D6.2 1st Summer School Lecture Notes

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COMPLETE ETN network 1st Training School, Turin, 19-22/06/2017

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1st training school of COMPLETE
June 19-22, 2017
Torino, Italy

Introduction to clouds

- Szymon MALINOWSKI

UNIVERSITY OF WARSAW


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CLOUD

Cloud – A visible aggregate of minute water droplets and/or ice particles in the atmosphere above the earth’s surface

Glossary of Meteorology, American Meteorological Society

Cloud – any visible mass of water droplets, or ice crystals, or a mixture of both that is suspended in the air, usually at a considerable height

Britannica Online

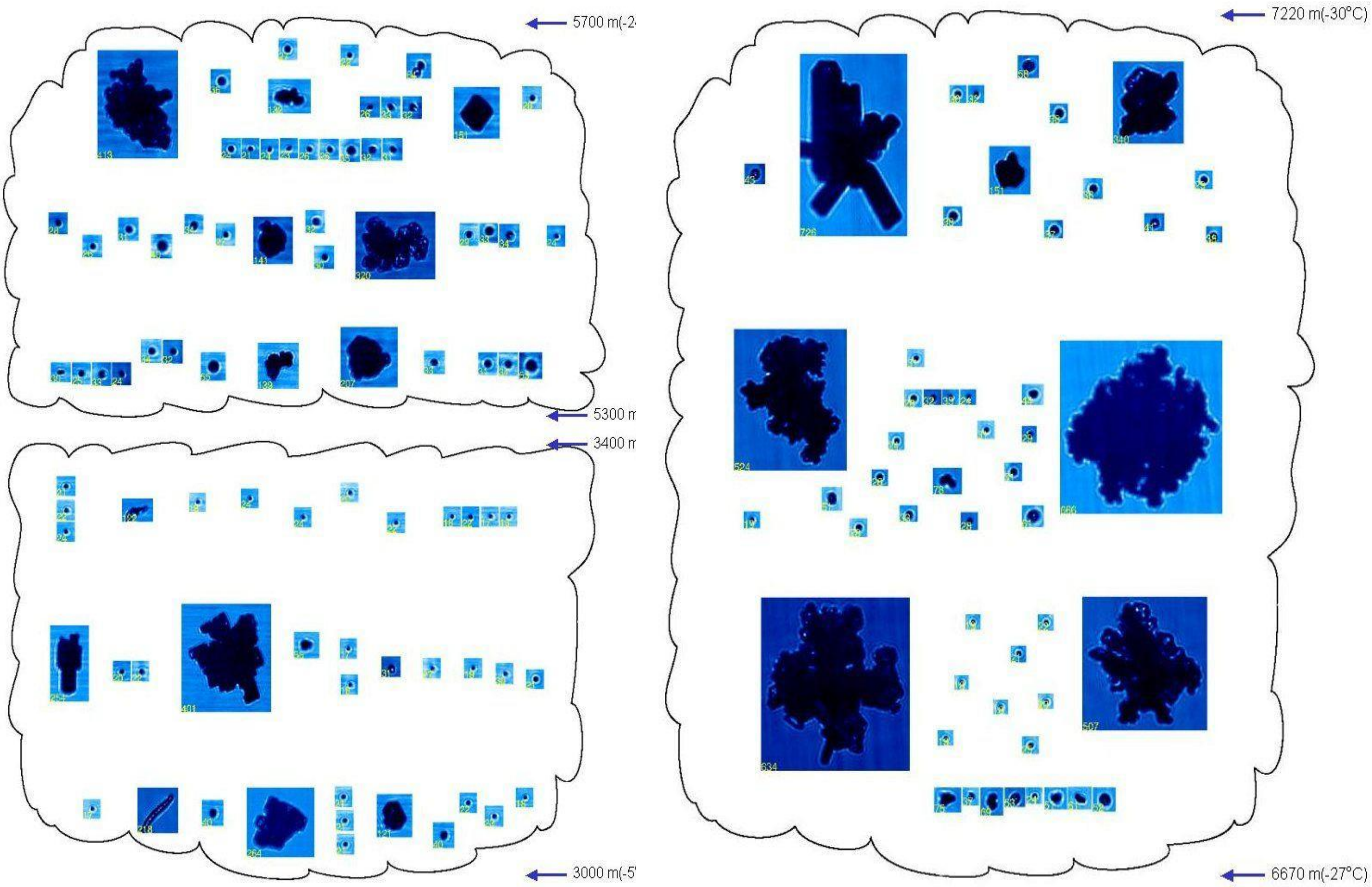
What is the typical size of aerosol and cloud particles ?

