Daytime Variation of Shortwave Direct Radiative Forcing of Biomass Burning Aerosols from GOES-8 Imager

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ABSTRACT

Hourly GOES-8 imager data (1344UTC-1944 UTC) from July 20-August 31, 1998 were used to study the daytime variation of shortwave direct radiative forcing (SWARF) of smoke aerosols over biomass burning regions in South America (4-16 S, 51-65 W). Vicarious calibration procedures were used to adjust the GOES visible channel reflectance values for the degradation in signal response. Using Mie theory and Discrete Ordinate Radiative transfer (DISORT) calculations; smoke aerosol optical thickness (AOT) was estimated at 0.67 μm. The GOES retrieved AOT was then compared against ground-based AOT retrieved values. Using the retrieved GOES 8 AOT, a four-stream broadband radiative transfer model was used to compute shortwave fluxes for smoke aerosols at the top of atmosphere (TOA). The daytime variation of smoke AOT and shortwave aerosol radiative forcing (SWARF) was examined for the study area. For selected days, the Clouds and the Earth’s Radiant Energy System (CERES) TOA SW fluxes are compared against the model derived SW fluxes.

Our results show that the GOES derived AOT is in excellent agreement with AERONET derived AOT values with linear correlation coefficient of 0.97. The TOA CERES estimated SW fluxes compare well with the model calculated SW fluxes with linear correlation coefficient of 0.94. The daytime diurnally averaged AOT and SWARF for the study area is 0.63±0.39 and –45.8±18.8Wm^{-2} respectively. This is among the first studies to estimate the daytime diurnal variation of SWARF of smoke aerosols using satellite data.

1. Introduction

Atmospheric aerosol particles perturb the radiative balance of the earth-atmosphere system through two different mechanisms. Through the direct effect (e.g. Penner et al. 1992) they scatter the incoming solar radiation thereby “cooling” the earth’s surface, while through the indirect effect they modify the shortwave reflective properties of clouds (e.g. Kaufman and Nakajima 1993) thereby increase the lifetime of clouds and suppressing drizzle formation. Due to their absorptive nature, smoke aerosols could also warm the atmosphere could lead to changes in atmospheric circulation. The direct radiative forcing of anthropogenic aerosols from sulfates, fossil fuel soot and organic aerosols range from -0.25 to -1.0 Wm^{-2} while the indirect radiative forcing estimates range from 0 to -1.5 Wm^{-2}. The radiative forcing of greenhouse gases on the other hand range from +2.1 to +2.8 Wm^{-2} (Houghton et al. 1996). These estimates show that the magnitudes of aerosol radiative forcing are almost equal to those of greenhouse gases but opposite in sign. However, considerable uncertainties exist in the estimates of aerosol radiative forcing due to their diverse chemical composition, microphysical properties and short residence times in the atmosphere.

Biomass burning in the tropics accounts for more than 114 Teragrams of smoke (Hao and Liu 1994) and has a significant radiative impact on regional (Christopher et al. 2000a; Kaufman and Nakajima 1993; Kaufman et al. 1998) and global climate (Penner et al. 1992; Hansen et al. 1997). Biomass burning is used to clear extensive areas of the forests and savannas for agricultural purposes and to accommodate the needs of the expanding population (Andreae 1991). The permanent removal of forests is replaced with grazing or cropland, while the land cleared for agricultural purposes is primarily used for shifting agriculture.

Most satellite remote sensing studies have used polar orbiting platforms to examine the radiative effects of aerosols (e.g. Christopher et al. 1996,1998, 2000a; Hsu et al. 2000). The major goal of this paper is to examine the daytime variation of direct shortwave radiative forcing (SWARF) of biomass burning aerosols at the TOA using the new generation of high spatial and temporal resolution GOES-8 imager. Biomass burning aerosols are first identified using a simple multi-spectral thresholding algorithm from the GOES 8 imager. Using Mie and Discrete Ordinate Radiative Transfer (DISORT) calculations, smoke aerosol optical thickness (AOT) is retrieved from the GOES 8 visible channel reflectances. The GOES retrieved AOT is compared against ground-based sunphotometer AOT values. These GOES 8 AOT values are then used in a four-stream broadband radiative transfer model to estimate the shortwave flux at the TOA for biomass burning aerosols. The SW flux in biomass burning regions from model calculations are then compared against broadband SW flux values from the Clouds and the Earth's Radiant Energy System (CERES) data. The shortwave fluxes over clear and aerosol regions are used to estimate shortwave aerosol radiative forcing (SWARF). The daytime direct SWARF forcing of biomass burning aerosols is then computed for the entire study area. This study is specifically focused upon the direct SWARF of biomass burning aerosols. The effect of smoke in modifying cloud properties and reflectance is not considered.

2. Data

Hourly GOES-8 data from July 20-August 31, 1998 between 4-16 S and 51-65 W were used. The GOES-8 imager has five channels centered at 0.67 ($\rho_{0.67}$), 3.9 ($T_{3.9}$), 6.8, 10.7 ($T_{10.7}$), 11.8 ($T_{11.8}$) μm where ρ and T denote reflectivity and temperature respectively. Channel 3 that is sensitive to mid-tropospheric water vapor is not used. Since the 3.9 μm channel has an emitted and reflected component, a sixth channel which is the reflected portion of channel 3 ($\rho_{3.9}$) is estimated by removing the thermal emission using the 10.7 μm channel (Greenwald and Christopher 2000). This $\rho_{3.9}$ information is useful in separating for smoke aerosols from low level water clouds (Kaufman and Fraser 1997; Christopher et al. 2000a). The sampled sub point spatial resolution of channel 1 is 0.57 x 1 km and for the other channels is 2.3 x 4.0 km (Menzel and Purdom 1994). The visible channel was sub sampled to match the resolution of the IR channels.

