The history of **Convection According to Betts and Miller**

A.K. Betts

http://alanbetts.com

Martin Miller Symposium

Convection in the Earth System

ECMWF

6 January, 2011

Early Years

- July 1969: Martin & 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
- 1974: Alan is *Convection Subprogramme and Airborne Mission Scientist* for GATE
- 1975: Mitch visits CSU
- 1976: Martin visits CSU
- 1978: Alan builds house in Vermont
- 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.**
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- **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.
- **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: Anaco, Venezuela, 1969

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***"

– inspired by this cloud

& the realization that even the 'expert' Herbert Riehl could not forecast daily tropical convection!

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

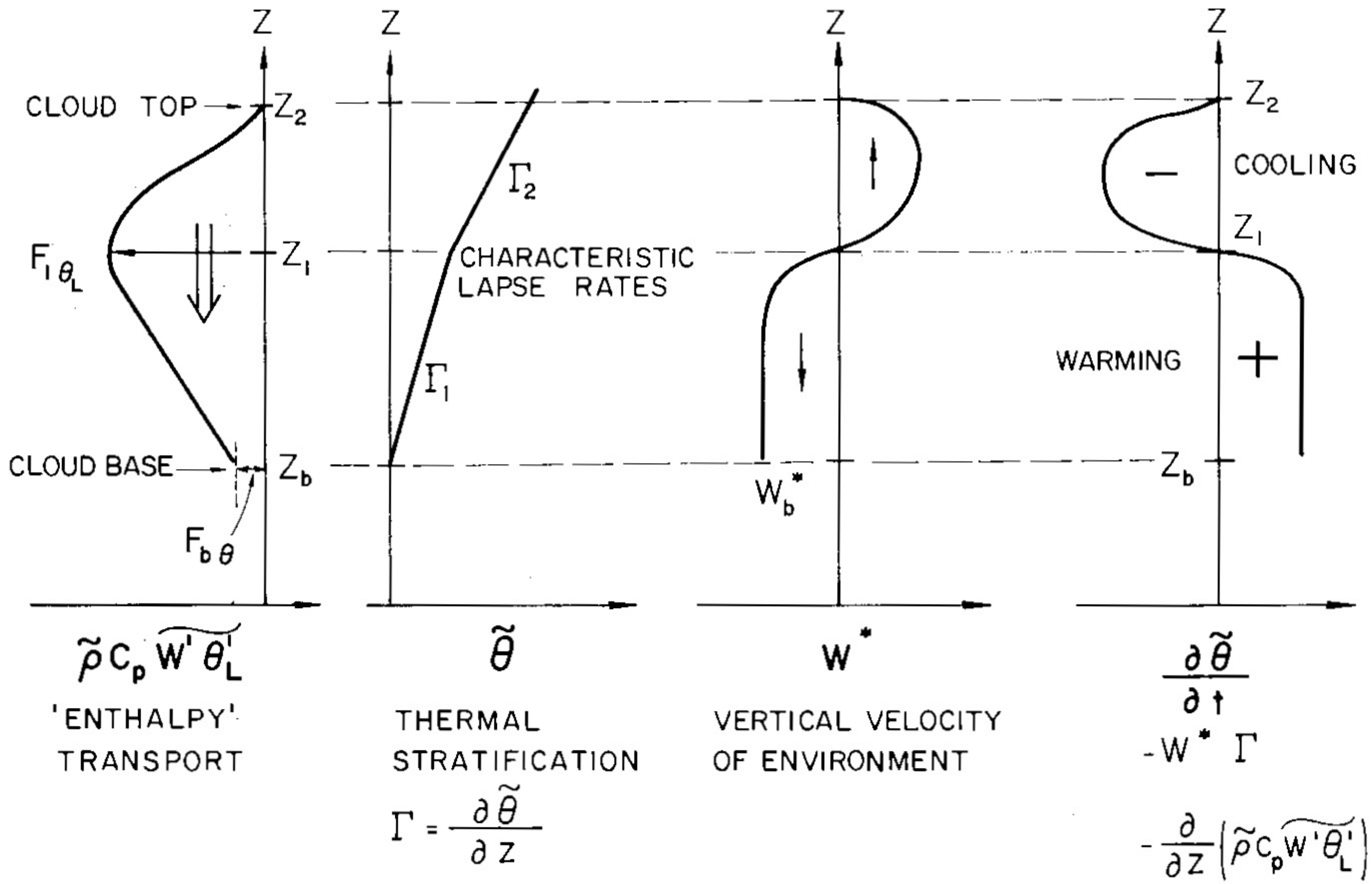


Figure 2. Sketch of the 'enthalpy' transport $\tilde{\rho}C_p\widetilde{W'\theta_L'}$ for a field of non-precipitating clouds; the thermal stratification; the parameterization of the modification of the mean atmosphere by the convection in terms of the vertical motion of the air between the clouds; and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

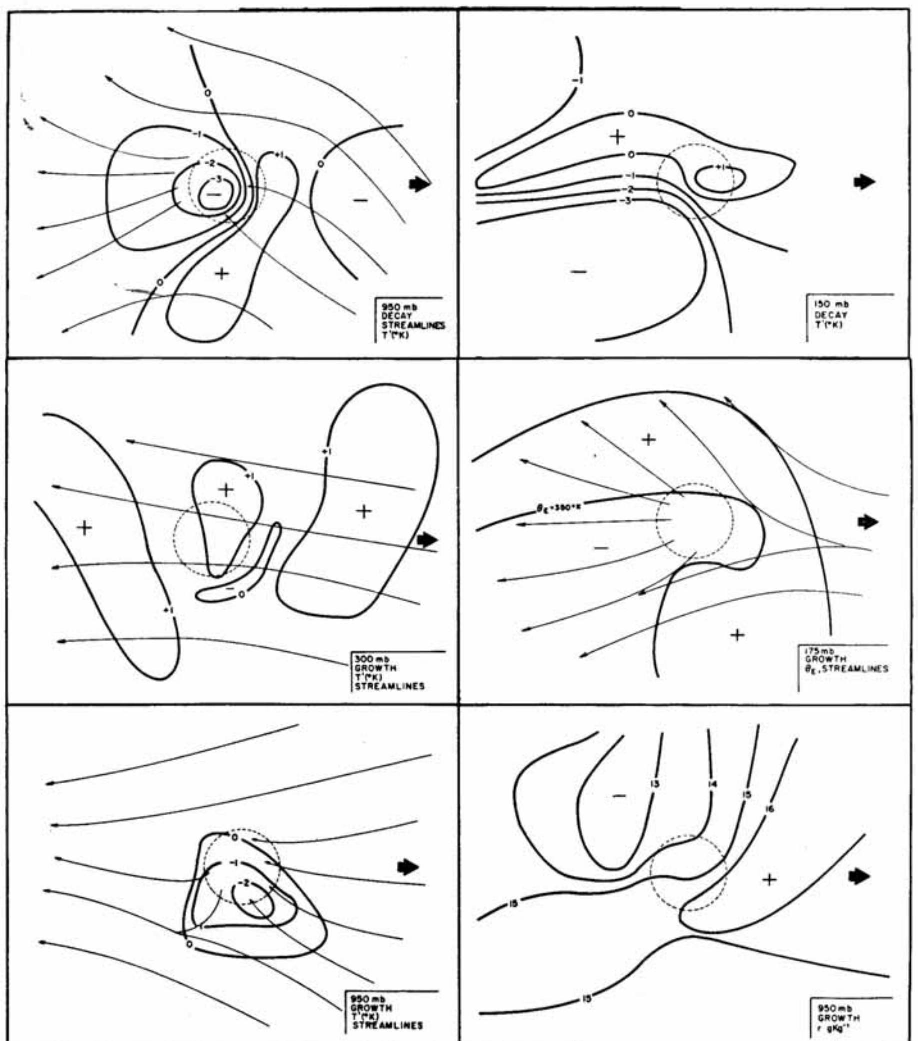


FIG. 2. Example mesoscale fields around a mean echo (diameter 25 km) at 950, 300 and 175 mb (growth) and at 950 and 150 mb (decay).