From a few nanometers: a few molecules condensed

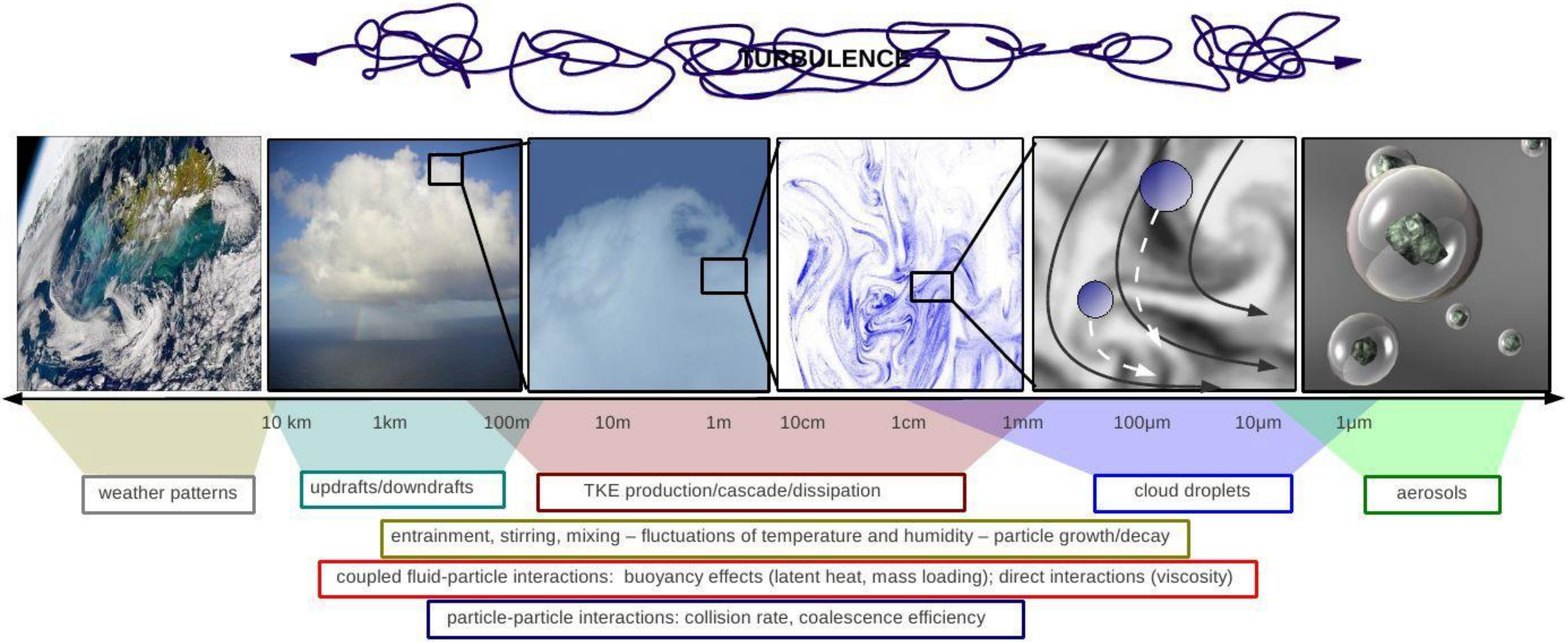
To a few centimeters: hailstones

Measurable parameters from in-situ observations

Particle size…………………..μm, mm, cm…………1μm<D<10cm
Number Concentration……..cm^{-3}; l^{-1}; m^{-3}……….$1000cm^{-3}<N<1m^{-3}$
Extinction Coefficient……….km^{-1}…………………$100km^{-1}<\beta<0.01\ km^{-1}$
Water Content………………g/m^3…………………$10g/m^3<W<0.0001g/m^3$



Cloud particles at various heights (temperatures) imaged by CPI (SPEC Inc.)