Channel 1 of the GOES-8 imager was not designed for long-term accurate radiometry and thus has no onboard calibration. However, other GOES channels have onboard calibration. Although, all channels of the GOES imagers undergo extensive calibration testing prior to launch (Weinreb et al. 1997), only the infrared channels (2-5) have onboard calibration. A lack of onboard calibration for the visible channel makes the reliable retrieval of aerosol optical depth more difficult because calibration errors are one of the largest sources of uncertainty in estimating visible optical depth from satellite radiance measurements (Pincus et al. 1997). However, using vicarious calibration methods GOES data has been used to successfully perform cloud (Greenwald and Christopher 1999, 2000; Greenwald et al. 1997) and aerosol optical thickness retrievals (Zhang et al. 2001).

There have been several recent attempts to assess and monitor the visible channel calibration through vicarious means (Bremer et al. 1998; Rao et al. 1999; Nguyen et al. 1999). These studies all report that the GOES-8 imager have undergone signal degradation due to the accumulation of material on the scanning mirror (Ellrod et al. 1998). The GOES-8 imager visible channel also suffered an unexpected drop of about 9% in signal response soon after launch (Ellrod et al. 1998). Based on GOES imager measurements of clear ocean scenes, Knapp and Vonder Haar (2000) have estimated this initial drop in response to be about 7.6%. The subsequent rate of degradation for the GOES-8 imager visible channel has been estimated to be about 5.6% per year (from August 1995-August 1999) that is consistent with a simple GOES-8/-9 intercalibration test used by Greenwald et al. (1997). Therefore, in this study we account for the degradation of the GOES-8 visible channel using the methodology described by Knapp and Vonder Haar (2000) that is similar to the method employed by Fraser and Kaufman (1986).

The GOES-8 AOT retrievals were compared against ground-based AOT values from the Aerosol Robotic Network (AERONET) (Holben et al. 1998). The sunphotometer radiances were measured at 340 nm, 380 nm, 440 nm, 500 nm, 670 nm, 870 nm, and 1020 nm and converted to AOT at these 7 wavelengths. The AOT values used in this paper are obtained after a careful cloud screening process as described in Holben et al. (1998) and the uncertainty in ground-based AOT values is on the order of 0.01 (Smirnov et al. 2000).

The Clouds and the Earth’s Radiant Energy System (CERES) scanner TOA flux values from the Tropical Rainfall Measuring Mission (TRMM) platform (Kummerow et al. 1998) are used to compare against the model-derived values. The CERES is a broadband instrument (Wielicki et al. 1996) that measures the TOA radiance in three bands (0.3 to > 50 μm, 0.3 - 5 μm, 8-12 μm) at a spatial resolution of about 20 km at nadir. The measured broadband radiances are converted to fluxes using angular dependence models (ADM's) (Wielicki and Green 1989) that were developed as part of the ERBE program. In previous research the CERES SW flux values have been used to estimate the SWARF of biomass burning aerosols over Central America (Christopher et al. 2000a).

Figure 1 (a-f) shows the area of study and is an example of GOES channel 1 images from 1445-1945 UTC. The two sites in Bolivia, Los Fieros and Concepcion, were sunphotometer measurements were available during 1998 are also shown. No AERONET measurements were available in Brazil during 1998 where the majority of biomass burning takes place (Prins et al. 1998; Christopher et al. 1998). Smoke aerosols are clearly visible in these images throughout the day and clouds are primarily in the northern portion of the image.

3. Method and Results

3.1 Smoke aerosol detection using the GOES-8 imager

Each GOES 8 imager pixel is classified into one of three categories; smoke aerosols, clouds and clear sky. Clear sky denotes areas where clouds and smoke aerosols are absent. The basic idea is to obtain clear sky (or background values) for each time period. Then smoke and cloudy pixels are identified if the measured values are greater than the background values by a certain threshold. The background values are obtained for each time period by assuming that the lowest channel 1 reflectances ($\rho_{0.63\ clear}$) over the study period corresponds to clear sky values. Similarly clear sky values for the reflectance portion of channel 2 ($\rho_{3.9\ clear}$) is obtained. The clear sky values are obtained from July when biomass burning is less prevalent over South America (Prins et al. 1998; Holben et al. 1996, Zhang et al. 2001). Although background optical depths are not zero, the lowest channel 1 reflectance for each time period during July provides the best chance for obtaining cloud and smoke free background values. Clear sky values for channel 4 ($T_{10.7\ clear}$) are obtained by averaging the channel 4 pixels that are identified if the channel 1 albedo is within ±0.02 of the channel 1 background value and if the standard deviation of a 3×3 box is less than 2K. Then all clouds with cloud top temperatures colder than 273K and with channel 1 reflectances greater than 35% are removed ($\rho_{0.63} > 0.35$ and $T_{10.7} < 273K$). This leaves the image with smoke aerosols and clouds with cloud top temperatures warmer than 273K. Clouds are now separated from smoke aerosols by using the $\rho_{3.9}$ information. Smoke aerosols due to their small sizes are nearly transparent at these wavelengths (Kaufman and Nakajima 1993; Christopher et al. 2000a) whereas clouds with water droplets scatter the incoming solar radiation based on their particle size (Greenwald and Christopher 2000). Further cloud screening is done if the following criteria are satisfied: ($\rho_{0.63} - \rho_{0.63clear}$)>0.05 and ($\rho_{3.9} - \rho_{3.9\ clear}$>0.03) and ($T_{10.7} - T_{10.7\ clear}$ > 10K). The first criteria identify pixels as cloudy if the difference between the clear and measured channel 1 reflectance is greater than 5%. The second threshold assumes that for cloudy pixels, water clouds have a difference in channel 2 reflectivity between measured and clear sky values of 3%. Since smoke aerosols are nearly transparent in channel 2, this criterion enables for separation between smoke and cloudy regions (Christopher et al.

