Progress Report for NASA EOS Validation Investigation MTPE S-97889-F
"Validation of the CERES Surface Radiation Budget Using Long-Term Observations from the Indian Ocean Experiment (INDOEX)"

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1 Accomplishments for the first 18 months

In the first year of research before the INDOEX field phase, the PI examined low cloud amount over the Indian Ocean in collaboration with S. Bony-Lena of LMD and quantified biases in CERES clear-sky shortwave fluxes related to scene identification. These projects were described in the progress report dated Dec. 1, 1998. A paper entitled "Indian Ocean Low Clouds During the Winter Monsoon" by Bony-Lena and the PI is being revised for publication in the *Journal of Climate*. We are using our new cloud climatology as the basis for characterizing the indirect radiative effects of aerosols using satellite data sets. The biases in the ERBE-like CERES shortwave fluxes are related to misidentification of clear scenes with large aerosol loading as cloudy scenes. This misidentification results in a systematic underestimate of the direct radiative forcing of aerosols, and it should affect both the CERES and ScaRaB data collected over the Indian Ocean. The bias should also propagate through the CERES SARB calculations. This analysis has been presented at the ALPS99 Conference on Remote Sensing in Méribel France and the April 1999 CERES Science Team Meeting. A copy of the Méribel abstract is attached. The PI is preparing the results for publication.

2 Description of an aerosol assimilation system

In the last 6 months, the PI participated in the INDOEX intensive field phase by providing 24 and 48-hour forecasts of aerosol optical depth over the Indian Ocean region. This work was done in collaboration with Phillip Rasch and Brian Eaton of NCAR's Climate and Global Division. The forecasts were used extensively to plan the deployment of the U.S. ships and aircraft involved in the experiment. We have converted the forecast system to an analysis system for producing a 4D gridded aerosol analysis for the Indian Ocean region. This data set will be used for future evaluation of the CERES SARB clear-sky fluxes for the Indian Ocean region. This work has been presented at the Spring 1999 AGU meeting [*Collins et al.*, 1999; *Rasch et al.*, 1999][1]), the Workshop on Mineral Dust in Boulder[2]), and the April 1999 CERES Science Team Meeting. At that meeting, Tom Charlock and the

[1]Please search for "Collins" under `http://www.agu.org/meetings/waissm99.html`.
[2]Please see `http://irina.colorado.edu/abs_posters.htm#p4`.

SARB working group endorsed development of the assimilation system for use in evaluating the SARB products. To the best of the PI's knowledge, aerosol assimilation has been attempted only once before. A hard-copy miniature of the poster presented at the Dust Workshop is attached.

The forecasting system consists of the Model of Atmospheric Transport and Chemistry (MATCH) combined with an assimilation package developed for atmospheric chemistry. The aerosols forecast by MATCH include sulfate, mineral dust, carbonaceous, and sea-salt aerosols. The model includes a detailed treatment of the sources, chemical transformation, and wet and dry deposition of the aerosol species. The aerosol forecasts involve a two-stage process. During the assimilation phase, the total column aerosol optical depth (AOD) is estimated from the model aerosol fields. The model state is then adjusted to minimize differences between the simulated AOD and satellite retrievals of aerosol optical depth. During the subsequent forecast phase, the aerosol fields are evolved using meteorological forecasts.

If it meets with the program managers' approval, the PI would like to focus his investigation on use of the aerosol assimilation within the SARB program. The objective would be to construct an objective 4D aerosol analysis analogous to standard meteorological analyses for the Indian Ocean region. The data set would be enhanced by assimilation of in situ observations from the field phase. According to the schedule for dissemination of preliminary data among the INDOEX Science Team, the in situ data should start becoming available in September 1999. The field data would enhance the fidelity of the analysis by:

- Assimilation of in situ estimates of aerosol optical depth from surface, ship, and aircraft observations.
- Assimilation of more accurate satellite retrievals tuned to confirm with in situ data (e.g., unpublished work by Rasheev et al, 1999).
- Assimilation using the vertical distribution of aerosols from lidar and aircraft observations.
- Species-specific assimilation using estimates of extinction by chemical type from surface and aircraft data.
- Improvements in aerosol optics from in situ measurements of aerosol extinction and hygroscopic growth factors.
- Assessment of accuracy of meteorological fields used in the chemical transport model from comparison against trajectories of neutral-buoyancy balloons.