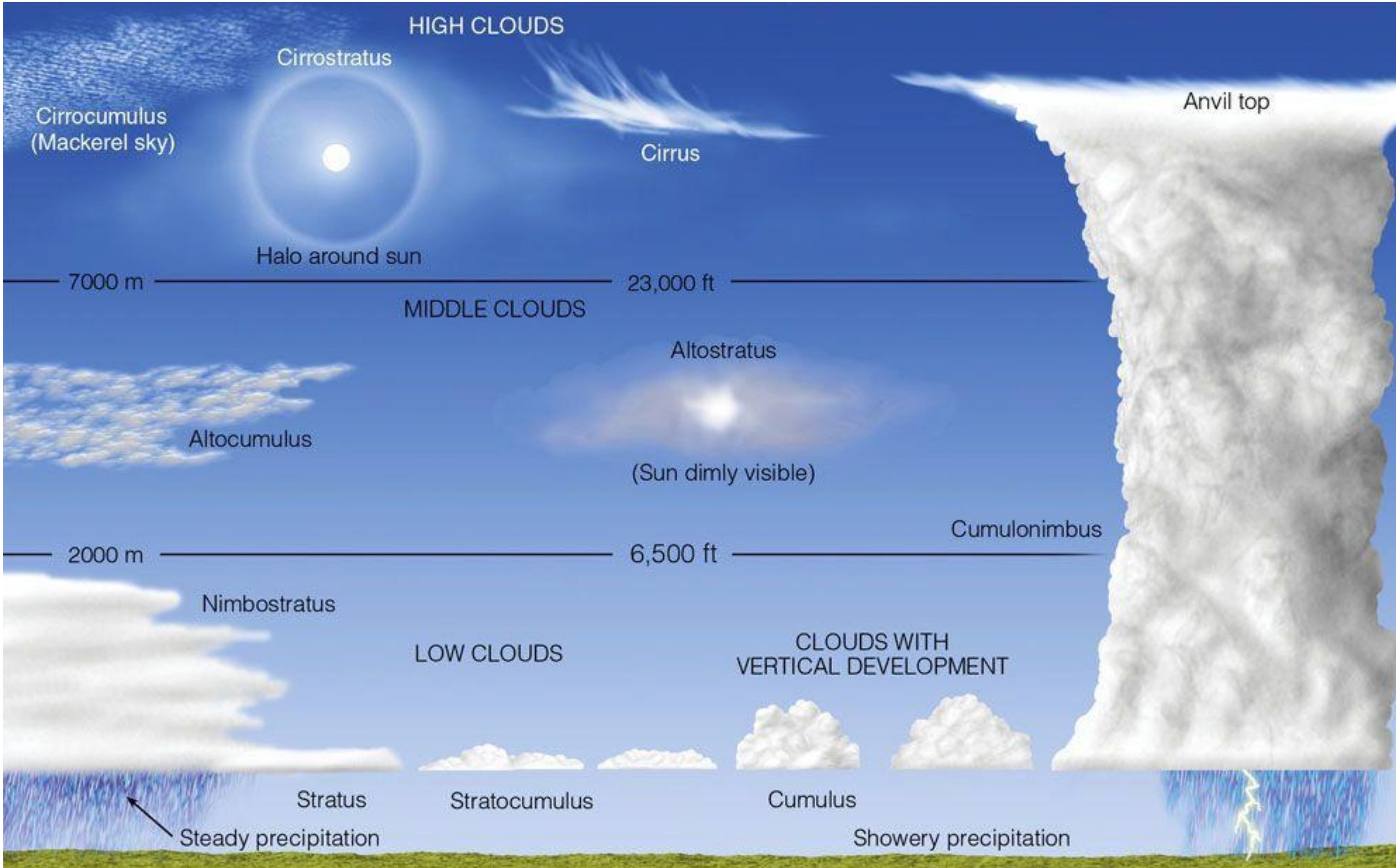


Clouds are dispersions of drops and ice particles embedded in and interacting with a complex turbulent flow. They are highly nonstationary, inhomogeneous, and intermittent, and embody an enormous range of spatial and temporal scales. Strong couplings across those scales between turbulent fluid dynamics and microphysical processes are integral to cloud evolution.