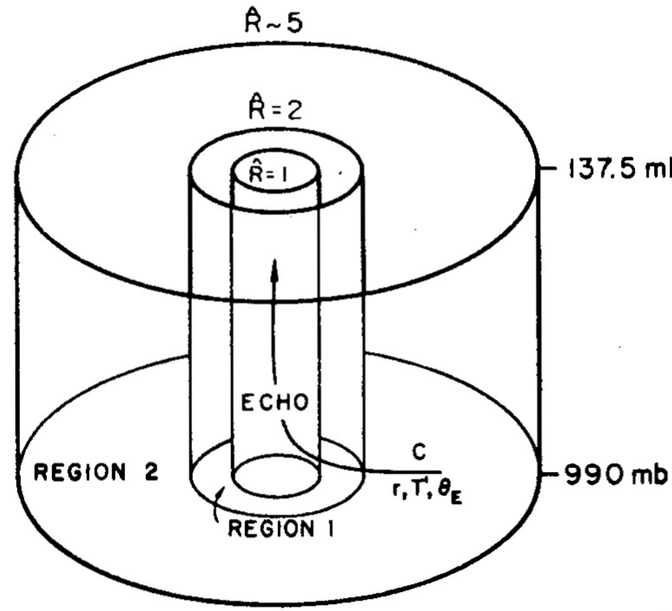


FIG. 1. Cumulonimbus model used for budget computations. Radius of 1, 2 boundary is twice that of echo.

(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

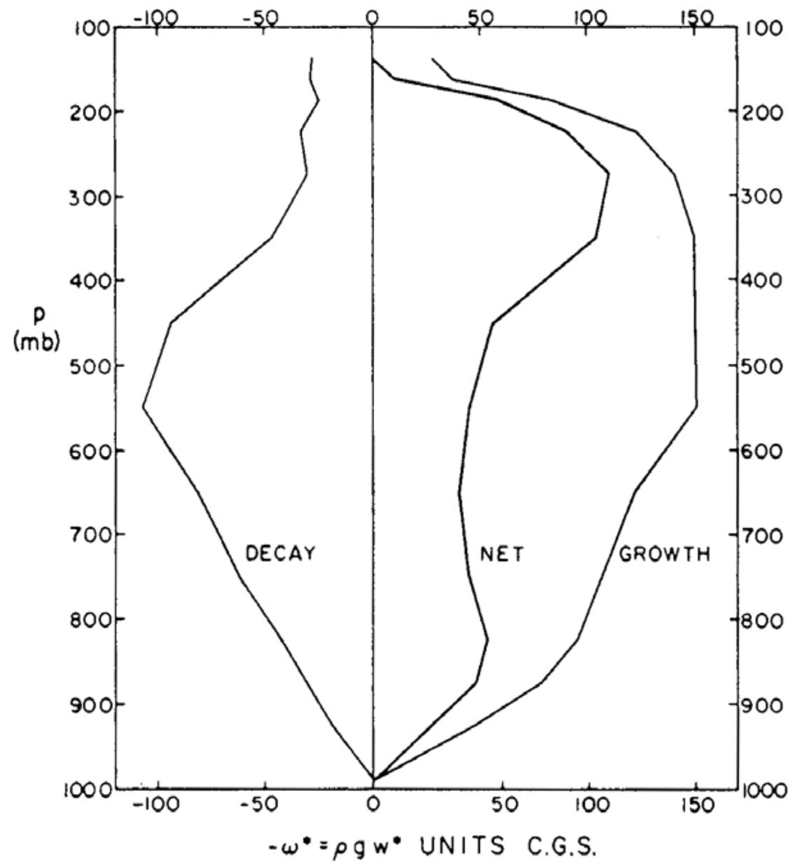


FIG. 4. Vertical mass flux ($-\omega^*$) vs pressure for growth and decay phases, and their sum (representing the net mass flux).

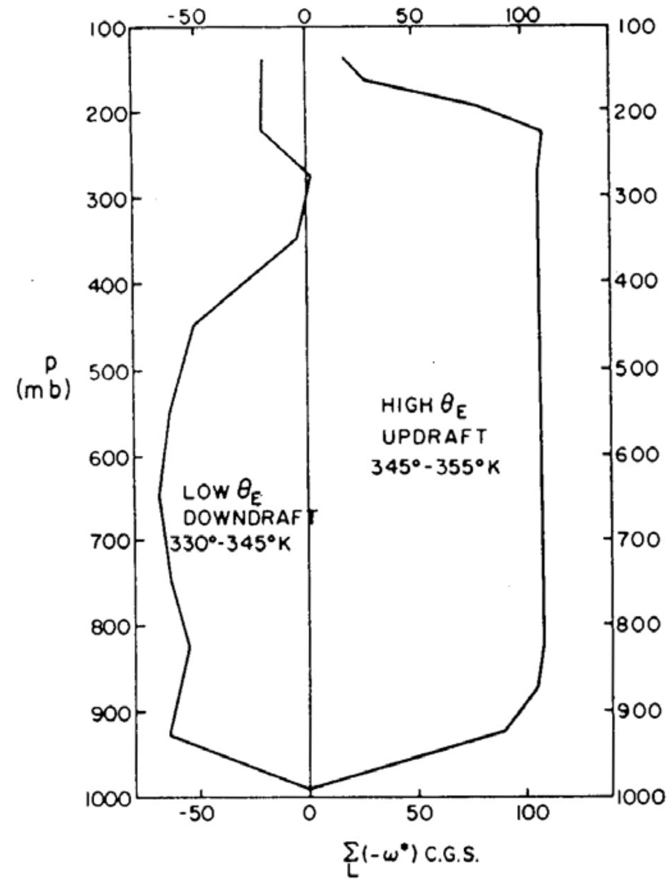


FIG. 6. Net vertical mass flux vs pressure for high (345–355K) and low θ_E (330–345K) ranges, depicting simplified updraft and downdraft.

Updraft & downdraft mass, water and θ_E fluxes

[Betts, JAS 1973]

Martin renting a Plymouth Fury-III to visit Bob & Joanne Simpson in Miami (1969)

– a UK grad student with no credit card

VIMHEX-1972: Carrizal Improved S-band radar

- **Tracked storms on radar**
- **Launched precalibrated rawinsondes every 90mins**

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

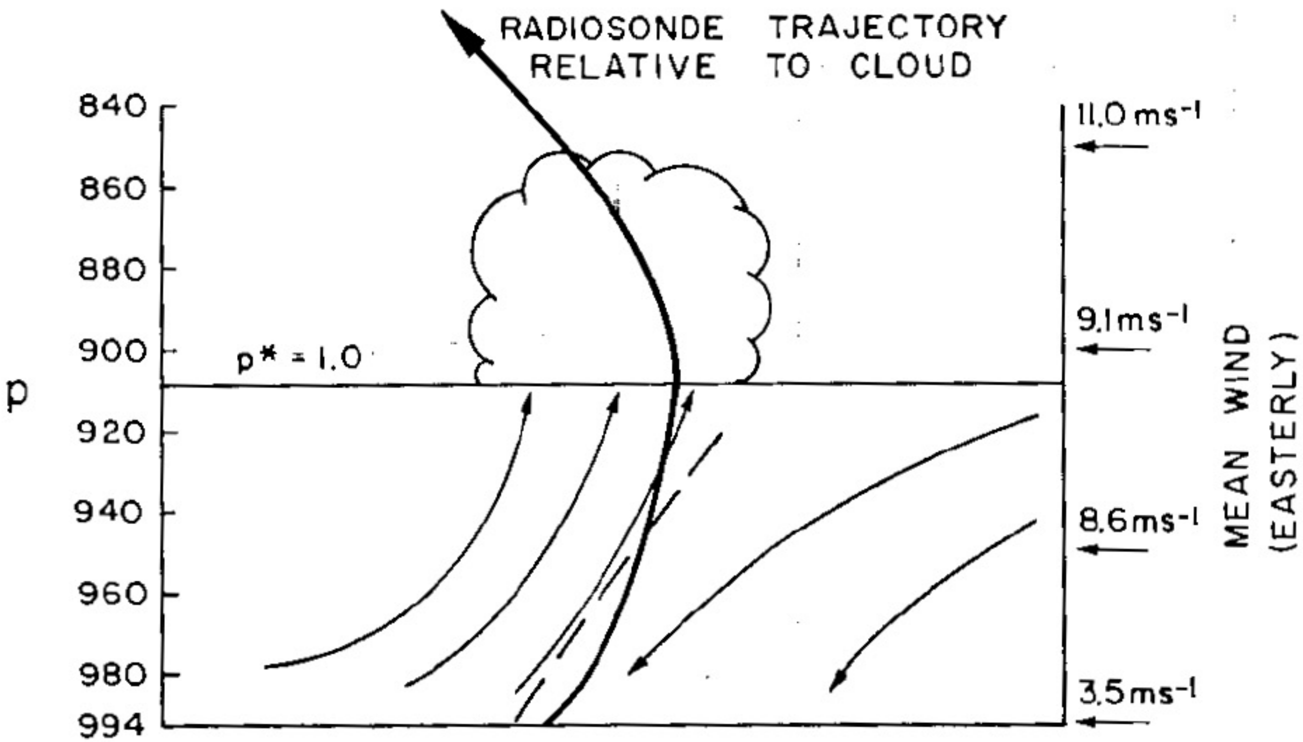


FIG. 2. Suggested circulation relative to a cloud in the sub-cloud layer, indicating how an ascending radiosonde can enter rising moister air in the upper part of the sub-cloud layer.

