CLOUD CLASSIFICATION AND OBSERVED PROPERTIES OF CLOUDS

(Supplement to Rogers and Yau, Ch. 5.)

Sources of material

- Rogers and Yau, Chap. 5
- Wallace and Hobbs, Chap. 5 (pp 215-238), misc. parts of Chap 4.
- Atmosphere (Peterson Field Guide), by V.J. Shaefer and J.Day
- International Cloud Atlas
- Cotton: Dynamics of Clouds and Storms (Academic Press)

Clouds and Precipitation - Definitions and Properties

CLOUD Category	PRECIPITATION Category	PRECIP. PROCESS
cloud droplets (~10 μm)	rain drops (~1 mm)	Warm Cloud (water phase only)
cloud ice (~100 μm)	hail(~1 cm) graupel(~0.5 mm) snow flakes(~1 mm) aggregates(~5 mm)	Cold Cloud (ice phase only) (or ice plus water phases)
Negligible fall speeds 10-50 cm s^{-1} 0.2 m s^{-1}	Significant fall speeds 1-50 m s^{-1} 5 m s^{-1}	*The distinct separation between cloud and precipitation promotes interactions which are important in the precipitation and electrification process*

Some related issues

- What is the distribution of cloud water and cloud ice (both of which are not readily detected by conventional meteorological radar)?
- What is the precipitation efficiency of clouds, and how does it vary globally (e.g., warm vs. cold cloud)?
- What are the relative roles of warm vs. cold cloud precipitation processes?
- Importance of the cloud water budget (condensation, evaporation, entrainment/detrainment, precipitation process) on the global water cycle.
- Role of aerosols in the precipitation process
- Relation between cloud physical processes and lightning

Cloud formation: The physical chain (note that thermodynamics -- e.g., latent heating -- and stability are important here):

Updraft (adiabatic cooling; consequence of thermodynamics and dynamics)

c) saturation
d) nucleation of cloud particles (water or ice) – to be considered after this unit
e) cloud vertical growth and evolution
f) development of precipitation (diffusion, collection)

The subject of microphysics describes the above chain of processes **a-d**.

Note that the ***updraft*** is needed to start this physical chain.

Categorization of cloud types (handout figures from International Cloud Atlas)

- Primary classification uses height of cloud base, and depth of cloud
  - low clouds (water, and ice in upper part if deep enough)
  - middle clouds (water or ice)
  - high clouds (all ice – typically)
- Secondary classification descriptors
  - stratiform (layered, weak $w < 1$ m s^{-1}) vs. cumuliform (vertical development, $w > 1$ m s^{-1})
  - cloud structural details (shape, patterns, extent of vertical development, etc)
  - presence of precipitation beneath cloud base
  - origin of clouds

2. *Cloud sizes and associated circulations*

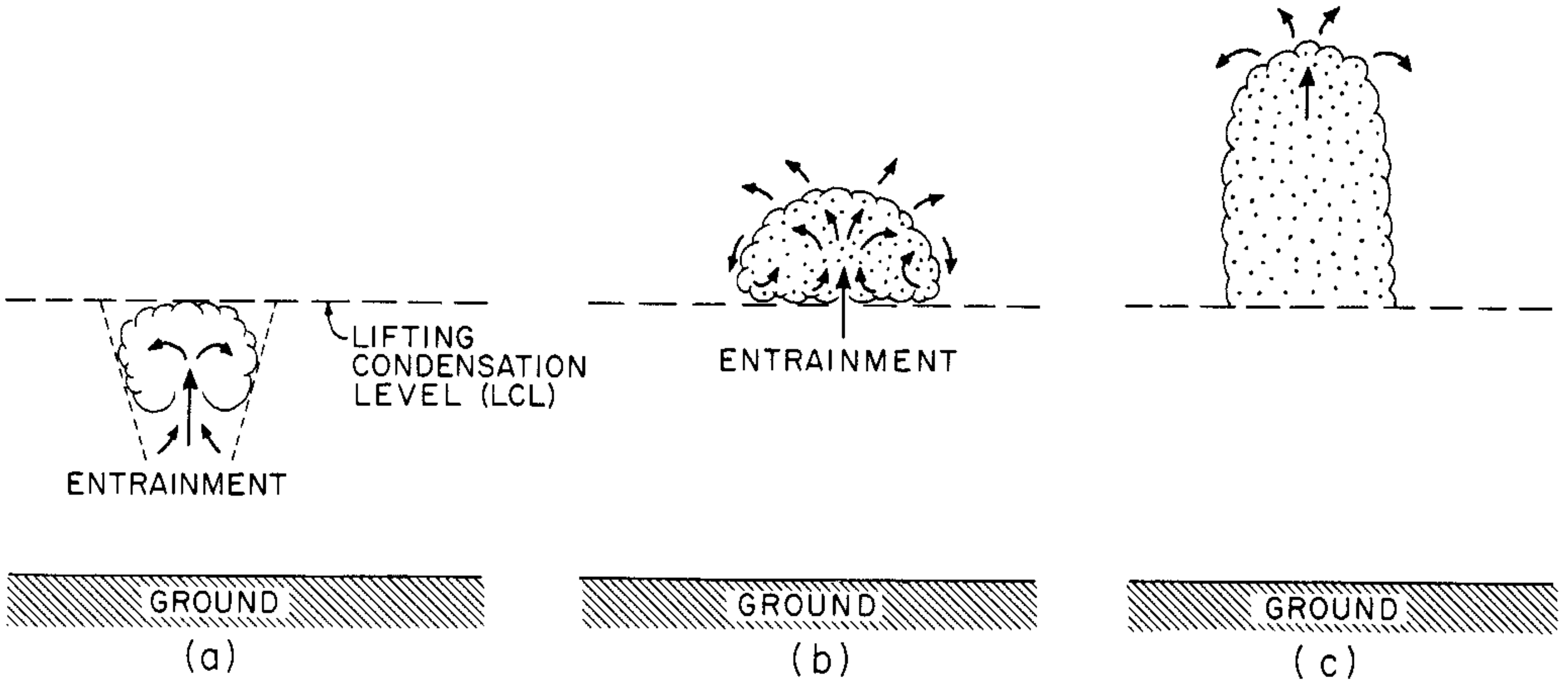
- The size and distribution of clouds is controlled by dynamical processes
  - microscale
  - mesoscale
  - synoptic scale
- Sizes of individual clouds
  - Cu puffs on the small end, to . . .
  - very large (synoptic scale) cloud shields that accompany midlatitude cyclones and frontal systems

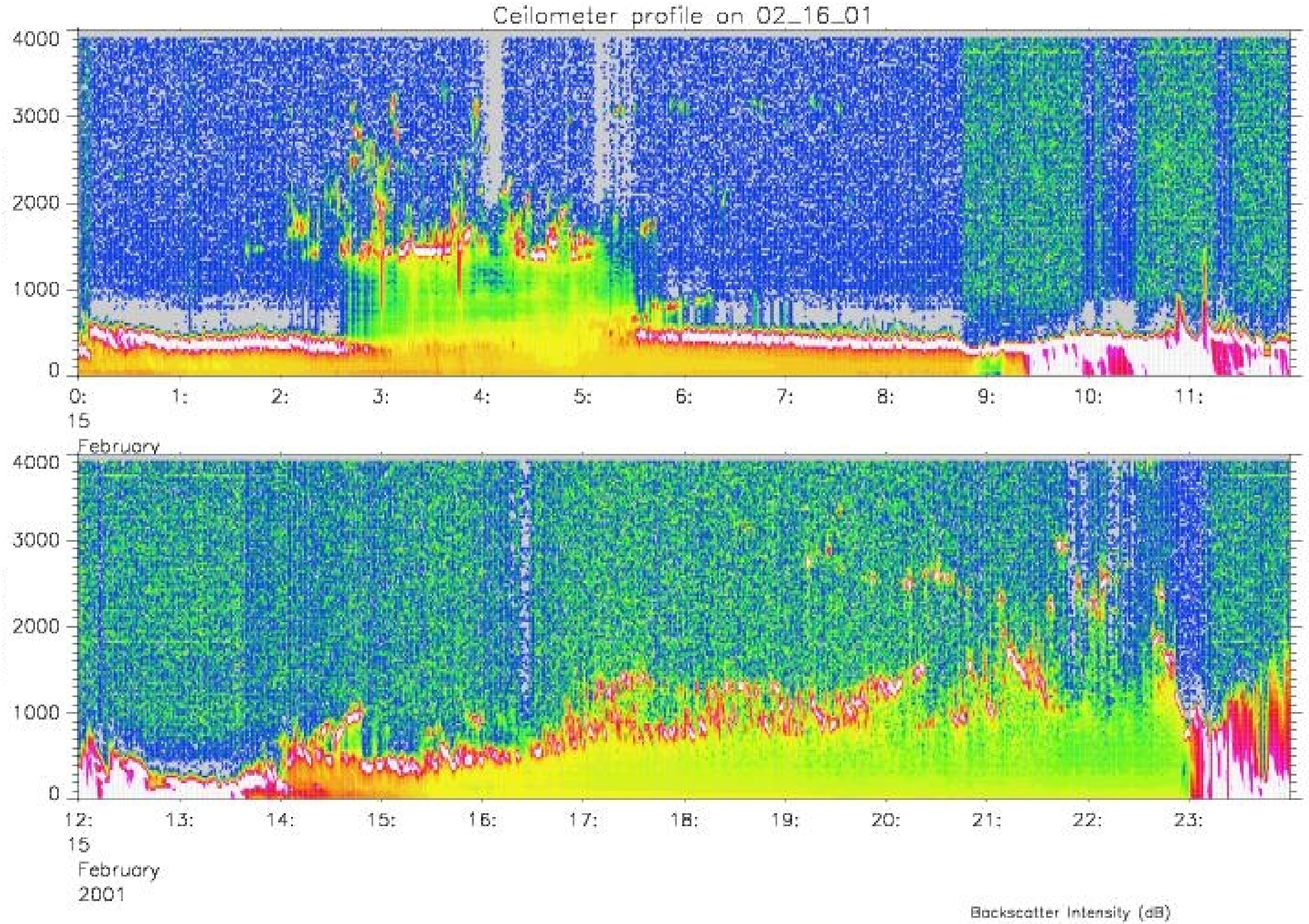
Details of cloud formation – dynamical processes (how the atmosphere is lifted)

