On the Estimation of Clear-Sky Upwelling Shortwave and Longwave

C.N. Long
Pacific Northwest National Laboratory
Richland, Washington

Introduction

Previous work (Long and Ackerman 2000; Long 2004) has concentrated on estimating the downwelling clear-sky irradiances and calculating the effect of clouds on the downwelling radiative energy budget. However, cloud forcing is defined for the difference between clear- and cloudy-sky net radiation, which includes the upwelling components. Thus, if we are to estimate the surface radiative cloud forcing, the means must be developed to estimate what the upwelling shortwave and longwave irradiance would be if the clouds were not present. Estimating the upwelling longwave (LW) is particularly troublesome in that the emitted upwelling LW is a function of the total surface energy exchange including latent and sensible heat, which is related to but not necessarily always totally driven by the radiative exchange alone, but also involves the evolving soil and vegetation properties and changes in soil moisture amounts.

Clear-Sky Upwelling Shortwave

The interpolation of clear-sky fit coefficients for clear-sky upwelling shortwave (SW) (SWup) estimation is problematic for changing conditions (i.e., snowfall, harvest, etc.) and do not capture the rapid changes. Even across the day, the surface bidirectional reflectance functions (BDRFs) are related to such things as wind conditions, vegetation type and health, accumulating or melting snow, and dew/frost/rain coating. These conditions can lead to large errors for these periods. There is typically a few percent albedo difference dependant on whether the sun is blocked or not, and the solar zenith angle. Nevertheless, the measured albedo does capture the changes due to specific surface condition and across the day.

A snowfall event at the Southern Great Plains (SGP) during December of 2003 (Figure 1) illustrates the problem of using only detected clear-sky data for fitting and interpolation to estimate clear-sky SWup. The top panel shows the measured and interpolated clear-sky estimated surface albedo, with the actual detected clear-sky data noted. Only the first and last days shown were fitted, with the intervening time using interpolated coefficients. The resulting estimated clear-sky SWup (bottom panel) shows the measured SWup is much larger than the corresponding interpolated clear-sky estimate, resulting in large errors. The clear-sky estimation using the measured albedo times the estimated clear-sky SWdn proves to be a much better estimation of clear-sky upwelling SW in this case.

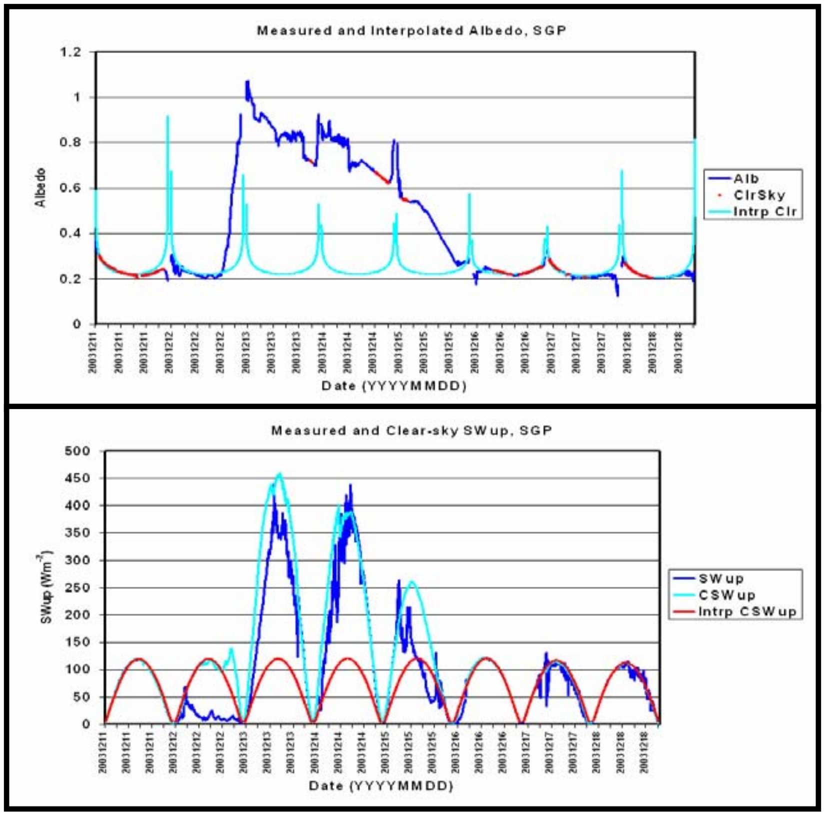


Figure 1. A snowfall event at the SGP during December of 2003. Top panel shows the measured (blue) and interpolated (light blue) surface albedo. Red dots denote detected clear-sky data. The resulting clear-sky SWup estimates are shown in the bottom panel. The measured (blue) SWup is much larger than the corresponding interpolated fitted clear-sky estimate (red). The light blue denotes the clear-sky estimation using the measured albedo times the estimated clear-sky SWdn.