Betts et al. BAMS 1974

Mean of 14 ascents through cloud-base

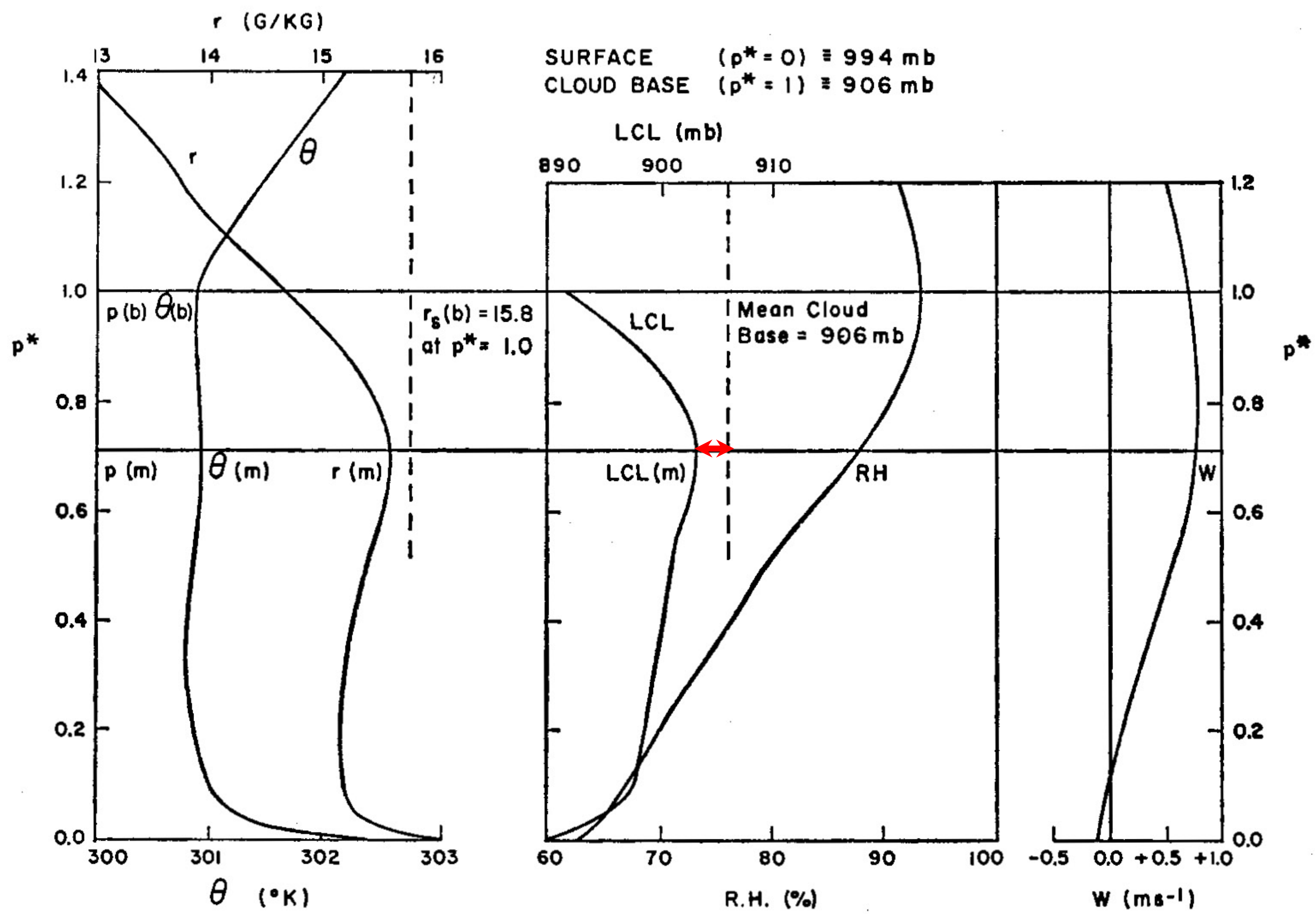
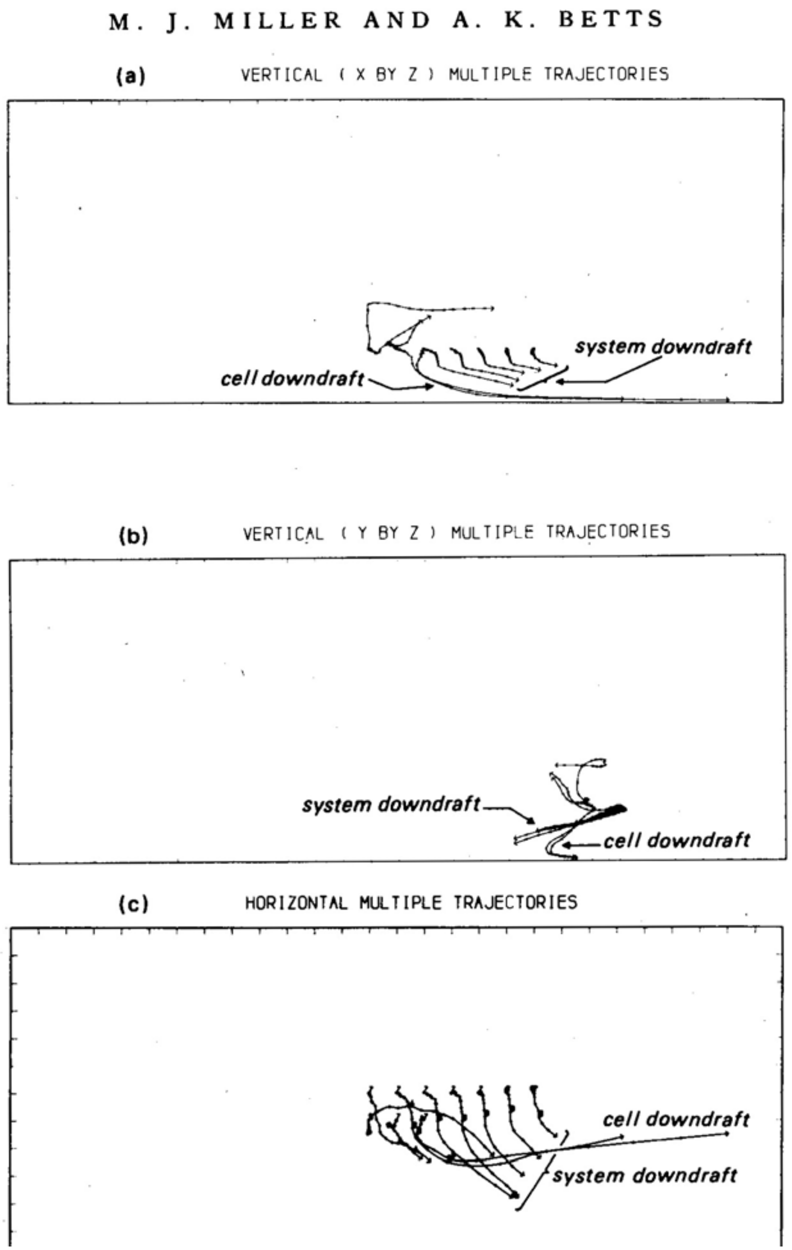


FIG. 1. Mean profile for 14 radiosonde ascents through cloud-base of potential temperature (θ), mixing ratio (r), lifting condensation level (LCL), relative humidity (RH), perturbation vertical velocity (w).

