1.2 AEROSOL DIRECT RADIATIVE FORCING FOR CLOUD-FREE CONDITIONS DEDUCED FROM CERES/TRMM SSF AND AERONET OBSERVATIONS

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1. INTRODUCTION

By linking top of the atmosphere (TOA) radiative fluxes obtained by CERES/TRMM with surface measurements of aerosol optical depths obtained with the AERONET instrument at the Kaashidhoo Climate Observatory (KCO), Satheesh and Ramanathan (2000) derived the first empirical estimates of the direct aerosol radiative forcing for aerosols over KCO. The goal of this study is to extend the Satheesh and Ramanathan findings to other oceanic AERONET sites. In addition to the CERES shortwave fluxes, an alternate approach is explored in which aerosol models in combination with CERES shortwave radiances are used to calculate the TOA shortwave flux. Both the CERES and the calculated shortwave fluxes are matched with coincident AERONET measurements of aerosol optical depths. The direct radiative forcing derived using the calculated fluxes proves to be insensitive to the aerosol model used in the calculations and consistent with the forcing derived using the fluxes in the CERES Single Scanner FOV (SSF) data.

2. DATA ANALYSIS

SSF data for TRMM (January – August, 1998) were analyzed for CERES observations that fell within ± 50 km of an oceanic AERONET Site for which AERONET observations provided a surface measurement of optical depth within ± 1 hr of the TRMM overpass. Cloud-free CERES FOVs were identified to be those for which retrievals of the aerosol optical depth were performed in more than 50% of the VIRS pixels (2-km resolution at nadir) that fell within the CERES FOVs (10-km resolution at nadir). Owing to an error in the version of the SSF data used here, only observations for which the CERES scanner was in the cross-track mode were used in this analysis. This restriction greatly reduced the number of matchups that could be analyzed.

As an alternate to using the CERES shortwave fluxes, TOA shortwave radiances and irradiances for cloud-free but hazy ocean scenes were calculated using plane-parallel radiative transfer theory. The aerosols used in these calculations were the average continental aerosol and tropical marine models described by Hess et al. (1998) and the NOAA Phase 1 and 2 models described by Stowe et al. (1997). The continental aerosol absorbs sunlight and is made up of relatively small particles. The NOAA models and the tropical marine model are nonabsorbing aerosols. The NOAA Phase 1 model has particles that are considerably smaller than those of the continental aerosol while the tropical marine model has particles that are substantially larger. For each aerosol model, the optical depth at a reference wavelength was adjusted until the calculated shortwave radiance matched that observed by CERES for the sun-target-satellite geometry of the observation. The optical depth that provided the match was then used in the radiative transfer model to calculate the TOA shortwave radiative flux.

In order to compare observations at different times and on different days, both the CERES-SSF fluxes and the calculated fluxes were used to obtain a diurnally averaged radiative flux for the day and the location of the observation. The radiative forcing is expressed in terms of the change in the diurnally averaged reflected shortwave flux due to the presence of the aerosol. In the case of the CERES fluxes, the diurnally averaged flux was obtained by using the angular directional models derived from the anisotropic factors used in CERES to obtain the shortwave fluxes from instantaneous radiances. The scene was presumed to remain cloud-free for the day of observation and the angular directional models for a Rayleigh atmosphere and for a cloud-free but hazy atmosphere were used to calculate the

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reflected shortwave fluxes for the distribution of solar zenith angles associated with the location and date of observation (Loeb et al. 2002). In the case of the alternate approach, the optical depth retrieved from the CERES shortwave radiance was held constant and radiative fluxes were then calculated for the diurnal distribution of solar zenith angles.

3. RESULTS

Figure 1 shows the diurnally averaged radiative forcing per unit 0.65-µm optical depth at latitudes of 5°N (solid curves) and 25°N (dashed curves) calculated for the different aerosol models and the different months of the year. The figure demonstrates that the diurnally averaged radiative forcing varies by 15% or less regardless of latitude and time of year. Also, as expected, different values of the forcing are obtained for the different models.

