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Boundary-Layer Cumulus Over Heterogeneous Landscapes: A Subgrid GCM Parameterization

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Abstract

We developed single-column parameterizations for subgrid boundary-layer cumulus clouds. These give cloud onset time, cloud coverage, and ensemble distributions of cloud-base altitudes, cloud-top altitudes, cloud thickness, and the characteristics of cloudy and clear updrafts. We tested and refined the parameterizations against archived data from Spring and Summer 1994 and 1995 intensive operation periods (IOPs) at the Southern Great Plains (SGP) ARM CART site near Lamont, Oklahoma.

We also found that: cloud-base altitudes are not uniform over a heterogeneous surface; tops of some cumulus clouds can be below the base-altitudes of other cumulus clouds; there is an overlap region near cloud base where clear and cloudy updrafts exist simultaneously; and the lognormal distribution of cloud sizes scales to the JFD of surface layer air and to the shape of the temperature profile above the boundary layer.

Summary of Activities and Results

1. Overview

During this last year of DOE funding, we redirected our research to utilize the SGP CART data from the Spring and Summer 1994, and the Spring and Summer 1995 IOPs. This research was aimed at parameterizing and forecasting attributes of the ensemble of subgrid boundary-layer cumulus clouds, including: **cloud-base height spreads, cloud-top height spreads, cloud size distributions,** and **dynamical cloud-type classifications**. We also began incorporating these single-column parameterizations into a mesoscale weather forecast model for testing.

2. Background and Results from the First Three Years (Dec 91 - Nov 94)

While we waited for the CART site to become fully operational, we developed and tested our boundary-layer cumulus parameterizations using data from a previously archived field experiment (HAPEX) in southern France. We discovered how to use temperature (T) and lifting-condensation-level (LCL) data from the surface layer to diagnose **cloud onset time** and **subgrid cloud coverage.**

Grad students Qing Zhang, and later Kelly Schrieber, analyzed HAPEX surface layer data from the King Air aircraft to develop joint frequency distributions (JFD) of T vs LCL. Meanwhile, I developed a "bigfoot" model to explain how the JFD shape should vary with heterogeneous landscapes, and I used this theory to guide the fitting of bivariate statistical functions to the observed JFDs. Both Qing and Kelly have finished their schoolwork and left our research group, but not before contributing to a paper (*J. of Atmos. Sci.*, in press, scheduled for Jan 96), a MS thesis, and presentations at numerous conferences (see bibliography). Details of this previous research are given in the *JAS* paper, attached as Appendix A.

3. Results During the Last Year (Dec 94 - Nov 95)

a. Equipment Purchase. It became obvious to us during summer 94 that our existing Macintosh workstations were unsatisfactory for running the netCDF software, required for getting the archived CART IOP data. Grad student Henryk Modzelewski, my computer system administrator, recommended that we purchase an entry-level Silicon Graphics (SGI) Indy workstation to remedy this problem, which we did in December 94. It has proved to be perfect for the job, and will also allow us to make runs of the full forecast model to test the parameterizations.

b. Case-Study Days. After examining the synoptic conditions for the Spring and Summer 94 IOPs for conditions of high pressure, we selected 1 May and 27, 28, and 31 July 94 as case-study days. On these days, initially clear skies changed to scattered to broken boundary-layer cumulus clouds by afternoon.

Stull and Berg presented results for the 1 May 94 case at the 1995 ARM Science Team meeting in San Diego. Selected figures from that poster are attached to this report (Figs 1 - 4). We also tested two additional days (28 and 31 July 1994), for

Modeled Size Distribution of Subgrid Clouds – A Case Study: 1 May 94 Lamont, OK.