Although our initial application was limited to the Indian Ocean, our methodology could be extended to derive global aerosol analyses combining in situ and remotely-sensed aerosol observations.

3 Details of the aerosol assimilation system

3.1 Simulated fields

Aerosols comprised of sulfate, soil dust, sea-salt, hydrophilic and hydrophobic black carbon, and hydrophilic and hydrophobic organic carbon are simulated by the model. In addition, passive tracers representing ^{222}Radon released from various continental regions are used to diagnose transport processes in the simulation. The passive tracers are tagged by source region, for example Africa, Indian, and south-east Asia.

The sulfate aerosol is represented by the mass of SO_4^{2-} and is derived from sources of DMS and SO_2. The processes affecting sulfur chemistry in the model include the large-scale advection and subgrid-scale transport by convection and diffusion, wet and dry deposition, and gas and aqueous phase chemistry [*Barth et al.,* 1999]. Sulfate is represented with a single mass-mixing ratio. Future versions will include explicit representation of sub- and super-micron sulfate aerosols. The methodology for soil dust is based upon the approach of *Tegen and Fung* [1994] with modifications to the soil mobilization to improve agreement with the Nimbus-7 absorptive-aerosol index from *Herman et al.* [1997] (*C. Zender, private communication*). The dust is resolved into 4 size classes for effective radii between 0.2–1 μm, 1–10 μm, 10–20 μm, and 20–50 μm. Dust is removed from the atmosphere by wet and dry deposition. Since estimates of soil moisture are not available from the NCEP operational analyses used for INDOEX (section 3.5), the soil mobilization is modified using a leaf-area index adapted from the NCAR Land-Surface Model (LSM) [*Bonan,* 1996].

In the current implementation, vertical profiles of sea-salt mass are diagnosed from the 10m wind speed using the approach of *Blanchard and Woodcock* [1980]. The diagnostic prescription will be replaced with a prognostic formulation [e.g., *Gong et al.* [1997*b*]; *Gong et al.* [1997*a*]] in future versions of the assimilation system. For the purpose of constructing operational forecasts, we have assumed that the diagnosed sea-salt and its optical depth are an accurate representation of the true sea-salt and have negligible uncertainties.

The black and organic carbon are separated into hydrophilic and hydrophobic classes. In the current implementation, the carbonaceous aerosols are not resolved into size bins. When carbon is emitted from the source regions, it is assumed to be entirely hydrophobic. The hydrophobic carbon is converted to hydrophobic carbon by an exponential decay law on a 1.2-day time-scale.

3.2 Chemical Transport Model

The assimilation system is based upon the Model of Atmospheric Transport and Chemistry (MATCH) [*Rasch et al.,* 1997]. The version of MATCH used during INDOEX is 3.3 [3]). For INDOEX, MATCH has been run in diagnosed mode [*Rasch et al.,* 1997] in which physical parameterizations are used to derived some of the fields required for integration of the model, for example the vertical convective mass fluxes and three-dimensional precipitation rates. These fields are generally not available in meteorological analyses and forecasts from

[3]The code is available from `ftp://ftp.cgd.ucar.edu/pub/eaton/match`

operational centers. The fields obtained from the meteorological analyses are linearly interpolated in time to the current time-step of the model. The time step is set to 40 minutes except for the sulfur package, which is integrated with a time step of 2 minutes [*Barth et al.,* 1999]. In each 40 minute time step, the input data is interpolated, the resolved-scale advection is computed, and then the physics and chemistry parameterizations are called. The assimilation of aerosol observations (section 3.3) is performed after the parameterizations.