In the results presented here, a preliminary solution is to use the measured albedo times the clear-sky downwelling SW (SWdn) estimate. However it is likely that a more refined solution for estimation of clear-sky SWup can be found. In contemplating the problem, other possible solutions come to mind, such as:

- Use any data that direct component is “strong” for fitting, i.e. use ratio of the measured/clear direct to accumulate data for fitting. This will increase the periods of data available for fitting. However, this still will not work for mostly cloudy or overcast days, and the interpolated function still may miss rapid changes.

- Use the above if available, else use the measured albedo, i.e. use a conditional approach to the calculation.

- Interpolate the function as a ratio of (with direct)/(without direct), i.e. use an analysis of the difference in albedo with or without the direct component, and adjust an “effective clear-sky albedo” as if there were a direct component for given conditions.

– Alternatively, use analysis to determine the climatological “average” percent difference of with and without direct component for a given site, and adjust an overall “effective clear-sky albedo” accordingly.

Clear-sky Upwelling Longwave

In developing a method for estimating the clear-sky upwelling LW (LWup), it is essential to note that LWup is a product of the total surface energy exchange, including latent and sensible heat. In addition, the relationship to the incoming radiative energy is dependent on the wavelength regime. For instance, LWup is related to the downwelling LW (LWdn) because the surface emissivity at a given wavelength is equal to the absorptivity at that wavelength. But in the case of shortwave radiation, some of the net SW deposition (SWnet, defined as SWdn minus SWup) for vegetated surface is converted into plant energy, not heat as is the case for bare soil or snow.

With only standard surface radiation and meteorological instrumentation, no direct measurement of sensible/latent heat exchange is available. However, these parameters are somewhat related to ambient relative humidity (RH) and wind speed (Wspd), measurements of which are available. Thus, one can use Clear-sky LWdn and SWnet, as well as Wspd and RH, as independent variables for empirical fitting and interpolation to estimate the clear-sky upwelling LW.

For fitting, the SW Flux Analysis (Long and Ackerman 2000) detects daylight clear-sky periods. Additionally, “effective LW clear sky” is detected using the variability of LW time series (after Marty and Philipona 2000) and the difference between air temperature and effective broadband LW sky brightness temperature. High/thin clouds have no appreciable effect on the surface downwelling broadband LW, thus are not considered “clouds” as far as the surface night-time radiative energy budget. The resultant detected clear-sky data are used to empirically fit functions to estimate flux for cloudy periods.

Fitting and Interpolation

Once clear-sky data are detected, the 24-hour local day is divided into 4 parts, denoted n1, d1, d2, and n2. Each part day with a minimum number of detected clear data is then processed using iterative fitting to exclude outliers. First, the radiative components are fitted as the major factors affecting the clear-sky LWup, capturing the majority of the radiative, latent, and sensible heat partitioning. The radiative components included are the LWdn at night, and LWdn and SWnet during daylight. Next, the RH (day only) and Wspd (day and night) are separately fitted to the residuals. These latter factors “nudge” the result per changes through the day. The Wspd variable is used in the form of (4th root - 1.0), since wind has a greater effect for small wind, but the increase in effect per increase in spd decreases rapidly for larger wind speeds. The changes in RH are related to both air temperature and moisture changes.

Interpolation of daily coefficients:

Surface moisture can change significantly over less than daily time scales. Similar to surface albedo (Section 2), rapid changes in vegetation/snow/dew/etc. significantly affect the radiative relationship at the surface. To account for these effects, we interpolate LWdn across all “clear enough” fitting (i.e., n1-d1-d2-n2). Because of day/night differences in surface (dew, frost, haze, etc.), we also interpolate all coefficients n1-n2, and d1-d2 from day to day. We then average the individual n1 and n2 period LWdn coefficients from the two types of interpolation.