- Saturation can be attained by
  - adiabatic cooling produced by upward motion
  - (and very rarely by pressure reduction at a fixed level)
  - isobaric diabatic cooling (e.g., radiation fog)

Stratus fractus on the downwind side of mountains

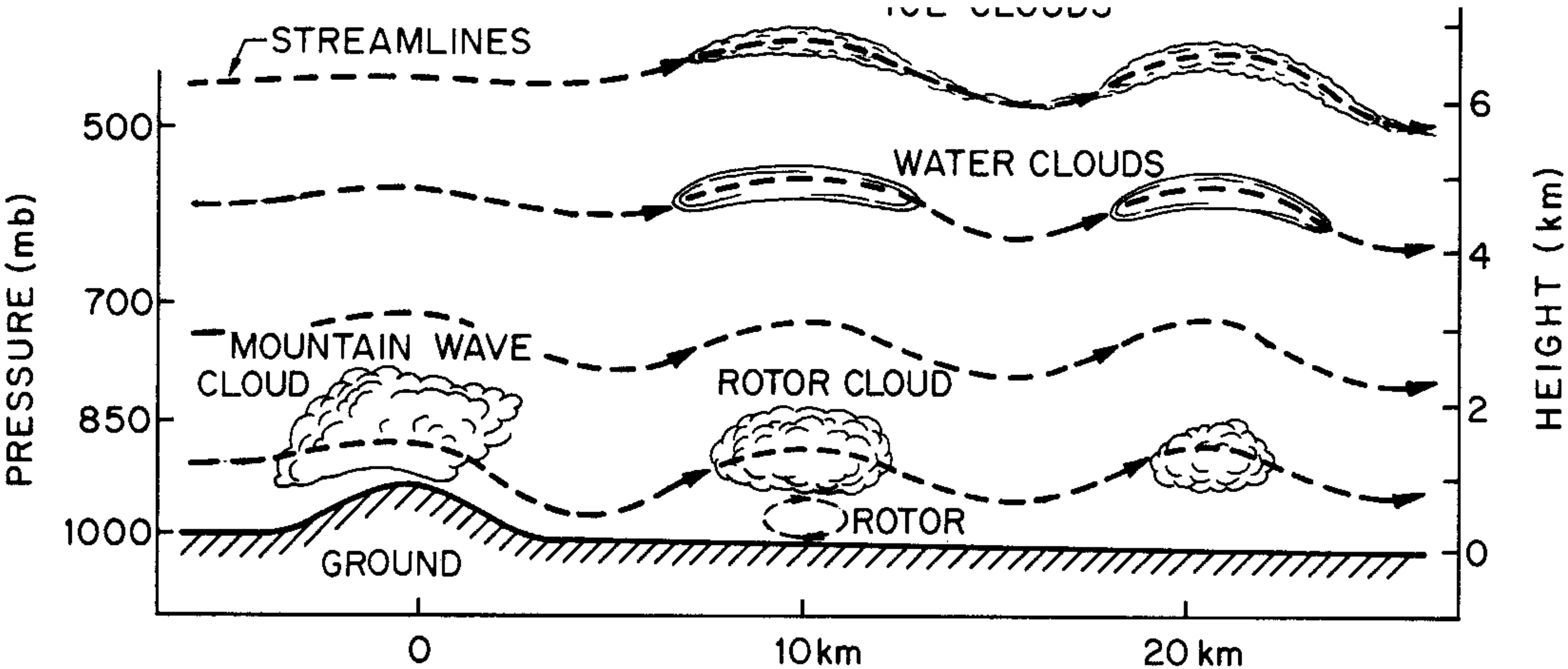
cloud formation from a warm thermal



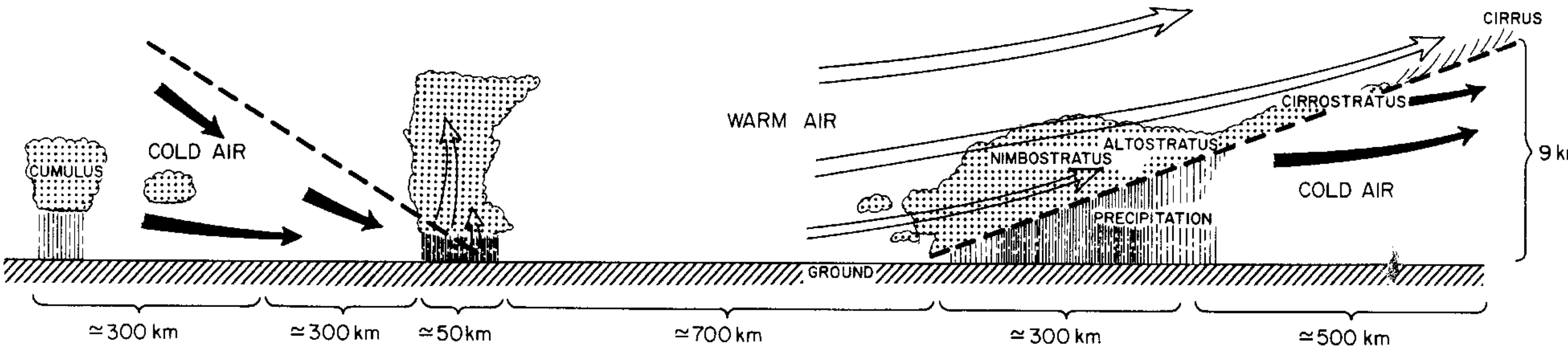


stratus with low cloud base of 200-300 m between 0000-0900 UTC. (b) Stratus with drizzle between 0930-1200. (c) low level stratus and fog 1200-1330. (d) development of stratocumulus and cumulus associated with the growth of the ABL between 1400-2300. (e) arrival of showers after 2300 UTC.

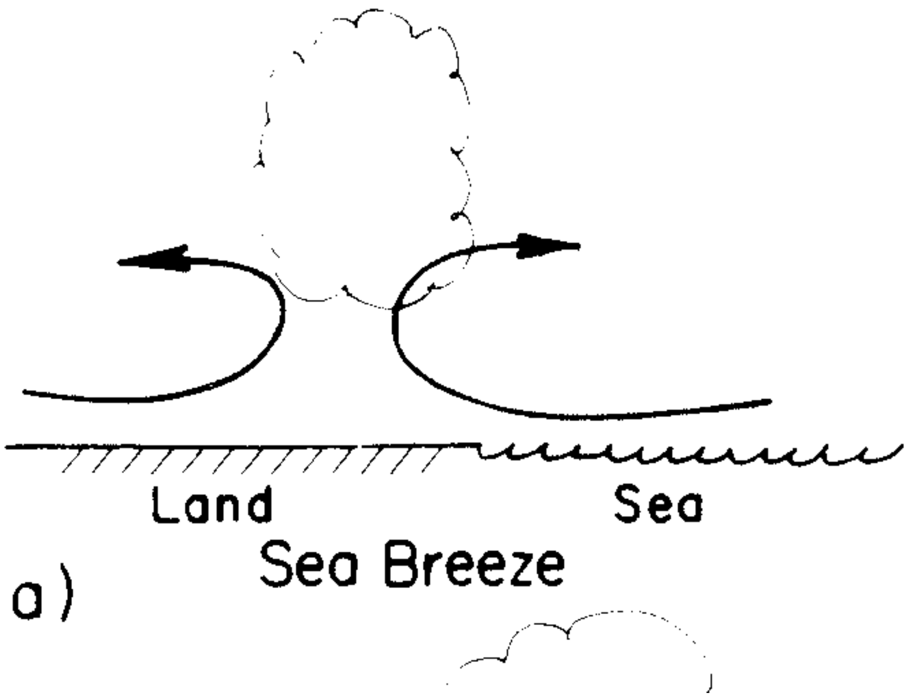
- Forced lifting by topographical features, including (i) lifting along the windward side of mountains, and (ii) lifting within the rising portion of mountain waves that exist within a stably-stratified atmosphere. These represent a form of gravity waves, where are common in the atmosphere, and which are caused by topography, wind shear, thunderstorms and hurricanes, jet streaks, etc.