Radiative forcing derived from the CERES SSF fluxes and AERONET optical depths for the five ocean sites for which a sufficient number of matchups were obtained are presented in Table 1. The value obtained for Kaashidhoo, –32 (±12) Wm^{-2} per unit optical depth at 0.67 µm agrees with the value derived by Satheesh and Ramanathan (2000), –25 Wm^{-2} at 0.5 µm The similarly low value obtained for the Dry Tortugas in the Caribbean suggests that the aerosol over that site is strongly absorbing, like the aerosol over Kaashidhoo. The large values of the direct forcing found for Bermuda in the North Atlantic and for San Nicolas west of Los Angeles are near the limit of what is expected for a nonabsorbing aerosol composed of small particles, the NOAA Phase 1 model shown in Fig. 1. These large values are discussed further below.

The forcing obtained by retrieving the aerosol optical depth from the CERES shortwave radiances and then using the retrieved optical depth to calculate diurnally averaged reflected shortwave flux leads to identical results for the various sites, i.e., within the range of uncertainty, regardless of the aerosol model used to calculate the forcing. For example, Figure 2 shows opticaldepths retrieved using CERES shortwave radiances and the AERONET optical depths for Bermuda. In Fig. 2, the optical depths in the SSF data are shown as Δ and the long-dashed line. These optical depths were retrieved from the 0.65-µm radiances for the VIRS fields of view that were identified as being cloud-free. Interestingly, for Bermuda, optical depths retrieved using the CERES shortwave radiances and the NOAA Phase 1 model compare better with the AERONET observations than do the optical depths derived from the cloud-free VIRS fields of view. Such agreement, however, is at best fortuitous. The degree to which the retrieved optical depths agree with the AERONET observations differs with each site.

TABLE 1. SENSITIVITY OF REFLECTED SHORTWAVE FLUX TO PRESENCE OF AEROSOL

Aeronet Site	Mean AERONET 0.67-µm optical depth	Flux Sensitivity (Wm^{-2} per unit 0.67-µm optical depth)	Cloud-Free Forcing (Wm^{-2})
Bermuda	0.13	54 ± 4	7.0
Dry Tortugas	0.16	19 ± 8	3.0
Kaashidhoo	0.16	32 ± 12	5.1
Lanai	0.07	36 ± 12	2.5
San Nicolas	0.07	56 ± 8	3.9

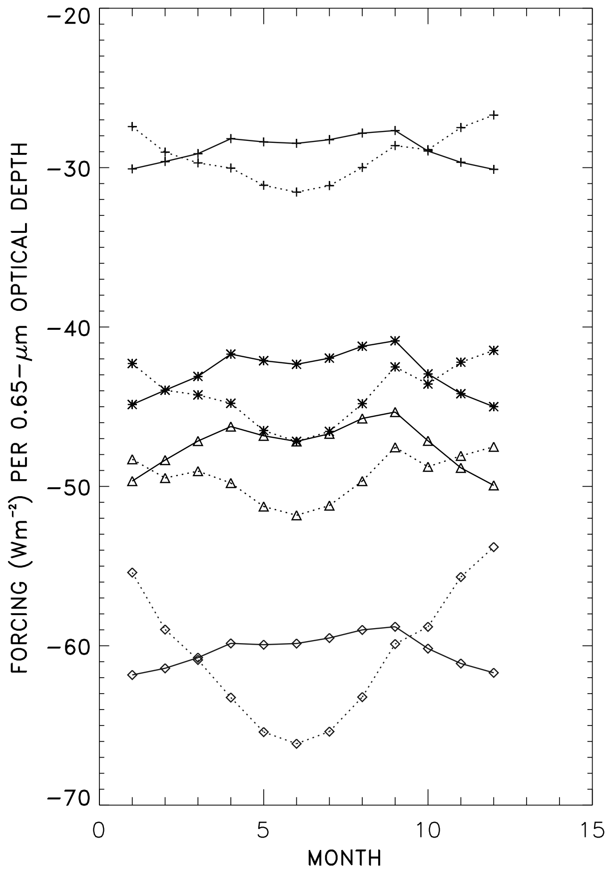

Figure 1. Cloud-free direct radiative forcing calculated for average continental (+), tropical marine (∗), NOAA Phase 1 (◊) and NOAA Phase 2 (Δ) aerosols. Solid curves are for 5°N and dotted curves are for 25°N.

