Aerosol Direct Effect from CERES and AERONET Observations

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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 emprical 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. The approach uses aerosol models in combination with CERES shortwave radiances for cloud-free ocean scenes. The aerosol model is used to retrieve optical depth from the CERES shortwave radiance and then the optical depth is used to generate a diurnally averaged radiative flux. This flux is matched with a coincident measurement of aerosol optical depth by AERONET. Various aerosol models were used in order to determine the range of fluxes and aerosol forcing that could be obtained with this approach. The derived forcing proved to be insensitive to the aerosol model and consistent with the forcing derived using the fluxes on the SSF and the ADMs used to generate those fluxes.

SSF Edition 1 and Edition 2 for TRMM (January – August, 1998) were analyzed for TRMM 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. In order to determine the aerosol direct effect, the CERES fields of view had to be cloud-free. Cloud-free CERES FOVs were identified to be those for which retrievals of the aerosol optical depth were performed for more than 50% of the VIRS pixels that fell within the FOV. Other methods for identifying cloud-free CERES FOVs were explored, such as limiting the variability of the VIRS reflectances within the FOV, but the different approaches gave identical results.

The aerosol models used to calculate the TOA flux were the average continental aerosol and tropical marine models described by Hess et al. (1998) and the NOAA Phase 2 model described by Stowe et al. (1997). The effects of cloud contamination within the CERES FOVs identified as being cloud-free were illustrated by the shifts in the retrieved optical depths obtained using 1) the subset of VIRS channel 1 radiances used to determine the optical depth reported on the SSF and 2) the VIRS radiances averaged over the CERES FOV. The retrieved optical depths obtained using the averaged radiances were greater than those obtained using the subsetted radiances. As might be expected, the optical depths obtained using the CERES shortwave radiances generally showed poorer agreement with the AERONET optical depths than that obtained with the VIRS radiances. For the broadband shortwave radiances, the aerosol signal must be detected against the background of Rayliegh scattering, which is larger for the broadband reflectance than for the narrow channel reflectance of VIRS, and the additional variability due to variations in ozone and water vapor.

All estimates of the sensitivity of the TOA shortwave flux to aerosol optical depth fell within the uncertainty derived for the slope of the TOA flux-optical depth linear regression. The value obtained for Kaashidhoo, –31 (±9) Wm^{-2} per unit optical depth at 0.67 μm agrees with the value derived by Satheesh and Ramanathan (2000), –25 Wm^{-2}. The similarly low values obtained for the Dry Tortugas and Barbados in the Caribbean suggest that the aerosol over those sites are also strongly absorbing like the aerosol over Kaashidhoo. The large sensitivities found for Bermuda, San Nicolas, and Lanai, are near the limits of what is expected for a nonabsorbing aerosol composed of small particles, as is the case for the NOAA Phase 1 aerosol model. 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 the contamination. Despite the large impact of the cloud contamination evident in the retrieved aerosol optical depths, the contamination had little effect on the estimated aerosol direct radiative forcing.

Estimates of the aerosol direct radiative forcing 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. The results were consistent with those obtained using the radiative fluxes and the ADMs used to produce the radiative fluxes on the SSF. 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.

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.

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.

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GOAL: **Deduce aerosol direct effect using CERES SSF radiances and AERONET optical depths following Satheesh and Ramanathan (2000).**

Method

- Identify cloud-free CERES fields of view
- Determine aerosol optical depth

$$I_\lambda(\tau_\lambda,\theta,\varphi,\theta_0)-I_{\lambda 0}(0,\theta,\varphi,\theta_0)=C_\lambda(\theta,\varphi,\theta_0)\tau_\lambda$$

Where

τ_λ is the optical depth at a reference wavelength**.**

$I_{\lambda 0}(0,\theta,\varphi,\theta_0)$ is the radiance for an aerosol-free atmosphere.

$C_\lambda(\theta,\varphi,\theta_0)$ is almost independent of aerosol optical depth.

- Use retrieved optical depth and radiative transfer model to determine TOA radiative flux.