The large-scale advection is performed with the semi-Lagrangian transport scheme developed by *Rasch and Williamson* [1990]. This scheme is applied to the aerosol mass-mixing ratios, the ^{222}Radon tracers, the specific humidity, and trace gases in the atmosphere. The sub-grid turbulent mixing is parameterized with vertical eddy diffusion. In the free troposphere, the diffusion is governed by a diffusion coefficient dependent on the local Richardson number. In the planetary boundary layer, the vertical transport is treated using a nonlocal diffusion scheme that incorporates counter-gradient transport terms [*Holtslag and Moeng,* 1991; *Holtslag and Boville,* 1993]. The convective transport of chemical species is treated with the same combination of convective parameterizations developed by *Zhang and McFarlane* [1995] and *Hack* [1994] used in the NCAR Community Climate Model CCM3 [*Zhang et al.,* 1997; *Kiehl et al.,* 1998]. The *Zhang and McFarlane* [1995] parameterization transports mass in ascending and descending plumes which can span the troposphere, while the *Hack* [1994] parameterization redistributes mass between adjacent layers in the model. The input meteorological fields are perturbed slightly to destabilize the temperature and moisture profiles with respect to convection following *Rasch et al.* [1997].

The dry deposition of sulfate, hydrophilic, and hydrophobic carbon is computed by computing a flux onto the Earth's surface assuming a single gravitational settling velocity for each species. The settling velocities are 0.2 cm/sec for sulfate (*H. Feichter*) and 0.1 cm/sec for carbon. The dry deposition of dust includes gravitational settling and turbulent deposition from the lowest layer to surface. The settling velocities for the 4 classes of dust in order of effective radius are 0.019, 1.4, 8.4, and 38 cm/sec. The turbulent deposition velocities are 0.3, 0.5, 7, and 25 cm/sec, respectively [*Seinfeld and Pandis,* 1997; , p. 971].

The aerosols interact with the representation of the hydrological cycle through several processes including the scavenging of aerosols by precipitation, the aqueous-phase reactions affecting sulfate distributions [*Barth et al.,* 1999], and the hygroscopic growth of the aerosols. Cloud amount is diagnosed from humidity, vertical motion, static stability, and precipitation using the same scheme employed in CCM3 [*Kiehl et al.,* 1998]. The condensed water in the clouds evolves following prognostic cloud-water parameterization developed by *Rasch and Kristjánsson* [1998]. The liquid and ice water in cloudy regions are affected by condensation, evaporation, precipitation, and resolved and sub-grid transport. The amount of precipitation and condensation are the primary inputs to the parameterizations of wet scavenging of soluble gases and aerosols. The precipitation is derived internally by the model run in the diagnosed mode since it is not generally available from operational meteorological analyses. The impact of inaccuracies in the diagnosed precipitation on wet deposition has been evaluated for lead derived from ^{222}Radon[*Rasch et al.,* 1997]. The model was integrated using meteorological fields from the NCAR CCM3, once with and once without the three-dimensional precipitation fields, convective transports, and cloud water fields output by CCM3. In the latter experiment, these fields were diagnosed by MATCH using the same procedures adopted for INDOEX. The monthly mean estimates of the wet deposition of lead differ by less than 10%, and the spatial correlations of the monthly means are greater than 0.9.

The scavenging of sulfate and hydrophilic carbon by precipitation includes removal by convective and stratiform rain forming within and falling into each grid-box. The fraction of the grid box scavenged by rain is estimated by multiplying the fractional cloud amount with the total surface area of the rain drops divided by the horizontal area of the grid. The surface area of the rain is estimated from the rain-rate following Balkanski. These aerosols can also be reintroduced by evaporation of precipitation. Similar processes are applied to the dust, although the dust parameterization does not distinguish between convective and stratiform precipitation. The wet removal of dust is proportional to the product of cloud amount, the rate of conversion of moisture to precipitation, and a unitless dust scavenging ratio [*Tegen and Fung,* 1994]. The dust can be released back into the atmosphere by evaporation of precipitation.

