Betts Research: *1969-1989:*
the inside story

Alan K. Betts

http://alanbetts.com

U. Miami

March 7, 2012

Early Years

- **July 1969: Martin Miller & Alan travel to Barbados (BOMEX), and Anaco, Venezuela (VIMHEX-69), and Miami (visit Joanne and Bob Simpson)**
- **Sept 1970: Alan leaves for post-doc at CSU (a week after PhD defense!)**
- **1972: Alan is field meteorologist for VIMHEX-72**
- **1973: Alan drafts GATE Convection plan**
- **1974: Alan is *Convection Subprogramme and Airborne Mission Scientist* for GATE**
- **1975-76: Mitch Moncrieff & Martin Miller visit CSU**
- **1976-77: VIMHEX papers**
- **1978: Alan builds house in Vermont**
- **1980-81: GATE review with Bob Houze**
- **1982-84: Saturation point analysis papers**
- **1983: Alan visits ECMWF, presents idea of convective adjustment to ECMWF workshop**
- **1986: Betts-Miller scheme published in QJ**

Early references: http://alanbetts.com

- **Betts, A. K., 1970: Cumulus Convection. Ph.D. Thesis, University of London, 151 pp.**
- **Betts, A. K., 1973: Non-Precipitating Convection and Its Parameterization. *Quart. J. Roy. Meteor. Soc.*, 99, 178-196.**
- **Betts, A. K., 1973: A Composite Mesoscale Cumulonimbus Budget. *J. Atmos. Sci.*, 30, pp. 597-610.**
- **Betts, A. K., 1974: The Scientific Basis and Objectives of the U.S. Convection Subprogram for the GATE. *Bull. Amer. Meteor. Soc.*, 55, pp. 304-313.**
- **Betts, A. K., 1975:** Parametric Interpretation of Trade-Wind Cumulus Budget Studies. *J. Atmos. Sci.*, 32, 1934-1945.
- **Betts, A. K., R. W. Grover and M. W. Moncrieff, 1976: Structure and Motion of Tropical Squall Lines over Venezuela. *Q.J. Roy. Meteor. Soc.*, 102, pp. 395-404.**
- **Moncrieff, MW, and MJ Miller (1976). The dynamics and simulation of tropical cumulonimbus and squall lines. QJRMS, 102, 373-394**
- **Betts, A. K., 1976: The Thermodynamic Transformation of the Tropical Subcloud Layer by Precipitation and Downdrafts. *J. Atmos. Sci.*, 33, pp. 1008-1020.**
- **Betts, A. K., 1976**: Modeling Subcloud Layer Structure and Interaction with Shallow Cumulus Layer. J. Atmos. Sci., 33, pp. 2363-2382.
- **Miller, M. J., and A. K. Betts, 1977: Travelling Convective Storms over Venezuela. *Mon. Wea. Rev.*, 105, pp. 833-848.**
- **Betts, A.K., 1978:** Convection in the Tropics. RS/RMS/AMS/DMG Conf. on Meteorology over the Tropical Oceans. *Quart. J. Roy. Meteor. Soc. Supplement*, 105-132.
- **Houze, R. A., and A. K. Betts, 1981:** Convection in GATE. *Rev. Geophys. and Space Phys.*, 19, 541-576.
- **Betts, A. K., 1982: Saturation Point Analysis of Moist Convective Overturning. *J. Atmos. Sci.*, 39, 1484-1505**
- **Betts, A. K., 1983: Atmospheric convective structure and a convection scheme based on saturation point methods. ECMWF Workshop on “Convection in large-scale numerical models” 28 Nov.-1 Dec, 1983, Reading U. K., pp.69-94. http://www.ecmwf.int/publications/library/ecpublications/_pdf/workshop/1983/Convection/betts.pdf**
- **Betts, A. K. and M. J. Miller, 1984: A new convective adjustment scheme, Pts. I and II. ECMWF technical Report No. 43, ECMWF, Reading, RG2 9AX, England, 68 pp. http://www.ecmwf.int/publications/library/ecpublications/_pdf/tr/tr43.pdf**
- **Betts, A. K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc., 112*, 677-692.**
- **Betts, A. K. and M. J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE-wave, BOMEX, ATEX, and Arctic Airmass data sets. *Quart. J. Roy. Meteor. Soc.*, 112, 693-710.**

Cloud transports and diabatic forcing are central to the climate system on all scales

- **BL clouds: surface coupling & vertical motion**
  - sensitivity to T, RH, aerosols, subsidence; and over land, diurnal cycle, water availability, CO_2
  - SWCF & LWCF: surface & TOA
- Deep clouds: forced by larger scales with tight coupling between precipitation, diabatic heating and vertical motion – *known in 1969*
- Deep clouds: cloud radiative forcing of same order as diabatic heating by WV phase change
- Cloud sensitivity to changing aerosols; vertical circulations and RH, increasing temperature and CO_2 - *for climate change issues*

Flew to Barbados on a VC10

(My first flight)

NOAA DC-6: BOMEX flights from Barbados in 1969

Martin Miller: Anaco, Venezuela, 1969

Grad student labor for Herb Riehl

Cloud Research on a golf-course

Anaco-1969

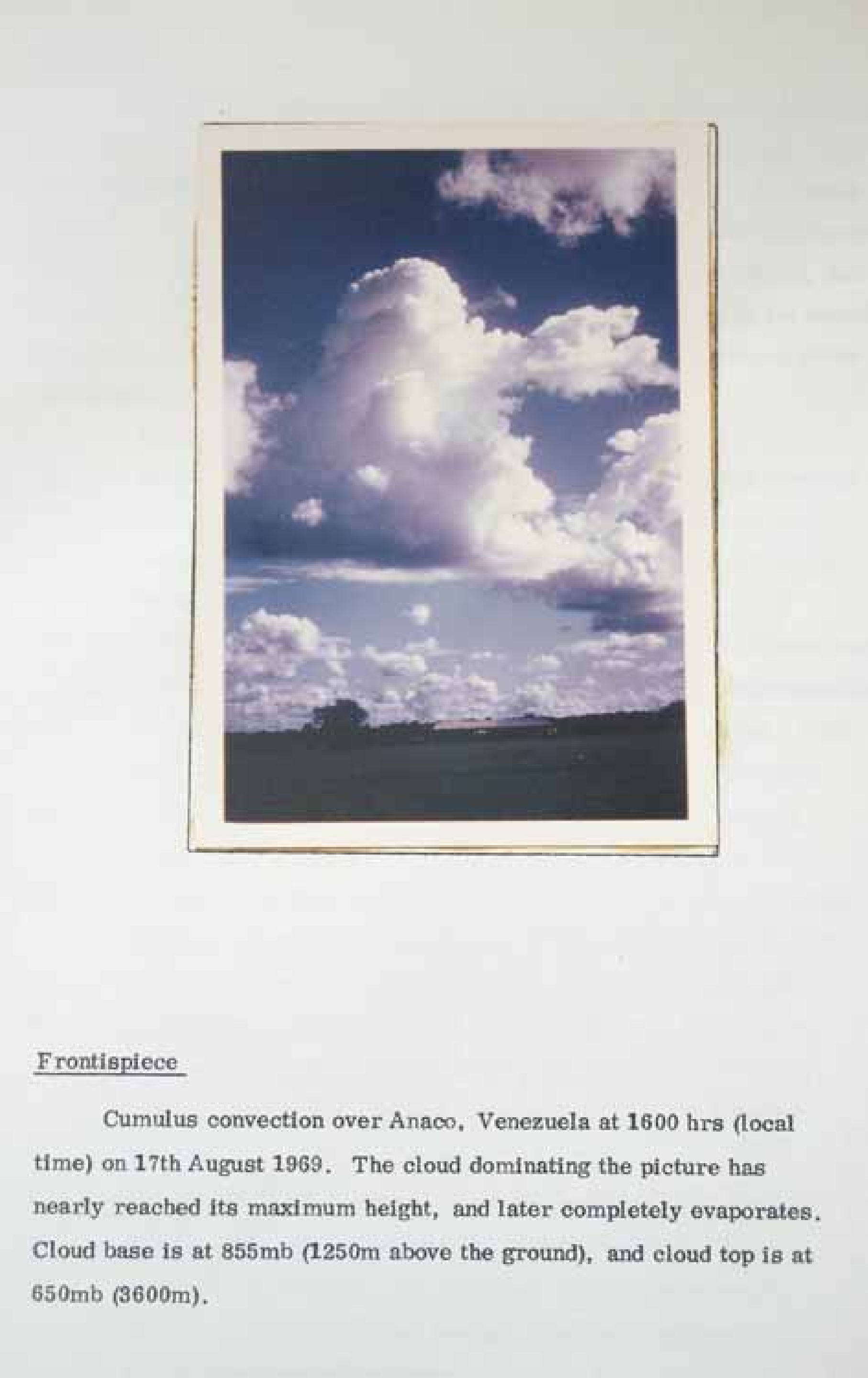
Betts filmed a lot of clouds!

I returned from Venezuela and wrote my 1970 PhD thesis “*Cumulus Convection*”

(Betts, QJRMS, Jan 1973)

– inspired by this cloud

& the realization that even the ‘expert’ Herbert Riehl could not forecast daily tropical convection – until it appeared on radar!

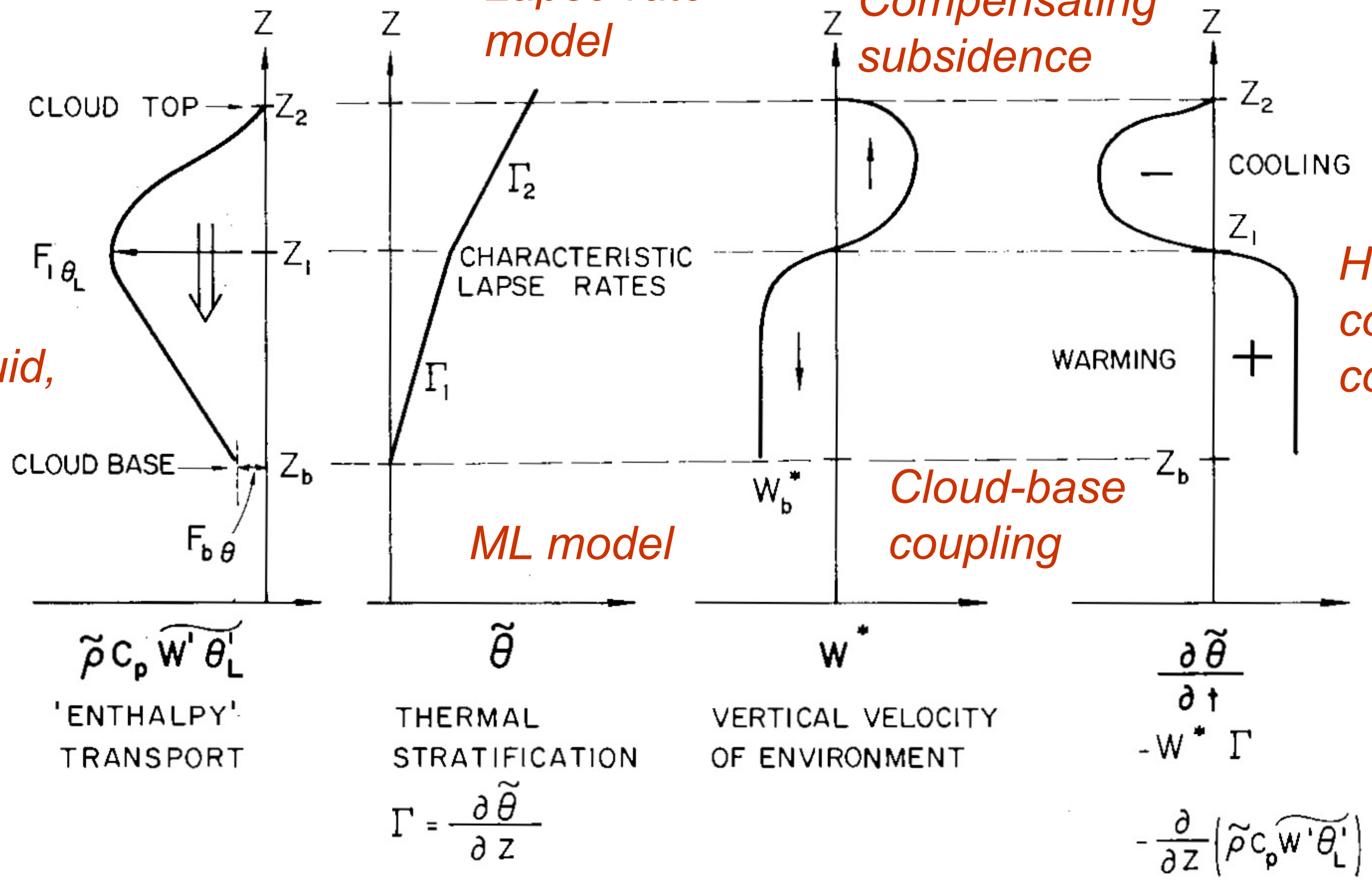


Frontispiece

Cumulus convection over Anaco, Venezuela at 1600 hrs (local time) on 17th August 1969. The cloud dominating the picture has nearly reached its maximum height, and later completely evaporates. Cloud base is at 855mb (1250m above the ground), and cloud top is at 650mb (3600m).