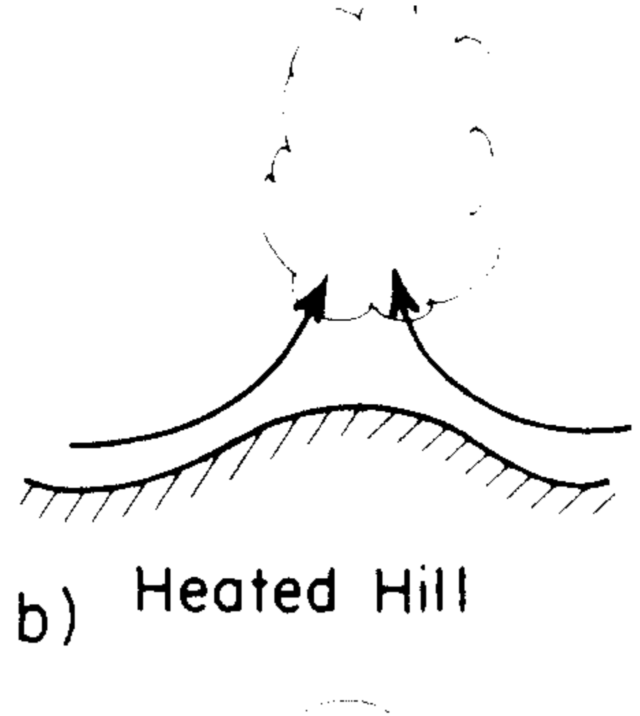


- Forced lifting of stable to conditionally unstable air by synoptic-scale systems (fronts, upper-level trofs, convergence into the center of cyclones, etc) and associated mesoscale instabilities, such as symmetric instability (see p. 39 of Rogers and Yau).



- Forced lifting along convergent boundaries produced by mesoscale circulations, such as those generated by horizontal contrasts in temperature (e.g., sea breeze, mountain breeze, etc.), or by density currents or outflows produced by thunderstorms. Fig. below from Cotton (1990, Storms)





others

- Diabatic cooling provided by emission of LW radiation, or by mixing, at low levels. This process is instrumental in producing low-level stratus clouds and fog.
- Adiabatic cooling produced by (rapid) pressure reduction at some fixed level. Examples are the tornado or funnel cloud, and "wake" orographic clouds.

CLOUD CLASSIFICATION AND OBSERVED PROPERTIES OF CLOUDS

- Go out and observe visual features
- Do you like sunsets?
- Examine the MIPS measurements in detail.
- Maintain a log for one week.

General characteristics of clouds

- Warm vs. cold clouds – definition
  - warm cloud - T > 0 °C throughout the depth
  - cold cloud - T < 0 °C throughout the depth, or in a portion
- Other general cloud properties to be defined:
  - 1) Time scales - a) *parcel* time scale; b) *cloud system* time scale
  - 2) Horizontal and vertical dimensions
  - 3) Microphysical properties
    - cloud liquid water content (r_c or ρ_c)
    - cloud droplet size spectrum
    - presence/absence of precipitation, rate of precipitation
  - 4) Kinematic properties
    - updraft/downdraft magnitude
    - turbulence intensity (TKE)
  - 5) Temperature range from cloud base to top; temperature of cloud base (thermo. char.)

Definitions

Define:

- T_c – cloud time scale
- T_p – H /w - parcel time scale
- w – typical updraft speed
- H – cloud depth
- $CR_\gamma = w \cdot \gamma_s$ – cooling rate (along a saturated adiabat) produced by updraft *w*
- ρ_c - cloud water content

Fog

- the least dynamic of all cloud types (but is still dynamic)
- T_c: 2-6 h, $w \sim 1$ cm s^{-1}, $H \sim 100$ m -> T_p = 100 m / 0.01 m/s = 10^4 s (~3 h)
- $\rho_c \sim 0.05$ to 0.2 g m^{-3} -> precipitation is unlikely
- CR_γ = (0.5 K / 100 m) (10^{-2} m/s) = 5 x 10^{-5} K s^{-1} = 0.2 K hr^{-1}
- radiative cooling rates are 1 to 4 K hr^{-1}
- turbulence is very low (flow is laminar)

Stratus (layered) clouds (St, Sc, Ns, As)

- T_c: 6-12 h; w ~ 10 cm/s H ~ 10^3 m -> $T_p = 10^3$ m / 10^{-1} m/s = 10^4 s
- $\rho_c \sim 0.05$ to 0.25 g m^{-3} (sometimes to 0.6 g m^{-3})
- CR_γ = (0.5 K/km)(10^{-1} m/s) = 5 x 10^{-4} K s^{-1} (2 K hr^{-1}) comparable to radiative cooling
- cooling, turbulence is small, but important in Sc transports (flux) and structure
- Sc and St can precipitate drizzle drops

Stratus (cont.)

Other:

- Fig. 5.10, R&Y
- hzn dimension quite large
- thickness several hundred meters to several km.
- LWC 0.05 to 0.30 g m^{-3} in St, to ~1.0 g m^{-3} in Ns
- Cloud droplet size: d ~10-30 μm
- thick St or Sc can precipitate drizzle droplets, if thick enough (define precipitate as downward water flux from cloud base)
- vertical motion ~ 1-100 cm/s
- more stable, less turbulence
- mixing not so important (except at top, very important in Sc clouds)
- Brief discussion of Sc clouds

Microstructure of stratus clouds

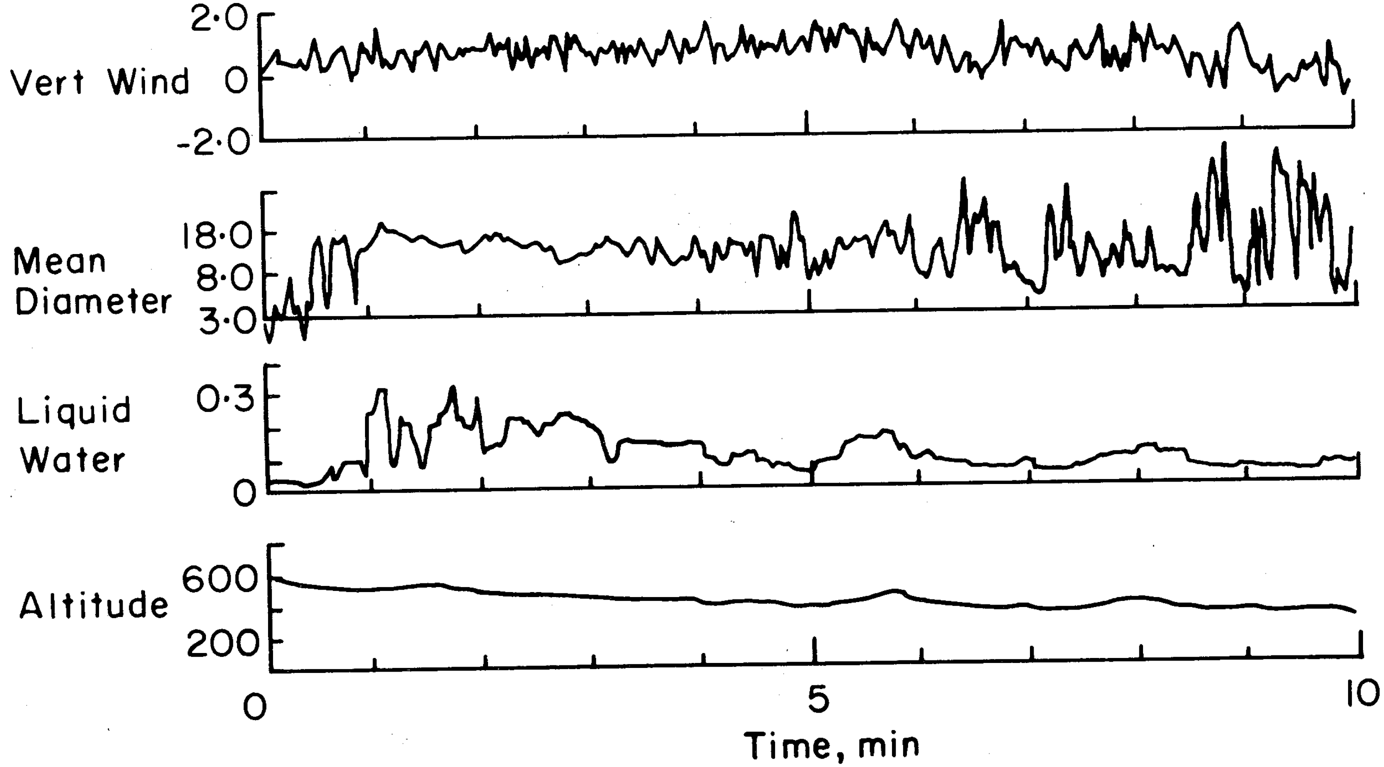


FIG. 5.10. Records of vertical air velocity (m/s), mean droplet diameter (μm), liquid water content (g/m^3), and altitude (m), during descent through marine stratus cloud. (From Telford and Wagner, 1981.)