Numerical simulation of Venezuela squall-line #47

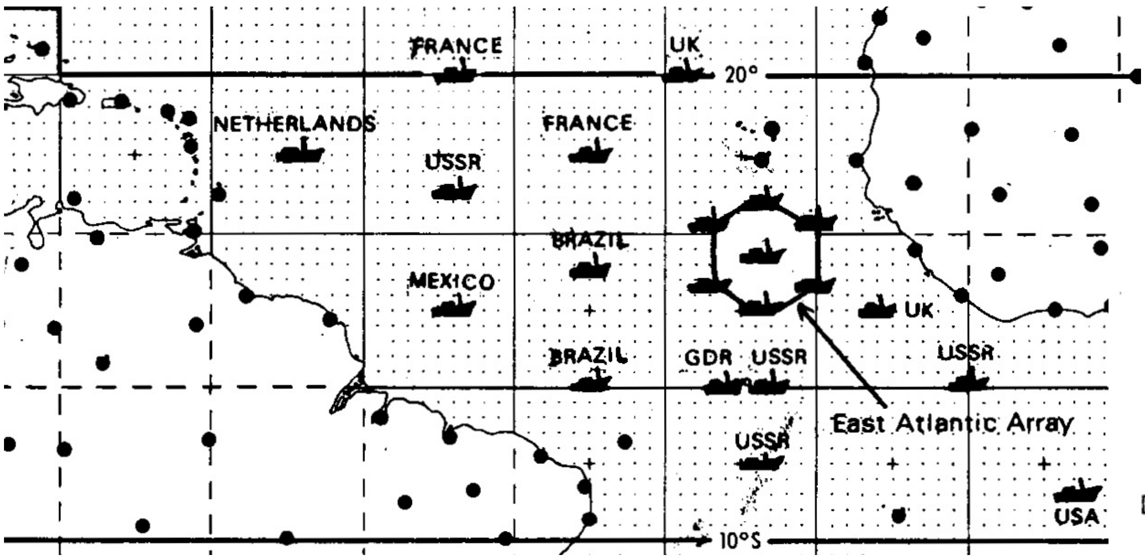
- 3-D trajectory analysis of cell and system downdrafts
- On 30x30x9 grid

[Moncrieff & Miller 1976
Miller and Betts 1977]



Trajectories starting from 750 hPa

GATE-1974



Ship array across Atlantic, mostly north of equator

Nested hexagons on ITCZ centered 8.5N,23.5W

7 research aircraft + dropsonde plane

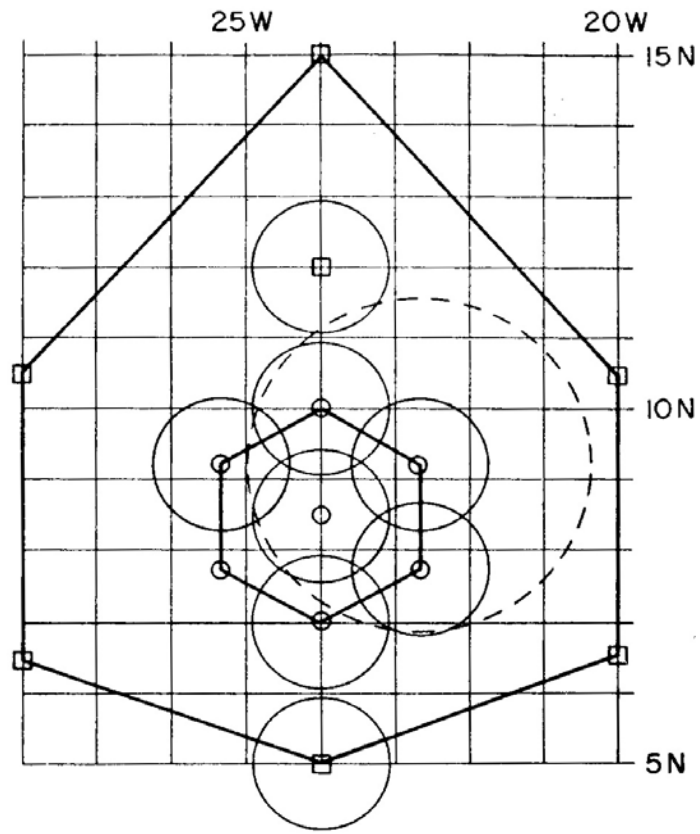
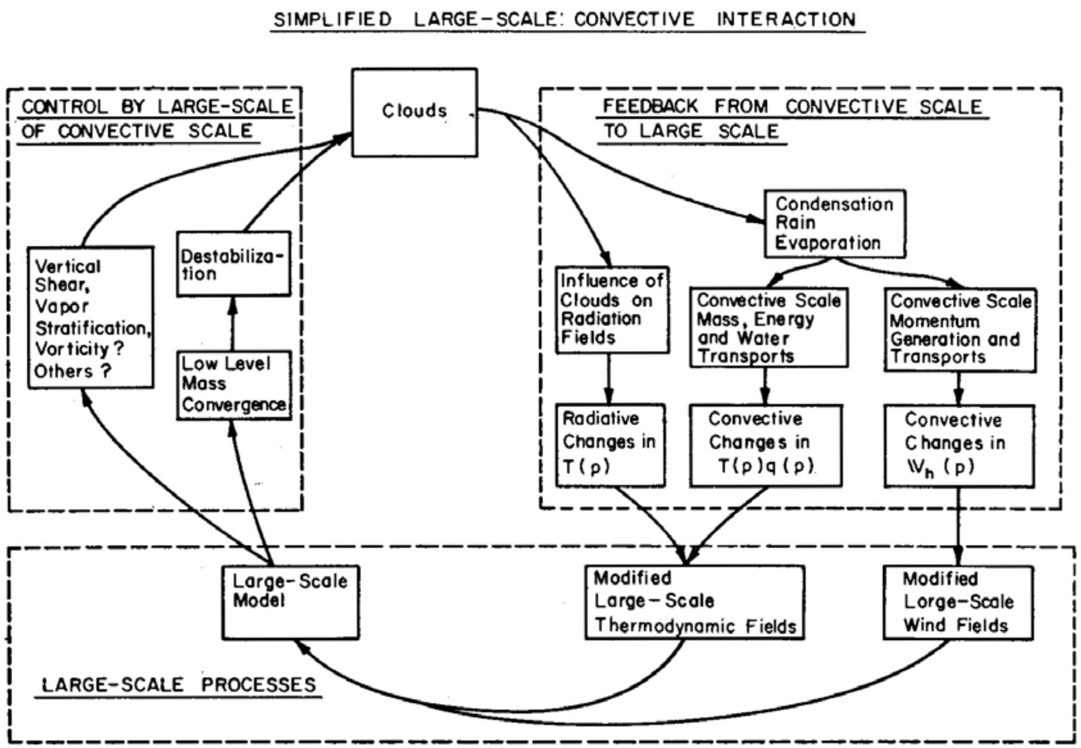
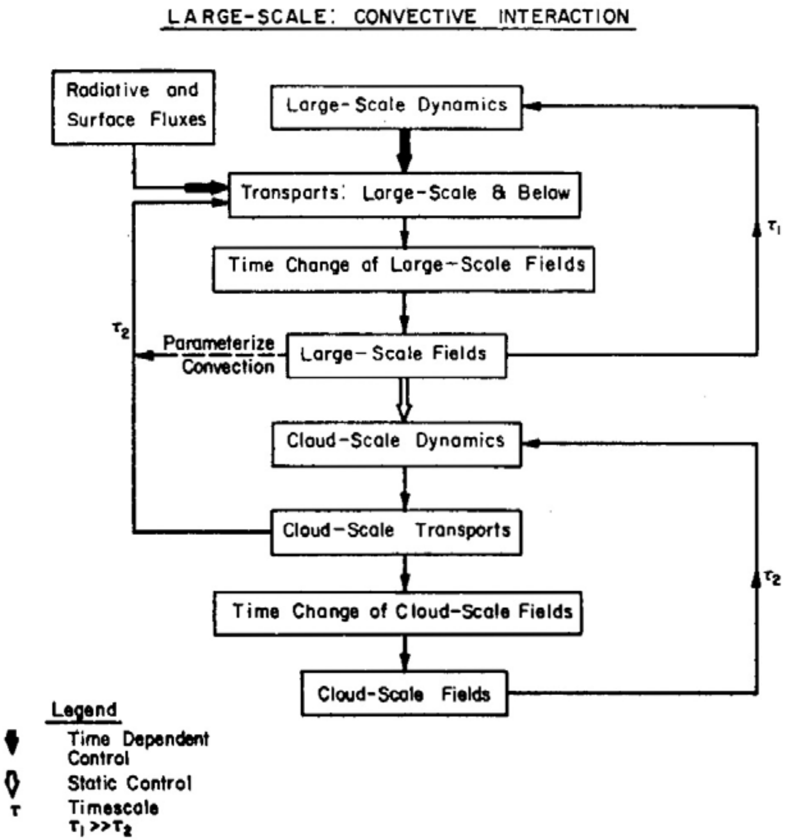


FIG. 12. The A/B and B network. The approximate coverage of overlapping radar scans is indicated for quantitative precipitation estimates during Phases I and II. In addition, the Quadra is planning greater qualitative coverage (indicated by dashed circle) for operational planning.

