Direct Aerosol Forcing in the Infrared at the SGP Site?

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Introduction

Low level haze is often observed during the night and early morning hours in many locations. This haze is typically formed during quiescent conditions by radiative cooling of the surface, which lowers the ambient temperature and consequently increases the near-surface relative humidity (RH). Many aerosols start to deliquesce around 75% relative humidity (RH) (depending on their chemical composition), and thus if the near surface RH increases above this level, haze will form.

The Atmospheric Radiation Measurement (ARM) Program's ultimate goal, stated simply, is to improve the treatment of radiative transfer in global climate models. Global climate models typically do not account for low level haze at night in their energy budget calculations. Our goal in this analysis is to investigate the impact of aerosol haze on the surface longwave radiative flux to determine if this is an important process that needs to be captured in global climate models.

Importance of Haze on the Surface Longwave Radiative Budget

As aerosols deliquesce, they become more liquid, and thus we performed a series of calculations to investigate the response of the infrared atmospheric window to small changes in the liquid water path (LWP). For these calculations, we used the Line-By-Line Radiative Transfer Model-discrete ordinate radiative transfer (LBLRTM-DISORT) forward model (Turner 2004) to compute the downwelling radiance from 8 to 13 μm for a range of LWP. We assumed an effective radius of 2 μm for these calculations since the droplets are not fully activated in haze conditions, and distributed the droplets in the lowest 200 m of the atmosphere. The results are shown in Figure 1. These results demonstrate that very small LWPs have an appreciable effect on the infrared window radiance, as LWPs of 0.5 and 1.0 g/m^2 increase the downwelling longwave surface flux by approximately 10 and 20 W/m^2, respectively. To put this into perspective, the uncertainty in the microwave radiometers LWP is about 25 g/m^2 (Westwater et al. 2001).

The radiance calculations in Figure 1 were computed using a mean atmospheric profile from May from the SGP. To investigate the influence of changing precipitable water vapor amounts and temperature, we used the Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997) to compute the downwelling longwave fluxes using mean atmospheric profiles for each month from the SGP (Figure 2). While the downwelling longwave fluxes are sensitive to the seasonal changes of water vapor and temperature, the cloud forcing associated with the haze layer is, to first order, essentially independent of the water vapor amount or temperature.

