Final 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 Introduction

During the course of the investigation, the focus of the research conducted under this grant has changed with the approval of the NASA program management. In the original proposal, the main objective was to evaluate the CERES Surface and Atmosphere Radiation Budget (SARB) surface fluxes using data collected during the INdian Ocean EXperiment (INDOEX). The evaluation would include the fidelity of the direct radiative effects of aerosols on the surface energy budget and the accuracy of the temporal interpolation of these fluxes using geostationary satellite data. Unfortunately, the malfunction of the CERES instrument on TRMM in August 1998 and the delay in the launch of Terra until after the INDOEX Intensive Field Phase in 1999 means that there is very little coincidence between INDOEX observations and CERES SARB data. Attempts to compare CERES SARB data with measurements from the INDOEX First Field Phase in February–March 1998 were not successive because of the very small number of collocated SARB fluxes and surface measurements. Since SARB does not yet include time interpolation, the tests of the interpolation procedure cannot be conducted.

In light of these difficulties, the PI and NASA agreed to devote the research supported by this grant to the creation of a global aerosol data set for use in CERES SARB. The data set would be generated using the aerosol assimilation system developed in the first three years of the proposal. This data will replace the aerosol climatologies used in the current version of the SARB processing. This task was completed in FY 2001, and the CERES science team now has an 8-month global aerosol data set for testing.

The major accomplishments of this investigation are:

- Analysis of low cloud distributions over the Indian Ocean using a unique geosynchronous satellite data set (section 2).
- Development of the first global aerosol model including assimilation of *in situ* and remotely sensed aerosol observations (section 3).

- First use of global aerosol forecasts (including assimilation) to help guide deployment of aircraft and ships in national and international field programs (section 4).
- Calculation of aerosol direct radiative forcing over the Indian subcontinent, southeast Asia, and southern China validated against INDOEX observations (section 5).
- Distribution of global aerosol assimilation to NASA instrument investigator teams, including CERES and PICASSO (section 6).
- Publication of six peer-reviewed papers (section 7) accompanied by thirteen published conference paper abstracts (section 9) and eight talks and presentations (sec 10).

2 Analysis of low clouds over the Indian Ocean

While low-level clouds over the Pacific and Atlantic oceans have been investigated extensively, low clouds over the Indian ocean are not as well characterized. The PI and collaborators examined the occurrence of non-overlapped low clouds over the Indian ocean during the North-East monsoon using several sources of data (section 7, publication #1). Climatologies derived from surface observations and from the International Satellite Cloud Climatology Project have been reviewed. Another cloud climatology has been developed using infrared and visible imagery from the geostationary Indian Satellite (INSAT). The new climatology has better spatial and temporal resolution than in situ observations. The three datasets are generally consistent and show several persistent features in the cloud distribution. During January–April, maxima in the occurrence of low clouds occur at subtropical latitudes over the Arabian sea, the Bay of Bengal, the China sea, and the southern Indian ocean. The predominant types of low clouds differ in the northern and southern areas of the Indian ocean region and China sea. The Arabian sea and the Bay of Bengal are covered mostly by cumulus clouds, while the southern Indian ocean and the China sea are covered mostly by large-scale stratiform clouds such as stratocumulus. These observations are consistent with atmospheric analyses of temperature, humidity and stability over the Indian ocean.

3 Development of aerosol assimilation model

A system for simulating aerosols has been developed using a chemical transport model together with an assimilation of satellite aerosol retrievals (section 7, publications #2–3). The system generated aerosol forecasts to guide deployment of ships and aircraft during INDOEX. The system consists of the Model of Atmospheric Transport and Chemistry (MATCH) combined with an assimilation package developed for applications in atmospheric chemistry. MATCH predicts the evolution of sulfate, carbonaceous, and mineral dust aerosols, and it diagnoses the distribution of sea-salt aerosols. The model includes a detailed treatment of the sources, chemical transformation, transport, and 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 improve the agreement between the simulated AOD and satellite retrievals of AOD. During the subsequent integration phase, the aerosol fields are evolved using meteorological fields from an external model. Comparison of the modeled AOD against estimates of the AOD from INDOEX sunphotometer data show that the differences in daily means are -0.03 ± 0.06. Carbonaceous, sulfate and sea salt aerosols agree with the in-situ measurements to 10-20%. Carbonaceous aerosols were estimated to be the dominant contributor (36%) to the AOD; dust (31%) and sulfate (26%) were also important. The residence time for sulfate and carbon is $\sim$7 and $\sim$8 days respectively, longer than globally averaged residence times of many modeling studies. Thus aerosols produced here during the winter monsoon may have a larger climate impact than the same emissions occurring where the residence time is shorter.