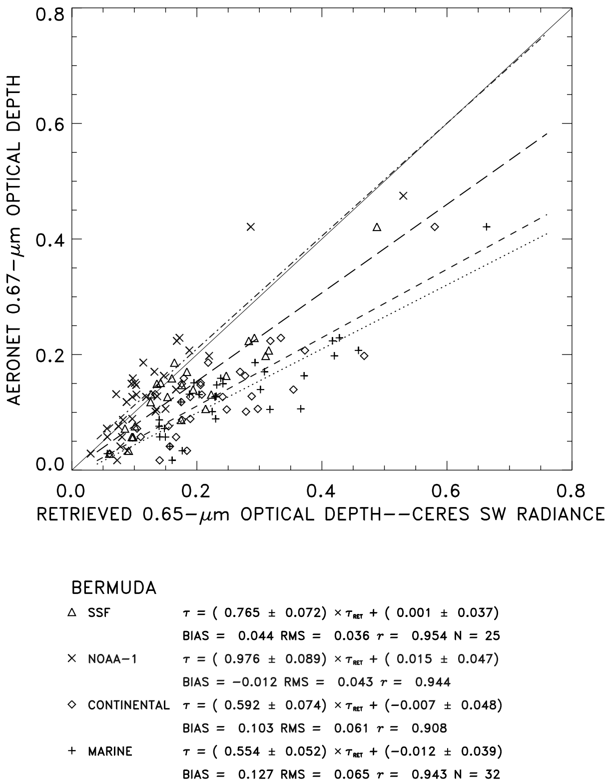

Figure 2. AERONET and Retrieved optical depths derived from CERES shortwave radiances. Least square fits are indicated by long-dashed line (SSF), short-dashed line (continental), dotted line (marine), and dash-dot line (NOAA Phase 1).

Figure 3 shows the diurnally averaged change in the reflected shortwave flux for Bermuda. Despite the differences in the agreement between the retrieved and AERONET optical depths, the values of the forcing for the different models agree to within the uncertainty due to the scatter in the data. The agreement arises because the optical depth derived using the shortwave radiance is a measure of the departure of the reflected shortwave radiance from that expected for a Rayleigh atmosphere. Since the retrieved optical depth is a linear function of this departure and since the effect of the aerosol on the diurnally averaged reflected shortwave flux is linear in optical depth, the departure of the reflected flux from that for a Rayleigh atmosphere is linearly proportional to the departure of the reflected shortwave radiance from that for a Rayleigh atmosphere. By using the AERONET optical depth to obtain the sensitivity of the reflected flux to aerosol burden, as opposed to using the retrieved optical depth, the effects of errors in the the retrieved optical depths are largely mitigated

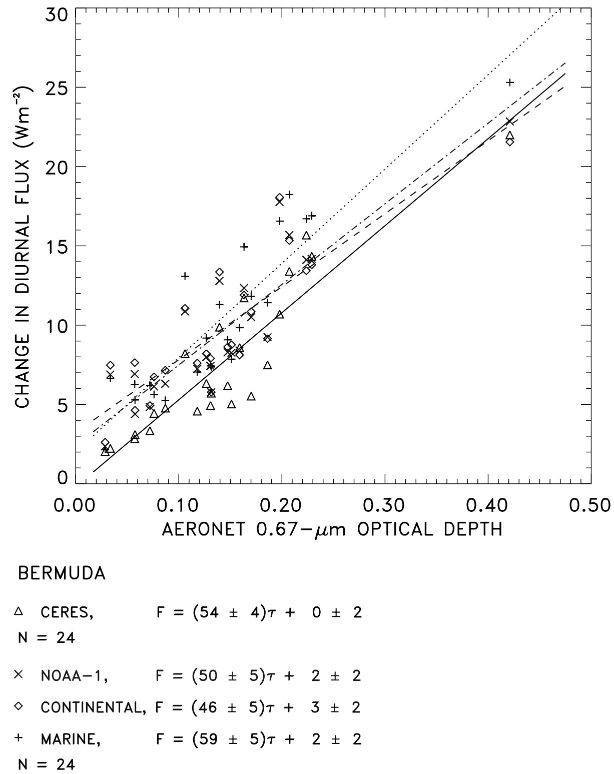

Figure 3. Same as Fig. 2 but for change in diurnally averaged reflected flux.