2000a). We inspected the quality of the smoke identification method by examining the images visually. The results of the smoke identification method are discussed in section 3. The algorithm is well suited to distinguish smoke aerosols from clear and cloudy regions when AOT is high (AOT >0.2). However cloud edges and optically thin aerosols pose problems.

3.2 Aerosol optical thickness retrieval using the GOES-8 imager.

A discrete ordinate radiative transfer (DISORT) model (Ricchiazzi et al. 1998) is used to pre-calculate the satellite measured spectral radiance as a function of aerosol optical depth, sun-satellite viewing geometry and surface albedo (Zhang et al. 2001). A tropical atmospheric profile of pressure, temperature, water vapor and ozone density is used (McClatchey et al. 1972). Therefore for a given satellite visible channel radiance and known sun-satellite view geometry an AOT value can be obtained from pre-computed tables. However, this method requires knowledge of aerosol properties such as aerosol size distribution and refractive index.

In this study, smoke aerosols were characterized as spheres that are well supported by previous studies (Martins et al. 1998). Therefore Mie calculations were performed to obtain the scattering and absorbing properties of aerosols. The biomass burning aerosols are characterized as an internal mixture of black carbon core surrounded by an organic shell (Ross et al. 1998; Zhang et al. 2001). A lognormal size distribution is assumed with an average volume mean diameter of 0.3 μm and a standard deviation of 1.8 (Reid et al. 1998). The densities of the black carbon core and the organic shell were assigned values of 1.8 gcm^{-3} and 1.2 gcm^{-3} respectively (Ross et al. 1998). The real part of the refractive index for the organic shell was assumed to be 1.5 (Reid et al. 1998). The real and imaginary part of the refractive index of the black carbon core is assumed to be 1.63-0.48i (Chang and Charamampoulos 1990). Assuming a mass fraction of the black carbon core to be 4.5% yielded a single scattering albedo (ω_0) of 0.90 (Zhang et al. 2001). Recent studies have shown that a ω_0 value of 0.90 at 0.67 um provides the best fit between satellite derived and AERONET derived AOT values (Zhang et al. 2001; Chu et al. 1998). However, retrieval of AOT from satellite measurements is sensitive to single scattering albedo assumptions (Fraser et al. 1984; Chu et al. 1998; Zhang et al. 2001). Zhang et al. (2001) provides a complete description of the methodology and the sensitivity of AOT retrievals due to uncertainties in ω_0 and surface albedo values.

Figure 2 shows the comparison between the GOES 8 and sunphotometer derived AOT values for two sites, Los Fieros and Concepcion, in Bolivia during the 1998 biomass-burning season. A 3×3 box surrounding the two sites was used from the GOES 8 data to account for navigational and registration uncertainties. Only data within ±15 minutes of each instrument (GOES 8 and sunphotometer) was used. The standard deviation in time (along ordinate) and space (abscissa) is also indicated. There is excellent agreement between the two independent methods of retrieving AOT with correlation coefficient of 0.97. The mean AOT values from GOES-8 and AERONET were 0.40±0.41 and 0.45±0.44 respectively. These results show that for point measurements, the satellite retrieved AOT values are in good agreement with AOT values obtained from ground-based measurements.

3.3 Calculation of shortwave flux (SW) using a four-stream model.

A delta-four-stream plane-parallel broadband radiative transfer model (Fu and Liou 1993) was modified to compute TOA SW flux values for biomass burning aerosols (Christopher et al. 2000b; Li et al. 2000). This model has been used to compute TOA (Reid et al. 1999; Christopher et al. 2000b, Li et al. 2000) and surface SW flux values (Christopher et al. 2000b) in biomass burning regions. The TOA SW flux is the ratio of the reflected to the incoming solar radiation (adjusted for the earth-sun distance) normalized by the solar zenith angle. The calculated downward SW irradiance values are in good agreement with measured pyranometer values when information about aerosol properties is available (Christopher et al. 2000b). The delta-four-stream approach agrees with adding-doubling calculations to within 5% for fluxes and is an improvement over the two-stream approach (Liou et al. 1988). In this model, the correlated-k distribution is used for gaseous absorption and emission. The gases considered in the model include H_2O, CO_2, O_3, O_2, CH_4, and N_2O. The radiative effects of Rayleigh scattering, liquid water droplets, ice crystal, continuum absorption of H_2O, and surface albedo are considered. The shortwave (SW) spectrum (0.2-4.0 μm) is divided into 6 bands: 0.2 - 0.7 μm, 0.7 - 1.3 μm, 1.3 - 1.9 μm, 1.9 - 2.5 μm, 2.5 -3.5 μm, and 3.5 - 4.0 μm. For the principal atmospheric gases, the four-stream approach matches line-by-line simulations of fluxes to within 0.05% for SW calculations. See Christopher et al. (2000b) for a complete description of the model and sensitivity results. When calculating the SW flux, the SZA for each GOES-8 pixel is used. The wavelength dependence of single scattering albedo and asymmetry parameter is from Christopher et al (2000b, Figure 2) and surface albedos are from Li et al. (2000) where the surface spectral albedo is specified according to ecosystem type.