Turbulence drives entrainment, stirring, and mixing in clouds, resulting in strong fluctuations in temperature, humidity, aerosol concentration, and cloud particle growth and decay. It couples to phase transition processes (such as nucleation, condensation, and freezing) as well as particle collisions and breakup. All these processes feed back on the turbulent flow by buoyancy and drag forces and affect cloud dynamical processes up to the largest scales.

Bodenschatz et al., Science, 2010.

Classification of clouds



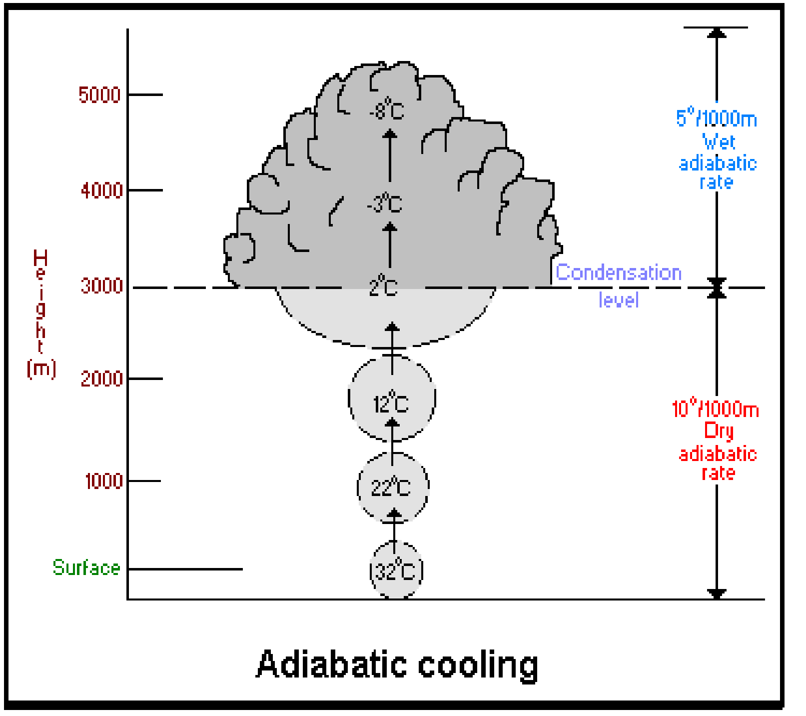
Cloud formation processes:

Condensation of water vapour into small droplets

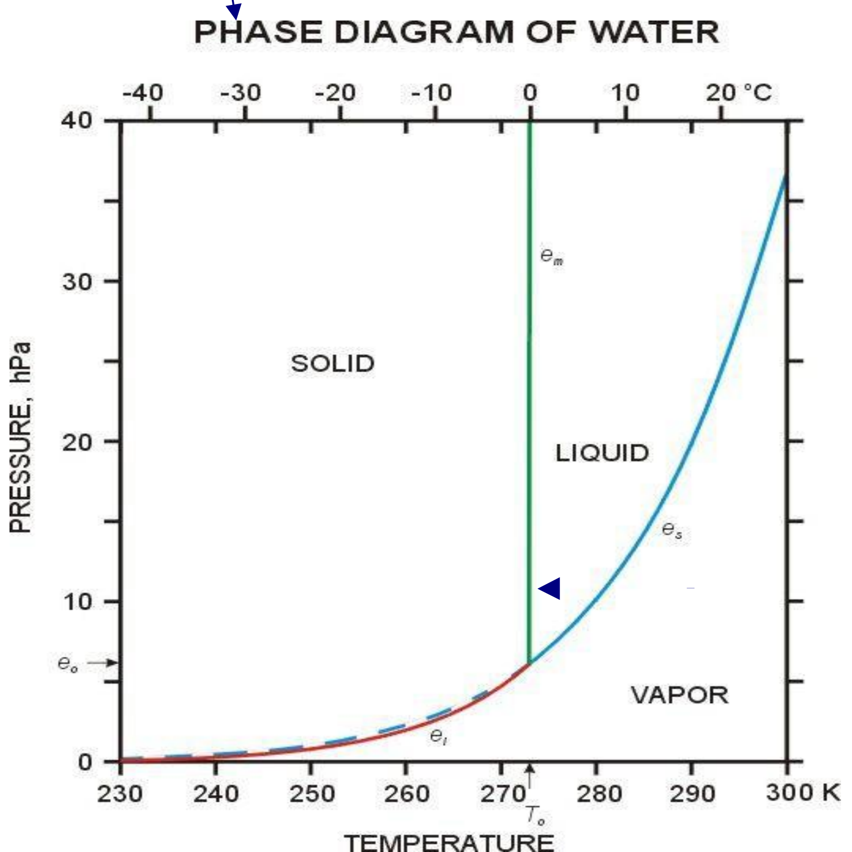
adiabatic expansion (e.g. ascending motions);

