Improved ARM-SGP TOA OLR Fluxes from GOES-8 IR Radiances Based on CERES Data

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Introduction

The radiation budget at the top of the atmosphere (TOA) is a quantity of fundamental importance to the Atmospheric Radiation Measurement (ARM) Program. Thus, it is necessary to measure the radiation budget components, broadband shortwave albedo and outgoing longwave radiation (OLR), as accurately as possible. Measurement of OLR over the ARM surface sites has only been possible since the advent of Clouds and the Earth's Radiant Energy System (CERES; Wielicki et al. 1998) in 1998. Prior to CERES, it was necessary to infer the OLR from the infrared (IR; 10.8 μm) channel on the Geostationary Operational Environmental Satellite (GOES) imager by applying a narrowband-to-broadband (NB-BB) conversion (Minnis et al. 1995). Broadband OLR has been derived from GOES-7, GOES-8, and GOES-10 data since 1994 (Khaiyer et al. 2002) as part of the NASA-Langley cloud and radiation products for the ARM Southern Great Plains (SGP) domain (available at: http://www-pm.larc.nasa.gov/SGP/arm-sgp.html or at the ARM data center). These GOES-derived broadband OLR data are based on an empirical relationship between April 1986 GOES-6 IR radiances and Earth Radiation Budget Experiment (ERBE) longwave (LW; 5-50 μm) fluxes and has an uncertainty of 7 Wm^{-2} or 3% (Doelling et al. 1999). CERES measures LW radiation over a greater spectral band, has more accurate calibrations, and has a more robust radiance to flux conversion algorithm than ERBE (Loeb et al. 2003). Additionally, the IR-channel spectral filters and calibrations for the GOES imagers can vary with satellite and, therefore, the NB-BB relationship may also vary with each GOES instrument resulting in potential biases that depend on the particular GOES satellite. Thus, the NB-BB OLR relationship should be updated using CERES with contemporary GOES data to provide more accurate TOA LW fluxes for ARM. The objective of this study is to improve the NB-BB relationship so that the OLR derived from GOES can be used more confidently for energy budget, cloud forcing, and modeling studies over the ARM SGP.

Data

The analyses in this study are confined to the SGP domain (32°N - 42°N; 91°W - 105°W) for the period, January - August 1998. GOES-8 imager data were obtained for each half hour during the period. They include 4-km 10.7 (IR) and 12.0-μm and 8-km 6.7-μm brightness temperatures. The 6.7-μm channel is denoted as the water vapor (WV) channel. The brightness temperatures T_λ are converted to spectral radiance L_λ using the Planck function at the central wavelength of the band. The GOES-8 data were analyzed to obtain cloud properties and fluxes as in Minnis et al. (2001). The pixel-level results were averaged on a 1° latitude-longitude grid yield mean spectral radiances and cloud properties for each half hour.

The CERES Single Scanner Footprint TOA/Surface Fluxes and Clouds (SSF) product combines broadband shortwave, LW (5 to 100 μm), and IR window (IW, 8-14 μm) radiances and fluxes with imager radiances and cloud products weighted by the CERES point spread function (Geier et al. 2001). On the Tropical Rainfall Measuring Mission (TRMM) satellite, the CERES footprints have a nominal resolution of 10 km and the NB radiances are from the visible infrared scanning radiometer(VIRS) imager (2-km resolution), which includes two solar, 3.7, 10.8, and 12.0-μm channels. The VIRS scans out to a maximum viewing zenith angle (VZA) of 47°. TRMM is in a precessing orbit with an inclination of 35° resulting in a complete sampling of all local hours at a given latitude equatorward of 37°N and 37°S during its 46-day repeat cycle. The parameter values for each SSF footprint were averaged on a 1°grid for each TRMM orbit to produce the CERES Monthly Gridded Surface Fluxes and Clouds (SFC) product. These gridded averages are available for each orbit. The CERES fluxes are matched within 15 minutes with collocated gridded GOES-8 IR imager radiances over the SGP domain resulting in approximately 13,000 matches.