Figure 4 shows the spatial distribution of AOT, SW flux and SW forcing for four time periods (1344, 1544, 1744, 1944 UTC) for August 28, 1998 over the area of study. Panels (a-d) show the smoke AOT for 1344, 1444, 1544 and 1744 respectively. Panels (e-h) are the corresponding SW flux values and Panels (i-l) are the SWARF values for the area. Note that the color-coding is different for each parameter to highlight the features of interest. Clouds are shown in white in each panel. The corresponding GOES channel 1 images can be seen in Figure 2. A comparison of figures 4a-d shows that the high AOT values are in Brazil, northeast of the two sunphotometer sites in Bolivia, that is an active biomass-burning region (Prins et al.1998; Christopher et al. 1998). The highest AOT values (2.5-3) are found during 1344 UTC over major biomass burning areas with smaller values towards the end of the day (1944 UTC). Downwind from these major biomass-burning areas in Brazil, AOT values are smaller (< 1.0) in Bolivia. The corresponding SW fluxes computed from the four-stream over the large AOT values are around 200 Wm^{-2}. The SW flux values decrease towards the end of the day (Fig. 4h). The mean AOT for the four time periods are 0.99±0.48, 0.89±0.39, 0.82±0.37 and 0.68±0.30 respectively. The corresponding SW flux values are 214.4±21.1, 220.5±21.5, 211.1±20.7, and 168.4±18.3 respectively. These SW flux values for biomass burning aerosols compare well with satellite-derived values from previous research (Christopher et al. 1998; Christopher et al. 2000a). The SWARF is defined as $S_o(\alpha_{clr}-\alpha_{aer})$, where α_{clr} and α_{aer} refers to clear and aerosol sky albedos respectively and S_0 refers to the solar constant adjusted for earth-sun distance and solar zenith angle (Christopher et al. 2000a). The

SWARF is obtained only for cloud free regions and the mean SWARF values from Fig 4(i-l) are –63.2±21.2, -54.8±20.2, -55.8±19.5, -55.0±14.3 respectively.

To check the consistency of the model calculated TOA fluxes, we used the CERES data from the Tropical Rainfall Measuring Mission (TRMM) platform for August 28, 1998 at 1848 UTC. The GOES 8 data were reduced to a spatial resolution of 4 km and the nominal spatial resolution at nadir of the CERES instrument is about 30 km (Kummerow et al. 1998). The CERES reports latitude, longitude values at the TOA (roughly 20 km). We therefore calculated the latitude, longitude values at the surface and spatial collocation between GOES 8 and CERES was performed using the point-spread function of the CERES scanner (Wielicki et al. 1996). The GOES 8 smoke identification method was used to determine if the CERES pixel was completely filled with smoke. The SW flux values for these smoke pixels were then used to compare against the model-calculated fluxes (Figure 4). There is excellent agreement between the CERES derived SW fluxes and model calculated fluxes (Linear correlation coefficient, R = 0.94). The histograms for the model and CERES derived fluxes are also shown. The mean and standard deviation of the SW fluxes for the model-calculated and CERES derived values are 170.4±33.1 and 163.0±40.2 respectively.

Using the GOES retrieved AOT, we examined the diurnal variation of the direct SWARF and AOT for the study area. Figure 5a shows the daytime diurnally averaged SWARF and AOT for biomass burning aerosols over the period of study. Also shown are the percentage coverage of smoke, clear and clouds with $T_{10.7} > 273K$. The AOT is quite uniform except for 1444 UTC and the SWARF closely follows the AOT trend. The diurnal variation of AOT is not necessarily a function of peak fire activities (Prins et al.

1998) due to synoptic conditions and cloud cover. Table 1 is a summary of the results from August 1998. The SWARF changes from –40 to –49 Wm^{-2} from 1344-1944 UTC with an average value of –45.8±18.8 Wm^{-2}. The mean AOT value over all time periods is 0.63±0.39. The SWARF values are large due to the large AOT and the persistent smoke coverage during August 1998. The average smoke coverage was about 60%. The percentage of clouds of cloud top temperatures greater than 273K was about 23%. Also shown in Table 1 are mean and standard deviation values for each class and for each time period and the number of images used. The daytime diurnally averaged mean clear sky channel 1 reflectance was 9.5±1.9 % and the smoke $\rho_{0.63}$ was 12.7±2.8%. Clouds with T10.7> 273K had channel 1 reflectances on the order of 24.9±14.1%. The $\rho_{3.9}$ values for smoke aerosols are less than that of clouds due to their small particle sizes. Figure 5b shows the SWARF as a function of AOT for the seven different time periods. A linear fit to the points is also shown for each time and the mean value is also indicated by the thick line. The diurnally averaged SWARF is related to AOT as: SWARF = -20.18-44.44×AOT(at 0.67 μm). The mean SWARF per unit AOT is –64.6 Wm^{-2}.

4. Summary

This study is among the first to estimate the daytime diurnal variation of smoke AOT and SWARF over biomass burning regions using GOES 8 imager data. Using GOES 8 retrieved AOT values; a broadband radiative transfer model is used to compute SWARF as a function of four major ecosystems in South America during August 1998. The GOES 8 AOT values compare well against AERONET AOT values (linear correlation coefficient = 0.97). The broadband SW flux values from the model are also in excellent agreement with SW flux values estimated from the CERES broadband scanner measurements (linear correlation coefficient = 0.94). The daytime diurnal variation of the SWARF for August 1998 for the entire study region is –45.8±18.8 Wm^{-2}. This study has addressed only the direct radiative forcing of biomass burning aerosols. The GOES data with its high temporal and spatial resolution could also be used to examine the impact of smoke aerosols on cloud properties such as cloud optical depth and particle size.

