# Analysis of Cloud Distributions and Radiative Heating Rates Over the Tropical Western Pacific Atmospheric Radiation Measurement Project Sites

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## Introduction

Vertical profiles of radiative heating are important for cloud evolution and for driving vertical motions that play a role in atmospheric circulations on a wide range of temporal and spatial scales. Obtaining the radiative heating is difficult as it generally requires detailed information about the vertical cloud structure to calculate radiative flux profiles. Previous estimates of radiative heating in the tropics have used various techniques including precipitation radar and aircraft (Cox and Griffith 1979), radiosonde budget analysis (Johnson and Ciesielski 2000), satellite cloud estimates (Zhang et al. 2004), and millimeter cloud radar (Jensen et al. 2002). There is now available a long time series of millimeter cloud radar observations at the Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) Tropical Western Pacific (TWP) sites making it possible for the first time to do a detailed analysis of tropical cloud cover and the associated radiative heating rate profiles. Millimeter cloud radars have been operating at Nauru since 1998, at Manus since 1999, and at Darwin since early 2005. Manus and Nauru radar data were processed along with measurements from radiosondes, surface meteorology sensors, and the microwave radiometer, to obtain cloud liquid and ice water content. With these profiles of cloud properties and associated temperature and humidity profiles from radiosondes, radiative fluxes were calculated using a 4-stream radiative transfer model. In this paper, we provide an outline of the technique along with observations from the three tropical ACRF sites.

The process of calculating radiative heating rates involves three steps: first gridded temperature/humidity profiles are derived from radiosondes and related measurements, second, cloud properties are derived from the radar, and third, radiative fluxes are calculated using a radiative transfer model. Each of these steps will now be outlined.

Radiosondes are normally launched twice per day at 00 and 12 Universal Time Coordinates at each of the tropical ACRF sites. Meanwhile, radar observations are available at very high time resolution. To provide a temperature/humidity background on which to examine cloud properties, a series of steps are taken to produce a merged sounding product that makes use of radiosondes in addition to other measurements. The procedure begins with interpolating the radiosonde data to a regular time/height grid. The water vapor profiles within this grid are then scaled to the column water vapor observed by the microwave radiometer. Finally, there tend to be significant temperature fluctuations in the boundary layer and these are accounted for by folding in temperature observations from the surface temperature measurement, which is available at one-minute temporal resolution. This temperature fluctuation is damped with altitude through the boundary layer such that the influence of the surface measurement decreases with altitude in the boundary layer. Above the boundary layer, the surface measurement is not used to influence the temperature profile.

The second step in the heating rate process is to calculate cloud properties from radar measurements. The procedure used is derived from the microbase product (Miller et al. 2003) which provides the input for the ARM Broadband Radiative Heating Rate Product. The microbase product was adapted for the tropics primarily in the treatment of mixed-phase clouds. Rather than prescribing a constant partitioning of ice and liquid as a function of temperature, a statistical approach was used that makes use of observations that record the probability of finding liquid in a layer below 0°C. This technique is described in Mather et al. (2006). Figure 1 shows a statistical representation of the cloud distributions observed at Manus and Nauru for extended periods (February – July 2000 at Manus and March – December 1999 at Nauru). These frequency distributions of cloud condensed water (liquid water content + ice water content) reveal distinct cloud features as well as similarities and differences between the two sites. Both sites have boundary layer cloud features with liquid water content increasing with altitude. The boundary layer feature is stronger at Nauru due to the tendency for that island to generate boundary layer clouds during convectively suppressed conditions (McFarlane et al. 2005). Both sites also exhibit a cirrus feature with ice water content decreasing with altitude. Here the frequency of cloudiness is greater at Manus because convection and anvil outflow were much more prevalent at Manus in 2000 than at Nauru in 1999. The most noticeable difference between the two sites, however, is in the mid-level clouds that are nearly absent at Nauru. This absence of mid-level clouds at Nauru is, again, associated with the lack of convective activity.