Shallow Cumulus Transports

Liquid water potential temperature



Lapse-rate model

Compensating subsidence

Irreversible upward liquid, downward enthalpy transports

Heating/ cooling couplet

ML model

Cloud-base coupling

θ_L model

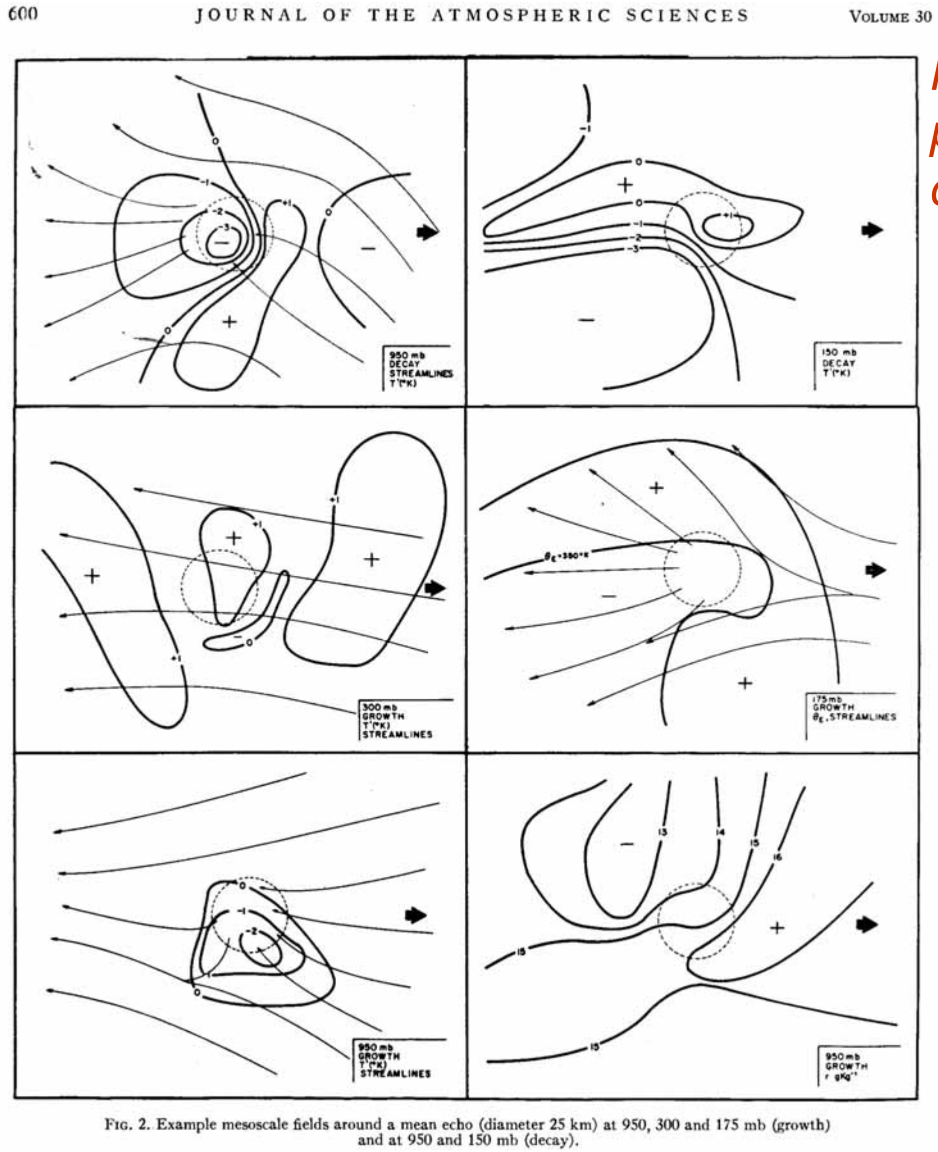
Figure 2. Sketch of the 'enthalpy' transport $\tilde{\rho} C_p \widetilde{W'\theta_L'}$ for a field of non-precipitating clouds; the thermal stratification; the parameterization of the modification of the mean atmosphere by the convection in terms of the vertical motion of the air between the clouds; and the local temperature change induced by the convection.

Tracking pibals with a theodolite

Great computer support: PDP-8S!

- Paper tape input
- Took 6+ hrs (all night) to process 8 soundings
- Raw data to p, T, q, u, v, θ, θ_E

Elegant Cb budget model but very primitive hand-drawn analyses



600 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 30

FIG. 2. Example mesoscale fields around a mean echo (diameter 25 km) at 950, 300 and 175 mb (growth) and at 950 and 150 mb (decay).

Note: no plotted data!

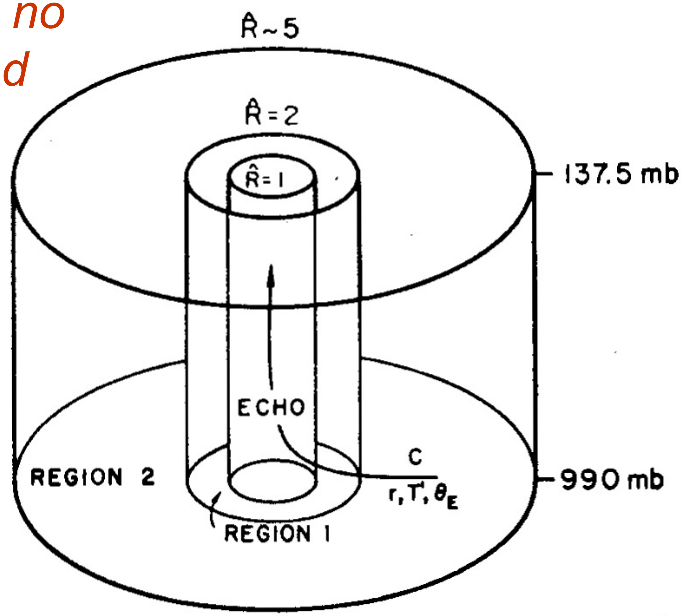


FIG. 1. Cumulonimbus model used for budget computations. Radius of 1, 2 boundary is twice that of echo.

(x,y) scaled to echo size (!)

Convergence and divergence into cylinder around radar echo for growth and decay phases and in 5K θ_E ranges

[Betts, JAS 1973]

Mesoscale Cumulonimbus budget:

Confirmed mass transport model: End of Kuo

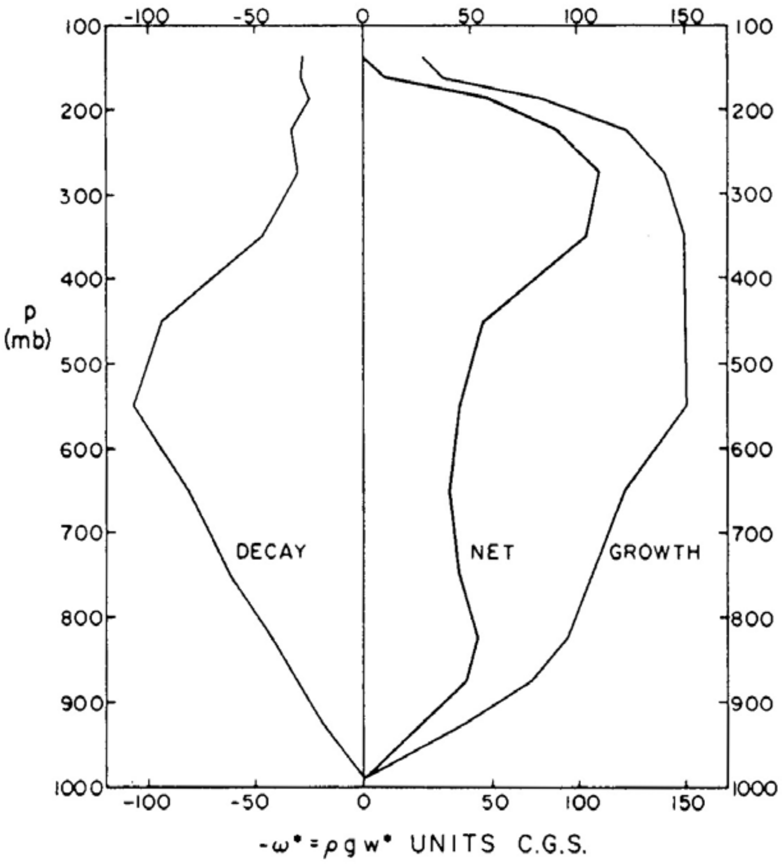


FIG. 4. Vertical mass flux ($-\omega^*$) vs pressure for growth and decay phases, and their sum (representing the net mass flux).

