The Next Generation Flux Analysis: Adding Clear-Sky LW and LW Cloud Effects, Cloud Optical Depths, and Improved Sky Cover Estimates

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Introduction

The original Shortwave Flux Analysis (SWFA), based on Long and Ackerman (2000) and Long et al. (1999), deals only with daylight shortwave (SW) data. The SWFA algorithm produces continuous estimates of clear-sky downwelling diffuse, direct, and total SW; estimated fractional sky cover; and identification of when the sky was cloudless. This algorithm package is being produced as an Atmospheric Radiation Measurement (ARM) value-added product (VAP), as described in Long and Gaustad (2001).

Subsequent efforts for analysis of surface broadband radiation and meteorological measurements now involve 24-hour output and include continuous estimates of the downwelling clear-sky and measured longwave (LW) irradiance. Thus, the new algorithm provides continuous 24-hour estimates of the effect of clouds on both the downwelling LW and SW portions of the surface radiative energy budget. For daylight periods of fractional sky cover greater than 80%, we also estimate the effective plane-parallel cloud base brightness temperature. Barnard and Long (2003, 2004) have developed the means of estimating the equivalent plane-parallel visible cloud optical depth for overcast skies using the diffuse cloud effect calculated from the SWFA. A method for inferring optical depths for partly cloudy skies is being investigated.

Estimating Clear-Sky Downwelling LW

Brutsaert (1975) developed a formulation based on Schwarzschild's equation of radiative transfer for estimating the clear-sky downwelling LW using only inputs of measured surface air temperature and moisture amount. He then used a U.S. standard atmosphere analysis to determine the needed "lapse rate coefficient" with a value of 1.24. Thus, the original Brutsaert formulation is:

$$\varepsilon_c \approx 1.24 * (e/T_a)^{1/7} \tag{1}$$

$$LW_c \approx \varepsilon_c * \sigma * T_a^4 \tag{2}$$

Where T_a is the ambient air temperature in K, e is the vapor pressure in mb, σ is the Stephan-Boltzman constant, ε_c is the effective clear-sky broadband emissivity, and LW_c is the estimated clear-sky downwelling LW. When this "lapse rate constant" of 1.24 is used and compared to clear-sky data, as screened with the Flux Analysis code, the root mean square (rms) disagreement from X = Y is about 16 Wm^{-2}, as shown in Figure 1. This plot also shows that the Brutsaert formulation produces a bias and offset compared to typical values for the Southern Great Plains (SGP). A least squares fit through these data produces a line with a slope of about 1.16 and an offset of -50 Wm^{-2}.