The SSF and SFC products also include the Meteorology Ozone Aerosol (MOA) product that incorporates vertical profiles of temperature and humidity from the European Centre for Medium-Range Weather Forecast analyses. These 6-hourly profiles were spatially and temporally interpolated at 10 mandatory levels between the surface and 100 hPa to match the GOES-8 data. They were then used to compute the column-weighted relative humidity (colRH). The colRH is defined as the height-weighted relative humidity in percent between the radiating surface (ground or cloud top) and 300 hPa.

Current OLR Narrowband to Broadband Relationship

Two empirical NB-BB relationships are considered here. Each is based on satellite imager data regressed with observed broadband radiances or fluxes. The first method relies on the IR channel, common on operational satellites, and an atmospheric profile term, that accounts for water vapor absorption (Minnis et al. 1991). The second method relies on a combination of spectral channels, minimally an IR and a WV channel, and is independent of profile data. These two methods are examined using regression analyses with the GOES-8, VIRS, and the CERES LW fluxes.

The current relationship (Minnis et al. 1995) is defined as follows,

$$OLR_{bb}\left\{Wm^{-2}\right\} = a_0 + a_1 M_{nb} + a_2 M^2{}_{nb} + a_3 M_{nb} \mathrm{In}\left(colRH\{\%\}\right) \quad (1)$$

where M_{nb} is the narrowband flux derived from L_{IR} as in Minnis et al. (1991). Figure 1 shows a scatterplot of the matched CERES OLR and GOES-8 M_{nb} and the regression curves and values of the regression coefficients. Increasing colRH reduces the OLR for a given value of M_{nb}. The regression has a 7.2 Wm^{-2} rms error, approximately the same as the error obtained by ERBE. The relationship explains 97% of the variance.