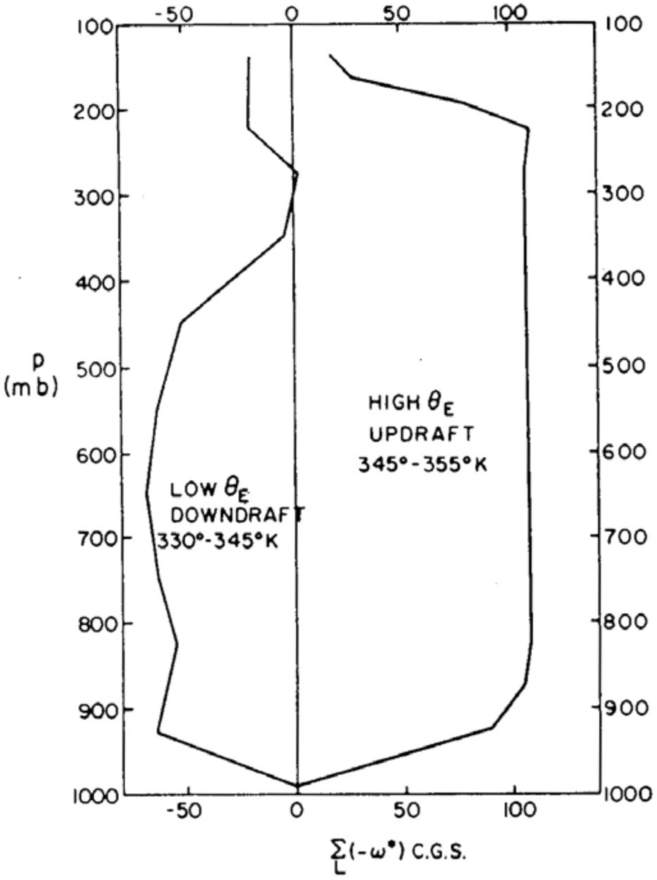
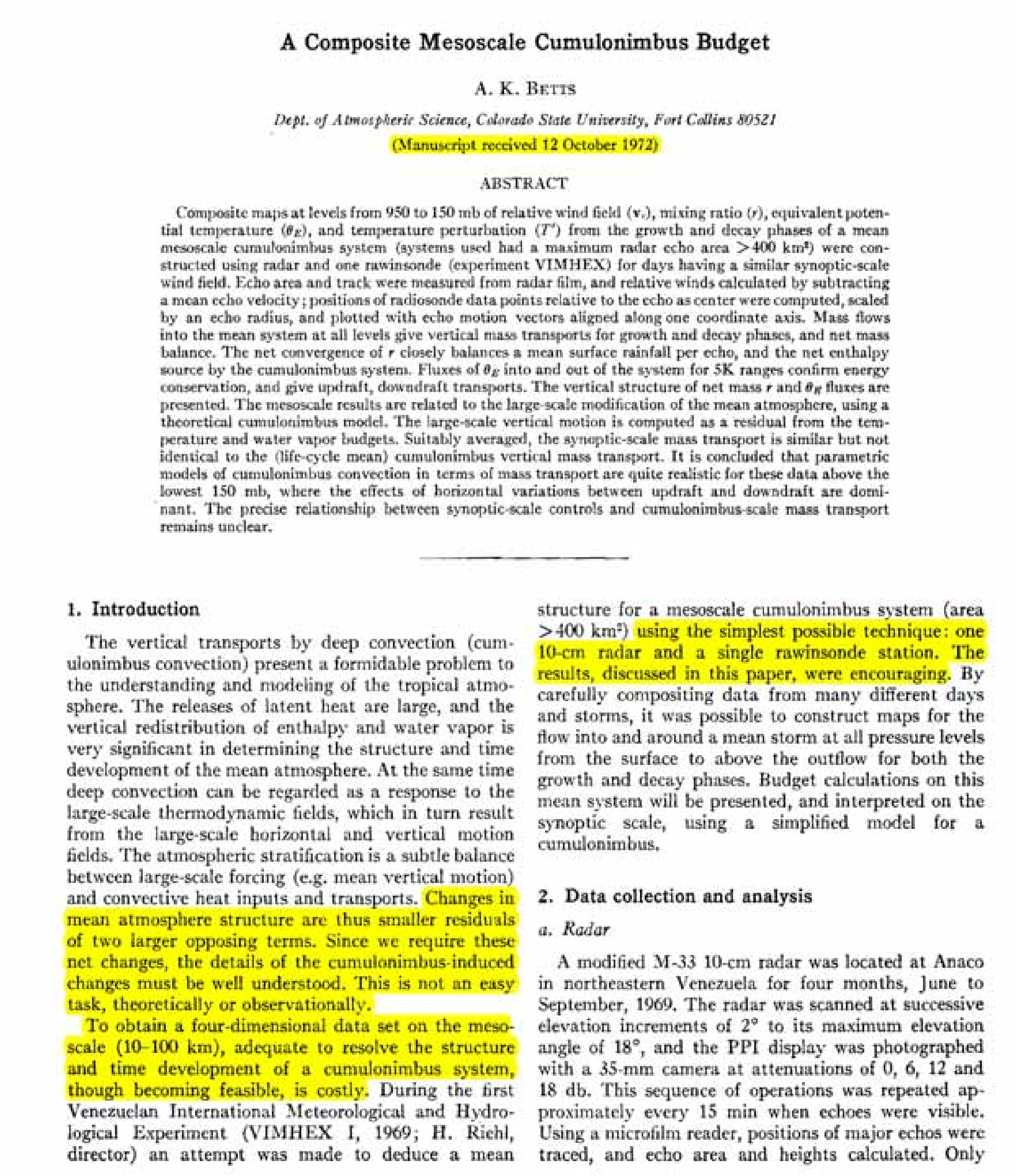


FIG. 6. Net vertical mass flux vs pressure for high (345–355K) .nd low θ_E (330–345K) ranges, depicting simplified updraft and lowndraft.

Updraft & downdraft mass, water and θ_E fluxes

[Betts, JAS 1973]

Inside story: post-doc with Herb Riehl



A Composite Mesoscale Cumulonimbus Budget

A. K. Betts

Dept. of Atmospheric Science, Colorado State University, Fort Collins 80521

(Manuscript received 12 October 1972)

ABSTRACT

Composite maps at levels from 950 to 150 mb of relative wind field ($\mathbf{v}_r$), mixing ratio (r), equivalent potential temperature (θ_E), and temperature perturbation (T') from the growth and decay phases of a mean mesoscale cumulonimbus system (systems used had a maximum radar echo area $>400\ \text{km}^2$) were constructed using radar and one rawinsonde (experiment VIMHEX) for days having a similar synoptic-scale wind field. Echo area and track were measured from radar film, and relative winds calculated by subtracting a mean echo velocity; positions of radiosonde data points relative to the echo as center were computed, scaled by an echo radius, and plotted with echo motion vectors aligned along one coordinate axis. Mass flows into the mean system at all levels give vertical mass transports for growth and decay phases, and net mass balance. The net convergence of r closely balances a mean surface rainfall per echo, and the net enthalpy source by the cumulonimbus system. Fluxes of θ_E into and out of the system for 5K ranges confirm energy conservation, and give updraft, downdraft transports. The vertical structure of net mass r and θ_E fluxes are presented. The mesoscale results are related to the large-scale modification of the mean atmosphere, using a theoretical cumulonimbus model. The large-scale vertical motion is computed as a residual from the temperature and water vapor budgets. Suitably averaged, the synoptic-scale mass transport is similar but not identical to the (life-cycle mean) cumulonimbus vertical mass transport. It is concluded that parametric models of cumulonimbus convection in terms of mass transport are quite realistic for these data above the lowest 150 mb, where the effects of horizontal variations between updraft and downdraft are dominant. The precise relationship between synoptic-scale controls and cumulonimbus-scale mass transport remains unclear.

1. Introduction

The vertical transports by deep convection (cumulonimbus convection) present a formidable problem to the understanding and modeling of the tropical atmosphere. The releases of latent heat are large, and the vertical redistribution of enthalpy and water vapor is very significant in determining the structure and time development of the mean atmosphere. At the same time deep convection can be regarded as a response to the large-scale thermodynamic fields, which in turn result from the large-scale horizontal and vertical motion fields. The atmospheric stratification is a subtle balance between large-scale forcing (e.g. mean vertical motion) and convective heat inputs and transports. Changes in mean atmosphere structure are thus smaller residuals of two larger opposing terms. Since we require these net changes, the details of the cumulonimbus-induced changes must be well understood. This is not an easy task, theoretically or observationally.

To obtain a four-dimensional data set on the mesoscale (10–100 km), adequate to resolve the structure and time development of a cumulonimbus system, though becoming feasible, is costly. During the first Venezuelan International Meteorological and Hydrological Experiment (VIMHEX I, 1969; H. Riehl, director) an attempt was made to deduce a mean structure for a mesoscale cumulonimbus system (area $>400\ \text{km}^2$) using the simplest possible technique: one 10-cm radar and a single rawinsonde station. The results, discussed in this paper, were encouraging. By carefully compositing data from many different days and storms, it was possible to construct maps for the flow into and around a mean storm at all pressure levels from the surface to above the outflow for both the growth and decay phases. Budget calculations on this mean system will be presented, and interpreted on the synoptic scale, using a simplified model for a cumulonimbus.

2. Data collection and analysis

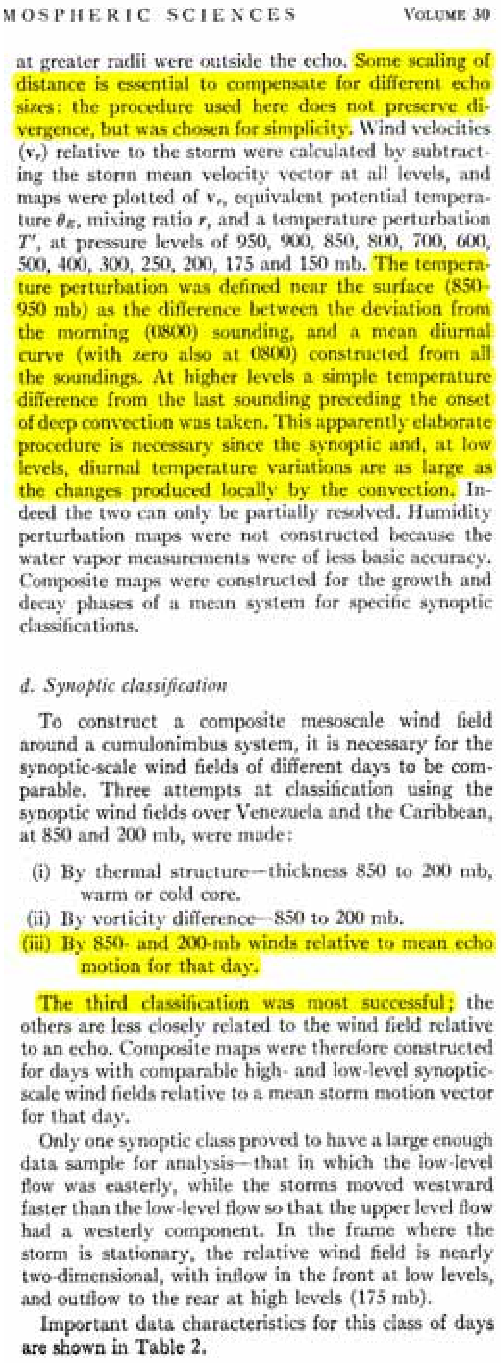
a. Radar

A modified M-33 10-cm radar was located at Anaco in northeastern Venezuela for four months, June to September, 1969. The radar was scanned at successive elevation increments of 2° to its maximum elevation angle of 18°, and the PPI display was photographed with a 35-mm camera at attenuations of 0, 6, 12 and 18 db. This sequence of operations was repeated approximately every 15 min when echoes were visible. Using a microfilm reader, positions of major echos were traced, and echo area and heights calculated. Only

Betts, JAS 1973

All the caveats of compositing data before computers

Analysis never repeated – shifted to 2-D line analyses



at greater radii were outside the echo. Some scaling of distance is essential to compensate for different echo sizes: the procedure used here does not preserve divergence, but was chosen for simplicity. Wind velocities ($\mathbf{v}_r$) relative to the storm were calculated by subtracting the storm mean velocity vector at all levels, and maps were plotted of $\mathbf{v}_r$, equivalent potential temperature θ_E, mixing ratio r, and a temperature perturbation T', at pressure levels of 950, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 175 and 150 mb. The temperature perturbation was defined near the surface (850–950 mb) as the difference between the deviation from the morning (0800) sounding, and a mean diurnal curve (with zero also at 0800) constructed from all the soundings. At higher levels a simple temperature difference from the last sounding preceding the onset of deep convection was taken. This apparently elaborate procedure is necessary since the synoptic and, at low levels, diurnal temperature variations are as large as the changes produced locally by the convection. Indeed the two can only be partially resolved. Humidity perturbation maps were not constructed because the water vapor measurements were of less basic accuracy. Composite maps were constructed for the growth and decay phases of a mean system for specific synoptic classifications.

d. Synoptic classification

To construct a composite mesoscale wind field around a cumulonimbus system, it is necessary for the synoptic-scale wind fields of different days to be comparable. Three attempts at classification using the synoptic wind fields over Venezuela and the Caribbean, at 850 and 200 mb, were made:

(i) By thermal structure—thickness 850 to 200 mb, warm or cold core.
(ii) By vorticity difference—850 to 200 mb.
(iii) By 850- and 200-mb winds relative to mean echo motion for that day.

The third classification was most successful; the others are less closely related to the wind field relative to an echo. Composite maps were therefore constructed for days with comparable high- and low-level synoptic-scale wind fields relative to a mean storm motion vector for that day.

Only one synoptic class proved to have a large enough data sample for analysis—that in which the low-level flow was easterly, while the storms moved westward faster than the low-level flow so that the upper level flow had a westerly component. In the frame where the storm is stationary, the relative wind field is nearly two-dimensional, with inflow in the front at low levels, and outflow to the rear at high levels (175 mb).

Important data characteristics for this class of days are shown in Table 2.

