Entrainment and Mixing in Cumulus Clouds

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25 March 2009

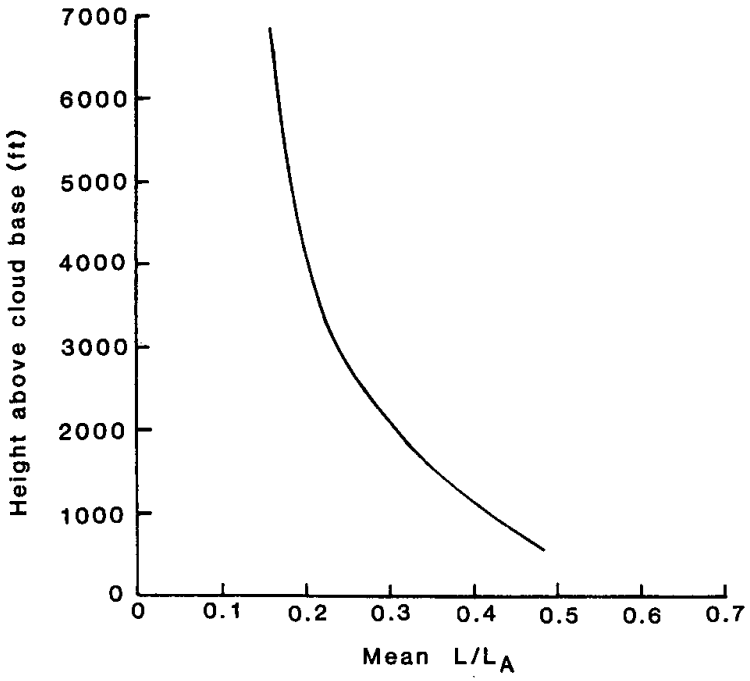
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Outline

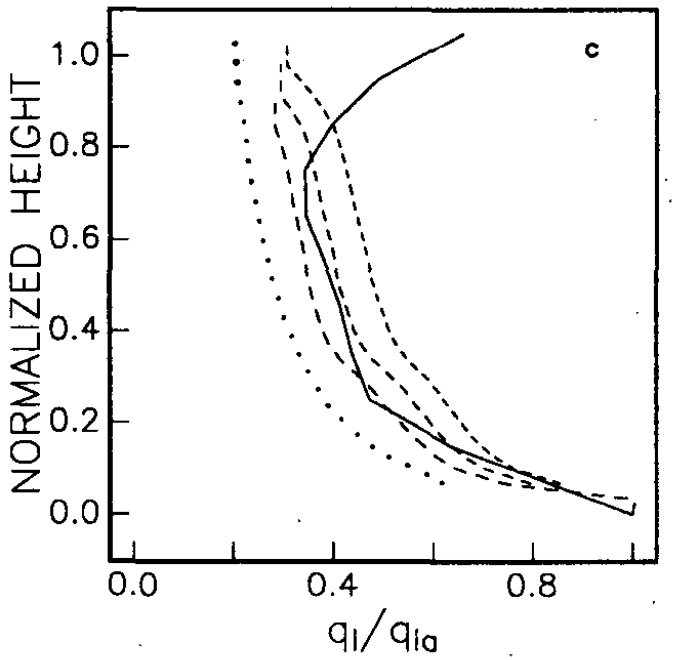
Cumulus clouds

Start Movie

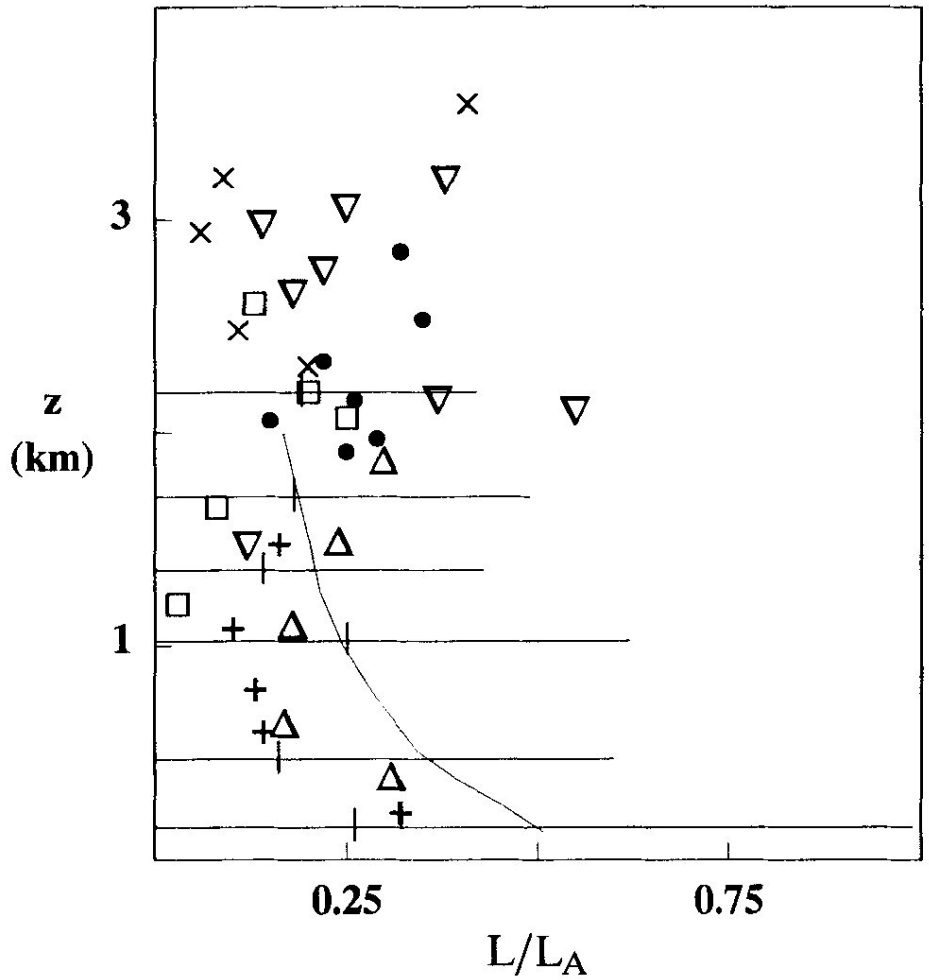
Liquid water content



From: Warner (1955)

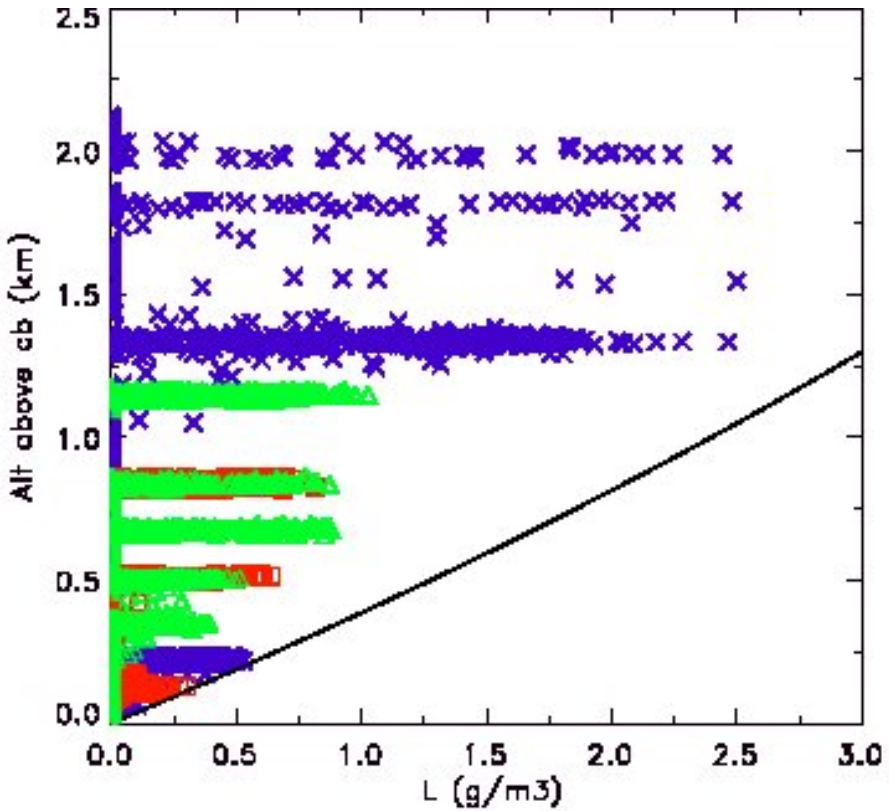


Raga et al (1990)



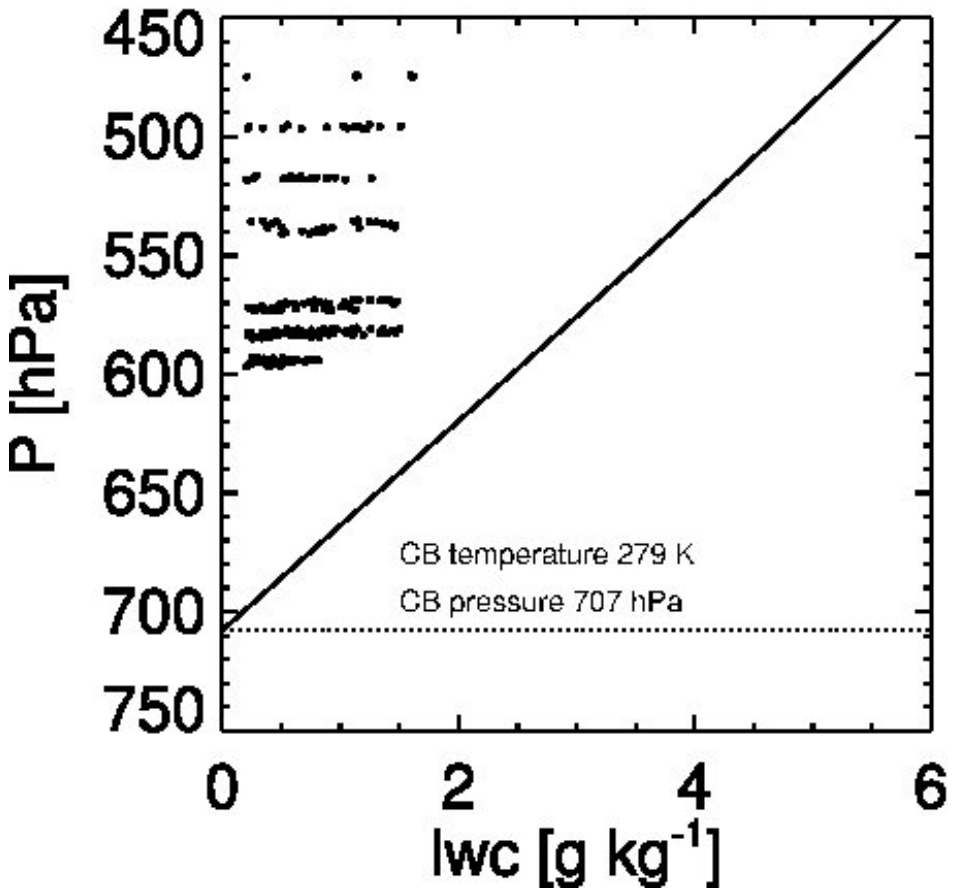
From: Blyth and Latham 1990

Liquid water content



Trade-wind cumulus clouds 2005

LWC - COPS



COPS cumulus clouds, 15 July 2007. *Justin Peter*

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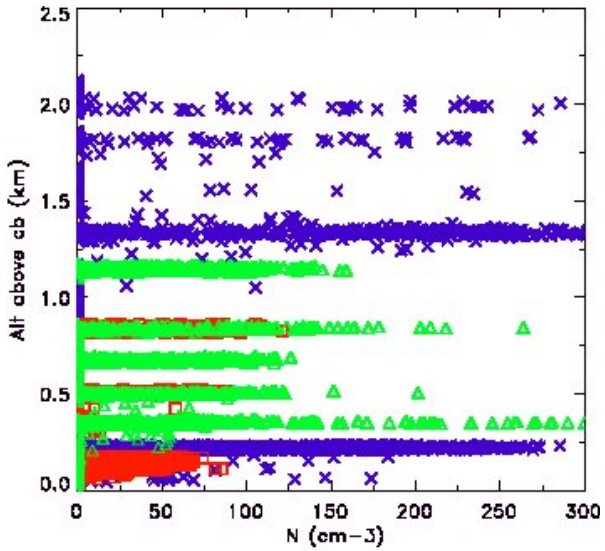
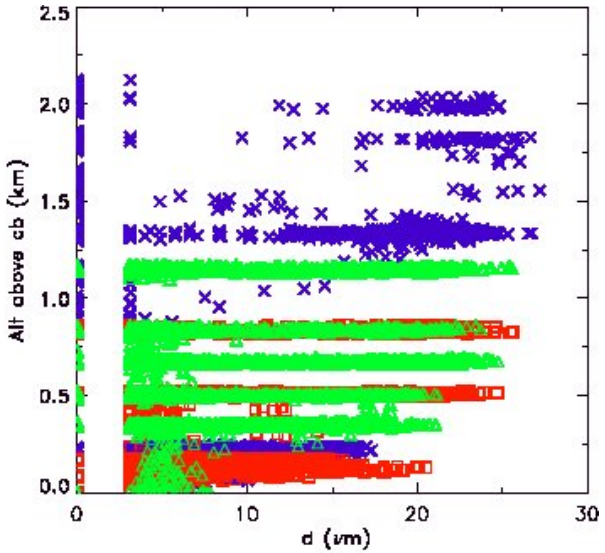
Concentration (N) and mean diameter (d)





Trade-wind cumulus clouds 2005

Entrainment

Two scales:

- Cloud scale - where does entrainment occur and what happens to entrained air?
- Small scale at boundaries - what is the mechanism for air exchange across boundaries?

Plumes, Thermals and Starting Plumes

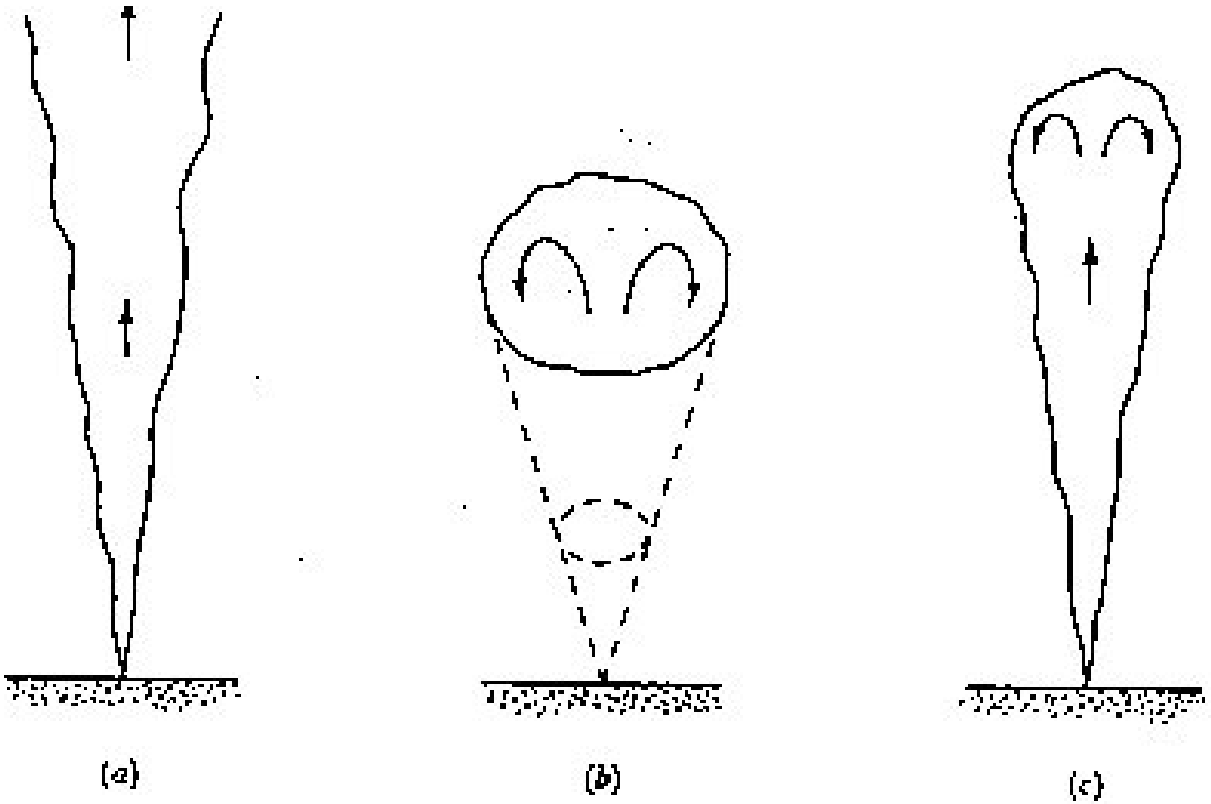
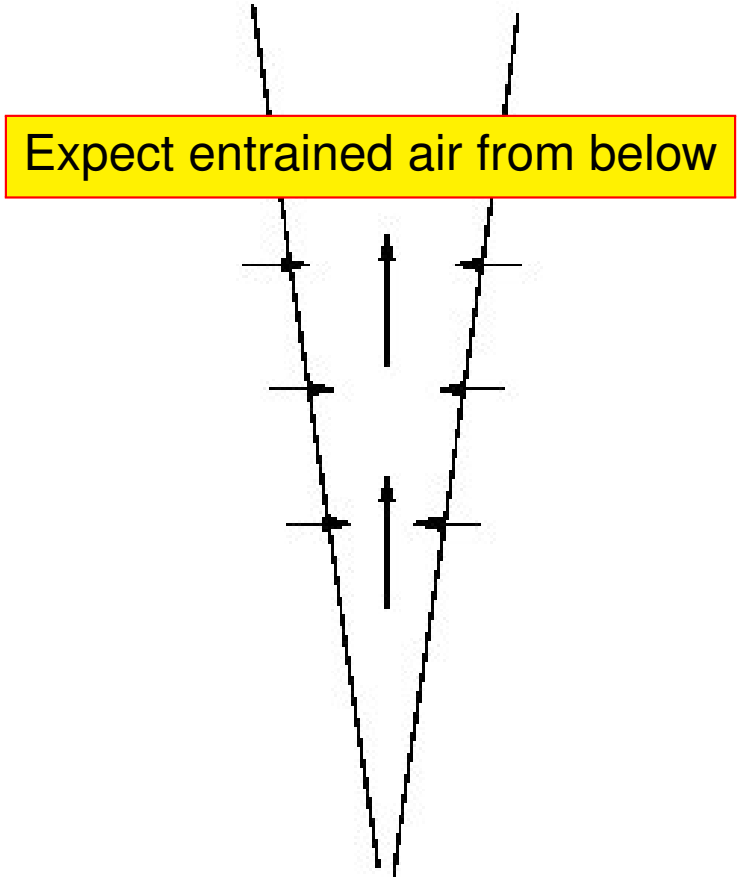
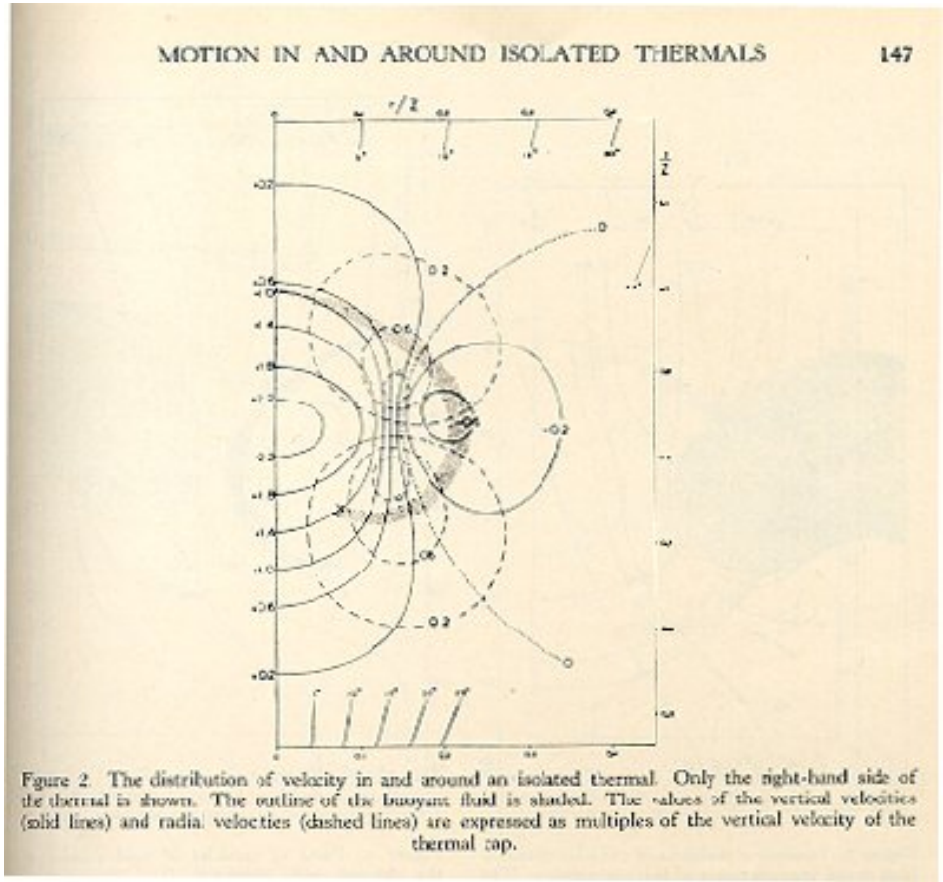


Fig. 6.1. Sketches of the various convection phenomena described in this chapter: (*a*) plume, (*b*) thermal, (*c*) starting plume. The arrows indicate the direction of mean motion. (From Turner 1969*a*.)