Interpolation across the day (See Figure 2 below):

To account for the changes between the 4 periods of the day, we weight the transitions at the period boundaries based on Local Standard Time. At local midnight we interpolate n2 from the previous local day to n1 of the current local day across two hours centered on local midnight and weighted by time. At local noon we interpolate d1 to d2 across 1/3 of the daylight period, again weighted by time. At sunrise and sunset we interpolate n1 to d1 and d2 to n2 for cosine of the solar zenith angle (CosZ) greater than 0.0 (solar zenith angle less than 90°) to a maximum CosZ limit (CZLim) weighted by the ratio (CosZ/CZLim).

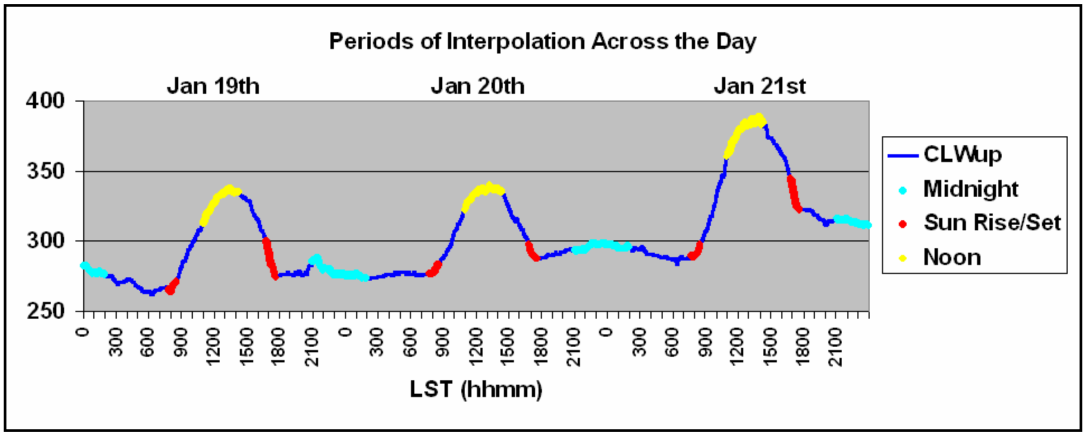


Figure 2. Example of calculated clear-sky LWup (blue) for three days from the Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) SGP site in January 2004 showing the interpolation periods of local midnight (light blue), sunrise/sunset (red), and local noon (yellow).

Figure 3 shows an example of the resulting fitting, interpolation described above for three days at the ACRF SGP Central Facility in January of 2004. Note that the daylight SW tends to increase the clear-sky LWup. On the overcast day of the 20th, clouds increase the actual LWup over the clear-sky amount due to the increased LWdn, except for mid-day where the “loss” of SWnet compensates for the gain in LWdn.

