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Annual Technical Progress Report
to the
Department of Energy
Atmospheric Radiation and Measurement Program (ARM)
for Year 2:
1 Dec 92 - 30 Nov 93

Parameterization of GCM Subgrid Nonprecipitating Cumulus and Stratocumulus Clouds Using Stochastic / Phenomenological Methods

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1. Executive Summary

Our overall project goal is to relate subgrid-cumulus-cloud formation, coverage, and population characteristics to statistical properties of surface-layer air, which in turn are modulated by heterogeneous land-usage within GCM-grid-box-size regions. The motivation is to improve the understanding and prediction of climate change by more accurately describing radiative and cloud processes.

The first step of our research utilizes field observations to diagnose the behavior and physical characteristics of subgrid cumulus ensembles, and to formulate theories to explain these observations. The second step is to approximate the theories into a simplified parameterization that is appropriate for GCMs. In the third step we calibrate the parameters in this model against detailed field observations. These steps utilize detailed measurements of the statistics of turbulent air in the surface layer, as measured by specially instrumented aircraft. The result is a calibrated subgrid parameterization that can be employed in single-column models of a GCM. The fourth step of our research is to incorporate the parameterization into a simple single-column computer model, and to test and refine the parameterization against cloud observations made at the ARM-CART sites.

As of August this year, we have completed the first two steps. The resulting theories and parameterization framework are described in a paper we are writing. This is more than a parameterization of past work, because it has implications which could advance our fundamental understanding of boundary-layer cumulus processes. We have made significant advances in step three: the data analysis needed for the calibration. Model development under step four is just beginning.

2. Progress Report

a. Review of Progress from Last Year (Year 1 of the Grant).

Prior to the ARM-CART sites coming on line this summer, we have been using existing data measured by instrumented aircraft during the HAPEX (Hydrologic-Atmospheric Pilot Experiment, 1986) field experiment in France. Based on the work last year, we have discovered that most of the subgrid cumulus characteristics can be explained using the joint frequency distribution of height of the lifting condensation level (LCL) vs virtual potential temperature (θ_v) for surface-layer air measured along the low-altitude flight tracks. As presented in Fig 2a of the progress report from last year (and also in Figs 1a & c from last year, but for convective available potential energy CAPE instead of virtual potential temperature), these joint distributions can be quite complex over heterogeneous surfaces such as within typical GCM grid boxes over land.

We realized that instead of trying to examine the whole grid box at once, a better approach is to study the joint distributions over subregions of relatively homogeneous surface characteristics, parameterize them, and then rebuild the complexity within a whole grid box by compositing the many simpler parameterized distributions. The activities to do this, as well as the discoveries that came from it, filled year 2 of our grant work, which we describe in detail below.

b. Current Personnel

Prof. Roland Stull - P.I.
Ph.D. Meteorology Student: Qing Zhang (left during Jun 93 to get married) - research assistant (RA)
M.S. Computer Sci. Student: Joe Farrenkopf - project assistant (PA)
M.S. Meteor. Student: Kelly McNerney (took over from Qing Zhang in Jun 93) - RA
Undergrad. Computer Sci. Major: Rudy Moore - student hourly worker
Undergrad. Computer Sci. Major: Rizwan Qureshi - student hourly worker
Other grad students and staff were employed for a month or two to help as needed.

c. Activity Summary for the Current Year (Year 2)

In a nutshell, our activities included:

- Breaking GCM size regions into smaller segments that allow better parameterization.
- Development of a procedure to correct for inertial navigation drift errors in the aircraft data.
- Acquisition of more field experiment data, including:
  + aircraft data over the ARM-CART site flown by Steve Oncley; and
  + cloud-free cases from the HAPEX field experiment in France.
- Progress in modifying our data ingest program to handle net-CDF, the data format coming from the ARM-CART site.

- Modification and re-organization of our data analysis programs to handle both the HAPEX and the ARM-CART data.
- Formulation of a theory nicknamed "bigfoot" to explain the joint frequency distribution of lifting-condensation-level height (LCL) and virtual potential temperature (T) as a function of Bowen ratio and solar heating. This theory applies to surface-layer air over a large area such as a GCM grid box.
- Definition of potential cumulus coverage "CuP" that utilizes the joint frequency distribution for a GCM box to diagnose cloud cover.
- Formulation of a stochastic theory for the disposition of thermals rising from the surface layer over a heterogeneous surface. One outcome of this theory is the prediction of a new "overlap" layer of air between the well-known subcloud and cloud layers, in which both cloudy and cloud-free updrafts co-exist. Such a layer has an important impact on cumulus cloud interaction with the boundary layer, and on cloud coverage and cloud population characteristics.
- Initial coding of a simple single-column GCM boundary-layer model, within which the cloud parameterizations can be tested.

d. Activity Details for the Current Year (Year 2)

Early this grant year, Ms. Qing Zhang used maps of the HAPEX region to identify sub-regions of relatively homogeneous land-use. Based on the known ground track of the aircraft over these subregions, she split the HAPEX flight track into 12 segments, where each segment was classified into one of five land-use categories.

In order to segregate the aircraft data by flight segment, it because clear that the we needed very accurate information of the position of the aircraft. Unfortunately, drift in the airborne inertial navigation system resulted in inaccurate positional information being recorded with the meteorological data. As the drift was found to be quite variable and unpredictable during any one flight, we developed a manual technique to correct the navigation information based on known landmarks and flight events.

When the aircraft data was segregated into these navigationally-corrected segments, we found that the joint frequency distributions were rather compact and usually mono-modal, as desired. Such distributions will allow better parameterization for use in GCMs.

Stull attended the ARM science-team meeting in Norman, OK, during March 1993, and presented some of the preliminary results described here.

