

Implementation Strategy

Answering the questions posed above will require an extensive theoretical radiative transfer modeling effort and an intensive field measurement and analysis program.

● Radiative Forcing Sensitivity Studies

An accurate theoretical determination of the wavelength-dependent, direct radiative forcing due to tropospheric aerosols in a vertically inhomogeneous, absorbing and scattering atmosphere, must be carried out. These investigations should employ standard meteorological profiles, together with a compilation of various natural and anthropogenic aerosol optical properties, to examine the sensitivity of the radiative fluxes at various atmospheric levels to:

- Single-scattering parameters (such as phase function, single-scattering albedo, and extinction optical depth).
- Vertical profiles of aerosols.
- Spatial (e.g., latitudinal) and temporal (e.g., seasonal) variations due to changes in solar insolation, aerosol characteristics, and surface albedo.

These computations should use measured radiative properties for the aerosols. There may be limitations in their use, but identifying these will help define the types of measurements that must be carried out in field programs. These same computations will be used to complete column-closure experiments by comparing the radiation perturbations measured at the top, bottom, and other levels of the atmosphere with calculations based on *in situ* and remote sensing measurements of the properties of the aerosol in the atmospheric column.

● Field Measurements

The direct, clear-sky radiative forcing (i.e., change in net radiative flux) caused by aerosols is related to the aerosol optical thickness through such factors as the underlying surface albedo and the aerosol chemical composition and size distribution. This forcing can be measured by surface and airborne radiometers and derived from satellite-measured radiances using retrieval algorithms. Similarly, optical thickness can be measured by surface and airborne photometers and radiometers, and also derived from satellite-measured radiances. Plotting measured radiative flux changes versus measured optical depths and performing a regression calculation will provide an empirical measure of the sensitivity of radiative forcing to changes in aerosol optical thickness. An important TARFOX objective is to compare this empirical measure of sensitivity to results of detailed radiative computations that use aerosol chemical, physical, and optical properties obtained from simultaneous

measurements.

Because the effects of aerosol scattering on upwelling radiation are generally stronger over low-albedo surfaces, the field measurements will be carried out primarily over ocean areas. Also, because we wish to observe the strongest possible effects of anthropogenically produced aerosols, the field study will be carried out off the east coast of the United States, in the summer of 1996. An example of the magnitude and spatial structure of aerosol optical depth in this geographical area is shown in **Figure 2**. These optical thicknesses were derived from AVHRR radiances with the same technique used to obtain Figure 1, but the results in Figure 2 apply to a single week, rather than the three-month average in Figure 1. During the three-week intensive field period of TARFOX (July 10-31, 1996) it is expected that several strong haze episodes, similar to that in Figure 2, will be observed and sampled.

Figure 3 summarizes the platforms and measurements planned for TARFOX. Daily satellite measurements in the TARFOX study region during the intensive field measurement program may provide sufficient aerosol variability for the background (natural) tropospheric aerosol optical thickness to be inferred from the minima observed. The difference between the mean aerosol optical thickness for the period and the background value, when multiplied by the sensitivity factor (slope), will yield a regional estimate of tropospheric aerosol radiative forcing for summer-time conditions in the U.S. eastern seaboard. However, a definitive determination of what portion of this forcing is due to anthropogenic aerosols will require careful analysis of other simultaneous data on the chemical, physical, and optical properties of the aerosol. During the intensive period, the satellite-derived optical depths for particular non-cloudy scenes (i.e., for a particular satellite overpass) will be compared with *in situ* measurements of aerosol profiles from the aircraft and the surface. The airborne measurements will provide vertical distributions of aerosol chemical composition, mass, size, and radiative properties (e.g., light-scattering efficiency, absorption efficiency, hygroscopic growth factor). The surface measurements will provide similar information but at fixed locations. Also, spectral optical depth measurements will be provided from sun-photometers on the aircraft and at the surface for comparison with the satellite measurements and vertical integrals of extinction from *in situ* sensors. Variabilities in the optical depth derived from the various measurements for a number of such scenes will be related to various *in situ* quantities, such as the amount of sulfate present, various chemical tracers and local winds.

The measurements that must be taken in the field program phase of this project are discussed in more detail below.

- **Satellite Observations**

Satellite observations will play several roles in TARFOX:

- **Experiment Coordination:** During the TARFOX Intensive Field Period (July 10-31, 1996), early-morning 5-channel, half-hourly images from the geosynchronous GOES-8 satellite will be used to define regions most likely to be cloud-free and hazy during overpass times of the four polar satellites listed in

Section 7.2. This information will be used in directing TARFOX aircraft and selecting periods for intensive ground observations.

- **Validation of Aerosol Optical Thickness (AOT) and Earth Radiation Budget (ERB) Products.** Satellite-derived AOT will be compared to 1) measurements by airborne and surface-based sunphotometers, and 2) vertical integrals of scattering and absorption coefficients measured from the aircraft and calculated from particle size, composition, and hygroscopic growth factors. Satellite-derived ERB products will be compared to measurements by airborne and ground-based radiometers and calculations from optical depth spectra and *in situ* chemical, physical, and optical measurements.
- **Determination of Radiative Forcing/Optical Depth Relationships.** The sensitivity of radiative forcing to aerosol optical depth will be determined by both the empirical and the intensive measurement/calculation approaches described above.
- **Extension to Other Regions of the Globe.** Validated AOT and ERB retrieval algorithms will be used with satellite data sets for other regions of the globe expected to have similar aerosol properties. Temporal and spatial patterns of AOT, ERB, and their ratio will be determined.