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

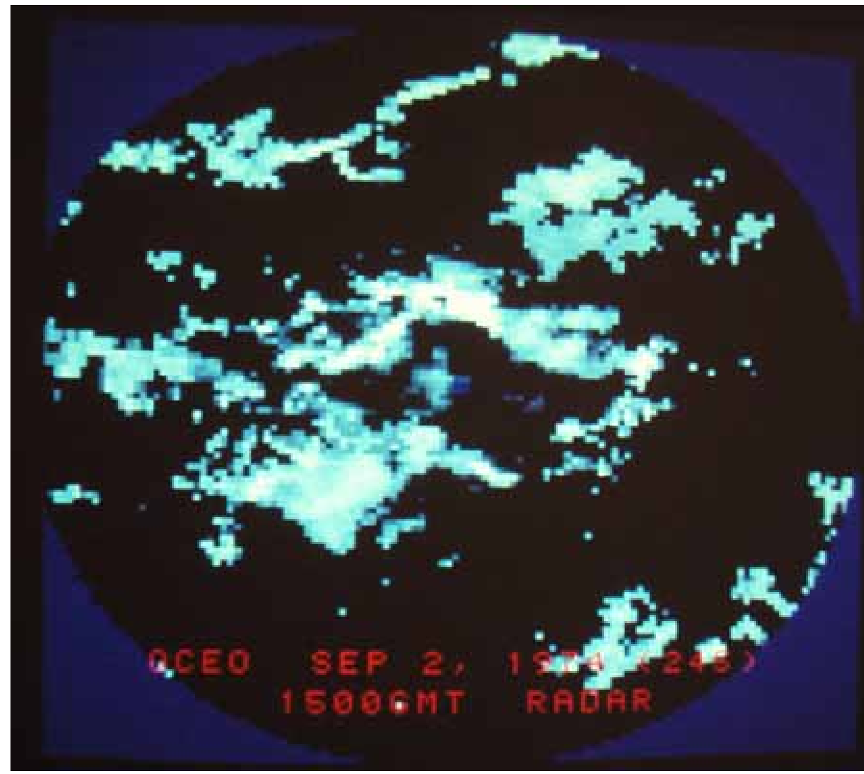




Scale-interaction diagrams are easy to draw!