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List of figures

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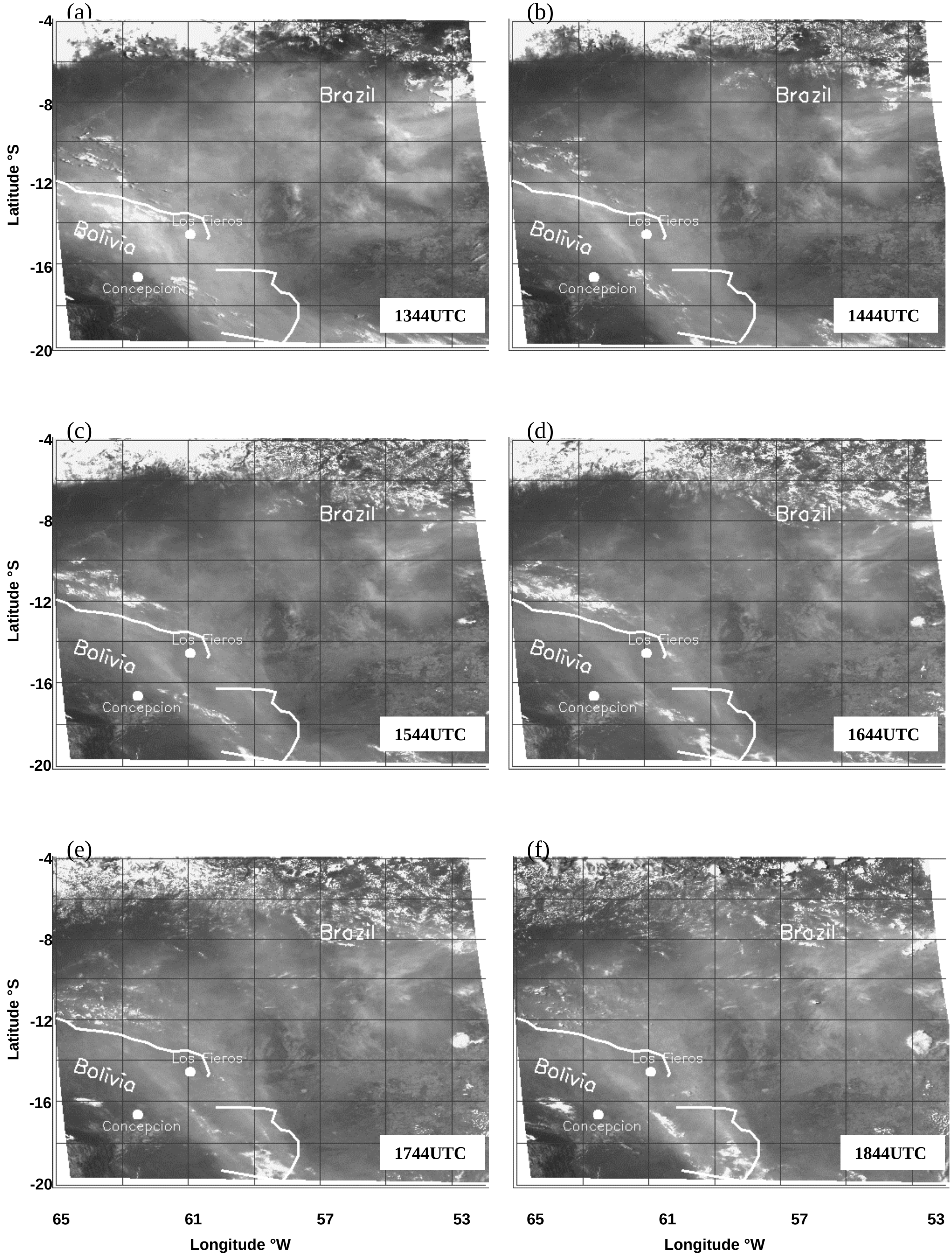
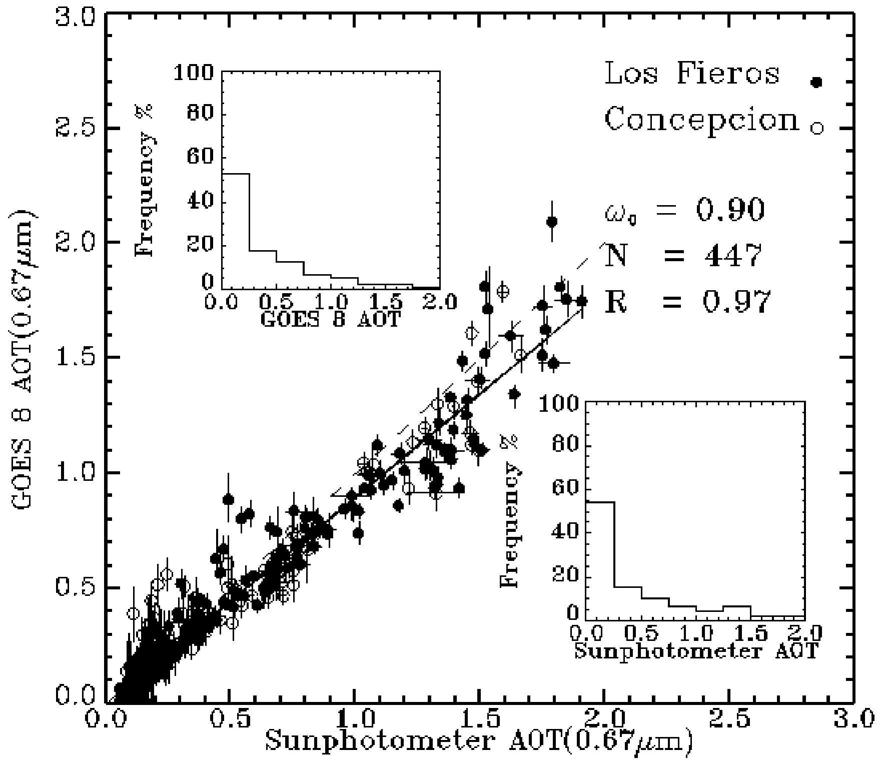
Table 1. Summary of Results From the Study Period for August 1998.