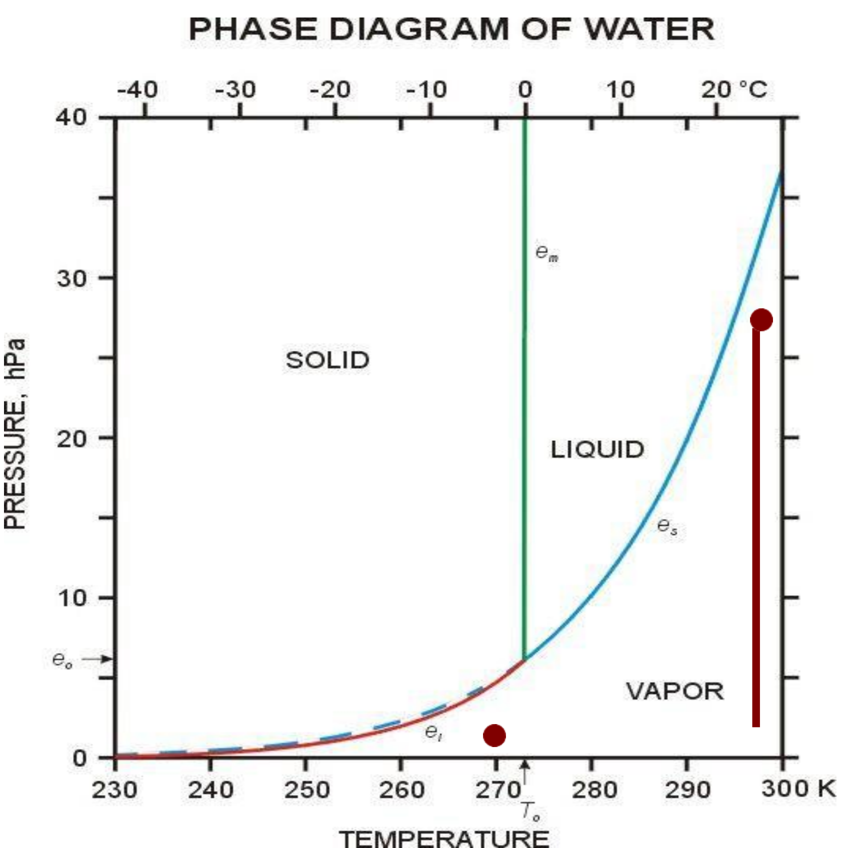
isobaric cooling (radiative, conductive);

isobaric mixing.

