Use of Cloud and Radiation Testbed Measurements to Evaluate Cloud Cover and Convective Parameterizations

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Abstract

We have used temperature and humidity soundings and radiation measurements from the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) site in northern Oklahoma to evaluate an improved cloud cover algorithm. We have also used a new single-column model cumulus parameterization to estimate convective heating and moistening tendencies at the CART site. Our earlier analysis of cloud cover showed that relatively dry atmospheres contain small cloud amounts.

We have found numerous periods during 1993 where maximum relative humidities within any layer of the atmosphere over the CART site are well below 60-80%, yet clouds are clearly reducing shortwave irradiance measured by a rotating shadowband radiometer. These ARM measurements support our earlier findings that most current climate models probably underestimate cloud coverage when relative humidities fall below the threshold humidities where clear skies are assumed.

We have applied a "detraining-plume" model of cumulus convection to the June 1993 intensive observation period (16-25 June 1993). This model was previously verified with GARP[(a)] Atlantic Tropical Experiment (GATE) measurements. During the June intensive observing period (IOP), relative humidities over the CART site are typically 20% less than tropical Atlantic GATE relative humidities. Our convective model calculates that evaporation of convectively induced cloud and rainwater plays a much more important role in the heating and moistening convective tendencies at the drier CART location. In particular, we predict that considerable cooling and moistening in the lower troposphere should occur due to the evaporation of convectively initiated precipitation.

(a) GARP - Global Atmospheric Research Program.

Cloud Cover and Radiation at CART

Clouds significantly perturb radiative processes in the atmosphere, yet they occupy areas considerably smaller than the grid size of most climate models. Therefore, most atmospheric columns within climate models are only partially covered by clouds. During climate simulations, fractional cloud coverage is usually diagnosed from model-calculated relative humidity. Figure 1 shows a summary of several algorithms for calculating cloud cover. In a recent investigation of cloudiness, Walcek (1994) showed that small cloud amounts are present at nearly all relative humidities, especially in the middle troposphere. In contrast, most climate models employ "critical" relative humidities ranging from 60-80% below which totally clear skies are specified. The broader shaded area on Figure 1 shows a compilation of cloud cover and relative humidity measurements Walcek compiled at a particular atmospheric level during a midlatitude cyclone over the eastern United States. The most significant difference between climate model formulations and these measurements is the persistence of relatively small cloud amounts at humidities well below the "cutoff" humidities used by climate models.

During most of 1993, routine measurements of relative humidity have been performed at the ARM CART site in northern Oklahoma. Additionally, a rotating shadowband radiometer has been recording solar irradiance, which is strongly modulated as clouds pass over the central facility. These radiometer measurements can be used as a crude indicator of partial cloudiness. We have found numerous periods when radiosondes launched from the central facility report humidities well below the "cutoff" humidities used by climate models throughout the depth of the atmosphere, yet downwelling shortwave irradiance is obviously perturbed by clouds.