Entrainment in Plume



Thermals



MOTION IN AND AROUND ISOLATED THERMALS 147

Figure 2. The distribution of velocity in and around an isolated thermal. Only the right-hand side of the thermal is shown. The outline of the buoyant fluid is shaded. The values of the vertical velocities (solid lines) and radial velocities (dashed lines) are expressed as multiples of the vertical velocity of the thermal cap.

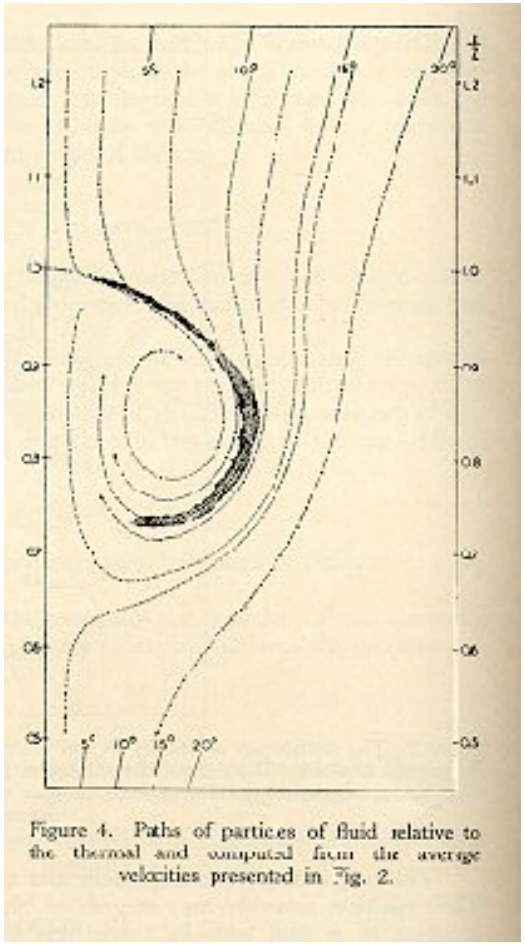


Figure 4. Paths of particles of fluid relative to the thermal and computed from the average velocities presented in Fig. 2.

From: Woodward 1959

Expect entrained air from above and below

Thermodynamic arguments

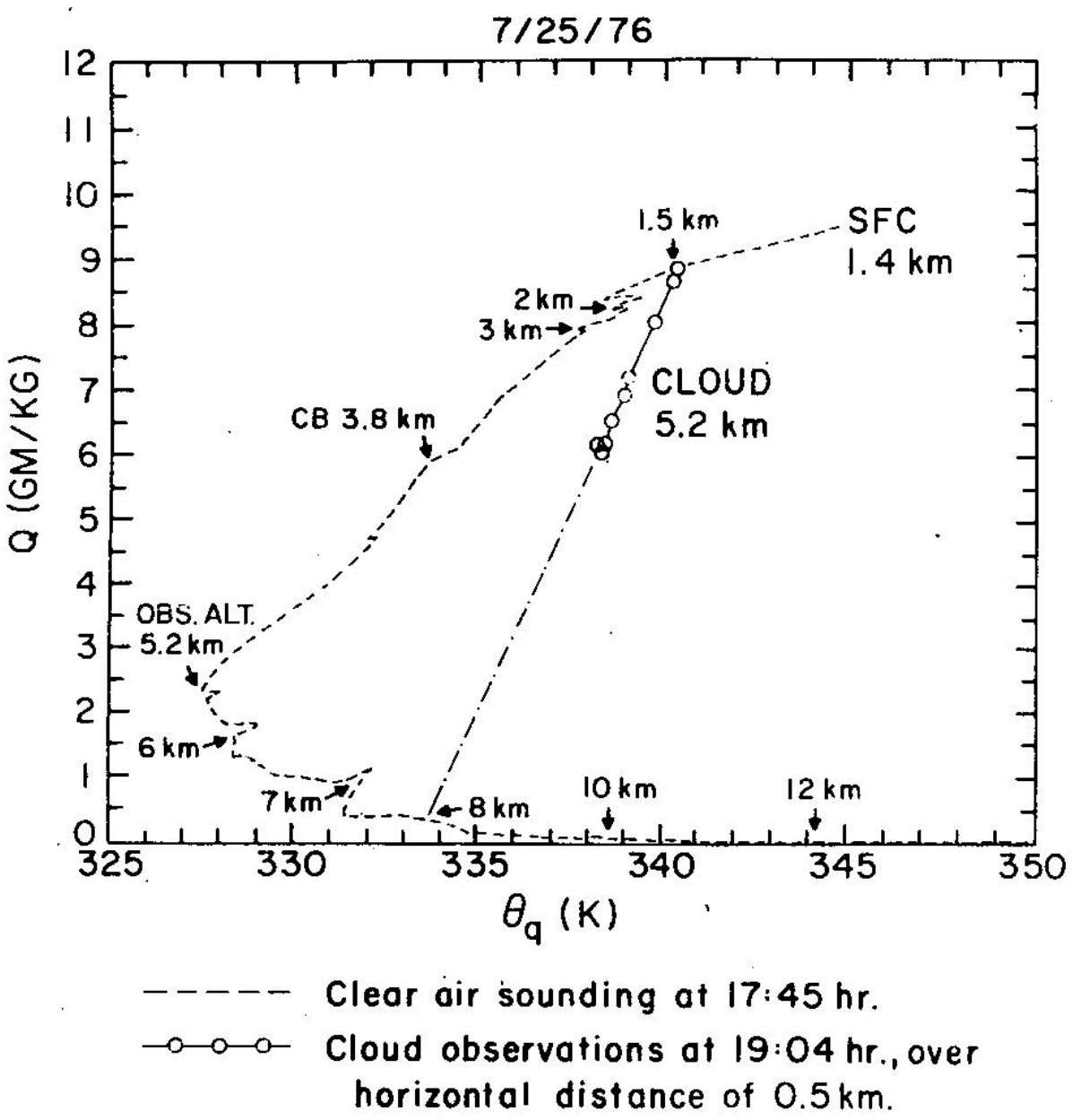
- Use thermodynamic tracers in cloud - conserved variables
- Use θ_q and Q (Paluch 1979). Invariant in adiabatic altitude changes and mix linearly.

$$\theta_q = T\left(\frac{1000}{p_d}\right)^{(R_d/C_p)/[1+C_w/C_{pd}Q]} \times \exp\left[\frac{qL}{C_{pd}T}/\left(1+\frac{Cw}{C_{pd}}Q\right)\right]$$

and

$$Q = q_v + q_l$$

From Paluch 1979



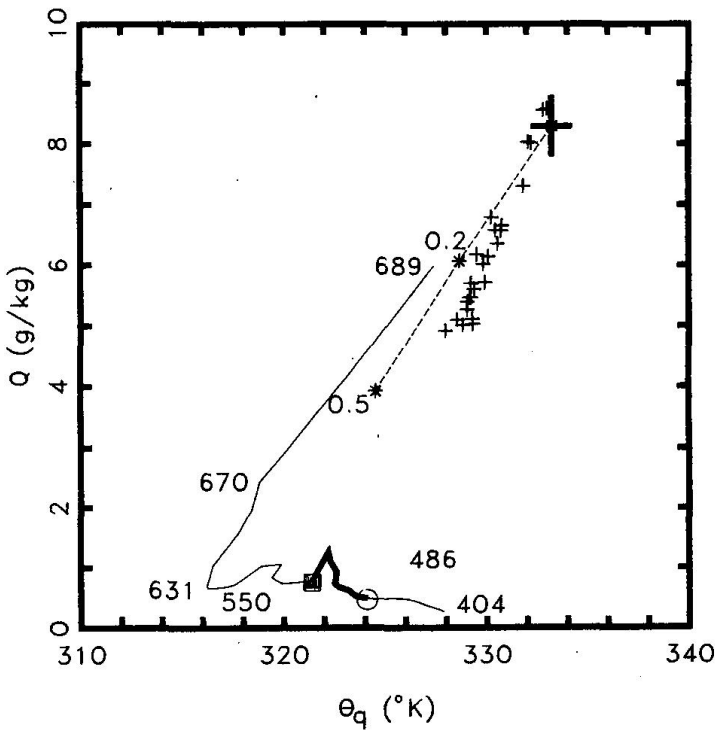


FIG. 4. As in Fig. 2. The sounding is labeled with pressure in mb and is annotated with the pressure of the cloud top (○) and of the penetration level (□). The dashed line shows the θ_q, Q-values for different parcels, each of which continually entrains at a constant rate as it ascends from cloud base. The two asterisks denote entrainment rates of 0.2 and 0.5 km^{-1}.

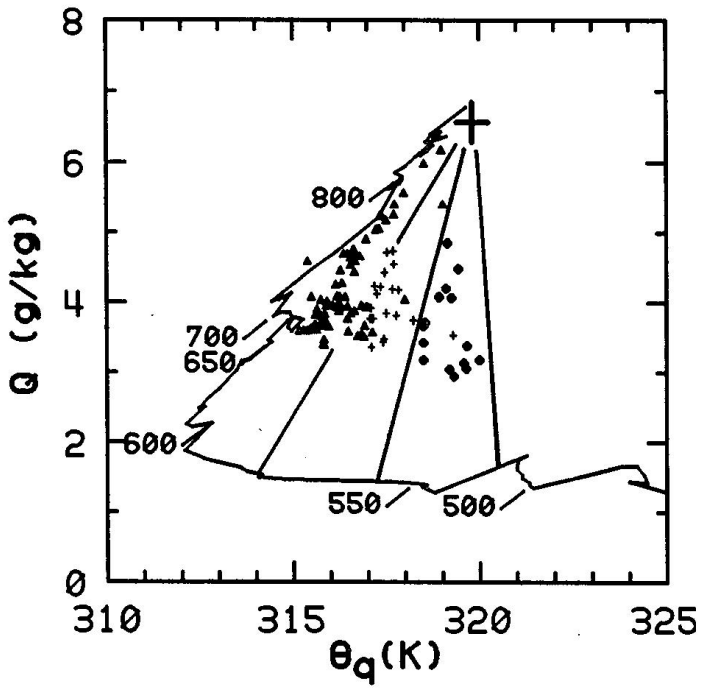


FIG. 6. As in Fig. 4, but for cloud 3 on 20 July 1978. The in-cloud observations from three passes are shown as ● (535 mb), + (575 mb) and △ (615 mb). The cloud-base value is shown with a large + and the lines indicate the approximate separation between the points on the three passes.

From: Blyth et al. 1988

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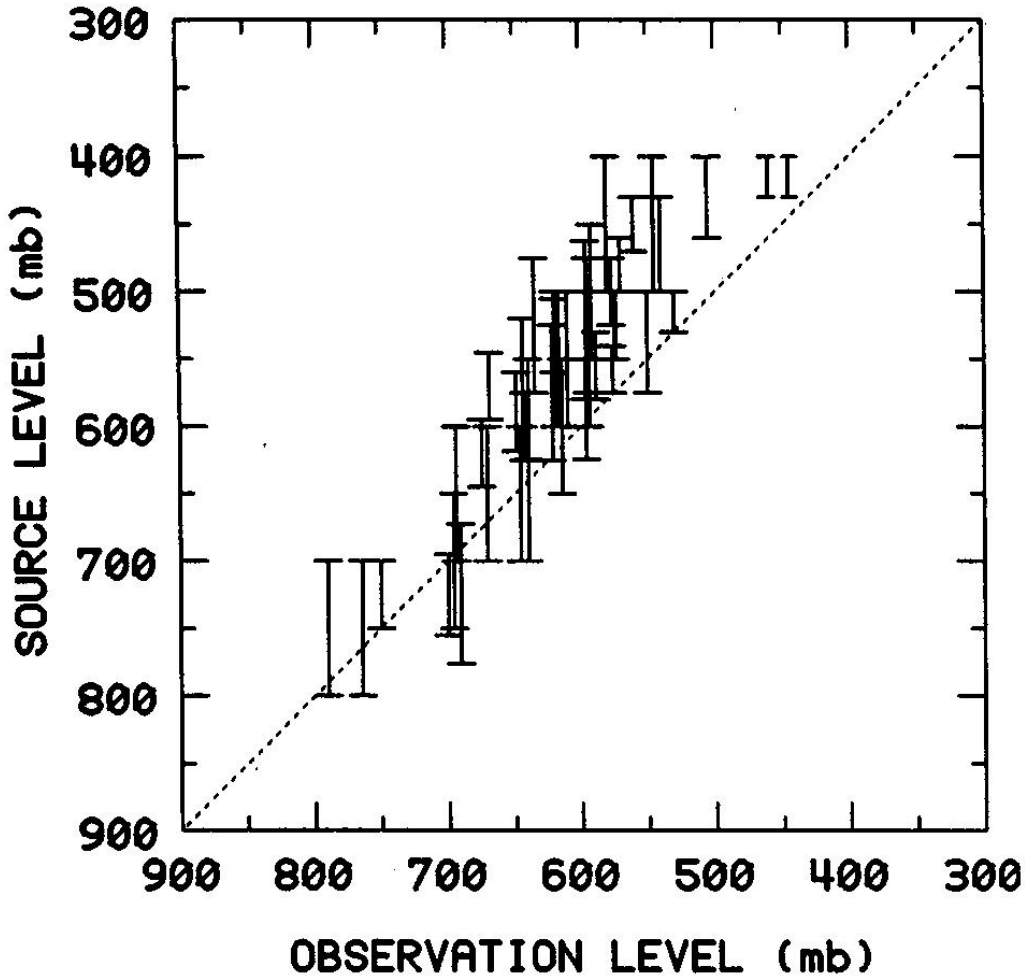
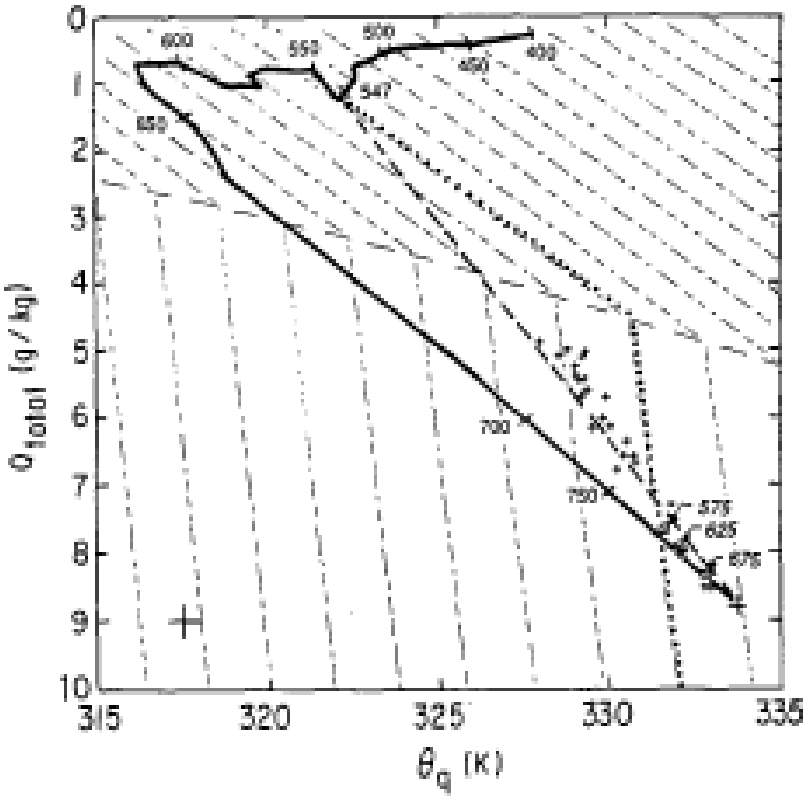
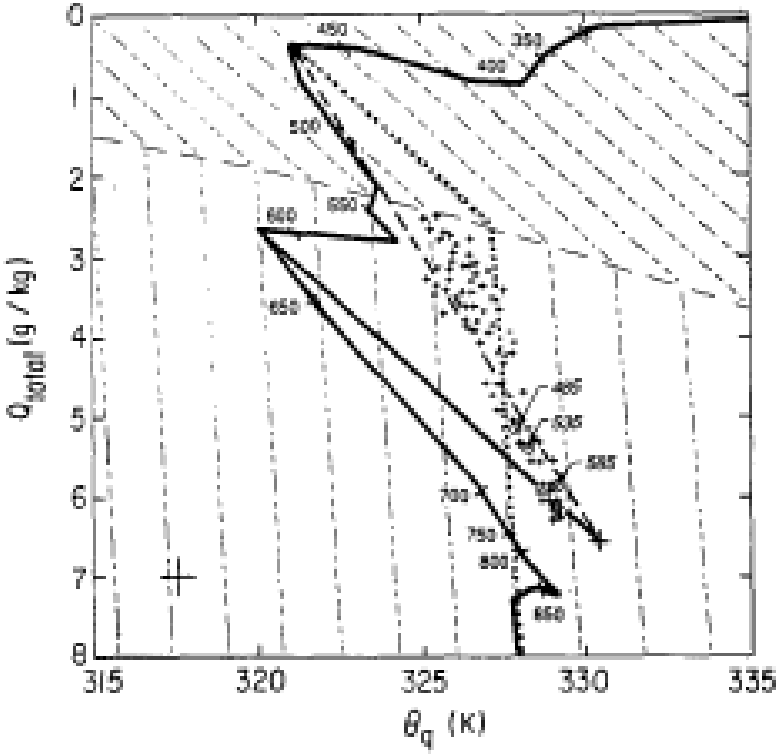


FIG. 10. The source level from which air was entrained into the cloud, as a function of the observation level in the cloud, for 44 cases taken from 44 different regions for which source levels could be determined. The error bars indicate the approximate ranges that are consistent with the observations.

Taylor and Baker

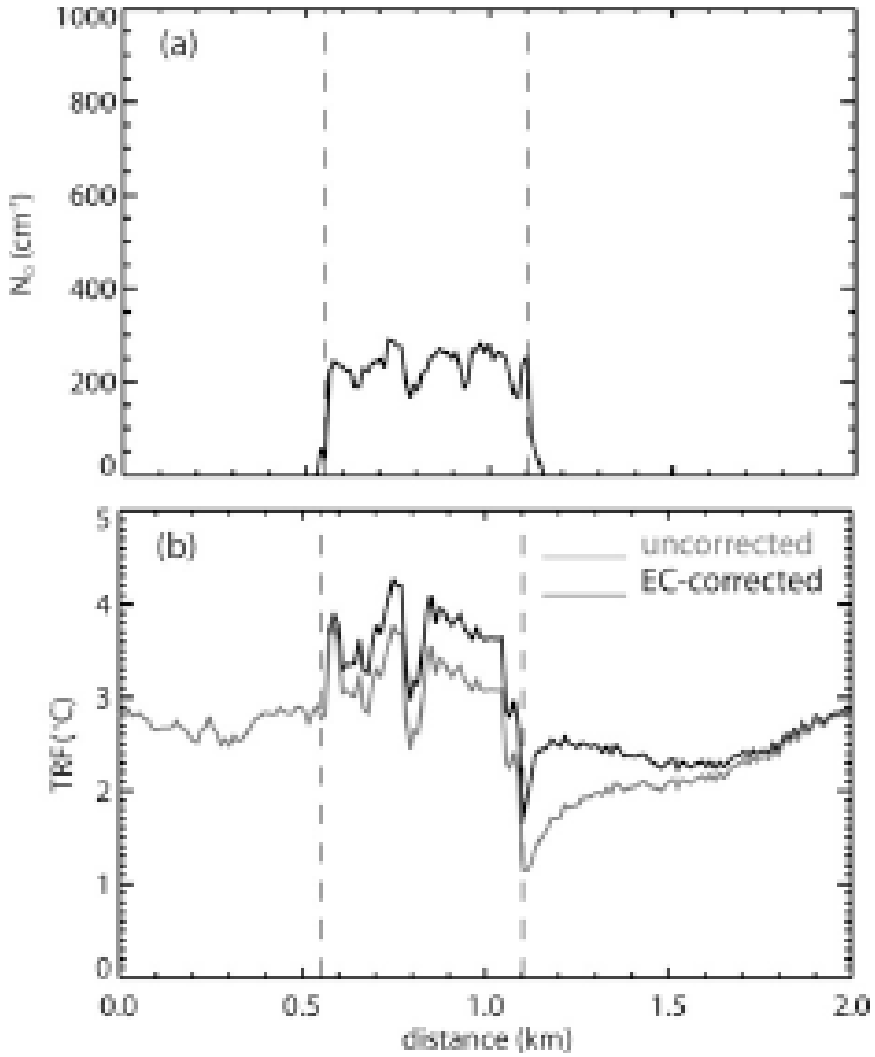




Taylor and Baker

- Distribution of points on Paluch diagram does not necessarily mean ascent of adiabatic parcel followed by mixing – same distribution if mixing occurs continuously as parcel ascends as long as +vely buoyant.
- Different from Raymond and Blyth

Wang and Geerts: cooling of reverse flow temperature probe



Wang and Geerts

"The EC [evaporative cooling] correction proposed herein should be applied to all those studies. Since most of the measurements in the papers listed above occurred at temperatures above -12C, their analyses are affected and some of their conclusions may be flawed."

