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FINAL Technical Progress Report

**Use of Cloud Observations and Mesoscale Meteorology Models to
Evaluate and Improve Cloud Parameterizations**

1 December 1991 - 30 September 1996

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1. Project Statement of Work

The main goal of this research effort is to improve methods for calculating cloud cover within climate models. Cloud cover observations are being used with standard meteorological observations to improve our ability to diagnose cloud cover in climate models. Until now, cloud cover and heights have been diagnosed from the U. S. Air Force RTNEPH and 3DNEPH archive, although recent CART measurements are also being analyzed. Improved cloud cover formulations have been compared with existing climate model algorithms.

Recently, we are also refining and validating an innovative Single Column Model (SCM) cumulus parameterization for calculating heating and moistening tendencies, and precipitation rates attributable to subgrid-scale convection not resolved by climate models. This SCM will be tested and evaluated using tropical convective measurements (GATE) and we will also use incoming measurements from the Oklahoma ARM site. Further development and testing of this SCM could improve our ability to predict convective effects in climate models. We will quantify the influence of convection on cloud cover using convective measures derived from this SCM.

The output of this research will be a family of validated algorithms for assessing cloud cover under a variety of stable, unstable, continental or oceanic conditions, and an improved cumulus parameterization scheme.

2. Project Progress:

1 Dec. 1991 - 30 Sept. 1996

During this research program, we have extrapolated the findings from our investigation of the Air Force 3DNEPH and RTNEPH (summarized in Walcek, 1994) to the incoming CART measurements from the Oklahoma site. Among our continuing investigations:

- Implementing an improved cloud cover algorithm in a mesoscale meteorology model and performing various sensitivity studies;
- Additional investigations of the influence of resolvable-scale upward motions on cloud cover;
- Evaluation of cloud cover algorithms using the Oklahoma CART measurements;
- Preliminary testing of a convective parameterization at the CART site;
- Testing the horizontal resolution dependence of our convective parameterization.

Each of these areas will be discussed in more detail here.

Mesoscale meteorology model studies - We have performed a series of multi-day simulations of atmospheric processes using an updated version of the NCAR MM4 mesoscale meteorology model. We have incorporated the improved cloud cover algorithms derived from earlier years of

this study, now published in Walcek (1994). These cloud cover algorithms were found to significantly *increase* the cloud cover used for calculating terms of the surface energy and water budgets. This increased cloud cover had the effect of significantly decreasing calculated afternoon temperatures and evaporation rates, while increasing night-time temperatures. A more interesting factor was our finding that the method for vertically aggregating cloud cover was a critical factor for the numerical treatment for clouds in climate models. The base version of the MM4 uses cloud cover from three generic layers (low, middle, and high clouds), and the optical depth and transmittance properties are assigned from a look-up table for each of these broad categories of clouds. When aggregating, it is assumed that these cloud layers randomly overlap.

Using the Air Force cloud data, we were able to accurately vertically aggregate cloud observations, and thus provide reliable estimates of cloud cover at *any* model or atmospheric layer. For our mesoscale simulations, we used a 15-level version of the MM4, and could thus explicitly estimate cloud cover at any level. However, this additional vertically-resolved cloud cover information could not necessarily be used with the existing radiative algorithms since the existing algorithms were "tuned" to the original crude 3-cloud-layer treatment. We therefore investigated several alternate overlap algorithms for aggregating cloud cover within this meteorology model. In one study, we simply used the maximum relative humidity and cloud cover in the original crude three layers to calculate cloud cover using our improved algorithms, then provided this result to the subsequent radiation algorithm. In another study, we explicitly calculated cloud cover at each MM4 layer, and used cloud properties interpolated from the original look-up table to specify their radiative effect. Two sub-studies of this method were then performed: assuming maximum, random, or minimum overlapping between the 15 cloud levels.