Aerosol Direct Radiative Effect

$$F = A\tau_\lambda + F_0$$

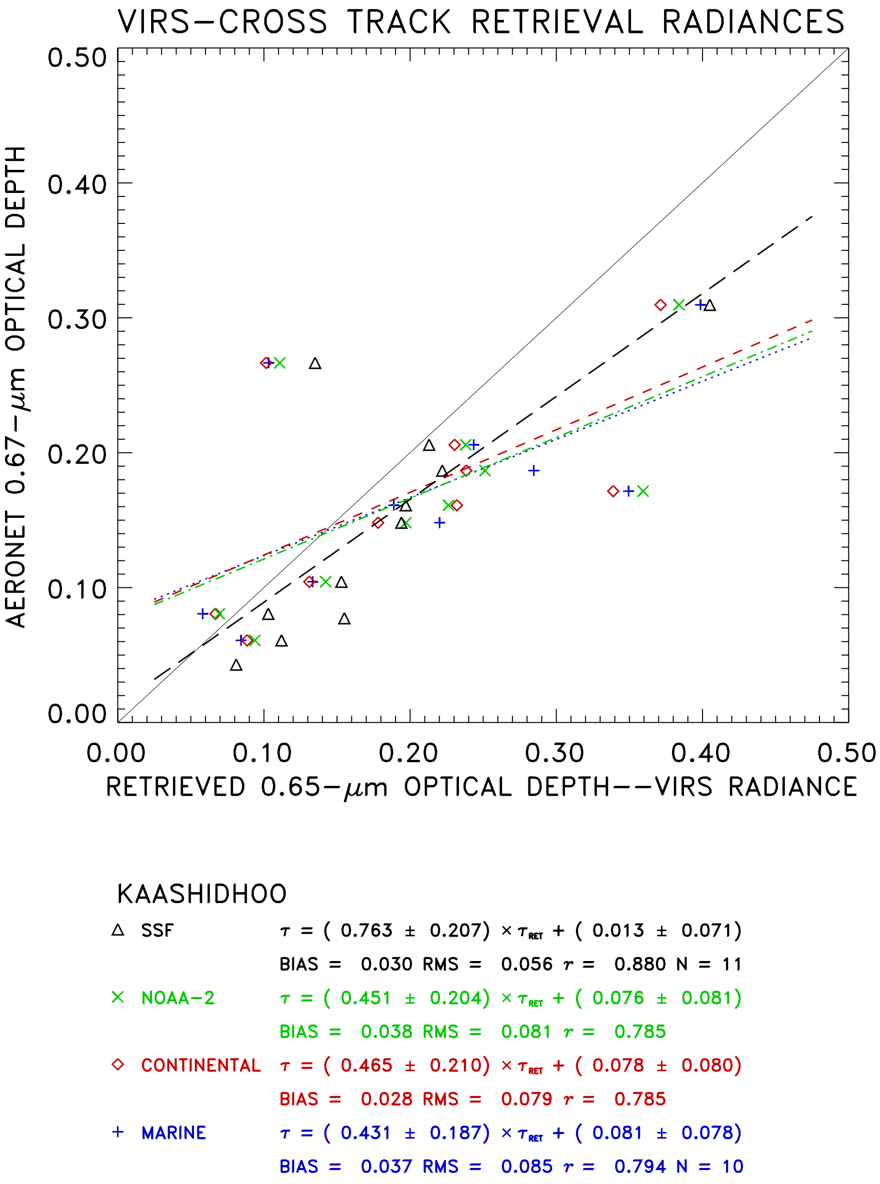
where

A is the sensitivity of the TOA flux to the aerosol (Wm^{-2} per unit optical depth) and is given by the slope of the linear least-squares fit of $F - F_0$ to the AERONET optical depth, τ_λ .

F_0 is the aerosol-free TOA flux.

Note: *Determination of* A *will prove to be independent of the radiative properties of the aerosol.*

AERONET and Retrieved Optical Depths



KAASHIDHOO

△ SSF τ = (0.763 ± 0.207) × τ_{RET} + (0.013 ± 0.071)
BIAS = 0.030 RMS = 0.056 r = 0.880 N = 11

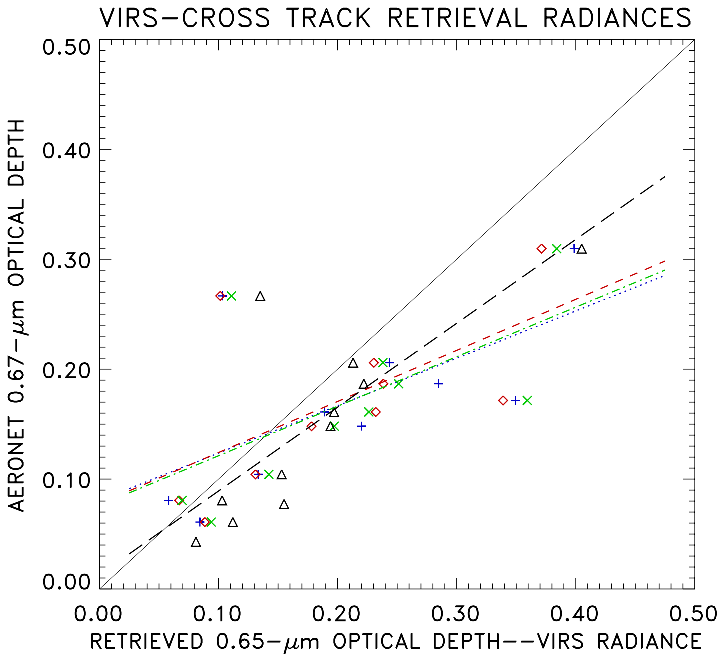
× NOAA–2 τ = (0.451 ± 0.204) × τ_{RET} + (0.076 ± 0.081)
BIAS = 0.038 RMS = 0.081 r = 0.785

◇ CONTINENTAL τ = (0.465 ± 0.210) × τ_{RET} + (0.078 ± 0.080)
BIAS = 0.028 RMS = 0.079 r = 0.785

+ MARINE τ = (0.431 ± 0.187) × τ_{RET} + (0.081 ± 0.078)
BIAS = 0.037 RMS = 0.085 r = 0.794 N = 10

- Retrievals based on VIRS channel 1 radiances for CERES FOV’s having at least 50% of VIRS pixels yielding optical depth retrievals.
- SSF results limited to cross track observations.
- AERONET observations within ± 1 hour.
- CERES observations within 50 km.

Check of Cloud Contamination for CERES Field of View



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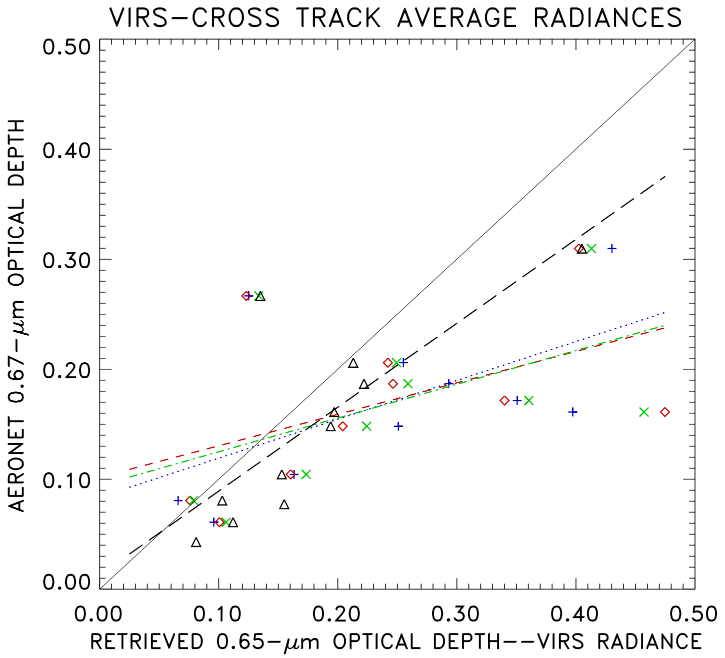