Downdrafts

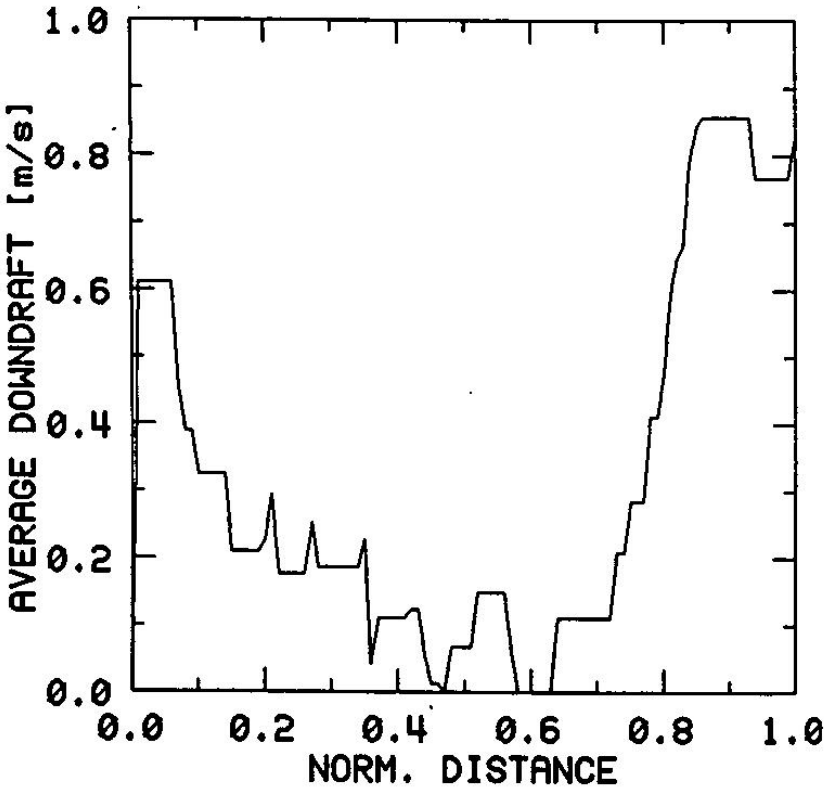
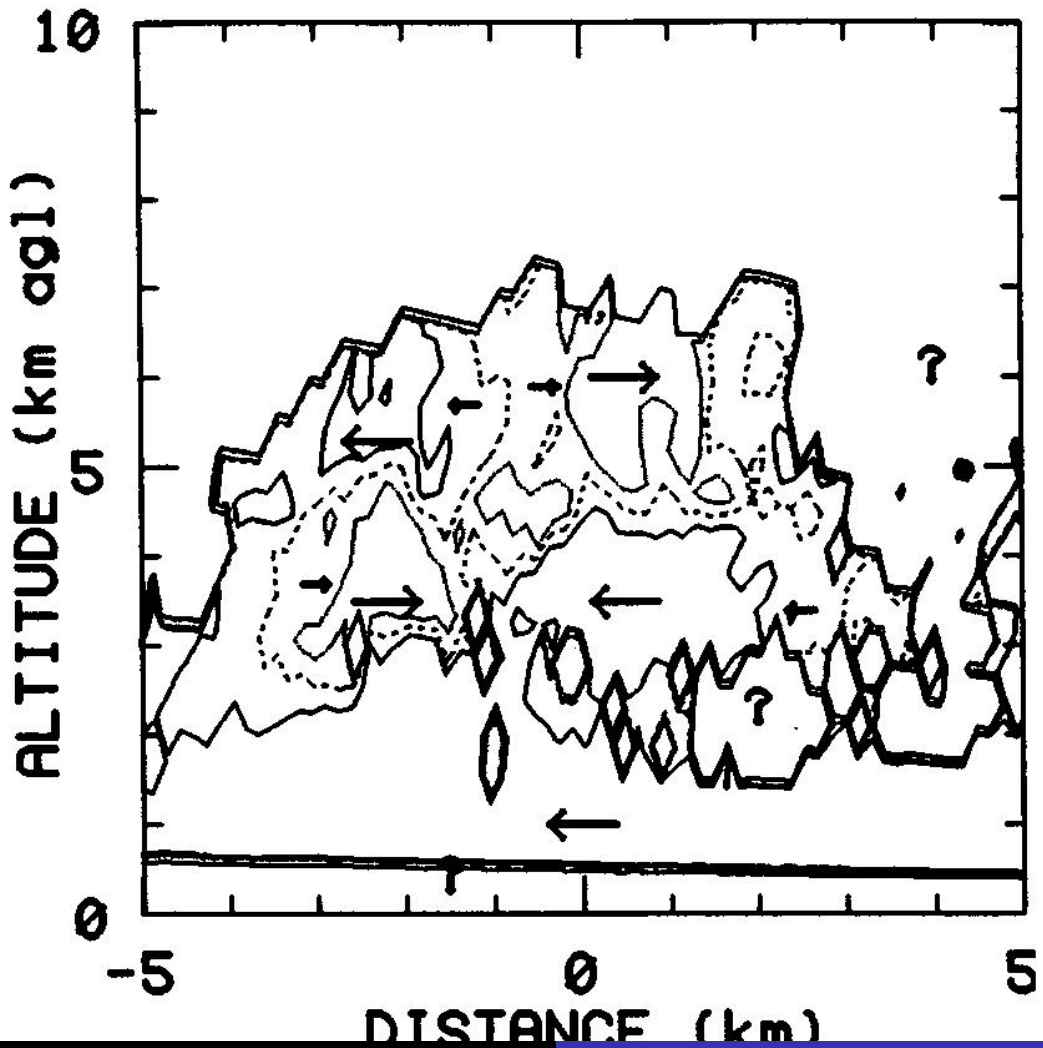
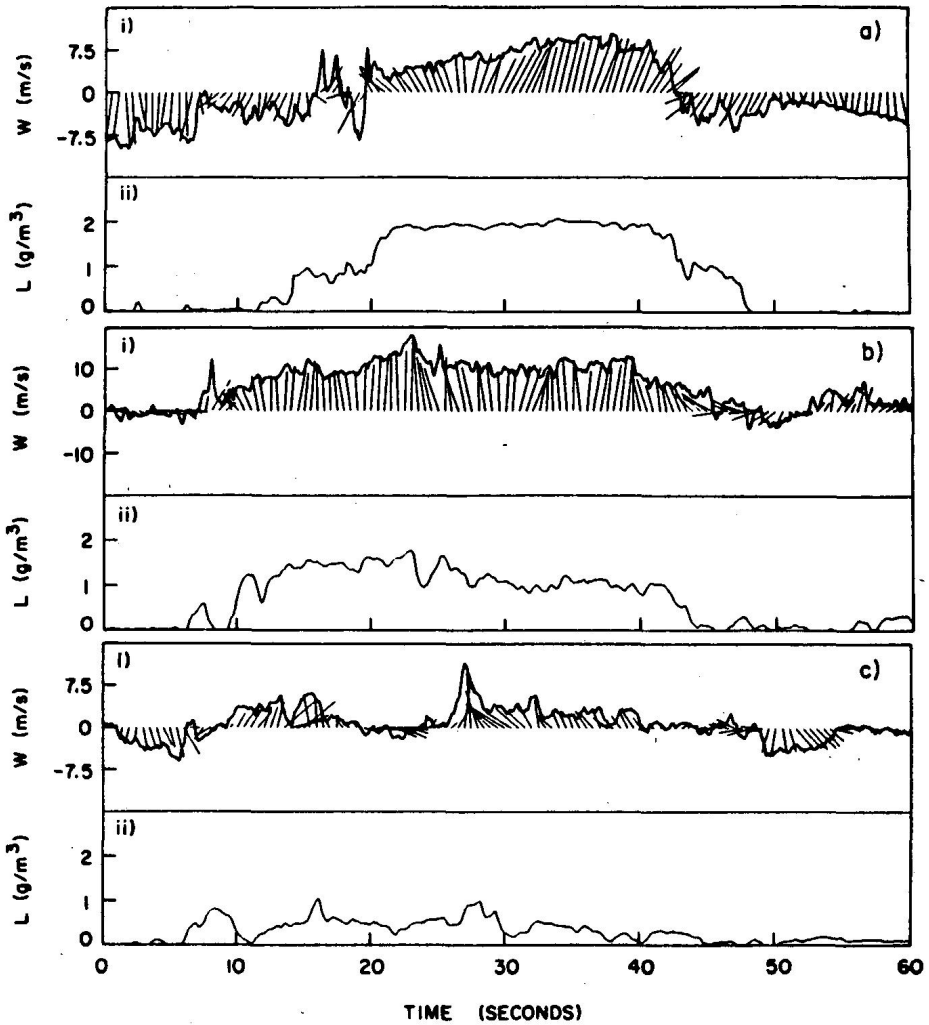


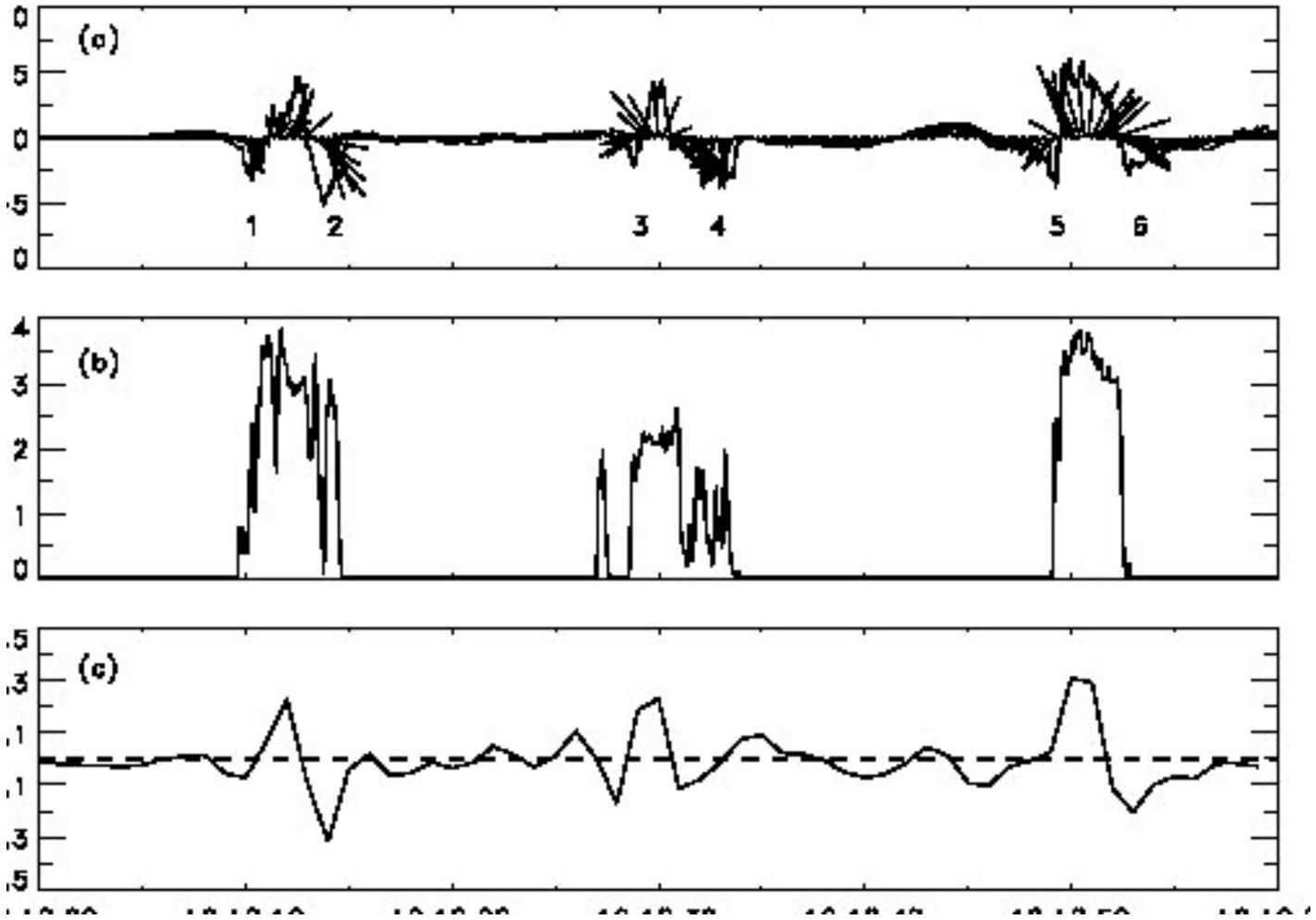
FIG. 13. The average downdraft measured in the 20 HIPLEX-1 clouds, as a function of the normalized distance from the upshear side of the cloud. The distance was normalized by dividing by the total length of the cloud penetration.