2.1 Cloud cover algorithm - The basic conclusions of our analysis of cloud cover is currently being published in Walcek (1994), and is summarized in Fig. 1, which shows observed cloud cover at about 800 mb as a function of relative humidity measured at this level. Confirming previous researcher's "intuition", we found that relative humidity appears to be the best single parameter for predicting cloud cover. Several relative humidity algorithms used by existing climate models are overlaid on a set of observations aggregated during the passage of a midlatitude cyclone over the eastern U. S. (shaded gray area) in Fig. 1. For this study, vertical distributions of fractional cloud coverage and related meteorology observations were interpolated onto the identical three-dimensional grid consisting of 15 tropospheric levels at various horizontal resolutions ranging from (80 km)² to (800 km)².

Despite a considerable level of uncertainty, the observations compiled on Fig. 1 suggest that cloud cover decreases exponentially as humidity falls below 100%, a functional form that is significantly different than most climate model formulations. Cloud cover, f , appears to be related to relative humidity (Rh) by the following exponential relationship:

$$f = A \exp\left[-\frac{1 - Rh}{B}\right], \quad (1)$$

where A and B are height- and resolution-dependent parameters optimally chosen to match observations. Functional forms for parameters A and B are provided in Walcek (1994).

Many climate models specify cloud amounts less than reported by these observations when relative humidities are less than 90-95% during this analysis period. This is especially true in the middle troposphere (850-600 mb), where most algorithms specify zero cloud amounts at relative humidities below 60 - 80%, while observed cloud amounts range from 20-60% at these height and humidity ranges. At humidities close to saturation, current algorithms probably slightly overestimate cloud coverage.

Convective instabilities in the atmosphere can decrease or increase cloud coverage at particular heights and relative humidities. In the upper troposphere, cloud amounts are greater under convectively unstable conditions relative to stable conditions at high relative humidities. In the lower troposphere, high humidity environments where convection is possible contain lower cloud amounts relative to stable conditions at the same relative humidity, which may result from cumulus-induced subsidence of dry air into the lower troposphere under convectively unstable conditions.

Virtually all climate models employ "threshold" relative humidities below which cloud cover is always zero, and our analysis shows little observational support for this assumption. Previous observational analyses and modeling studies have actually extrapolated trends measured within relatively narrow and moist humidity ranges outside the ranges where measurements were available, thus generating a need for "threshold humidities". For example, Slingo (1980) noted a trend in low cloud cover when relative humidity was 65-90%. However, Slingo's cloud observations were limited to this relatively narrow humidity range, making it impossible to infer cloud cover under drier conditions. Simple extrapolation of the approximately linear trend at this higher humidity range suggested that cloud cover would vanish at a threshold relative humidity. In our study, we sampled cloud cover estimates under a much wider range of relative humidities at any atmospheric level, and in particular we sampled periods and areas when relative humidities are considerably lower than 70%. Thus, the observations presented here do not necessarily disagree

with previous observational studies, but these observations are gathered over a wider range of environmental conditions.

We have used temperature and humidity soundings and radiation measurements from the ARM CART site in northern Oklahoma to evaluate the cloud cover algorithms described above. A key difference between our observations and previous algorithms is that according to our analysis, relatively dry atmospheres contain small cloud amounts, whereas climate model formulations allow no clouds. We have found numerous periods during 1993 where maximum relative humidities within any layer of the atmosphere over the CART site are well below the 60-80% "threshold relative humidities" used by existing climate models, and yet clouds are clearly (no pun intended) reducing shortwave irradiance measured by a rotating shadowband radiometer.