Likelihood of ice and precipitation in clouds

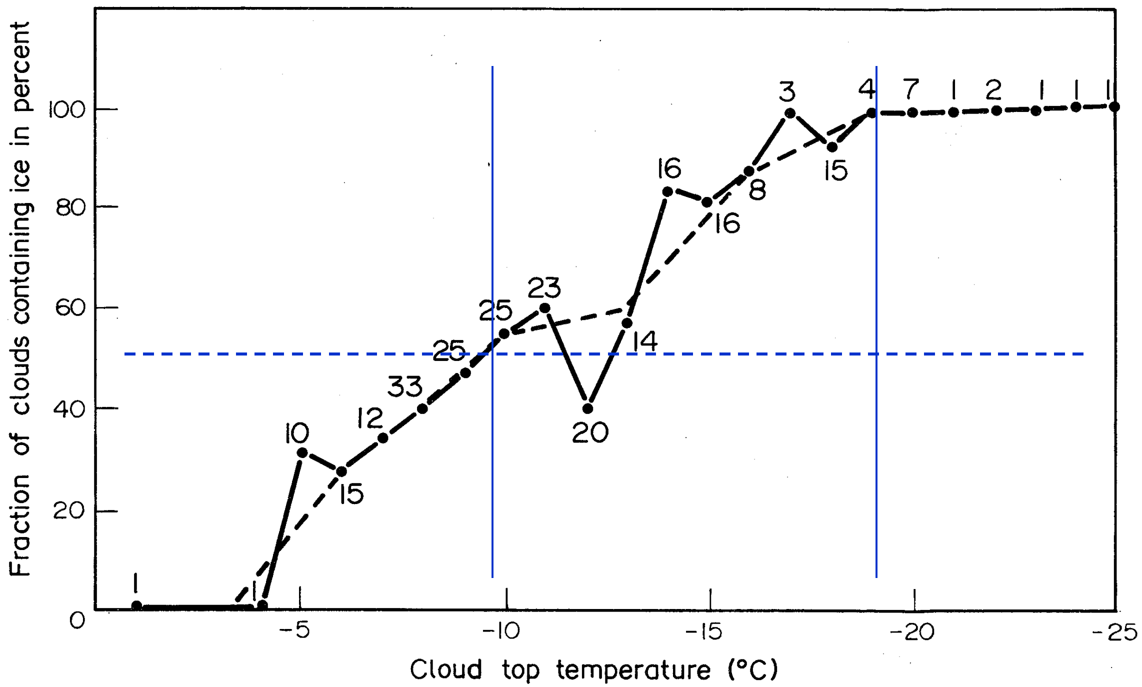


FIG. 5.11. The fraction of clouds containing ice as a function of cloud top temperature, from observations of 258 clouds by several investigators in different regions. The number above each point is the number of observations at that temperature; the dashed curve is a three-point running mean. (From Houghton, 1985, after Hobbs *et al.*, 1974.)

Cumulus clouds (up to ~ 4 km deep, non-precipitating)

- T_c: 10-30 min; w = 3 m/s; H = 1500 m -> T_p = 1500 m / 3 m s^{-1} = 500 s
- $\rho_c \sim 0.3$ g m^{-3} (sometimes exceeding 1 g m^{-3})
- precipitation is likely only in shallow maritime Cu
- CR_γ = (0.5 K km^{-1}) (3 m/s) = 1.5 x 10-2 K s^{-1} = 50 K hr^{-1}
- moderate turbulence; RMS velocity (from aircraft measurments) of 1-3 m/s; important

Cu (cont.)

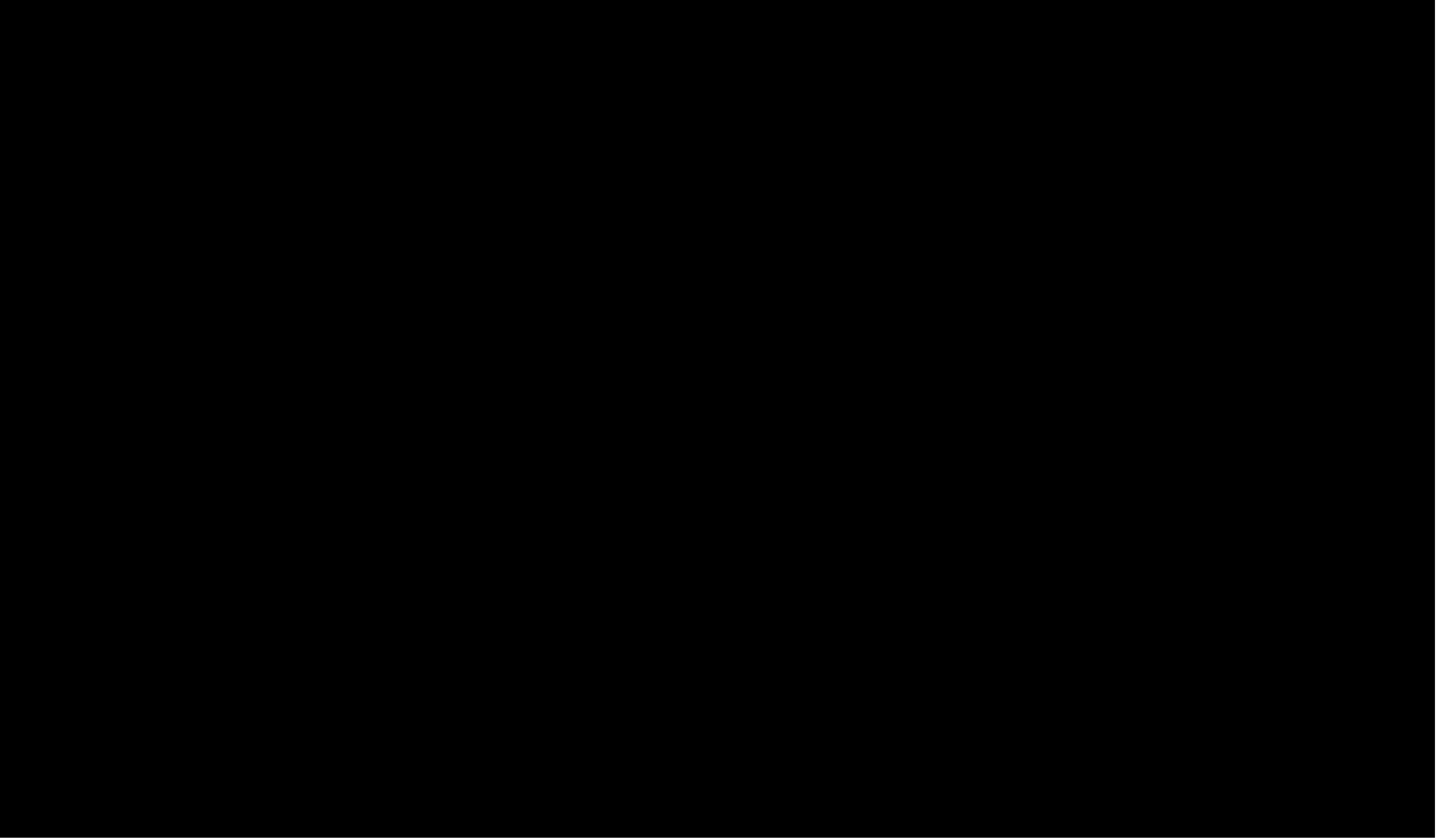
Good example of Cu cloud analysis in R&Y