KAASHIDHOO

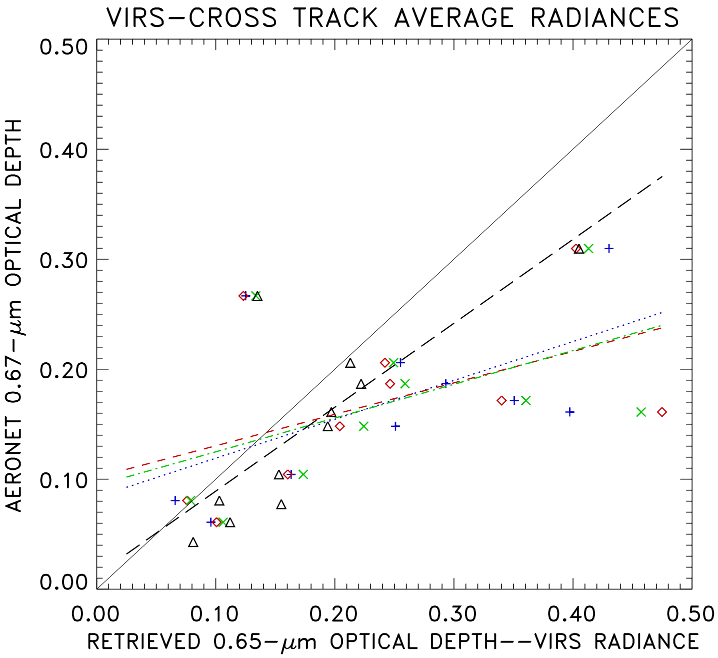
△ SSF τ = (0.763 ± 0.207) × τ_{RET} + (0.013 ± 0.071)
BIAS = 0.036 RMS = 0.055 r = 0.880 N = 11

× NOAA–2 τ = (0.307 ± 0.184) × τ_{RET} + (0.094 ± 0.087)
BIAS = 0.076 RMS = 0.107 r = 0.713

◇ CONTINENTAL τ = (0.286 ± 0.182) × τ_{RET} + (0.102 ± 0.088)
BIAS = 0.067 RMS = 0.111 r = 0.697

+ MARINE τ = (0.353 ± 0.177) × τ_{RET} + (0.084 ± 0.083)
BIAS = 0.073 RMS = 0.099 r = 0.759 N = 10

Optical Depth Retrieved with CERES Shortwave Radiance



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△ SSF $\tau = (0.763 \pm 0.207) \times \tau_{RET} + (0.013 \pm 0.071)$
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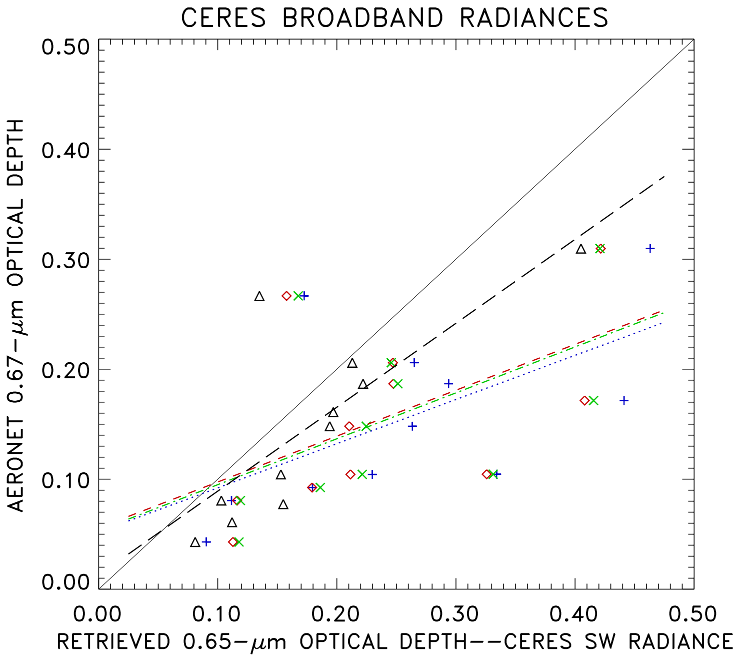