Observations of Thermals



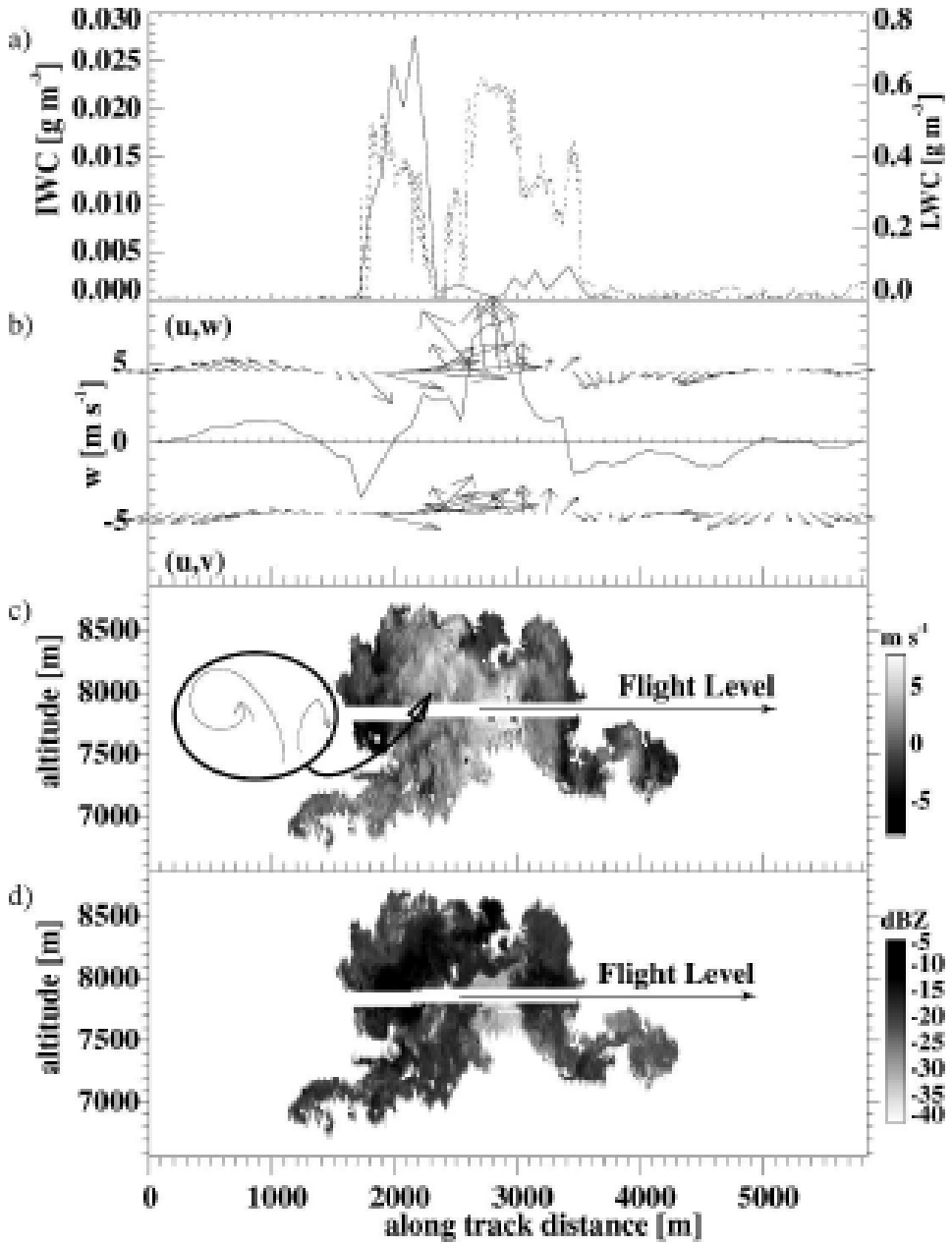


19 July 1981, CCOPE, Montana: 1625 - 1633

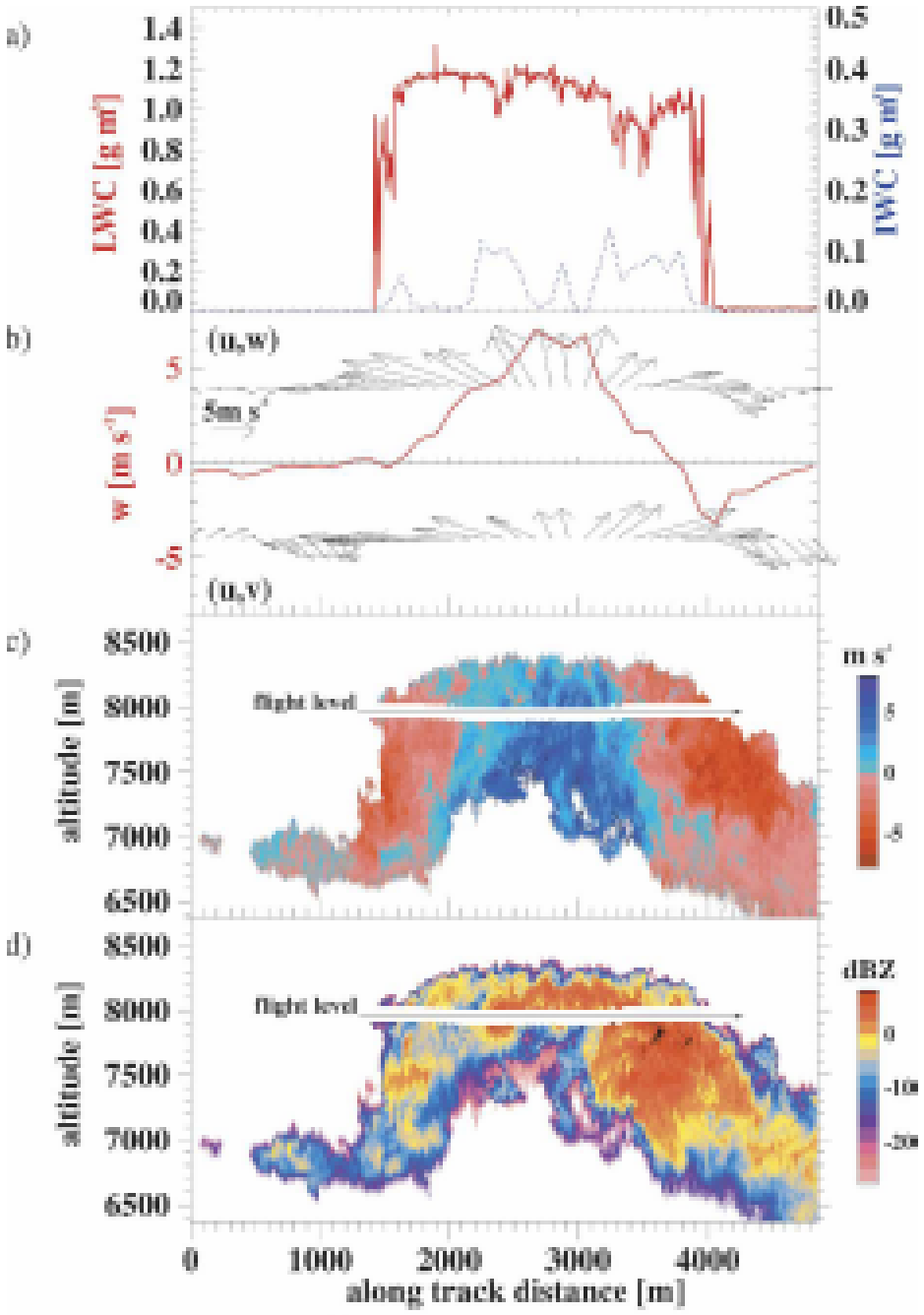


July, 1995, SCMS, Florida

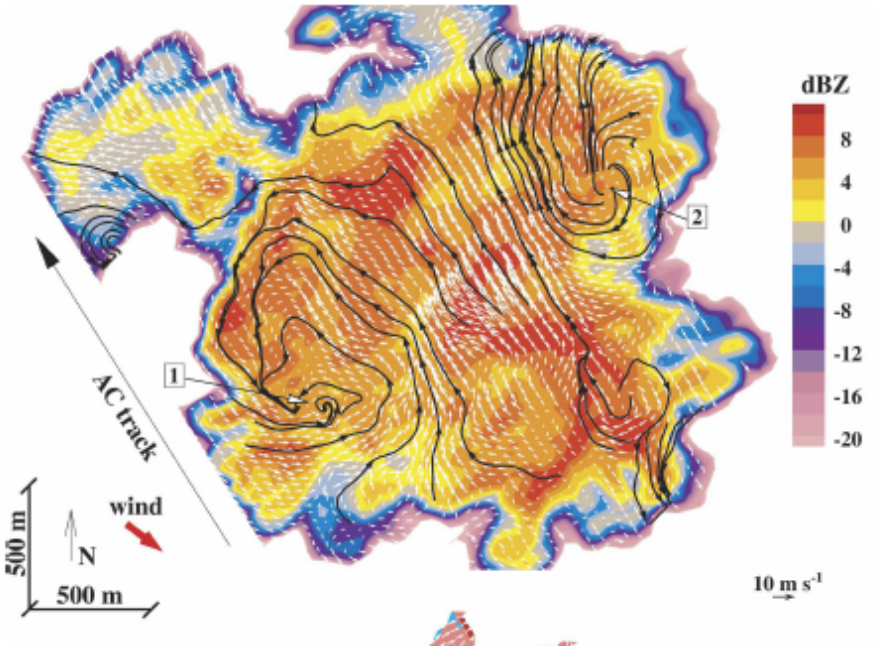
Damiani et al



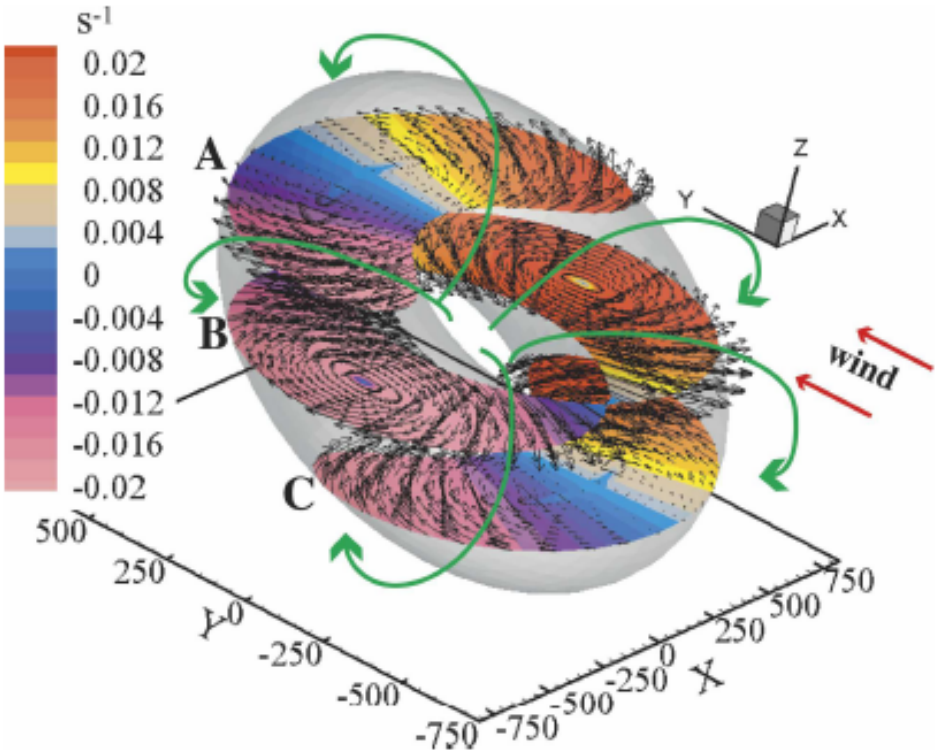
Damiani et al



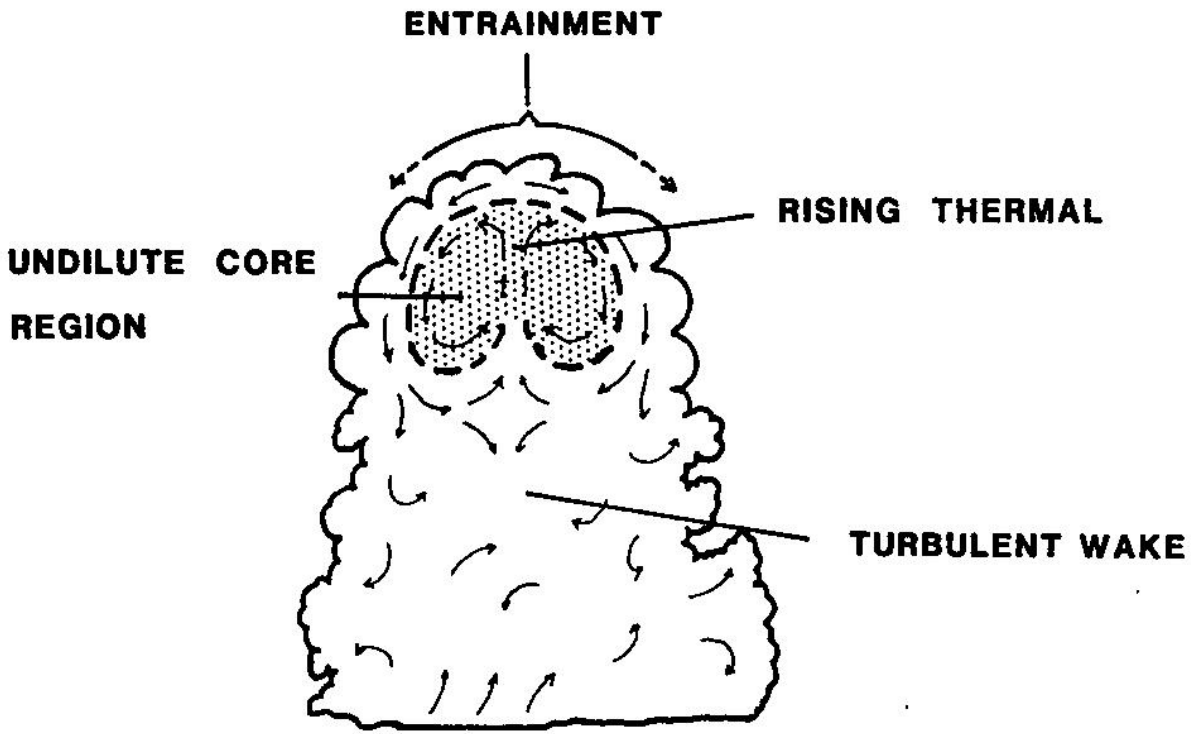
Damiani et al



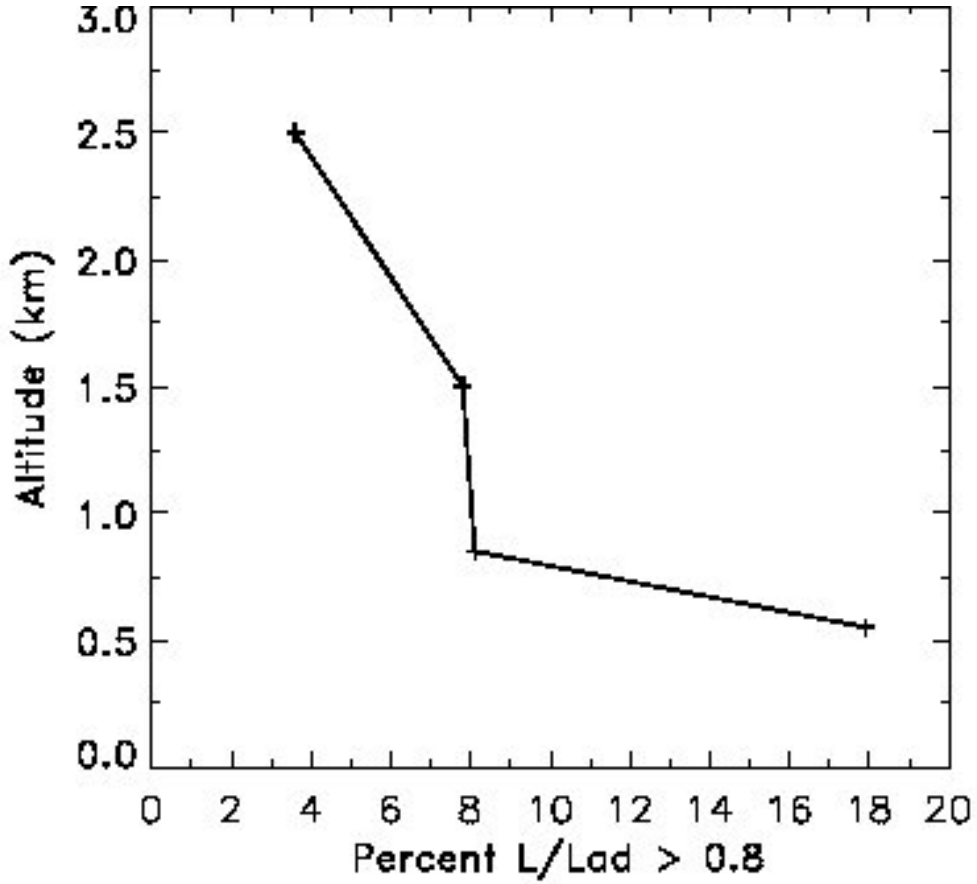
Damiani et al



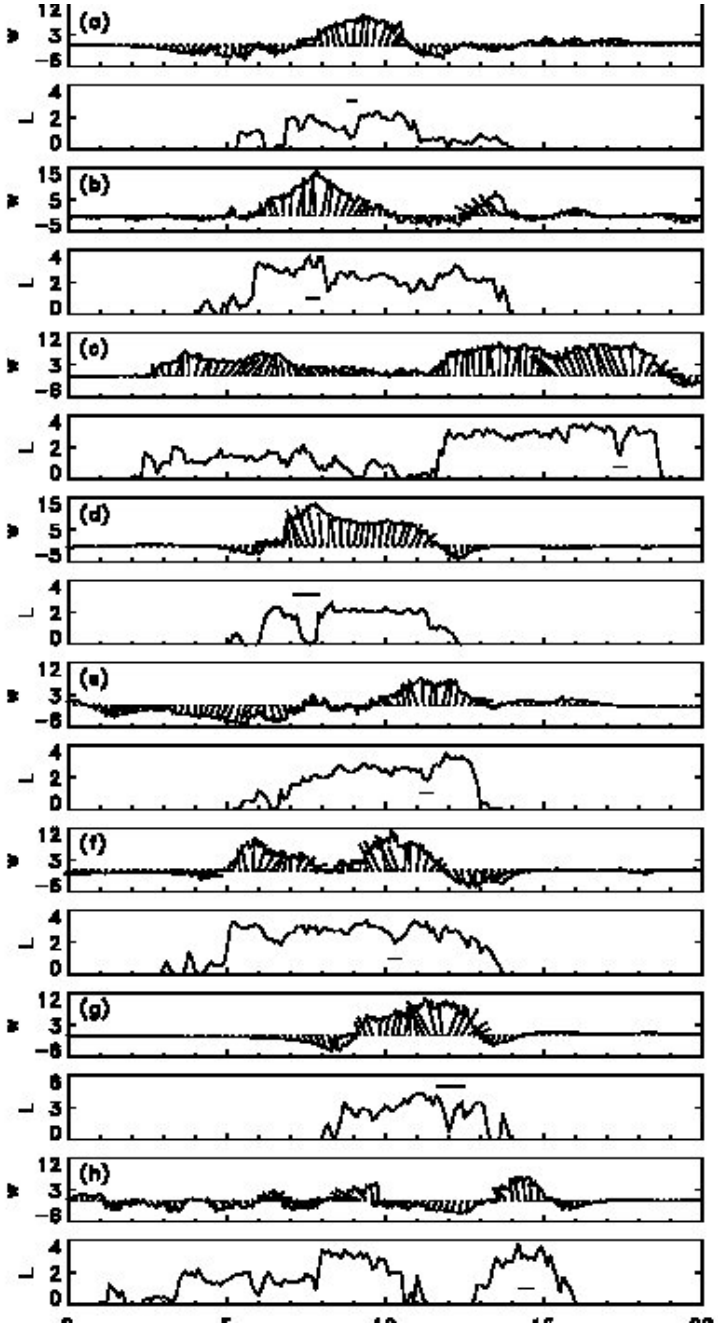
Schematic picture of thermals and entrainment



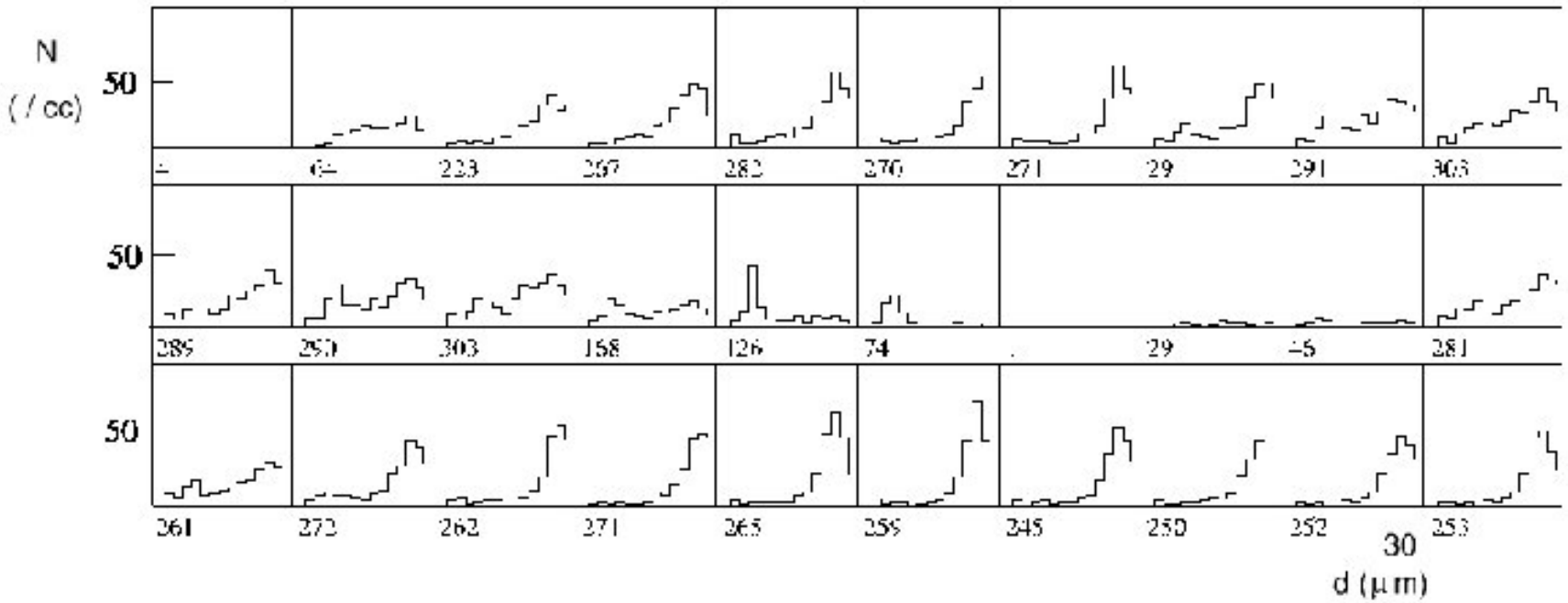
Erosion of the core



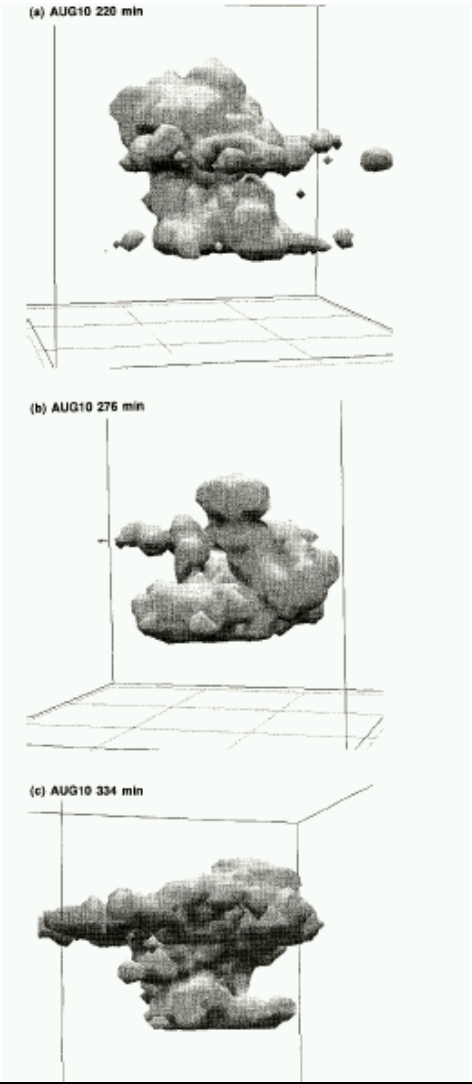
Reduced LWC in middle of updraft



Drop size distribution in the hole



Cloud models: Richard Carpenter



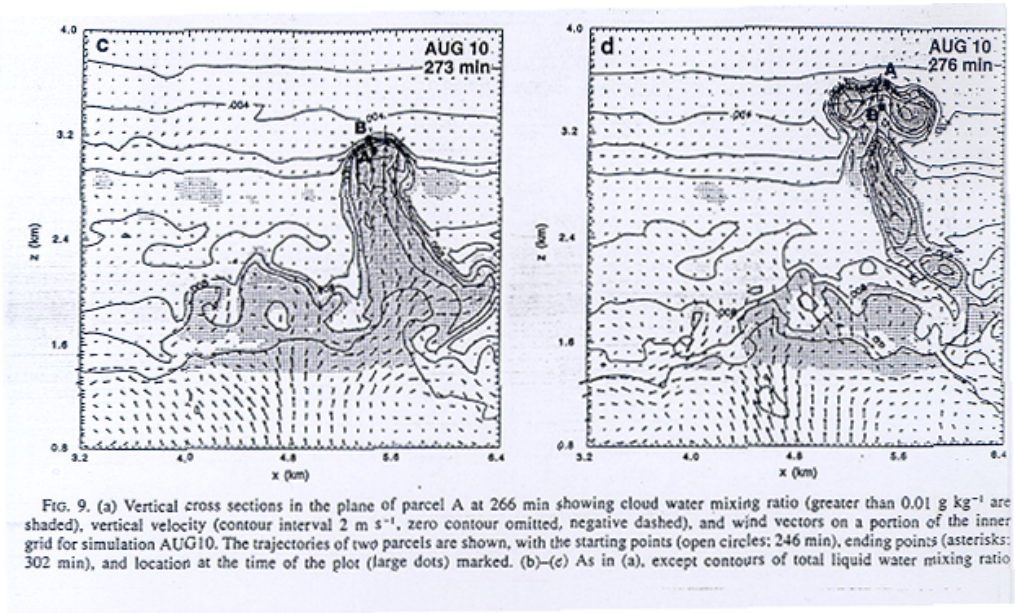
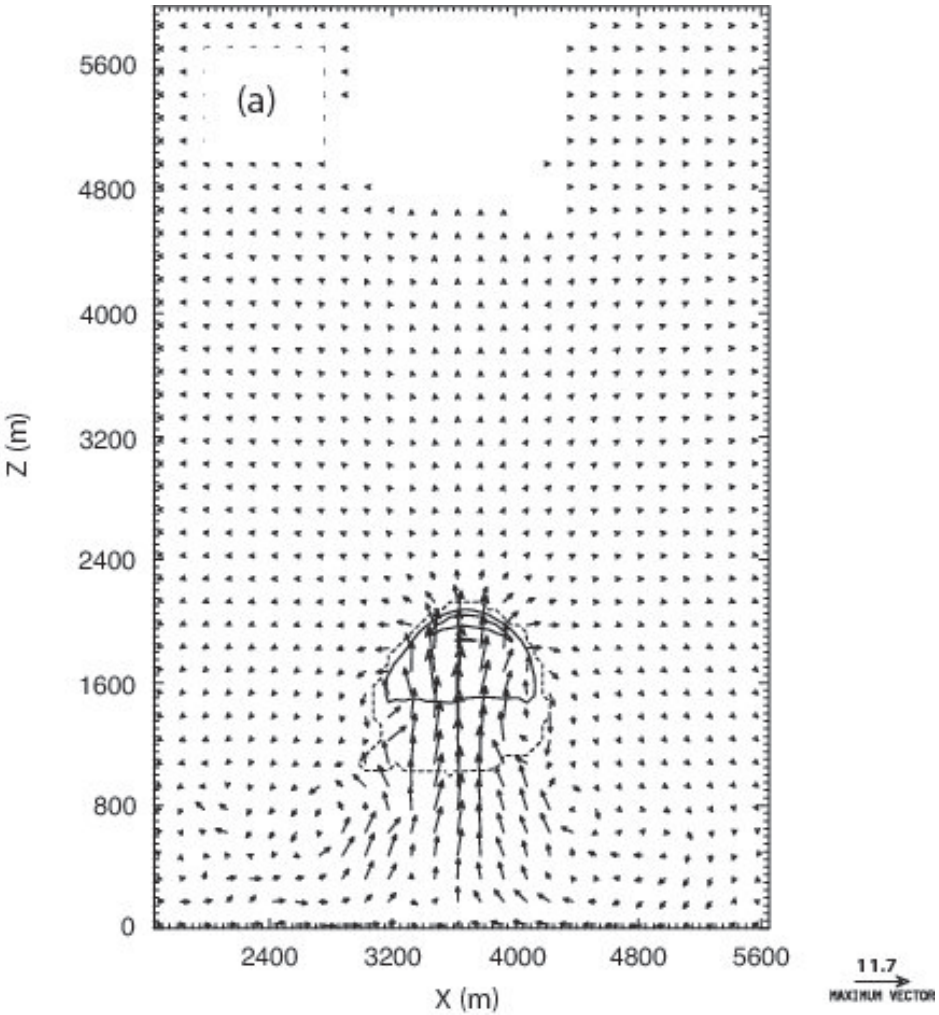