It became apparent from the data that heterogeneity in the surface-layer air resulted from land-use factors compounded with cloud-shading factors. Cloud shading factors were found to be difficult to separate from the other factors, given the nature of the field experiment data. A solution was devised to measure the land-use factors during cloud-free days, to then assume these factors change little during a period of a few days, and then subtract their effects on subsequent cloudy days to yield the cloud-shading effects.

To this end, we acquired from the National Center for Atmospheric Research (NCAR) cloud-free aircraft data that was archived from the HAPEX experiment. As this data was in a slightly different format than that of the previously acquired data, Kelly McNerney rewrote our data reduction computer programs and also took the opportunity to reorganized the programs.

To expedite processing of the massive amounts of aircraft data, we found it necessary this year to buy a 1.2 Gbyte hard disk to provide temporary storage. The processed files are much smaller, and are then archived onto DAT tapes purchased last year.

In late Spring before Ms. Zhang left to get married, she trained Ms. Kelly McNerney to take over the data analysis project. Kelly McNerney also got married this August, but will return to work on this research.

As we studied the segmented frequency distributions, we saw that the distributions often had oval shapes with major and minor axes that sometimes switched orientation from segment to segment. To try to explain this, Stull developed a theory to show how heterogeneous land use and cloud-shading might causes variations of temperature and humidity in the surface layer, leading to the distributions we observed. As some of the observed distributions had shapes that looked somewhat like a footprint, we nicknamed this theory "bigfoot".

Meanwhile, Dr. Steve Oncley at NCAR flew the NCAR King Air aircraft over the ARM-CART site in Oklahoma as part of his calibration efforts during Fall 1992. We communicated our needs to him in advance (attending the ARM science team meetings paid off), so he modified his flight plan slightly to measure turbulence data in the surface layer. While limitations in his budget prevented flights over the whole CART region, his data is an important first step in order to calibrate the subgrid cumulus formulation for the particular heterogeneous surface in Oklahoma. We have acquired this aircraft data from NCAR, but have delayed analysis of it until we finish learning all we can from the HAPEX data.

Eventually, we hope to parameterize these relationships as a function of land-use, so that satellite-based land-use inventories such as that collected by Fairly Barnes (another pay-off from the ARM meeting) can be used to estimate the joint frequency distribution, instead of having to fly aircraft over each GCM grid surface.

During early June 93, Stull traveled to England to report on cumulus cloud research to a special Boundary-Layer Cloud Parameterization workshop organized by ECMWF. A workshop paper resulting from this meeting is attached as an appendix. Stull also participated in the ARM-proposal review panel in Denver later that same month.

When Qing Zhang and Kelly McNerney used the HAPEX data to make predictions of forced and active cloud cover, they found some occasions when forced and active clouds could not be adequately distinguished. By investigating this behavior we have come to understand that there is an "overlap" layer between the cloud and subcloud layer, and that this overlap layer is related to cloud activity and coverage.

Stull is currently developing a theory to explain this behavior. As it turns out, this theory has the potential to not only explain cloud onset time and coverage, but might also be able to explain the heretofore unparameterizable shape parameters for the lognormal cloud-size distributions characteristic of cumulus populations.

Rudy Moore and Rizwan Qureshi have been writing graphics software to enable us to plot and overlay the hundreds of thousands of data points associated with aircraft turbulence data. Except for a few minor bugs which are being squashed, version 1 of this program was complete and fully functional as of about May 93. This program was used extensively by Qing Zhang and Kelly McNerney for their data analysis. In June 93, Rudy and Rizwan started writing version 1.5, which will incorporate the capability to ingest net-CDF files, the file format used for the ARM-CART data. As of August 93, the net-CDF ingest code is almost operational, and a user interface for it is being build.

During August 93 we acquired the workstation that was in the budget for this year. Included was a color printer to allow us to display the frequency distributions.

Joe Farrenkopf recently switched to be a computer science MS-degree major, after finishing his MS in Meteorology. He has begun to develop a simple single-column boundary-layer model, within which we can test our various cumulus parameterizations. He has also been in charge of maintaining our hardware and software.

e. Results to date

Fig 1 shows the flight track over the HAPEX region, split into 12 segments of roughly homogeneous land-use. A similar segregation will be made for aircraft data over the ARM-CART site in Oklahoma.