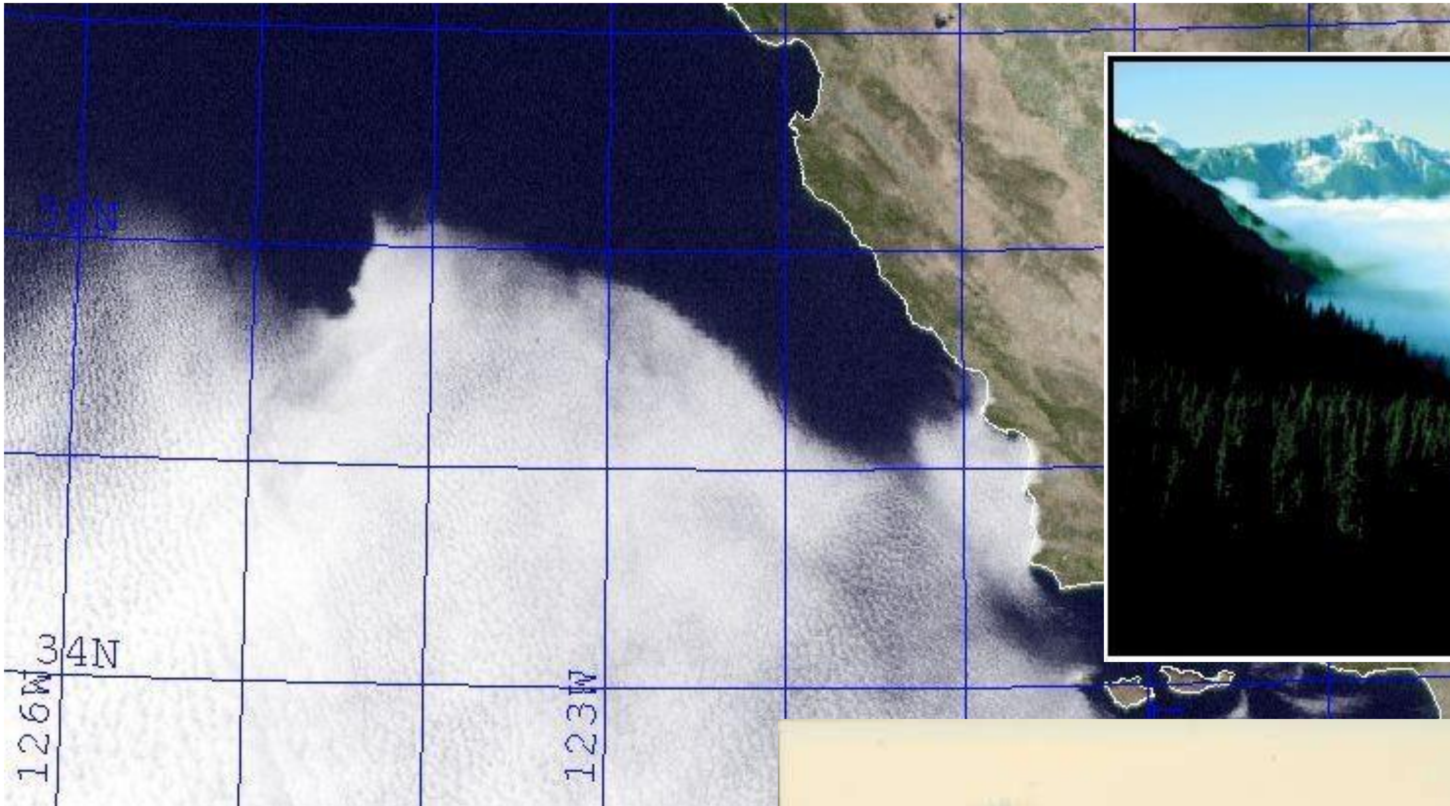


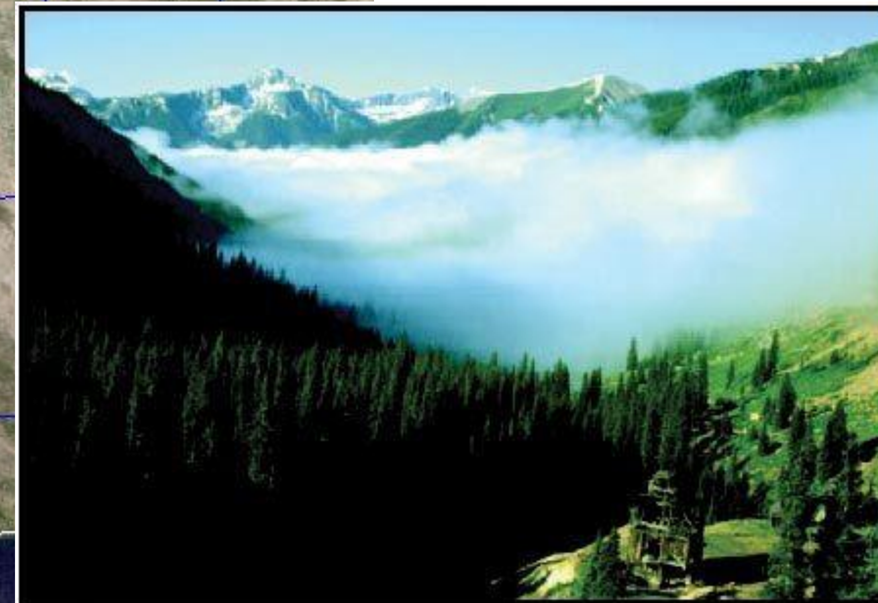
Adiabatic cooling





Examples of condensation (formation of clouds) due to adiabatic expansion.