and the resulting forcing is relatively insensitive to the aerosol model used to derive the optical depth and radiative flux. Indeed, Figure 4 shows estimates of the forcing obtained using the retrieved optical depths, instead of the AERONET optical depths, with the radiative fluxes. In the case of the SSF estimates, the CERES estimates of the diurnally averaged reflected fluxes were combined with the SSF optical depths. The estimates of the forcing differ substantially for the different models. The sensitivities shown in Fig. 4 are more in line with the theoretically expected sensitivities shown in Fig. 1. Nearly identical results are obtained for the other oceanic sites studied here.

As mentioned earlier, Table 1 gives rather large estimates of the aerosol direct radiative forcing in the case of Bermuda and San Nicolas when compared with the theoretically expected values shown in Fig. 1. Since such large sensitivities might be caused by cloud contamination, the criteria used to identify cloud-free CERES FOVs were altered to determine the effect of cloud contamination. While the retrieved optical depths were rather sensitive to the degree of cloud contamination, the estimates of the

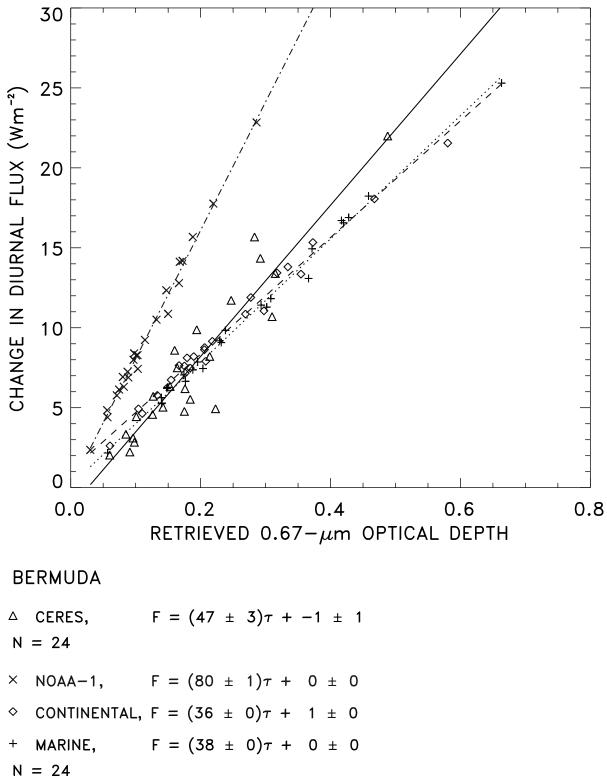

Figure 4. Same as Fig. 3 but for retrieved optical depths.

forcing proved to be rather insensitive to the contamination. The compensation of errors in the retrieved optical depths mentioned earlier evidently includes effects due to minor cloud contamination.

4. Discussion

Estimates of the aerosol direct radiative forcing for cloud-free regions derived using CERES shortwave radiances and an aerosol model with simultaneous surface observations of aerosol optical depth proved to be insensitive to the aerosol model. These estimates of the forcing were consistent with those obtained using the radiative fluxes in the CERES SSF data. Distinctly different aerosol forcing was found in different regions. Low values are probably associated with strongly absorbing aerosols. High values are difficult to reconcile with realistic aerosol models, but suggest the presence of a nonabsorbing aerosol with small particles. The effects of cloud contamination on the findings appeared to be negligible.

Acknowledgment

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References

Hess, M., P. Koepke, and I. Schult, 1998: Optical properties of aerosols and clouds: The software package OPAC. *Bull. Amer. Meteor. Soc*. **79**, 831-844.

Loeb N.G. and S. Kato, 2002: Top-of-atmosphere direct radiative effect of aerosols from the Clouds and the Earth's Radiant Energy System Satellite Instrument (CERES). *J. Climate* (in press).

Satheesh, S.K. and V. Ramanathan, 2000: Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface. *Nature*, **405**, 60-63.

Stowe, L.L., A.M. Ignatov, and R.R. Singh,. 1997: Development, validation, and potential enhancements to the second-generation operational aerosol product at the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration. *J. Geophys. Res*., **102**, 16,923-16,934.