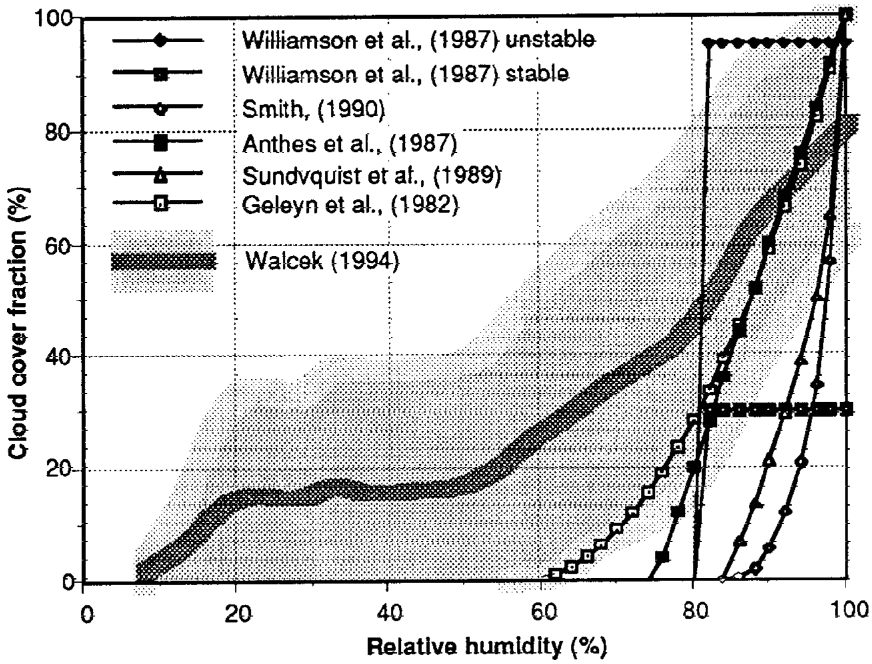

Figure 1. Fractional cloud coverage as a function of relative humidity at 800 mb according to various formulations used by meso- and global-scale atmospheric models. Shaded curve and area shows mean ± one standard deviation of 3DNEPH cloud cover at specified relative humidity during five noon periods during 20-24 April 1981.

Figure 2 shows one example of this behavior. This figure plots downwelling irradiation as a function of time on 20 June 1993. Following a clear morning, intermittent clouds pass over the central facility from 16-19 UTC. Along the horizontal axis are heavy tick marks denoting the time when balloon sondes were launched, along with the maximum relative humidity measured during their ascent through the troposphere.

Figure 3 shows one sounding taken close to 18 UTC, a period when cloud cover was significant. The maximum relative humidity within this sounding is 62% at 850 mb. This humidity is well below the humidity where clouds are allowed to occur according to many climate models. We realize that this single measurement cannot be used unambiguously to evaluate cloud fractional coverage parameterizations, but we have found numerous such periods during the CART observation periods. These results, when viewed in the context of our earlier studies, suggest that small cloud amounts do occur at humidities well below the "cutoff" humidities currently used to assess climate change.

Evaluation of CART Measurements with Detraining Convection Model

Under conditionally unstable conditions, convection that cannot be resolved by larger scale atmospheric models significantly influences larger scale temperature, moisture, and momentum fields. These "neglected" motions must be accounted for, usually in a simplified or parameterized fashion. We have developed a conceptually new approach for simulating the integrated impacts of convective-scale processes within larger scale atmospheric models.

In our model, we assume that buoyantly accelerated motions are initiated by turbulent impulses within an atmospheric column. In unstable areas, turbulently "kicked" parcels will accelerate up according to the following equation of buoyant acceleration:

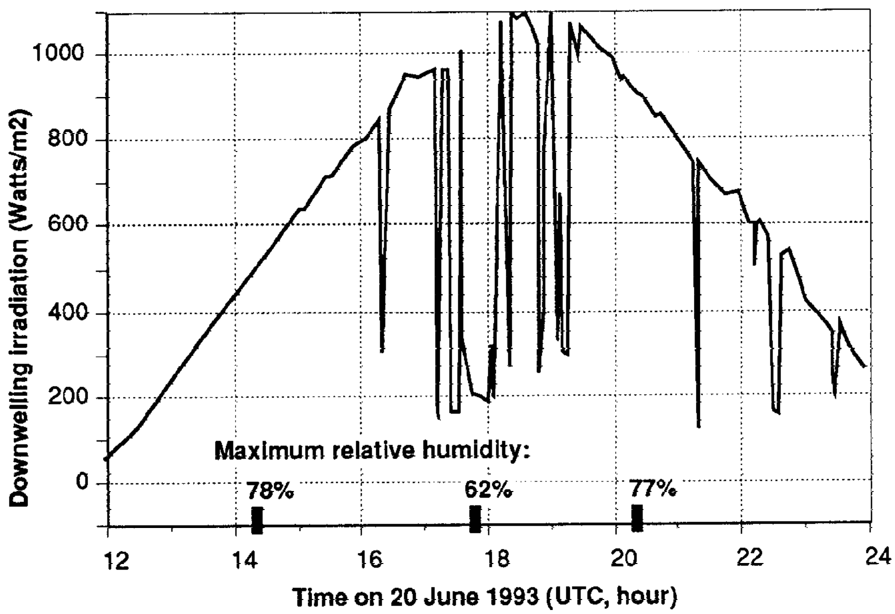

Figure 2. Downwelling irradiation measured by rotating shadowband radiometer at the ARM CART central facility in northern Oklahoma on 20 June 1993. Heavy ticks along horizontal axis correspond to times when balloon sondes were launched to measure vertical profiles of meteorology. Maximum relative humidities within each sounding are shown above each measurement time.