Three points of entry are found for anthropogenic aerosol to the INDOEX region: a strong near surface southward flow near Bombay; a deeper plume flowing south and east off Calcutta, and a westward flow originating from southeast Asia and entering the Bay of Bengal. All three plumes are strongly modulated by a low frequency change of meteorological regime associated with the Madden Julian Oscillation. The analysis suggests that India is the dominant source of aerosol in the Arabian Sea and Bay of Bengal near the surface, but that Asia, Africa and the rest of world also contribute at higher altitudes. India and Asia contribute about 40% each to the total column mass of air reaching the Maldives, the balance of air comes from other source regions. Although the initial application is limited to the Indian Ocean, the methodology could be extended to derive global aerosol analyses combining in situ and remotely-sensed aerosol observations.

4 Support of international field experiments with NASA participation

4.1 INDOEX

In order to help plan the research aircraft missions during INDOEX, the aerosol assimilation model was used to generate 24 and 48-hour forecasts of the total aerosol optical depth (AOD). The validation time of the forecasts was 6 GMT, which corresponds to 11 AM local time at the Maldives where INDOEX was based. The aerosol forecast consisted of a two-stage process. During the first stage the model was run using a combination of alternating analysis and forecast fields from the NCEP aviation analysis. Estimates of AOD derived from AVHRR imagery were assimilated at the time steps matching the satellite observation times. During the second stage, only NCEP forecast fields were used, and no satellite data was available. Thus, the simulated aerosol field were constrained as strongly as possible during the first stage by observations of the meteorological fields and the satellite retrievals. During the second stage no observations were available, and the simulation was expected to depart more strongly from an accurate forecast. NASA's participation in INDOEX included Brent Holben and his CIMEL instruments at Kaashidhoo and Malé; Jim Spinhirne and Judd Welton with their micropulse lidars; and the CERES science team and its special CERES measurements over the INDOEX experimental domain.

4.2 PEMT-B

Vertical profiles of aerosol and gas phase species were measured near Hawaii on April 9 and 10, 1999 during NASA's Pacific Exploratory Mission-Tropics B (PEMT-B) program (section 7, publication #4). These measurements characterized aerosol microphysics, inferred chemistry, optical properties and gases in several extensive dust and pollution plumes, also detected by satellites, which had 10,000km trajectories back to sources in Asia. Size resolved measurements indicative of aerosol sulfate, black carbon, dust, light scattering and absorption allowed determination of their concentrations and contributions to column aerosol optical depth. The aerosol assimilation system was used to predict aerosol and gas concentrations and the aerosol optical effects along our flight path. Flight measurements confirmed the "river-like" plume structures predicted by the system and showed close agreement with the predicted contributions of dust and sulfate to aerosol concentrations and optical properties for this global-scale transport model. Consistency between satellite, model, and in situ assessment of aerosol optical depth was found, with few exceptions, within about 25%. Both model results and observations confirmed that this aerosol was being entrained into the marine boundary layer between Hawaii and California where it can modify the type and concentration of cloud condensation nuclei in ways that may alter properties of low level clouds. These observations document the significance and complexity of long-range aerosol transport and highlight the potential of the aerosol assimilation to extend observational and address related issues on global scales.

4.3 ACE-Asia and CLAMS

The PI and colleagues have also provided forecasts of aerosol distributions for mission planning during the Aerosol Characterization Experiment (ACE-Asia[1]) and the Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS[2]). The forecasts for both experiments are given on the MATCH website (section 8). NASA is the lead agency for CLAMS, and there is significant NASA participation in ACE-Asia (see projects under `http://www.ogp.noaa.gov/ace-asia/links`).