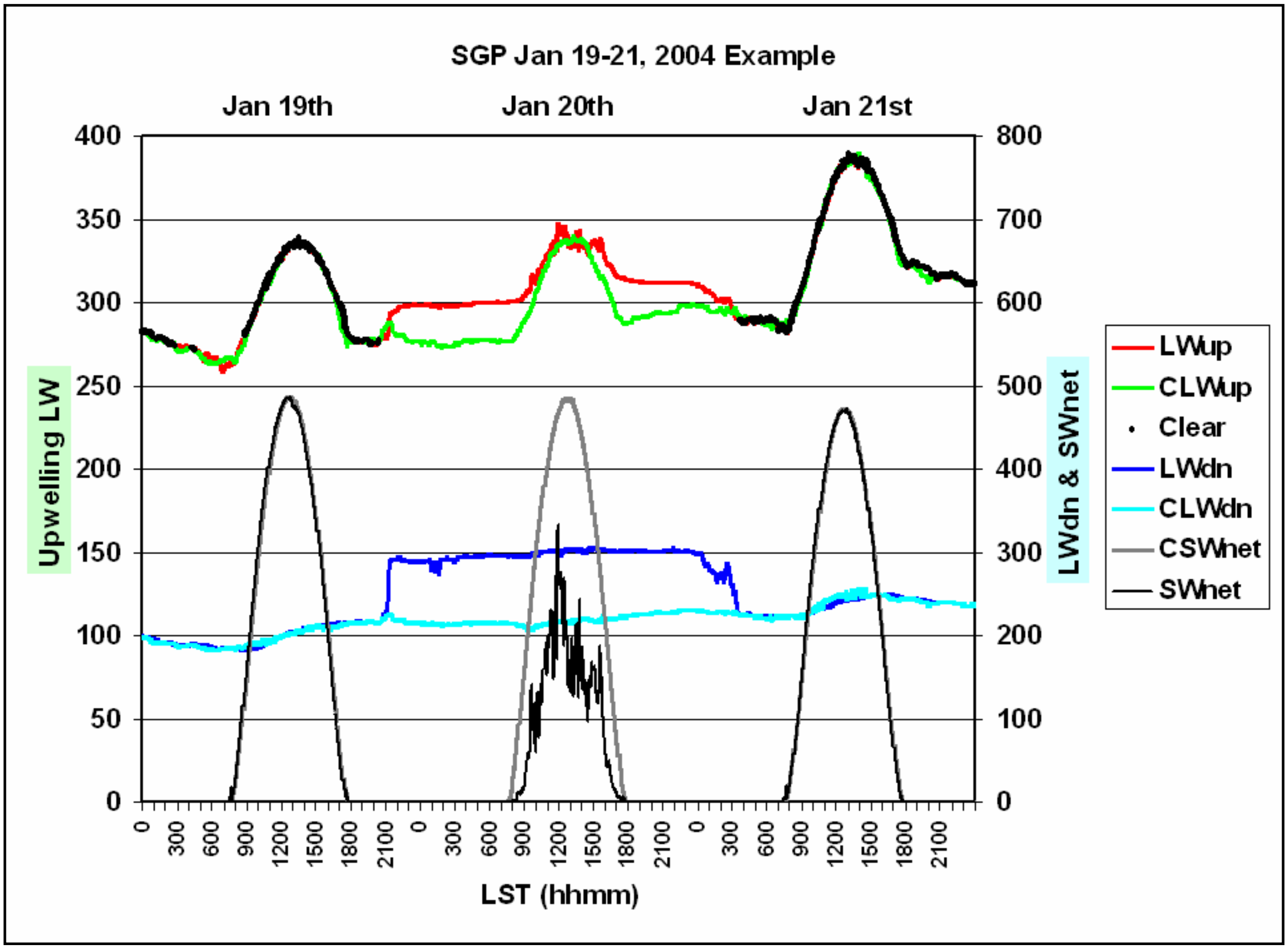
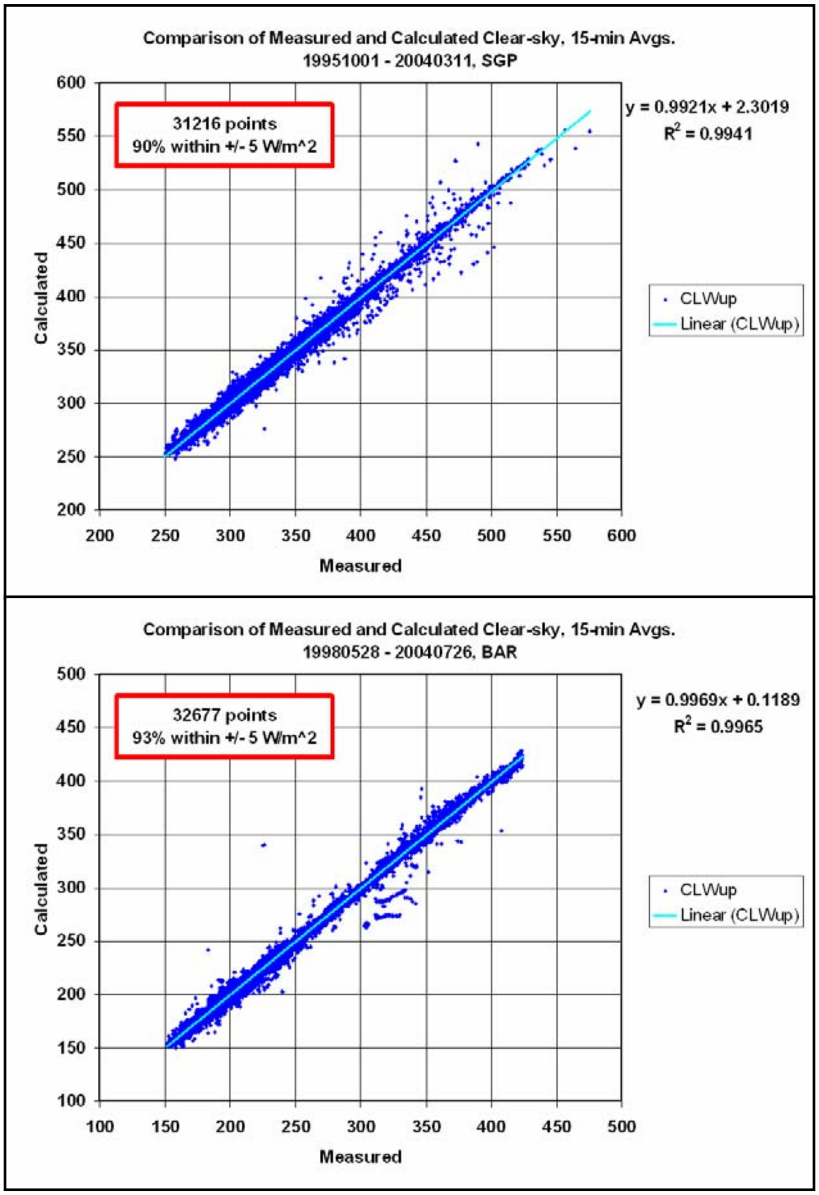