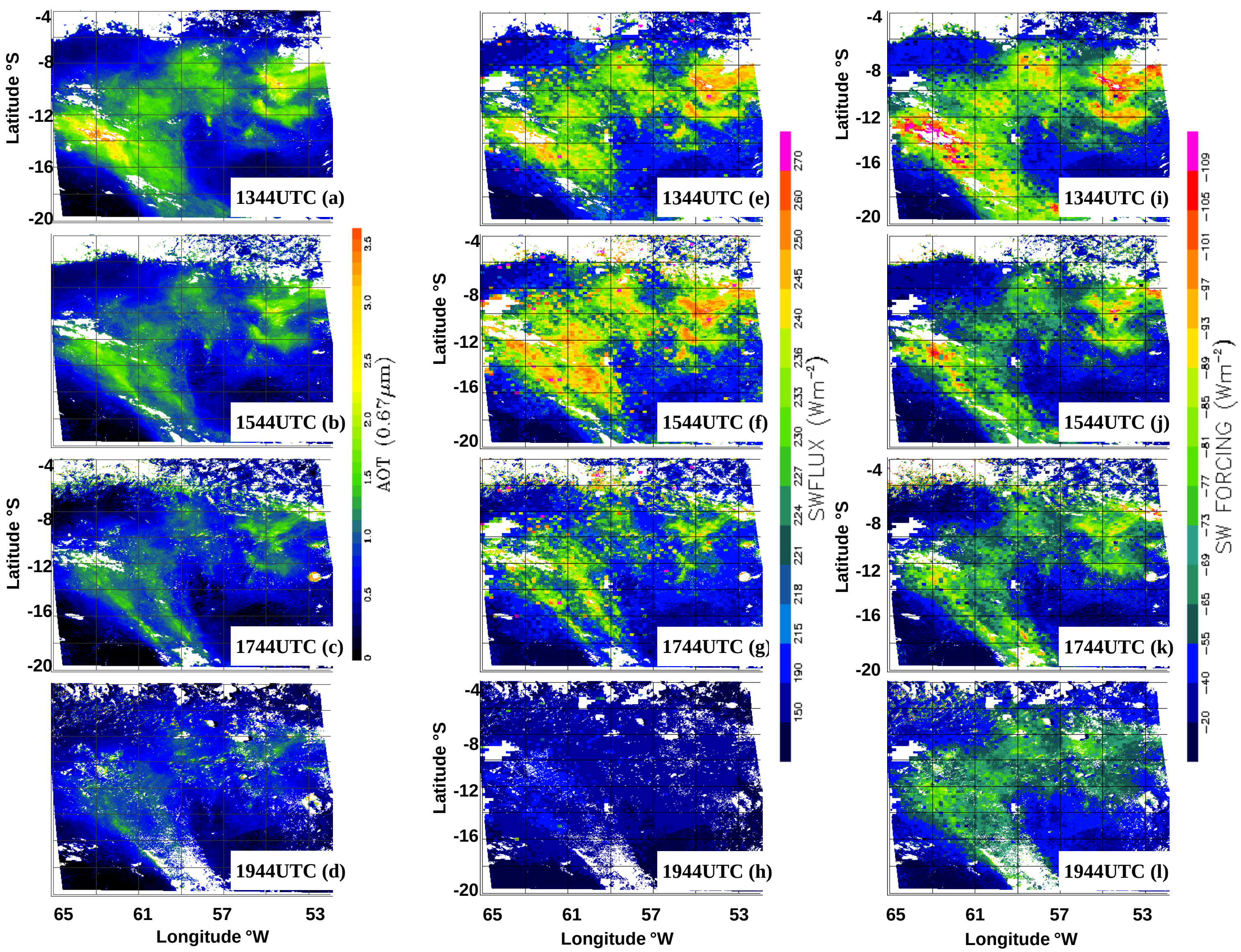
	1344	1444	1544	1644	1744	1844	1944	Average
AOT(0.67μm)	0.65±0.45	0.55±0.33	0.66±0.38	0.70±0.39	0.65±0.37	0.59±0.39	0.49±0.29	0.63±0.39
% clear	13.7	14.1	6.0	5.6	9.8	15	17.9	10.9
$\rho_{0.67}$ (%)	8.0±1.5	8.4±1.4	9.6±1.6	10.7±1.8	10.9±1.7	10.4±1.6	10.1±1.7	9.5±1.9
$\rho_{3.9}$ (%)	5.7±2.9	6.5±3.3	8.0±	9.2±4.5	9.1±4.0	8.6±3.7	10.0±4.2	8.0±4.1
$T_{10.7}$ (K)	298.0±3.4	300.4±3.9	302.8±4.4	303.4±4.3	302.2±4.3	299.8±3.3	298.0±2.6	300.1±4.2
% smoke	64.2	62.7	61.8	60.0	60.6	54.4	48.5	59.6
$\rho_{0.67}$ (%)	12.2±3.4	11.1±2.4	12.2±2.4	13.2±2.5	13.6±2.5	13.8±2.9	13.7±2.6	12.7±2.8
$\rho_{3.9}$ (%)	5.6±3.1	7.1±3.5	7.8±3.9	8.7±4.3	9.0±4.3	9.0±4.2	10.1±5.0	7.9±4.2
$T_{10.7}$ (K)	297.2±3.6	299.2±4.2	300.0±4.5	300.7±4.8	299.8±4.2	298.4±3.6	297.9±2.8	299.1±4.3
% cloud ($T_{10.7}$ <273K)	5.5	4.6	5.6	5.9	6.2	9.3	11.8	6.7
$\rho_{0.67}$ (%)	47.0±20.5	48.3±21.9	47.7±21.3	44.9±21.3	47.8±21.6	48.2±21.8	45.8±21.1	47.0±21.3
$\rho_{3.9}$ (%)	8.5±5.3	8.2±5.3	8.8±5.6	8.4±5.8	7.5±5.8	7.0±5.1	7.8±5.7	8.0±5.5
$T_{10.7}$ (K	255.6±16.0	256.4±15.7	254.8±16.7	251.9±18.3	247.9±20.4	245.2±21.1	243.5±21.2	250.2±19.5
% cloud ($T_{10.7}$ >273K)	16.6	18.6	26.6	28.6	23.5	21.2	21.8	22.8
$\rho_{0.67}$ (%)	24.9±14.2	26.4±15.7	24.0±13.9	24.3±13.4	25.9±14.1	26.4±14.7	23.7±13.5	24.9±14.1
$\rho_{3.9}$ (%)	11.5±4.2	11.9±3.8	12.5±4.1	13.4±4.4	14.3±5.1	14.3±5.4	15.6±6.4	13.2±4.9
$T_{10.7}$ (K)	286.4±6.5	288.0±6.8	289.6±7.0	290.3±7.0	289.9±7.2	288.0±7.0	288.4±7.3	289.0±7.1
$\rho_{0.67clear}$ (%) TOA	7.4±1.4	7.8±1.4	8.4±1.5	9.3±1.6	9.8±1.5	9.6±1.4	9.3±1.3	8.8±1.7
$\rho_{0.67clear}$ (%) sfc.	5.8±1.5	6.2±1.5	6.7±1.6	7.6±1.7	7.9±1.6	7.2±1.4	6.2±1.2	6.8±1.7
SW flux (aerosol) (Wm^{-2})	196.0±23.9	198.1±22.1	207.0±23.3	208.1±23.1	200.4±22.3	184.8±21.9	156.2±18.1	196.6±26.6
SW flux (clear) (Wm^{-2})	148.6±16.4	158.1±18.1	162.8±18.9	161.0±18.7	152.9±17.58	136.6±15.3	110.9±13.5	150.9±22.7
SWARF (Wm^{-2})	-47.4±20.8	-40.0±17.4	-44.2±19.0	-47.2±19.2	-47.5±18.3	-48.2±18.0	-45.3±13.9	-45.8±18.8
A*	-19.52	-13.28	-13.75	-15.76	-18.22	-22.67	-24.18	-20.18
B*	-43.04	-48.85	-46.04	-44.69	-45.09	-42.98	-42.87	-44.44
SWARF/AOT (Wm^{-2})	-62.56	-62.13	-59.79	-60.45	-63.30	-66.64	-67.05	-64.62
SZA range (deg)	29-56	18-47	12-41	14-44	24-52	38-62	52-73	
VZA range (deg)	12-36	12-36	12-36	12-36	12-36	12-36	12-36	
Number of images	20	12	24	18	15	13	12	