- hzn dimension: one to several km
- vrt dimension: one to several km
- w: +/- several m/s (Fig. 5.4, 5.5); fluctuations
- modt turbulence (Fig. 5.5), increases with height
- produced by mixing and shear generation
- The mixing process is important in determining cloud structure.
- Liquid water content ~0.5 to 1.0 g m-3; highest within active updrafts.
- a) almost always less than adiabatic (~0.5 adiabatic)
- -> thermo. anal. suggests cloud-top entrainment as shown in Fig. 5.8.
- Paluch diagram: conservative variables Q and θ_q
- $Q = r_{vs} + r_c$ (total water r_T or Q) (2.38)
- $\theta_q = T(p_o/p)R_d/(c_{pd}+c_wQ) \exp[(r_{vs}L_{vl})/T(c_{pd}+c_wQ)]$ (2.43)

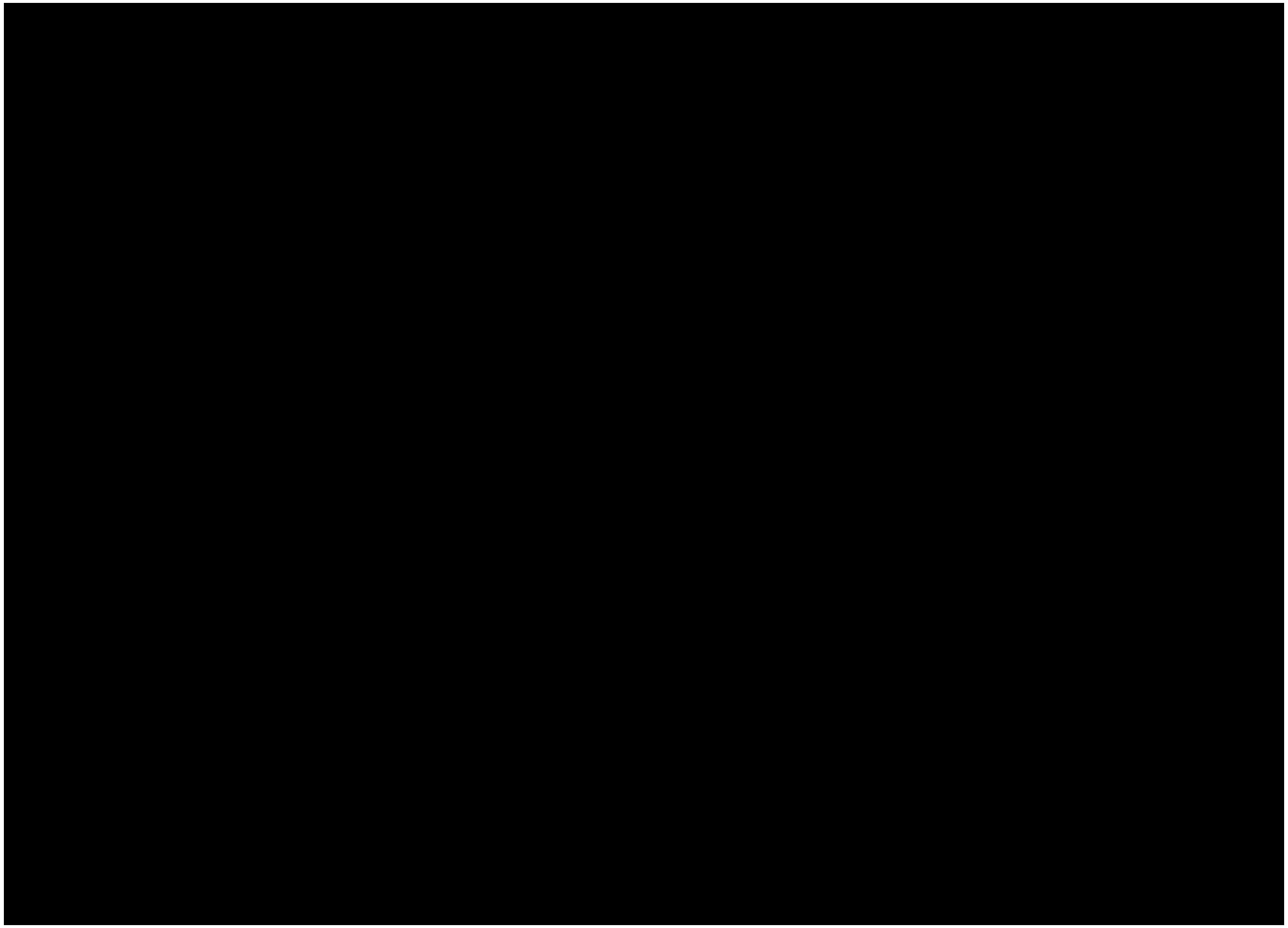
Cu (cont.)

b) as cloud vigor increases well beyond several m/s, adiabatic cloud cores can develop.

- Cloud droplet spectra
- variation over depth of cloud (Fig. 5.7) - this points to evolution via the condensation process that we will consider in Chap. 7.
- continental clouds:
  - d ~ 10-15 mm (Fig. 5.9)
  - narrow spectra
- maritime clouds
  - d ~ 25-30 mm
  - broad spectra - makes maritime Cu more efficient precip. producers.



(a) Vertical air velocity (with positive values indicating updrafts and negative values downdrafts), (b) liquid water content, and (c) droplet size spectra at points 1, 2, and 3 in (b), measured from an aircraft as it flew in a horizontal track across the width and about half-way between the cloud base and cloud top in a small, warm, nonraining cumulus cloud. The cloud was about 2 km deep. From Wallace and Hobbs



(a) Percentage of marine cumulus clouds with indicated droplet concentrations. (b) Droplet size distributions in marine cumulus cloud. (c) Percentage of continental cumulus clouds with indicated droplet concentrations. (d) Droplet size distributions in a continental cumulus cloud. Note change in ordinate from (b).

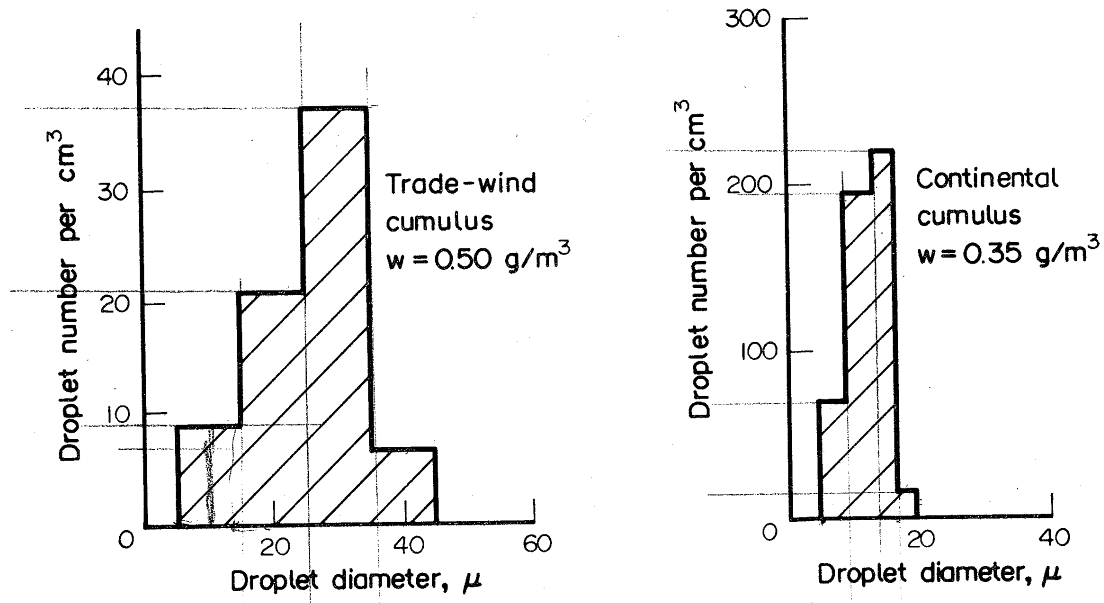


FIG. 5.9. Droplet spectra in trade-wind cumulus off the coast of Hawaii and continental cumulus over Blue Mts. near Sydney, Australia. (From Fletcher, 1962, after Squires, 1958a.)

Cu con clouds

- T_c = 20 to 45 min; w=10 m/s; H=5 km -> T_p = 5000 m / 10 m s^{-1} = 500 s
- ρ_c = 0.5 to 2.5 g m^{-3} -- these clouds will in general precipitate
- CR_γ = (0.5 K km^{-1}) (10 m/s) = 5 x 10^{-2} K s^{-1} = 180 K hr^{-1}
- turbulence is strong
- Example in Rogers and Yau - read it!