3.3 Assimilation Package

The assimilation procedure is similar to the mathematical analysis commonly used for meteorological assimilation [*Lorenc,* 1986]. The procedure for aerosols was adapted from an assimilation package developed for modeling trace gases in the stratosphere [*Levelt et al.,* 1998; *Lamarque et al.,* 1999]. The method is designed to minimize differences between column integrated quantities from a model and observations. In this application, the column integrated quantities are the modeled and retrieved aerosol optical depths denoted τ_m and τ_o, respectively. Typically one has to define a linear operator H to interpolate from the model grid to the individual observations. This operator can also be represented as a matrix. Since we average the high-resolution satellite observations onto the same grid used by MATCH, in our case H is the identity matrix I. The values of τ_m immediately after assimilation are may be written as:

$$\tau_m' = \tau_m + K(\tau_o - H\tau_m) \tag{1}$$

where K is the Kalman gain matrix. It is defined in terms of the distributions of errors in the model and data. The variances and covariances of the modeled and observed fields are represented by matrices M and O, where each row and column represents a different model grid or observation site. The on-diagonal elements are the RMS errors in the model and data at a given location, and the off-diagonal elements give the error covariances. If one assumes that the errors are Gaussian distributed and that the errors in model and data are uncorrelated, then K is given by:

$$\begin{aligned} K &= M\,H^T\,(H\,M\,H^T + O)^{-1} && (2) \\ &= M\,(M + O)^{-1} && (3) \end{aligned}$$

If the observational errors are negligible compared to the model uncertainties, then $K \simeq I$ and eqn. 1 yield $\tau_m' \simeq \tau_o$. In this limit, the assimilation procedure forces the model estimates to agree with the observations. In our application, the observational errors cannot be neglected, and the procedure gives a "softer" adjustment to the model.

The errors in the satellite data are assumed to be uncorrelated at the horizonal length-scale of the model. Therefore the observational error matrix O is diagonal. The errors in individual estimates of τ_o include a mean error $\epsilon_o = 0.04$ and a fractional uncertainty in the estimate of $f_o = 0.2$ [*Stowe et al.,* 1997]. Therefore O is given by

$$O = \left[(f_o \, \tau_o)^2 + (\epsilon_o)^2 \right] I \tag{4}$$

The expression for the model covariance matrix has the form:

$$M(d) = \left[(f_m \, \tau_m)^2 + (\epsilon_m)^2 \right] \exp \left[\frac{-d^2}{2 \, \ell_{mx}} \right] \tag{5}$$

Here d is the horizontal distance between two model grid-points and $\ell_{mx} = 100$ km is the horizontal correlation length-scale for errors in the model fields.

The assimilation is used to apply a correction to the model at each model time-step immediately following a satellite overpass (section 3.3). The duration of the satellite overflights of the INDOEX region is generally less than 20 minutes, or 50% of the model time-step. Because of the short duration of the satellite data and the rapid evolution of the aerosol field, the corrections required to obtain τ'_m from τ_m are applied only at one time step.

Since the model estimate of τ_m includes contributions from four different aerosol species, the assimilation problem is under-determined. It is not clear a priori how to partition the correction from τ_m to τ'_m among the various species. The indeterminacy can be reduced once the in situ observations of chemical speciation become available from INDOEX surface sites. However, an ad hoc assumption is required for partitioning the correction when the observations include only total aerosol optical depth. Since the objectives of INDOEX are focused on continental aerosols, the model calculation of sea-salt optical depth, τ_s is assumed to be exactly correct. The difference $\widehat{\tau_o} = \tau_o - \tau_s$ is assumed to be contributed by a combination of sulfate, dust, and carbonaceous aerosols. The assimilation is then applied to $\widehat{\tau_m} = \tau_m - \tau_s$ to correct the non-sea-salt aerosols in the model. The mass mixing ratios for sulfate, dust, and carbonaceous aerosols at all model levels are multiplied by the ratio $\widehat{\tau_m}'/\widehat{\tau_m}$. Since the aerosol optical depths are proportional to the mixing ratios, this adjustment guarantees that the modeled optical depth equals $\widehat{\tau_m}'$.