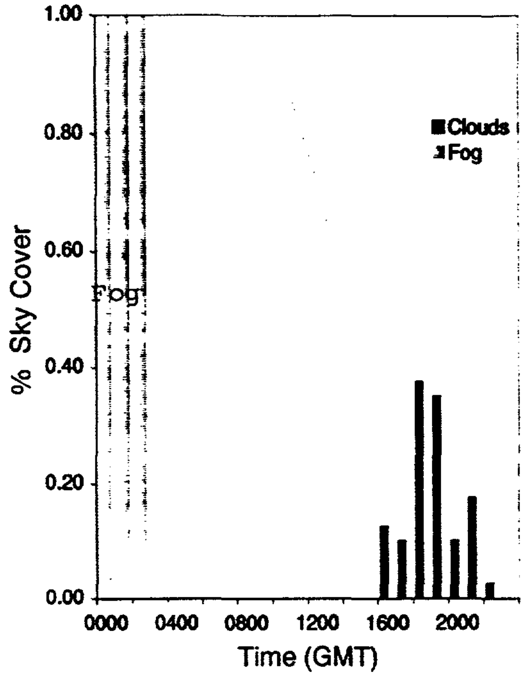

Fig 1. Observed coverage vs time at the CART site, for this case.

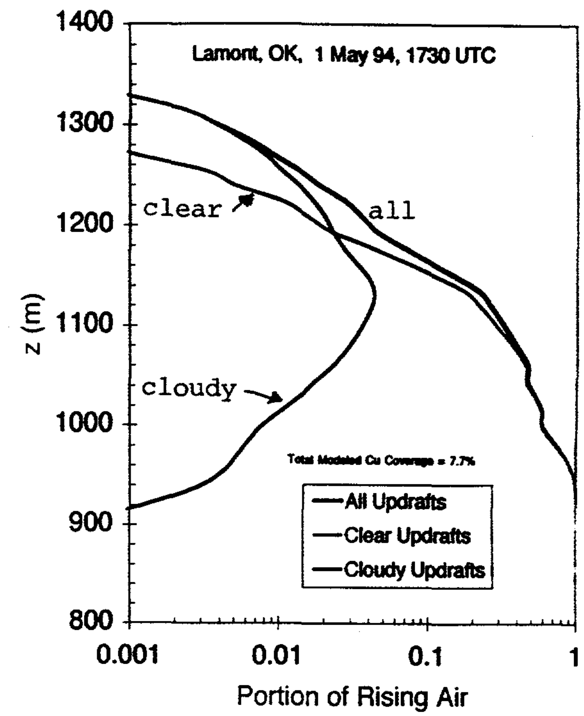

Fig 2. Modeled coverage of various types of updrafts vs height. The overall cumulus coverage is modeled to be 7.7% at 1730 UTC.

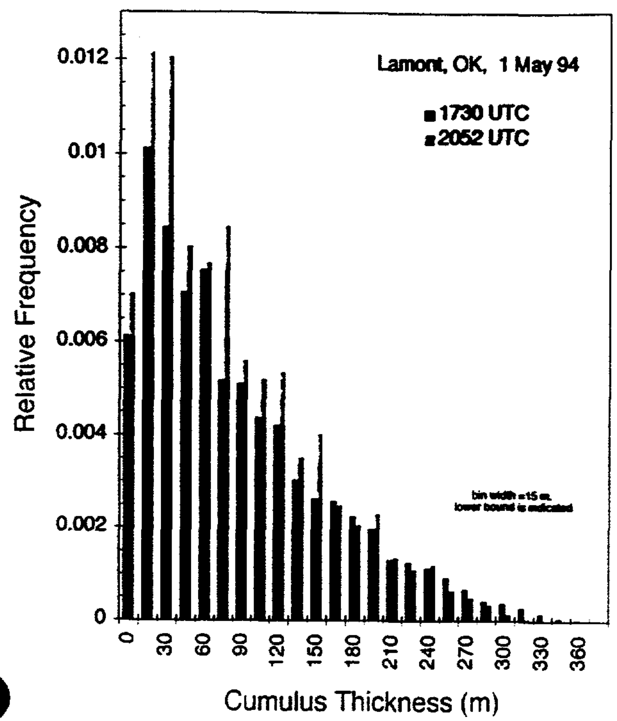

Fig 3. Modeled distributions of cloud thickness.