KAASHIDHOO

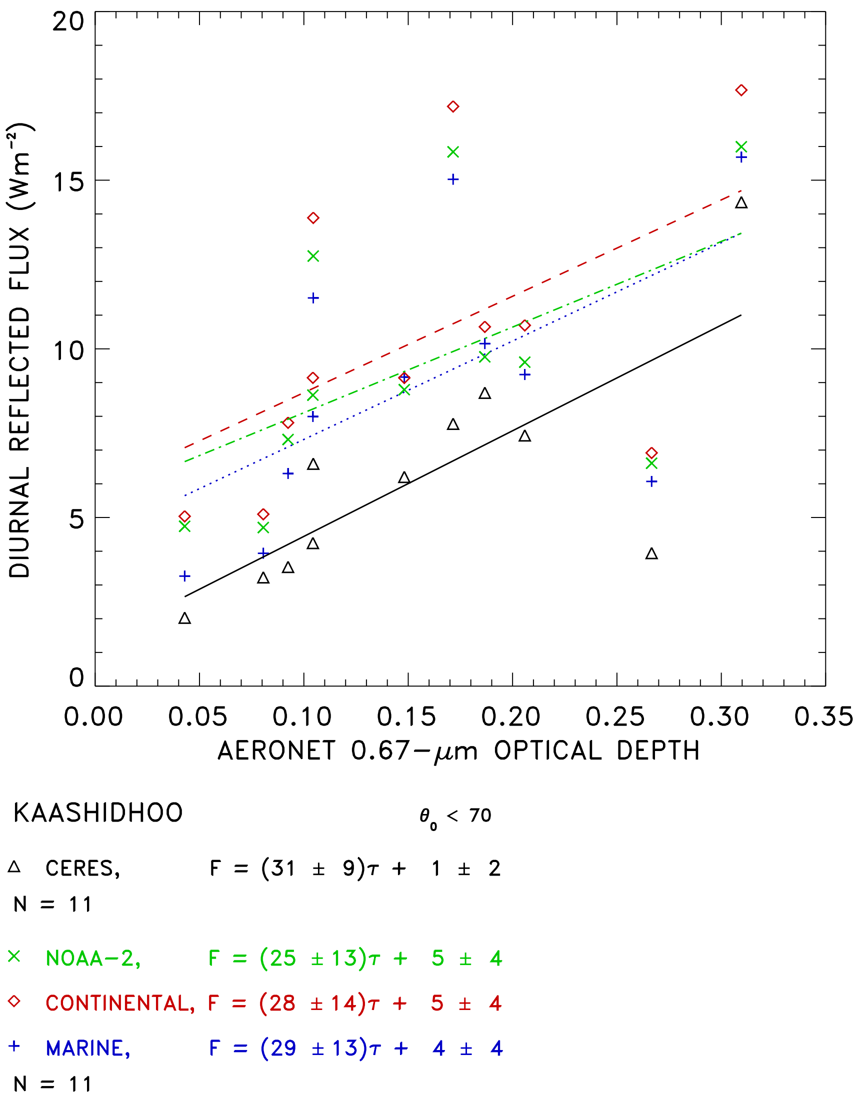
△ SSF $\tau = (0.763 \pm 0.207) \times \tau_{RET} + (0.013 \pm 0.071)$
BIAS = 0.036 RMS = 0.055 r = 0.880 N = 11

× NOAA–2 $\tau = (0.417 \pm 0.221) \times \tau_{RET} + (0.053 \pm 0.094)$
BIAS = 0.090 RMS = 0.088 r = 0.730

◇ CONTINENTAL $\tau = (0.417 \pm 0.218) \times \tau_{RET} + (0.056 \pm 0.092)$
BIAS = 0.084 RMS = 0.088 r = 0.734

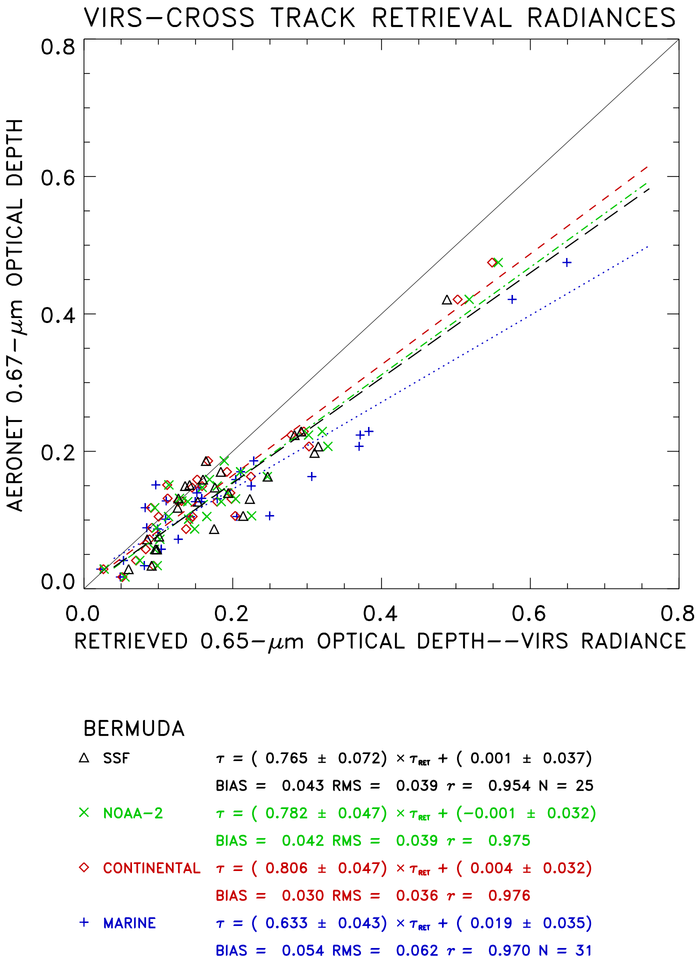
+ MARINE $\tau = (0.401 \pm 0.182) \times \tau_{RET} + (0.052 \pm 0.087)$
BIAS = 0.103 RMS = 0.094 r = 0.769 N = 11

Diurnally Averaged TOA Flux and AERONET Optical Depth



- CERES estimate based on directional model derived from ADMs.
- Flux sensitivity is insensitive to aerosol model.
- Sensitivities consistent with 25 Wm^{-2} obtained by Satheesh and Ramanathan (2000).