Figure 3. Same as Figure 2, but showing the results of all interpolation including day-to-day. Shown referenced to the left axis are the measured (red) and clear-sky (green) LWup. Black dots represent detected clear-sky data. Referenced to the right axis are the measured (blue) and clear-sky (light blue) LWdn, and the measured (black) and clear-sky (gray) net SW.

Figure 4 compares the calculated clear-sky LWup to the corresponding measured LWup for data from the ACRF SGP site and North Slope of Alaska (NSA) site at Barrow detected as clear-sky using the methods described here. In both cases over 90% of the calculations fall within +/- 5 Wm^{-2} of the measurements. The uncertainty for cloudy periods has yet to be estimated, but the agreement during clear-sky periods shown is encouraging.



Comparison of Measured and Calculated Clear-sky, 15-min Avgs.
19951001 - 20040311, SGP

Comparison of Measured and Calculated Clear-sky, 15-min Avgs.
19980528 - 20040726, BAR

Figure 4. Comparison of detected clear-sky measured upwelling LW to corresponding calculations, 15-minute averages for over eight years of SGP data (top plot), and six years of Barrow data.

Analysis Results

The methodology described here is combined with previous methodology (Long and Ackerman 2000; Long 2004) in an analysis of the surface radiative energy budget, effects of clouds on that budget, and the total net surface radiative cloud forcing for the SGP and NSA data. Figure 5 shows monthly estimates of radiative cloud effect and radiative cloud forcing for the SGP Central Facility spanning from mid 1995 through early 2004. In the aggregate, clouds decrease the downwelling SW on average

