Comparison of Computed and Measured Cloudy-Sky Shortwave (SW) in the ARM Enhanced Shortwave Experiment (ARESE)

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Introduction

Discrepancies between computed and measured shortwave (SW) are shown for full-sky and clear-sky conditions. We then focus on a single case (1749 UTC, October 31, 1995) in the Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE) wherein the cloudy sky appears to absorb ~100 W/m^2 more SW than is computed with theory. The discrepancy in this case is much larger than was commonly found for April 1994 or Fall 1995. For this case, we test various batteries of inputs for the radiative transfer code. The inputs tested are based on different combinations of 1) remote sensing instruments to describe cloud properties, 2) physical assumptions for internal properties of the cloud, and 3) aerosol types and altitude distributions. Cloud profiles are illustrated here for a few of the combinations that we tested. Only combinations that included strongly absorbing aerosol produced theoretical atmospheric absorption that was close to observations. This result should be considered as a preliminary sensitivity study. Advances in remote sensing (some of which are anticipated) and a greatly expanded temporal domain would permit more credible inferences to be made from this type of investigation.

Computed and Measured Fluxes (September 25—November 1, 1995)

Tables 1 and 2 are available on-line in CAGEX (CERES/ARM/GEWEX Experiment; Charlock and Alberta, 1996; http://snowdog.larc.nasa.gov:8081/cagcx.html). CERES is the Clouds the Earth's Radiant Energy System satellite program (Wielicki et al. 1996); GEWEX is the Global Energy and Water Cycle Experiment. CAGEX Version 2.1.0 is based on the mean of half-hourly differences of computed and measured fluxes for the Southern Great Plains (SGP) Central Facility (CF) site in daylight from September 25 to November 1, 1995, during the ARM Enhanced SW Radiation Experiment (ARESE). Fluxes were computed with a modified Fu and Liou (1993) code; CAGEX has included tests with the Chou (1992) and MODTRAN3 (Anderson et al. 1995) codes. Temperature and humidity soundings were taken from 3-hourly radiosonde measurements. The column aerosol spectral optical depth from the multifilter rotating shadowband radiometer (MFRSR; Harrison et al. 1994) was provided by Harrision and Michalsky at the State University of New York (SUNY)-Albany. Spinhirne at the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center (GSFC) supplied vertical profiles of aerosol from the micropulse lidar (MPL; Spinhirne 1993); these were averaged and used throughout the record to vertically apportion the time varying MFRSR total for the column. Single-scattering albedos and asymmetry parameters of aerosol were taken from the models of d'Almeida et al. (1991) and Tegen and Lacis (1996). For optical depth outside the MFRSR bands, scaled values were developed using d'Almeida et al. (1991) and Tegen and Lacis (1996). The d'Almeida et al. (1991) aerosol model accounts for swelling with humidity. The full-sky (all-sky or total-sky) results in the top table used cloud retrievals of fractional area, optical thickness, height of top, and estimate of height of base from Geostationary

Table 1. Full-sky aerosol sensitivity.

Biases (W/m^2)	A	B	C	D	E	F	G	H	I	J	K	L	M
TOA Insolation	713	713	713	713	713	713	713	713	713	713	713	713	713
SFC Common domain	718	718	718	718	718	718	718	718	718	718	718	718	718
TOA Net	-29	-25	-33	-27	-29	-29	-28	-26	-23	-20	-17	-29	-29
TOA Reflected SW	29	25	33	27	29	29	28	26	23	20	17	29	29
TOA Albedo	.039	.033	.044	.036	.038	.038	.037	.034	.030	.026	.023	.039	.038
Atm. Absorption	-62	-67	-58	-58	-66	-60	-60	-55	-50	-44	-38	-62	-62
Transmittance	.053	.069	.038	.049	.061	.051	.051	.048	.044	.040	.035	.053	.053
SFC Insolation	38	49	27	35	44	37	37	34	31	28	25	38	38
SFC Direct Down	-24	11	-54	-24	-26	-24	-25	-27	-27	-27	-27	-24	-23
SFC Diffuse Down	63	38	82	60	71	61	63	62	60	56	53	62	62
SFC Net	30	39	21	28	35	29	29	27	24	22	19	30	30
SFC Reflected SW	9	11	7	8	10	9	9	9	8	8	7	9	9
SFC Albedo	.003	.003	.003	.003	.003	.003	.004	.004	.004	.004	.004	.003	.003