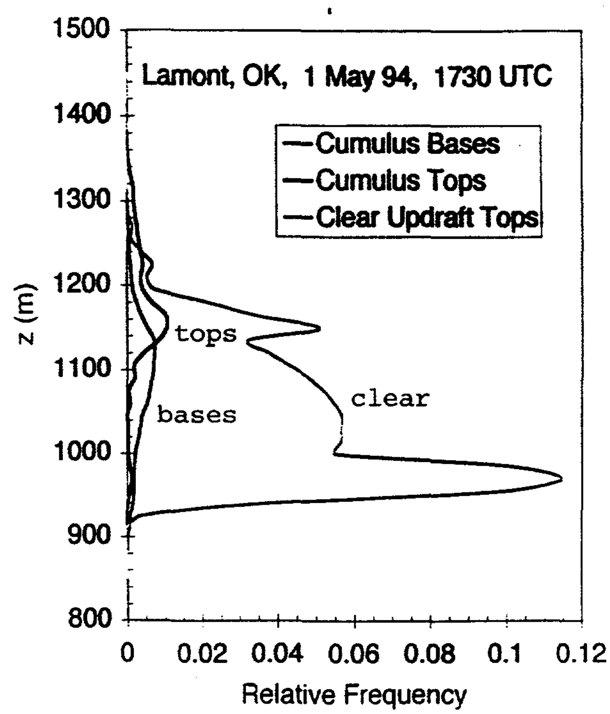

Fig 4. Modeled distribution of locations of cloud tops, bases, and clear-updraft tops.

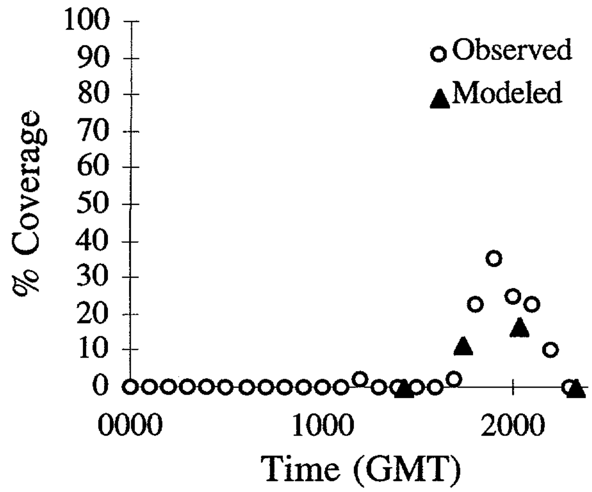

Fig 5. Observed and modeled cloud coverage vs time for 28 Jul 94 at Lamont OK.

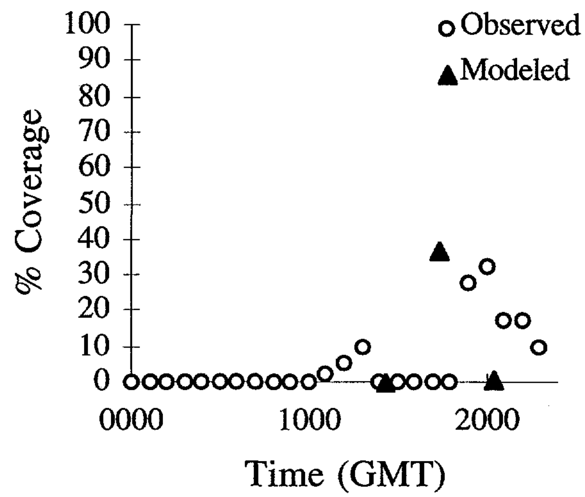

Fig 6. Observed and modeled cloud coverage vs time for 31 Jul 94 at Lamont OK.

