member of the California Bar (1983-present).

Post-Doctoral Fellow, Mainz University, Germany (1972-1973). National Research Associate, NASA Ames Research Center (1974-1977). Senior Scientist, Systems Application Inc., San Rafael CA (1977 – 1980). Associate, Law Firm of McCutchen, Doyle, Brown and Enersen, San Francisco (1983-1984). Assistant Regional Counsel, U.S. EPA, Region IX, San Francisco, (1984-1992).

Founder of the Bay Area Environmental Research Institute, San Francisco, CA (1992). Currently, Director of Research. Guest Investigator on the UARS Satellite Science Team using the satellite data to explore the effects of the Pinatubo aerosol on atmospheric radiation. Principal Investigator on several Cooperative Agreements with NASA Ames Research Center. Currently investigating the effects of aerosols on atmospheric radiation during ACE-2.

Publications

2000:

Pilewskie, P., M. Rabette, R. Bergstrom, J. Marquez, B. Schmid, and P. B. Russell, The discrepancy between measured and modeled downwelling solar irradiance at the ground: Dependence on water vapor, *Geophys. Res. Lett.*, 27, 137-140, 2000.

1999:

Bergstrom, R.W. and P.B. Russell, Estimation of aerosol radiative effects over the mid-latitude North Atlantic region from satellite and in situ measurements, *Geophys. Res. Lett.*, 26, 1731-1734, (1999).

1998:

Sokolik, I., O.B. Toon and R.W. Bergstrom, "Modeling the Radiative Characteristics of Airborne Mineral Aerosols at Infrared Wavelengths," *J. Geophys. Res.*, 103, 8813-8826, (1998).

Pilewskie, P. et al. (including R.W. Bergstrom), Observations of the spectral distribution of solar irradiance at the ground During SUCCESS," *Geophys. Res. Lett.*, 25, 1141-1144, 1998.

1997:

Russell, P.B. S. Kinne and R.W. Bergstrom: "Aerosol climate effects: Local radiative forcing and column closure experiments," *J. Geophys. Res.*, 102, 9397, (1997)

Kinne, S. et al (including R.W. Bergstrom), "Cirrus Cloud Radiative and Microphysical Properties from Ground Observations during FIRE '91," *J. Atmos. Sci.*, 54, 2320 (1997).

Seignuer, C., et al (including R.W. Bergstrom), "Formulation of a Second-Generation Reactive Plume and Visibility Model," *J. Air & Waste Man. Assoc.*, 47, 176 (1997)

Five Other Relevant Papers:

Wu, X.H., S. Seignuer and R. W. Bergstrom "Evaluation of a sectional representation of aerosol size distributions for calculations of optical properties," *J. Geophys. Res.* 101, 19277, (1996)

Bergstrom, R.W., B.L. Babson and T.P. Ackerman, "Calculation of Multiply Scattered Radiation in Clean Atmospheres," *Atmos. Environ.*, 15, 1821 (1981).

Bergstrom R.W. and J.T. Peterson, 'Comparison of Observed and Predicted Solar Radiation in an Urban Area," *J. App. Met.*, 16, 1107 (1977).

Bergstrom, R.W. "Extinction and Absorption Coefficients of Atmospheric Aerosols as a Function of Particle Size," *Beiträge zur Physik der Atmosphäre*, 46, 223 (1973).

Bergstrom, R.W. "Comments on the Estimation of the Absorption Coefficients of Atmospheric Aerosols," *Beiträge zur Physik der Atmosphäre*, 46, 198 (1973).

(f) Michael A. Box
Abbreviated Curriculum Vitae

B.Sc. (Hons) in Physics, Monash University (Australia), 1969. Ph.D. Physics, Sydney University (Australia), 1975.

Research Assistant, Melbourne University, 1975-76. Research Scientist, Institute for Atmospheric Optics and Remote Sensing (NASA Langley Research Center), 1977-79. Senior Postdoctoral Fellow, Atmospheric Physics, University of Arizona, 1979-80. Lecturer and Senior Lecturer, School of Physics, University of New South Wales, 1981-present. Executive Assistant to Head of School, 1998-2000.

Member, International POLDER Science Working Team. Member, International Aerosol Radiative Forcing Science Team.

Publications:

2000

M. J. Kay and M. A. Box, Radiative effects of absorbing aerosols and the impact of water vapour. *J. Geophys. Res.*, in press.