Cloud cover and vertical velocity - continued our analysis of cloud cover and its relationship with related meteorological parameters using the U. S. Air Force cloud cover archive. We have developed resolution-dependent algorithms that can calculate cloud cover at any level of the troposphere using the averaged relative humidity of the layer that agrees with cloud cover reported by surface observers, aircraft, and satellite observations archived in the U. S. Air Force 3DNEPH archive. We are currently evaluating these cloud cover algorithms using the incoming ARM CART shortwave radiation measurements, and are attempting to ascertain the general applicability of our previous studies. We find that cloud cover algorithms used by current climate models underpredict cloud cover under dry conditions, and our analysis of cloud cover measurements shows that cloud amount increases with increasing humidity at all relative humidities. We see no clear evidence that cloud cover vanishes at a "critical humidity". Based on these initial comparisons, we feel that current climate models cannot adequately assess the *changes* in cloud cover that may result from small changes in relative humidity in a modified climate. Thus, a potentially important feedback between climate change and changes in cloud cover are probably not adequately simulated by current models of global warming.

Convective parameterization testing at the CART site - Atmospheres where convective motions are possible contain significantly different cloud cover than stable atmospheres. Thus, we began searching for measures of convective activity that could be used to quantify the effects of convection on cloud cover. Following the suggestion of Xu and Krueger (1991), we hypothesize that convective mass fluxes should be correlated with cloud cover. However, estimating convective mass fluxes is a complicated problem. In order to address this problem, we have developed an innovative approach to modeling cumulus ensembles. This model diagnoses convective mass

fluxes from local atmospheric structure, and can successfully simulate heating and moistening tendencies, and precipitation rates measured during GATE. The model and some preliminary results are presented here. Ultimately, we hope to use this model to diagnose convective mass fluxes that will be needed for inferring cloud cover.

We have developed a multi-stream model of convection for diagnosing vertical profiles of heat ($\partial T/\partial t$) and moisture ($\partial q_v/\partial t$) tendencies, and precipitation rates attributable to buoyantly-forced motions. Mass fluxes between atmospheric layers are calculated by assuming that buoyantly-accelerated plumes detrain mass as they rise, in contrast to conventional models that treat cumulus clouds as entraining entities. This parameterization has been evaluated using GATE measurements, and we find that periods of heavy convection are associated with deeper unstable layers, suggesting that approximately 2-3 % of the mass within unstable atmospheric layers is "lofted" per hour. In addition, our results suggest that cumulus updrafts more efficiently transport mass vertically in low shear, high humidity environments. Our parameterization includes effects associated with updrafts and downdrafts, cumulus-induced subsidence, and generation and evaporation of precipitation using relatively sophisticated treatment of microphysics. While our model makes no assumptions about larger scale forcings, the calculated heating and moistening rates attributable to convective processes naturally balance larger-scale destabilization tendencies. This detraining model is conceptually simpler yet more physically representative of actual cumulus ensembles, and may eventually yield more accurate treatment of convection within numerical weather prediction models.

Dynamics - In our model, buoyantly-accelerated motions are initiated by turbulent impulses of heat, moisture and vertical velocity. In unstable layers, turbulently-"kicked" parcels accelerate up according to:

$$\frac{dw}{dz} = \frac{g}{w} \left[\frac{T_{vp} - T_{ve}}{T_{ve}} - q_l \right], \quad (2)$$

where w is the parcel vertical velocity, q_l is the condensed water content of the rising parcel, T_{vp} and T_{ve} are the virtual temperature of the rising parcel and the surrounding environment, and g is the gravitational acceleration. Adiabatic properties are assumed for the calculation of the initial acceleration as well as the height to which buoyantly-dislodged parcels can potentially rise in an unstable column. As buoyantly-accelerated parcels rise, they mix with their surrounding environment. Previous mass-flux models of convection (e. g., Arakawa and Schubert, 1974) assume that air from outside the cloud is "entrained" into cumulus updrafts and carried upward.