Check of Cloud Contamination



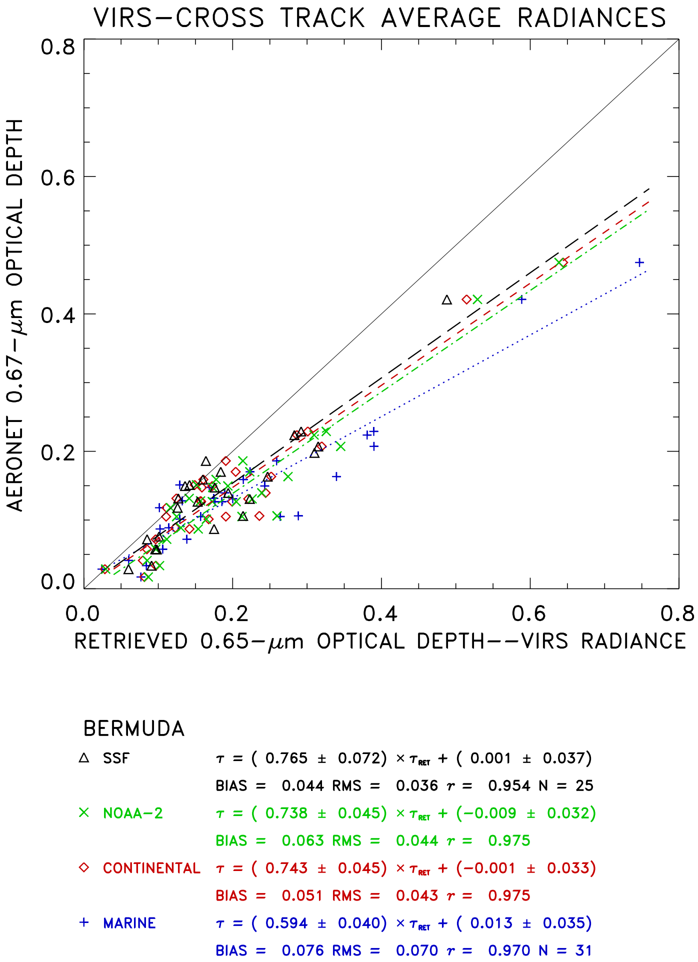
BERMUDA

△ SSF τ = (0.765 ± 0.072) × τ_{RET} + (0.001 ± 0.037)
BIAS = 0.043 RMS = 0.039 r = 0.954 N = 25

× NOAA–2 τ = (0.782 ± 0.047) × τ_{RET} + (–0.001 ± 0.032)
BIAS = 0.042 RMS = 0.039 r = 0.975

◇ CONTINENTAL τ = (0.806 ± 0.047) × τ_{RET} + (0.004 ± 0.032)
BIAS = 0.030 RMS = 0.036 r = 0.976

+ MARINE τ = (0.633 ± 0.043) × τ_{RET} + (0.019 ± 0.035)
BIAS = 0.054 RMS = 0.062 r = 0.970 N = 31



BERMUDA

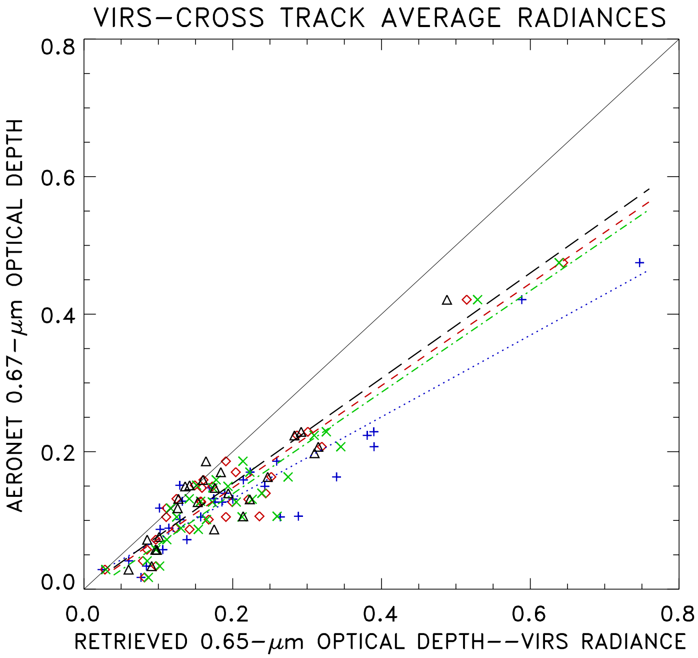
△ SSF τ = (0.765 ± 0.072) × τ_{RET} + (0.001 ± 0.037)
BIAS = 0.044 RMS = 0.036 r = 0.954 N = 25