Example from Montana (continental Cu con cloud)

Aircraft measurements illustrate cloud structure:

Kinematics

Updraft, downdraft, turbulence

Microphysics

Liquid water content

Drop size distribution

Thermodynamics

Mixing process

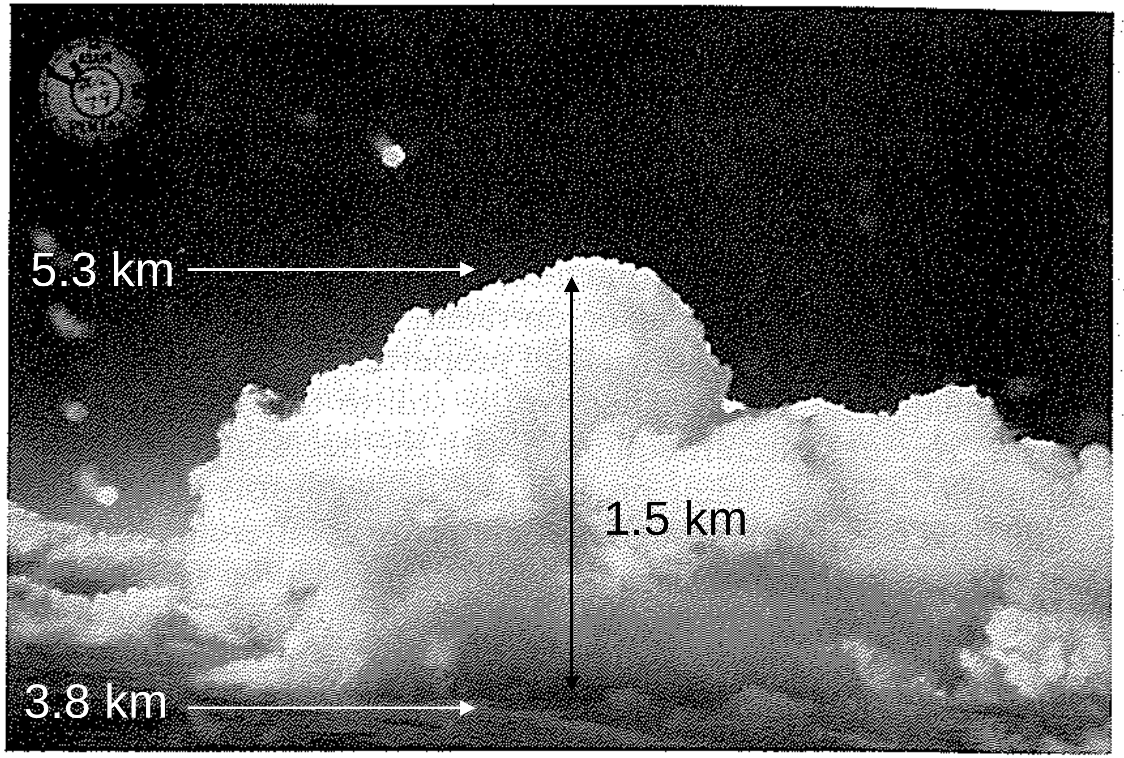


FIG. 5.3. Photograph of cumulus cloud taken at 2250 GMT on July 19, 1979, near Miles City, Montana. This is the cloud that was sampled for some of the illustrations that follow. (Photo courtesy of George Isaac and AES.)

Cloud base height: 3.8 km
Cloud base temperature: 1.2 C (p = 635.5 hPa)
Cloud thickness: 1.5 km
Aircraft samples every 300 m in height

Two cloud segments indicated by LWC

Updraft of ~3 m/s within each cloud segment, downdraft on cloud edge

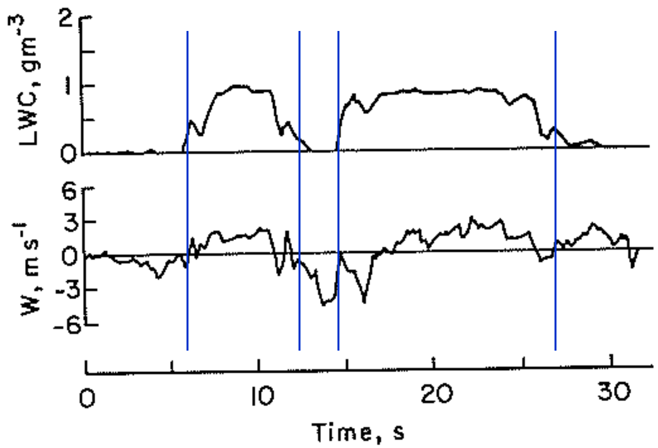


FIG. 5.4. Measurements of water content and updraft velocity in the cloud of Fig. 5.3 along a track at altitude of 4.58 km. (Adapted from Schemenauer *et al.*, 1980.)

Both updraft and downdraft increase with increasing height

The RMS value of w also increases with height

Turbulence intensity (turbulent energy dissipation, ε) increases dramatically with height

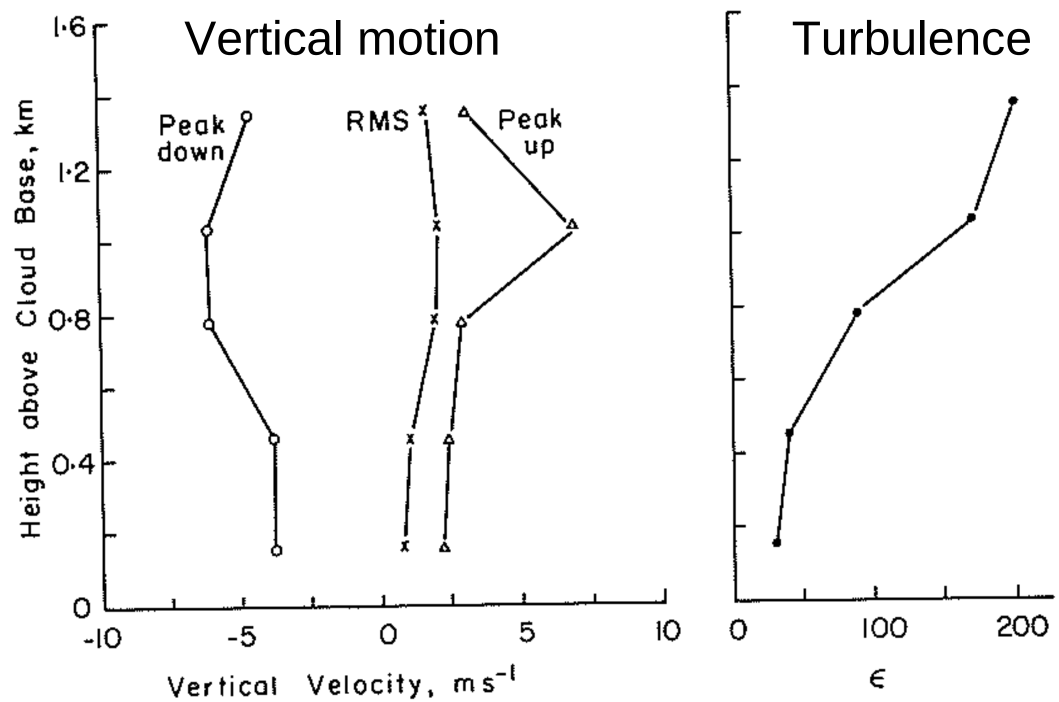


FIG. 5.5. Maximum observed updrafts and downdrafts and RMS vertical velocity plotted against height above cloud base. Also shown is the computed turbulent energy dissipation rate, ε, in units of $cm^2\, s^{-3}$.

Liquid water content vs. height

Plots the the average c and maximum χ both increase with height

The average χ is about 50% the adiabatic value

The maximum χ is close to adiabatic

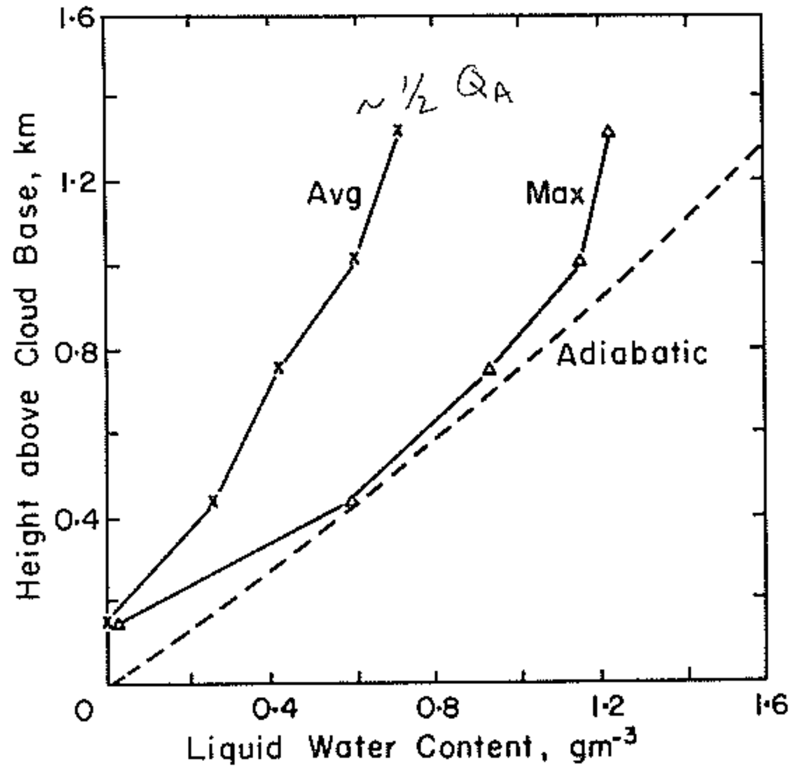


FIG. 5.6. Maximum, average, and adiabatic liquid water contents plotted against height above cloud base. (Adapted from Schemenauer *et al.*, 1980.)