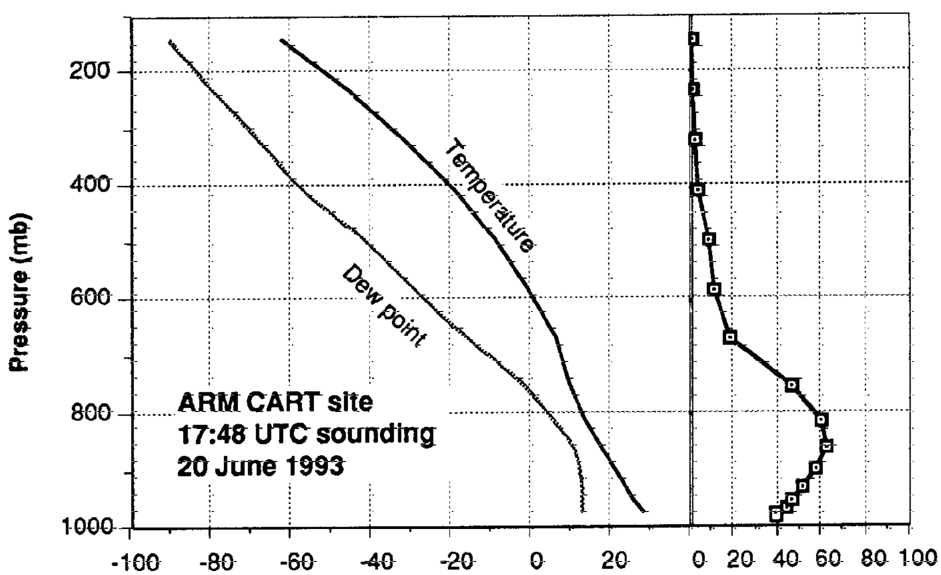

Figure 3. Vertical distribution of temperature and humidity measured at the ARM CART central facility in northern Oklahoma on 20 June 1993 at 17:48 UTC.

$$\frac{dw}{dz} = \frac{g}{w}\left[\frac{T_{vp} - T_{ve}}{T_{ve}} - q_l\right] \quad (1)$$

where w is the parcel vertical velocity, T_{vp} is the virtual temperature of the rising parcel, T_{ve} is the virtual temperature of the surrounding environment through which the parcel rises, and *g* is the gravitational acceleration. The condensed water content of the parcel (q_l) is the total water content (assumed constant during lifting) of the parcel minus the saturated vapor mixing ratio at any level above the lifting condensation level. The temperature and water vapor mixing ratio can be obtained by assuming dry followed by moist adiabatic ascent. As buoyantly accelerated parcels rise, they mix with their surrounding environment. Previous mass-flux models of cumulus convection (e.g., Arakawa and Schubert 1974) assume that air from outside the cloud is "entrained" into cumulus updrafts and carried upward. Such a model of entraining plumes may reasonably simulate the behavior of **dry** plumes. However, in moist plumes where condensation and evaporation are occurring, Warner (1970) demonstrated that such a simplified conceptualization of convective dynamics is inconsistent with observations.

Since entrainment and mixing of dry air into a cloud usually produce negatively buoyant mixtures, these mixtures will decelerate and "detrain" from the convective plume. Based on this physical principle, we propose that moist convective plumes **detrain** mass as they rise and mix through a drier environment. Mathematically, this can be expressed as the following equation describing the mass (M) or mass flux of a rising parcel or plume of air

$$\frac{dM}{dz} = -\frac{M}{l_d} \quad (2)$$

where l_d is a characteristic "detrainment length" that determines the rate at which a buoyant plume "sheds" mass as it rises. We assume that l_d is locally defined, determined by the details of how a moist plume interacts with the environment into which it is growing at each level. For example, detrainment lengths should be shorter (i.e., more detrainment) when environmental humidities are low, since drier air will induce more evaporation and produce more negatively buoyant mixtures as it commingles with a convective plume.