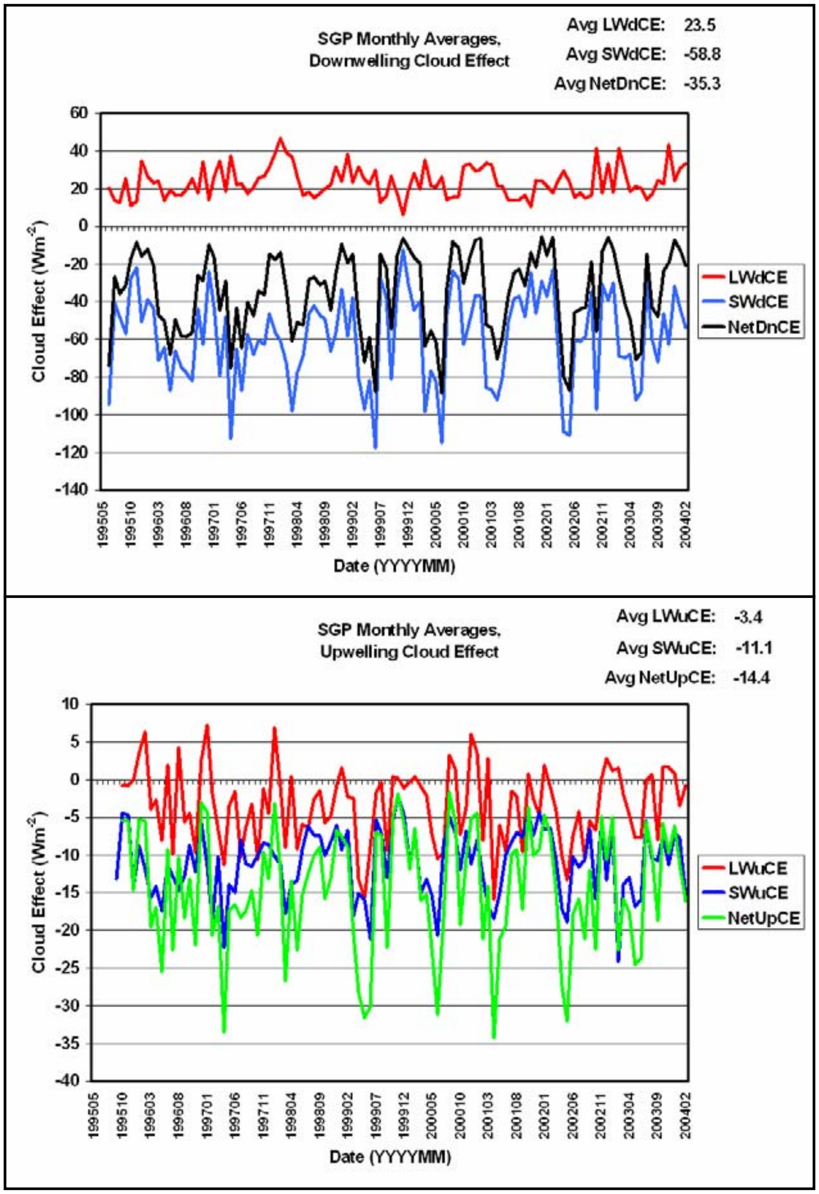


Figure 5. Monthly estimates of radiative cloud effect and radiative cloud forcing for the SGP Central Facility spanning from mid 1995 through early 2004. The upper plot shows the downwelling LW (red), SW (blue), and net cloud effect as the difference between the measured minus the clear-sky values. The lower plot shows the new upwelling cloud effect estimates discussed here for the LW (red), SW (blue) and net (green).

by 59 Wm^{-2}, while at the same time increasing the downwelling LW about 24 Wm^{-2}, for a net decrease of 35 Wm^{-2}. In the upwelling case, clouds decrease the SWup by about 11 Wm^{-2}, but also slightly decrease the upwelling LW by 3 Wm^{-2}. Thus the net upwelling effect is 14 Wm^{-2}.

Figure 6 shows the net downwelling and upwelling cloud effect of Figure 5. These values are then used to calculate the monthly net surface radiative cloud forcing. These results show that across this time span, the SGP Central Facility experienced an average net cloud forcing of about 21 Wm^{-2}, all derived from surface radiative and meteorological measurements alone. These results can be used as independent data for model and satellite comparisons.