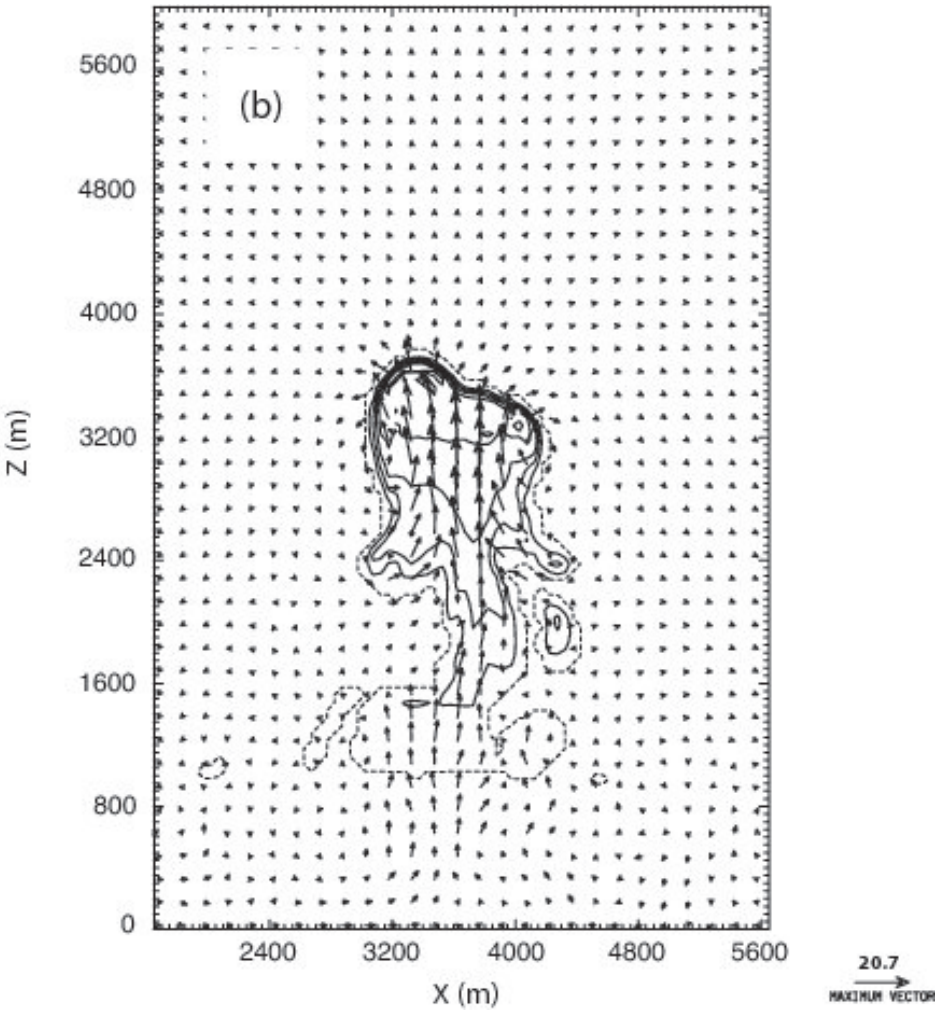
FIG. 9. (a) Vertical cross sections in the plane of parcel A at 266 min showing cloud water mixing ratio (greater than 0.01 g kg^{-1} are shaded), vertical velocity (contour interval 2 m s^{-1}, zero contour omitted, negative dashed), and wind vectors on a portion of the inner grid for simulation AUG10. The trajectories of two parcels are shown, with the starting points (open circles: 246 min), ending points (asterisks: 302 min), and location at the time of the plot (large dots) marked. (b)–(c) As in (a), except contours of total liquid water mixing ratio

From Carpenter et al (1990)

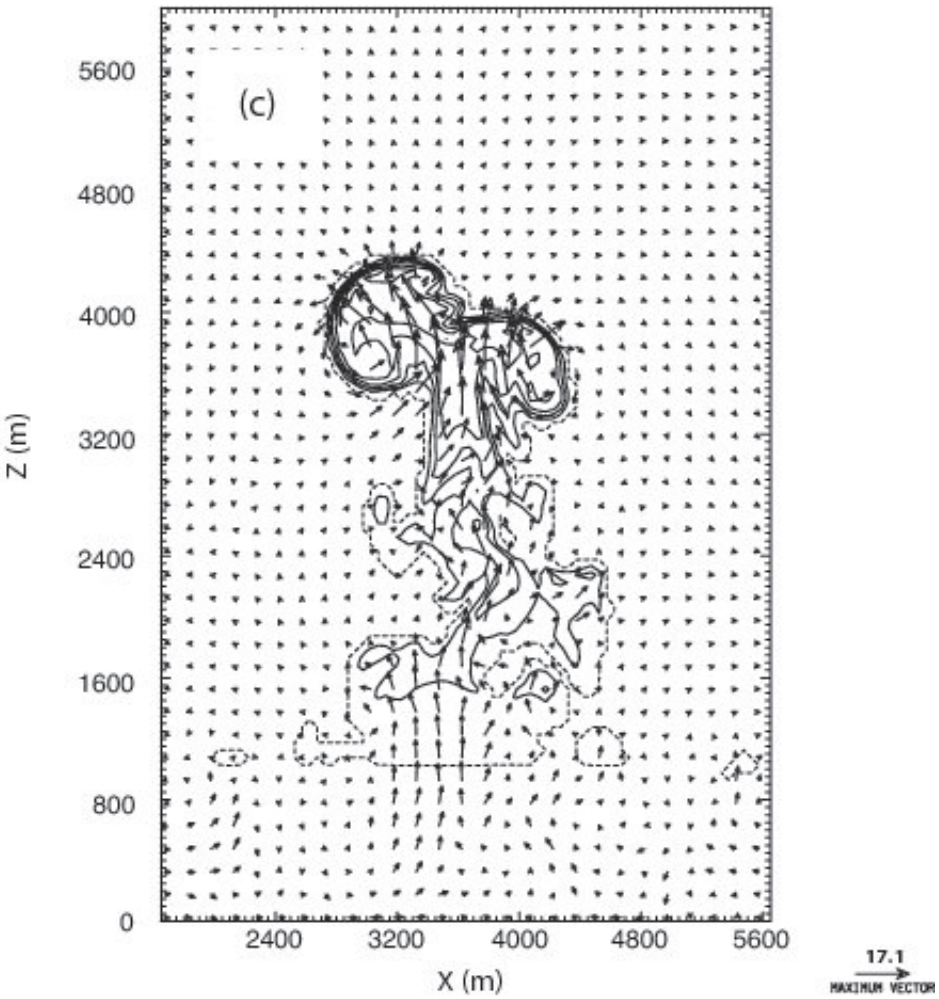
Model of Cu cloud showing thermal



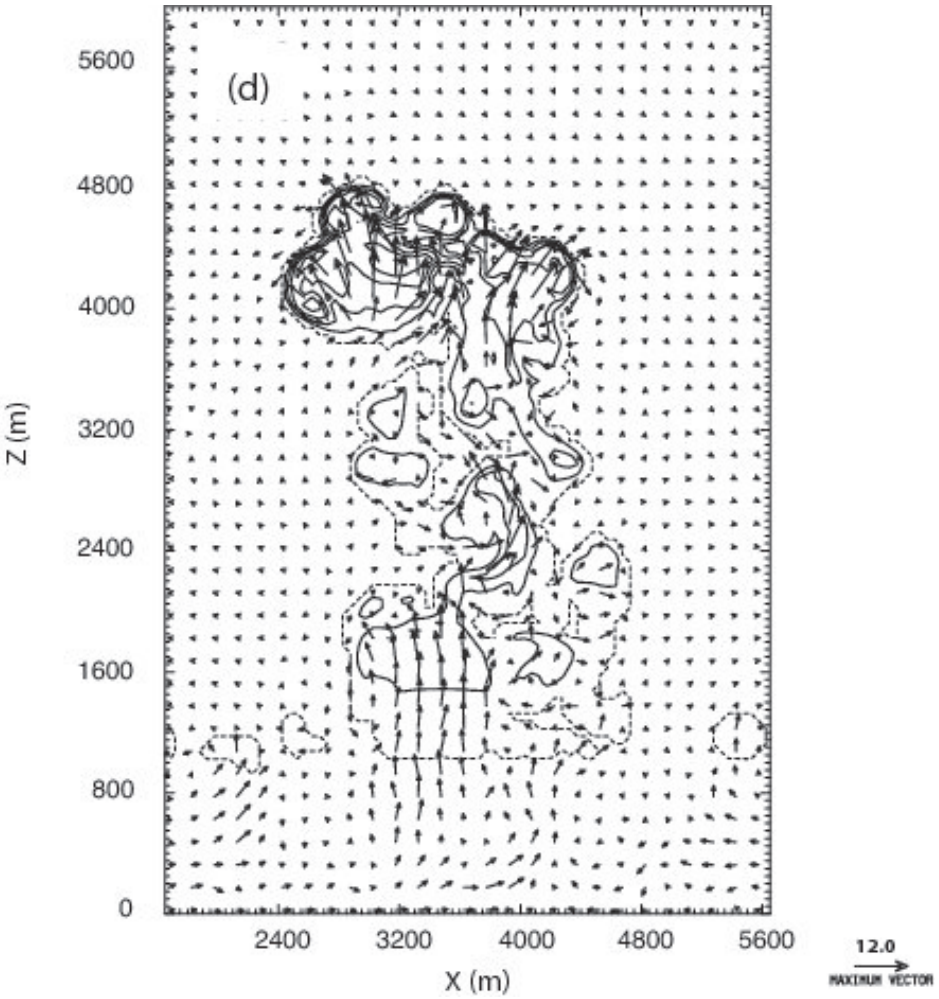
Model of Cu cloud showing thermal



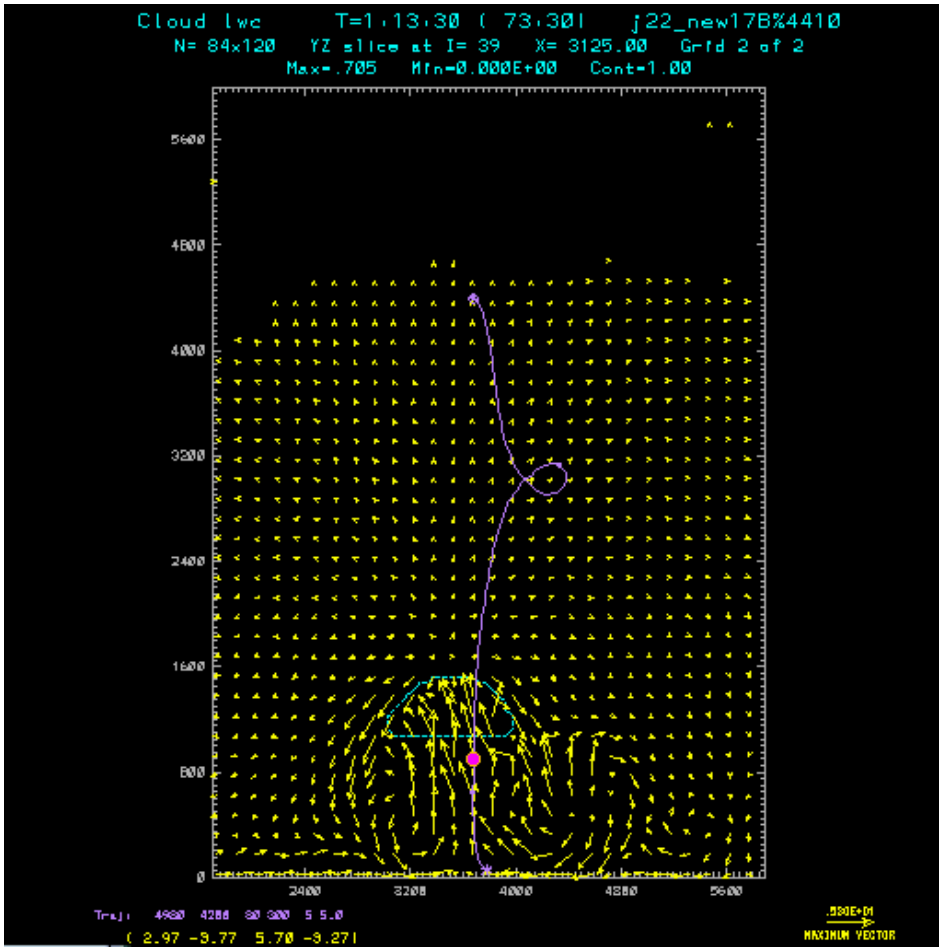
Model of Cu cloud showing thermal



Model of Cu cloud showing thermal

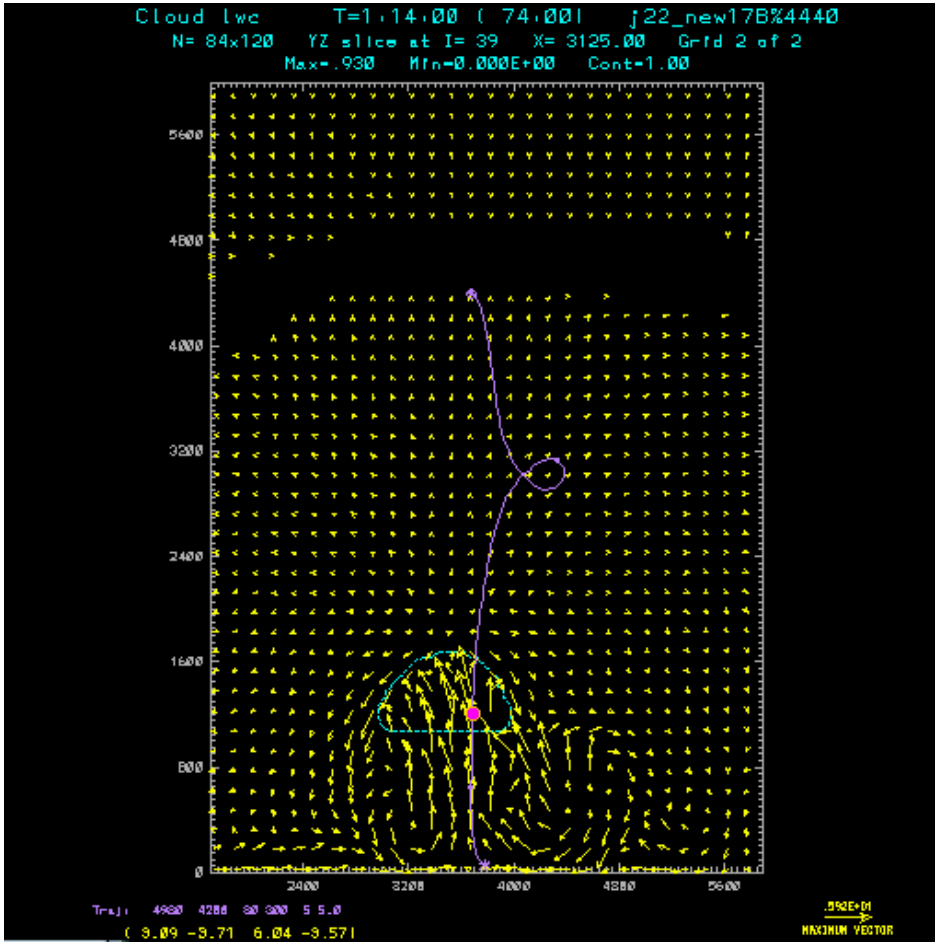


How clouds entrain



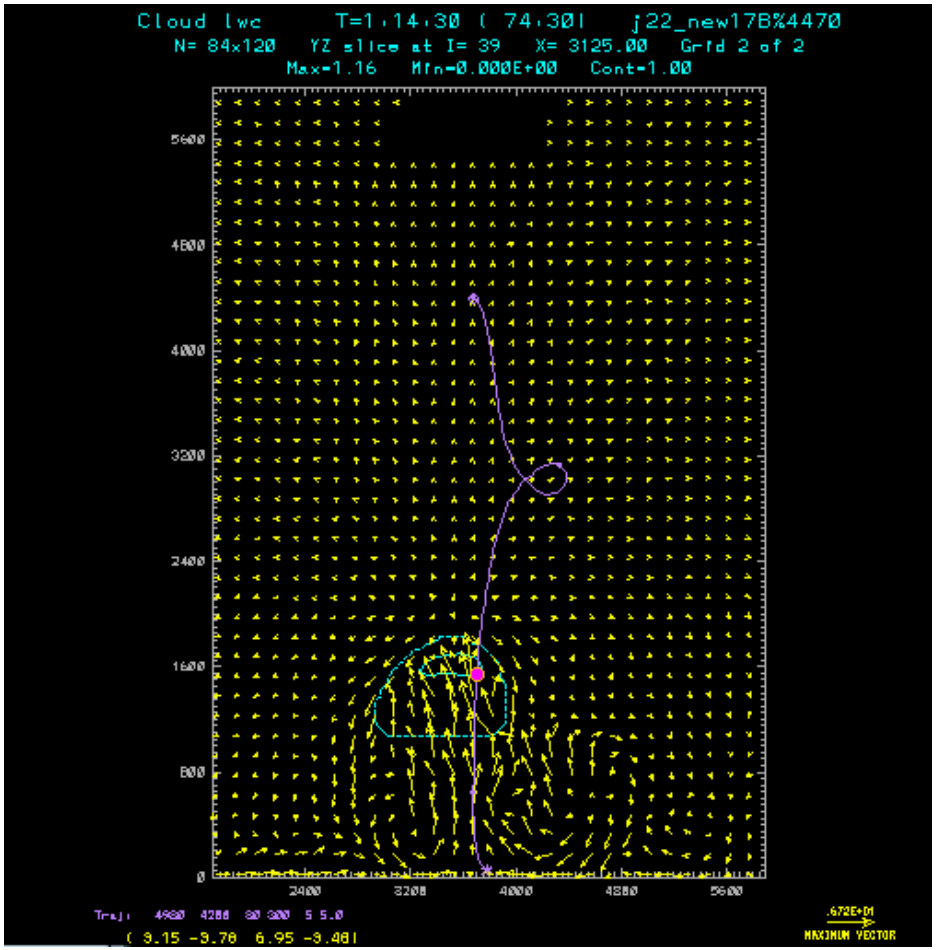
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



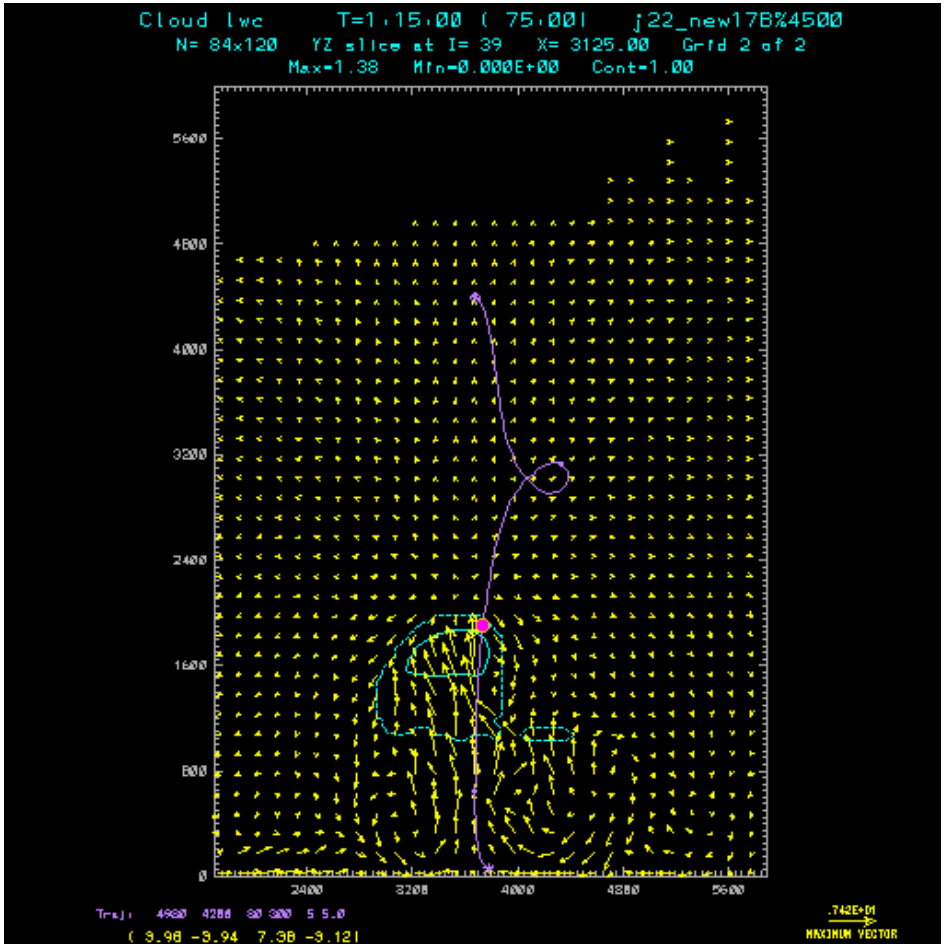
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