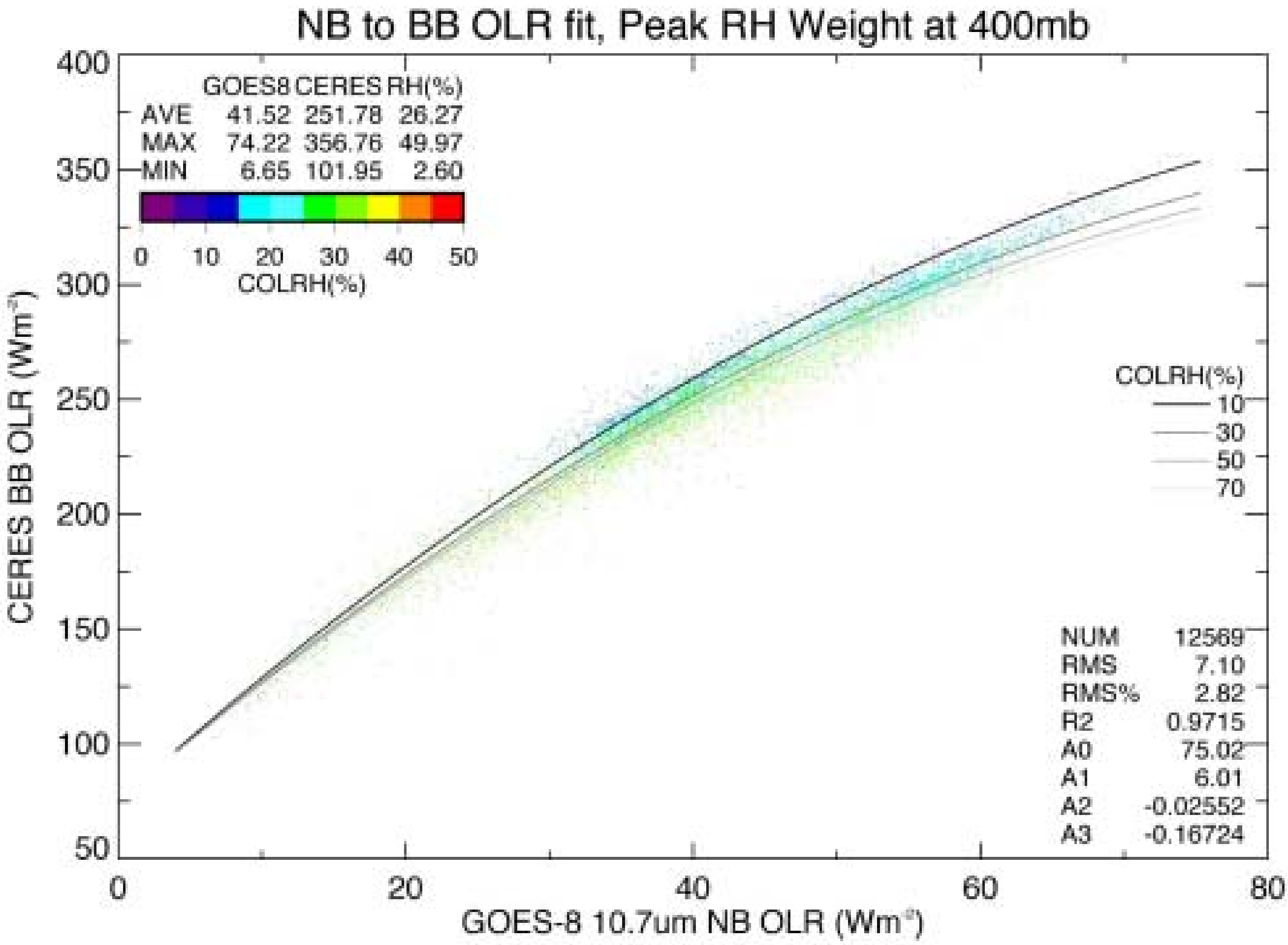

Figure 1. Scatterplot of CERES OLR and GOES-8 IR fluxes for January to August 1998. Individual points are color coded by colRH. Curves indicate the regression fits of Eq. 1 for particular colRH given on the right side. Regression statistics and coefficients are given in the lower right.

Comparison of Height-Weighted Relative Humidity Functions

Currently, the GOES-8 NB-BB relationship uses colRH, which weighs the upper tropospheric humidity more than that at lower levels, where water vapor actually has more of an impact on the OLR. A different height weighting scheme might improve the OLR relationship. Following the weighting scheme of Allen et al. (1999), the relative humidity (RH) weighting function for a peak pressure level given a sounding profile is defined as $\exp(-2[\ln(P_{level}\{mb\}) - \ln(P_{peak}\{mb\})]^2)$. Figure 2 plots the RH weighting functions as a function of peak pressure where the weight is equal to unity. The weights decrease with pressure difference relative to the peak pressure. The summed RH weighting functions (RHwf) for all pressure levels is computed for each peak pressure. A NB-BB regression was performed for each peak pressure by using Eq. 1 and replacing the last term with $a_3M_{nb}RHwf^{0.4}$. The power term yields a smaller rms error than the log term. The rms errors are plotted as a function of pressure level in Figure 3. The minimum error is between 400-450 hPa and is equivalent to the rms error given by the colRH term. This is consistent with the conclusions of Allen et al. (1999) that the clear-sky OLR is most sensitive to mid-troposphere humidity. The sensitivity is not highly variable; the rms error at the 850-hPa level is within 4% of that at the 400-hPa level. Possible explanations are that the soundings are too coarse temporally, vertically, and spatially or that the level RH needs further weighing by temperature.