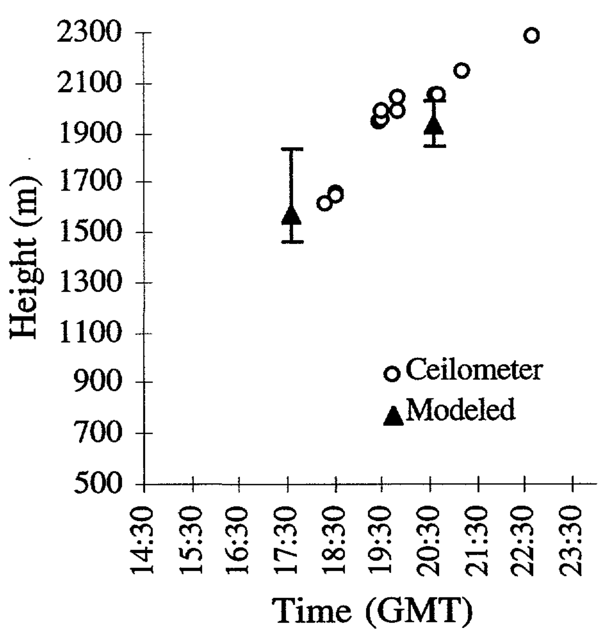

Fig 7. Ceilometer cloud base height and modeled cloud base height for 28 Jul 94 at Lamont OK. Bars show ranges of modeled values.

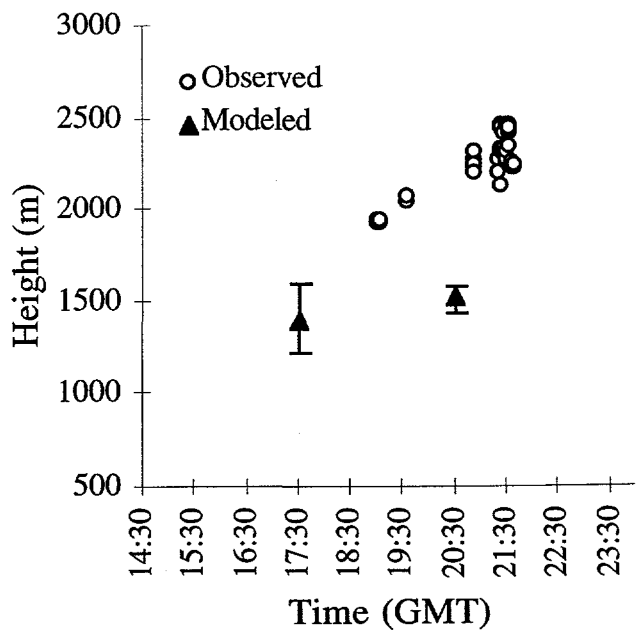

Fig 8. Ceilometer cloud base height and modeled cloud base height for 31 Jul 94 at Lamont OK. Bars show ranges of modeled values.

which we attach figures (5 - 8) of parameterized and measured cloud coverage and cloud-base heights.

c. Data Acquisition. Meteorological data has been obtained by grad student Larry Berg from the ARM Experiment Center. We have received data for the radiosondes, Surface Meteorological Observation Stations (SMOS), Energy Balance Bowen Ratio (EBBR) sensors, solar and infrared radiation observing stations, tower data, and the Oklahoma and Kansas State Mesonet for the spring and summer 1994 & 1995 IOPs. FORTRAN code was developed by Larry to read the data using the library functions supplied with the netCDF software. Temperature and humidity profiles were obtained from the sondes, and were used to estimate mid-mixed layer state of the atmosphere.

Sensible and latent heat fluxes were obtained by Larry Berg for the EBBR closest to the central facility (number 13). Problems with moisture build up on the inside of the sensor dome of the EBBR were reported at the 1995 ARM Science Team Meetings by Mike Splitt. The problem seemed to occur for cases with southerly winds which did not provide adequate ventilation to the instrument. The observed winds from the SMOS at the central facility during the days of interest had a northerly component, and the EBBR was adequately ventilated.