5 Calculation of aerosol radiative forcing for Indian Ocean Basin

The PI and collaborators have simulated the direct radiative forcing by aerosols over the Indian Ocean region for the Indian Ocean Experiment (INDOEX) Intensive Field Phase during Spring 1999 (section 7, publications #5–6). The forcing is calculated for the top-of-atmosphere (TOA), surface, and atmosphere by differencing shortwave fluxes computed with and without aerosols. The calculation includes the effects of sea-salt, sulfate, carbonaceous, and soil-dust aerosols. The aerosol distributions are obtained from a global aerosol simulation including assimilation of satellite retrievals of aerosol optical depth. The time-dependent three-dimensional aerosol distributions are derived with a chemical transport model driven with meteorological analyses for this time period. The surface albedos are obtained from a land-surface model forced with an identical meteorological analysis and satellite-derived rainfall and insolation. These calculations are consistent with in situ observations of the surface insolation over the central Indian Ocean and with satellite measurements of the reflected shortwave radiation. The calculations show that the surface insolation under clear skies is reduced by as much as 40 W/m^2 over the Indian subcontinent by natural and anthropogenic aerosols. This reduction in insolation is accompanied by an increase in shortwave flux absorbed in the atmosphere by 25 W/m^2. The inclusion of clouds in the calculations changes the direct effect by less than 2 W/m^2 over the Indian subcontinent, although the reduction is much larger over China.

The radiative properties of the simulated aerosols are in good agreement with the in situ observations. The model reproduces the observed single-scattering albedo to within ± 0.02, and it reproduces the measured sensitivities of the TOA and surface forcing to AOD to within 3 W/m^2 per unit AOD. The model also simulates the chemical speciation of the aerosol measured at INDOEX surface sites to within 10–20% (section 7, publication #3). Based upon the agreement with the observations,

[1] `http://saga.pmel.noaa.gov/aceasia/`

[2] `http://www-clams.larc.nasa.gov/clams`

we have used the model to calculate the aerosol distributions and radiative effects over the Indian Ocean and surrounding continental regions.

The aerosol surface forcing decreases the surface insolation by 15–20% over the continental areas and therefore significantly alters the surface energy budget. The increased shortwave absorption is accompanied by changes to the time-mean solar heating rates of up to 0.8 K/day. The maximum relative perturbation to the shortwave heating rate is 130% during the INDOEX IFP. Most of this perturbation is contributed by the effects of carbonaceous aerosols. The relative change in the heating rate from anthropogenic aerosols should be compared to the 50% change in the shortwave heating rate calculated for the dust aerosols observed during MONEX [*Ellingson and Serafino,* 1984; *Ackerman and Cox,* 1987].

The large magnitude of the forcing by aerosols has several implications. First, the aerosol forcing is as large or larger than other heat sources and sinks, for example shortwave cloud forcing, which are currently included in the land-surface model and meteorological analysis system. Second, aerosol forcings of the magnitude observed during INDOEX could have a significant impact on the regional atmospheric and oceanic dynamics. Other studies using general circulation models (e.g., *Ramanathan et al.* [2001]; *Kiehl et al.* [2001]) are underway to examine the atmospheric response. Studies of the coupled ocean-atmosphere response are needed to understand the effects on the regional climate system. Finally, it is clear that anthropogenic aerosols have significantly altered the radiative transfer over India and China. Projections of the aerosols released from these countries after further industrialization indicate that this region will be the dominant source of anthropogenic aerosols by 2025 [*Nakicenovic and Swart,* 2000]. Modeling studies of the aerosol forcing over the next century which are consistent with INDOEX observations are urgently needed for climate-change assessment.

6 Interaction with NSF and NASA modeling and satellite programs

The parameterizations developed for the aerosol assimilation are currently being adapted to the the NCAR Community Climate System Model (CCSM) [*Boville and Gent,* 1998]. The PI is leading this effort to integrate the major natural and anthropogenic aerosols into CCSM. This important step in the involution of CCSM to treat the principle climate forcings would not have been possible without the support provided under this grant. The PI has also received new funding under NASA's Atmospheric Chemistry Modeling and Analysis Project (ACMAP, NRA-00-OES-09) to continue his research in aerosol assimilation. The PI and investigators at NASA's Data Assimilation Office are beginning to coordinate research to insure that the efforts at both institutions are complementary. The PI has also provided a full eight months of aerosol assimilation fields to the CERES SARB team, as agreed by the PI and the program manager. The PICASSO science team is now exploring the use of aerosol assimilation to assist in the design and interpretation of the PICASSO experiment. The PI has provided sample fields to PICASSO instrument scientists.