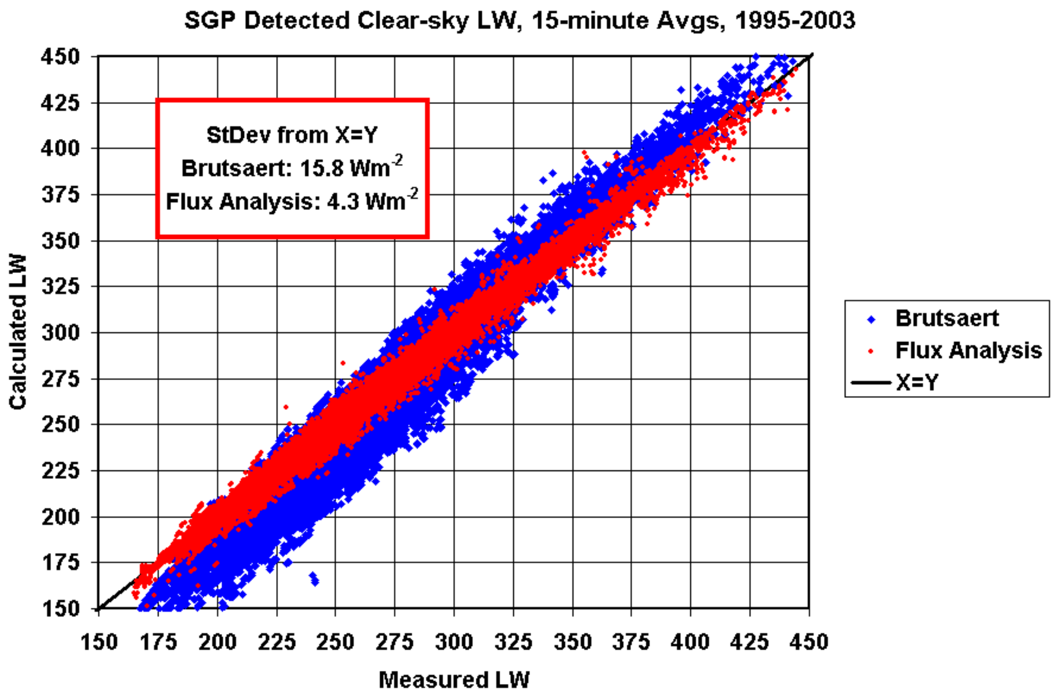


Figure 1. Comparison of measured clear-sky downwelling LW with that estimated by the Brutsaert formula (blue) and that from fitting to detected clear-sky measurements (red).

But with the SWFA, we know when the skies were clear during the daylight hours. After a methodology proposed by Marty and Philipona (2000) using the variability of the LW time series, nighttime data are also analyzed for the occurrence of clear skies and, at least, for the occurrence of low and middle cloudiness. The running standard deviation over a 21-minute period centered on the time of interest is calculated from the LW measurements. We also calculate the effective broadband sky brightness temperature using the Stephan-Boltzman relation:

$$T_e = (LW/\sigma)^{0.25} \tag{3}$$

For nighttime data of interest, if the running standard deviation is less than some limit, and the difference between the ambient air temperature and T_e is greater than some limit, those data are designated as "clear in the LW." For the analysis presented here, these limits were set as 0.7 Wm^{-2} and 12°C, respectively. We use these day and night detected clear-sky data to invert Eqs. 1 and 2 and calculate a lapse rate coefficient for each clear-sky data point. We then average the resultant values in an iterative process that removes outliers to produce one value to represent the appropriate portion of the day and interpolate between these values for cloudy days and times similar to the technique used in the

SWFA for SW coefficients (Long and Ackerman 2000). We use the daylight data to determine daylight coefficients.

Quite often, at night, especially under clear and calm conditions, the lapse rates of temperature and moisture can differ from those typically found during the day (Turner and Long 2004). On clear, calm nights, when inversions typically form, the inversions tend to deepen over the course of the night, if the entire night remains calm and clear. Thus, nighttime “LW clear” data are separated into two sets for fitting: sunset through local midnight and local midnight through sunrise. Figure 2 shows four successive days that were fairly cloud free at the SGP central facility (CF) in April 2003. In this figure, the day and night detected clear-sky LW measurements are used to calculate the dry “k” coefficients. Note that the “k” coefficient changes fairly quickly from sunrise until about 1 to 2 hours later, and again from about an hour before sunset to shortly after sunset. We interpolate the “k” coefficients across the day in a similar manner. We use the two nighttime values to interpolate linearly through the night from a half an hour after sunset until sunrise. Then, we interpolate from the sunrise value to the daylight value over the next 90 minutes, and we use the daylight value from then through an hour before sunset, where we interpolate from the daylight value to the first half night value over the next 90 minutes. Figure 2 shows this interpolation pattern (black line) for April 11, 2003.

Figure 2. Clear-sky “k” coefficient calculated from detected clear-sky data for April 9 (red), April 10 (yellow), April 11 (light blue), and April 12 (blue), 2003. Black line is interpolated fit for April 11, 2003.