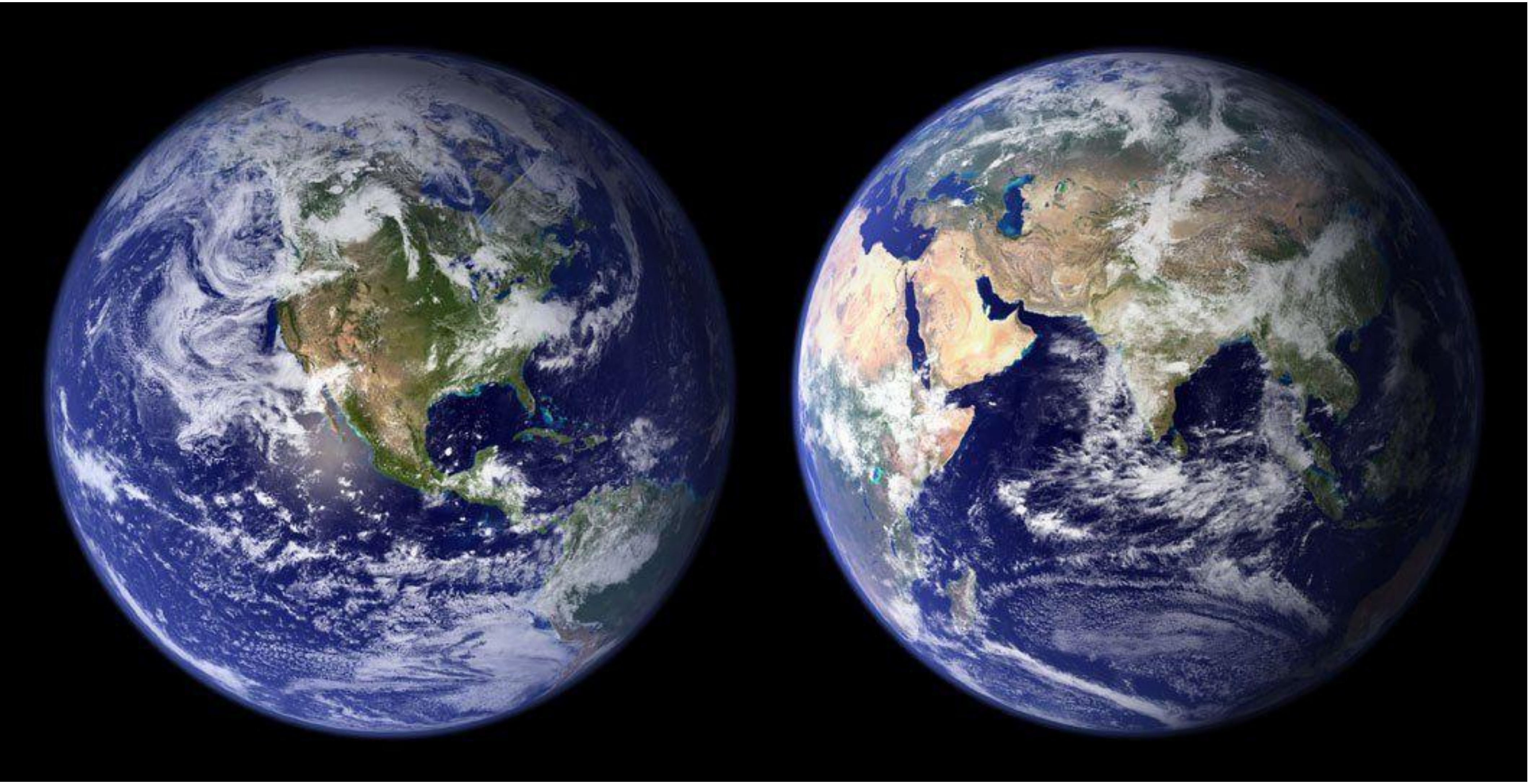




Examples of condensation
(formation of clouds)
due to isobaric cooling.