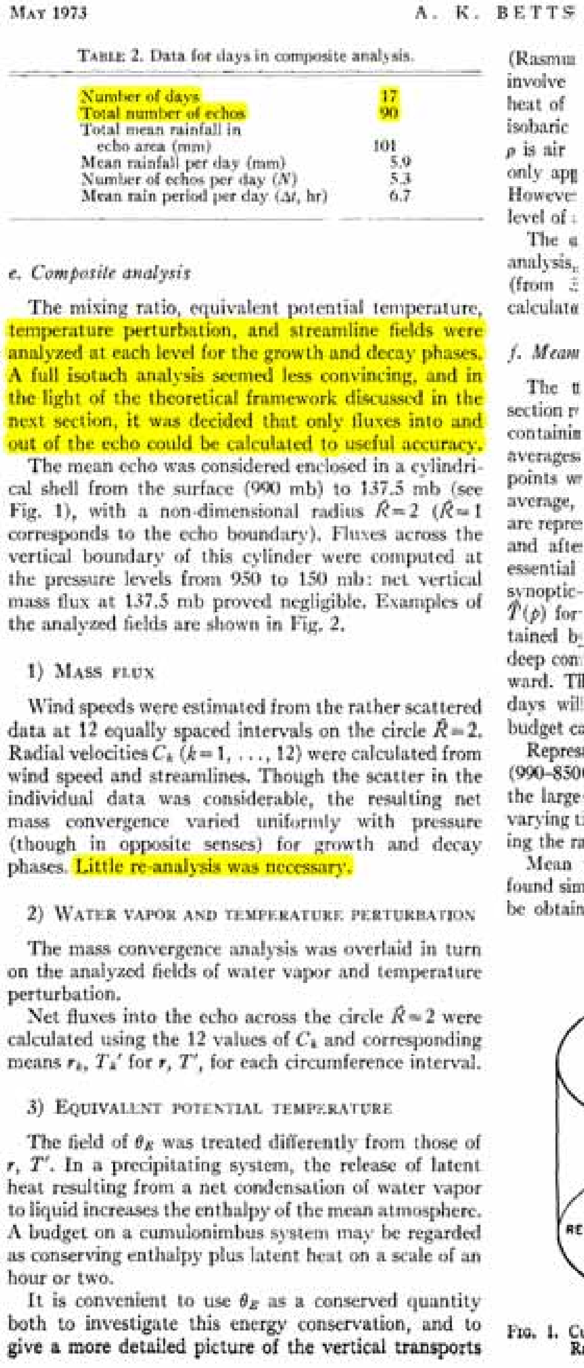


TABLE 2. Data for days in composite analysis.

Number of days	17
Total number of echos	90
Total mean rainfall in echo area (mm)	101
Mean rainfall per day (mm)	5.9
Number of echos per day (N)	5.3
Mean rain period per day (Δt, hr)	6.7

e. Composite analysis

The mixing ratio, equivalent potential temperature, temperature perturbation, and streamline fields were analyzed at each level for the growth and decay phases. A full isotach analysis seemed less convincing, and in the light of the theoretical framework discussed in the next section, it was decided that only fluxes into and out of the echo could be calculated to useful accuracy.

The mean echo was considered enclosed in a cylindrical shell from the surface (990 mb) to 137.5 mb (see Fig. 1), with a non-dimensional radius $\hat{R}=2$ ($\hat{R}=1$ corresponds to the echo boundary). Fluxes across the vertical boundary of this cylinder were computed at the pressure levels from 950 to 150 mb: net vertical mass flux at 137.5 mb proved negligible. Examples of the analyzed fields are shown in Fig. 2.

1) MASS FLUX

Wind speeds were estimated from the rather scattered data at 12 equally spaced intervals on the circle $\hat{R}=2$. Radial velocities C_k ($k=1,\ldots,12$) were calculated from wind speed and streamlines. Though the scatter in the individual data was considerable, the resulting net mass convergence varied uniformly with pressure (though in opposite senses) for growth and decay phases. Little re-analysis was necessary.

2) WATER VAPOR AND TEMPERATURE PERTURBATION

The mass convergence analysis was overlaid in turn on the analyzed fields of water vapor and temperature perturbation.

Net fluxes into the echo across the circle $\hat{R}=2$ were calculated using the 12 values of C_k and corresponding means r_k, T_k' for r, T', for each circumference interval.

3) EQUIVALENT POTENTIAL TEMPERATURE

The field of θ_E was treated differently from those of r, T'. In a precipitating system, the release of latent heat resulting from a net condensation of water vapor to liquid increases the enthalpy of the mean atmosphere. A budget on a cumulonimbus system may be regarded as conserving enthalpy plus latent heat on a scale of an hour or two.

It is convenient to use θ_E as a conserved quantity both to investigate this energy conservation, and to give a more detailed picture of the vertical transports

Visit Bob & Joanne Simpson in Miami (1969)
Martin Miller renting a Plymouth Fury-III
– a UK grad student with no credit card

VIMHEX-1972: Carrizal Improved S-band radar

- **Tracked storms on radar**
- **Launched precalibrated rawinsondes every 90mins**
- **2-D analysis & 3-D model**

Betts, Grover & Moncrieff, QJRMS 1976

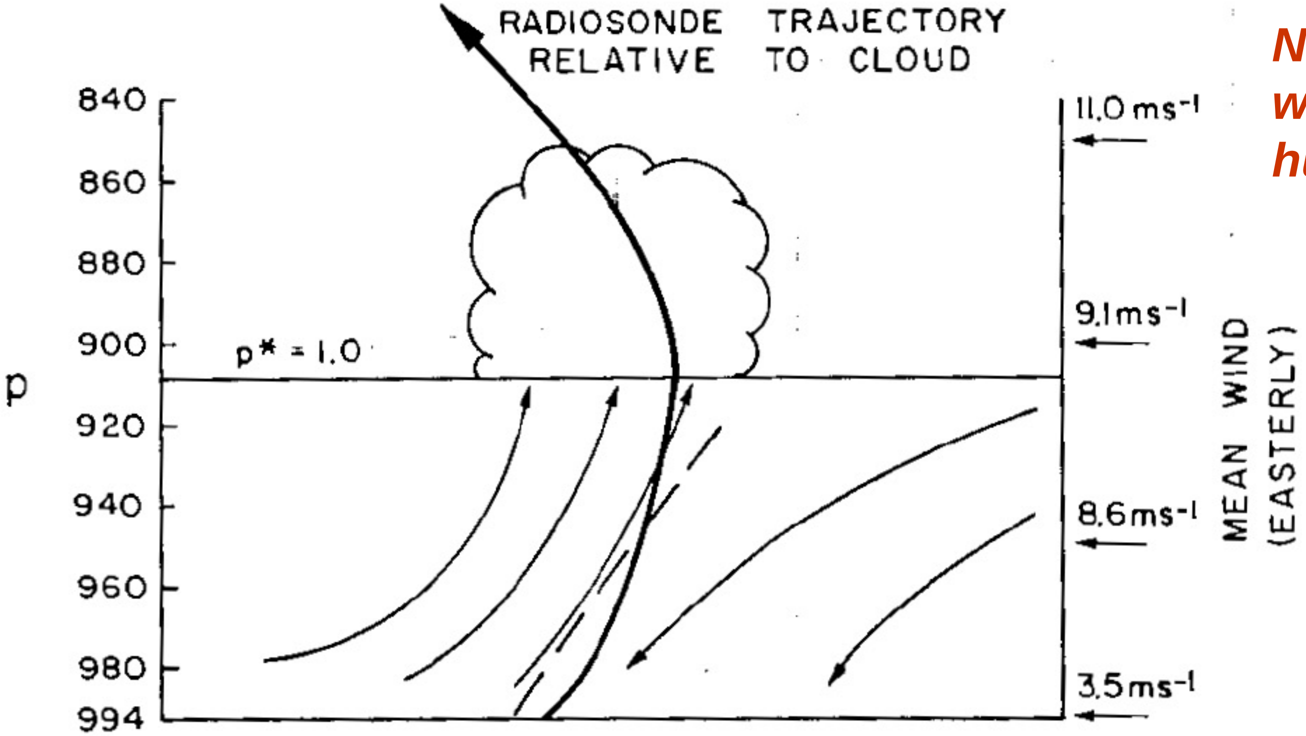
Betts, JAS 1976

Miller and Betts, MWR 1977

Squall-line approaching VIMHEX-1972

Herbert Riehl arriving at field site

Calibrated humidity by timing when sonde entered cloud-base



New VIZ sondes with good humidity

FIG. 2. Suggested circulation relative to a cloud in the sub-cloud layer, indicating how an ascending radiosonde can enter rising moister air in the upper part of the sub-cloud layer.

Betts et al. BAMS 1974

Mean of 14 ascents through cloud-base

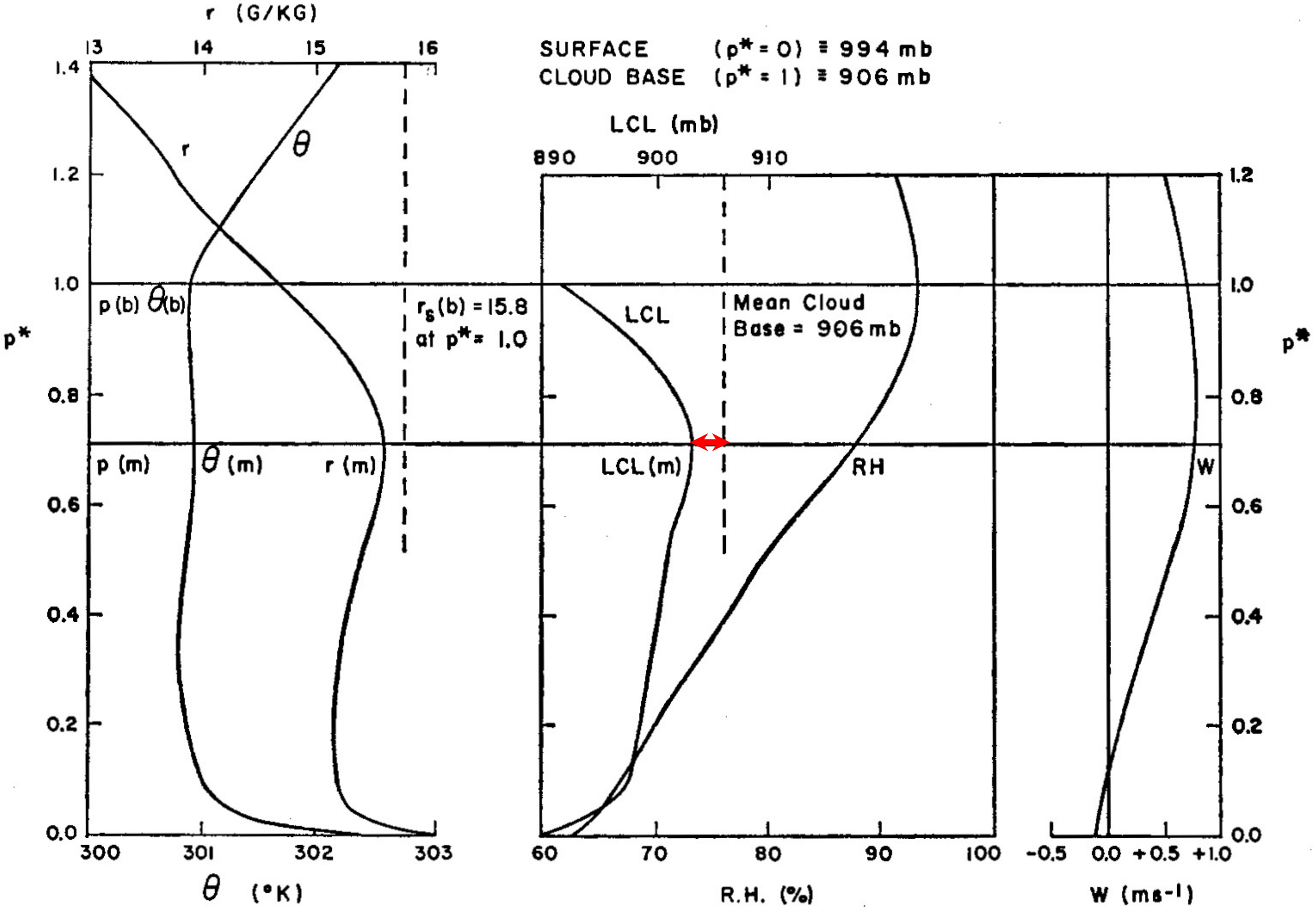


FIG. 1. Mean profile for 14 radiosonde ascents through cloud-base of potential temperature (θ), mixing ratio (r), lifting condensation level (LCL), relative humidity (RH), perturbation vertical velocity (w).