Column A - Calculations use core input (d'Almeida et al. continental aerosols; MFRSR optical depth)
Column B - Core input, but no aerosols
Column C - Core input, but aerosol optical depth doubled
Column D - Core input, but aerosol absorption doubled
Column E - Core input, but d'Almeida ocean model aerosols
Column F - Core input, but d'Almeida urban model aerosols
Column G - Core input, but Tegen and Lacis 0.5 micron mineral dust aerosol model
Column H - Core input, but Tegen and Lacis 1.0 micron mineral dust aerosol model
Column I - Core input, but Tegen and Lacis 2.0 micron mineral dust aerosol model
Column J - Core input, but Tegen and Lacis 4.0 micron mineral dust aerosol model
Column K - Core input, but Tegen and Lacis 8.0 micron mineral dust aerosol model
Column L - Core input, but Spinhirne marine model used for vertical profile of optical depth
Column M - Core input, but older Fu-Liou (6 SW band) aerosol treatment for calculations

Operational Environmental Satellite (GOES)-8 (Minnis et al. 1995). The observed top-of-atmosphere (TOA) fluxes used to form the biases were based on narrowband GOES-8 radiances, converted to broadband fluxes by Minnis et al. (1995).

All numbers in Tables 1 and 2 are biases (calculations minus observations), except for the first two rows giving "TOA Insolation" (the mean for a 3x3 array of gridboxes) and (surface) "SFC Common domain" (which is the TOA insolation for the slightly different time domain for which we have surface measurements in the central gridbox). All integers in Tables 1 and 2 have units of W/m^2. All numbers in Tables 1 and 2 with decimals (i.e., .053) are dimensionless. For a look at the aerosol effect on the bias as calculations minus observations, note columns A (which includes aerosols in the Fu-Liou code) and B (no aerosols) in the lower (clear-sky table), and focus on the rows for SFC insolation (total direct plus diffuse downwelling SW flux), SFC direct down (direct beam projected to the horizontal), and the SFC diffuse down. Columns A (aerosols) and B (no aerosols) for SFC Insolation have respective biases of 40 W/m^2 and 54 W/m^2, yielding a smaller aerosol forcing-14 W/m^2 (4054=-14) than the much larger estimated systematic error (40 W/m^2). On an optimistic note, there is a small bias (as found by Halthore et al. 1997) of 11 W/m^2 (Column A) in SFC direct down; if aerosols had been excluded, the SFC direct down bias would have been huge at 62 W/m^2 (Column B). Columns B (no aerosols) and C (doubled aerosol) are the only cases for which we have assumed completely unrealistic aerosol conditions in the radiative transfer simulation; except for the unrealistic Columns B and C, the bias in SFC direct down remains within fairly comfortable bounds (6 W/m^2 to 13 W/m^2) for a variety of assumed aerosol optical properties. The bias in SFC direct down is huge in the upper table for full-sky conditions, as expected; this is due to the mismatch in cloudiness between the satellite (which defines clouds for the calculations by observing a large area) and the surface site (which measures flux at a single point).

The large (40 W/m^2) bias for SFC insolation in the lower table (clear sky) for Column A (default aerosols) is an example of "the clear sky insolation bias." This was reported by Wild et al. (1995) for general circulation model (GCM) codes and has been described over SGP by Kato et al.

Table 2. Clear-sky aerosol sensitivity.

Biases (W/m^2)	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
TOA Insolation	714	714	714	714	714	714	714	714	714	714	714	714	714
SFC Common domain	744	744	744	744	744	744	744	744	744	744	744	744	744
TOA Net	-28	-22	-33	-26	-27	-27	-27	-25	-21	-18	-16	-28	-28
TOA Reflected SW	28	22	33	26	27	27	27	25	21	18	16	28	28
TOA Albedo	.037	.029	.044	.034	.035	.036	.035	.032	.028	.024	.020	.037	.036
Atm. Absorption	-58	-63	-52	-53	-62	-56	-56	-51	-45	-40	-34	-58	-58
Transmittance	.054	.072	.038	.050	.064	.052	.053	.049	.046	.041	.037	.054	.055
SFC Insolation	40	54	28	37	47	39	40	37	34	31	27	40	41
SFC Direct Down	11	62	-32	11	8	11	9	6	6	6	6	11	13
SFC Diffuse Down	30	-8	61	27	40	28	30	31	28	25	21	29	28
SFC Net	27	38	17	25	33	26	26	24	22	19	16	27	28
SFC Reflected SW	13	16	11	13	15	13	13	13	12	12	11	13	13
SFC Albedo	.009	.008	.009	.009	.009	.009	.009	.010	.010	.010	.010	.009	.009