Figure 4 shows schematically the motions considered within conditionally unstable environments in our conceptual model of cumulus convection. Air that can accelerate upward under the influence of buoyant forces (as defined using Equation [1]) constitutes what is referred to as the "primary plumes." Air within the primary plumes is "shed" according to Equation (2). As detrained air at each atmospheric level mixes with its environment, various mixtures will accelerate upward or downward, depending on their buoyancy. We assume that a uniform distribution of mixtures is formed as air is shed from the "primary" updrafts. These mixtures constitute the "secondary plumes" shown in Figure 4, and these mixtures rise or sink to their level of neural buoyancy, again shedding mass along the way. All motions cease as these secondary plumes reach their level of neutral buoyancy. The net result of these motions is to redistribute air within a vertical atmospheric column. Redistributed air will transport heat, moisture, or any other trace constituents from the layer where these motions are initiated to the layers where these motions ultimately stop.

Condensed cloudwater is produced as air is vertically displaced by cloudy updrafts. Condensed water can either

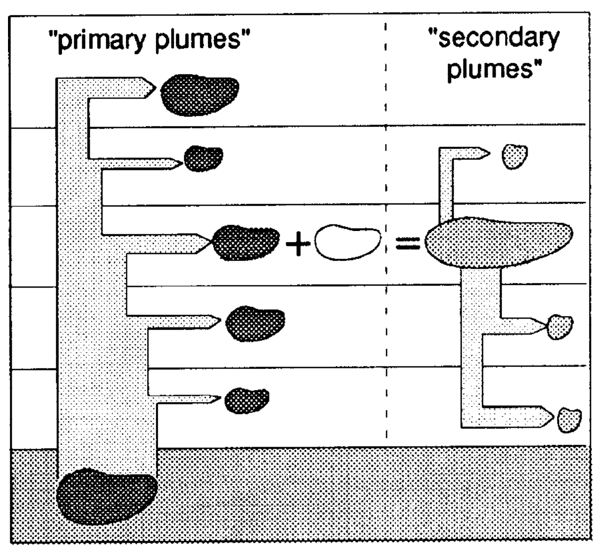

Figure 4. Schematic model of convective motions used to calculate tendencies in temperature and humidity in unstable environments.

evaporate or coalesce to form precipitation. We allow cloudwater to evaporate within a characteristic time that depends on the relative humidity of the layer where buoyantly displaced parcels rise. The formation of precipitation is calculated following Kessler (1969). If a given layer of the atmosphere is near 100% humidity, then cloudwater deposited into that layer will most likely form precipitation. In contrast, condensed water deposited into a drier layer will be more likely to evaporate, leading to a net moistening of the layer.

Equations (1-2), together with buoyant acceleration information describing the range of mixtures that can occur as convective plumes rise and mix with their environment, enable us to estimate the sources and destinations of all buoyantly induced motions that occur within an unstable column of the atmosphere and, thus, to construct a "transilient" matrix (Stull 1988) to describe the local temporal tendencies of heat, moisture, and other conserved tracers.

This convection model has been evaluated and tuned using measurements taken during the GATE tropical measurement program. From that evaluation, we learned that an approximately fixed fraction of the mass within any unstable layer (defined as any layer where parcels can accelerate up from that layer following a small vertical velocity impulse) left that layer per unit time. GATE measurements show that during periods when the upper troposphere is relatively dry, convective activity is suppressed, suggesting that buoyant plumes detrain their mass at lower levels, yielding less lifting, condensation, and precipitation. In the context of our model, we specify relatively short detrainment lengths of 1-2 km when environmental humidities are less than about 60%. However, when the middle troposphere was closer to saturation (>80 Rh), our model required relatively long detrainment lengths (>10 km). When approximately 1.5% to 4% of the mass of any unstable layer exits the layer each hour in convective plumes, we can reasonably calculate the precipitation rates, heating tendencies, and moisture tendencies measured during GATE. Figure 5 shows the heating rates measured and calculated during the entire GATE phase 3 period (29 Aug - 18 Sept 1974).

Figure 5 shows that this model of convective activity can reasonably simulate cumulus activity under tropical conditions. We now apply this identical model to 10 days of soundings measured in northern Oklahoma during June 1993 as part of one IOP of the ARM CART program. The CART curve shows the 10-day average of the convective heating tendency.