Many linear systems: quasi-2D

The Thermodynamic Transformation of the Tropical Subcloud Layer by Precipitation and Downdrafts

Alan K. Betts

Department of Atmospheric Science, Colorado State University, Fort Collins, Colo. 80523

(Manuscript received 9 September 1975, in revised form 27 January 1976)

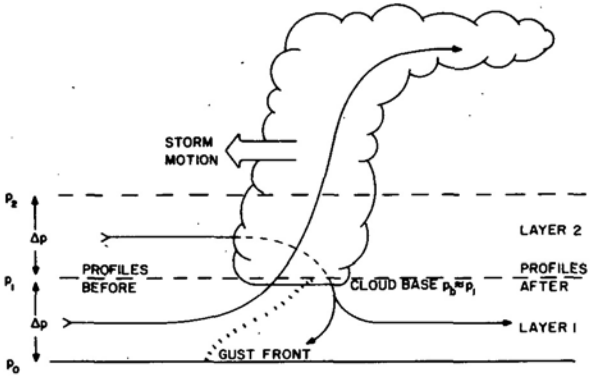


Fig. 2. Schematic airflow relative to travelling mesosystem, showing two-layer model exchange: inflow layer p_0 to p_1 ascends in updrafts and inflow layer p_1 to p_2 descends in downdrafts in replacement. (Actual flow inside system will be both three-dimensional and transient, not two-dimensional as sketched.)

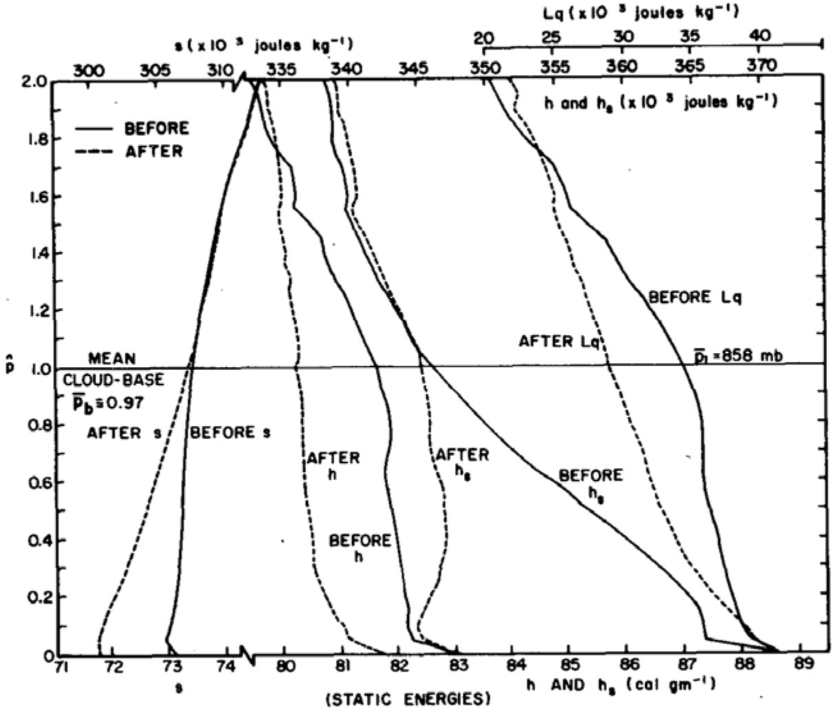


Fig. 5. Mean profiles before and after the passage of a convective system. The curves are averages of 21 before-after sounding pairs.

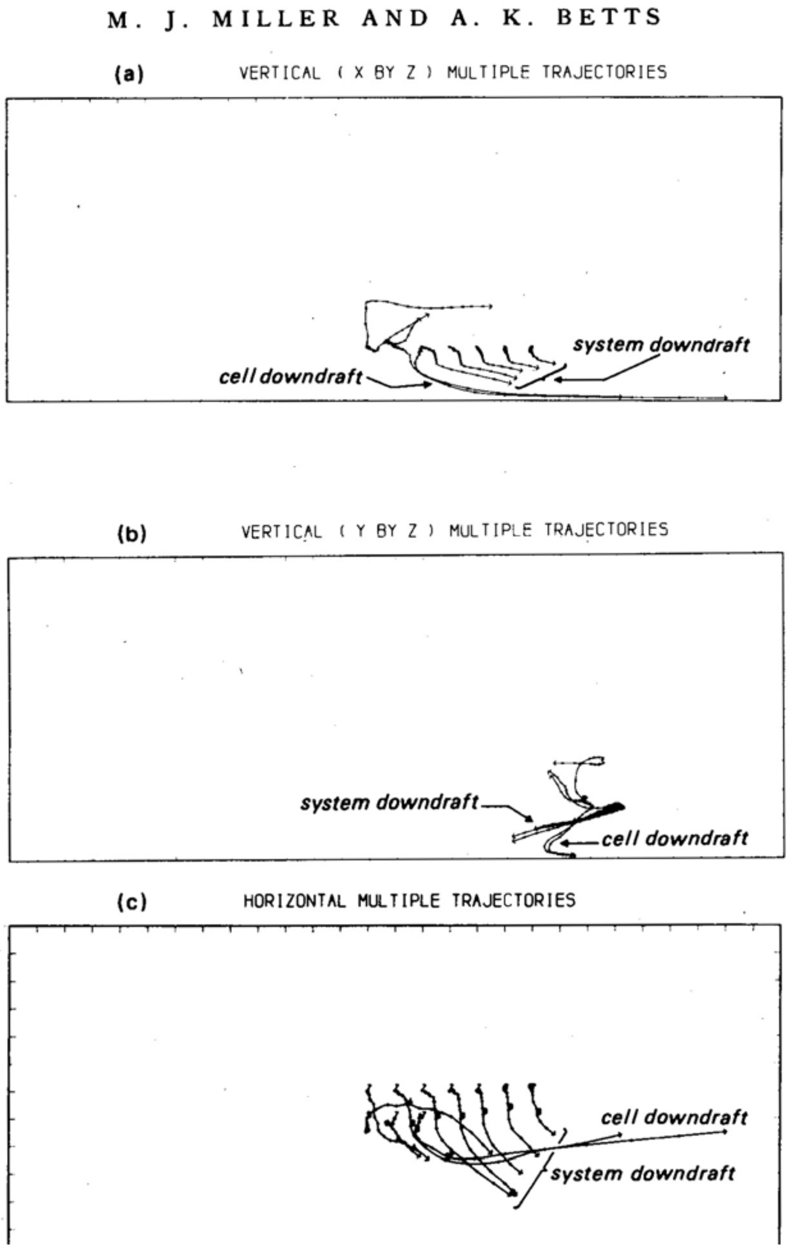
- Diagnostics of BL transformation using 2-D framework of inflow/outflow; updraft/downdraft
- Conservation of mass & moist static energy/θ_E

Numerical simulation of Venezuela squall-line #47

- 3-D trajectory analysis of cell and system downdrafts
- On 30x30x9 grid

[Moncrieff & Miller 1976

Miller and Betts 1977]

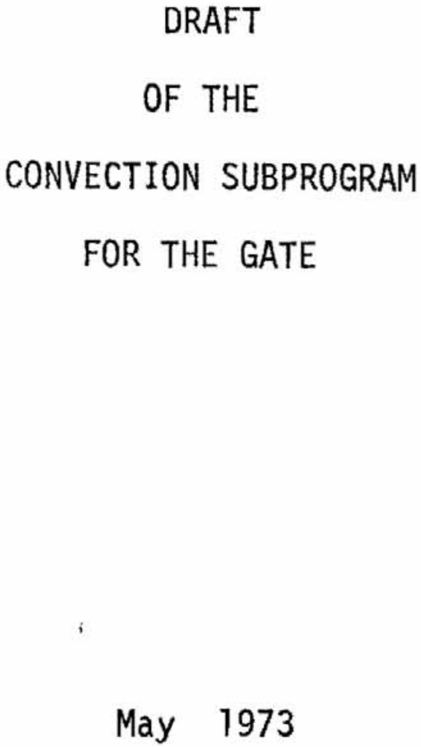


Trajectories starting from 750 hPa

By now an ‘expert’ on tropical convection?

- Reality was
- All subprograms written (synop, BL, radn, oceanog.
- Not the key one
- Situation desperate!

- *But Smagorinsky would let me come to parameterization club!*



DRAFT

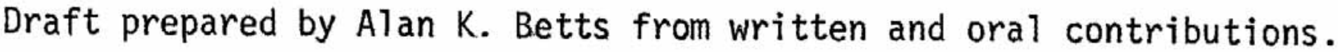
OF THE

CONVECTION SUBPROGRAM

FOR THE GATE

May 1973

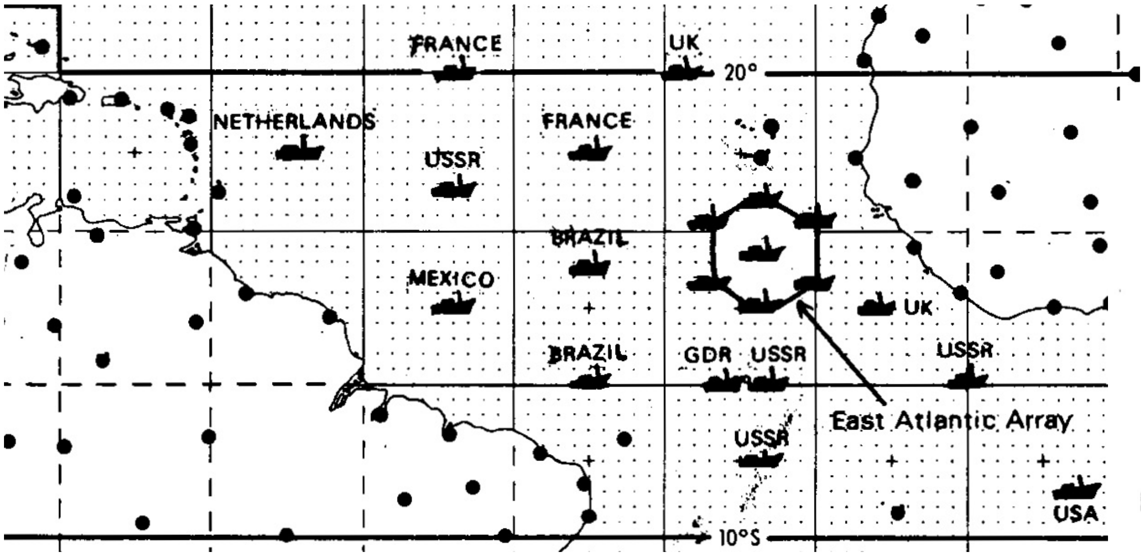
Published BAMS, 1974



Draft prepared by Alan K. Betts from written and oral contributions.

(Visited Arakawa, Yanai, Zipser, Reed, Young, Ogura)

GATE-1974



Ship array across Atlantic, mostly north of equator

Nested hexagons on ITCZ centered 8.5N,23.5W

7 research aircraft + dropsonde plane *(Mission scientists: Betts, Zipser, Cox, Lemone…)*