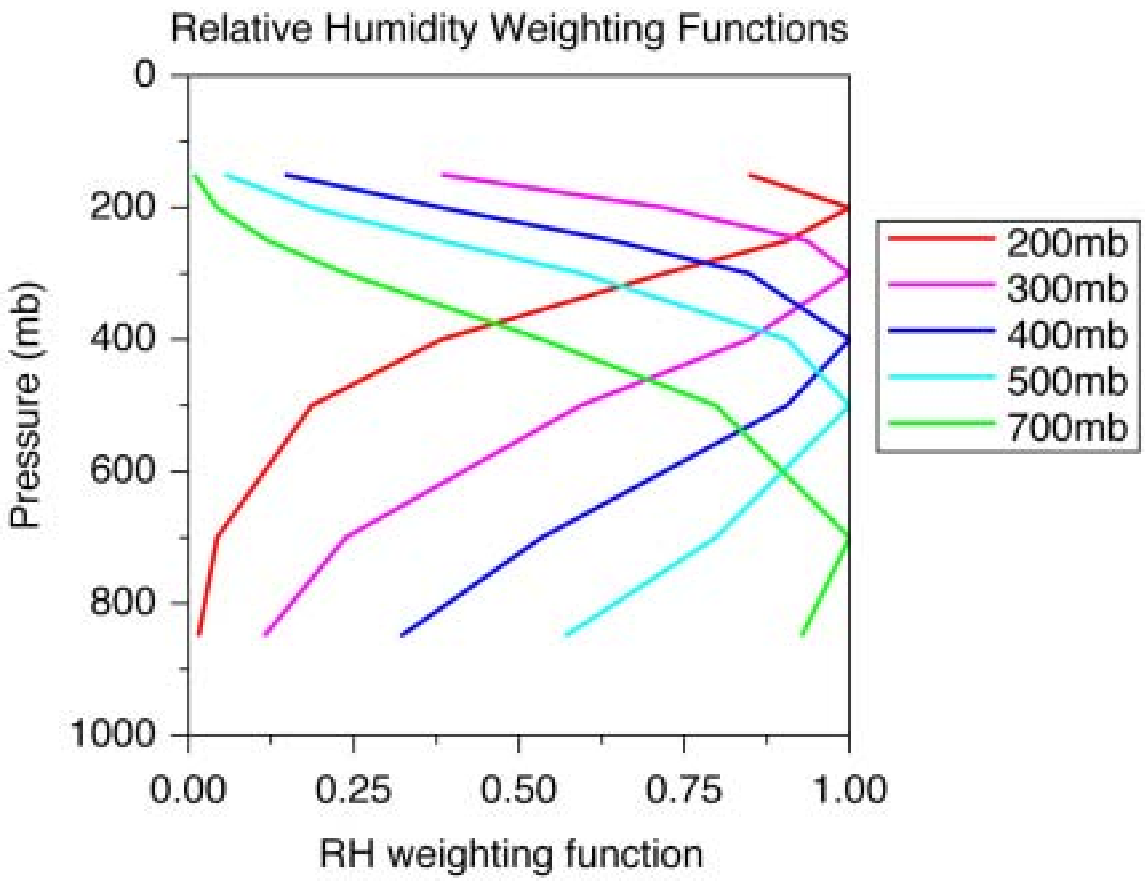

Figure 2. Relative humidity weighting functions as functions of pressure for the peak pressure levels given in the legend.

Effects of Other Variables on the Clear-Sky OLR

Factors other than colRH can affect the propagation of LW radiation through a clear atmosphere. The amount of clear-sky water vapor absorption is also a function of the precipitable water, skin temperature, and lapse rate as well as humidity. To determine the importance or ranking they have on water vapor absorption, the residuals of Eq. 1 were computed using the first 3 coefficients (no colRH term). These residuals were correlated with column precipitable water, skin temperature given by the CERES SFC dataset, colRH, and lapse rate, which is defined as the difference between the skin and 300-hPa temperature. The parameter statistics are given in Table 1. The colRH is the best term for predicting