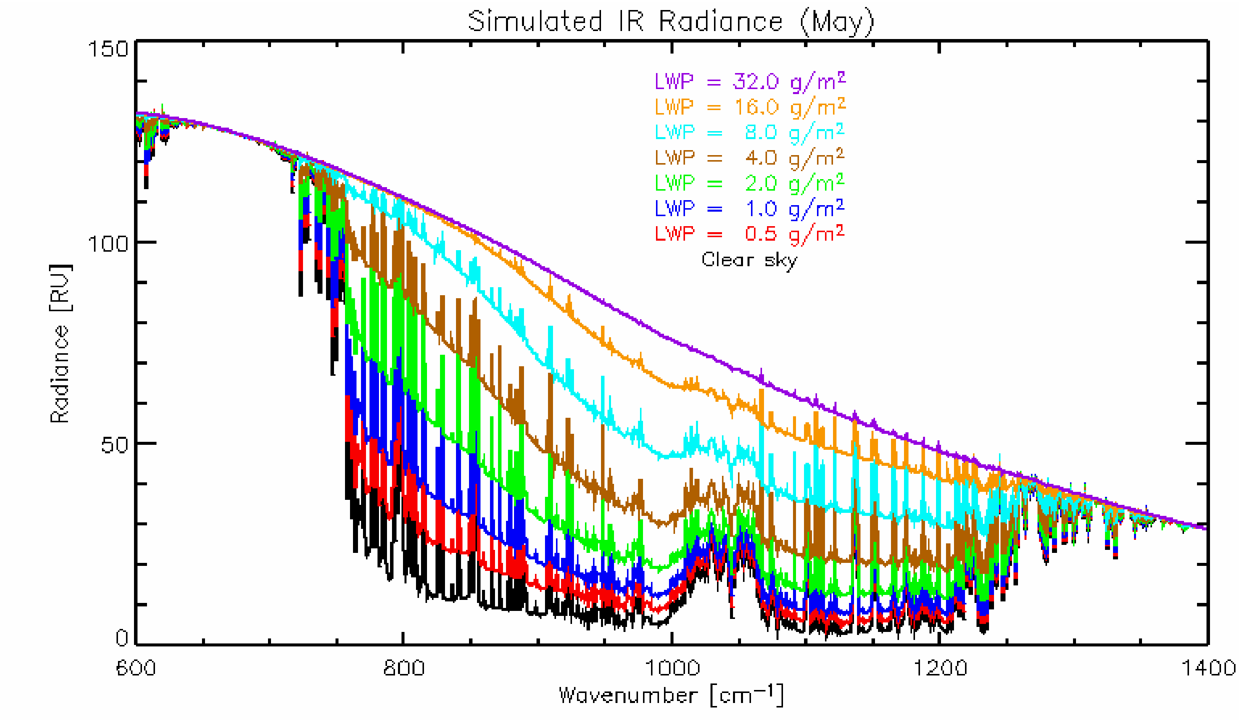

Figure 1. Downwelling infrared radiance computed using the mean atmospheric state for May from the SGP for a range of "haze layers" with small droplets (effective radius of 2 μm) and small LWPs. A 'radiance unit (RU)' is a mW/(m^2 ster cm^{-1}). The infrared window is very sensitive to the presence of liquid water, and a LWP of 0.5 g/m^2 yields an additional 10 W/m^2 of downwelling longwave flux relative to the flux from the clear-sky.

The detection of the presence of the haze layers and determining their LWPs is challenging using the current suite of ARM sensors. We have attempted to identify the presence of aerosol haze layers by looking at the downwelling longwave flux. Long (2004) has developed a longwave clear sky model based upon the work of Brutsaert (1975). This model uses only surface measurements of ambient temperature (T_a), vapor pressure (e), and RH to predict the clear-sky longwave (CLW) flux at the surface:

$$CLW = \varepsilon_c \, \sigma T_a^4$$

$$\varepsilon_c = c\left(\frac{e}{T_a}\right)^{1/7}$$

$$c = k + RHfac$$

where σ is the Stefan-Boltzmann constant, ε_c is the effective clear sky emissivity, and k and RHfac are fitted parameters. The constant k is related to the lapse rate of the atmosphere, while the RHfac is needed to account for the apparent increase in the downwelling flux (relative to broadband observations) as the RH increases. Details of how these two constants are determined are given in