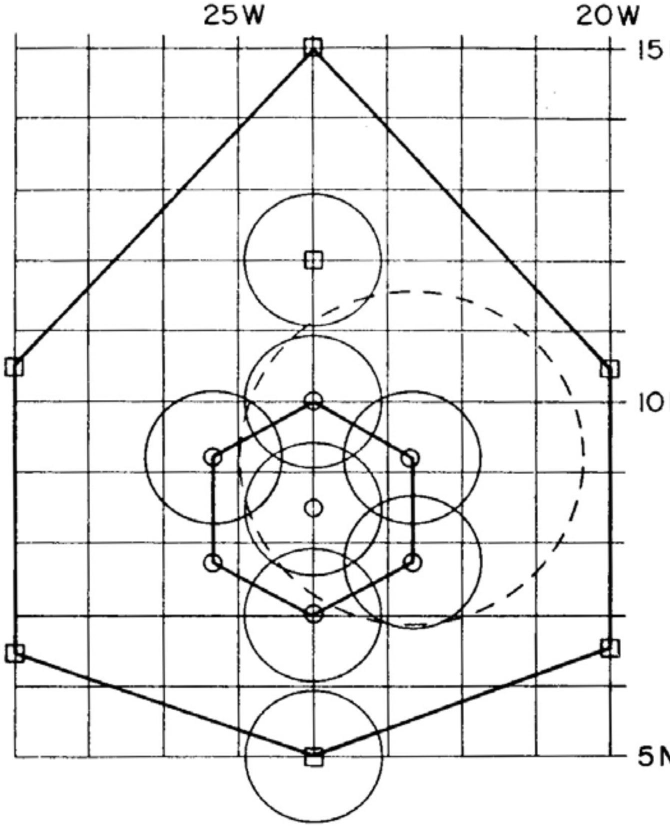
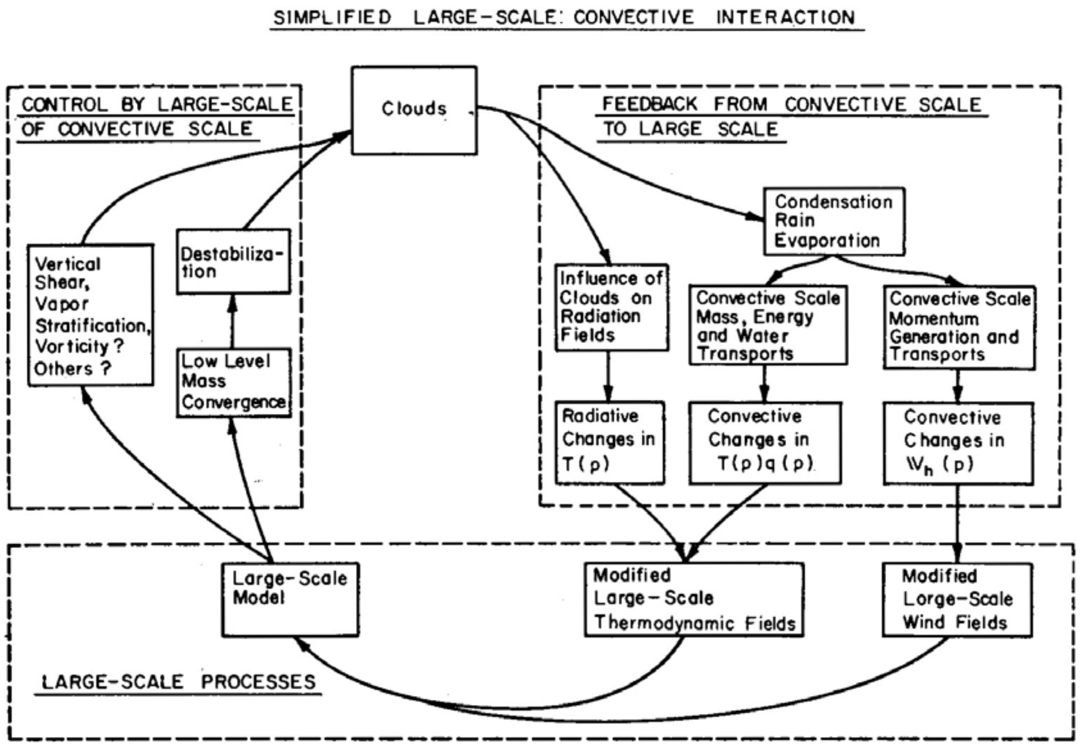
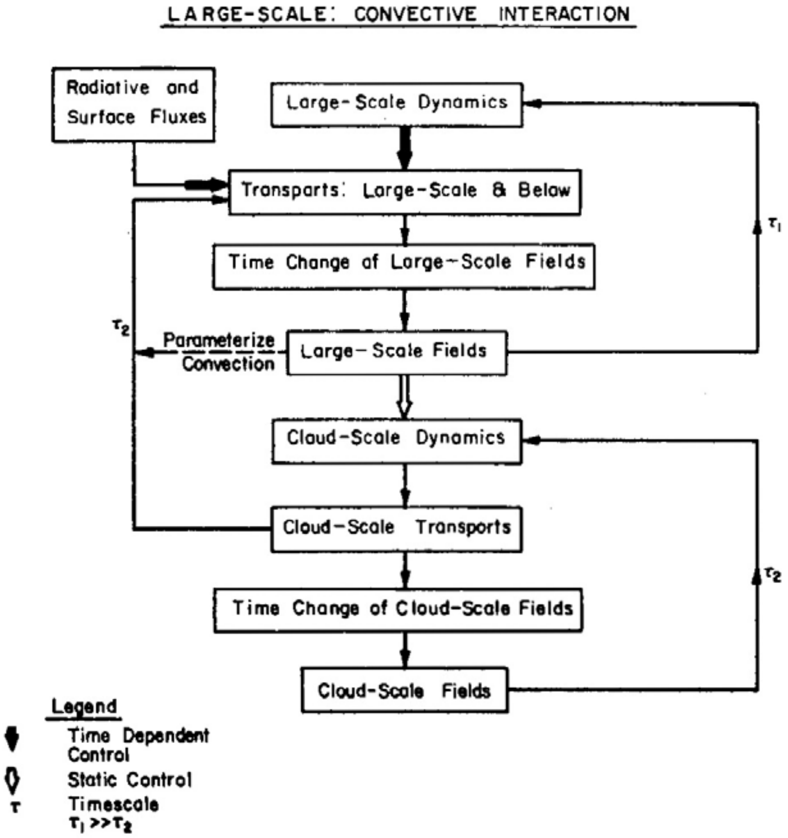


FIG. 12. The A/B and B network. The approximate coverage of overlapping radar scans is indicated for quantitative precipitation estimates during Phases I and II. In addition, the Quadra is planning greater qualitative coverage (indicated by dashed circle) for operational planning.

GATE political objective: US-USSR collaboration Scientific objective: address cumulus parameterization problem



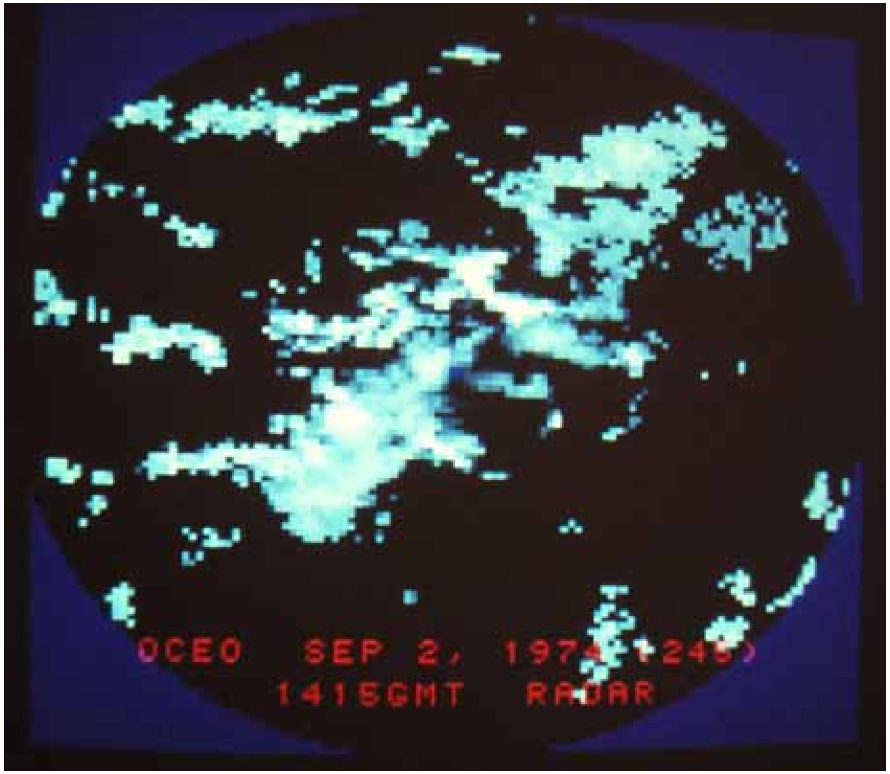


Scale-interaction diagrams are easy to draw!

Betts, BAMS 1974

OPEC: oil embargo

GATE day 245, Sept 2, 1974
Oceanographer radar



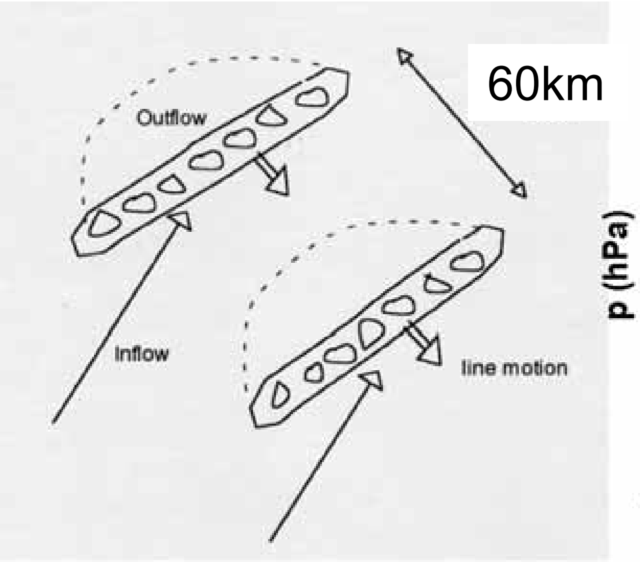
1415 UTC

1500 UTC

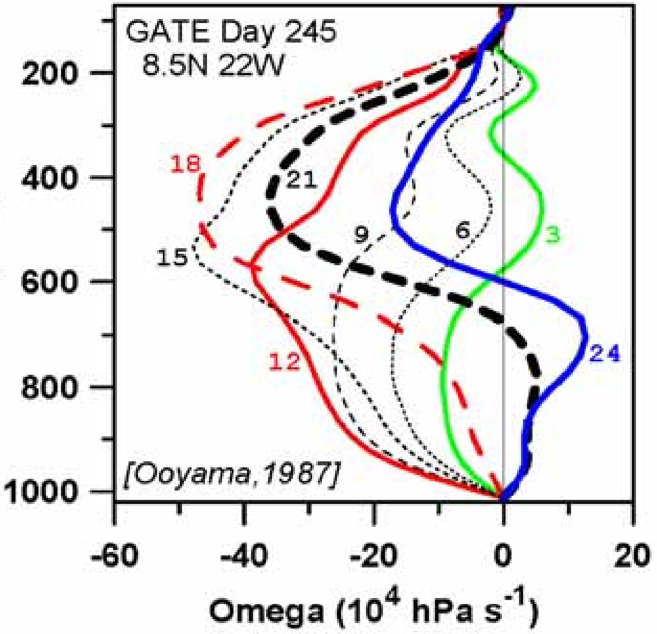
SE Ship position of inner array; range 100km

Note SW-NE bands & fast evolution

Reality - GATE ‘cloud cluster’ lifecycle on day 245 in 1974



Bands oriented along the low level shear, with inflows from SW, developing anvil outflow to the rear



03 low level convergence

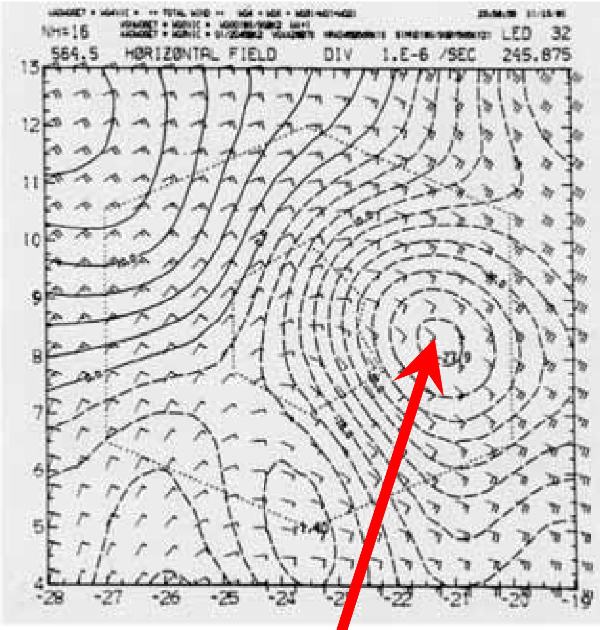
12 peak ascent mid-trop.

18 peak at 400mb

21 peak 600mb converg.