Courtesy of Dr. Sonia Lasher-Trapp

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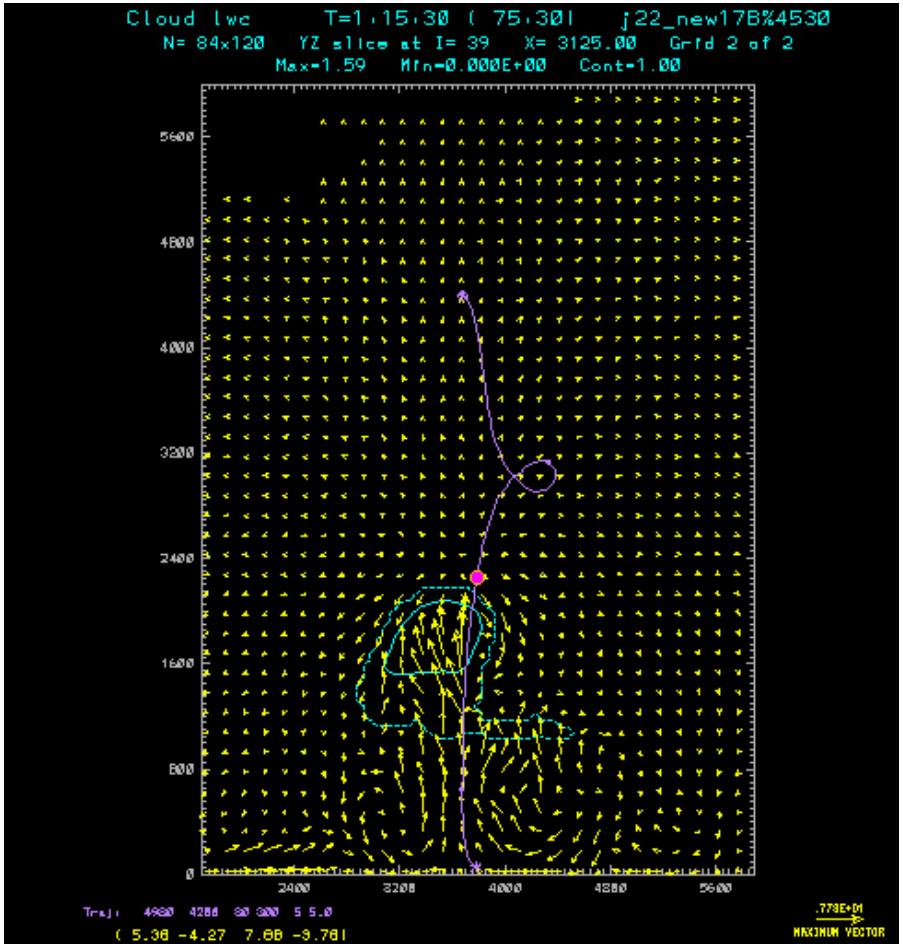
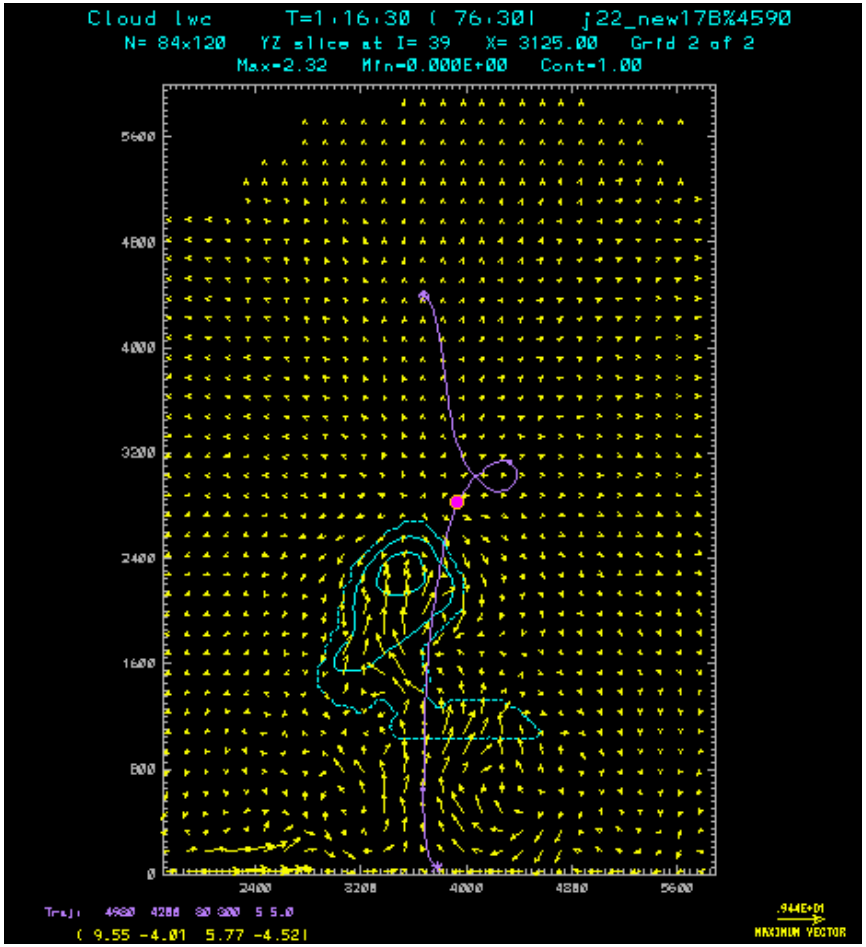


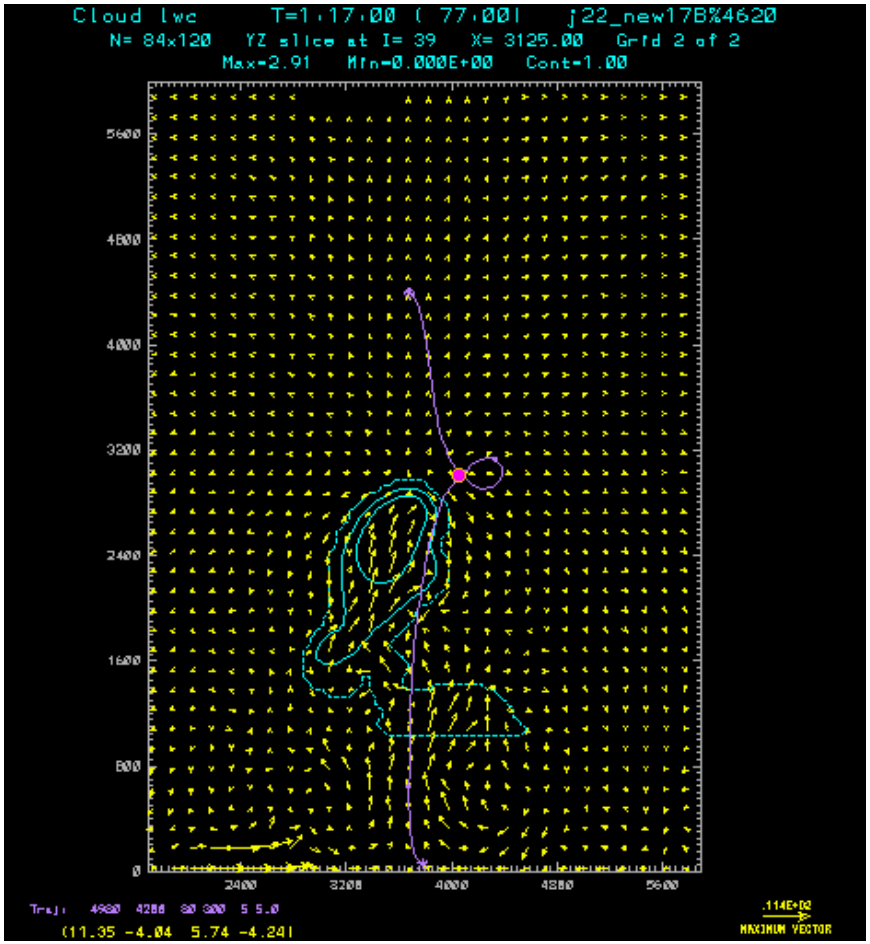
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



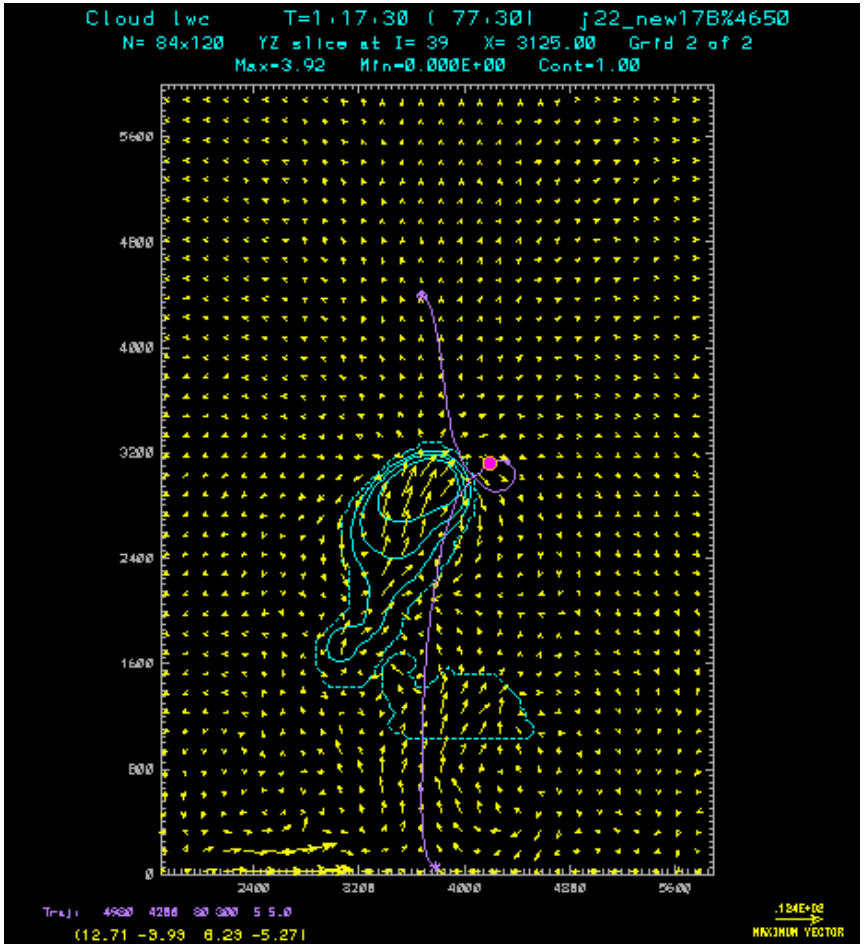
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



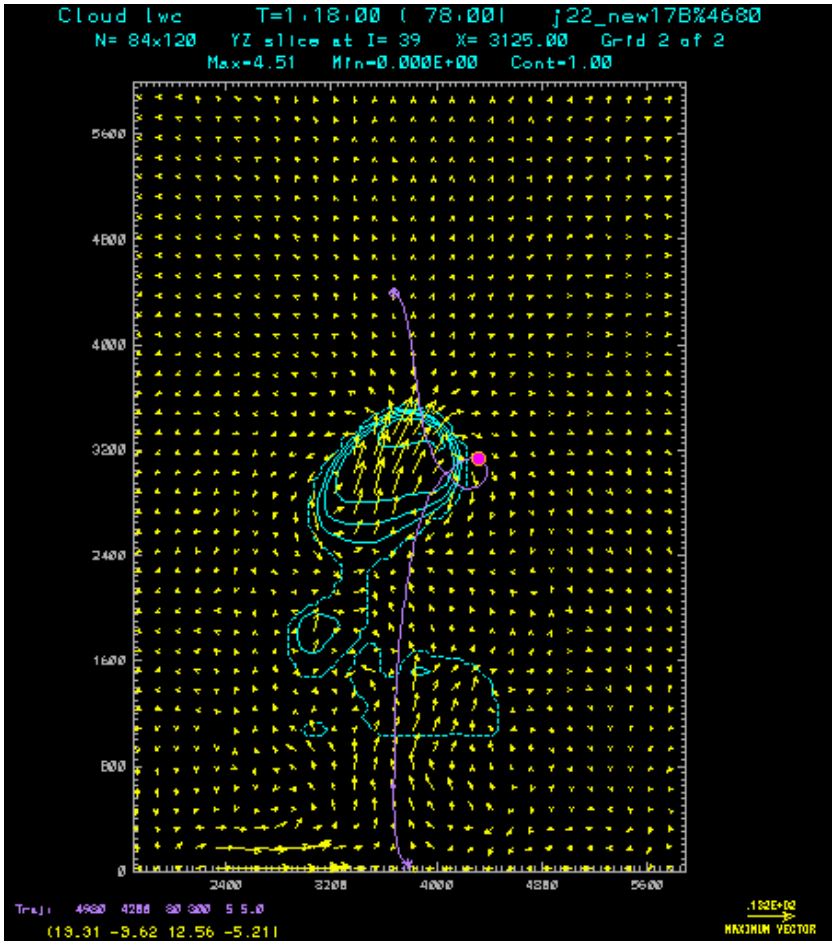
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



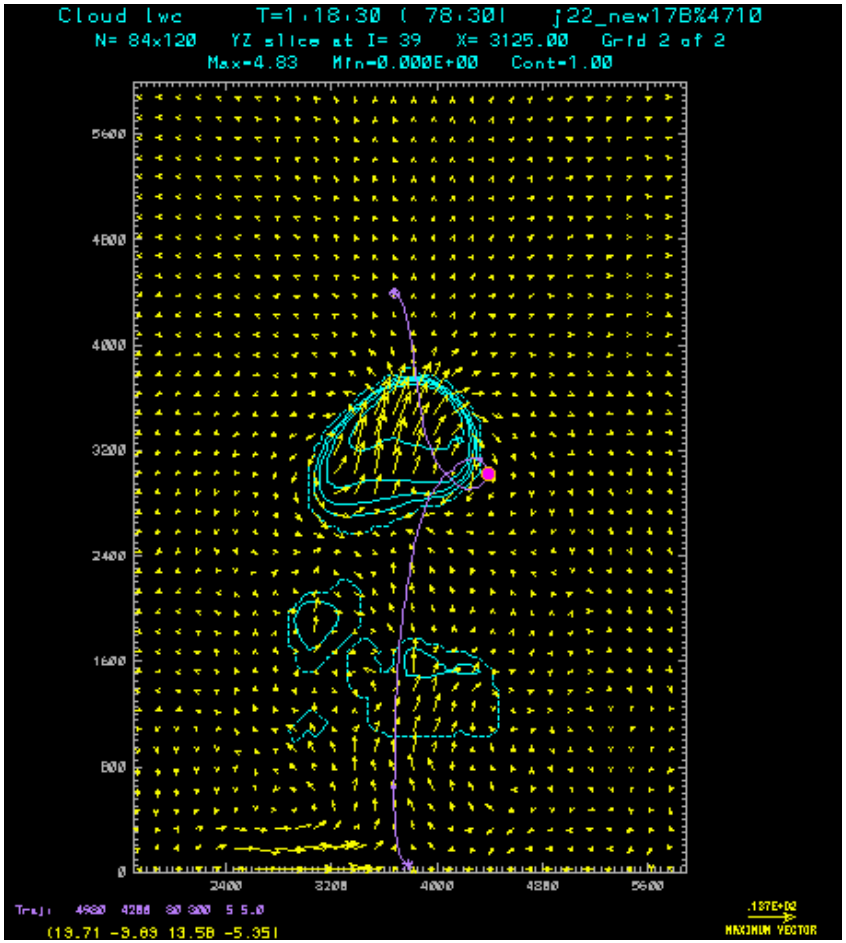
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



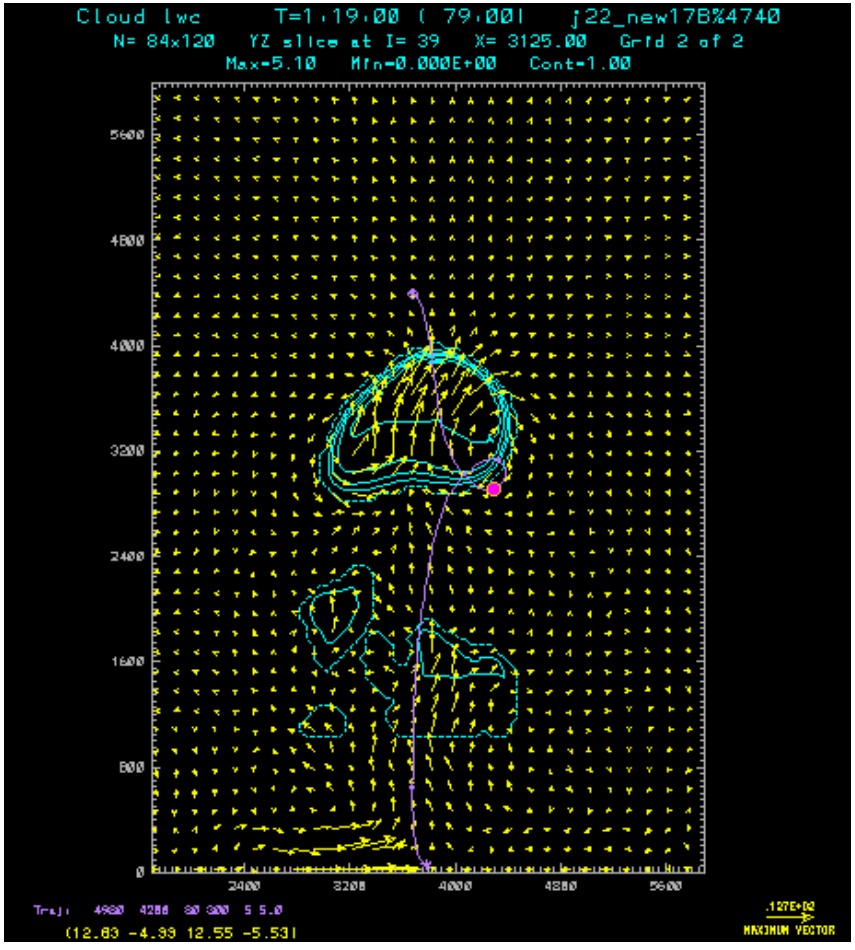
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



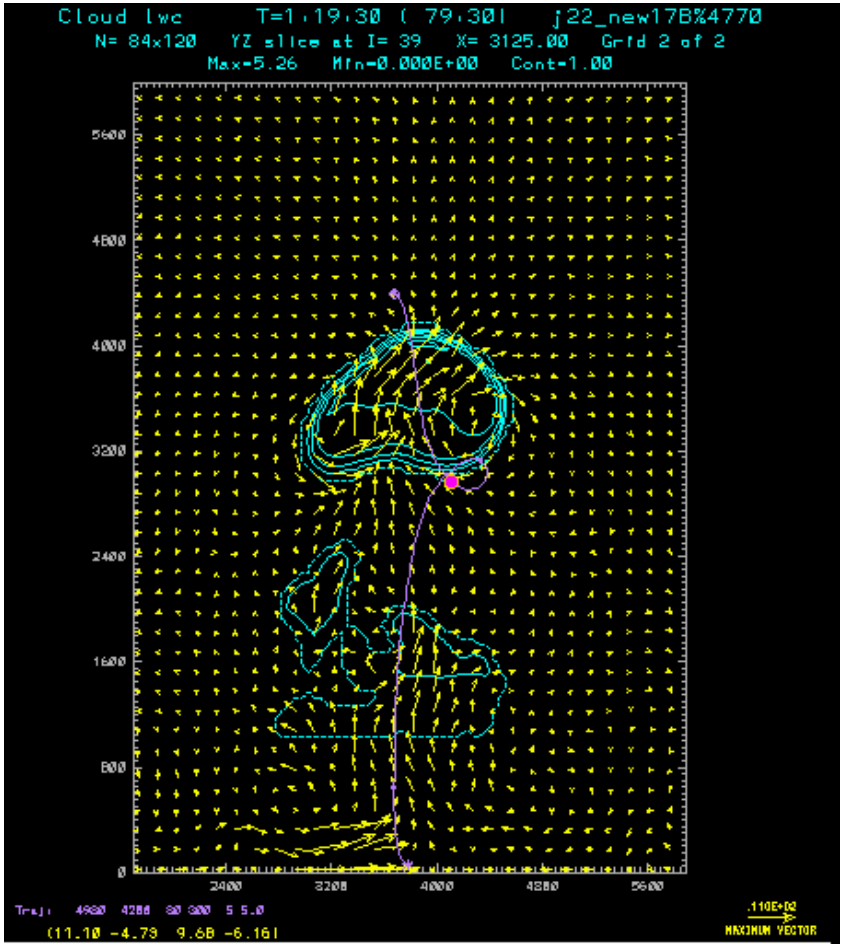
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



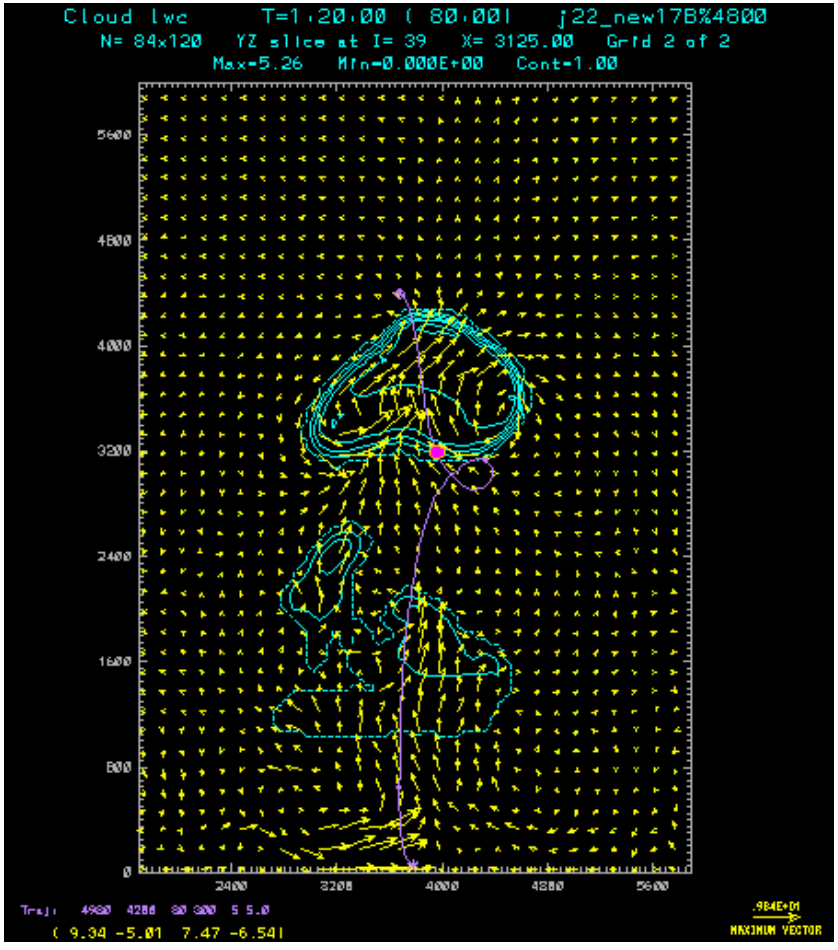
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