3.4 Satellite retrievals of aerosol optical depth

Estimates of column-integrated aerosol optical depth have been derived from imagery from the Advanced Very High Resolution Radiometers (AVHRR) on NOAA-14 using the second-generation Pathfinder aerosol algorithm [*Stowe et al.,* 1997]. The characteristics of the AVHRR data are given in *Kidwell* [1998]. The basis of the Pathfinder algorithm is a pre-computed look-up table relating variations in AVHRR visible radiances measured at 0.63 μm to variations in aerosol optical depth. The aerosol is assumed to have optical characteristics similar to those of a marine aerosol [*Stowe et al.,* 1997]. The Pathfinder method is limited to ocean regions where the surface reflectivity is a known function of wind-speed [e.g., [*Mishchenko and Travis,* 1997]] and is close to 0 in the spectral bandpass of the AVHRR instrument. The method is further limited to cloud-free pixels identified using the CLAVR1 cloud-screening algorithm [*Stowe et al.,* 1998]. Thus the assimilation is performed only for cloud-free ocean regions. Errors in, for example, the terrestrial sources for aerosols can be addressed only after the air masses containing these aerosols are advected over the open oceans. However, the assimilation can be readily extended to continental regions using surface-based instruments, e.g. sun photometers, and the next generation of satellite retrievals.

The second-generation Pathfinder data set compares favorably with sun-photometer observations [*Stowe et al.,* 1997]. Relative to sun-photometer data from three surface sites, the systematic error is less than 10%, and the random error is approximately $\sigma_\tau = 0.04$. The Pathfinder group is developing error estimates specifically for dust (*L. Stowe, private communication*). Like other aerosol retrieval schemes of its class, the errors in τ from the NOAA Pathfinder algorithm can be large when the observed aerosol departs significantly from the properties adopted in the retrieval [*Mishchenko and Travis,* 1997].

Satellite retrievals based upon AVHRR data for the Indian Ocean region have been assimilated for INDOEX. The NOAA satellites are polar orbiters with local crossing times during daylight hours of 13:30 and 7:30 for NOAA-14 and 15, respectively. During INDOEX, the visible imagery from NOAA-15 is adversely affected by large solar zenith angles and is not used for aerosol retrievals. Usually 3 images from NOAA-14 from afternoon overflights of the INDOEX region are available for assimilation. The time separation between successive images corresponds to the orbital period of approximately 102 minutes. Both Local Area Coverage (LAC) imagery with 1.1 km nadir resolution and Global Area Coverage (GAC) imagery subsampled to 3×5 km resolution have been used for the INDOEX forecasts. Only data from the anti-solar side of the visible imagery is used in the retrievals to avoid problems with sun-glint [*Stowe et al.,* 1997]. Images from successive orbits are separated by approximately 26° of longitude. The restriction to the anti-solar portion of each image yields satellite maps of aerosols that span the meridional extent of the INDOEX region and extend approximately 13 in longitude.

3.5 Meteorological fields

For INDOEX, the assimilation system has been integrated using meteorological fields from the operational forecasts and analyses from the National Center for Environmental Prediction (NCEP)[*Caplan et al.,* 1997; *Parrish et al.,* 1997]. The spectral truncation of the NCEP products is T126, which is equivalent to a horizontal resolution of approximately 0.9 degrees on the equator. There are 384 longitude and 192 Gaussian-grid latitude intervals. The products are vertically discretized on 28 sigma levels identical to the levels used in the NCEP/NCAR reanalysis [*Kalnay et al.,* 1996]. As noted in section 3.2, the three-dimensional precipitation field is required to estimate the wet-deposition rates, but generally only the surface precipitation fields are available in operational products. The precipitation field is derived within MATCH using the physical parameterizations from the NCAR CCM3.

During the assimilation phase, the fields from the 6-hourly analyses are alternated with forecast fields for the 3-hour midpoints between adjacent analyses to give 3-hourly temporal resolution. During the forecast phase, the 3-hourly forecast fields are input to the model. Since MATCH has been integrated in a global mode, the global NCEP fields are ingested. NCEP has provided the fields within approximately 6 hours after the validation time for the analyses. The NCEP fields were selected for use in INDOEX because they are readily available in near real-time, but MATCH can and has been integrated with meteorological data from ECMWF, Florida State University [*Krishnamurti et al.,* 1991], and GCM simulations [*Rasch et al.,* 1997].

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