24 descent over ascent

565hPa



21UTC mid-tropospheric convergence peaks at 2.8 10^{-5} in decay phase (> low-level convergence at any time)

I mulled over this for 8-10 years

- **In 1978 I built a passive solar, wood-heated, PV-powered, post & beam house in Vermont (no phone, no internet) and thought about atmospheric convection…**
- **Betts, A. K., 1982: Saturation Point Analysis of Moist Convective Overturning. *J. Atmos. Sci.*, 39, 1484-1505**
- **Betts, A. K., 1983: Atmospheric convective structure and a convection scheme based on saturation point methods. ECMWF Workshop on "Convection in large-scale numerical models" 28 Nov.-1 Dec, 1983, Reading U. K., pp.69-94. http://www.ecmwf.int/publications/library/ecpublications/_pdf/workshop/1983/Convection/betts.pdf**
- **DETAILED OVERVIEW of concepts and framing of convective adjustment**

Concept for Betts-Miller scheme

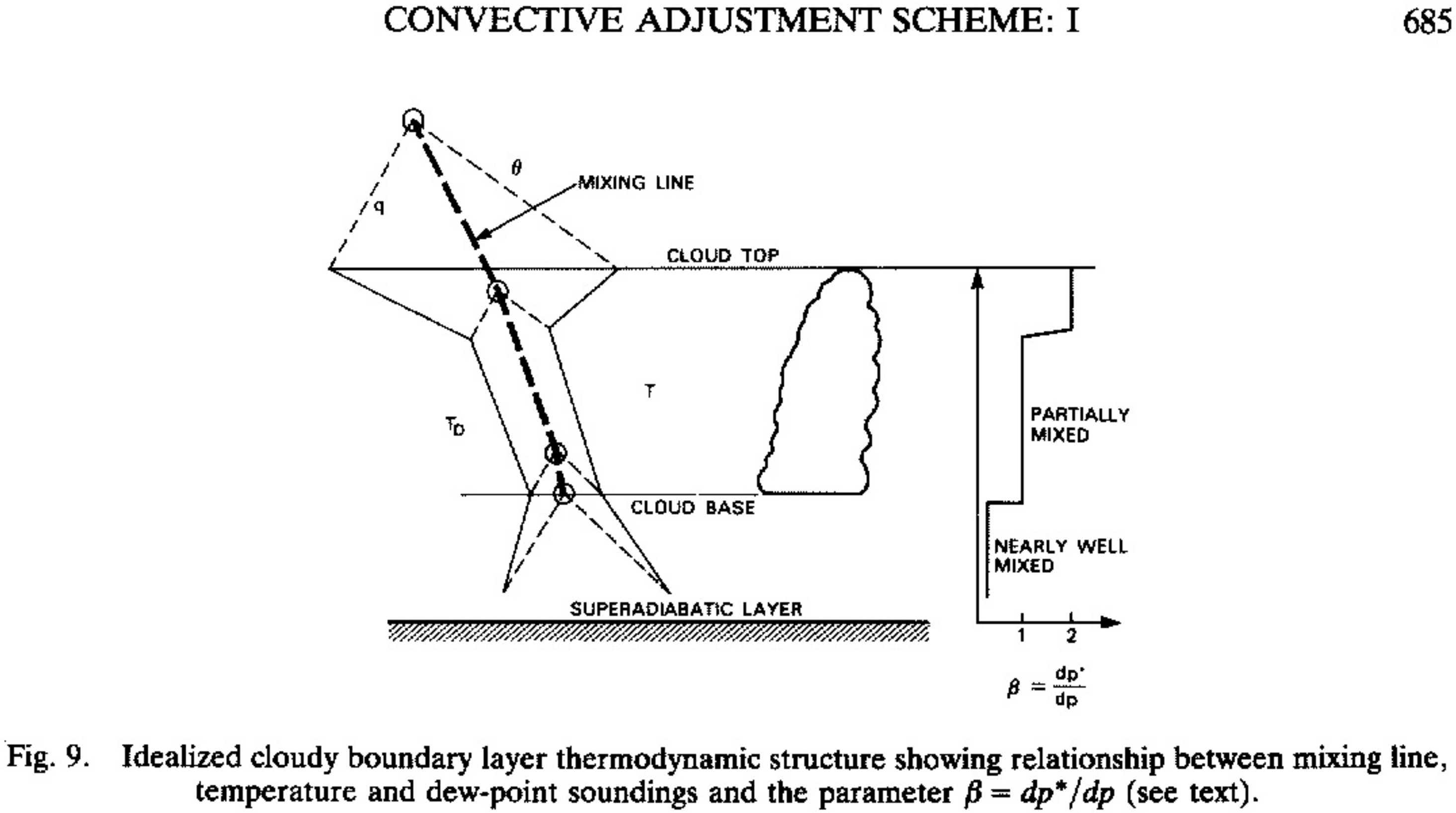
- Calculating transports from the details with so many coupled processes with so many unknowns and unresolved scales *may drift to unrealistic atmospheric structure (eg Arakawa & Schubert, 1974) ("poor climate")*
- So adjust with finite timescale to vertical (T,q) structure, satisfying θ_E conservation, in a way consistent with observed "quasi-equilibrium"
- Unstable to moist adiabat, minimum at freezing level and subsaturated.
- Guarantees quasi-realistic coupling of mass and energy transports and vertical structure
- *Use: parameterization & idealized models to understand coupled system*

Shallow and Deep Convection Differ

- Shallow – first order: non-precipitating: structure forcing & transports tightly coupled

- Deep – first order only: precip. coupled to deep single vertical mode forcing with conservation of θ_E
- *Convective mesoscale mode issue (Betts, A.K.: 1997, The Parameterization of deep convection, Ch.10)*

Shallow ‘mixing line’ scheme

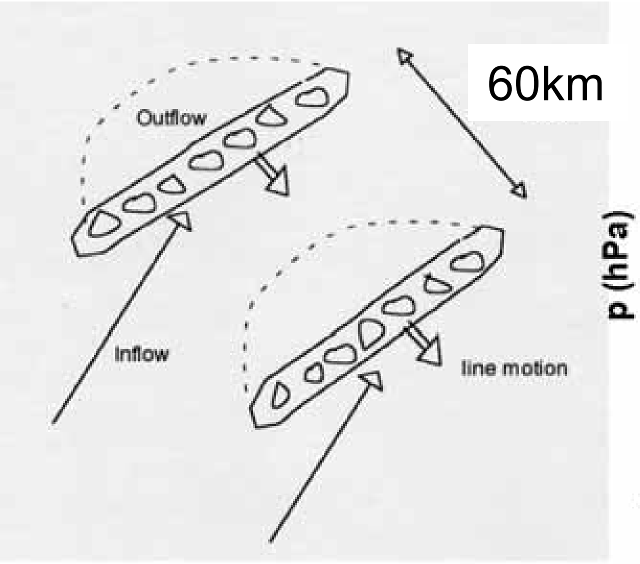


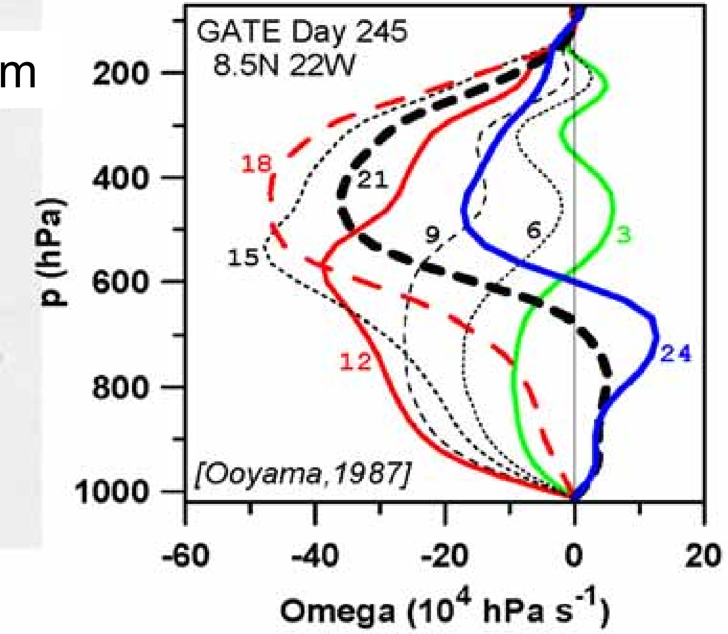
CONVECTIVE ADJUSTMENT SCHEME: I 685

Fig. 9. Idealized cloudy boundary layer thermodynamic structure showing relationship between mixing line, temperature and dew-point soundings and the parameter $\beta = dp^*/dp$ (see text).

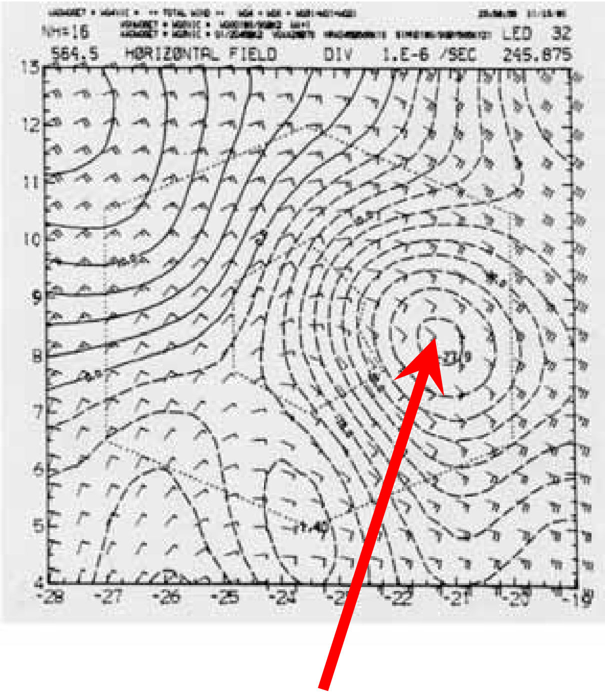
- *Based on Betts, JAS 1975, parameterized mixing line*
- **Maintain structure in the face of external forcing guarantees realistic transports (*Betts, A.K., 1997: Trade Cumulus: Observations and Modeling, Ch.4*)**

Deep - GATE ‘cloud cluster’ lifecycle on day 245 in 1974





565hPa



Bands oriented along the low level shear, with inflows from SW, developing anvil outflow to the rear

[See review in Betts 1997]

03 low level convergence

12 peak ascent mid-trop.

18 peak at 400mb

21 peak 600mb converg.

24 descent over ascent

21UTC mid-tropospheric convergence peaks at 2.8 10^{-5} in decay phase (> low-level convergence at any time)

Mass transports and precipitation flux only loosely coupled

- **The Key Convective Modes**
- **Arakawa and Chen [1987]**.... used canonical correlation analyses on the GATE Phase III data [Esbensen and Ooyama 1983] and an Asian data set [He et al. 1987] to show there were **three principal modes of coupling of (Q_1-Q_R) and Q_2.**

- ***Mode 1*** **is the principal deep convection mode** associated with net precipitation and a **single cell of mean upward vertical motion in the troposphere**, although within that there are moist updrafts and downdrafts.
- ***Mode 2*** is described by Arakawa and Chen as the component representing deviations of “large-scale” condensation and evaporation

