Shortwave Flux Closure Experiments at Nauru

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Introduction

The absorption and distribution of shortwave radiation in the atmosphere is one of the main drivers of the climate system. Through extensive satellite studies the Earth radiation budget has been well characterized and general circulation model (GCM) simulations of top of the atmosphere fluxes generally agree well with observations (Li et al. 1997). However, measurements and model estimates of the amount of shortwave radiation absorbed in the atmosphere differ by up to 30 W/m^2 (Li and Moreau 1996). In order to perform realistic climate simulations, this problem needs to be resolved. One way of understanding the uncertainties in our knowledge of how clouds affect shortwave radiation is by performing a flux closure experiment in which observed cloud and atmospheric properties are input to a radiative transfer model and calculated fluxes are compared to observed fluxes. The flux closure concept is a useful way of testing both model and cloud retrieval physics and assumptions.

We use a data set from the Atmospheric Radiation Measurement (ARM) Program's site on the island of Nauru in the tropical Pacific and a state-of-the-art radiative transfer model to perform a shortwave flux closure experiment. The overall goal of the experiment is to determine whether we can accurately model the statistics of the shortwave downwelling surface fluxes at Nauru during conditions of clear sky and liquid water clouds. We are also interested in investigating what level of cloud information is sufficient to predict these surface fluxes to a certain accuracy. In this preliminary study, we are using a small dataset and concentrating on gaining familiarity with the data, working out cloud property retrieval techniques, and understanding the uncertainties associated with the model and the observations.

Procedure

During each 30-minute period in which there are no radar-detected ice clouds or heavy precipitation, we retrieve one-minute resolution vertical profiles of liquid water content and effective radius from the Millimeter Wavelength Cloud Radar (MMCR) and Microwave Radiometer (MWR) for non-precipitating liquid clouds. Three weeks of MMCR data (from December 1998) were processed, resulting in approximately 7000 minutes of cloud retrievals.

For each 30-minute period, we retrieve vertical profiles of temperature, relative humidity, and pressure from the radiosonde launched nearest in time. For each minute, the total column water vapor is scaled by the retrieved water vapor from the MWR, both to correct for the dry bias present in many Vaisala sondes, and to provide higher time resolution of water vapor. We include layers of oceanic and sulfate aerosols with a constant optical thickness of 0.054 and a vertical extinction profile derived from preliminary micropulse lidar (MPL) retrievals (personal communication from James Campbell, 1999).

We perform one-dimensional broadband solar radiative transfer on the retrieved profiles at one-minute intervals using the Spherical Harmonics Discrete Ordinates Method (SHDOM) model (Evans 1998). The broadband calculation uses the new correlated k-distribution based on the shortwave version of the Rapid Radiative Transfer Model (RRTM) (Mlawer et al. 1997), which contains 13 bands in the shortwave from 2600 cm^{-1} to 50000 cm^{-1}, each with 16 k's. Cloud and aerosol optical properties are calculated for each band using Mie theory.

Modeled shortwave downwelling surface fluxes are compared to observed fluxes. The observed total downwelling flux is computed as the "component sum" of the diffuse flux from the Precision Spectral Pyranometer (PSP) and the direct flux from the Normal Incidence Pyrheliometer (NIP) times the cosine of the solar zenith angle (Michalsky et al. 1999).

Cloud Property Retrieval Methods

Retrieving vertical profiles of cloud properties, such as liquid water content and effective radius, needed for radiative transfer is an ongoing research area (e.g., Dong et al. 1998; Sassen et al. 1999). We examine several retrieval methods that use the MMCR alone or combine it with the MWR to add the constraint of total liquid water path (LWP) to the retrieval. Each of these methods contain several assumptions that may not be adequate/true for tropical cumulus clouds.

The first method ("MWR only") uses the MMCR only for cloud boundaries and assumes an adiabatic profile of liquid water content with total LWP equal to that retrieved from the MWR. This is the simplest method, and includes no observed information about the vertical structure of the cloud. The second method ("MMCR only") assumes a lognormal droplet distribution with fixed number concentration ($N = 75$ cm^{-3}) and distribution width ($\sigma = .35$). Liquid water content and effective radius are derived at each range gate from relationships between the radar reflectivity and moments of the lognormal droplet distribution. This method captures the vertical variability in the cloud, but assumes a fixed number concentration is representative of all clouds in the region.