× NOAA–2 τ = (0.738 ± 0.045) × τ_{RET} + (–0.009 ± 0.032)
BIAS = 0.063 RMS = 0.044 r = 0.975

◇ CONTINENTAL τ = (0.743 ± 0.045) × τ_{RET} + (–0.001 ± 0.033)
BIAS = 0.051 RMS = 0.043 r = 0.975

+ MARINE τ = (0.594 ± 0.040) × τ_{RET} + (0.013 ± 0.035)
BIAS = 0.076 RMS = 0.070 r = 0.970 N = 31

Optical Depths Retrieved using CERES Shortwave Radiance



BERMUDA

△ SSF $\tau = (0.765 \pm 0.072) \times \tau_{RET} + (0.001 \pm 0.037)$

BIAS = 0.044 RMS = 0.036 r = 0.954 N = 25

× NOAA–2 $\tau = (0.738 \pm 0.045) \times \tau_{RET} + (-0.009 \pm 0.032)$

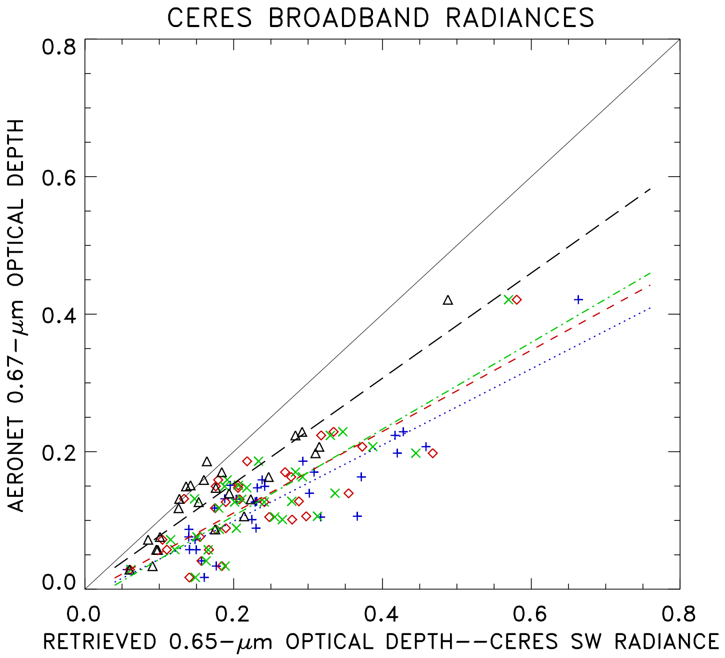
BIAS = 0.063 RMS = 0.044 r = 0.975

◇ CONTINENTAL $\tau = (0.743 \pm 0.045) \times \tau_{RET} + (-0.001 \pm 0.033)$

BIAS = 0.051 RMS = 0.043 r = 0.975

+ MARINE $\tau = (0.594 \pm 0.040) \times \tau_{RET} + (0.013 \pm 0.035)$

BIAS = 0.076 RMS = 0.070 r = 0.970 N = 31



BERMUDA

△ SSF $\tau = (0.765 \pm 0.072) \times \tau_{RET} + (0.001 \pm 0.037)$

BIAS = 0.044 RMS = 0.036 r = 0.954 N = 25

× NOAA–2 $\tau = (0.631 \pm 0.073) \times \tau_{RET} + (-0.020 \pm 0.046)$

BIAS = 0.108 RMS = 0.055 r = 0.919

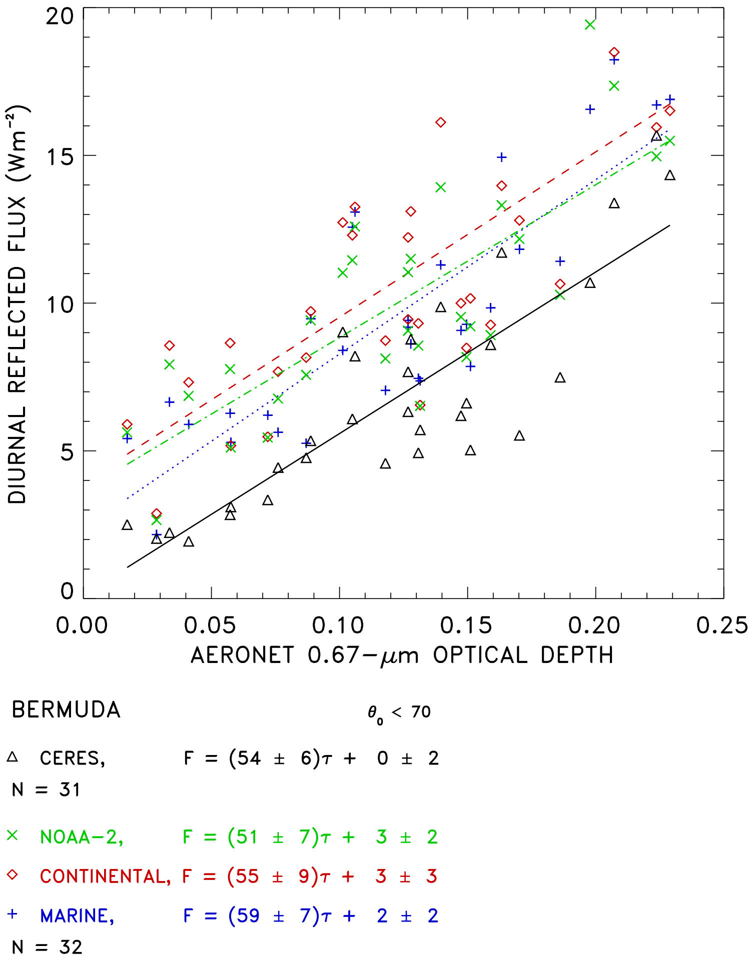
◇ CONTINENTAL $\tau = (0.592 \pm 0.074) \times \tau_{RET} + (-0.007 \pm 0.048)$

BIAS = 0.103 RMS = 0.061 r = 0.908

+ MARINE $\tau = (0.554 \pm 0.052) \times \tau_{RET} + (-0.012 \pm 0.039)$

BIAS = 0.127 RMS = 0.065 r = 0.943 N = 32

Diurnally Averaged TOA Flux and AERONET Optical Depth



- Flux sensitivity is insensitive to aerosol model.
- Sensitivities are Significantly larger than those for Kaashidhoo.

Aerosol Models

- NOAA Phase 1, (*Stowe et al. 1997*)

  A = 52 Wm^{-2} per unit 0.55-µm optical depth.

- NOAA Phase 2, (*Stowe et al. 1997*)

  A = 36 Wm^{-2} per unit 0.55-µm optical depth.