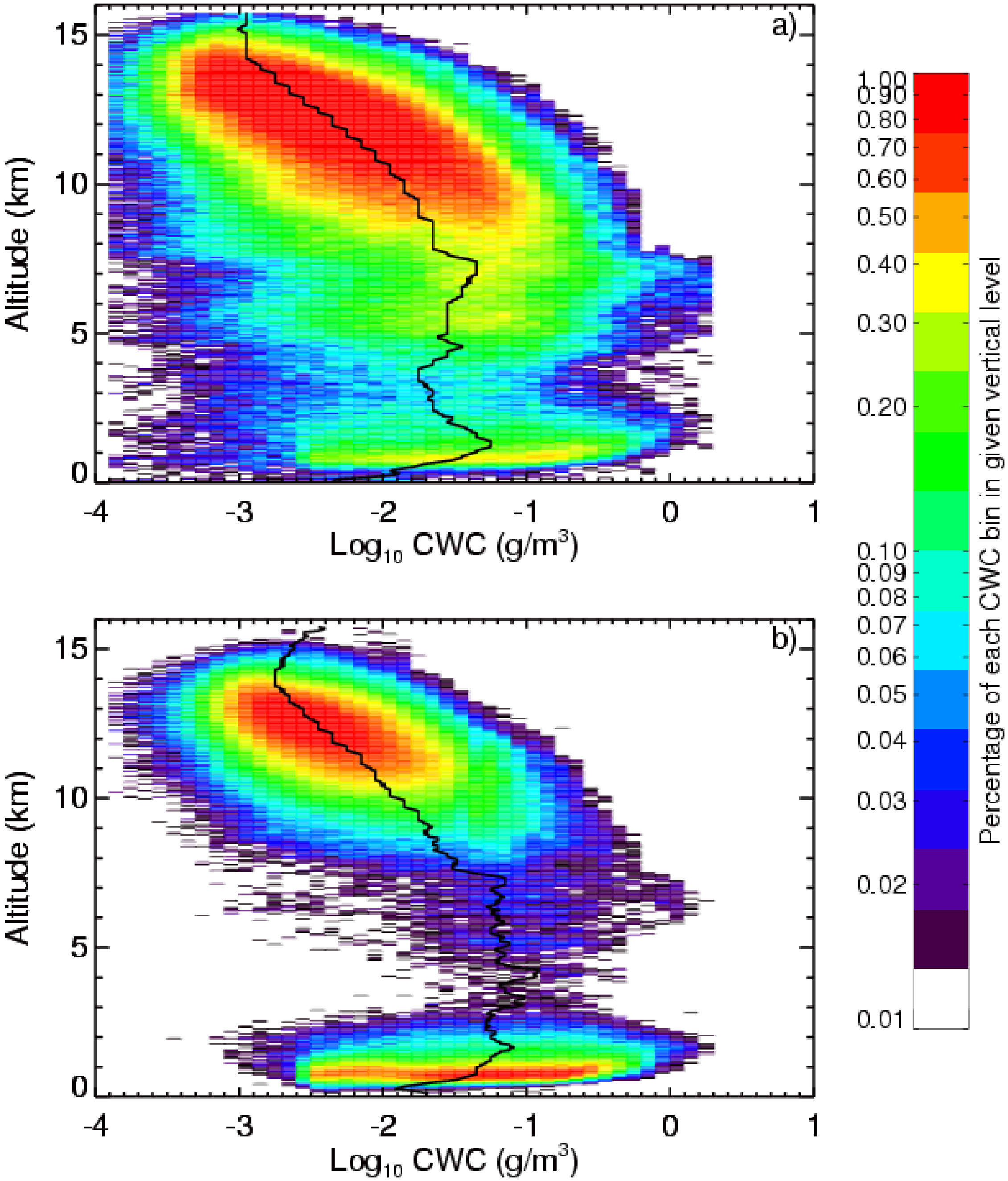
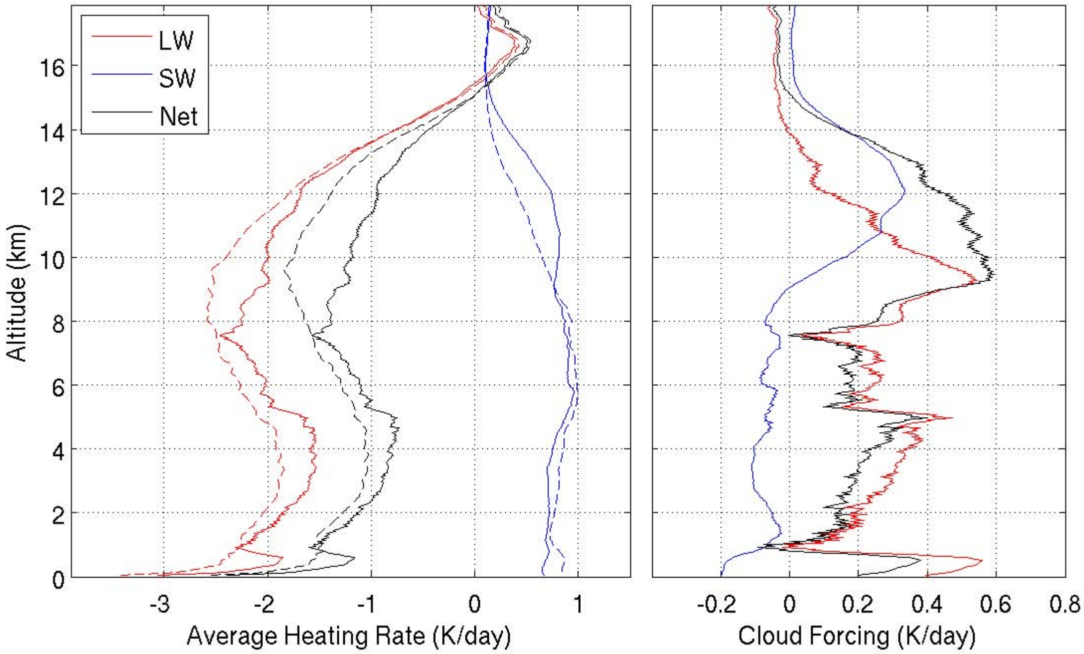