1999

G. Taha and G. P. Box, New method for inferring total ozone and aerosol optical thickness from multispectral extinction measurements using eigenvalue analysis. *Geophys. Res. Lett.*, 26, 3085-3088, 1999.

C. Sendra and M. A. Box, Retrieval of the phase function and scattering optical thickness of aerosols: a radiative perturbation theory application. *J. Quant. Spect. Rad. Trans.*, 64, 499-525, 1999.

M. A. Box and C. Sendra, Retrieval of the albedo and phase function from exiting radiances with radiative perturbation theory. *Applied Optics*, 38, 1636-1643, 1999.

C. Sendra and M. A. Box, Information content of the kernel matrix for the phase function retrieval problem. *Applied Optics*, 38, 1644-1647, 1999.

1998

P. E. Loughlin and M. A. Box, Investigating biological response in the UVB as a function of ozone variability using radiative perturbation theory. *Photochem. Photobiol.*, B43, 73-85, 1998.

1997

M. A. Box, P. E. Loughlin, M. Samaras and T. Trautmann, Applications of radiative perturbation theory to changes in absorbing gas. *J. Geophys. Res.*, 102, 4333-4342, 1997.

Five Other Relevant Papers:

G. P. Box, M. A. Box and J. Krucker, Information content and wavelength selection in multispectral radiometers. *J. Geophys. Res.*, 101, 19,211-19,214, 1996.

M. A. Box and T. Trautmann, Computation of anthropogenic sulphate aerosol forcing using radiative perturbation theory. *Tellus*, 46B, 33-39, 1994.

G. P. Box, K. M. Sealey and M. A. Box, Inversion of Mie extinction measurements using analytic eigenfunction theory. *J. Atmos. Sci.*, 49, 2074-2081, 1992.

G. Viera and M. A. Box, Information content analysis of aerosol remote sensing experiments using singular function theory. 1: extinction measurements. *Applied Optics*, 26, 1312-1327, 1987.

M. A. Box, P. Attard, G. Bryant and B. H. J. McKellar, Sum rules for Mie scattering. *J. Opt. Soc. Am. A*, 4, 795-799, 1987.

5. CURRENT AND PENDING SUPPORT

5.1 Principal Investigator

Short Title	Agency/Task No.	Investigator Months per Year	Dollar Value	Duration	Status
Improved Exploitation of Field Data Sets in GACP	NASA RTOP 622-44-75-10	3	\$175,000 in FY00 (+\$60,000 for field experiment)	10/98-9/01	Funded
ACE-2 Ship Sunphotometry and Integrated Analyses	NOAA Interagency Transfer of Funds NAAZ0000700110	2	\$99,000 in FY99	4/97-3/00	Funded
Composite Data Analyses for Pinatubo Volcanic Aerosols for SAGE II	NASA RTOP 621-45-51-10	2	\$57,000 in FY00	10/95-9/00	Funded
SAGE III Science Team	NASA RTOP 229-10-32-00	2	\$125,000 in FY99	11/90-9/00	Funded
Satellite-Sunphotometer Studies of Aerosol, Water Vapor and Ozone	NASA NRA 99-OES-44	3	\$225,000 in FY00	2/00-9/02	Requested

5.2 Co-Investigators*

Short Title	Agency/Task No.*	End Date	Investigator-Months per Year/ Level of Effort			
			J. Livingston	B. Schmid	J. Redemann	R. Bergstrom
Improved Exploitation of Field Data Sets in GACP	NASA RTOP 622-44-75-10	9/01	2/17%	3/25%	6/50%	
ACE 2 Ship Sunphotometry & Integrated Analyses	NOAA Interagency Transfer of Funds NAAZ0000700110	3/00	4/33%	2/17%	2/17%	2/16%
Composite Data Analyses for Pinatubo Volcanic Aerosols for SAGE II	NASA RTOP 621-45-51-10	9/00				
SAGE III Science Team	NASA RTOP 229-10-32-00	9/00	4/33%	5/42%	1/8%	
Satellite-Sunphotometer Studies of Aerosol, Water Vapor and Ozone	NASA NRA 99-OES-44	9/02	3.7/31%	3.7/31%	5.4/45%	2.4/20%

*PI, Award Amount, Period of Performance, Project Title, and Status are described in preceding Section 5.1.