The third method is based on the work of Frisch et al. (1995), and combines the MMCR and the MWR by assuming a lognormal droplet distribution with $\sigma = .35$ and N constant with height, where N is constrained by the total LWP from the MWR. This method has the advantage of including both the vertical variability and the constraint of the total LWP from the MWR. However, this method was originally developed for mid-latitude stratus clouds, and may not be appropriate for tropical cumulus.

Figure 1 shows observed cloud properties for some typical shallow cumulus at Nauru. The top panel shows retrieved cloud base and top heights from the MMCR and MPL. The bottom panel shows the LWP retrieved from the MWR and the vertically integrated reflectivity from the MMCR. There is an obvious bias in the LWP retrievals, with values of over 50 g/m^2 during clear-sky periods. There is also a slight offset in the peaks of the LWP and integrated reflectivity which may be due to the physical offset of the two instruments or to timing errors in the computer system of one of the instruments.

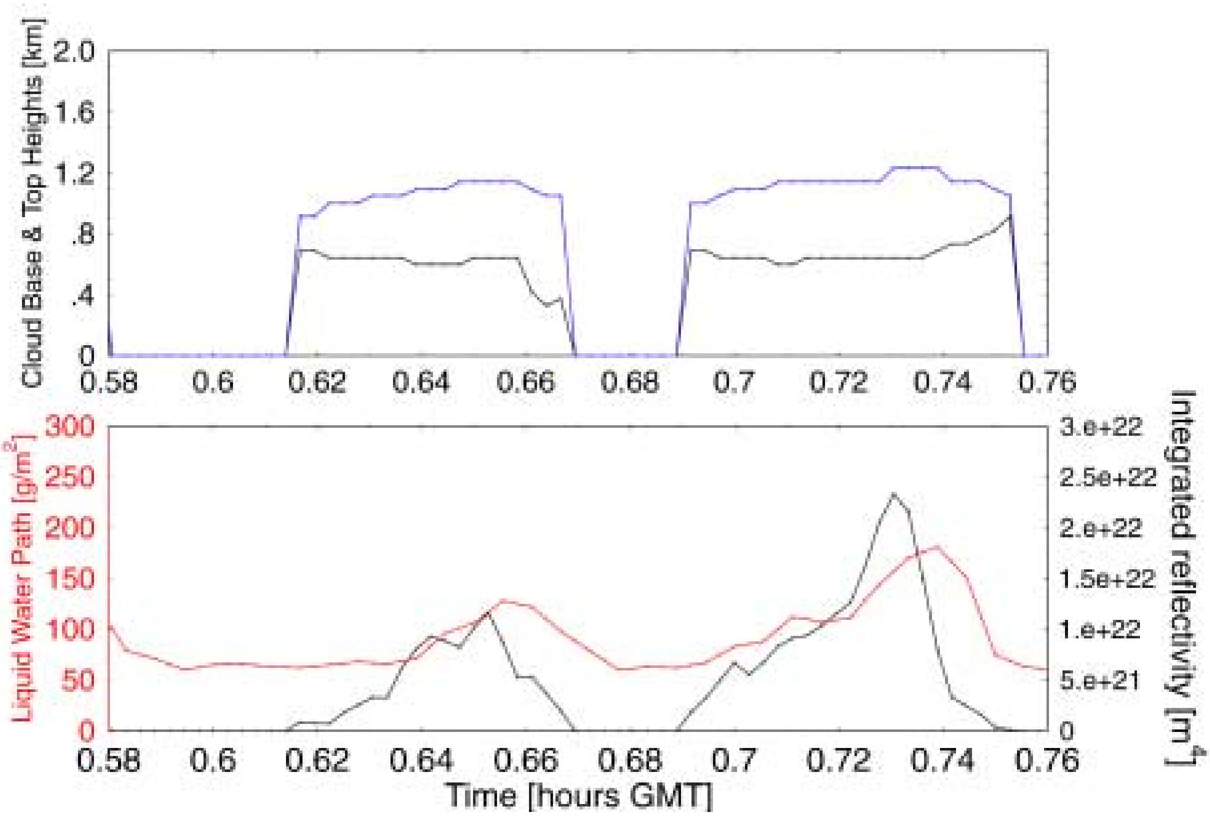

Figure 1. a) Cloud base and top heights from MMCR/MPL for typical cumulus clouds at Nauru. b) Liquid water path from MWR and vertically integrated reflectivity from MMCR for above clouds.

Figure 2 shows retrieved cloud properties for the retrieval methods described above. The Frisch method has difficulty near cloud edges, with retrieved number concentrations greater than 5000 cm^{-3}. The large retrieved values near cloud edges in this method are due primarily to the LWP offset; small values of reflectivity near the cloud edges are associated with unreasonably large LWP values, and there is no constraint to limit the number concentration to reasonably expected values. The adiabatic (MWR only) and MMCR only methods seem to provide reasonable retrievals, but they do not take full advantage of both instruments and rely quite heavily on assumptions about the number concentration or adiabatic shape of the clouds which might not be true.