Column A **-** Calculations use core input (d'Almeida et al. continental aerosols; MFRSR optical depth)
Column B **-** Core input, but no aerosols
Column C **-** Core input, but aerosol optical depth doubled
Column D **-** Core input, but aerosol absorption doubled
Column E **-** Core input, but d'Almeida ocean model aerosols
Column F **-** Core input, but d'Almeida urban model aerosols
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Column H **-** Core input, but Tegen and Lacis 1.0 micron mineral dust aerosol model
Column I **-** Core input, but Tegen and Lacis 2.0 micron mineral dust aerosol model
Column J **-** Core input, but Tegen and Lacis 4.0 micron mineral dust aerosol model
Column K **-** Core input, but Tegen and Lacis 8.0 micron mineral dust aerosol model
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(1997). A comparable bias was found in CAGEX Version I (Charlock and Alberta, 1996) for April 1994. When scaled to 24-hour global insolation, these biases are comparable to those reported for the world average [of those sites with Global Energy Balance Archive (GEBA) radiometers] in the Global Energy and Water Experiment (GEWEX) Surface Radiation Budget (SRB) Project (Whitlock et al. 1995) for full-sky conditions. Arking (1996) has speculated that such biases in the world domain are caused by a component of water vapor absorption that is not parameterized in current radiative transfer codes. The magnitude of the clear-sky biases using CAGEX have been confirmed by independent calculations by Henry Leighton and Rolf Stuhlmann, Jean-Jacques Morecrette, and Qiang Fu (personal communication). Chou and Zhao (1996) and Waliser et al. (1996), however, have not found such biases in clear skies over the tropics. Zender et al. (1997) emphatically state that there is no evidence for a clear-sky insolation bias in ARESE when measurements from the special Radiation Measurement System (RAMS) radiometers (Valero et al. 1997b), which do not separate the direct and diffuse beams, are used. The problem in CAGEX and in Kato et al. (1997) is notable in the diffuse beam. The clear-sky bias in CAGEX is reduced, but not eliminated, when compared with RAMS measurements.

In the upper table (full-sky) and lower table (clear-sky), there are large biases in atmospheric absorption. The sense of the bias for both surface insolation and for reflection at TOA is the same: the theoretical atmosphere does not absorb enough. Biases in atmospheric absorption for full-sky and clear-sky are comparable, in contrast to the "anomalous cloud absorption" described at other locations by Cess et al. (1995), Ramanathan et al. (1995), and Pilewskie and Valero (1995). A later section will illustrate possible aerosol impacts on absorption by cloudy skies. It is interesting to note that for both full-sky and clear-sky calculations, the biases in atmospheric absorption, TOA albedo, and SFC insolation have the smallest absolute magnitudes (Column K) for strongly absorbing aerosol [8 gm mineral dust particles from Tegen and Lacis (1996)]. We regard the mean biases for both full-sky and clear-sky absorption as significant discrepancies. They indicate a problem with either 1, 2, or 3, or some combination of 1, 2, and 3: 1) the measurements of fluxes, 2) the theoretical calculation of fluxes, and 3) the inputs assumed for the theoretical calculation.

Focus Limited to 1734-1804 UTC on October 31,1995

In the discussion of time-mean (September 25-November 1, 1995) bias in the previous section, Table 1 for full-sky used cloud properties from Minnis et al. (1995) GOES-8 retrievals for cloud height and cloud optical depth. The upper portion of Column A yields biases (calculations minus measurements) for TOA reflected SW of 29 W/m^2 (the bias in TOA fiet SW is -29 W/m^2) and for SFC insolation of 38 W/m^2. The time-mean full-sky theoretical atmosphere both reflects (to space) and transmits (to the surface) more radiation than is observed; it does not absorb enough. Is this lack of absorption an artifact of the cloud properties reported from GOES-8?