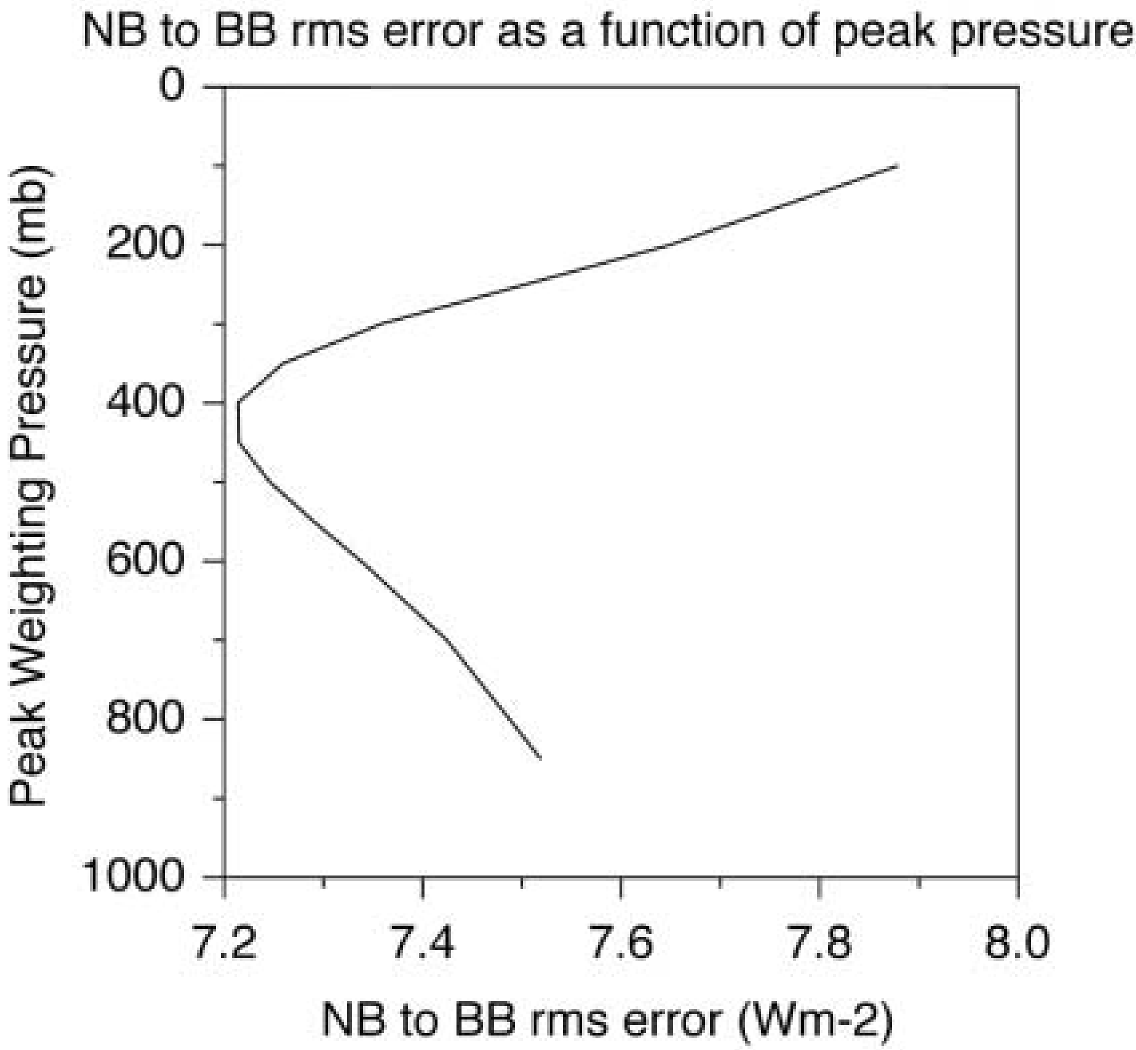

Figure 3. Rms error (Wm^{-2}) as function of peak pressure level for Eq. 1 with the last term replaced by $a_3 M_{nb}$ RHwf $^{0.4}$.

water vapor absorption, whereas the precipitable water is the least correlated. The precipitable water weights the humidity most near the surface where the skin and air temperature differences are at a minimum. Currently, inclusion of the colRH term reduces the rms error by 0.8 Wm^{-2}. Given, the correlations in Table 1, it may be possible to further reduce the rms error by 0.4 Wm^{-2} using lapse rate or skin temperature in addition to colRH.

Multiple IR Channel Regressions with CERES OLR

The WV channel is useful for estimating upper tropospheric humidity. The IR and 12.0-μm channel are in the atmospheric window and are sensitive to low level humidity and skin temperature. The GOES-8 spectral response functions are plotted in Figure 4 along with the VIRS IR channel. The GOES-8 and

Table 1. The mean, minimum, maximum value and the correlation coefficients of the residuals of Eq. 1 without the last term for the variables given in the left column.