However, we are again ultimately trying to estimate the clear-sky downwelling LW, which includes the definition of what we mean by “clear sky.” Thus, we should try to differentiate between the effects of thin boundary layer haze, which can have a significant impact on the downwelling LW (Turner and Long 2004), and what surface observers and sky imagers tend to classify as “cloud.” It is well known that at a relative humidity (RH) of about 75 to 80%, hygroscopic nuclei tend to start accumulating liquid water forming haze. Thus, during the fitting and interpolation process, we first use the SWFA detected clear-sky data to calculate a daylight average lapse rate coefficient (k) for ambient RH values less than 75 to 80%. We interpolate these coefficients. Then, we process those data again for SWFA clear-sky occurrences with an RH greater than 75 to 80%. We use these high RH data to calculate individual "C" coefficients, from which we subtract the corresponding "k" coefficients from the previous run. We then use all the resultant difference data to calculate a relationship between the RH measurements and the lapse rate coefficient difference due to high RH values using a simple power law formulation. In this way, we determine the difference between the "dry" value of the lapse rate coefficient and the additional influence of the relatively humid ambient conditions that are conducive to haze formation. We call this value an "RH Factor" and use it to adjust the clear-sky LW calculations in an attempt to compensate for haze effects. Once the lapse rate coefficients have been interpolated through time, the result is used to calculate the estimated clear-sky LW similar to the Brutsaert formulation, with the exception that the lapse rate coefficient "C" is calculated for each data time and substituted for the "1.24" in Eq. 1. The coefficient "C" is calculated as:

$$C = k + \mathrm{RHFactor} = k + a(\mathrm{RH})^{b} \tag{4}$$

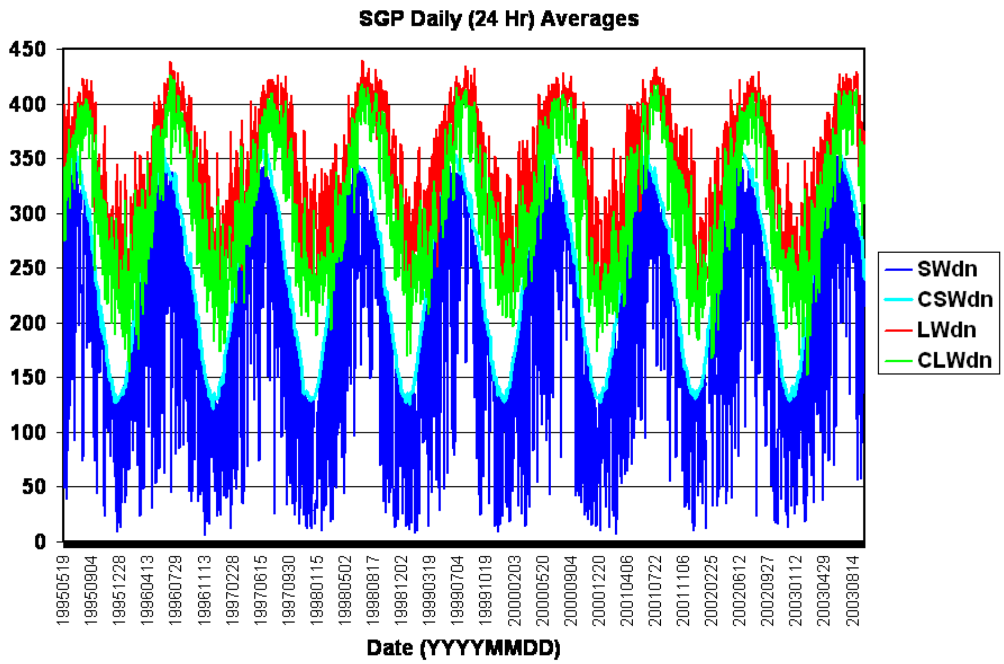
where k is the interpolated dry lapse rate coefficient, and "a" and "b" are the previously determined coefficients for calculation of the "RH Factor."

Table 1 summarizes the iterative methodology described above. The red points in Figure 1 show the daylight comparison result of the above outlined LW flux analysis process, using the same measured data as that in blue detected as clear sky. It is shown that the clear-sky LW estimates exhibit much better agreement with the measurements, with rms disagreement from X = Y now decreased to about 4 Wm^{-2}.

Table 1. Brief description of the iterations used in the LW flux analysis for estimating clear-sky LW.