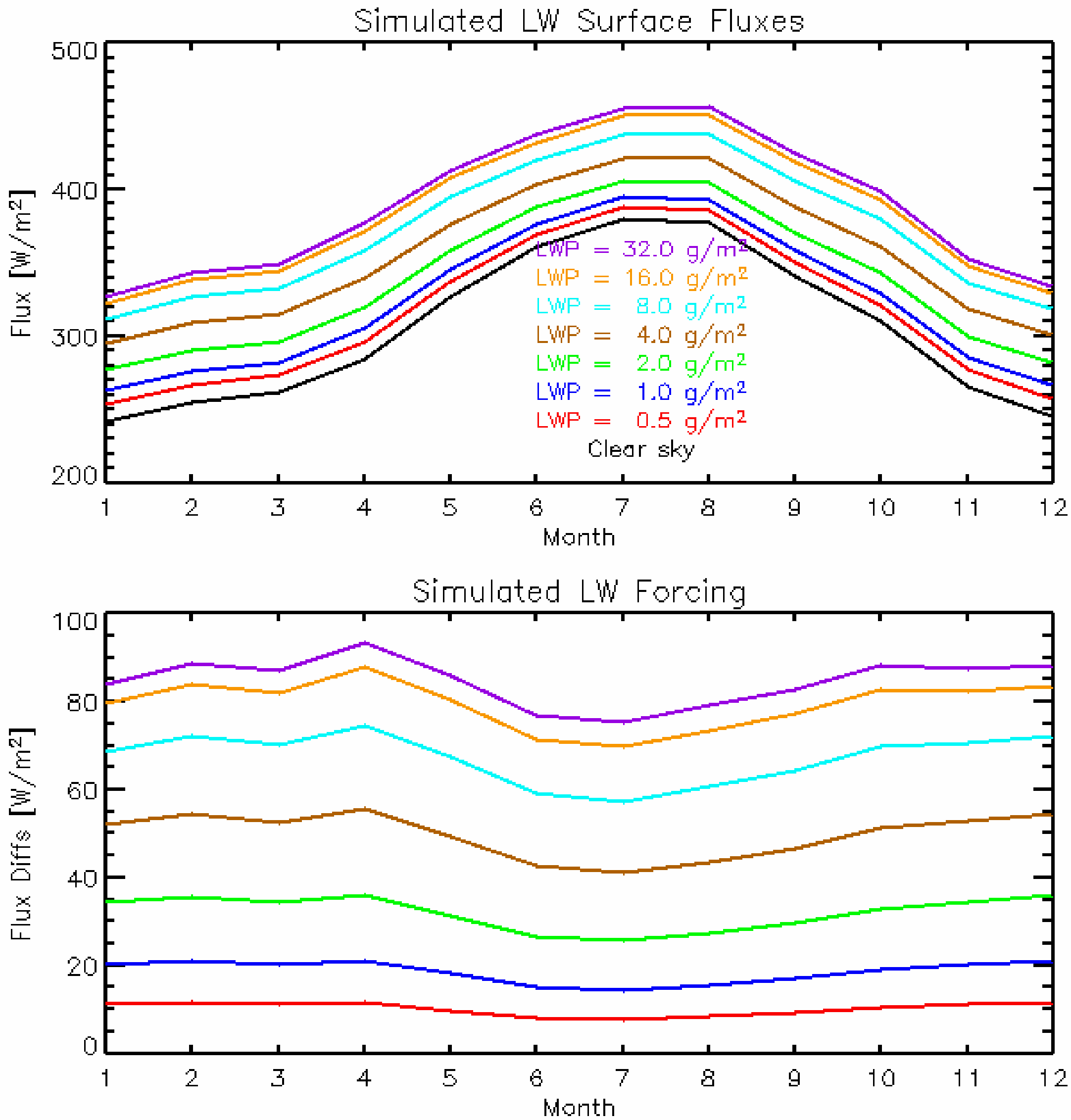

Figure 2. Downwelling longwave flux, and associated longwave cloud forcing at the surface, computed using RRTM and monthly mean atmospheric state profiles from the SGP for a variety of LWPs. The magnitude of the cloud forcing is only slightly modified by the seasonal changes of temperature and precipitable water vapor.

Long (2004). However, since the RHfac accounts for the additional longwave flux that is associated with higher RH, we can compute RHflux from the same relations assuming that k = 0.

We propose that the RHflux can be used as a proxy for the longwave flux contribution from aerosol haze layers. The RHflux is only appreciably different than zero when an inversion is present and the surface RH is high. For example, these conditions existed during the nighttime hours (00-12 Universal Time Coordinates [UTC]) on April 9, 2003 (Figure 3). Comparing the observed downwelling flux from the three pyrgeometers and the atmospheric emitted radiance interferometer (AERI) (following Clough et al. 2000) at the SGP site with RRTM calculations (wherein the surface, 25 m, and 60 m water vapor and