In order to verify the boundary layer cumulus model, human observations from the central facility of cloud coverage were used. Archived synoptic data from the University of Wisconsin-Madison, Department of Atmospheric & Oceanic Sciences were used to insure that the days that were chosen met the criteria of calm winds and clear skies, and to learn of the general synoptic conditions.

d. Parameterization Method. To parameterize boundary-layer clouds we need surface-layer quantities, because it is surface-layer air that rises to make clouds. However, many GCMs do not resolve the surface layer. Therefore, we interpolate between the mid-mixed-layer and the surface skin to find values that are representative of the surface layer.

First, Stull's (1994) convective transport theory is applied to find the ground skin lifting condensation level (Z_{lcl}) and skin virtual potential temperature (θ_v) using central facility sonde estimates of the the mixed layer depth and moisture and the central facility EBBR (number 13) flux values. That is, we back out skin state, knowing the surface flux and the mid-mixed-layer states.

Then we assume that surface-layer air consists of a mixture of air from near the skin, and from the mid-mixed-layer. The mixture must lie on a mixing line connecting these two original states. The distance from one end to the other along the line represents the relative portions of air that are mixed. Based on our experiments, we find that in the surface layer, the ratio of mixed-layer to skin-layer air is about 6 to 1 (Fig 9). This ratio is a function of time of day.

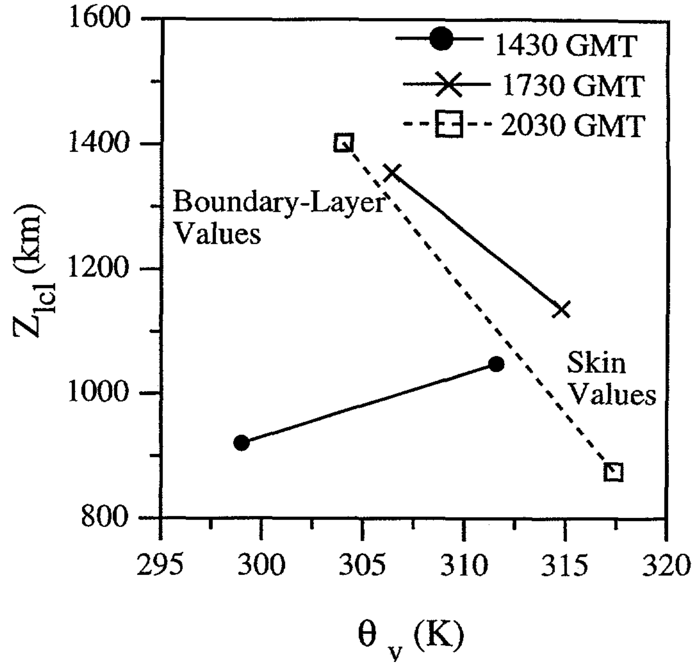

Fig 9. Boundary-layer and skin values of Z_{LCL} and θ_V for different times on 31 July 94 at Lamont, OK.

This resulting mixture state is used to locate the center (mean) of a joint frequency distribution (JFD) of Z_{lcl} and θ_v , where the JFD is a statistical representation of a heterogeneous surface, typical of many landuse regions. As was discovered during the first three years of our research, the portion of this JFD that lies to the right of the mean atmospheric sounding is a direct measure of the expected cloud coverage amount.

Comparisons of model estimated and measured values show that the scheme has skill at estimating both cloud coverage and cloud base height. The 28 July 94 run did a better job estimating both the cloud coverage and the cloud base height. The 27 July 94 case was not as successful predicting either the cloud cover or the cloud base heights. We are investigating the causes for this behavior.

We just received Spring and Summer 1995 data from the ARM experiment center, and are beginning to process it. We are continuing the model verification process by comparing modeled cloud base heights to the ceilometer measurements. We are also preparing to use additional sondes and EBBR measurements to include advection over the site for use in the UW forecast model.

e. Forecast Model. A quasi-three-dimensional model was used together with the boundary-layer cumulus cloud parameterization to forecast cloud evolution under varying meteorological conditions. This model utilized a transilient turbulence algorithm, and an area flux-preserving advection algorithm. The forecasts give the growth of the mixed layer due to surface forcing, variation of humidity, and surface temperature, all of which are needed by the cumulus scheme. It quickly became clear that the boundary-layer forecasts did not adequately account for differential advection.