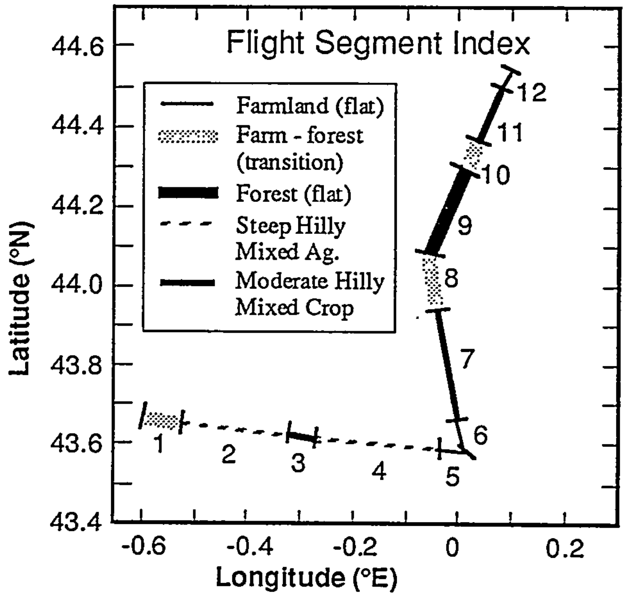
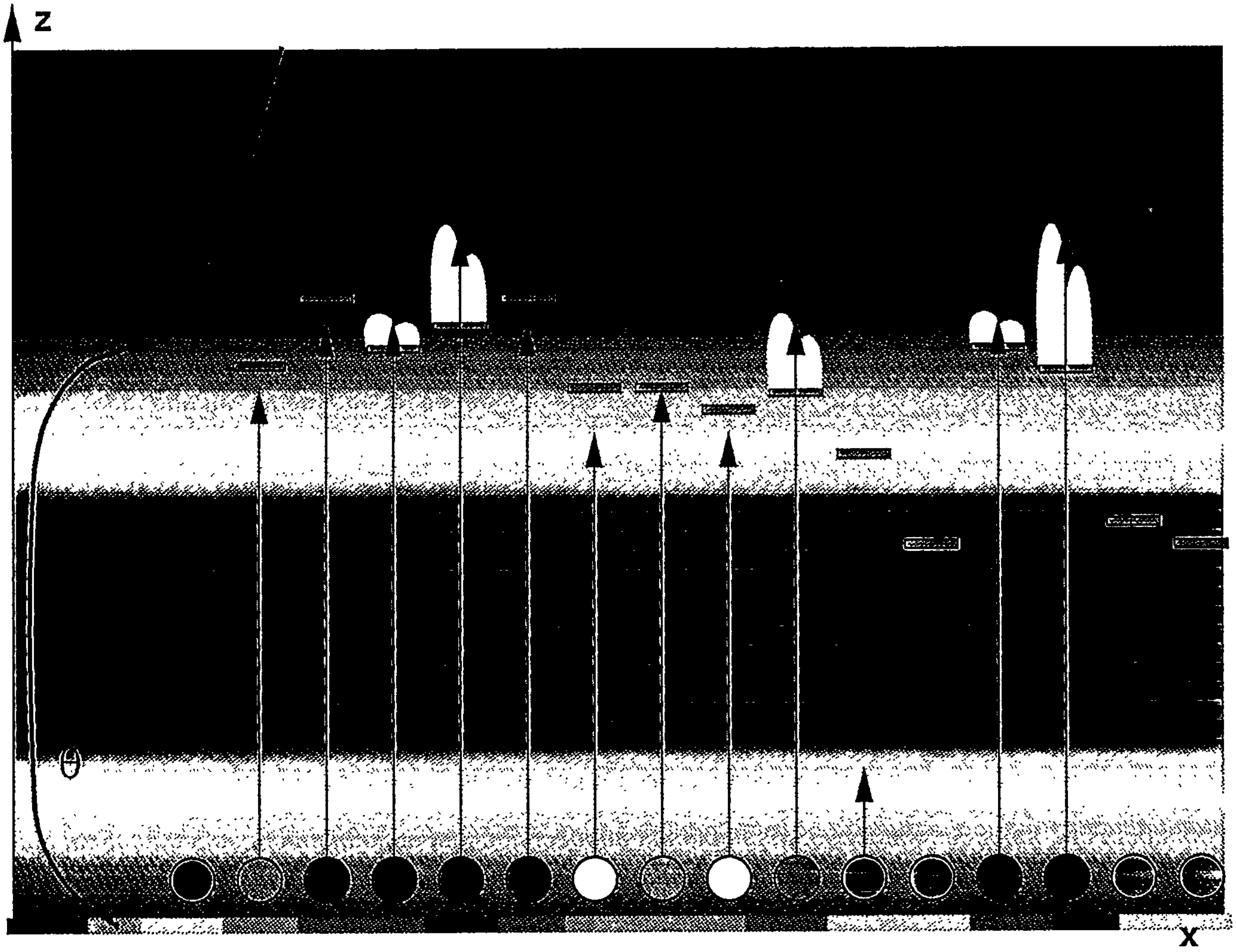


Fig 1. Land usage under HAPEX flight track.

Fig 2 is a sketch illustrating how the data points measured by aircraft along a horizontal flight track can be interpreted as air parcels. The buoyancy of each parcel as quantified by its virtual potential temperature can be used with the mean sounding to estimate the height to which each parcel might rise. The LCL of each parcel indicates the height needed to rise in order to form a cloud. As sketched in Fig 2, some rising parcels never rise sufficiently height to make clouds, while other rising parcels make clouds of different depths and having different cloud base heights.



Background colors correspond to the horizontally-averaged potential temperature, θ, in the convective mixed layer. Heterogeneous land use, illustrated with the black and gray line segments at the bottom, cause turbulent temperature fluctuations in the surface-layer air, illustrated with air parcels of different colors. These parcels rise to their level of neutral buoyancy, shown by the vertical arrows. Moisture also varies from parcel to parcel, causing corresponding fluctuations in the height of the lifting condensation level (LCL), shown by the blue/black horizontal dashes. Those parcels that rise above their own LCL can create cumulus clouds.