Betts, BAMS 1974

GATE day 245, Sept 2, 1974
Oceanographer radar

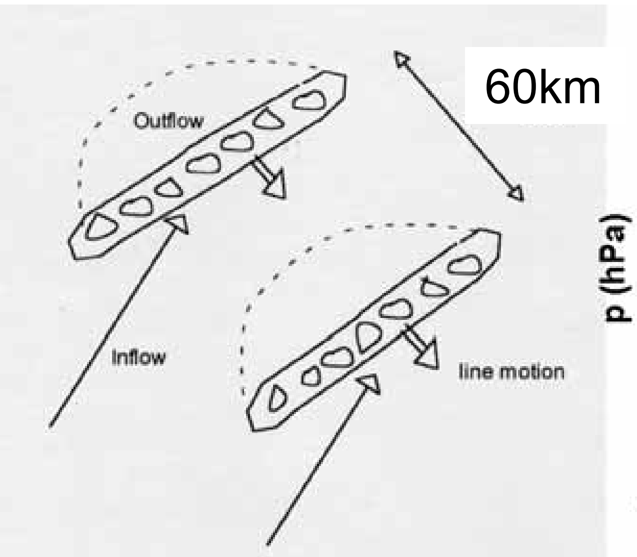


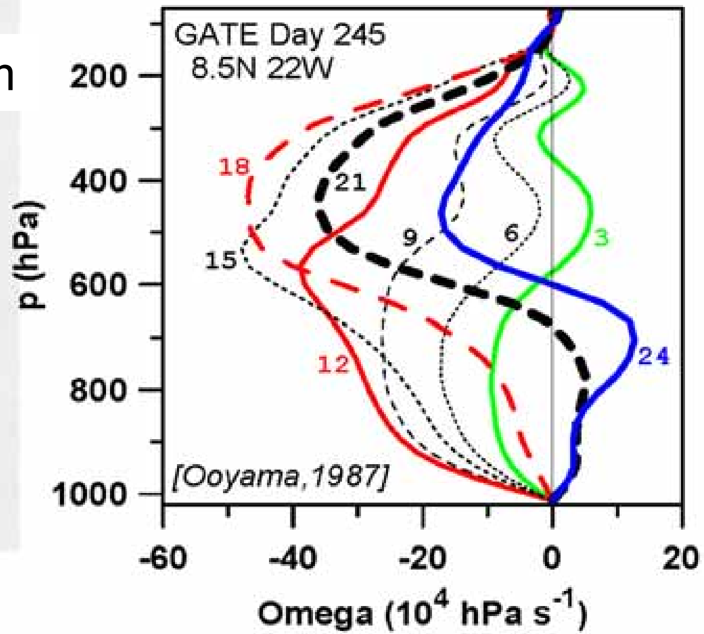
1415 UTC **1500 UTC**

SE Ship position of inner array; range 100km

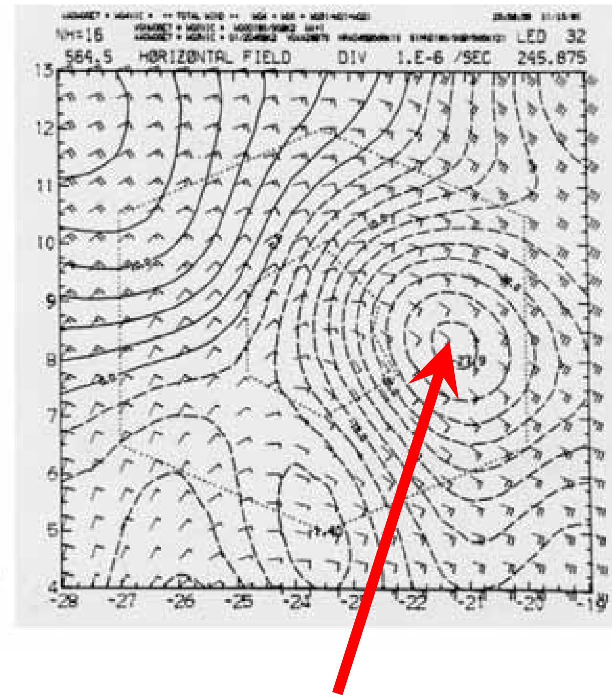
Note SW-NE bands & fast evolution

Reality - GATE 'cloud cluster' lifecycle on day 245 in 1974





565hPa



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

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

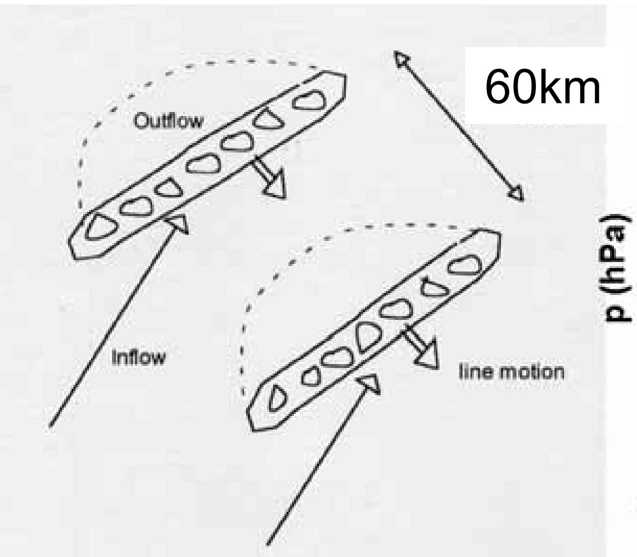
I mulled over this for 8-10 years

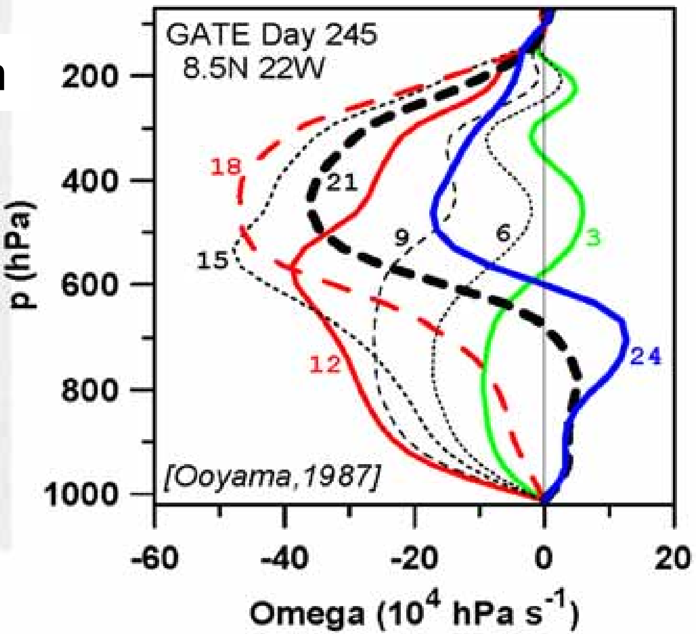
- In 1978 I built a passive solar, wood-heated, PV-powered post & beam house in Vermont (no phone, no internet) and thought about atmospheric convection
- **Betts, A. K., 1982: Saturation Point Analysis of Moist Convective Overturning. *J. Atmos. Sci.*, 39, 1484-1505**
- **Betts, A. K., 1983: Atmospheric 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 1983-1986

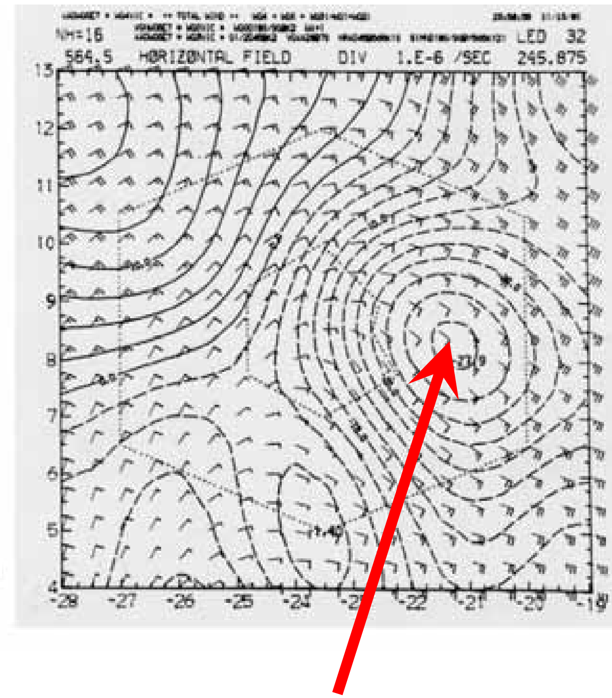
- Calculating transports from the details with so many coupled processes with so many unknowns and unresolved scales *may drift to unrealistic atmospheric structure (eg Arakawa & Schubert, 1974)*
- So adjust with finite timescale to vertical (T,q) structure, satisfying θ_E conservation, in a way consistent 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**

Reality - 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]

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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

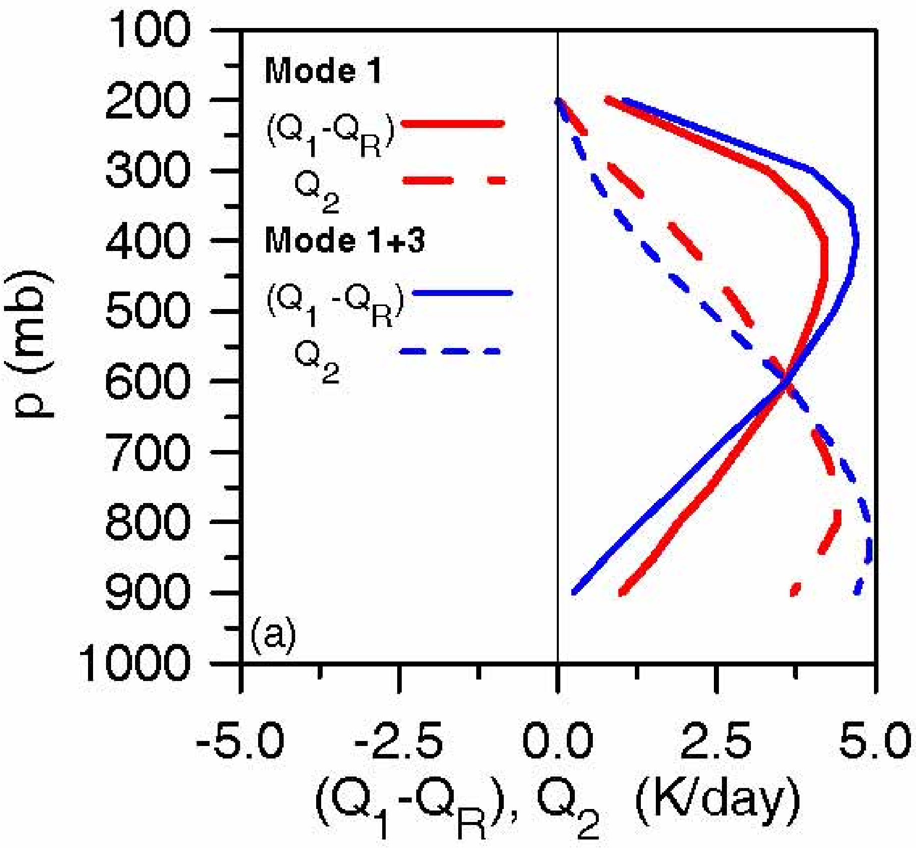
  Heating over cooling couplet driving circulation with no net precipitation

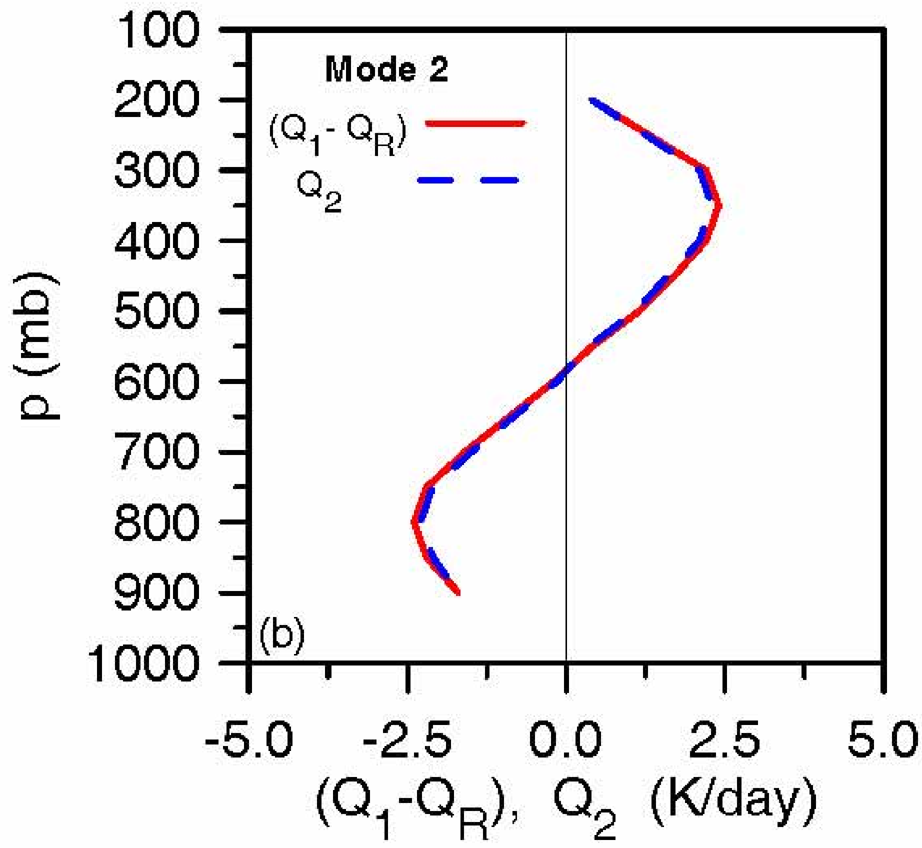
- ***Mode 3***... is a modulation of Mode 1, which *increases* the mid-tropospheric θ_E flux, without impact on net precipitation.