- Average Continental, (*Hess et al. 1998*)

  A = 27 Wm^{-2} per unit 0.55-µm optical depth.

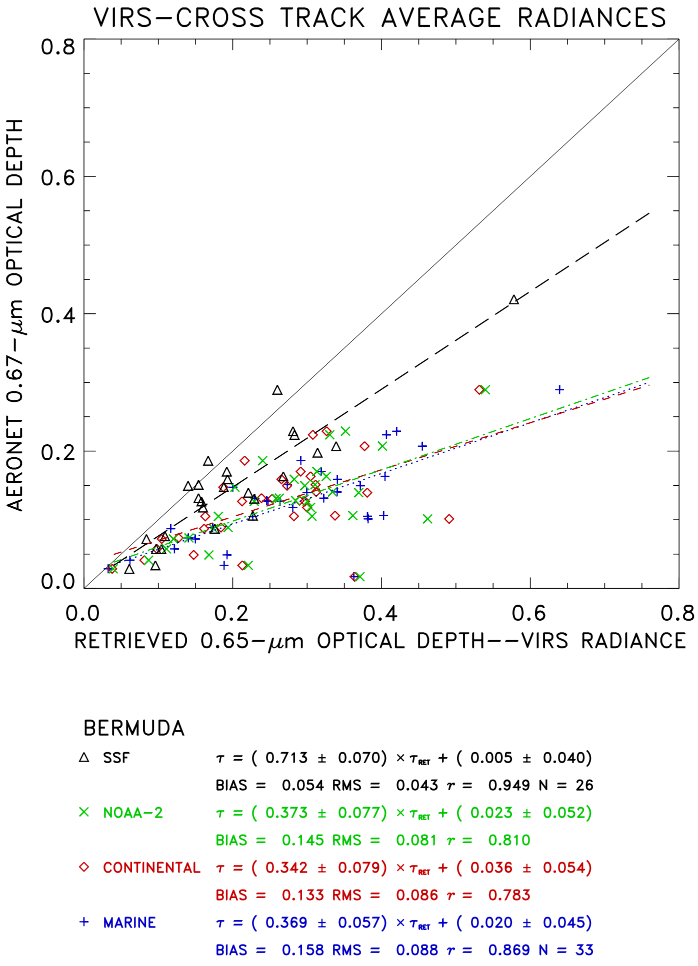
- Tropical Marine, (*Hess et al. 1998*)

  A = 34 Wm^{-2} per unit 0.55-µm optical depth.

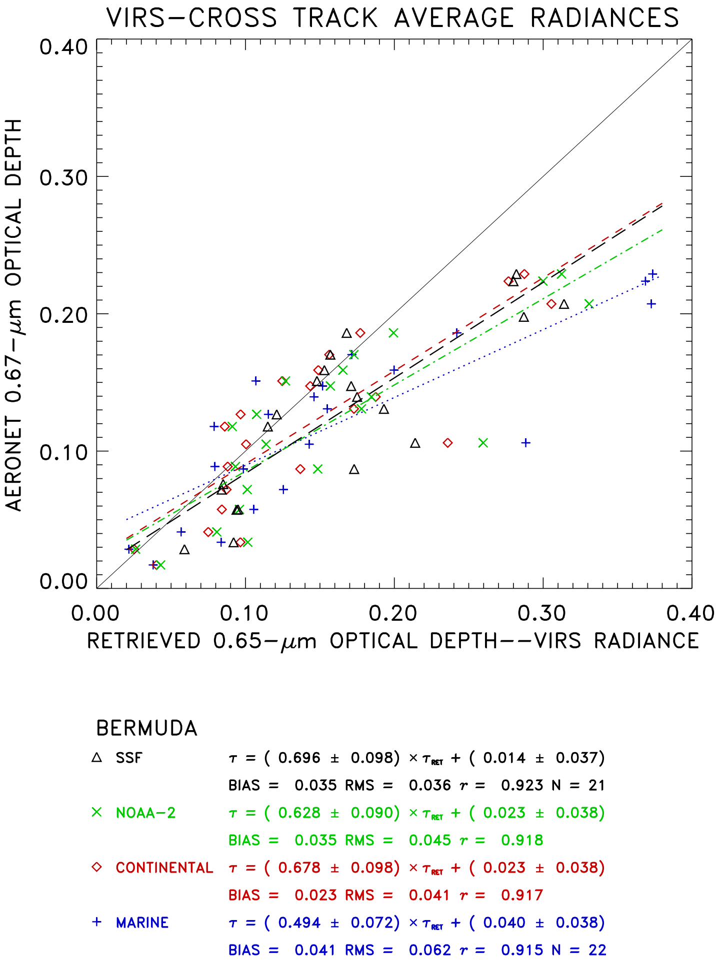
Calculations for March 1 at the equator for 0.55-µm optical depth of 0.3.