Fig. 2

HAPEX (9 May) FLIGHT 1, TRACK 1, S 6

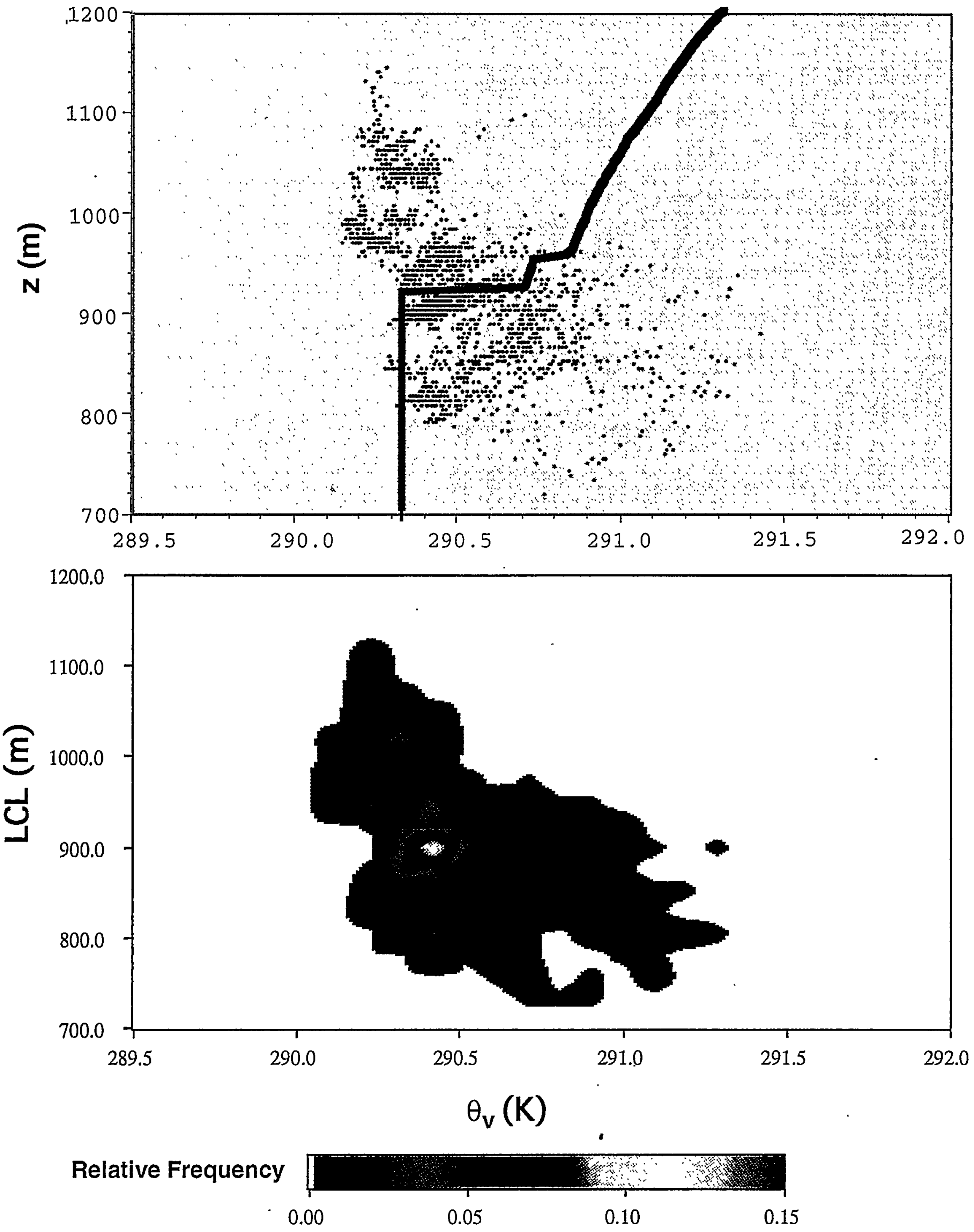


Fig. 3

Joint Frequency Distribution in the Surface Layer

HAPEX Flight 1, Track 1, 9-May-86

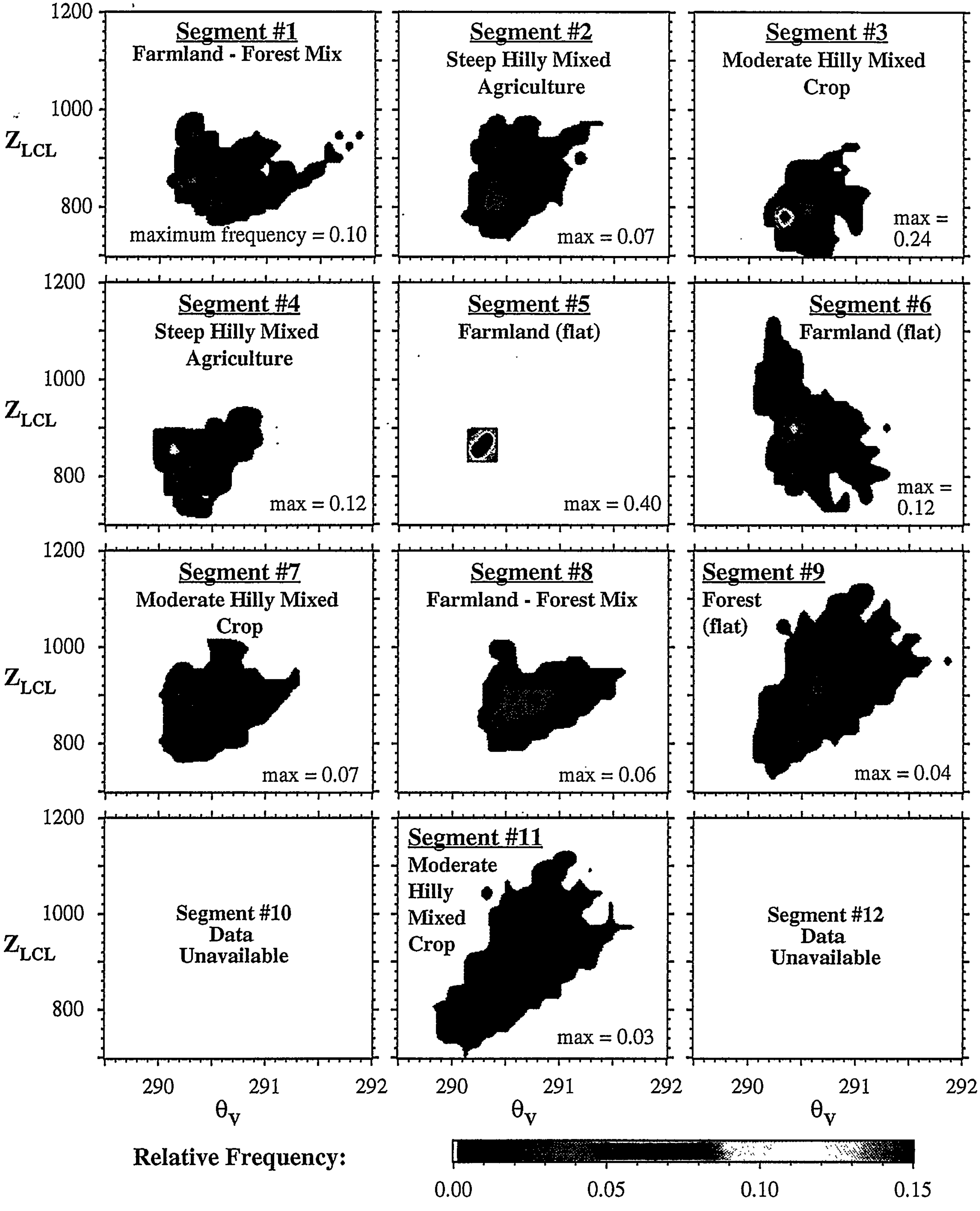


Fig. 4

When the parcels within any single flight segment are sorted by their various temperatures and LCLs and then counted, the result is the desired joint frequency distribution. This is shown in Fig 3a, where each data point represents a parcel. Fig 3b shows the same information, but color contoured.

By superimposing the frequency distribution for any segment on the mean boundary-layer sounding for that segment (e.g., Fig 3a), the cumulus potential (CuP) coverage can be calculated. Those points on the frequency distribution to the right of the sounding can potentially form cumulus clouds, because their LCL is lower than the sounding height at their temperature, which indicates the height to which they would rise. Those points to the left of the sounding are unlikely to make cumulus. As the location of the center of the frequency distribution moves relative to the temperature and depth of the mixed layer during the course of a diurnal cycle, the cloud coverage amount changes correspondingly.