Cloud droplet measurements

The number concentration decreases with height.

Why?

The average diameter increases with height.

Why?

The cloud droplet size spectra (far right) increase in width with height.

Why?

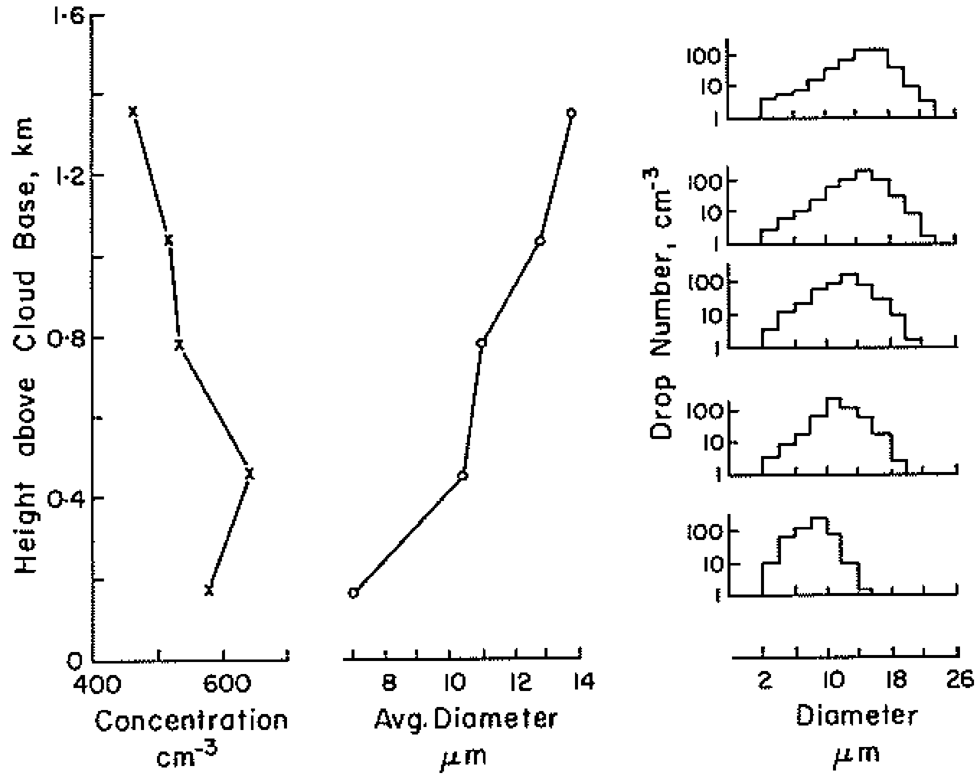


FIG. 5.7. Variation with height of the average droplet concentration and the average droplet size. The form of the average droplet spectrum at each height is also shown. (Adapted from Schemenauer *et al.*, 1980.)

Thermodynamics and Mixing

Use of a conserved thermodynamic parameter to infer mixing between the cloud and adjacent subsaturated atmosphere.

Two conserved thermodynamic parameters are used to infer mixing:

Total water Q and wet equivalent potential temperature (see pp. 25-26)

The results shows that the observed cloudy air is the result of mixing between air from cloud base and cloud top

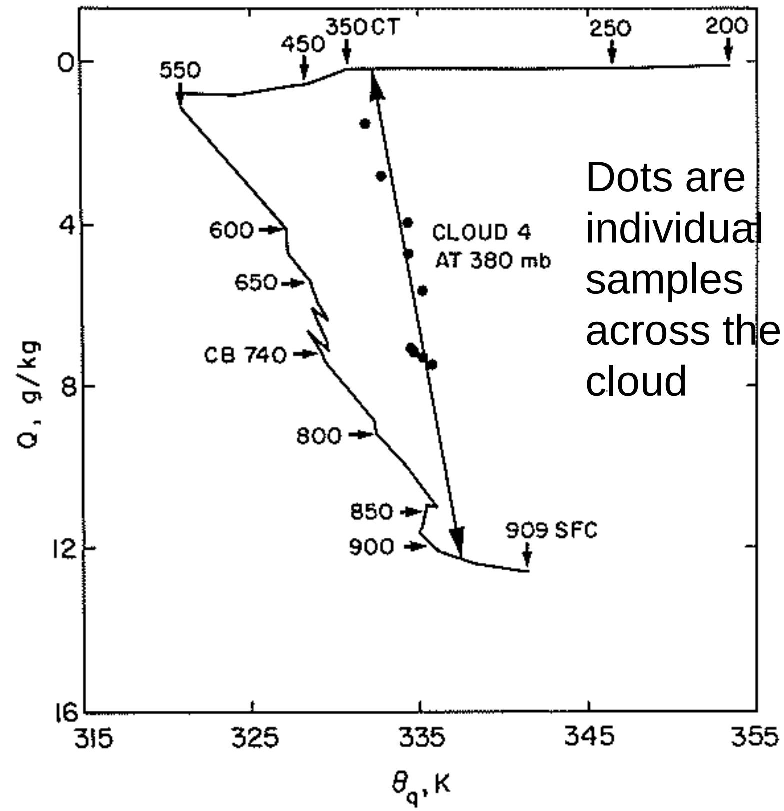


FIG. 5.8. Environmental sounding, plotted on coordinates of Q versus θ_q (a Paluch diagram). Cloud base (CB) and cloud top (CT) are indicated. Consecutive measurements at one level in the cloud are shown by points. (From Reuter and Yau, 1987a.)

$$Q = r_v + r_{ca}$$

$$q_q = T\left(\frac{100\ kPa}{p_d}\right)^{R_d/(c_p + c_w Q)} \exp\left(\frac{r_{vs} L}{T(c_p + c_w Q)}\right) \qquad (2.43)$$

Cb clouds (thunderstorms)

- T_c > 45 min; w = 20 m/s; h = 12 km -> T_p = 12000 m / 20 m s^{-1} = 600 s
- ρ_c = 1 to >5 g m^{-3}
- turbulence is usually intense (severe to extreme); large eddies
- CR_γ = (0.5 K km^{-1}) (20 m/s) = 0.1 x K s^{-1} = 360 K hr^{-1}
- -> T_p may not be representative for precipitation processes.

Cb (cont.)

- complex dynamics, thermodynamics and microphysics (very few conservative tracers)
- Note: θ_q is not conserved since these clouds precipitate
- θ_e or θ_w are only approximately conserved (assuming no mixing) in general
  - (get reduction from melting, increase from freezing)
- presence of ice and water phases complicates thermodynamics, microphysics
- Vigorous (updrafts to >50 m s^{-1})
- Figs. 5.12, 5.13, extra