To investigate this, we focus in on a single half-hour time block, centered on 1749 UTC on October 31, 1995, over the SGP CF during ARESE. Aircraft measurements on the previous day (October 30) indicated substantial "cloud anomalous absorption" of SW (Zender et al. 1997; Valero et al. 1997a). The atmospheric absorption computed for this half-hour block on October 31 with GOES-8 cloud properties displays even larger bias (not shown) than the full-sky time-mean bias in Table 1; biases for the other half-hour blocks of October 31 (not shown) are similar. The cloud optical depth for this half-hour mean calculation was based on a single snapshot of pixel-scale retrievals from the GOES-8 visible channel, averaged over a 0.3 deg by 0.3 deg gridbox. Seeking a possible improvement in cloud properties, the SGP microwave radiometer (MWR) is substituted for the liquid water path (LWP); this greatly increases the cloud optical depth. In addition, the ground-based lidar MPL value is substituted for the height of cloud bottom; the MPL base is much lower than the base estimated from GOES-8. The surface measurements are half-hour means of typically 1-minute data. We retain the instantaneous snapshot GOES-8 retrieval of cloud top height (for which satellites are well regarded) and the GOES-8 estimate of TOA broadband reflection (for which there is no substitute in this case).

The initial cloud physics used in the single half-hour time block, centered on 1749 UTC on October 31, 1995, is illustrated in the upper left panel of Figure 1. As many low-level clouds show an integrated LWC (g/m^3) increasing linearly from cloud base to cloud base to cloud top, this assumption has been used to distribute the total LWP (g/m^2) within the cloud that is observed by the MWR from the ground. A fixed droplet concentration, here N=100 droplets/cm^2, is assumed. As this version of the Fu-Liou code does not accept droplets with size below 4 jim, mass closure requires that we decrease N at the very bottom of the cloud (note plot of N vs. pressure in upper left panel). Closure assumptions from this point also yield the variation of droplet size with height. Using these cloud physics assumptions and LWP from MWR (Figure 1, upper left) as opposed to GOES-8 optical depth, we obtain a dramatic change of the biases in Tables 1 and 2. The upper left panel in Figure 1 gives the bias in the SW NET for calculated fluxes (which use these assumptions) minus measured fluxes; the biases "TOA (Wm^{-2}) = -105" and "SFC (Wm^{-2}) = -2" indicate that the theoretical atmosphere now reflects enormously more to TOA than the measurements, and the theoretical surface absorption (net) is now in close agreement with measurements. The change has not, however, delivered a solution for atmospheric absorption, which in this case has the huge error "ATM (Wm^{-2}) = -102." Theory still does not produce enough atmospheric absorption for cloudy skies.

The upper left panel of Figure 1 is the base state. In each other panel, different assumptions are used for internal cloud physics, but the same remote sensing packages are used to characterize the gross cloud properties. In the upper right panel of Figure 1, a fixed cloud droplet radius of 10 gm is assumed, and we discard the base state assumption of a fixed droplet concentration of N=100 droplets/cm^3; the bias in atmospheric absorption is still huge at -99 W/m^2. In the two lower panels of Figure 1, the LWC (g/m^3) is assumed to be distributed homogeneously with altitude in the cloud, this was also assumed in Table 1, but not in the two upper panels of Figure 1. With LWC homogeneously distributed, huge errors in atmospheric absorption are still produced with the assumption of constant droplet concentration of N=100 droplets/cm^3 (absorption bias-104 W/m^2 in lower left panel) and the assumption of constant droplet radius of 10 Pm (absorption bias -95 W/m^2 in lower right panel). The bias in atmospheric absorption for calculations using a concentration of N=1000 droplets/cm^3 is larger (not shown).

We are confronted with cloudy-sky conditions wherein theoretical absorption for the atmospheric column is significantly less than observations, both for theory using Minnis et al. (1995) GOES-8 cloud optical depths (time averaged results in Table 1) and for theory using ground-based microwave LWP and an ensemble of cloud physics assumptions (half-hour case results in Figure 1). Is aerosol absorption a possible solution? Perhaps. Under cloudy conditions, the MFRSR aerosol optical depths used