**Figure 1**. Frequency Distribution of cloud condensed water content at Manus, top (Feb-July 2000) and Nauru, bottom (Mar-Dec 1999). Colors represent the frequency with which a given Condensed Water Content is observed at a given altitude.

The final step in the process is to calculate radiative fluxes and heating rates using the temperature/humidity structure and cloud profiles as input. Radiative fluxes were calculated using a 4-stream correlated-k model (Fu and Liou 1992). Figure 2 shows composite heating rate profiles

a. Manus



b. Nauru

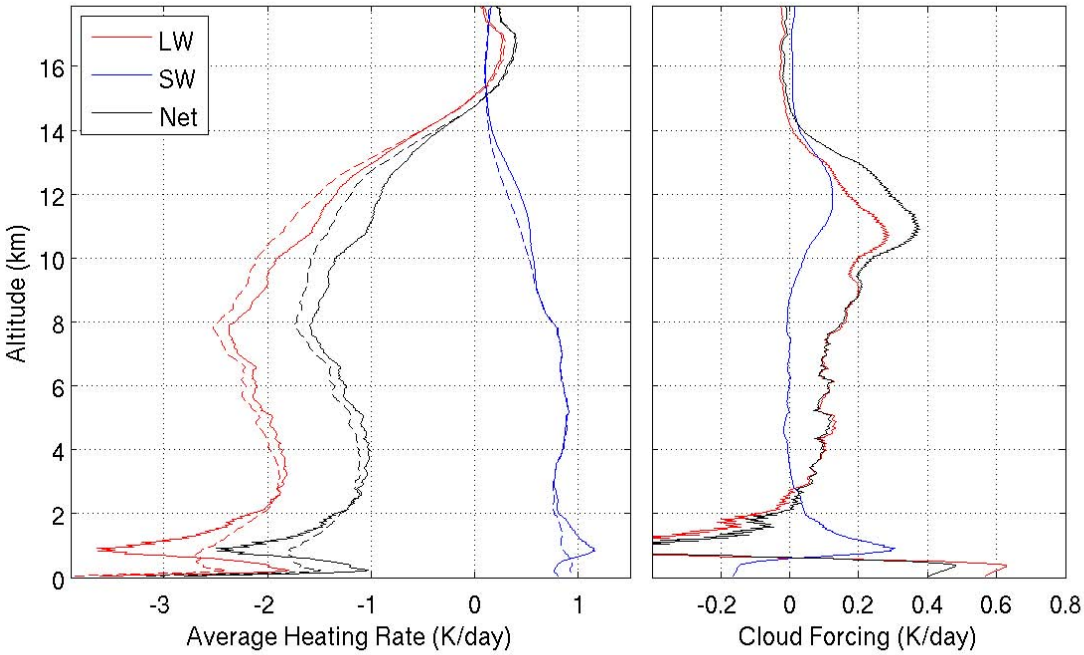


**Figure 2**. Averaged profiles of radiative heating rates at Manus (top) and Nauru (bottom) for the same periods as for the cloud distributions to the left. In the left panels, dashed lines are clear-sky calculations while solid lines are for all-sky conditions. In the right panels, the net heating due to clouds (all-sky heating minus clear-sky heating) is shown.