Iteration #	Task
RH1	Use SWclr, RH <80%, calc fit "k" and interpolate
RH2	Use SWclr, RH >80%, and prev. interpolated "k," calc RHFactor coefficients
Fit1	Use SWclr and RHFactor, calc. "C" coeff, fit and interpolate
Fit2	Use prev. interp. "k", include LW <CLW+4.0, calc. "C" coeff, fit and interpolate
Fit3	Use prev. interp. "k," detect night LWclr, calc night "C," fit and interpolate 3/day
Fit4	Use 3/day interpolated "k" coeff. to calculate estimated continuous Clear LW

As with the SWFA algorithm, one of the benefits of the flux analysis methodology is the ability to study long-term trends. An example is shown in Figure 3, the time series from the available data at the SGP CF. The top plot represents the time series of clear- and all-sky downwelling SW and LW, while the bottom plot represents the cloud effect as a difference between the clear- and all-sky amounts. Note the approximately one-month lag of the LW budget from the SW budget. This lag is correlated with the well-known lag of average ambient air temperatures behind the seasonal solar cycle.



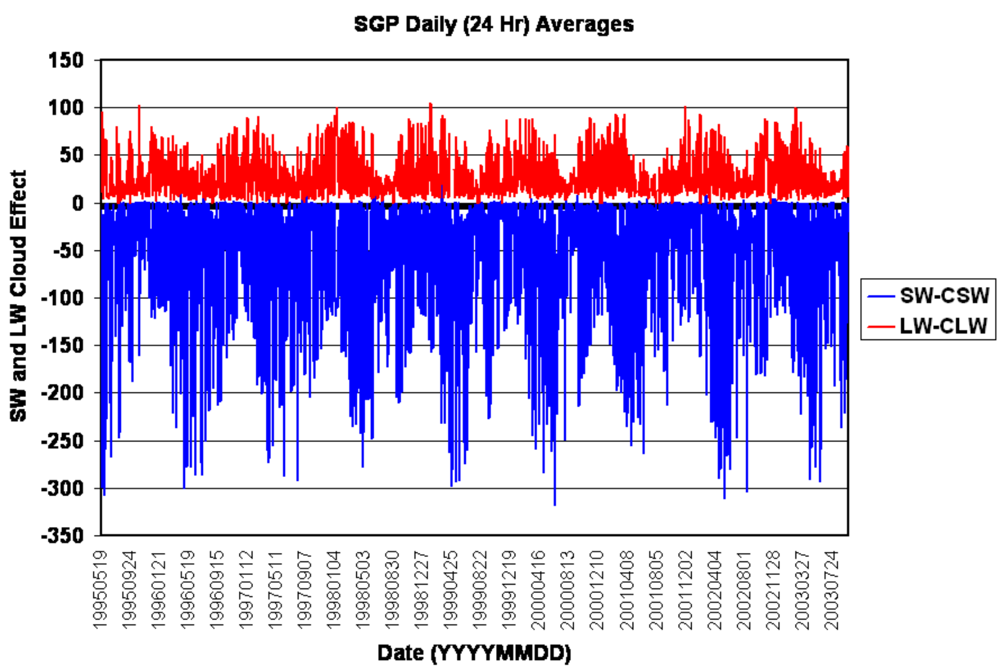


Figure 3. Clear- (CSWdn, CLWdn) and all-sky (SWdn, LWdn) daily averages of SW and LW (top) from 19950519 - 20030927 for the SGP CF. The bottom plot shows the cloud effect as the flux differences.