  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!

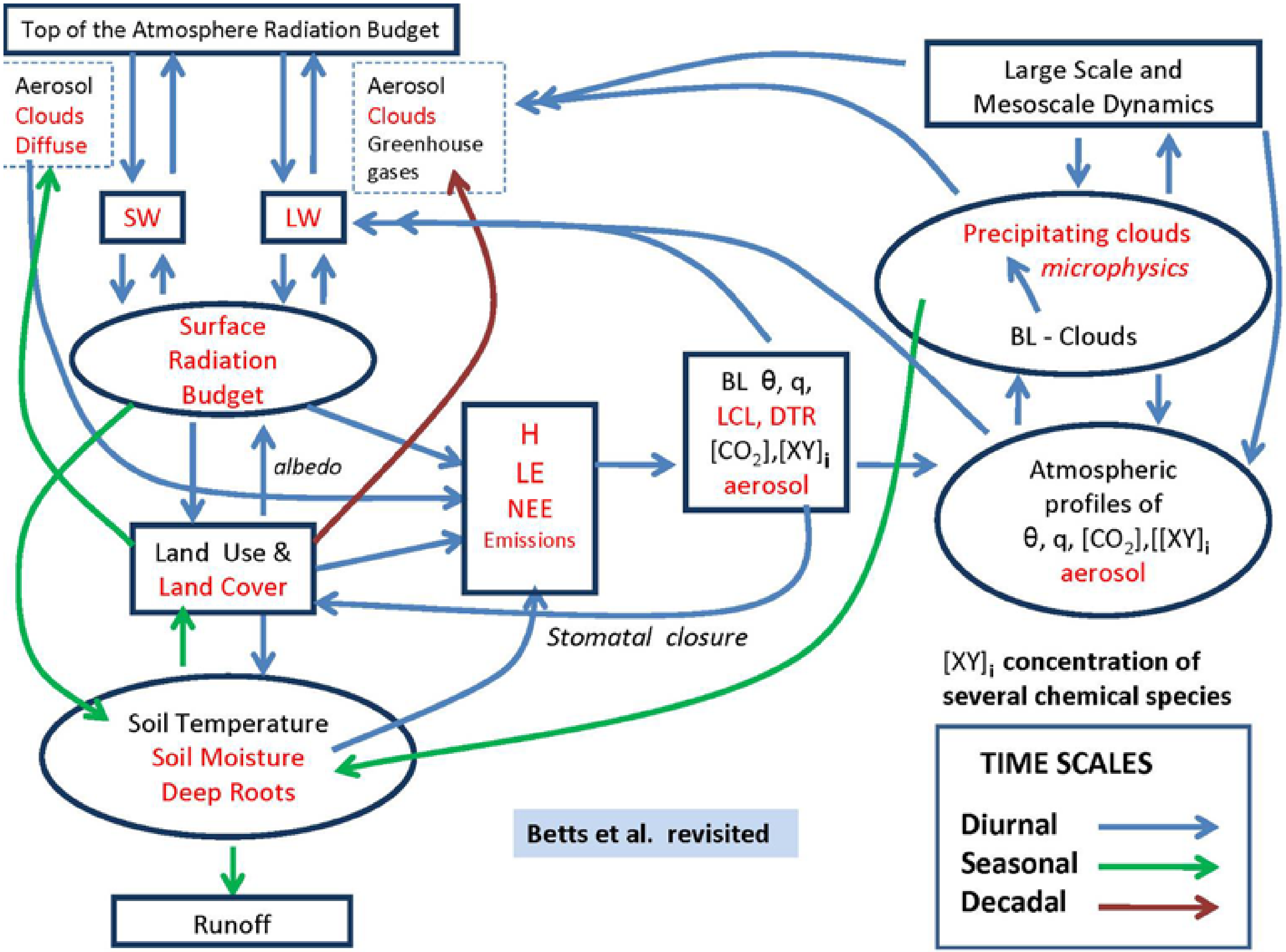
- **How well do *convective models* represent the bulk properties of cloud systems?**
- Do they represent the dominant convective modes as well **as the SW and LW cloud forcing**?
- Can we quantify the coupling of diabatic processes and evaluate them against observations?

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

Conceptual challenges

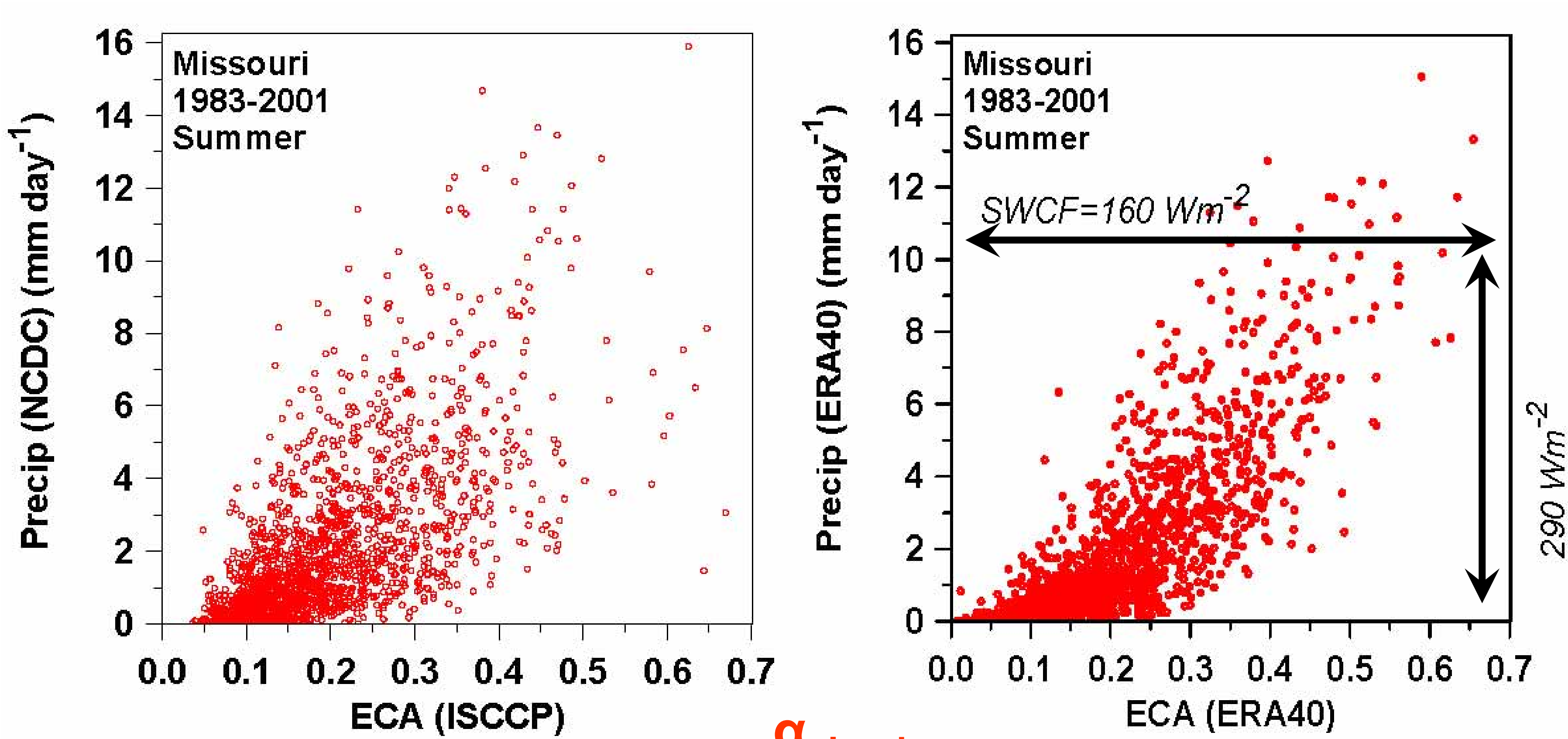
- Mass transports and precipitation only loosely coupled - dependent on cloud structure and microphysics eg. Precipitation-evaporation couplets can drive circulations with little net precipitation
- **Microphysics depends on aerosols – poorly known on global scale**
- **The diabatic cloud radiative forcing 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?**
- ***Then how do we handle the microphysics!***

Process diagrams get more complex!