Fig. 4 shows frequency distributions for every segment, from a flight track on 9 May 1986. Some of the distributions were elongated in one direction, with the major axis running upper-left to lower right (see segment 6), while the distributions over other segments were oriented virtually orthogonal (e.g., segment 9). In particular, the distribution for segment 9 looked like a footprint.

Stull developed a theory showing how variations in the Bowen ratio and absorbed solar radiation (insolation) can alter the temperature and moisture perturbations in the air parcels. These perturbations result in variations in LCL and potential temperature that cause the joint frequency distributions to spread out. Fig 5 shows the outcome of this theory. Because of the footprint shape of one of the observed joint distributions, the theory was nicknamed "bigfoot". This theory has the added benefit of providing a framework within which the distributions can be parameterized as a function of land use, such as sketched in Fig 6.

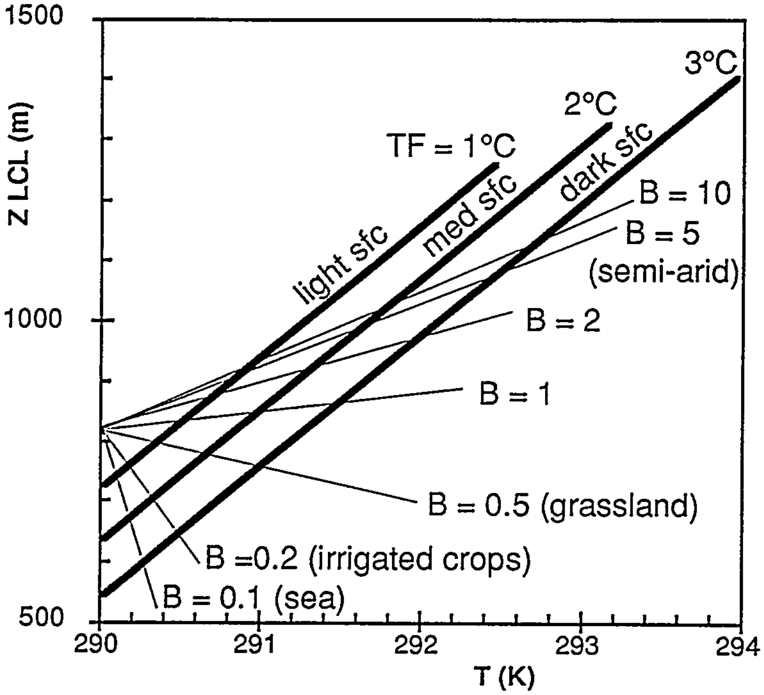


Fig 5. Variation of LCL and virtual potential temperature with Bowen ratio (B) and temperature excess (TF) caused by various amounts of insolation.