In order to remove those obstacles, we have acquired a sophisticated three-dimensional, mesoscale, non-hydrostatic, weather forecast model with advanced parameterization of physical phenomena. This model will allow a more reliable forecast of meteorological conditions, even when initialized by the single CART site. Nevertheless, we will carefully validate surface temperature and subsidence forecasts from this model, which are critical for correct boundary-layer cloud diagnosis.

f. Relocation. In July 1995, the PI (Stull) and four of his graduate students moved to the University of British Columbia (UBC) in Vancouver, Canada. While most of the fourth-year funds had been utilized before this move, there was a small portion remaining that was subgranted from the University of Wisconsin (UW) to UBC, so that we could finish our research. At that time, Greg Tripoli, a professor remaining at UW, agreed to become a co-PI to oversee the research and funds from UW.

4. Discoveries

In addition to our goal of parameterizing cumulus coverage and size distributions, we are also making discoveries about the fundamental nature of boundary-layer cumulus. We have shown that cumulus cloud-base altitudes are not uniform over a heterogeneous surface. The tops of some cumulus clouds can be below the base-altitudes of other cumulus clouds. There is an overlap regions near cloud base where there simultaneously exists both clear and cloudy updrafts.

Also, while the distribution of cloud sizes has long been known to be lognormal, the scaling of that lognormal distribution from day to day was unknown. In fact, we had previously obtained the surprising result that the size distribution does not scale to boundary layer scales, such as z_i the mixed-layer depth. During the present DOE research, we have discovered that the controls of this lognormal distribution are the JFD of surface layer air and the shape of the temperature profile above the boundary layer.

5. Ongoing Research

Although the grant has ended, our work continues at UBC. Larry Berg will use the ARM-CART data, including the Spring and Summer 95 IOP data that just arrived, to test and refine the parameterizations. The current scheme predicts vertical attributes of the cloud ensemble and the percentage of cloud cover. He is extending the work to predict the horizontal size distribution, which he will relate to cloud thickness and Z_{lcl}, using fractal methods. Also, SIROS measurements will be incorporated to estimate the cloud coverage.

Larry will write his MSc thesis this Spring 96, and might also present his results at the ARM Science Team meeting scheduled for March 96 in San Antonio, TX. Also, we have begun to write a journal paper about these new results, a draft of which is attached as Appendix B.

We were recently granted aircraft time on the Univ. of Wyoming King Air, which we plan to bring to the SGP CART site during July-Aug 96. This will be a collaborative field program, sponsored by NSF. With this aircraft we plan to measure directly the JFD of z_{LCL} vs θ_v in surface layer air, so we won't have to make crude assumptions about it as we are now. We will share this aircraft data with other ARM researchers.

6. Publications & Presentations Resulting from this Grant

a. *Previous 3 Years*

Journal Publications

Stull, R.B., 1992: Impact of boundary-layer clouds – a case study of cover hours. *J. Climate*, **5**, 390-394.

Stull, R.B., 1994: A convective transport theory for surface fluxes. *J. Atmos. Sci.*, **51**, 3-22.

Thesis

Santoso, E., 1994: *Wind Profiles in the Convective Surface Layer*. M.S. Thesis, Dept. of Atmos. & Ocean. Sci., Univ. of Wisconsin - Madison. 59 pp

Presentations (not including those at ARM Science Team Meetings)

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.

Stull, R.B., 1994: Boundary-layer cumulus over land: some observations and conceptual models. *Proceedings of the ECMWF Workshop on Boundary Layer Clouds. Reading, England. 8-11 June 1993.* 299-318.