Check of Cloud Contamination

Optical depth retrieval performed for 10% of CERES FOV

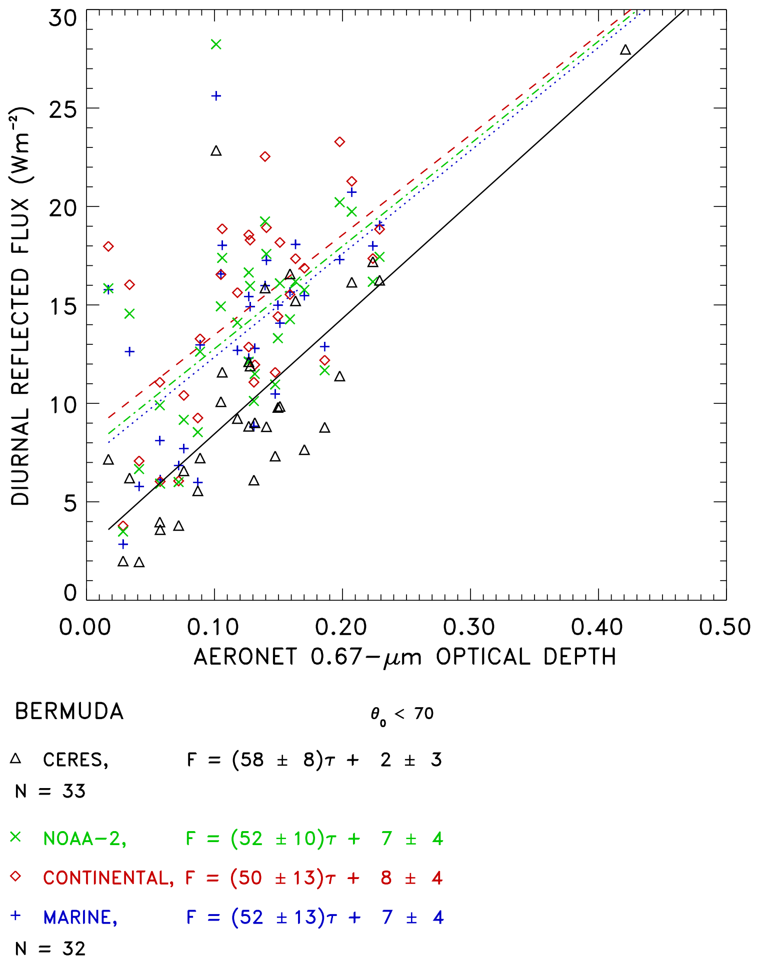


Optical depth retrieval performed for 80% of CERES FOV

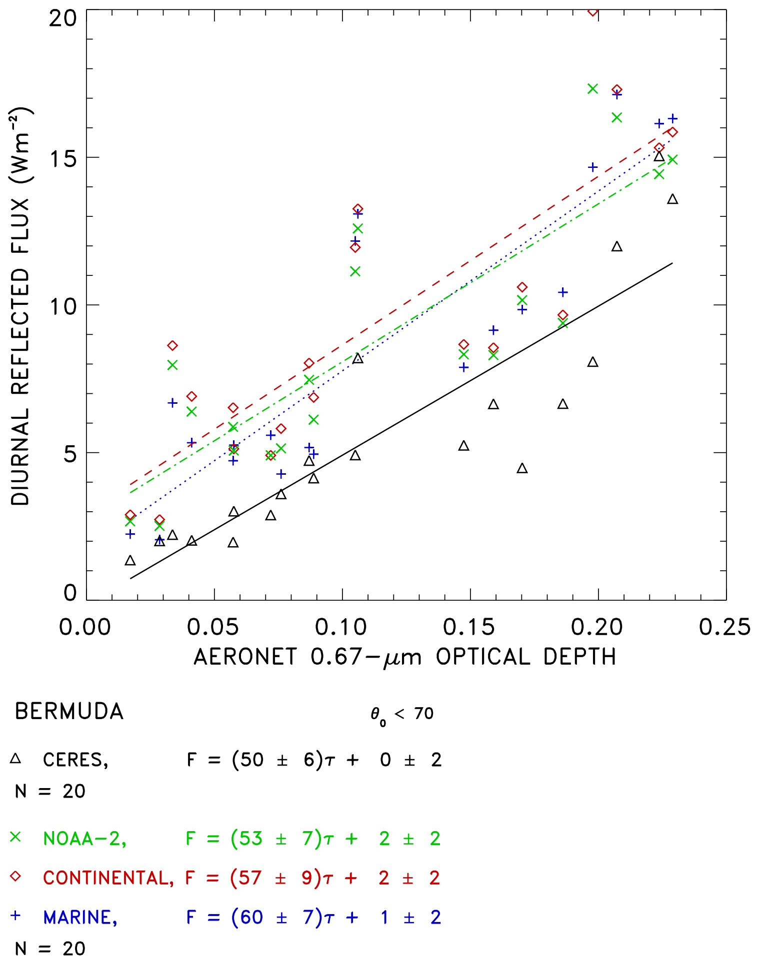


Diurnally Averaged TOA Flux and AERONET Optical Depth

Optical depth retrieval performed for 10% of CERES FOV



Optical depth retrieval performed for 80% of CERES FOV



Why is the derived forcing insensitive to aerosol optical properties?

- Anisotropy of cloud-free ocean scene depends mainly on Rayliegh scattering and ocean reflectance and depends only weakly on aerosol properties.
- Departure of the TOA radiative flux from aerosol-free value is linearly proportional to departure of shortwave radiance from aerosol-free value.
- Departure of shortwave radiance from aerosol-free value is linearly proportional to AERONET optical depth.

TOA Flux Sensitivity to Unit Aerosol Optical Depth

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})
Barbados	0.15	31 ± 5	4.6
Bermuda	0.13	54 ± 6	7.0
Dry Tortugas	0.16	22 ± 7	3.5
Kaashidhoo	0.16	31 ± 9	5.0
Lanai	0.07	49 ± 11	3.4
San Nicolas	0.07	57 ± 7	4.2

Conclusions

- Distinctly different sensitivities of the TOA flux to aerosol optical depths are found in different locations. In some locations, rather large sensitivities are encountered.
- Sensitivities appear to be insensitive to the degree of cloud contamination.
- Because the anisotropy of the cloud-free ocean is governed primarily by the ocean and Rayleigh scattering, estimates of the radiative forcing due to aerosols obtained by correlating AERONET optical depths with estimates of the TOA shortwave flux obtained from optical depths retrieved for the shortwave radiances are relatively insensitive to the aerosol model.