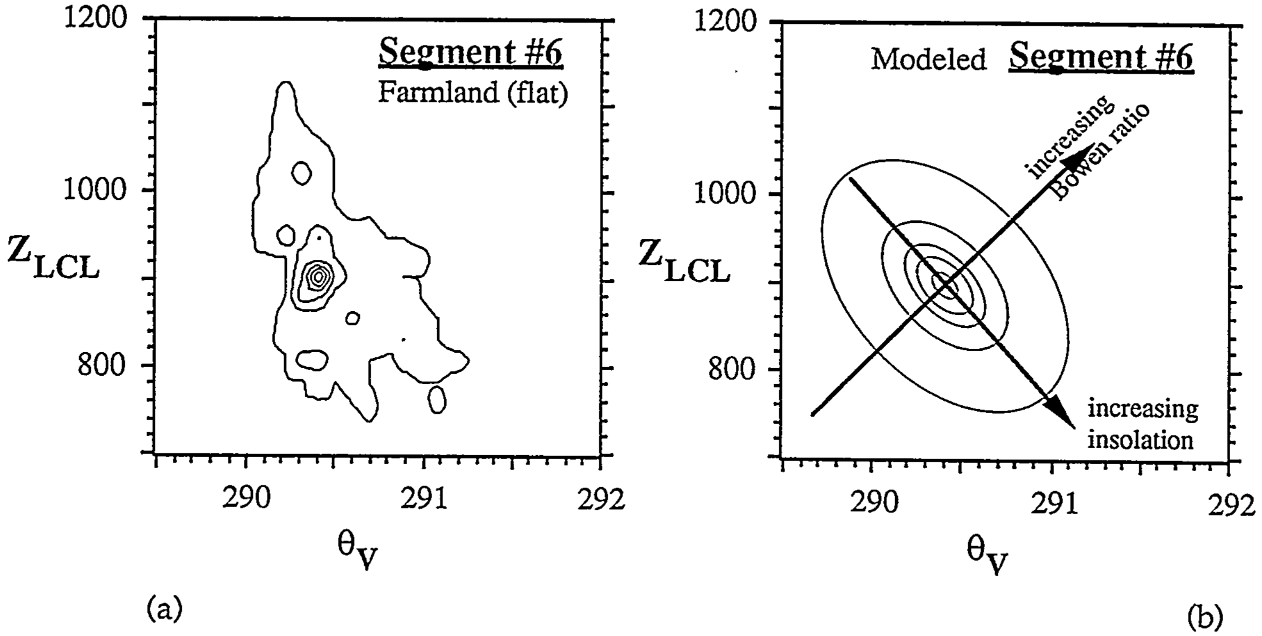


Fig 6. (a) Discrete relative frequency distribution of virtual potential temperature, θ_V(K), and height of the lifting condensation level, z_{LCL}(m), as observed in surface-layer air during segment 6, track 1, flight 1 of HAPEX. Tic marks indicate the sorting bin size. Contours drawn every 0.02, except first contour at 0.001; max. relative freq. = 0.12. (b) Parameterized model of the joint distribution data which approximates the measured distribution of (a).

By forecasting the mean boundary layer characteristics in and parameterizing the joint distribution, it is possible to forecast the onset time of cumulus (when the distribution first crosses the sounding) and the potential cumulus coverage (by integrating that portion of the distribution to the right of the sounding). Both of these quantities are very important for GCM forecasts. Fig 7 sketches a single-column forecast of boundary layer profile superimposed on a parameterized joint distribution. The subgrid cumulus coverage would be forecast from the portion of the distribution to the right of the sounding.

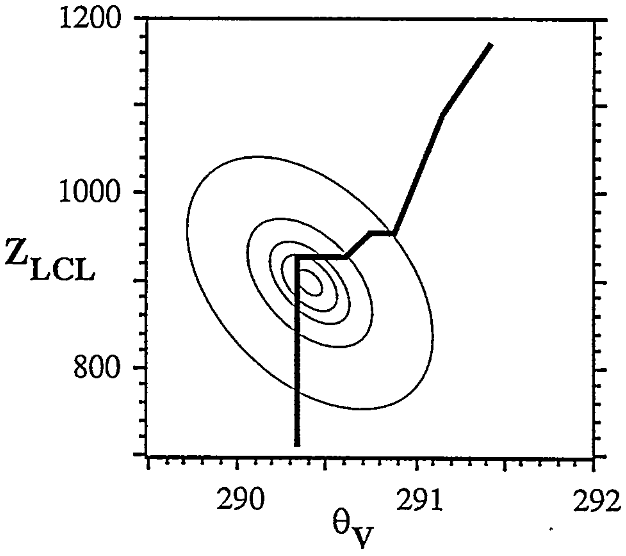


Fig 7. Smooth contours represent values of constant frequency distribution of virtual potential temperature θ_V (K)vs z_{LCL} (m) for surface-layer air. Superimposed as the heavy line is a plot of the environmental sounding of θ_V vs height z.

Cloud ensemble size distributions can also be determined from the joint frequency distribution. To do this, conceptually (Fig 8) divide the joint distribution into three sectors that represent different physics : (1) points cooler than that of the mean mixed layer (ML) temperature (extrapolated vertically across the whole figure), (2) points warmer than the mean ML temperature but which are above the sounding, and (3) points warmer than the ML but which are below the sounding. As sketched in Fig 9, sector (1) indicates the fraction of air that will not likely rise. Sector (2) contains those points that will rise from the surface layer, but which will not likely form clouds. Sector (3) contains those points that rise and form clouds.

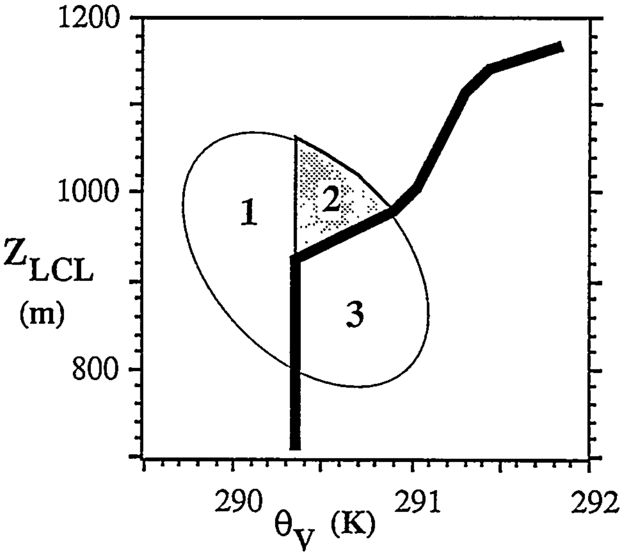


Fig 8. Three sectors of the joint frequency distribution. Sector (1) contains parcels that probably will not rise; (2) contains parcels that will rise without forming a cloud; (3) contains parcels that will rise and form clouds.