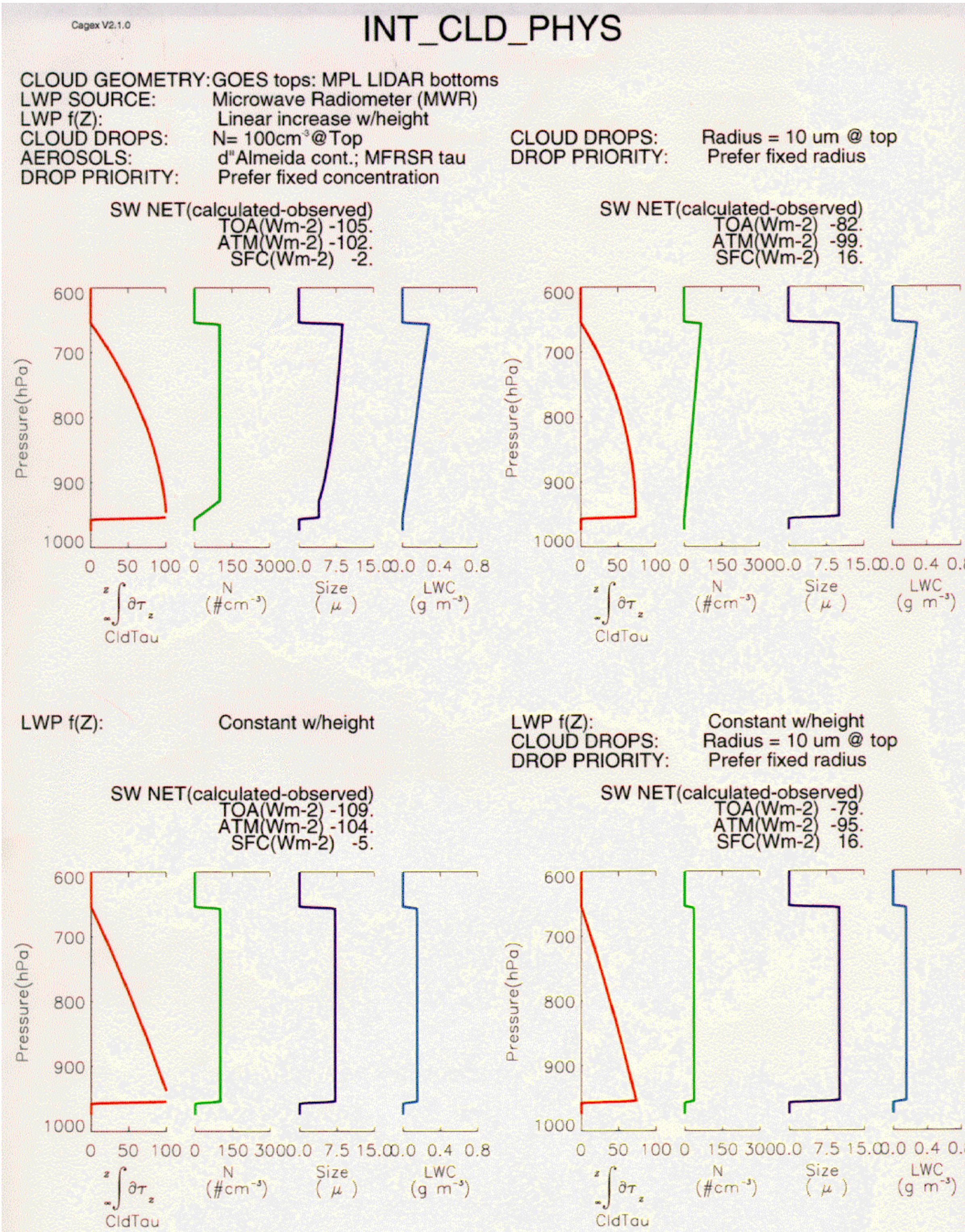

Figure 1. Biases in SW net fluxes (calculated minus observed) with d'Almeida et al. (1991) continental aerosol for four sets of assumed cloud physical properties. ATM (atmosphere) and SFC (surface). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/charlock-98.pdf*.)

in all of these calculations were interpolations from early and later clear-sky measurements; MFRSR does not retrieve aerosol optical properties for cloudy skies. All of the calculations in Figure 1 also used the d'Almeida et al. (1991) *continental* aerosol, which is only weakly absorbing.

A set of grossly different aerosol optics is used for the cloudy-sky radiative transfer calculations depicted in Figure 2. The aerosol optical depth is *doubled* from the interpolated values used in Figure 1. The optical properties are changed to those of large 8 Pm mineral dust particles (Tegen and Lacis 1996), which absorb more strongly than the previous continental aerosol. Figure 2 is a sensitivity study. We do not know the real aerosol optical depth or optical properties that occurred on October 31, 1995, at SGP, but blowing dust was frequently reported at the SGP site during ARESE. While the spectral distribution of optical depths inferred from MFRSR during clear periods did not suggest the presence of large particles, it is possible that higher aerosol optical depths and larger aerosol particles were present during some cloudy periods. The effect of the doubled aerosol optical depth and enhanced aerosol absorption is dramatic. The biases for atmospheric absorption in the panels of Figure 2 ranges from -17 W/m^2 to -32 W/m^2, which is much reduced from the d'Almeida et al. (1991) continental aerosol of Figure 1 (-95 W/m^2 to -102 W/m^2).