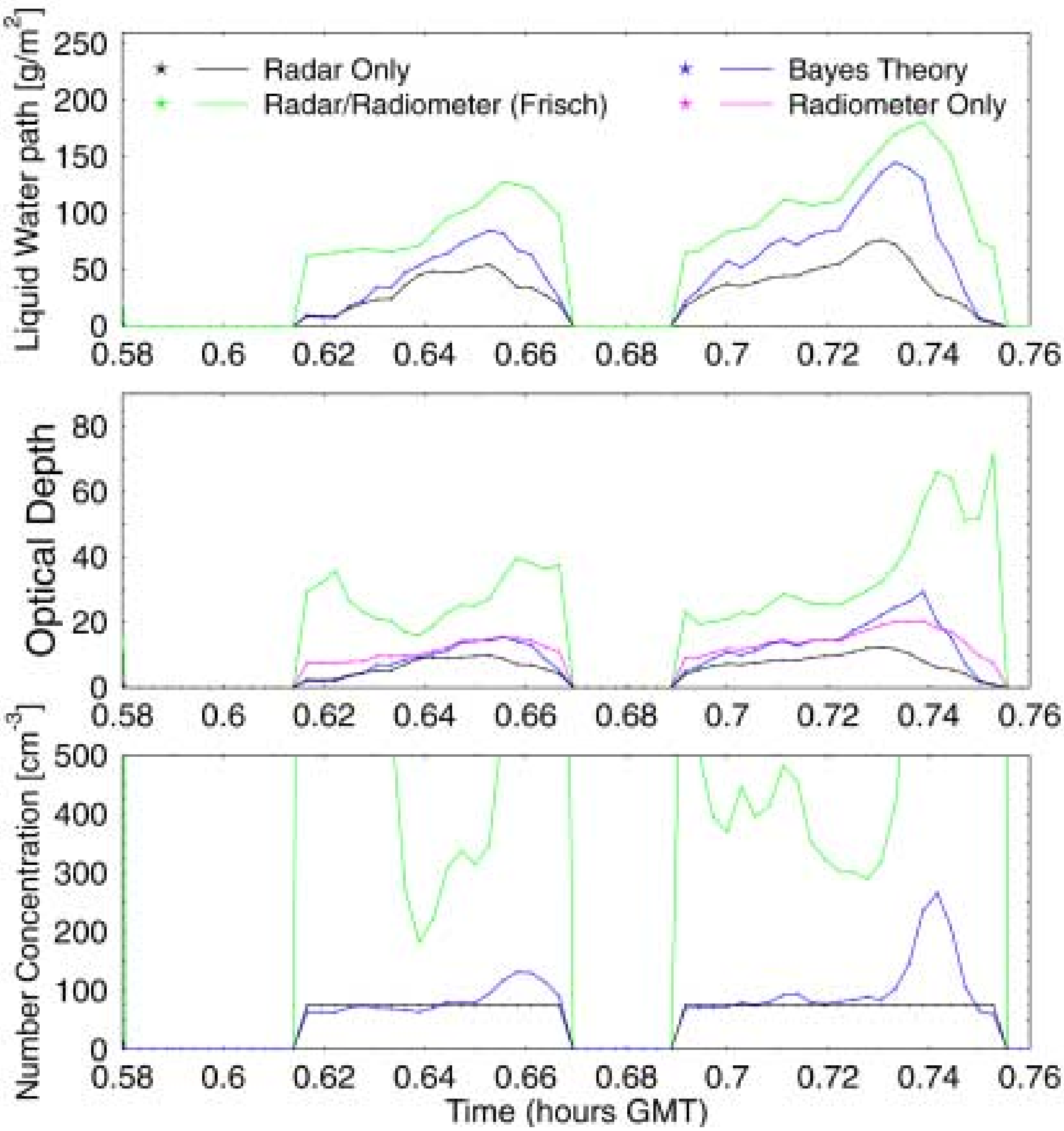

Figure 2. Retrieved LWP from each of the retrieval methods for the above clouds. b) Retrieved optical depth from each method. c) Retrieved number concentration.

Bayes' Theory Retrievals

In order to improve cloud property retrievals, we desire a combined instrument method that can take into account both the uncertainties in the observed variables and known physical information about the type of clouds being modeled to avoid unrealistic retrievals. We introduce a new cloud retrieval method based on Bayes' theorem of conditional probability:

$$p(x \mid y) = \frac{p(y \mid x)p(x)}{\int p(y \mid x)p(x)\,dx}.$$

In the retrieval method we define x as the vector of cloud properties we wish to retrieve (the parameters r_o, σ, and N of a lognormal droplet distribution), and y as the vector of observables (LWP from the MWR and integrated reflectivity from the MMCR). Then Bayes' theorem relates the probability, p(x|y), of retrieving a set of cloud properties, x, given a set of observables, y, to the prior probability distribution of the cloud properties, p(x), and the forward probability distribution of the observables given the cloud properties, p(y|x).

To develop a prior distribution for shallow tropical cumulus clouds, we use in situ Forward Scattering Spectrometer Probe (FSSP) cloud droplet size distributions measured during the Small Cumulus Microphysics Study over Florida. We create a prior distribution of cloud properties (r_o, σ, and N) by matching the 2nd, 3rd, and 6th moments of the FSSP droplet distribution. We use these particular moments of the droplet distribution since the 2nd moment is related to optical depth or extinction