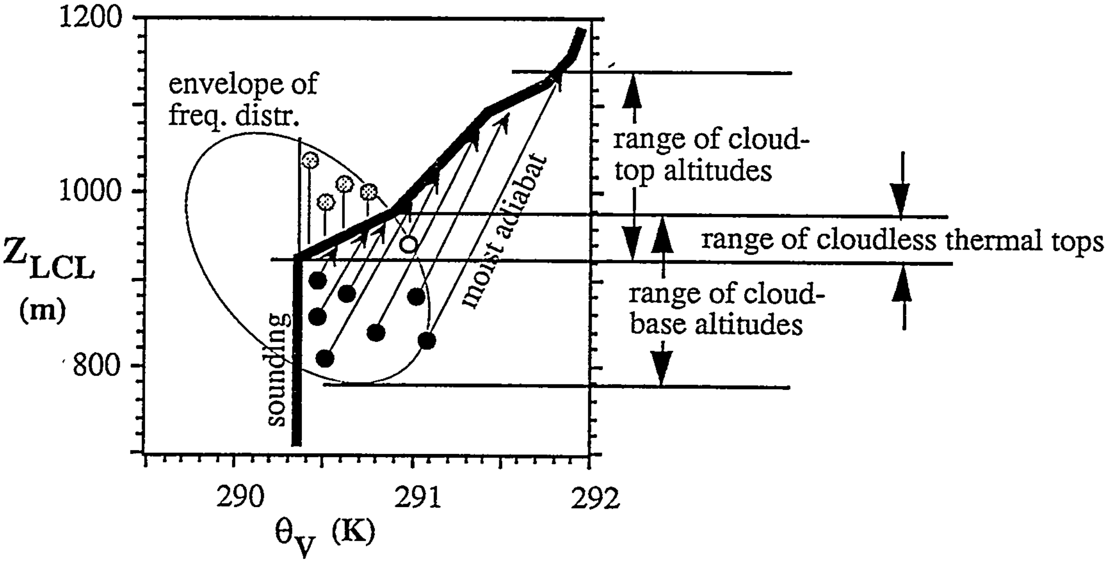


Fig 9. Parcels in sector two, indicated with gray shading, rise from the surface layer until they hit the sounding, without forming clouds. The other parcels, colored black, reach their LCL, and then continue rising along a moist adiabat. For many of these latter parcels, such as the one colored white, they rise without condensation past other cloud bases before reaching their own cloud base.

When the extent of buoyant rise for points from sectors (2) and (3) are plotted, taking into account rise along moist adiabats from sector (3), the result indicates that there are three layers in the cloudy boundary layer (see Fig 10). The bottom layer is the well-known sub-cloud layer, where all the updrafts are cloud-free. The top layer is the cloud layer, where all the updrafts are cloudy. In between is an "overlap" layer, with both cloudy and cloud-free updrafts. This layer is not quite like the transition layer described by Malkus for tropical cumulus, nor is it quite like the entrainment zone described by Deardorff et al, nor is it like the LCL zone described by Wilde et al. We are investigating the nature of this overlap zone to determine its relationship between coupling between the subcloud and cloud layers, and to determine the size distributions of cumulus cloud ensembles.

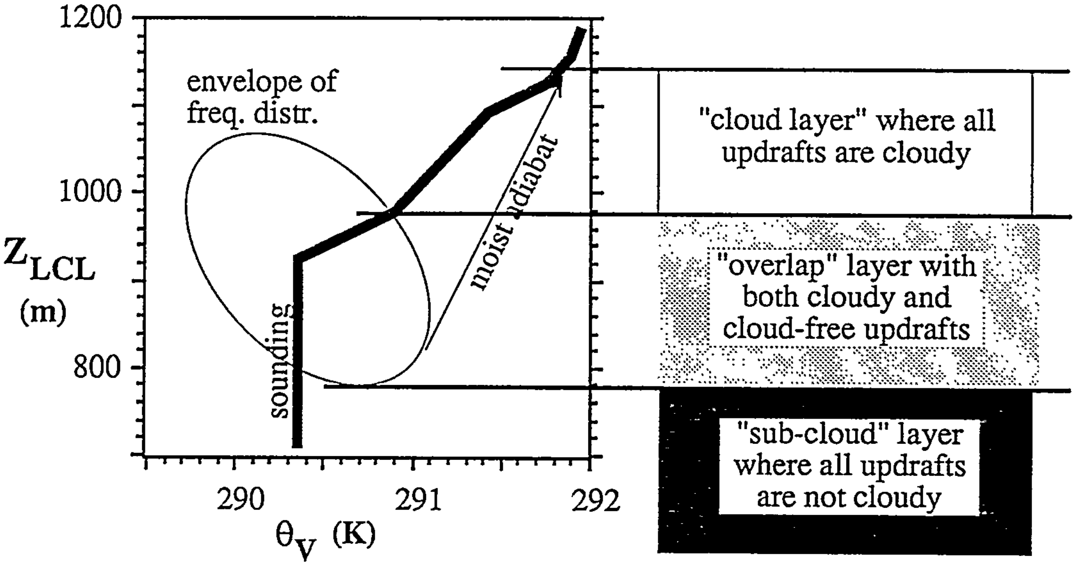


Fig 10. Three layers can be identified in the boundary layer. The cloud and subcloud layers have the conventional definitions of cloudy and non-cloudy air. The middle "overlap" layer has both cloudy and cloud-free updrafts.

Stull has found that the joint distributions are well modeled by a normalized 2-D exponential distribution. This fits the data better than a Gaussian distribution. As of August 93 he has done the initial coding of this distribution into a model that includes the mixed layer sounding and moist adiabatic processes. This will allow him to study cloud width and depth distributions as a function of mixed-layer characteristics.

f. Relationship to general goals.