Estimating LW Fractional Sky Cover and Brightness Temperature

Durr and Philipona (2004) have presented a method for estimating the LW effective fractional sky cover using downwelling LW measurements. This method uses an analysis of the variability of the LW time series and the ratio of the "effective LW emissivity" from measured LW over the "effective clear-sky LW emissivity" ($\varepsilon_m/\varepsilon_c$), similar to Brutsaert. These researchers used human-observer reports of sky conditions to develop a relationship between reports of low- and mid-level cloudiness and the magnitudes of the effective emissivity ratio and standard deviation of the downwelling LW time series. They show that their methodology agrees with observer reports about 85% of the time within 1 okta (12.5%) of sky cover and about 95% of the time within 2 oktas (25%). While this might be considered a large amount of uncertainty, it is still consistent day and night information on cloud presence at the low and middle levels. However, Durr and Philipona (2004) use a climatological formulation to estimate the effective clear-sky emissivity for any given time. Because the methodology described in the previous section actually determines the relevant effective clear-sky emissivity value from the surrounding time series of the data, estimating LW effective sky cover might show some improvement over the climatological approach.

Takara and Ellingson (2003) proposed a methodology for estimating what they term as LW "effective cloud fraction" using spectral measurements in the 8 – 12 micron infrared window. Their method specifically used measurements from an atmospheric emitted radiance interferometer (AERI) to estimate the clear-sky and overcast values that could then be compared to the measurements to infer cloud amount with independent pixel approximation (IPA) arguments. Given the adaptation nature of the Brutsaert method described here, the Flux Analysis produces a continuous clear-sky LW estimate and has access to the measured LW. All that is needed is some estimate of the equivalent downwelling overcast LW, and the same IPA-type arguments can be applied as in the Takara and Ellingson method. During the Cloudiness Intercomparison intensive operational period held in early 2003 at the SGP CF, one of the instruments fielded was a Heitronics infrared thermometer (IRT) with a narrow (2.6°) field of view and sampled at a rate of 10 Hz. These data are intended to be used to infer cloud base (or in reality effective cloud radiating surface) temperature and an estimate of cloud base heights. But the inferred cloud radiating temperature, in conjunction with the estimated effective broadband LW clear-sky emissivity, can be used to estimate the equivalent downwelling overcast LW.

With the IRT measurements, cloud effective radiating brightness temperature can be directly inferred, after accounting for the intervening atmosphere effects, then LW effective cloud fraction estimated. Conversely, given an estimate of LW effective sky cover and IPA arguments, the cloud brightness temperature can be estimated from the broadband data. Using the SWFA inferred sky cover is problematic in that, as noted previously, high cloud amounts included in the SWFA sky cover do not appreciably impact the surface downwelling LW. Thus, under the presence of high cloud, the brightness temperature estimates suffer from large uncertainties. Current efforts are geared toward further investigation of these possibilities.

Estimating Cloud Visible Optical Depths

The technique of Barnard and Long (2003, 2004) has been incorporated into the Flux Analysis code to estimate the effective plane-parallel spherical droplet visible cloud optical depth. The Barnard and Long technique is based on optical depth retrievals using the Min and Harrison (1996) method, so, in effect, they produce similar values. The SWFA estimate of sky cover is used to screen for times when the sky is overcast (sky cover >95%), and the direct relationship is applied.

For sky cover values less than overcast, we are testing a method that tries to compensate for the fact that Mother Nature rarely, if ever, presents us with uniformly distributed cloud fields. Thus, occurrences of positive cloud forcing often skew retrievals over short (15-minute) time scales when using surface hemispheric measurements. If one assumes that a time series analysis of the measured over clear sky ratio of direct SW can be used to produce an equivalent uniformly distributed average cloud field effect, we can use the resultant flux value to estimate the effective plane parallel cloud optical depths for partly cloudy skies during daylight hours. While work is certainly continuing, preliminary estimates for overcast and partly cloudy skies have been provided as part of the current Clouds with Low Optical (Water) Depths initial comparison of techniques for dealing with optically thin and low liquid water amount cloudiness.

Summary

The development of the next generation of the surface Flux Analysis Code is well underway. This new version includes all that comes from the SW Flux Analysis, plus 24-hour data, estimates of cloud visible optical depths, and continuous clear- and all-sky surface downwelling LW. In addition, there appears to be the possibility of inferring LW effective fractional sky cover and effective cloud base radiative surface temperatures from these analyses, especially with the inclusion of IRT data in the analysis.

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