
Alan K. Betts

http://alanbetts.com

U. Miami

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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

- Moncrieff, MW, and MJ Miller (1976). The dynamics and simulation of tropical cumulonimbus and squall lines. QJRMS, 102, 373-394
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!
Shallow Cumulus Transports

Liquid water potential temperature

Figure 2. Sketch of the ‘enthalpy’ transport $\tilde{\rho} C_p \tilde{W} ' \tilde{\theta}_L'$ 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

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 $\theta_E$ ranges

[Betts, JAS 1973]
Mesoscale Cumulonimbus budget: Confirmed mass transport model: End of Kuo

Updraft & downdraft mass, water and $\theta_E$ fluxes

[Betts, JAS 1973]
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 (v), mixing ratio (r), equivalent potential temperature (θ_v), 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 km²) were constructed using radar and one radionuclide (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 radionuclide data points relative to the echo 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 outflow source by the cumulonimbus system. Fluxes of σ_g 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 σ_g 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. Suiitably 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 km²) using the simplest possible technique: one 10-cm radar and a single radionuclide station. The results, discussed in this paper, were encouraging. By carefully compiling 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 about 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 echoes were traced, and echo area and heights calculated. Only
All the caveats of compositing data before computers

Analysis never repeated – shifted to 2-D line analyses
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

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 ($\theta$), 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 $p_s$ to $p_t$ ascends in updrafts and inflow layer $p_s$ to $p_t$ 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/$\theta_E$
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!**

Published BAMS, 1974

May 1973

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

(Visited Arakawa, Yanai, Zipser, Reed, Young, Ogura)
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
SE Ship position of inner array; range 100km
Note SW-NE bands & fast evolution

1500 UTC
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 convergence
24 descent over ascent

21UTC mid-tropospheric convergence peaks at 2.8 \times 10^{-5} \text{ 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…


• 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* (e.g., Arakawa & Schubert, 1974) (“poor climate”)

• So adjust with finite timescale to *vertical* $(T,q)$ structure, satisfying $\theta_E$ 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 $\theta_E$

- Convective mesoscale mode issue *(Betts, A.K.: 1997, The Parameterization of deep convection, Ch.10)*
Shallow ‘mixing line’ scheme

- 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)

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

[See review in Betts 1997]
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 $\theta_E$ flux, without impact on net precipitation.

Upward $\theta_E$ flux is *not uniquely* coupled to the precipitation.

[See review in Betts 1997]
Convective Modes 1 to 3

- Same precipitation
- Different $\theta_E$ flux

- 'Mesoscale mode'
- Condensation/evaporation: no precipitation or $\theta_E$ 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-Amazôñian 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.*

• $\text{CO}_2$ budgets $\rightarrow$ 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