Stull, R.B., 1994: Surface flux parameterization for free convection. *Preprint Volume of the European Geophysical Society Workshop on Surface Fluxes, Grenoble, France, April 1994.*

Stull, R.B. and E. Santoso, 1994: New flux profile relationships for the surface layer during free convection. *Preprint Volume of the European Geophysical Society General Assembly, Grenoble, France, April 1994.*

Stull, R.B., K.M. Schrieber, and Q. Zhang, 1994: Boundary layer cumulus over a heterogeneous surface during HAPEX-MOBILHY. *Preprint Volume of the European Geophysical Society General Assembly, Grenoble, France, April 1994.*

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.

b. New During Year 4

Publications

Berg, L.K., and R. Stull, 1995: Coverage, onset time, and size distributions of cumulus humilis clouds. (being written, to be submitted to *J. Atmos. Sci.*)

Schrieber, K. R. Stull, and Q. Zhang, 1995: Distributions of surface-layer buoyancy vs LCL over a heterogeneous land surface. *J. Atmos. Sci.* (in press).

Theses

Berg, L.K., 1995: *Size distributions of boundary layer cumulus.* M.Sc. Thesis. Atmospheric Science Programme. The University of British Columbia. (being written)

Schrieber, K., 1995: *Observations of Surface-Layer Characteristics and Their Relationship to Boundary-Layer Cumulus Clouds.* MS Thesis. Dept. of Atmospheric & Oceanic Sciences. University of Wisconsin-Madison. 61pp.

Presentations

Schrieber, K., and R. Stull, 1995: Forecasting boundary layer cumulus over heterogeneous surfaces. *Preprints from the 11th Symposium on Boundary Layers and Turbulence, March 27-31, 1995, Charlotte, NC.* American Meteorological Society. supplement.

Stull, R., L.K. Berg, H. Modzelewski, and K. Schrieber, 1995: Size distributions of boundary layer clouds. Poster at the ARM Science Team Meeting, March 1995, San Diego. 4pp.

Stull, R., and K. Schrieber, 1995: Size distributions of boundary-layer clouds. *Preprints from the 11th Symposium on Boundary Layers and Turbulence, March 27-31, 1995, Charlotte, NC.* American Meteorological Society. 217-219.

7. Personnel

During the first two years of research, graduate student Qing Zhang worked on this project with me, together with undergraduate-student programmers Rudi Moore and Mohammad Rizwan Quershi, and with help from graduate student Joe Farrenkopf. During the second year, graduate student Kelly (McNerney) Schrieber joined our team. Qing and Joe finished school and left our research group at the end of the second year as did the two programmers, while Kelly increased her work on the project. Assisting Kelly during year three were graduate students Grant Brohm and Edi Santoso. Edi has also been extending some of the offshoot research leading to a better understanding of wind profiles in the unstable surface layer. Kelly finished her MS thesis in 1995. Larry Berg and Henryk Modzelewski joined the research team in Fall 1994. Larry will finish his MSc thesis in Spring or Summer 1996, and continue his research using data to be collected with the King Air aircraft. Henryk has been invaluable as computer system administrator, and with his help on various programs, although he will do his PhD research in a different area. Prof. Greg Tripoli joined as unfunded co-PI to oversee the grant from Univ.of Wisconsin.

Appendix A

Publication in Press Jan 96

Preprint – pulled for separate processing

Distributions of Surface-Layer Buoyancy vs LCL Over a Heterogeneous Land Surface

Kelly Schrieber*, Roland Stull† and Qing Zhang*

Boundary Layer Research Team

*Dept. of Atmospheric & Oceanic Sciences, University of Wisconsin-Madison

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(submitted to *J. Atmos. Sci.*, April 94)

(revised, June 95)

(final revision, Oct 95)

Preprint pulled for Separate processing

Publication in Press - Jan. 1996

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Appendix B

Manuscript in Preparation

Preprint – pulled for separate processing

Coverage, Onset Time, and Size Distributions of Cumulus Humilis Clouds

Larry Berg & Roland Stull

Atmospheric Science Programme, Dept. of Geography

The University of British Columbia

Vancouver, BC, V6T 1Z2 Canada

Preprint / pulled for separate processing

~~(submitted to *J. Atmos. Sci.*, *** 95)~~

(in preparation Jan 96)

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