Factor	Mean	Minimum	Maximum	Correlation Coefficient
Precipitable Water (cm)	1.29	0.28	4.62	0.067
Skin Temperature (K°)	283.5	263.3	311.8	0.227
ColRH (%)	26.5	10.0	82.2	0.508
Lapse Rate T_{skin}-T_{300mb} (K°)	32.7	8.2	72.4	0.272

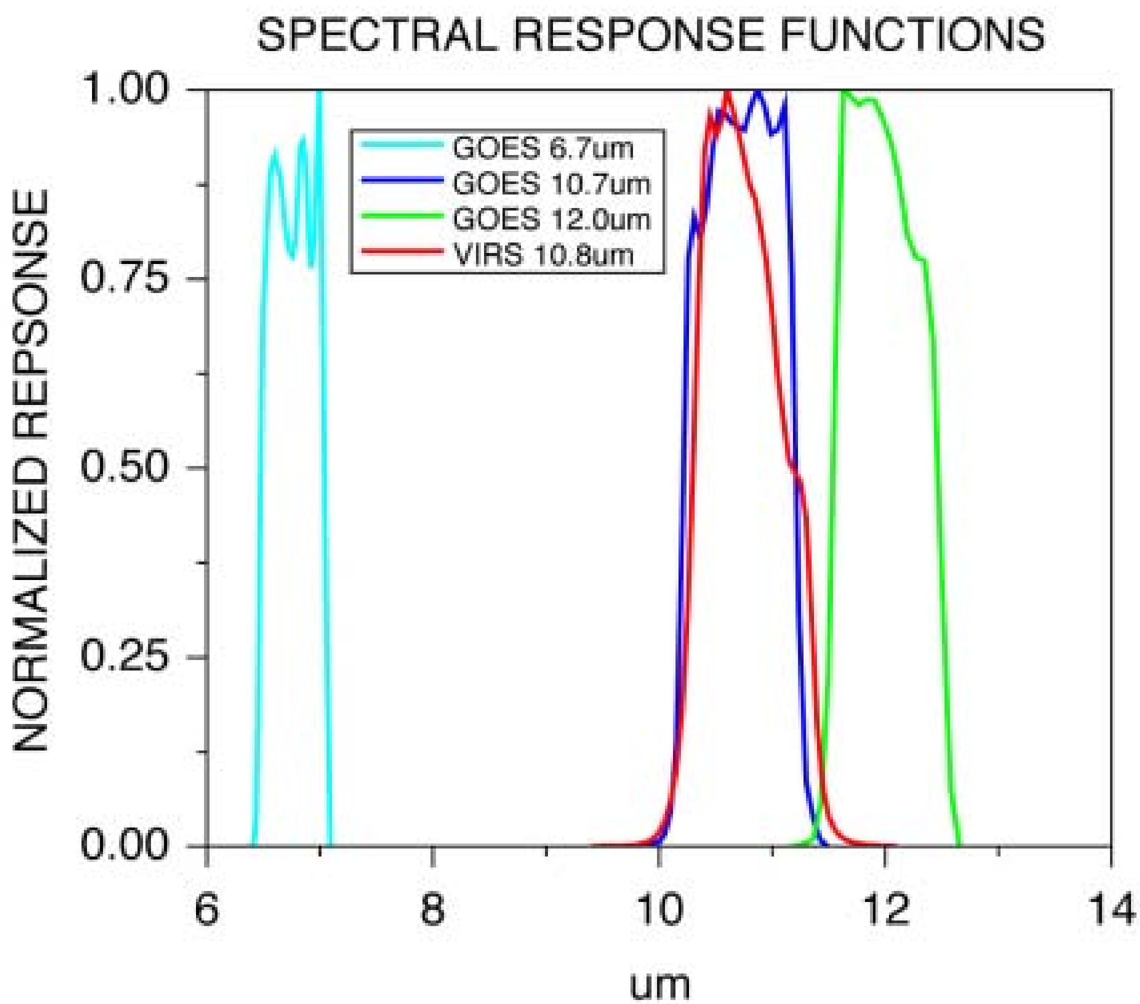

Figure 4. Spectral response functions for various GOES-8 and VIRS longwave channels.