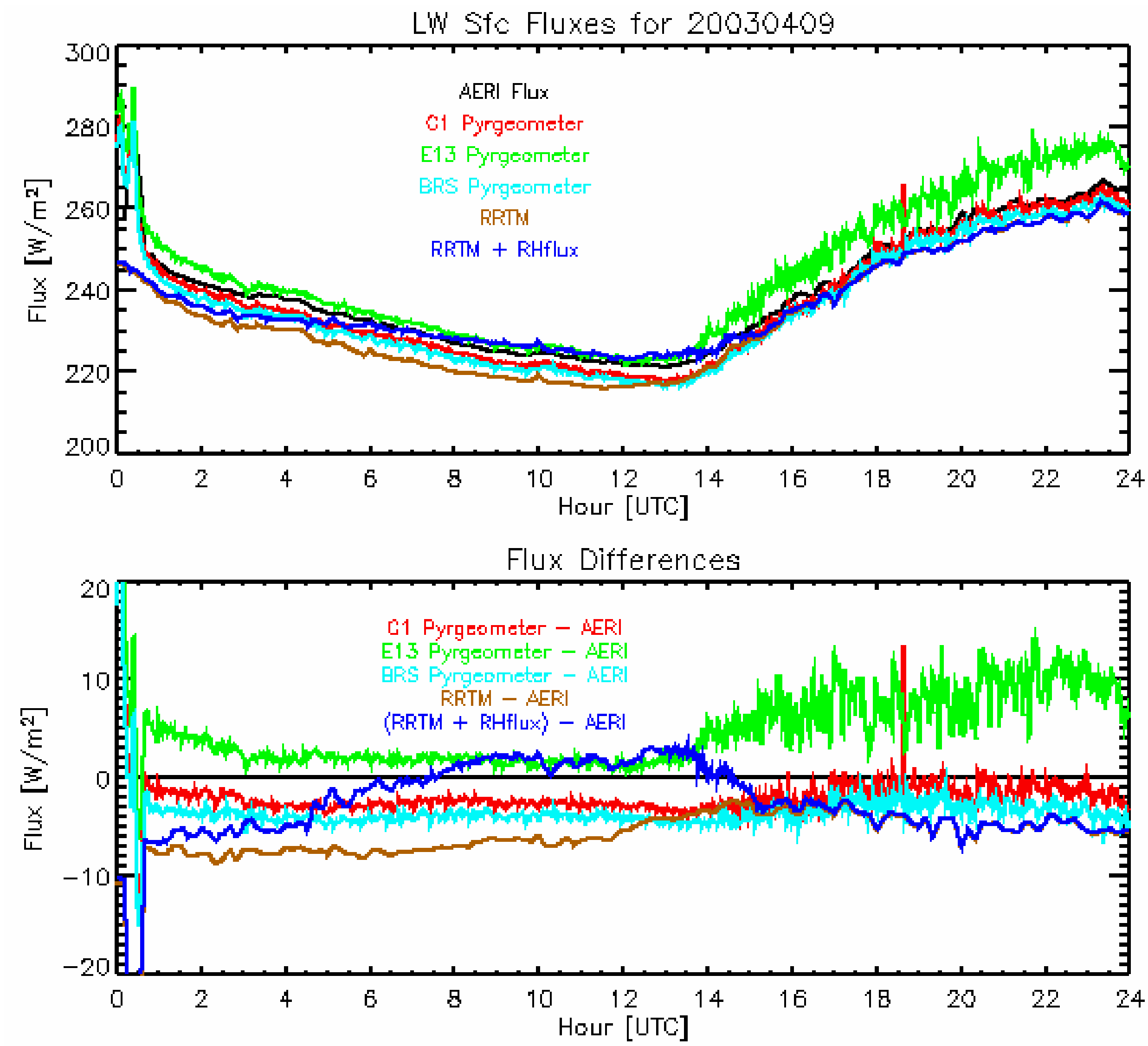

Figure 3. Surface, 25 m, and 60 m ambient temperatures and surface RH observations for April 9, 2003, at the SGP (top), with the corresponding observed and calculated longwave surface fluxes (middle). The RRTM clear-sky flux is smaller than all of the observed fluxes, but if the RHflux is added to the clear-sky flux, the sum is among the spread of the different observed fluxes (bottom).

temperature observations were used in the calculations) demonstrate that the RRTM clear-sky calculation is about 7 W/m^2 lower than the AERI flux observations. However, the sum of the RRTM clear sky flux and the RHflux is within the spread of the observed fluxes, which suggests that the RHflux is reasonably defined.

We analyzed surface meteorology data from the SGP central facility from 2002 to 2003 to determine how frequently the meteorological conditions were right for haze to form. A frequency distribution of RH demonstrated that during the daytime (12-24 UTC) that only 35% of the observations has RH above

75%, whereas over 70% of the nighttime observations have RH values above this threshold. Furthermore, an analysis of this data as a function of month demonstrated little seasonal dependence.

We also looked at the frequency of the strength of the temperature inversion, defined as the difference of the observation on the 60 m tower and the surface. The data from 2002 to 2003 showed that during the night that approximately 50% of the observations had a moderate temperature inversion of greater than 2 K, and about 15% had a strong temperature inversion of greater than 4 K. The number of strong temperature inversions is fairly independent of month, but there are a higher number of moderate temperature inversions from April to August as compared to the other months. Very few (<5%) of the daytime data from February to November had inversions of 2 K or greater.

The distribution of the RHflux as a function of time of day, separated by the strength of the inversion, demonstrates that significant RHflux values (from 3 to 19 W/m^2) often exist during the nighttime but that there are very few cases where the RHflux is above 3 W/m^2 during the daytime (Figure 4). The strong and moderate inversion cases (Figures 4a and b) show that the RHflux tends to increase throughout the night. The two distributions of the RHflux for the moderate inversion cases are due to the seasons; the warmer summer months (when the ambient temperature is higher and thus the flux contribution is greater due to the fourth power dependence on temperature) is the upper distribution, while data from the other seasons define the lower distribution of points.

Summary

An aerosol haze with a small amount of liquid water near the surface can have a large impact on the downwelling longwave flux, as a haze with a LWP of 0.5 g/m^2 contributing approximately 10 W/m^2 to the flux. Aerosol haze forms during temperature inversions when the high surface RH values are above the deliquescence point of aerosol, and these conditions occur frequently at night during all seasons at the SGP site. Using RHflux as an estimate of the contribution of the aerosol haze to the downwelling LW flux, we have shown that values ranging up to almost 20 W/m^2 persist for hours at a time. This bias is significant, both in terms of size and duration, and thus the impact of aerosols and haze on the long surface radiative budget needs to be accounted for in climate models.