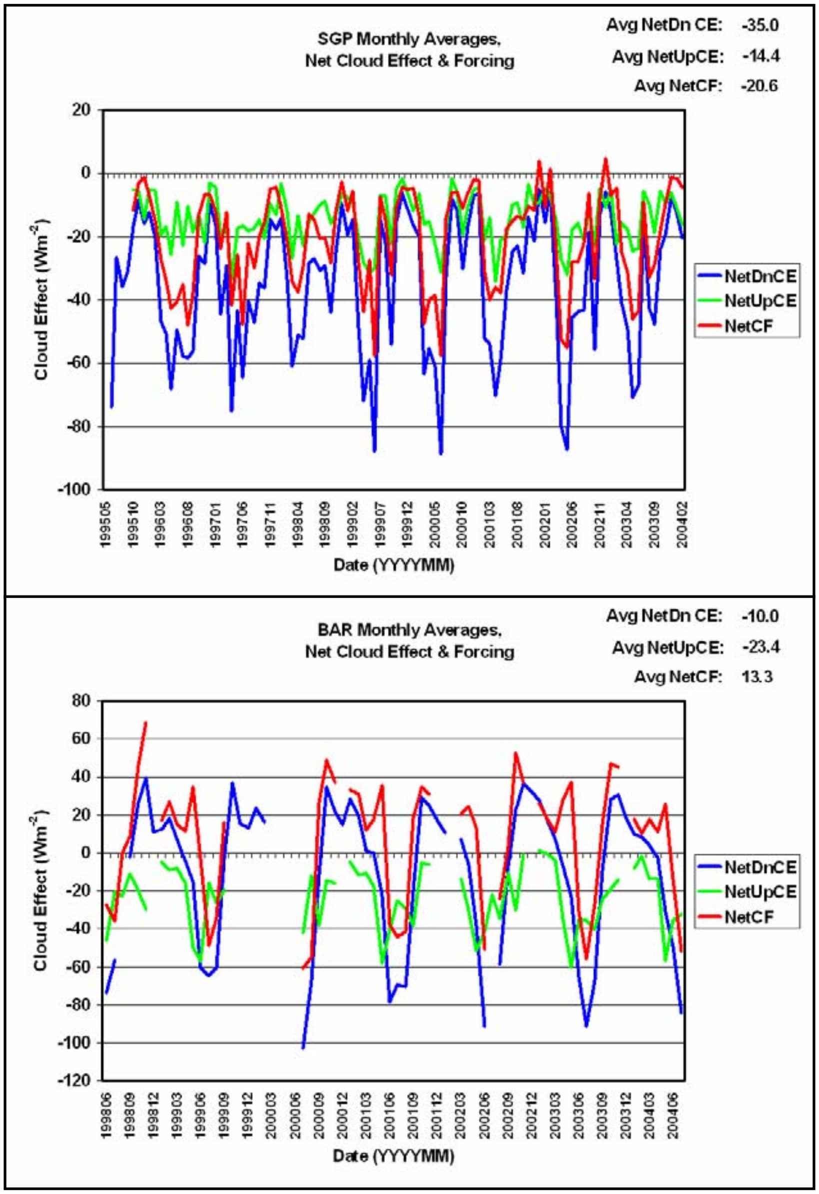


Figure 6. The upper plot repeats the net downwelling (blue) and upwelling (green) cloud effect of Figure 5. These values are then used to calculate the monthly net surface radiative cloud forcing (red). The lower plot is similar to the upper right plot, but for the NSA Barrow site spanning from mid 1998 through mid 2004.

The lower plot is similar to the upper right plot, but for the NSA Barrow site spanning from mid 1998 through mid 2004. In this case, the monthly average time series has more gaps due to missing data in this harsh environment. With the available data over this period, we see that on average the magnitude of the net downwelling cloud effect is smaller than that for the SGP, decreasing the downwelling irradiance by only about 10 Wm^{-2}. Clouds decrease the net upwelling irradiance by 23 Wm^{-2} resulting in an overall positive surface radiative cloud forcing of 13 Wm^{-2}. As expected, clouds in general decrease the radiative energy deposition into the surface over what it would be for clear skies at the SGP, but increase the overall radiative energy input into the surface at the NSA.

Summary

If we are to estimate the surface radiative cloud forcing, the means must be developed to estimate what the upwelling shortwave and longwave irradiance would be if the clouds were not present. We present here methodologies developed for estimating the clear-sky upwelling SW and LW components using only standard surface radiation and meteorological measurements. Thus, the clear-sky estimates, as well as the calculated cloud effects and surface radiative cloud forcing, are derived independent from data that are typically used in model calculations and satellite retrievals such as sonde profiles (measured or interpolated) and aerosol optical depth measurements. These results can be used as independent data for model and satellite comparisons.

References

Long, CN, and TP Ackerman. 2000. “Identification of Clear Skies from Broadband Pyranometer Measurements and Calculation of Downwelling Shortwave Cloud Effects.” *Journal of Geophysical Research* 105(D12)15609-15626.

Long, CN. 2004. “The Next Generation Flux Analysis: Adding Clear-sky LW and LW Cloud Effects, Cloud Optical Depths, and Improved Sky Cover Estimates.” In *Proceedings of the Fourteenth ARM Science Team Meetings*, Albuquerque, New Mexico, March 22-26.

Marty, C, and R Philipona. 2000. “The clear-sky index to separate clear-sky situations in climate research.” *Geophysical Research Letters* 27:1641–1644.