VIRS IR channels are nearly identical. Since the 6.7-µm channel measures upper level humidity that, presumably, is taken into account in (1) with the colRH term, it might be possible to better estimate the RH effect using the WV channel. Figure 5 shows a scatterplot of the GOES-8 IR narrowband fluxes with the CERES OLR fluxes as in Figure 1, except that the individual values are given a color according to the 6.7-µm brightness temperature. The color separation is greater for IR fluxes exceeding 30 Wm^{-2}

than seen for colRH (Figure 1). Greater WV temperatures indicate a drier upper troposphere and greater OLR. For cold clouds the 6.7-μm and IR temperatures are similar and, therefore, for IR fluxes less than 30 Wm^{-2} the color separation is function of the IR flux.

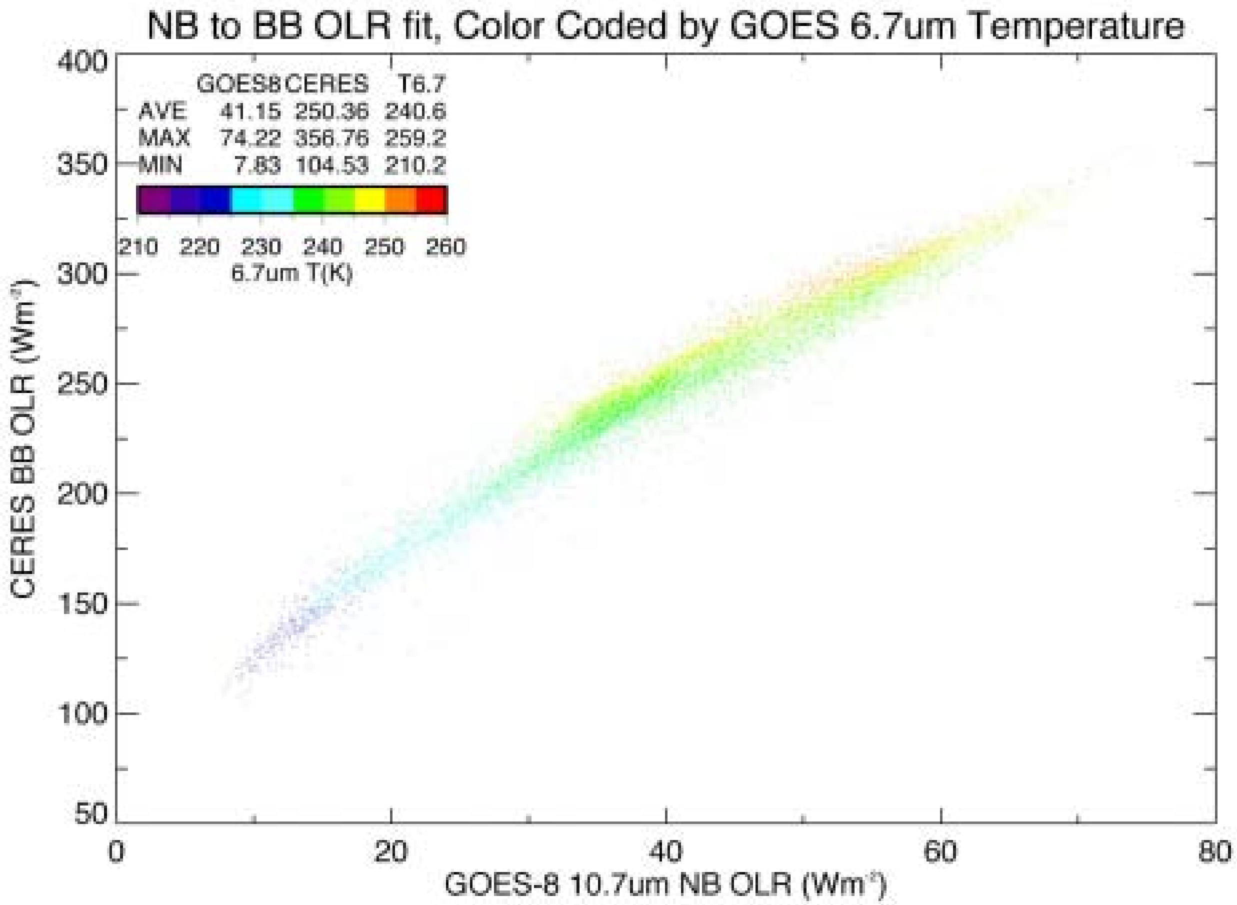

Figure 5. CERES OLR and GOES-8 IR fluxes for January - August 1998. Individual points are color coded according to the 6.7-μm temperature.