Courtesy of Dr. Sonia Lasher-Trapp

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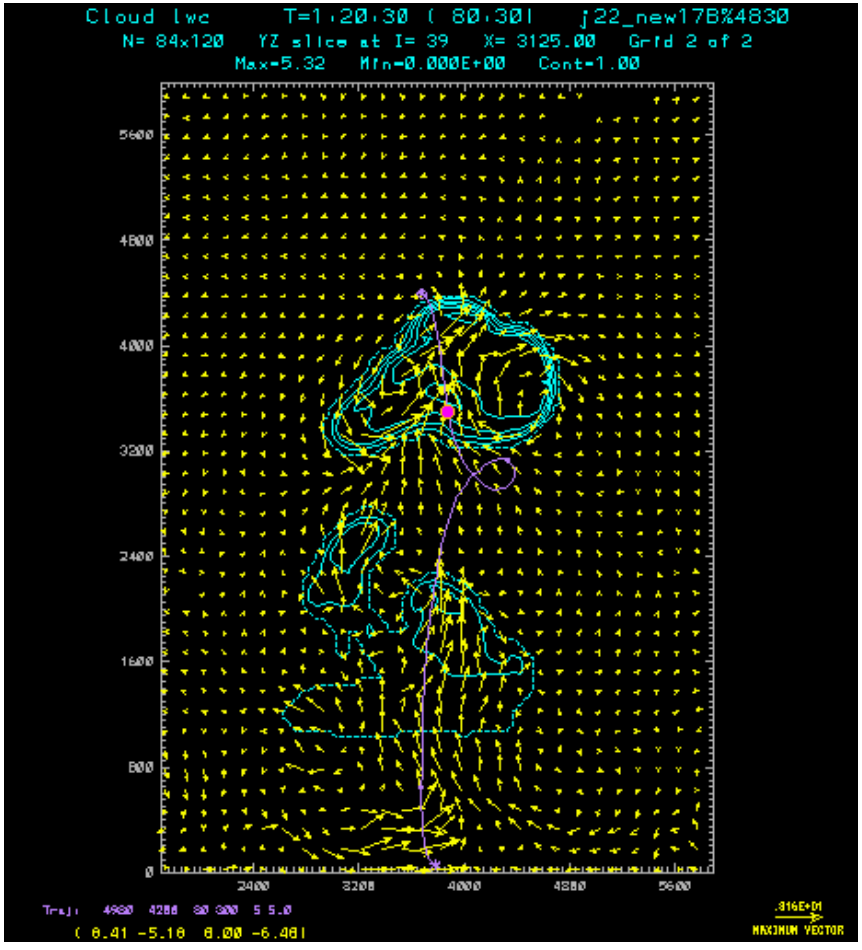
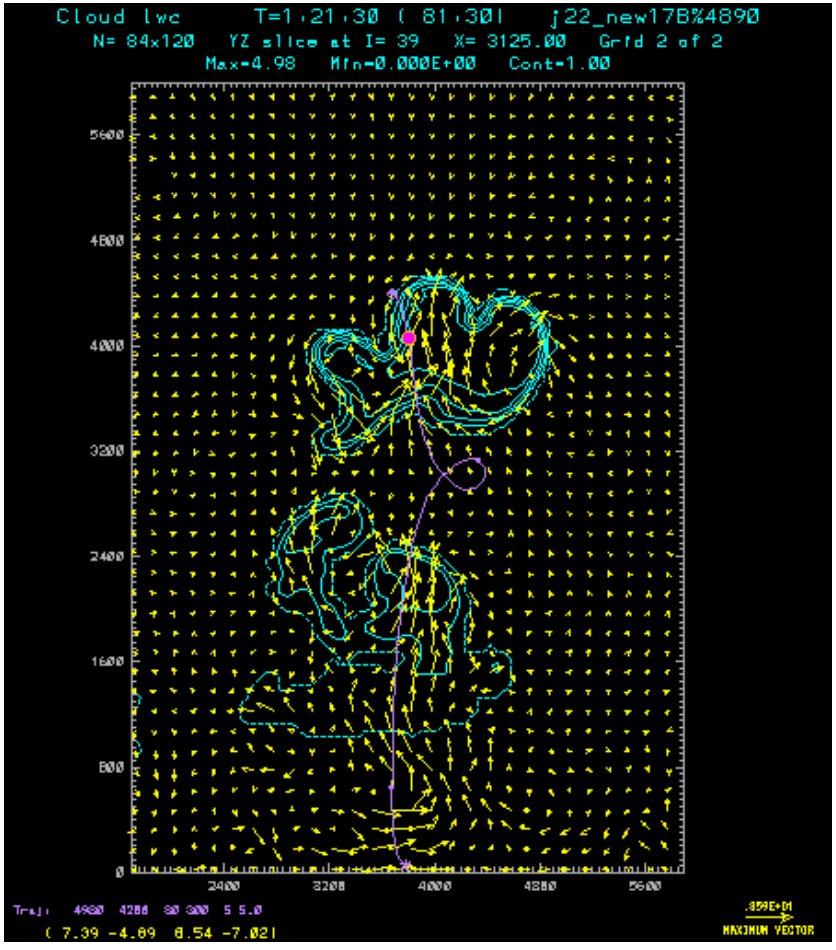


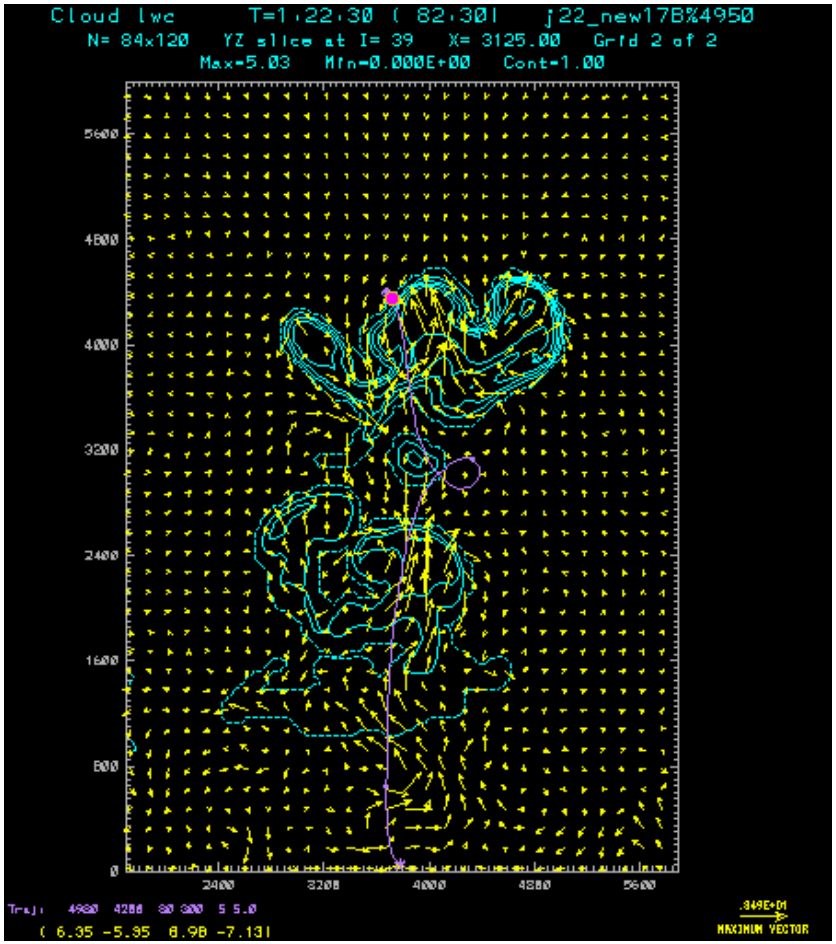
Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain



Courtesy of Dr. Sonia Lasher-Trapp

How clouds entrain

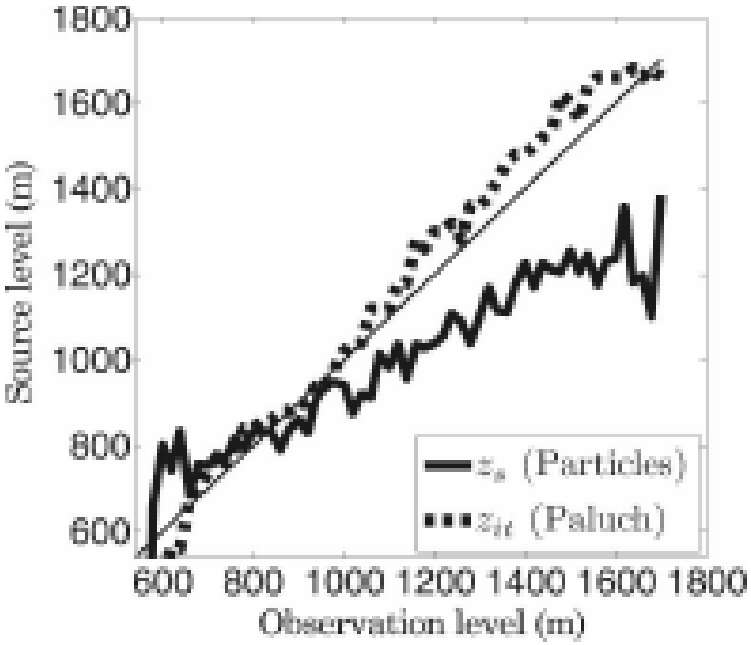


Courtesy of Dr. Sonia Lasher-Trapp

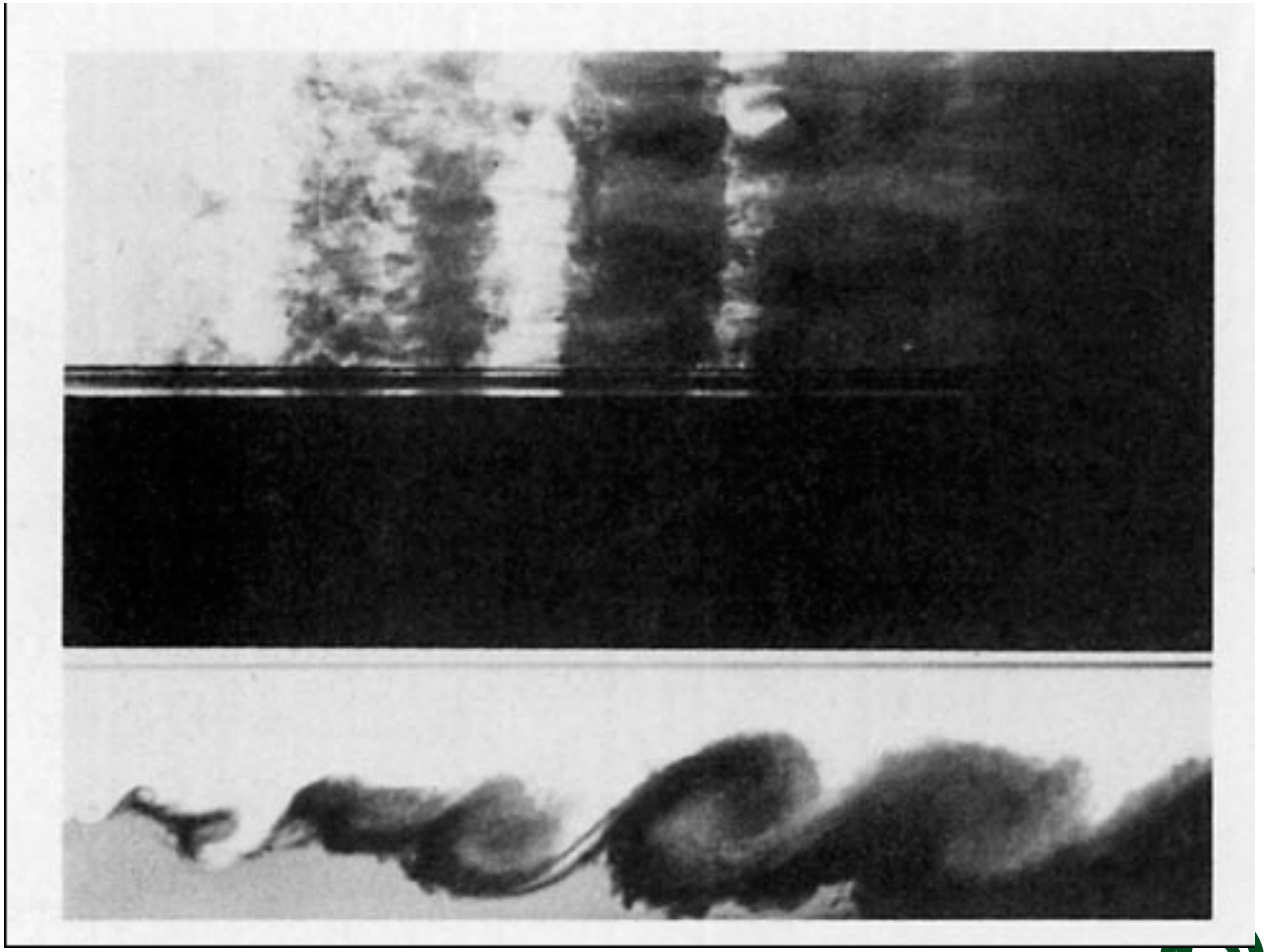
Heus et al: Modelling results

"The obtained Paluch diagrams are found to be similar to many results in the literature, but the source of entrained air found by particle tracking deviates from the source inferred from the Paluch analysis.
Whereas the classical Paluch analysis seems to provide some evidence for cloud-top mixing, particle tracking shows that virtually all mixing occurs laterally.
Particle trajectories averaged over the entire cloud ensemble also clearly indicate the absence of significant cloud-top mixing in shallow cumulus clouds."

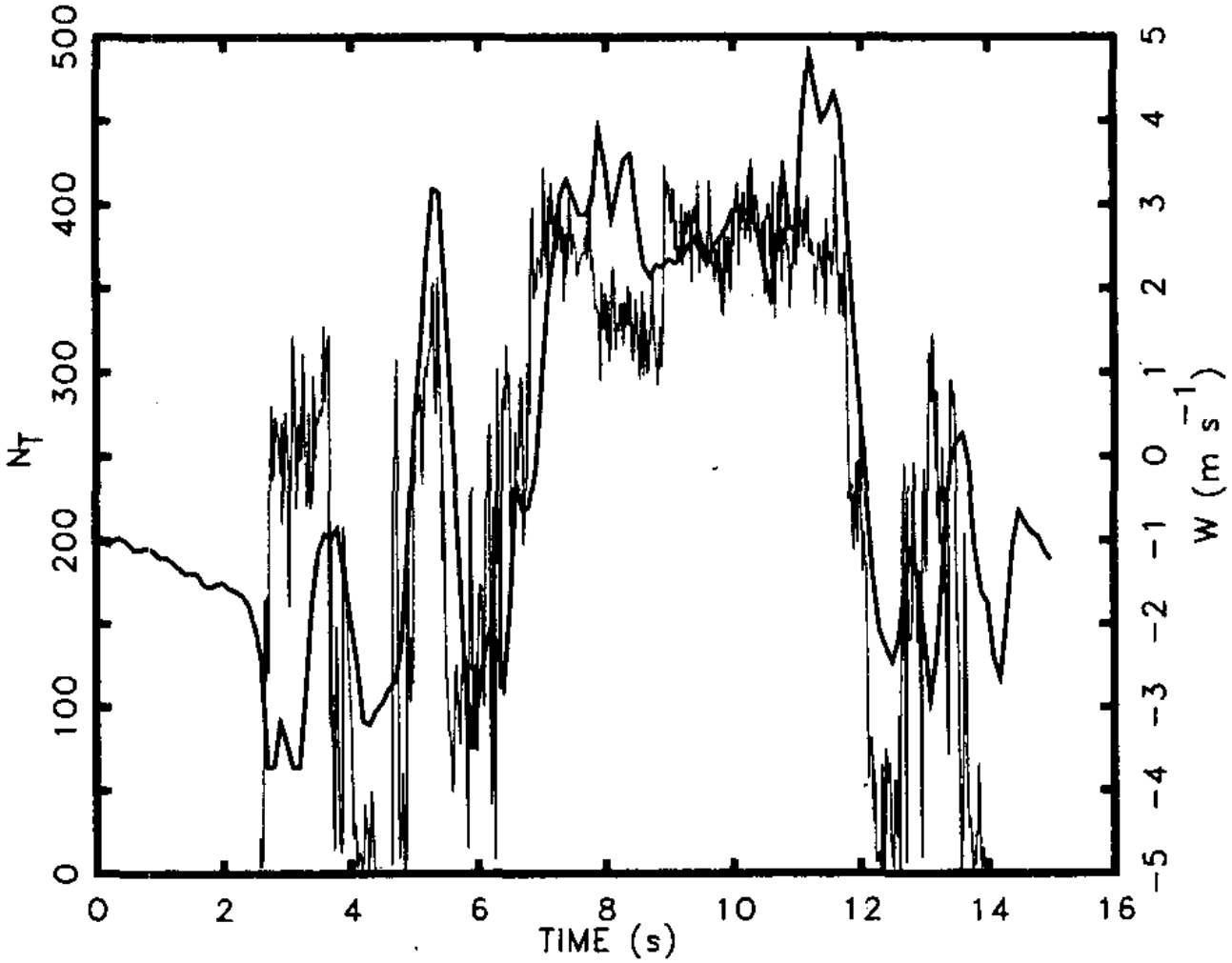
Heus et al


1800
1600
1400
1200
1000
800
600
Source level (m)
600 800 1000 1200 1400 1600 1800
Observation level (m)
z_s (Particles)
z_{it} (Paluch)

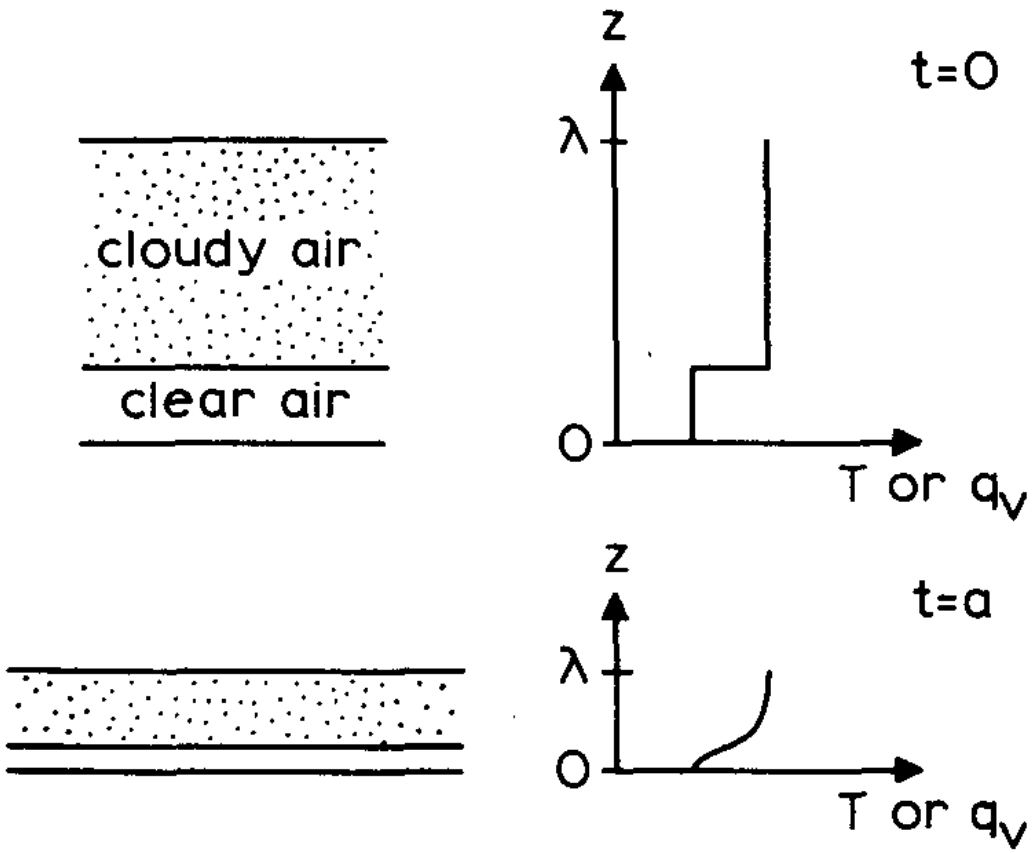
What happens at the boundaries?