Each flight leg is over a distance of about 50 km, which corresponds to less than a single grid cell in a typical GCM. Thus, our data represents subgrid information. By parameterizing this distribution as a function of known surface conditions and resolved GCM mean variables, we can use it to forecast the amount of subgrid clouds. By incorporating parameters into the modeled frequency distribution, and calibrating those parameters based on aircraft data from various ARM-CART sites around the world, we should be able to develop a parameterization with wide utility that can be used without future need for aircraft data.

Of the output products listed below from our original grant proposal, methods to forecast the ones with check marks will be completed by the end of year 2.

- ✓ Cumulus field onset and disappearance times
- ✓ Average cloud cover (0-100%)
- Cloud type (cumulus, stratocumulus)
- ✓ Distribution of cloud-base heights
- ✓ Distribution of cloud-top heights (log-normal parameters)
- ✓ Distribution of cloud widths (log-normal parameters)
- ✓ Cloud life-cycle dynamic category (Stull: 1985):
- Cloud forcing type (Agee: 1987):
- Mesoscale organization, if any
- Ventilation rate of moisture and other greenhouse gases from the boundary layer to the rest of the troposphere
- ✓ Boundary layer depth and growth (thickness of the high moisture layer)
- Entrainment rate of gases from higher in the troposphere down toward the surface
- Approximate subgrid layer-average radiative heating/cooling within clouds.

3. Unusual Developments

As stated in the progress report last year, the field experiment data acquired from NCAR proved difficult to read and unpack. This has continued to be a problem, but we have made arrangements to import the data directly from NCAR over internet rather than using tapes. This arrangement is working fine.

4. Plans for the remainder of year 2

Rizwan and Rudy expect to finish coding the netCDF ingestor by the end of September 93. They will then continue modifying the graphing package to allow data manipulation prior to plotting.

During the next three months McNerney and Stull will begin analyzing the cloud-free data from HAPEX, and continue to analyze more of the cloudy cases.

Farrenkopf will add the "bigfoot" parameterization and the cumulus potential coverage (CuP) to his single column forecast model.

Stull will continue both analytical derivations and numerical integrations of the CuP approach, and will write the results for a paper to be submitted to JAS.

5. Summary of Work to be Preformed During Year 3

We will analyze the ARM-CART aircraft data gathered by Oncley to measure the joint frequency distributions over the CART site.

We will continue analysis of the HAPEX data, particularly for the clear days.

We will identify and hopefully quantify the impact of cloud shading on surface heterogeneity, and study the feedback on triggering of new clouds.

We will derive and code an algorithm using the maximum likelihood method of statistics to fit the observed joint frequency distributions with parameterized ones. This we will apply to all the flight segments we have analyzed, from both the HAPEX and ARM-CART sites.

A table of these distribution parameters as a function of land-use will be compiled, so that composite frequency distributions can be constructed over GCM grid-box size areas.

Additional data from other existing data sets, such as FIFE and/or STORM-FEST, will be acquired and analyzed.

We will begin quantifying the Agee cloud forcing type, and attempt to parameterize the mesoscale organization of cumulus clouds.

The single-column boundary layer model will be enhanced with all the new parameterizations, and will be tested against daily ARM-CART data.

A paper about the relationship of the joint frequency distributions to land use will be written and submitted for publication in a journal.

Theories concerning convective transport theory will be refined and tested against other data sets. A paper about mixed-layer levelness will be written for publication.

We will continue to improve the plotting packages needed for our analyses.

6. List of Publications Resulting from this Research

From Year 1:

Stull, R.B., 1992: A convective transport theory for surface fluxes. *J. Atmos. Sci.*, 50, (in press).

Stull, R.B., 1992: A theory for mixed-layer top levelness over irregular topography. *Preprint Volume of the American Meteorological Society's 10th Symposium on Turbulence and Diffusion, 29 Sep - 2 Oct 1992, Portland, OR.* American Meteorological Society, 45 Beacon St. Boston, MA 02108.J92-J94.

Stull, R.B., 1992: A convective drag theory for surface fluxes. *Preprint Volume of the American Meteorological Society's 10th Symposium on Turbulence and Diffusion, 29 Sep - 2 Oct 1992, Portland, OR.* American Meteorological Society, 45 Beacon St. Boston, MA 02108. 196-199.

Zhang, Q., 1992: Diagnostic determination of boundary-layer cumulus clouds using HAPEX aircraft data. *Preprint Volume of the American Meteorological Society's 10th Symposium on Turbulence and Diffusion, 29 Sep - 2 Oct 1992, Portland, OR.* American Meteorological Society, 45 Beacon St. Boston, MA 02108. 40-43.

From Year 2:

Stull, R.B., 1993: Boundary-layer cumulus over land: some observations and conceptual models. *Proceedings from the ECMWF/GCSS Workshop on Parameterization of the Cloud Topped Boundary Layer. Reading, UK, 8-11 June 1993.* ECMWF Workshop Series. (in press).

Stull, R.B., Q. Zhang, and K. McNerney, 1993: Boundary-layer cumulus onset and coverage over a heterogeneous surface. (being written; to be submitted to JAS).

A copy of the first publication from year 2 is attached. The second paper will cover material already summarized in this progress report, but with the mathematical details and computer results added.

7. Incremental Budget Request for Year 3 Funding

The funds for year 2 will be totally spent by the end of the this budget year. A copy of the budget for year 3, is on the next page. The total dollar amount requested for year 3 has not changed, although minor changes have been made to most categories to reflect current overhead, fringe, and salaries. There is no change to the number of personnel requested. No equipment is requested.