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

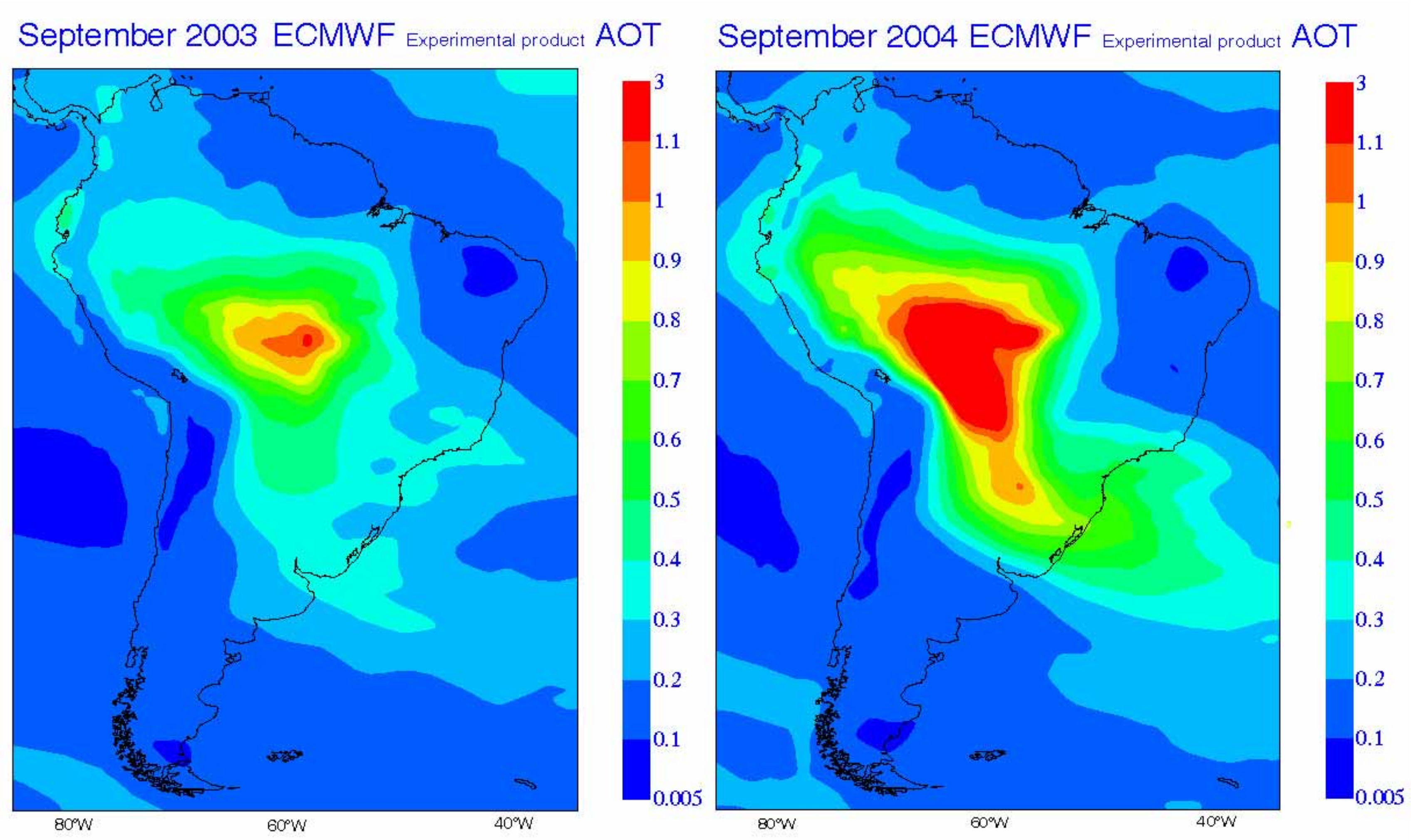
Precipitation to SWCF



α_{cloud}

- Relation of precipitation forcing to SWCF differ between ERA40 and data

Aerosol issues: South America



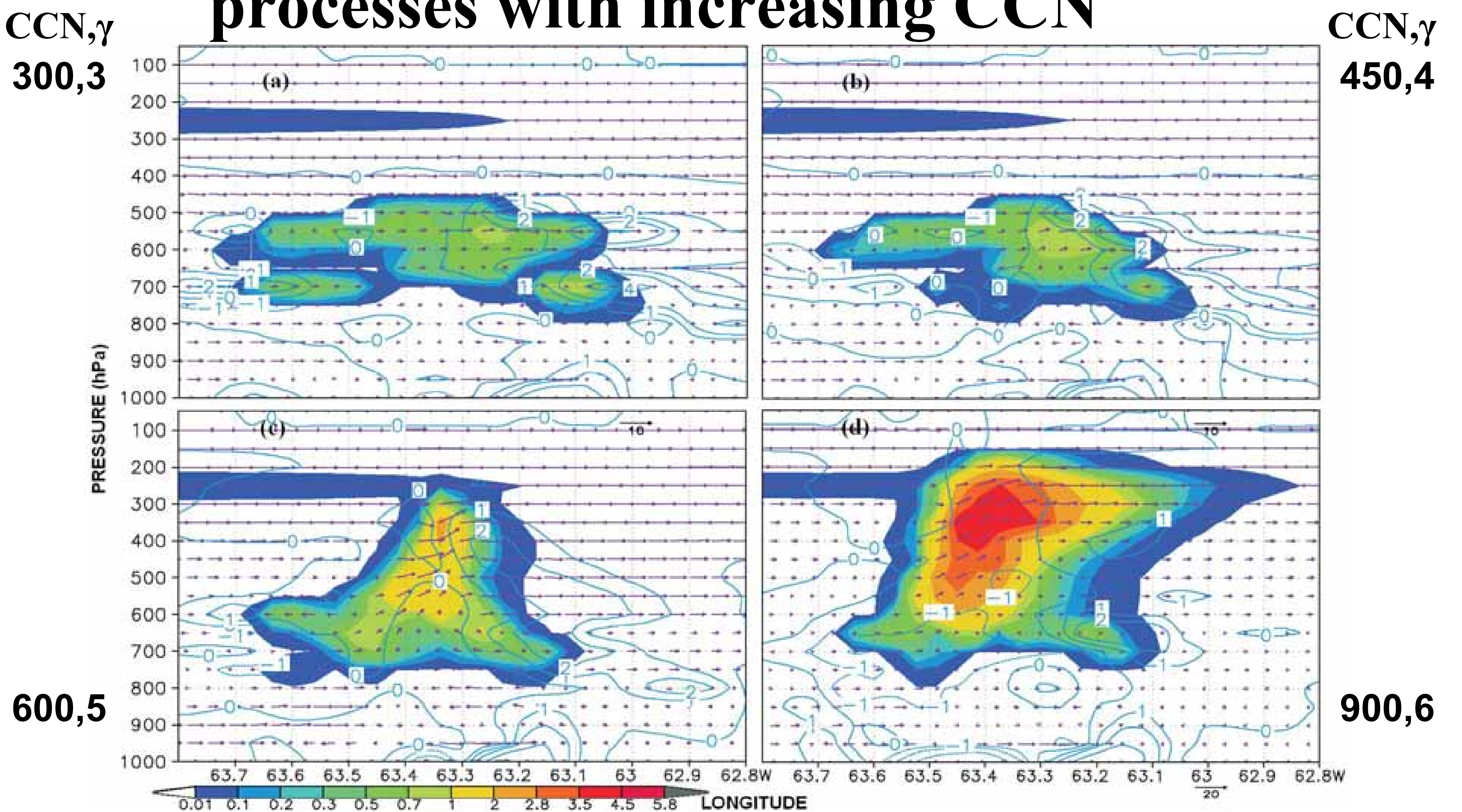
- Amazonian September '**fire season**' is variable *(Morcrette, 2009)*
- Impacts **microphysics/dynamics**
- Impacts surface **net ecosystem exchange** – **diffuse penetrates canopies**

Is there a way forward?

- What can we learn from SCMs and CRMs with specified external forcing?
- Do they have the *freedom to develop* these 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?**

Change from warm to cold rain processes with increasing CCN

(Martins et al. JGR 2009)



- With increasing CCN concentrations (*and parameterized drop spectrum*), cloud droplet number, maximum updraft speeds, peak rainfall rates, cloud & ice water concentrations and cloud top heights all increased.

Final remarks!

- 41 years ago we set off to Venezuela as graduate student ‘labour’ for Herbert Riehl
- We have spanned an era in the study of tropical convection and the development of numerical forecast models!
- My thanks to Martin and ECMWF for so many enjoyable and fruitful years of collaboration