The results presented here are preliminary only, but do indicate the possible magnitude and frequency of occurrence of the phenomenon. A more definitive study is needed, but that study necessarily will need to involve improved continuous characterizations of the temperature and moisture profiles for the radiative transfer modeling, and improved broadband longwave measurements for comparison. However, ARM is already striving towards both of these requirements, and thus the needed data should be available for future study.

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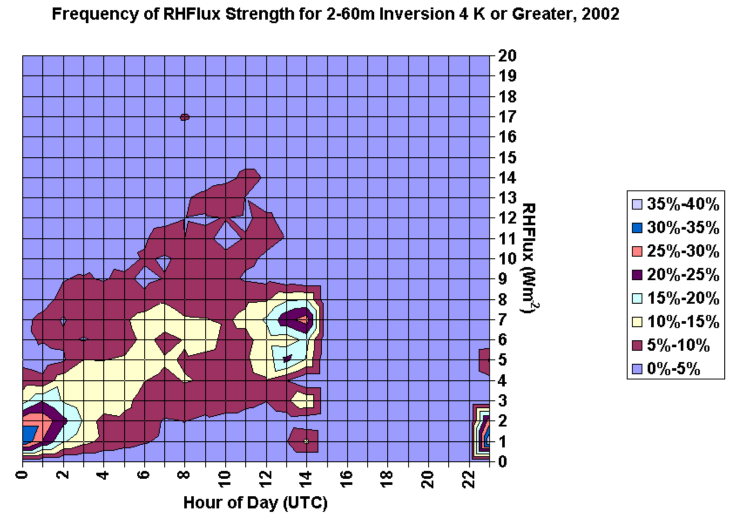

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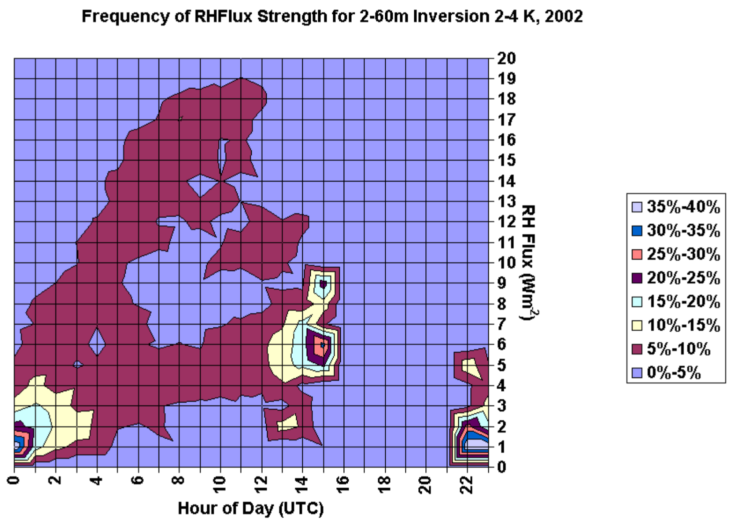

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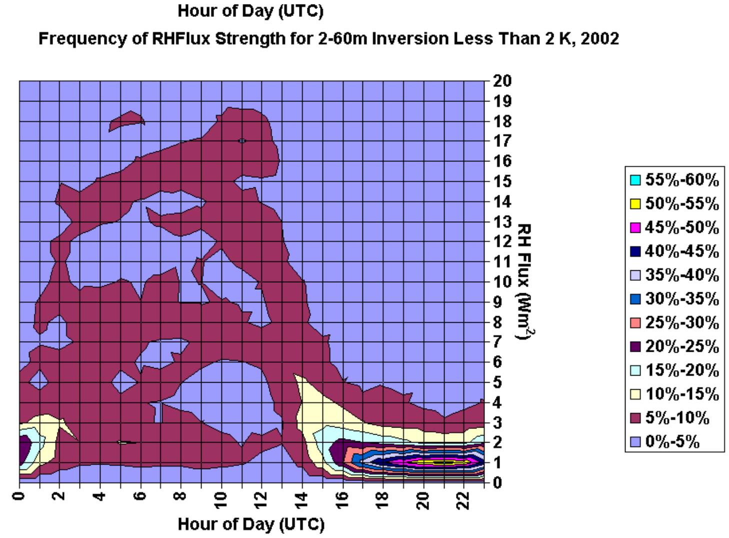

Figure 4. (a) RHflux distributions by inversion strength: strong inversions with temperature differences between the 60 m and surface observations greater than 4 K, (b) moderate inversions with temperature differences between 2-4 K, and (c) "weak" inversions with differences less than 2 K.

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