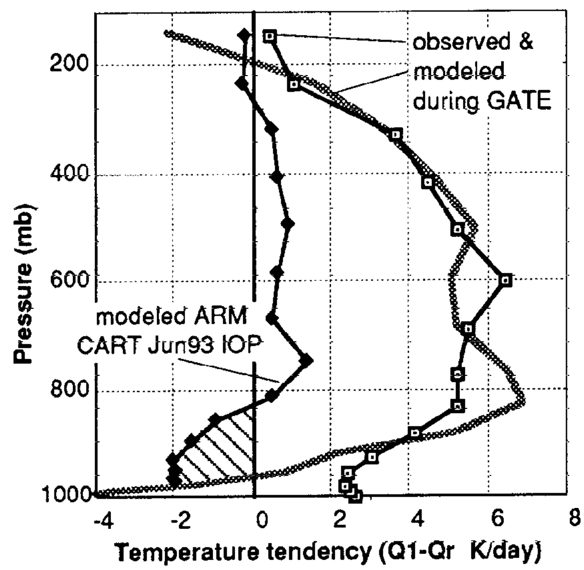

Figure 5. Convective heating rates as a function of height in the atmosphere over the GATE and CART sites. Stippled area denotes significant cooling due to evaporation of falling precipitation.

At this time, we do not have observations of either the heating tendencies or precipitation available to evaluate our model calculations. However, we do find considerably less convective activity at the CART site during this time relative to the GATE period. More interestingly, we find significant cooling of the lower troposphere by convective processes that did not occur during GATE. We attribute this to evaporation of precipitation falling through a much drier atmosphere.

Figure 6 compares the vertical distributions of relative humidity during GATE and the June 1993 ARM CART period. At the continental Oklahoma site, relative humidities are lower by approximately 20% at all levels. In a drier atmosphere, greater evaporation of cloudwater will probably lead to greater detrainment (thus smaller "detrainment lengths" within our model) from convective plumes. Evaporation of precipitation in a dry atmosphere will moisten and cool the lower troposphere. Both of these evaporation effects would probably be enhanced at the Oklahoma site relative to the tropical GATE site.

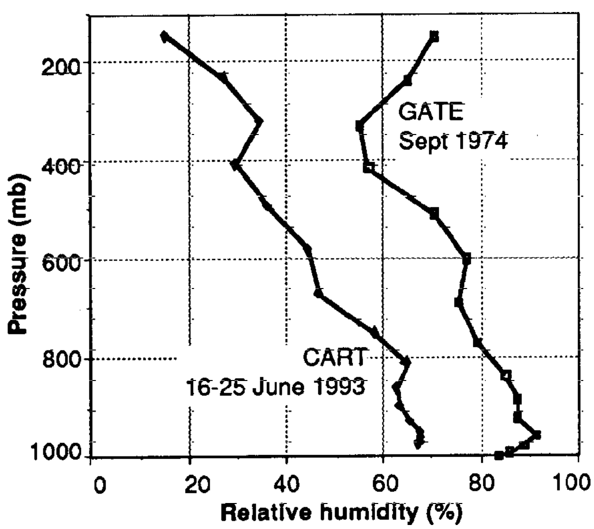

Figure 6. Relative humidity during GATE (September 1974, tropical Atlantic) and during 16-25 June 1993 at the ARM CART central facility in northern Oklahoma.

Discussion and Conclusions

Balloon-borne soundings and surface-based radiation measurements from the ARM CART site in northern Oklahoma show that relatively dry atmospheres contain significant cloud cover. These ARM measurements support our earlier findings that most current climate models probably underestimate cloud coverage when relative humidities fall below the threshold humidities where clear skies are assumed.

We have applied a "detraining-plume" model of cumulus convection to the June 1993 IOP. This model was previously verified with GATE tropical measurements. During the June IOP, relative humidities over the CART site were typically 20% less than GATE relative humidities in the tropical Atlantic. Our convective model calculates that evaporation of convectively induced cloud and rainwater plays a much more important role in the heating and moistening convective tendencies at the drier CART location.

In particular, we predict that considerable cooling and moistening in the lower troposphere under convective conditions should occur due to the evaporation of precipitation. Unfortunately, we do not yet have access to measurements of precipitation or convective heating or moistening tendencies to verify whether our model is accurately diagnosing convective processes. As measurements become available, we plan to further evaluate and improve the convective model so that it consistently reproduces both tropical oceanic (GATE) and continental (CART) conditions.

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