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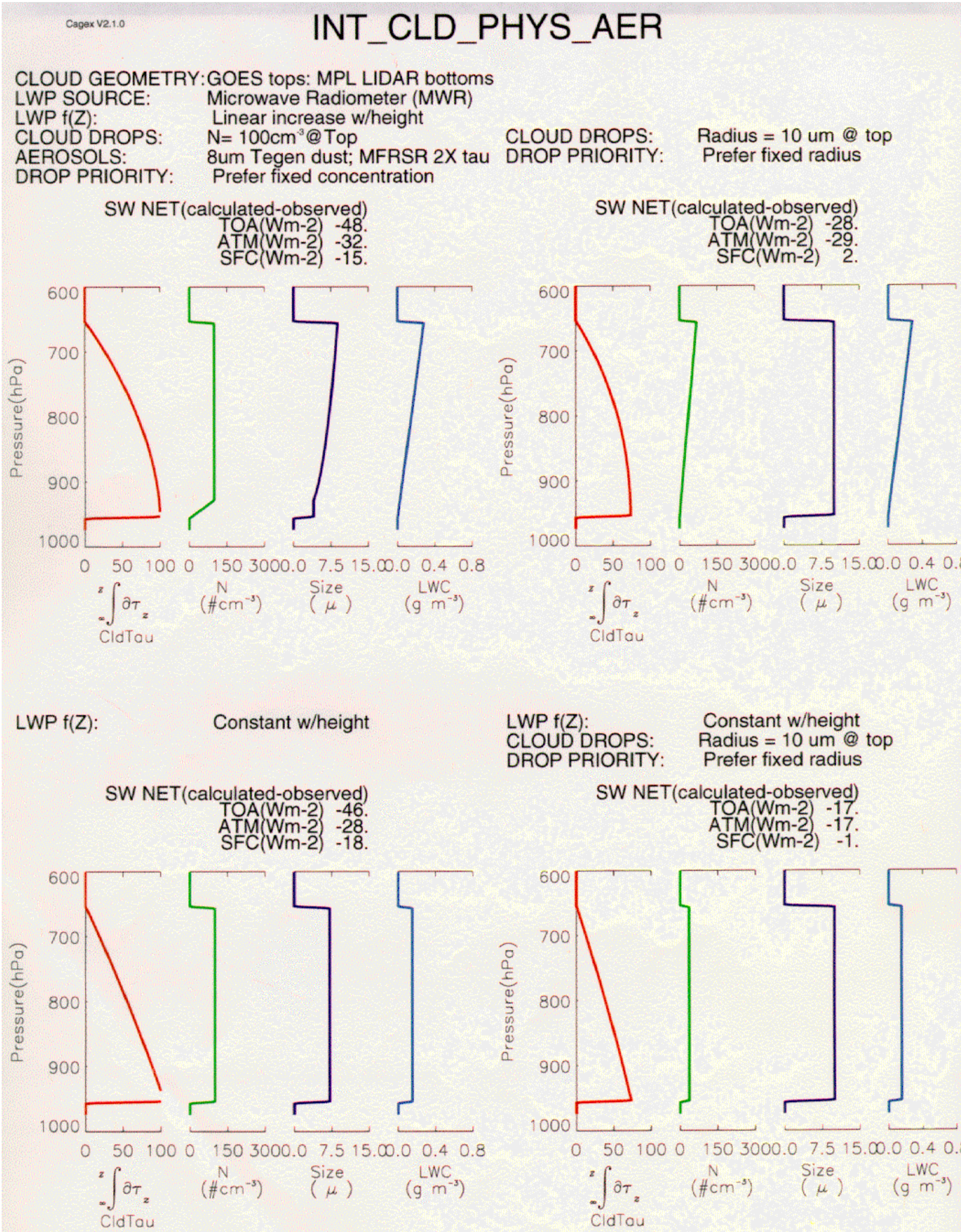

Figure 2. Biases in SW net fluxes (calculated minus observed) with Tegen and Lacis (1996) 8 micron mineral dust aerosol at DOUBLED optical depth for four sets of assumed cloud physical properties. ATM (atmosphere) and SFC (surface). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/charlock-98.pdf*.)

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