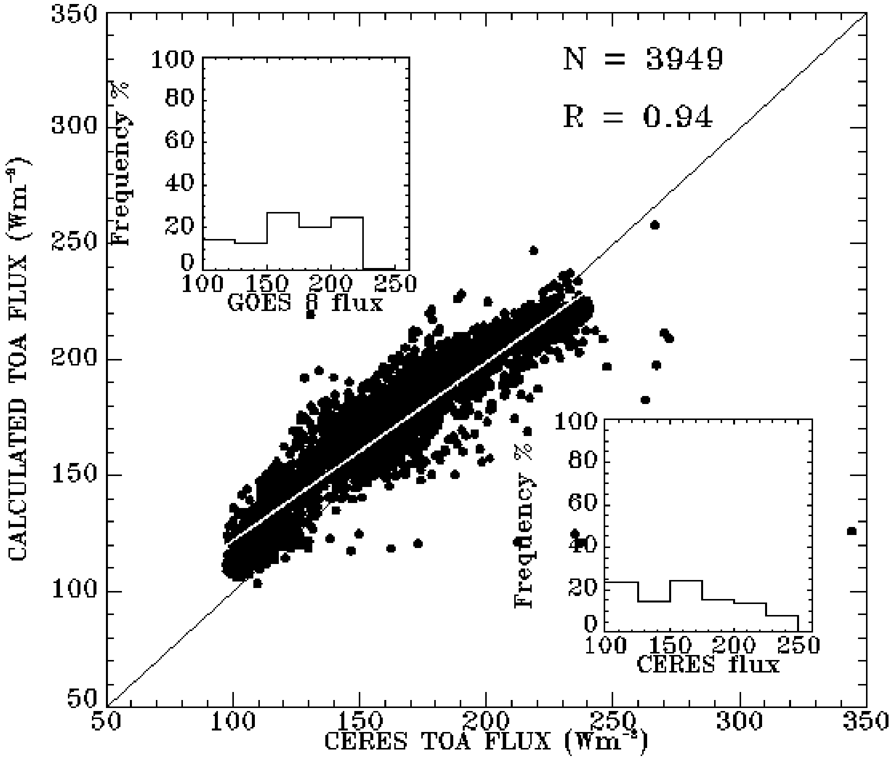
*SWARF = A + B × AOT


(a)
(b)
(c)
(d)
(e)
(f)
Brazil
Bolivia
Los Fieros
Concepcion
1344UTC
1444UTC
1544UTC
1644UTC
1744UTC
1844UTC
Latitude °S
-4
-8
-12
-16
-20
65
61
57
53
Longitude °W