From Baker et al. (1984)



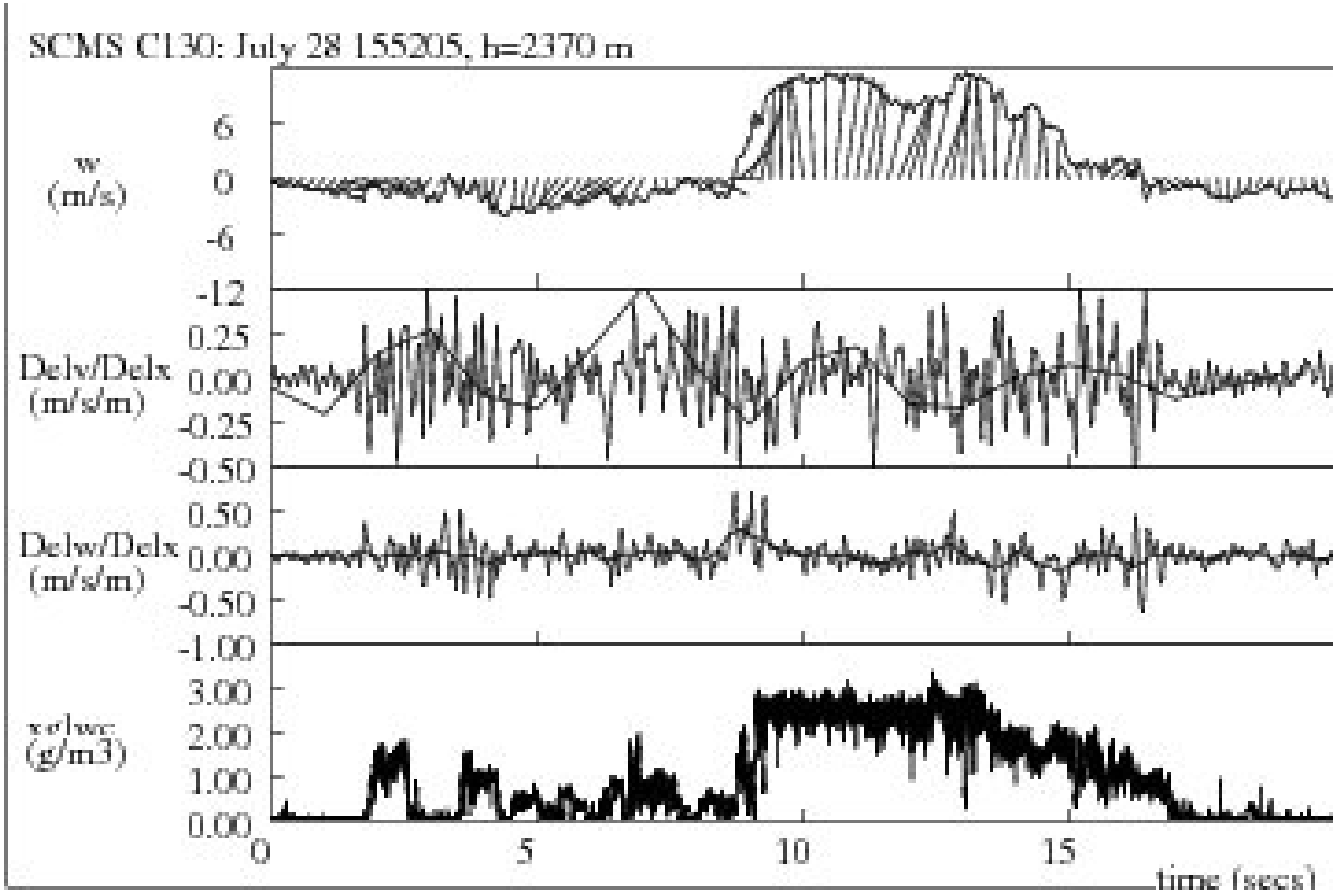
From Jensen and Baker (1989)


cloudy air
clear air
z
t=0
λ
0
T or q_v
z
t=a
λ
0
T or q_v

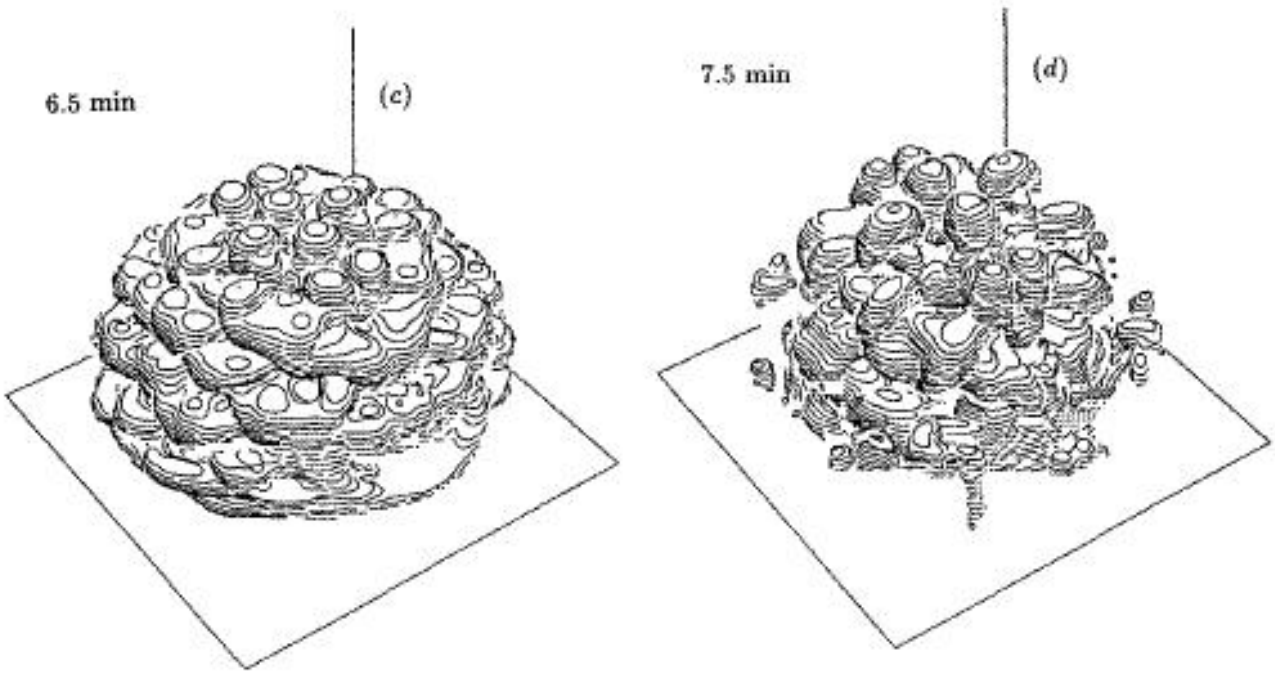
Cloud edges

- The sharpness of cloud edges must tell us something about the relative magnitudes of the processes strengthening and weakening the gradients there
- Gradients are sharpened due to buoyancy and smoothed out due to turbulent eddies

Gradients in LWC and vertical wind; convergence



Does this happen at the edges of Clouds?



From Grabowski and Clark (1993)

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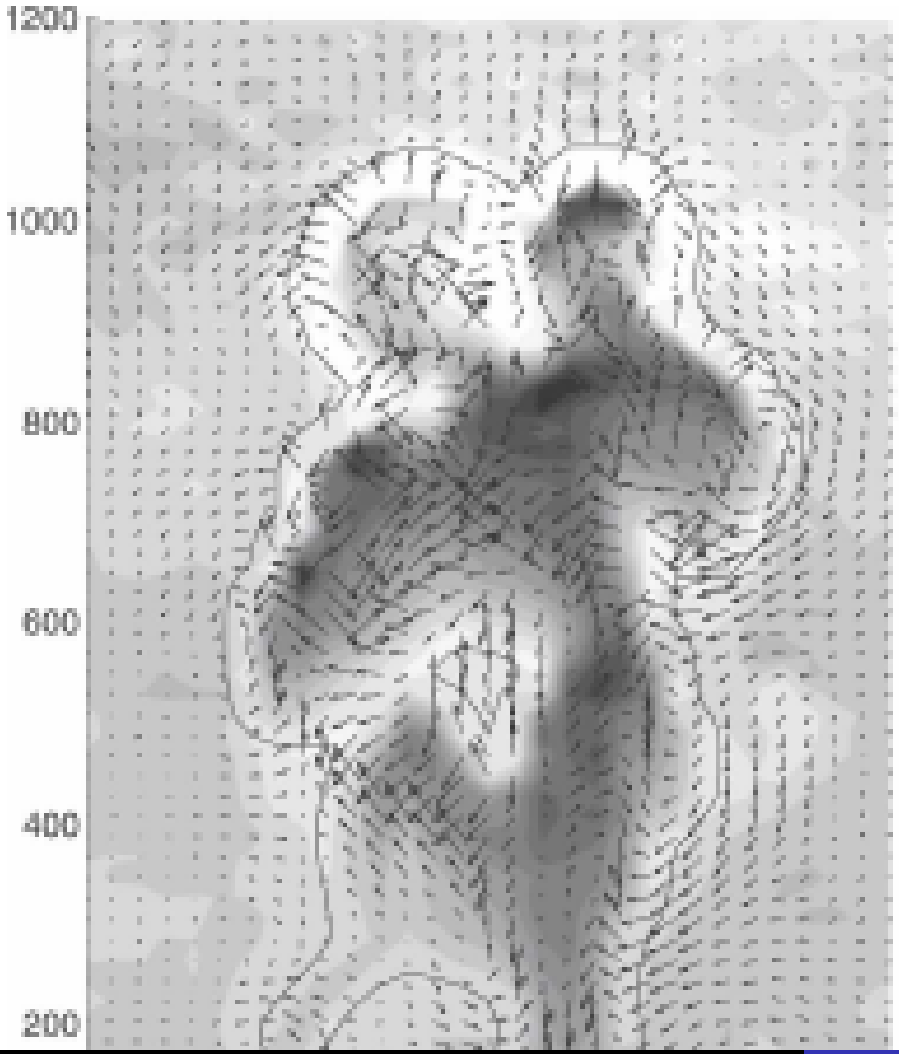
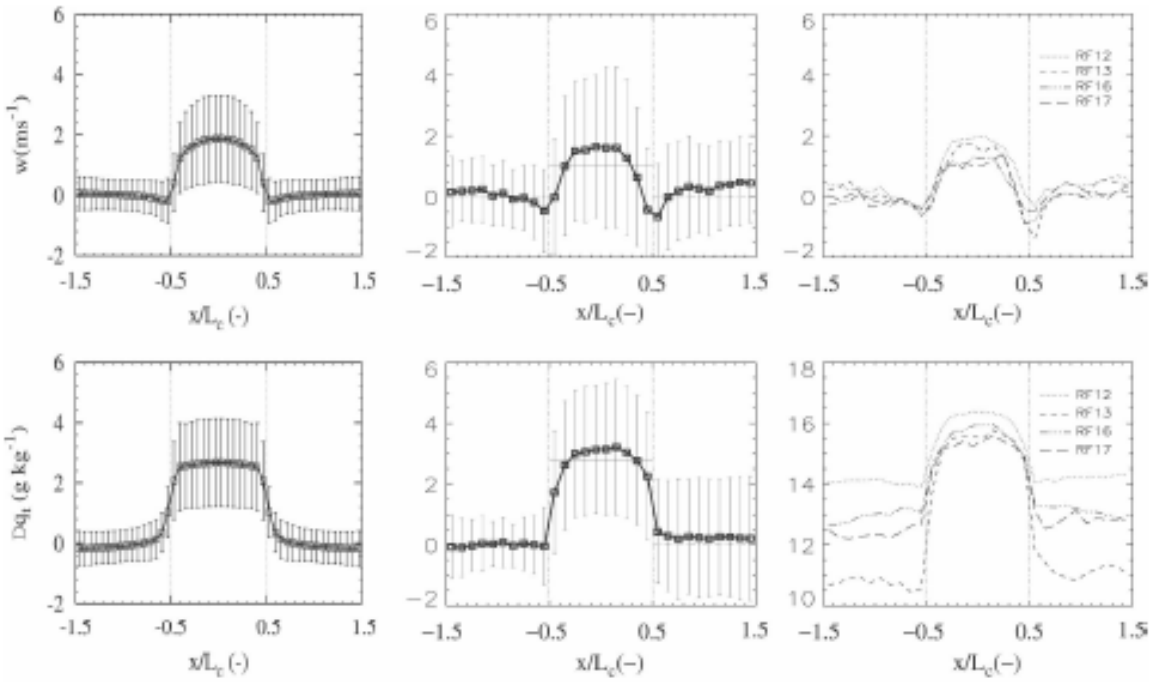
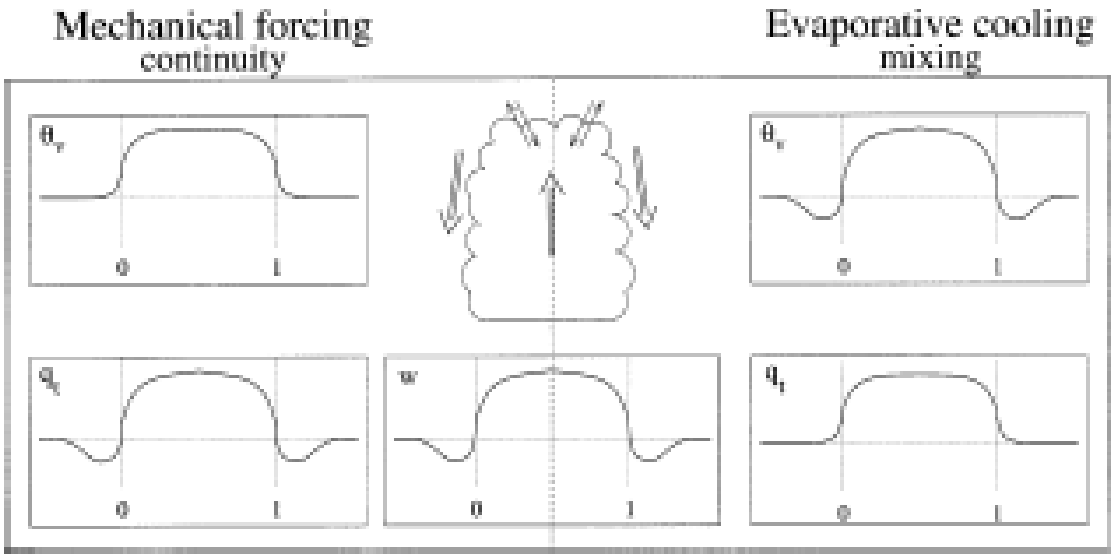
Heus and Jonkers: cloud-edge downdrafts





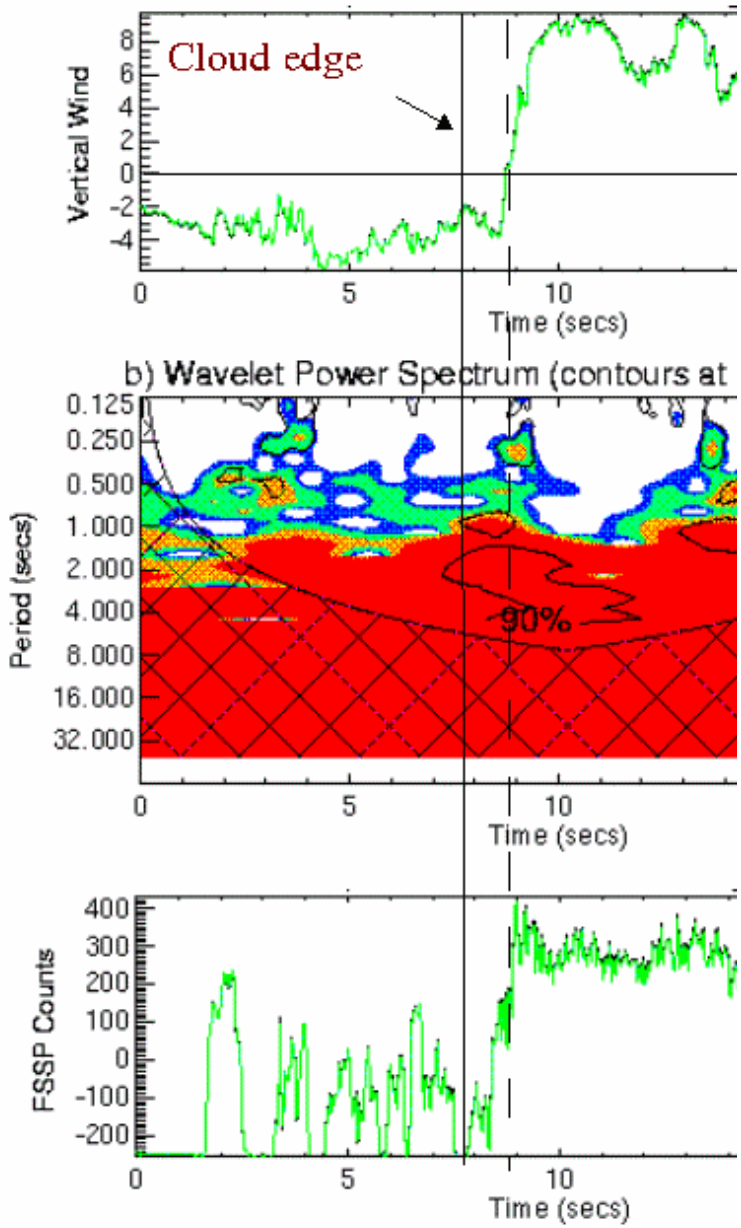
Heus and Jonkers, 2003

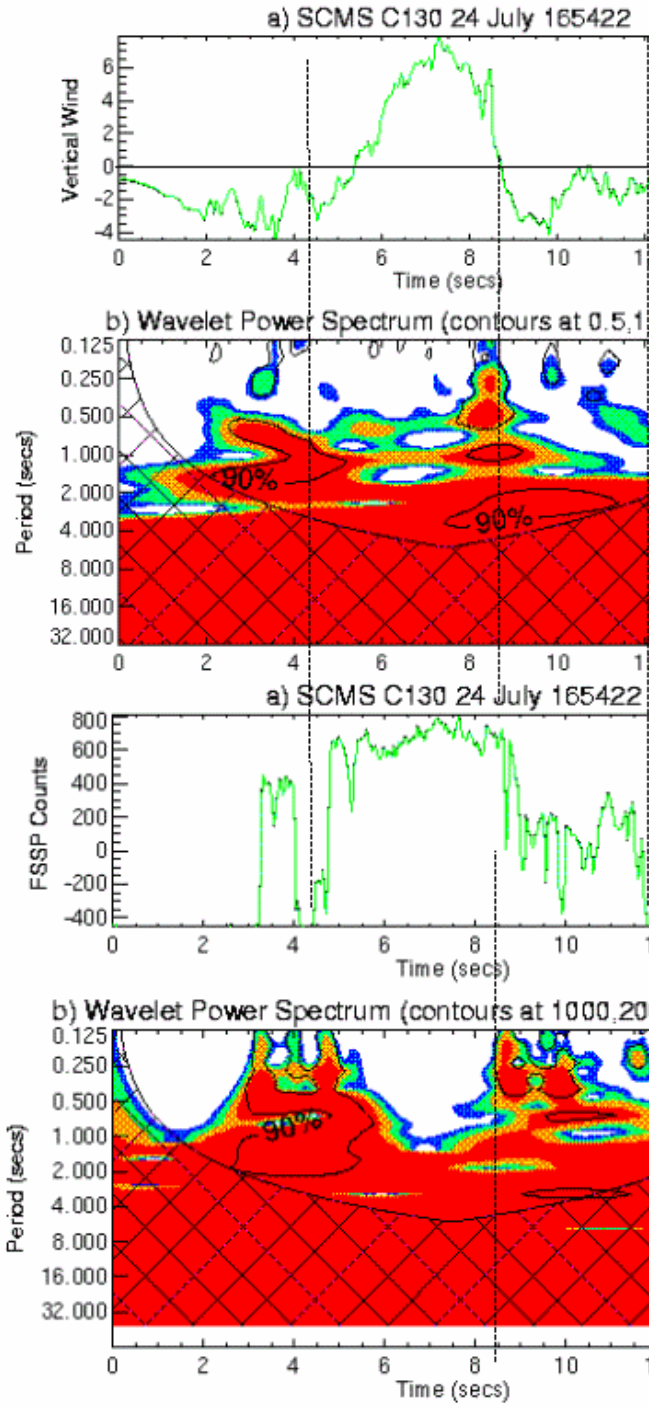
Schematic of cloud with descending shell



Rodts et al., 2003

SCMS C130 28 July 155205




a) SCMS C130 24 July 165422
Vertical Wind
Time (secs)
b) Wavelet Power Spectrum (contours at 0.5,1
Period (secs)
90%
90%
a) SCMS C130 24 July 165422
FSSP Counts
Time (secs)
b) Wavelet Power Spectrum (contours at 1000,20
Period (secs)
90%
Time (secs)

Summary

- Does entrainment occur at ascending cloud top?
  - Not the edges of thermal
  - At rear of thermal
- Some model results suggest lateral entrainment?
- Thermals important for circulating the entrained air down the edges and into centre
- Dilution of thermal about 3-5 mins?
- How long for molecular mixing vs bulk transport
- Need improved in-cloud temperature probes to make progress

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Acknowledgements

Many thanks to:
William Cooper, Sonia Lasher-Trapp and Jorgen Jensen,