To determine the best combination of GOES-8 longwave channels and their contribution to the OLR, the dataset used in Figure 1 was combined with the other GOES-8 and VIRS 1° gridded spectral radiances. In this case, the VIRS and CERES LW radiances would have an exact time match whereas, the GOES-8 data are matched within 15 minutes and were likely observed at different viewing angles since the GOES-8 viewing zenith angles over the SGP domain vary between 40° and 60°. For the GOES-8 and VIRS radiances, the current limb darkening function was applied (Minnis et al. 1991) and for the CERES IW channel, the CERES window limb darkening function (Loeb et al. 2003) was used. Narrowband channel radiances were regressed with CERES OLR to yield the rms errors given in Table 2. Both linear and squared radiance terms were used. The VIRS and GOES-8 rms errors are similar, since the response functions are nearly identical, and the time matches were relatively close for 1° regions. The best single GOES-8 channel predictor is the 12-μm channel, which includes some water vapor absorption. The 12-μm rms error is 1 Wm^{-2} less than that of the IR. This reduction is equivalent to that for the colRH term. The combination of the 12-μm and IR channels did not result in additional accuracy. The addition of the 6.7-μm channel with the IR reduces the rms error by 2 Wm^{-2} and there is only a slight reduction in rms error when the WV is combined with the 12-μm channel. Interestingly enough, the VIRS IR and GOES-8 WV combination reduces the rms error by 3.3 Wm^{-2}. This is in part due to the fact that the VIRS IR imager radiances are weighted by the CERES point spread function and have the same time and geometry as CERES. There is a 0.5 or 1.5 Wm^{-2} reduction using the CERES window channel than from the 12 μm and IR channels respectively and in combination with the GOES-8 6.7 μm channel, the rms error is reduced by half. The combination of the CERES window channel and GOES-8 WV channel has the greatest correlation with OLR. This probably suggests that ozone, which affects the IW radiance, but not the IR and 12-μm radiances, has a measurable effect on the OLR. Parameterization of the ozone column absorption may improve the correlation of GOES-8 radiances with OLR.

Table 2. Satellite channels (defined by the left and middle columns) radiances and their squares are regressed with CERES OLR from January to August 1998 and the rms errors are given in the right column.

Satellite	Channel (μm)	RMS Error (Wm^{-2})
GOES-8	6.7	22.94
GOES-8	10.7	7.98
GOES-8	12.0	7.03
GOES-8	10.7 + 12.0	7.04
GOES-8	10.7 + 6.7	6.03
GOES-8	12.0 + 6.7	5.80
GOES-8	12.0 + 6.7 + 10.7	5.82
VIRS	10.8	7.87
VIRS + GOES-8	10.8 + 6.7	4.58
CERES	Window	6.44
CERES + GOES-8	Window + 6.7	3.34

Conclusions

GOES-8 IR narrowband to broadband coefficients were derived based on Eq. 1 from CERES OLR over the ARM SGP domain and yield a rms error of 7.2 Wm^{-2} or 2.8%. The rms error is similar to the historical ERBE and GOES-6 relationship, but the CERES OLR should be more reliable. The GOES-8 WV, IR, and 12-μm three channel multiple correlation reduces the rms error to 5.8 Wm^{-2} or 2.3%. The colRH term remains the best predictor of the water vapor effect in the OLR when it is correlated only with the GOES-8 IR channel. The humidity level most sensitive to the OLR is in the 400 to 450 mb range over the SGP and is already taken into account with the colRH term. Other variables, such as skin temperature and lapse rate have a small effect on the OLR except for precipitable water has negligible impact. Based on the CERES window channel correlation, it appears that an ozone absorption parameter may decrease the error in the narrowband-broadband relationship using channels available on operational satellites.

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