derived from these radiative transfer calculations for Manus and Nauru. In each case, results are shown for clear and all-sky conditions along with the net impact of clouds, obtained by subtracting the clear-sky heating from the all-sky heating. The clear-sky heating profiles were obtained by simply removing all clouds from the atmospheric column and re-running the radiative transfer model. No adjustments of the temperature/humidity profiles were made. There are several significant differences in the Manus and Nauru heating rate structures that relate to the cloud profile differences described above. At Manus, the prevalence of mid and high-level clouds gives rise to greater cloud-induced heating through much of the column relative to Nauru and a lot more structure than Nauru in the middle troposphere, between approximately 4 and 8 km. Conversely, the Nauru heating profiles show a strong signature associated with boundary layer clouds with heating at cloud top and cooling below cloud base.

The Tropical Warm Pool-International Cloud Experiment (TWP-ICE; May et al. 2004) will provide several opportunities to advance this work on tropical heating rates. One of the primary goals of TWP-ICE was to provide in situ observations of ice cloud properties for the purpose of improving ground-based remote sensing retrievals of those properties. Thus a focus of future work will be to examine the retrievals of cirrus properties that have been used for this work in light of these in situ cloud property measurements. TWP-ICE also featured increased frequency of radiosonde launches (four per day at Darwin) and a network of five sites around Darwin where radiosondes were launched eight times per day. This dense network and enhanced frequency will provide an opportunity to examine issues related to temporal and spatial variability for the temperature and water vapor inputs. Figure 3 shows preliminary calculations of the radiative heating rate profiles derived for the TWP-ICE period using the four per day radiosondes launched from the Darwin site. The basic structure is very similar to the structure observed at Manus and Nauru. The most noticeable difference in these profiles is the variability between the surface and approximately 8 km. Instantaneous heating rates can be quite large, often exceeding 10-20 K/day and these large values are often found near cloud boundaries. Over months, these large individual events are smoothed out but over the short TWP-ICE period, the contribution of individual events is still significant giving rise to the apparent noise in the vertical heating structure.

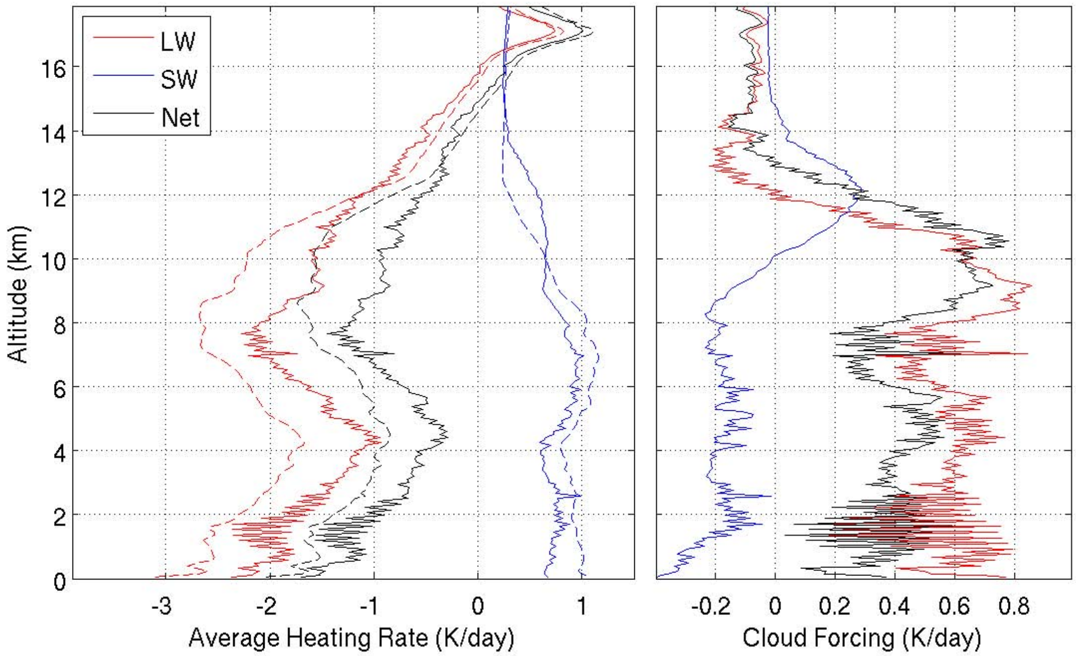


**Figure 3**. As for Figure 2, all-sky, clear sky, and cloud heating are shown, but for Darwin during the TWP-ICE period, January 21 – February 12, 2006.

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