However, in moist plumes where condensation and evaporation are occurring, Warner (1970) demonstrated that entraining models of convective clouds are inconsistent with observations. Due to evaporation of cloudwater, many mixtures of cloud and environmental air will be negatively buoyant, and will quickly separate from an upward-moving plume. This explains the typical cumulus cloud shape where the width of the cloud decreases with height. Thus we propose that moist plumes detrain mass as they rise through and mix with a drier environment. Mathematically, this can be expressed as the following equation describing the mass flux (M_c , $\text{kg m}^{-2} \text{h}^{-1}$) of an ensemble of convective updrafts:

$$\frac{dM_c}{dz} = -\frac{M_c}{l_d} \quad (3)$$

where l_d is a characteristic "detrainment length" that determines the rate of "shedding" of mass from an upward-moving plume. Many factors should influence l_d , but probably the most important is the relative humidity of the environment into which a convective ensemble grows. In a drier environment, greater evaporation of cloudwater will produce more negatively buoyant mixtures, leading to more "detrainment".

Horizontal resolution dependence of convective parameterizations - Any parameterization of subgrid-scale convective effects will contain an implicit resolution dependence, since the level of conditional instability in the atmosphere is inherently resolution dependent. If a particular convective parameterization is used in the identical physical atmospheric model only at a different horizontal or vertical resolution, The classical method for diagnosing instabilities in the atmosphere is to define Convective Available Potential Energy (CAPE) as the integrated temperature excess of a parcel of air lifted dry and moist adiabatically from near the surface to the upper troposphere. When averaged over a large enough area containing convective instabilities it is possible to have a conditionally stable sounding at all levels

3. Peer-reviewed Journal Articles, Conference Presentations, abstracts, resulting from this research effort:

3.1 Conference presentations and seminars -

Results of our research efforts have been presented at a variety of scientific forums. The following is a list of scientific meetings where ARM-sponsored research efforts were presented and acknowledged.

Walcek, C. J., 1992: Extrapolating cloud-scale microphysical, dynamic and radiative processes to global and climatic scales: how accurately to we know the fractional area of cloud coverage?

- Proceedings: WMO Workshop on Cloud Physics and Applications to Global Change. Toronto, Canada, August 1992.
- Walcek, C. J., 1992: Cloud cover and its relationship with relative humidity during a springtime midlatitude cyclone: some implications for climate models. Proceedings: 11th Conference on Clouds and Precipitation. Montreal, Canada, August 1992, vol 2, 1128-1131.
- Walcek, C. J. 1992: Parameterization of cloudiness in climate models. Invited seminar speaker, Department of Physics, Dalhousie University, Halifax, Nova Scotia, Canada, Nov. 1992.
- Walcek, C. J., 1993: Factors influencing regional-scale cloud cover: Investigations using satellite-derived cloud cover and standard meteorological observations. Extended Abstracts: 4th Symposium on Global Change Studies, specialty conference at American Meteorological Society Annual Meeting, Anaheim, CA Jan 1993.
- Walcek, C. J. 1993: Convection in RADM. Colloquium and Workshop on Multiscale Coupled Modeling. NASA-sponsored workshop, Calverton, MD, Feb 1993
- Walcek, C. J. 1993: Factors influencing regional-scale cloud cover: investigations using satellite-derived cloud cover and standard meteorological observations. Presentation and Poster, ARM Science Team Meeting, Norman OK, March 1993.
- Walcek, C. J., and H. Qi 1993: A cumulus parameterization scheme of detraining drafts. Extended Abstracts: 20th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, San Antonio, TX, May 1993, 345-348.
- Walcek, C. J. and H. Qi 1994: Use of CART measurements to evaluate cloud cover and convective parameterizations. Poster presentation, ARM Science Team Meeting, Charleston, SC, Feb. 1994
- Walcek, C. J., and H. Qi 1994: Cumulus clouds parameterized as detraining plumes. Extended Abstracts: 10th Conference on Numerical Weather Prediction, American Meteorological Society, Portland, OR, July 1994.

3.2 Peer-reviewed publications -

- Walcek, C. J., 1994: Cloud cover and its relationship to other meteorological factors during a springtime midlatitude cyclone. *Monthly Weather Review*, **122**, 1021-1035.
- Walcek, C. J. and E. Brankov, 1994: The influence of entrainment-induced variability of cloud microphysics on the chemical composition of cloudwater. *Atmos. Res.*, in press.