and the 3rd and 6th moments are related to the observed variables, LWP, and radar reflectivity, respectively. We retrieve a vector of cloud properties (r_o, σ, and N) for each point where the FSSP total number concentration is > 10 cm^{-3}. Bayes' theorem is then used to calculate the probability of cloud properties given the observed LWP and integrated reflectivity (IZ). The retrieved cloud properties are the mean of the probability distribution:

$$< x >= \int x\, p(x \mid y)\,dx = \frac{\int x\, p(y \mid x)p(x)\,dx}{\int p(y \mid x)p(x)\,dx},$$

integrated over 100,000 random vectors of cloud properties.

Using the Bayes' theory method, uncertainty in the observed variables can be included by modeling the forward probability, p(y|x) as a multi-dimensional normal distribution with mean y_{sim} and standard deviation σ_y,

$$p(y \mid x) = N(y - y_{sim}; \sigma_y).$$

In this equation, y_{sim} is a vector of the simulated value of the observables calculated for each point (r_o, σ, N) in the prior distribution from the relationships between the parameters of the lognormal distribution and the reflectivity and liquid water content, and σ_y is a vector of uncertainties associated with each of the observed variables.

Figure 2 also shows the retrieved cloud properties for the Bayes' theory retrievals. The retrieved number concentrations and optical depth have reasonable magnitudes and the shape of the optical depth and number concentration curves follow the observed variables more closely than any of the other methods. Including the uncertainty in the observed LWP, as well as the prior information, allows the Bayes' method to produce realistic retrievals even near the cloud edges.