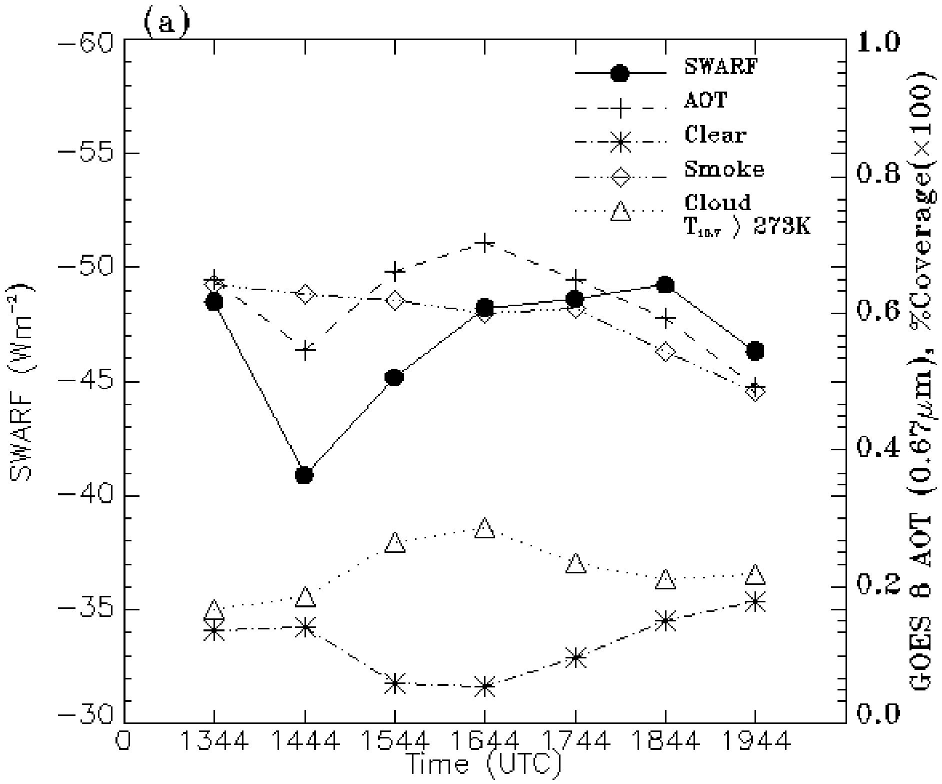


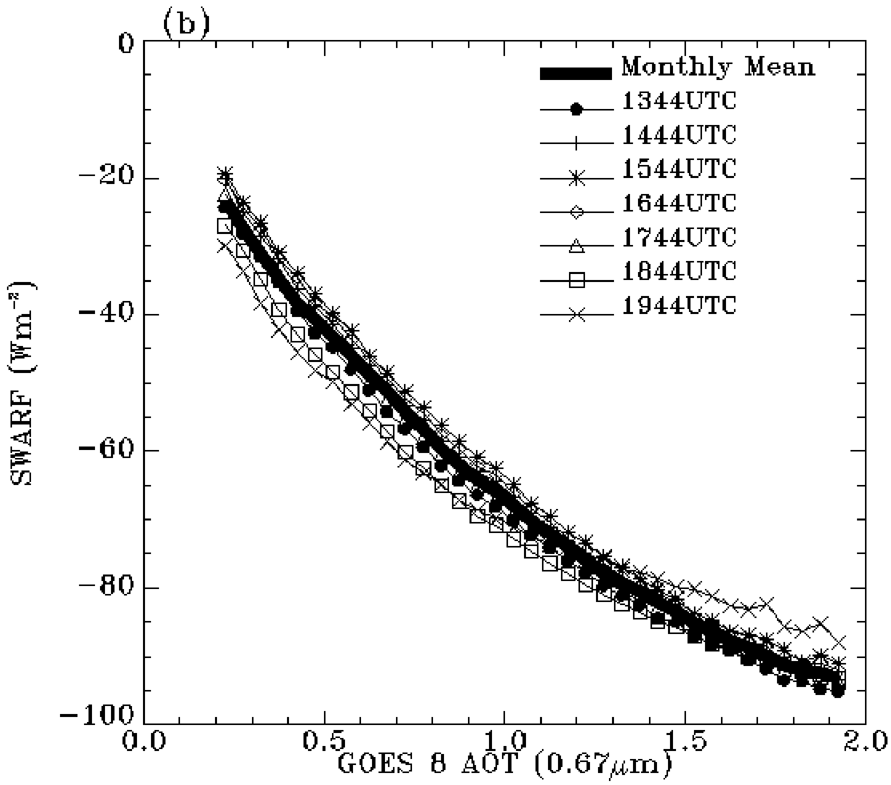
Los Fieros
Concepcion
ω0 = 0.90
N = 447
R = 0.97
GOES 8 AOT(0.67μm)
Sunphotometer AOT(0.67μm)
Frequency %
GOES 8 AOT
Frequency %
Sunphotometer AOT


1344UTC (a)
1544UTC (b)
1744UTC (c)
1944UTC (d)
1344UTC (e)
1544UTC (f)
1744UTC (g)
1944UTC (h)
1344UTC (i)
1544UTC (j)
1744UTC (k)
1944UTC (l)
Latitude °S
Longitude °W
AOT (0.67μm)
SWFLUX (Wm-2)
SW FORCING (Wm-2)



N = 3949
R = 0.94
CALCULATED TOA FLUX (Wm⁻²)
CERES TOA FLUX (Wm⁻²)
Frequency %
GOES 8 flux
Frequency %
CERES flux


(a)
SWARF
AOT
Clear
Smoke
Cloud
T10.7 > 273K
SWARF (Wm⁻²)
GOES 8 AOT (0.67μm), %Coverage(×100)
Time (UTC)
−60
−55
−50
−45
−40
−35
−30
0
1344
1444
1544
1644
1744
1844
1944
1.0
0.8
0.6
0.4
0.2
0.0


(b)
Monthly Mean
1344UTC
1444UTC
1544UTC
1644UTC
1744UTC
1844UTC
1944UTC
SWARF (Wm⁻²)
GOES 8 AOT (0.67μm)
0
−20
−40
−60
−80
−100
0.0
0.5
1.0
1.5
2.0