- ***Aircraft Observations***

Aircraft in TARFOX will serve as mobile platforms for determining, in transects and vertical profiles, aerosol chemical, physical, and optical properties, plus precursor gases, tracers, water vapor, radiative fluxes (upward and downward, shortwave and longwave) and, potentially, backscatter profiles and radiance spectra useful for deriving aerosol, water vapor, and surface properties. Measured aerosol properties will include chemical composition, size distribution, light scattering and absorption coefficients, asymmetry factor, hygroscopic growth, and optical depth spectra (ultraviolet through near-infrared). Airborne lidar and imaging spectrometer measurements could provide vertical profiles of aerosol backscatter and water vapor, plus retrievals of aerosol and surface properties, analogous to retrievals performed by a variety of satellite radiometers (cf. Section 7.2). Because water vapor will have a strong effect on measured radiation fields, it will be measured by both *in situ* and remote techniques, so that aerosol and water vapor effects can be separated.

Flights will sample regions determined by satellite analyses to be cloud-free and have maximum aerosol optical depth, or alternatively will span contrasting hazy and clean areas. Coordinated flights by several aircraft will permit: (1) radiative flux measurements above or below aerosol layers while the layer optical depth is measured from below, (2) simultaneous *in situ* aerosol measurements at different heights, to document differences in the vertical column, and (3) simultaneous optical depth measurements from below and within or above sampled aerosol layers, to separate tropospheric haze optical depth from those of the stratosphere or thin cirrus clouds.

The primary aircraft base for TARFOX will be the NASA Wallops Flight Facility at Wallops Island, Virginia.

- ***Surface-Based Observations***

Extensive radiation, aerosol, trace gas, and precipitation measurements are currently being made in the Atmospheric Ocean Chemistry Experiment (AEROCE) network (Bermuda, Barbados, Tenerife, Miami). There are also several continuously operated, well instrumented, surface aerosol monitoring sites in the North Atlantic operated by [NOAA/ERL](#), [NASA/GSFC](#) and the [WMO](#) Global Atmospheric Watch (GAW) program. In addition, lidar and possibly other measurements are expected to be made at Wallops Island. Measurements taken at some of these sites include:

- Aerosol radiative properties (e.g., extinction and scattering coefficients, phase function).
- Air and aerosol chemical properties (e.g., precursor gas concentrations, soluble aerosol species, elemental carbon, trace metals, radiotracers, relative humidity).
- Aerosol physical properties (e.g., size distribution, particle shape).
- Spectral optical depths and spectral and broadband radiation fields (e.g., sun-photometers, shadow band radiometers, scanning radiometers, upward and downward facing pyranometers and pyrgeometers).
- Lidar measurements of aerosol backscatter vertical profiles.

- **Integrated Analyses**

The combined surface, air, and space data sets will permit a wide variety of closure analyses. Specifically, in-situ measurements of aerosol light-scattering, absorption, and forward/backscatter ratios at a given height will be used to derive the basic quantities needed to determine the effects of aerosols on solar radiation, namely, extinction, single-scattering albedo, and asymmetry factor. "Internal closure" will be assessed by comparing the quantities thus derived with those deduced from the simultaneous insitu measurements of particle size distribution and chemical composition. Analyses will seek to apportion the measured extinction by chemical species and hence (although more problematically) by source. The main tool for this analysis will be multiple linear regression. At each altitude in the vertical profiles of aerosol properties, the measured aerosol scattering and absorption coefficients will be regressed onto the co-measured mass concentrations of the various chemical components of the aerosol. This will yield the chemically specific mass scattering efficiencies and hence the relative contribution of each component to the light scattering at that altitude. Weighted vertical integration of these scattering budgets will then yield a chemical "budget." This statistical approach has proven fruitful in visibility studies, which are similar in this aspect to TARFOX.

"External column closure" will be assessed by vertically integrating the two types of aircraft-determined extinction and comparing the resulting optical depths with those simultaneously derived from the airborne sunphotometers, satellite radiometers, and ER-2

imaging spectrometers. Another aspect of column closure will be comparisons of aerosol radiative forcing, or radiative flux changes, determined by: (1) airborne flux radiometer measurements, (2) satellite flux retrievals from radiance measurements, and (3) flux calculations from (a) in-situ measured aerosol scattering, absorption, and asymmetry factors, (b) the same properties derived from size distribution and composition measurements, and (c) sunphotometer- and satellite-derived optical depths with ancillary single-scattering albedos and asymmetry factors. The sensitivity of radiative forcing to changes in aerosol optical thickness will be derived from the detailed *in situ* measurements and compared to the empirical sensitivity obtained by regressing satellite-derived radiative forcing vs. satellite-derived optical depth.

Such closure analyses will yield critically needed assessments and reductions of the uncertainties in deriving anthropogenic aerosol radiative forcing for use in climate models. The closure analyses that use satellite optical depth and flux results will provide tests and, where necessary, improvements of the satellite retrieval algorithms. The resulting validated algorithms will permit extensions of the TARFOX results beyond the TARFOX period and to other areas dominated by similar aerosols (e.g. the European Atlantic coast).

[Return to Contents](#)

[Continue to Operational Logistics](#)

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Last updated July-20-2002