Results

Due to the unrealistic number concentrations and optical depths retrieved by the Frisch algorithm, we did not perform radiative transfer on these retrievals. For the other 3 retrieval methods, Table 1 shows the results of the radiative transfer calculations. The model calculations tend to overestimate the observed surface flux. However during December 1998 (which was the first month of observations at Nauru), the pyranometer domes were not cleaned daily and so the observed surface fluxes are probably biased low due to the presence of sea salt on the dome during the study period (TWP Site Scientist Data Report for November 1998 - December 1998). The MWR only method has the lowest average difference of the three methods, but this is probably due to a cancellation of errors between the sea salt on the pyranometer domes and the overestimate of liquid water path by the MWR.

Table 1. Radiative transfer results for three different cloud retrieval methods.

Retrieval Method	Flux Difference	30-Minute RMS Error
Radiometer Only	11 W/m^2	71 W/m^2
Radar Only	36 W/m^2	70 W/m^2
Bayes Theory	31 W/m^2	69 W/m^2

Figure 3 shows the rms errors for each of the three methods as a function of averaging time. Due to the extreme variability of the broken cumulus clouds over Nauru and the differing fields of view of the instruments, averaging over at least several hours is required to reduce rms errors to the level of the bias.

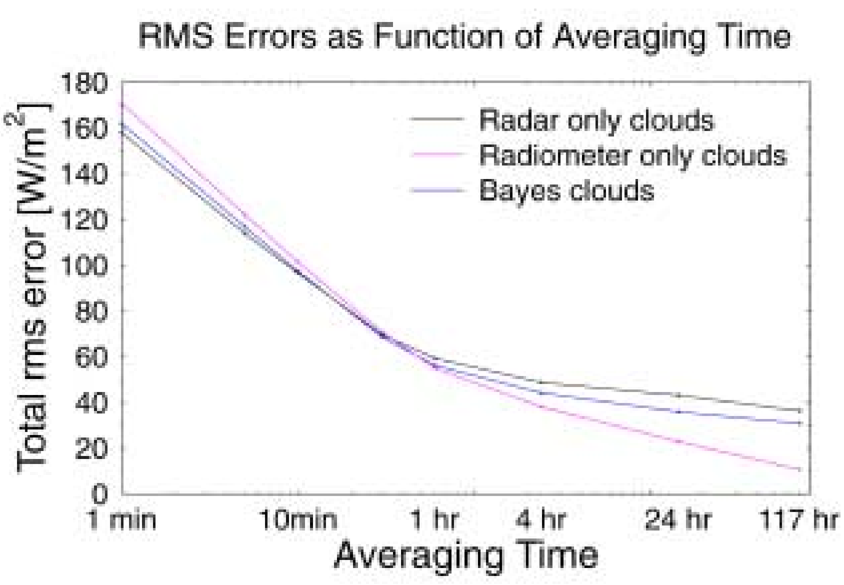

Figure 3. RMS errors as a function of averaging time.

Conclusions and Future Work

Using the current dataset, the radiative transfer model tends to overestimate the observed surface flux. We believe that this is in part due to biases in the observed fluxes and that the model overestimate will be reduced when more accurate datasets are available. There are also some uncertainties in the inputs to the radiative transfer model. To improve these input properties, we hope to incorporate results from the Nauru '99 field experiment such as in situ aerosol properties, aerosol optical depths, and surface albedo measurements. We also plan to process more radar data so that we can compare the statistics of modeled and observed fluxes over longer time periods.

The Bayes' theory method seems a promising way to include both a priori knowledge about cloud microphysics and uncertainty in observed parameters in a retrieval method. We plan to extend the Bayes' method to retrieve cloud properties at each range gate, and to test it against in situ observations of cloud properties. We also hope to include information from an optical probe, such as the 2D Cloud probe, in addition to the FSSP to obtain information on small raindrops or drizzle to include in the prior distributions.

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