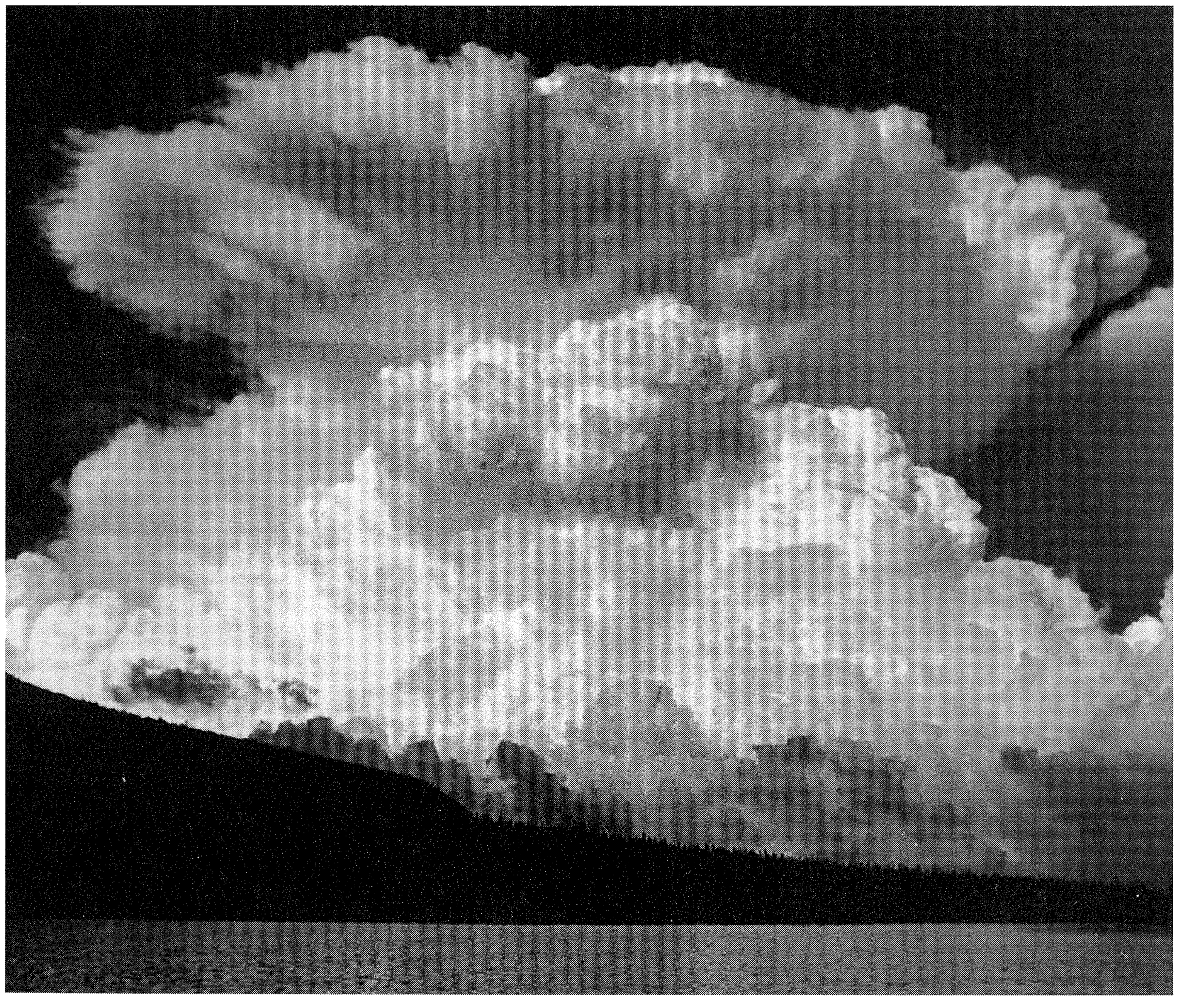


FIG. 8.4. Photograph of the large cloud associated with the Big Thompson Canyon storm on 31 July 1976. The photo, reproduced here with permission as it appeared in the report by Maddox et al. (1977), was taken by John Asztalos.

Measurements with cumulnimus clouds

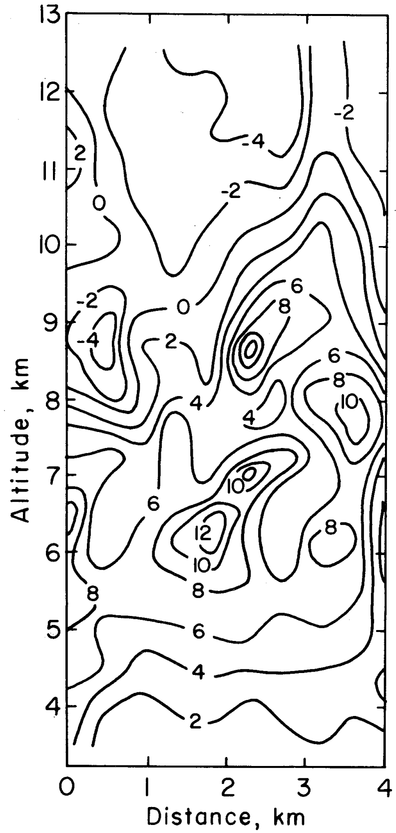


FIG. 5.12. Vertical cross section of vertical air velocity (m/s) in a thunderstorm obtained from a series of dropsonde measurements. (From Bushnell, 1973.)

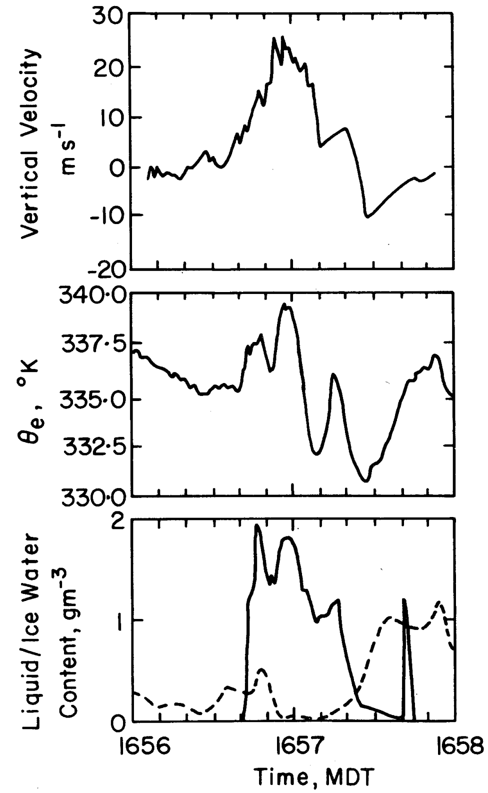


FIG. 5.13. Records of vertical air velocity, equivalent potential temperature, liquid water content (solid), and ice content (dashed) in the core of a thunderstorm. (From Heymsfield and Musil, 1982.)

Dropsonde
Vertically-pointing Doppler radar
Multiple Doppler radar analses

Aircraft

orographic clouds

- motion is quasi-horizontal, so appropriate T_p is found from hzn dimension and speed.
- T_c = hours, up to 1 day; w = 1 m/s; T_p = 20000 m / 15 m s^{-1} = 22 min
- $\rho_c \sim 0.2$ g m^{-3}
- $CR_\gamma \sim 18$ K hr^{-1}
- turbulence - variable (small to large)

Cirrus clouds (all ice) (Ci, Cs, Cc)

- extensive areal extent world-wide (along with Sc)
- w: 1-50 cm/s
- large ice crystal diameters 0.2-5 mm (0.5 typical)
- large terminal fall speeds -> often precipitate (virga)
- ice water content ~ 0.1 g m^{-3}

Aircraft measurement of cloud parameters

- temperature: Rosemount (reverse flow)
- humidity: Cambridge dewpoint hygrometer
- LWC: J-W meter
- w: a/c response, gust probe
- u,v: INS
- particle spectra: PMS 1-D and 2-D, foil impactor

Cloud measurements during PIOWS

Cloud vertical vertical motions and precipitation substructures

- Wyoming Cloud Radar (WCR)
- Wyoming Cloud Lidar (WCL)

Microphysical in situ probes

- forward scattering spectrometer probe (FSSP)
- Cloud Droplet Probe (CDP)
- two-dimensional cloud probe (2DC)
- two-dimensional precipitation probe (2DP)
- one-dimensional cloud probe (1DC)
- Cloud Particle Imager (CPI)
- Rosemount icing detector (RICE)
- King liquid water (LWC) or Gerber probe
- Counterflow Virtual Impactor (CVI)

Some references*

- www.meteo.uni-bonn.de/projekte/4d-**cloud s/tools/probes/**
- http://www.eol.ucar.edu/raf/instruments.html
- http://ams.allenpress.com/archive/1520-0426/20/1
- http://ams.allenpress.com/archive/1520-0426/22/1
- http://ams.allenpress.com/archive/1520-0426/22/5

* Search for “cloud probes” and “precipitation probes” at the AMS web site

Problem 5.2 - An example illustrating the smallness of an aircraft sample measurement volm vs. cloud volm. Are the measurements representative?

Given:

- cross-sectional area of device (spectrometer), A = 20 cm2
- aircraft speed, V = 80 m s-1
- sample time Δt = 2 min
- Assume: cloud volume approximated by a cylinder 4 km high (H=4000 m)

Then:

- cloud diameter = $V\Delta t$ = 80 m/s x 120 s = 9600 m
- cloud volume = $\pi(d/2)^2H = \pi$ (9600 m/2)^2 (4000 m) = 2.9 x 10^{11} m^3
- aircraft probe volume = Ad = (20 cm^2) (1 m^2 / 10^4 cm^2) 9600 m = 19.2 m^3
- Thus, the fraction of cloud volume sampled by one aircraft pass is 19.2 m^3 / 2.9x10^{11} m^3 = 6.62 x 10^{-11} or 6.62 x 10^{-9} % (!!!)
- Is this statistically significant?

Problem assignment

- Read Rogers and Yau, Chap. 5
- Problems 5.1, 5.3, 5.5
- Read Chap. 6