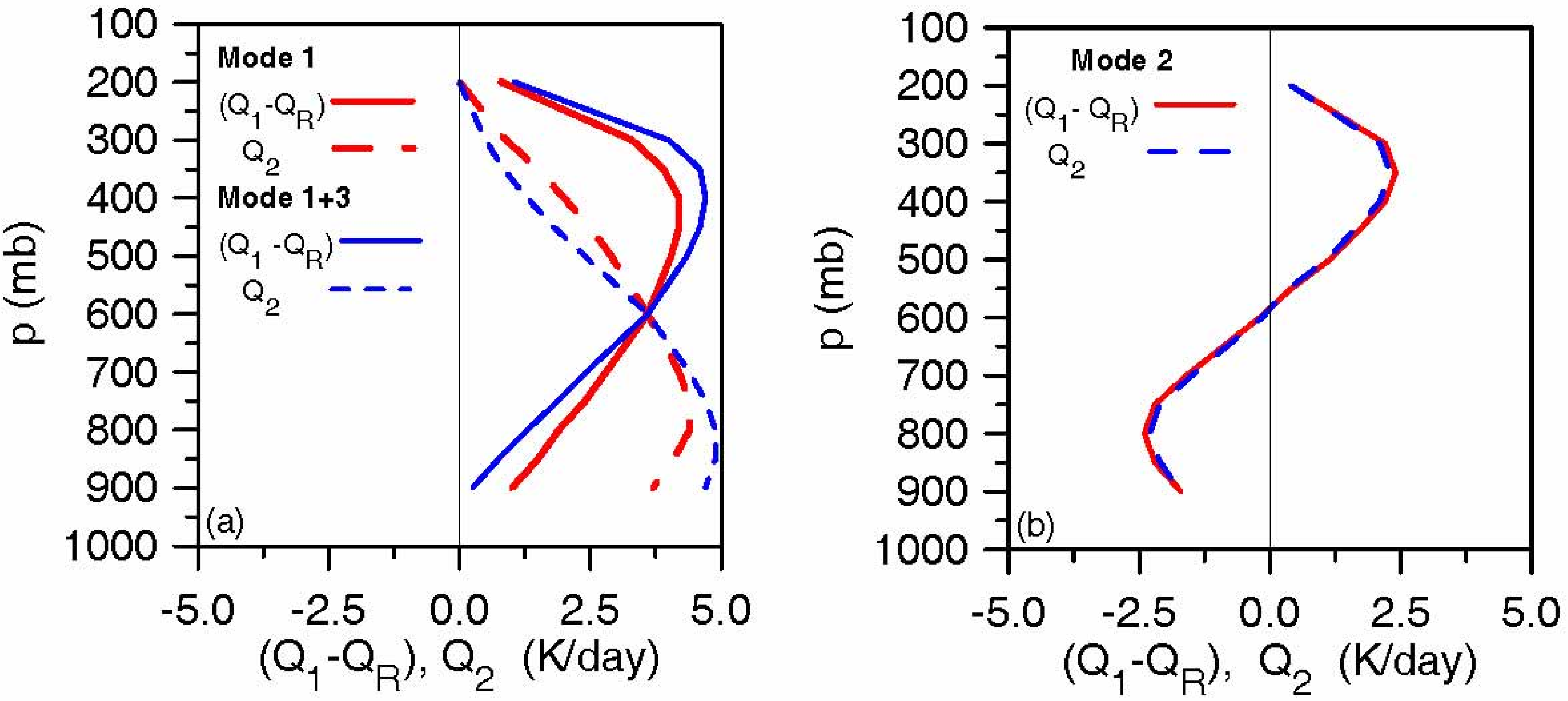
  Heating over cooling couplet driving circulation with no net precipitation

- ***Mode 3***... is a modulation of Mode 1, which *increases* the mid-tropospheric θ_E flux, without impact on net precipitation.

  Upward θ_E flux is *not uniquely* coupled to the precipitation.

[See review in Betts 1997]

Convective Modes 1 to 3



- **Same precipitation**
- **Different θ_E flux**

- **'Mesoscale mode'**
- Condensation/evaporation : no precipitation or θ_E flux

Many Questions 25 years on!

- How well do *convective models* represent the bulk properties of cloud systems?
- Do they represent the dominant convective modes as well as the SW and LW cloud forcing?
- Can we quantify the coupling of diabatic processes and evaluate them against observations?

- Can we evaluate convective vs stratiform precipitation, updraft and downdraft mass fluxes, and their microphysics against observations?

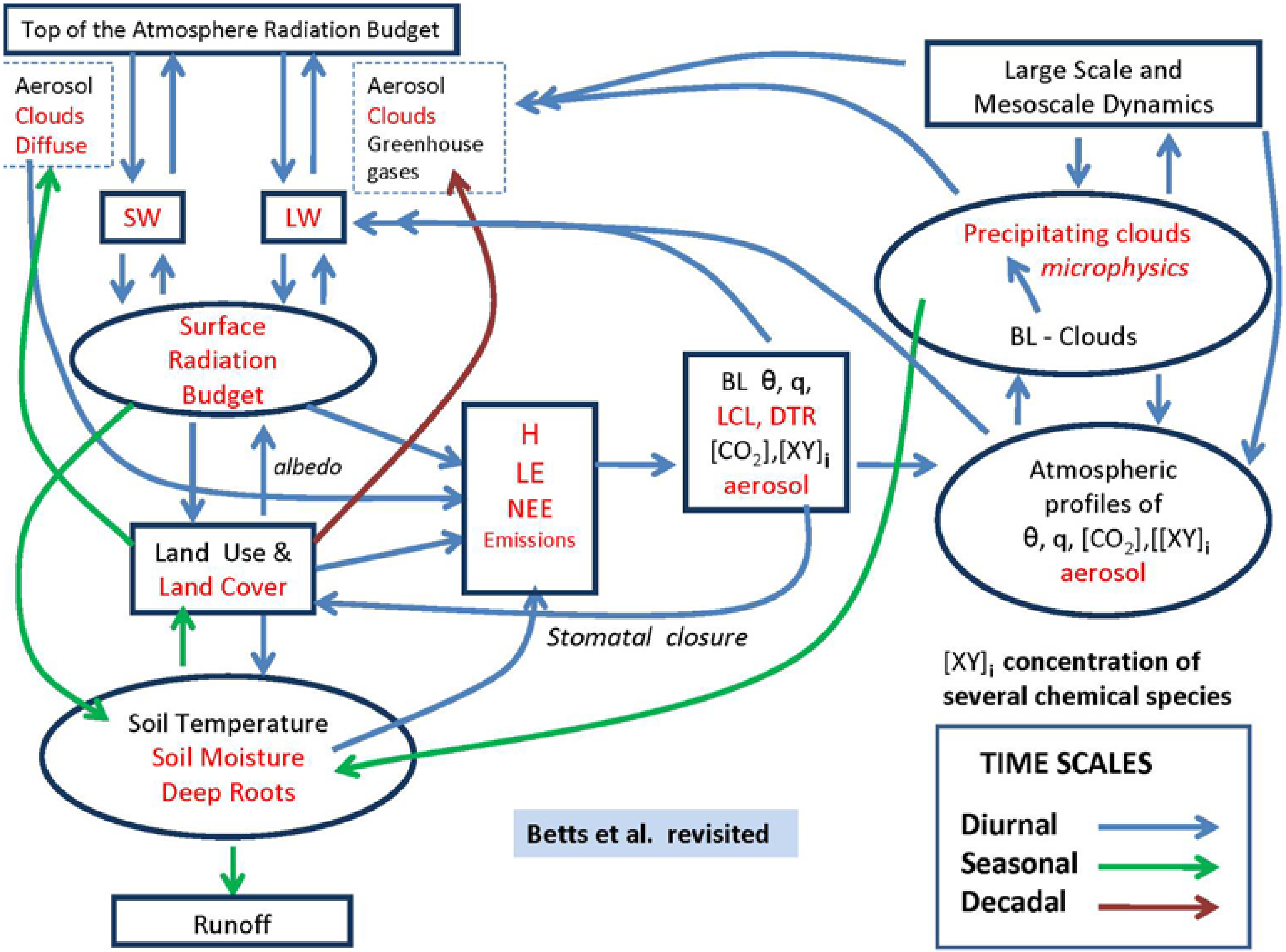
Conceptual challenges

- **Mass transports and precipitation only loosely coupled - dependent on cloud structure and microphysics eg. Precipitation-evaporation couplets can drive circulations with little net precipitation**
- **Microphysics & dynamics depend on aerosols – poorly known on global scale, but analyses coming**
- **The diabatic cloud radiative forcing and the latent heating diabatic forcing are of the same order**
- **Surface forcing is coupled radiatively to clouds & the large-scale circulation evolves quickly in mesoscale convective systems**
- **Can we parameterize or must we (partially) resolve cloud-scale? Still unanswered!**
- ***How do we handle the microphysics!***

Discussion

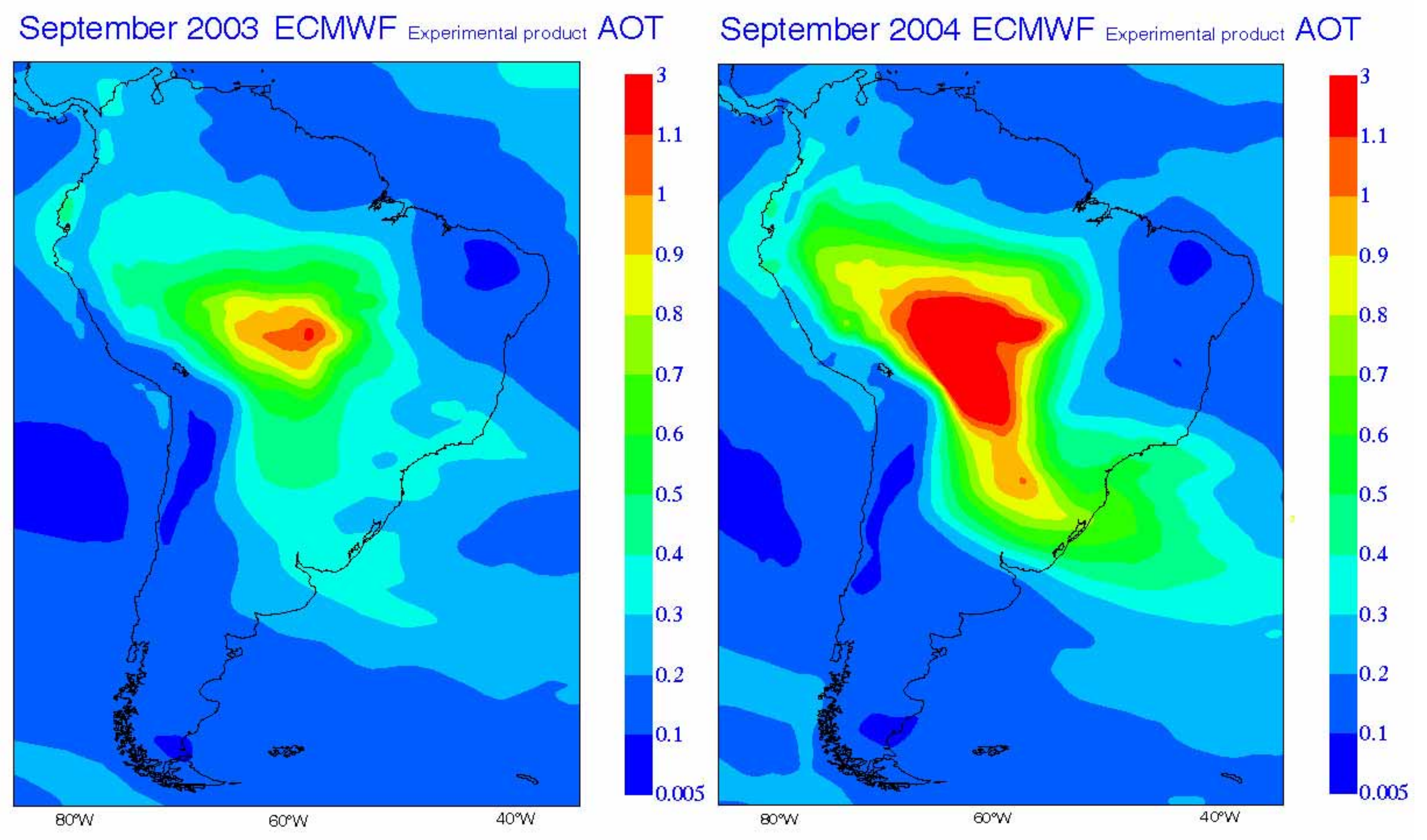
- More detailed reviews: see research talks at http://alanbetts.com/research
- **Betts, A. K., 1983**: Atmospheric convective structure and a convection scheme based on saturation point methods. ECMWF Workshop on “Convection in large-scale numerical models”

Process diagrams get more complex!



LBA-Amazônian research: Betts and Silva Dias, JAMES 2010

Aerosol issues: South America



- Amazonian September 'fire season' is variable *(Morcrette, 2009)*
- Impacts microphysics/dynamics
- Impacts surface net ecosystem exchange – diffuse penetrates canopies

Is there a way forward?

- **What can we learn from SCMs and CRMs with specified external forcing?**
- **Do they have the *freedom to develop* all the convective modes**
- **Is the radiative coupling realistic?**
- **How do we parameterize the microphysics and aerosols? *Which partly determine the coupling of updraft/downdraft mass circulations and precipitation.***
- **CO_2 budgets → mass transports?**

Final remarks

- 42 years ago I set off to Venezuela as graduate student ‘labor’ for Herbert Riehl
- Work has spanned an era in the study of tropical convection, BLs, land-atmosphere coupling, numerical model evaluation, and understanding climate change