7 Peer-reviewed publications

1. Bony, S., W.D. Collins, and D.W. Fillmore, 2000: Indian Ocean low clouds during the winter monsoon. *J. Climate*, vol. 13, 2028–2043.

2. Collins, W.D., P.J. Rasch, B.E. Eaton, B.V. Khattatov, J.-F. Lamarque, and C.S. Zender, 2001: Simulating aerosols using a chemical transport model with assimilation of satellite aerosol retrievals: Methodology for INDOEX. *J. Geophys. Res.*, vol. 106, 7313–7336.

3. Rasch, P.J., W.D. Collins and B.E. Eaton, 2001: Understanding the Indian Ocean Experiment (INDOEX) aerosol distributions with an aerosol assimilation. *J. Geophys. Res.*, vol. 106, 7337–7356.

4. Clarke, A., W.D. Collins, P.J. Rasch, V. Kapustin, K. Moore, and S. Howell, 2001: Pollution transport on global scales: Measurements and model predictions. In press, *J. Geophys. Res.*

5. Ramanathan, V., P.J. Crutzen, J. Lelieveld, D. Althausen, J. Anderson, M.O. Andreae, W. Cantrell, G. Cass, C.E. Chung, A.D. Clarke, W.D. Collins, J.A. Coakley, F. Dulac, J. Heintzenberg, A.J. Heymsfield, B. Holben, J. Hudson, A. Jayaraman, J.T. Kiehl, T.N. Krishnamurti, D. Lubin, A.P. Mitra, G. McFarquhar, T. Novakov, J.A. Ogren, I.A. Podgorny, K. Prather, J.M. Prospero, K. Priestley, P.K. Quinn, K. Rajeev, P.J. Rasch, S. Rupert, R. Sadourney, S.K. Satheesh, P. Sheridan, G.E. Shaw, and F.P.J. Valero, 2001: The Indian Ocean Experiment: An integrated assessment of the climate forcing and effects of the great Indo-Asian haze. In press, *J. Geophys. Res.*

6. Collins, W.D., P.J. Rasch, B.E. Eaton, D.W. Fillmore, J.T. Kiehl, T.C. Beck, and C.S. Zender, 2000e: Simulation of aerosol distributions and radiative forcing for INDOEX: Regional climate impacts. In press, *J. Geophys. Res.*.

8 Websites

1. http://www.cgd.ucar.edu/cms/match

9 Conference papers, symposia, and abstracts (published)

1. Collins, W.D., P.J. Rasch, and B.E. Eaton, 1999: Forecasting aerosols using a CTM with assimilation of satellite aerosol retrievals: 1. Methodology for INDOEX. 1999 Spring Meeting, American Geophysical Union. *EOS*, vol. 80 (no. 17), pp. S31–S32.

2. Rasch, P.J., W.D. Collins, and B.E. Eaton, 1999: Forecasting aerosols using a CTM with assimilation of satellite aerosol retrievals: 2. A 4D aerosol analysis for INDOEX. 1999 Spring Meeting, American Geophysical Union. *EOS*, vol. 80 (no. 17), p. S32.

3. Collins, W.D., P.J. Rasch, D.W. Fillmore, C.S. Zender, J.T. Kiehl, and B.E. Eaton, 1999: Direct radiative forcing and heating during INDOEX: Results from an aerosol analysis with assimilation. 1999 Fall Meeting, American Geophysical Union. *EOS*, vol. 80 (no. 46), p. F183.

4. Rasch, P.J., W.D. Collins, and B.E. Eaton, 1999: A prototype global aerosol analysis using assimilation of satellite retrievals of optical thickness. 1999 Fall Meeting, American Geophysical Union. *EOS*, vol. 80 (no. 46), p. F193.

5. Andronache, C., L.J. Donner, C. Semas, J.T. Kiehl, P.J. Rasch, W.D. Collins, and M. Ko, 1999: A high-resolution mesoscale model study of the indirect effects of aerosols during INDOEX. 1999 Fall Meeting, American Geophysical Union. *EOS*, vol. 80 (no. 46), p. F162.

6. Ramanathan, V., M.O. Andreae, J. Anderson, G. Cass, T. Clarke, W.D. Collins, J. Coakley, B. Gandrud, A. Heymsfield, A. Jayaraman, J.T. Kiehl, J. Ogren, J. Prospero, T. Novakov, and K. Prather, 2000: The Indian Ocean Experiment: An overview of the aerosol climate forcing with implications to climate change. XXV General Assembly, European Geophysical Society. *EGS Newsletter*, vol. 74, p. 189.

7. Collins, W.D., P.J. Rasch, B.E. Eaton, D.W. Fillmore, J.T. Kiehl, and C.S. Zender, 2000: Simulation of aerosol distributions and radiative forcing for INDOEX. XXV General Assembly, European Geophysical Society. *EGS Newsletter*, vol. 74, p. 189.

8. Clarke, A.D., W.D. Collins, P.J. Rasch, V.N. Kapustin, K. Moore, and S. Howell, 2000: Pollution transport on global scales: Measurements from PEMT-B confirm model predictions. 2000 Spring Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 19), p. S118.

9. Collins, W.D., A.D. Clarke, P.J. Rasch, K. Moore, and V. Kapustin, 2000: Analysis of the PEMT pollution event on April 10, 1999 using an aerosol assimilation model. 2000 Spring Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 19), p. S127.

10. Collins, W.D., and P.J. Rasch, 2000: Assimilation of atmospheric aerosol observations. Invited presentation, 2000 Spring Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 19), p. S98.

11. Rasch, P.J., and W.D. Collins, 2000: The modulation of constituent transport by important transient features of the general circulation. 2000 Spring Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 19), p. S154.

12. Collins, W.D., P.J. Rasch, E.J. Welton, C.T. Beck, and J.S. Spinhirne, 2000: Assimilation of space-based aerosol lidar measurements for studying African dust: Methodology. 2000 Fall Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 48), p. F70.

13. Rasch, P.J., W.D. Collins, and D. Winker, 2000: Assimilation of space-based aerosol lidar measurements for studying African dust: Results. 2000 Fall Meeting, American Geophysical Union. *EOS*, vol. 81 (no. 48), pp. F43–F44.

10 Talks and presentations

1. Collins, W.D., P.J. Rasch, and B.E. Eaton, 1999: Forecasting aerosols using a CTM with assimilation of satellite aerosol retrievals. Workshop on Mineral Dust, Jun. 9–11, 1999, Boulder, Colorado.

2. Collins, W.D., P.J. Rasch, and B.E. Eaton, 1999: A prototype global aerosol analysis using assimilation of satellite retrievals of aerosol optical thickness. NCAR ACD Workshop on Chemical Data Assimilation and Applications to Satellite Observations, Nov. 8–9, 1999, Boulder, Colorado.

3. Collins, W.D., 2000: Simulation of aerosol effects on the climate system: Future directions for the CAM. NCAR CSM Workshop, Jun. 27–29, 2000, Breckenridge, Colorado.

4. Collins, W.D., P.J. Rasch, and B.E. Eaton, 2000: Assimilation of atmospheric aerosol observations. Invited presentation, University of Utrecht, Sep. 12, 2000, Utrecht, The Netherlands.

5. Collins, W.D., 2001: Aerosol assimilation in a GCM. Invited presentation, Twenty-third CERES Science Team Meeting, NASA Langley Research Center, Jan. 23–25, 2001, Hampton, Virginia.

6. Collins, W.D., 2001: Modeling of aerosols with assimilation of satellite and surface aerosol observations. Invited presentation, Geophysical Fluid Dynamics Laboratory, Princeton University, Apr. 5, 2001, Princeton, New Jersey.

7. Collins, W.D., 2001: Aerosols, clouds, and the global environment: New techniques for modeling. Invited presentation, National Science Foundation, May 11, 2001, Ballston, Maryland.

8. Collins, W.D, 2001: Improved estimates of global atmospheric shortwave absorption by aerosols in clear and cloudy atmospheres. Chapman Conference on Atmospheric Absorption of Solar Radiation, Aug. 13–17, 2001, Estes Park, Colorado.

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