Examples of condensation
(formation of clouds)
due to isobaric mixing of
two humid unsaturated
airmasses.

Rayleigh scattering – Blue Marble
Mie scattering – Cloud Cover



http://earthobservatory.nasa.gov/Features/BlueMarble/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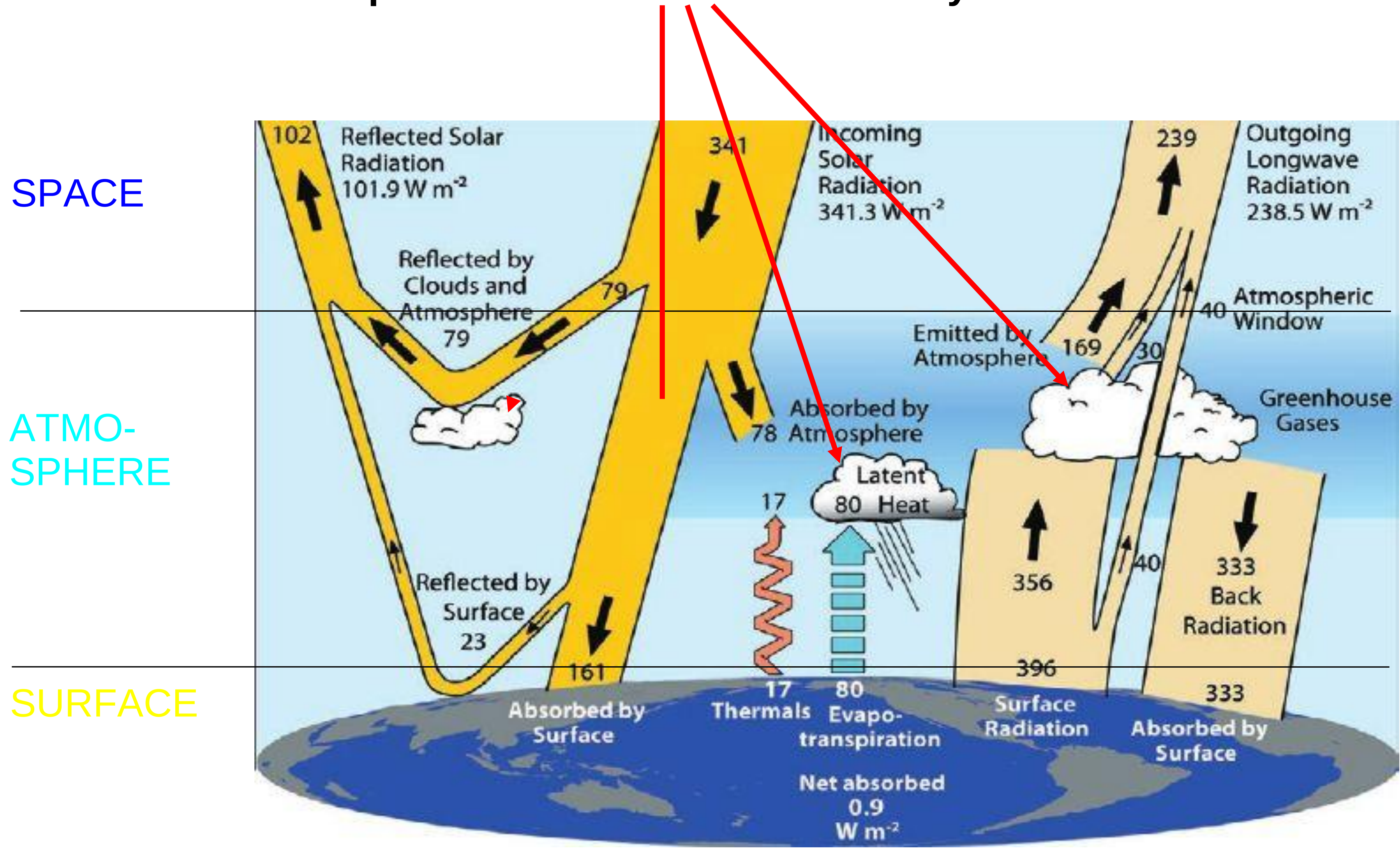
Importance of clouds in climate system



Trenberth et al, 2009, BAMS

Stevens 2005, ARES

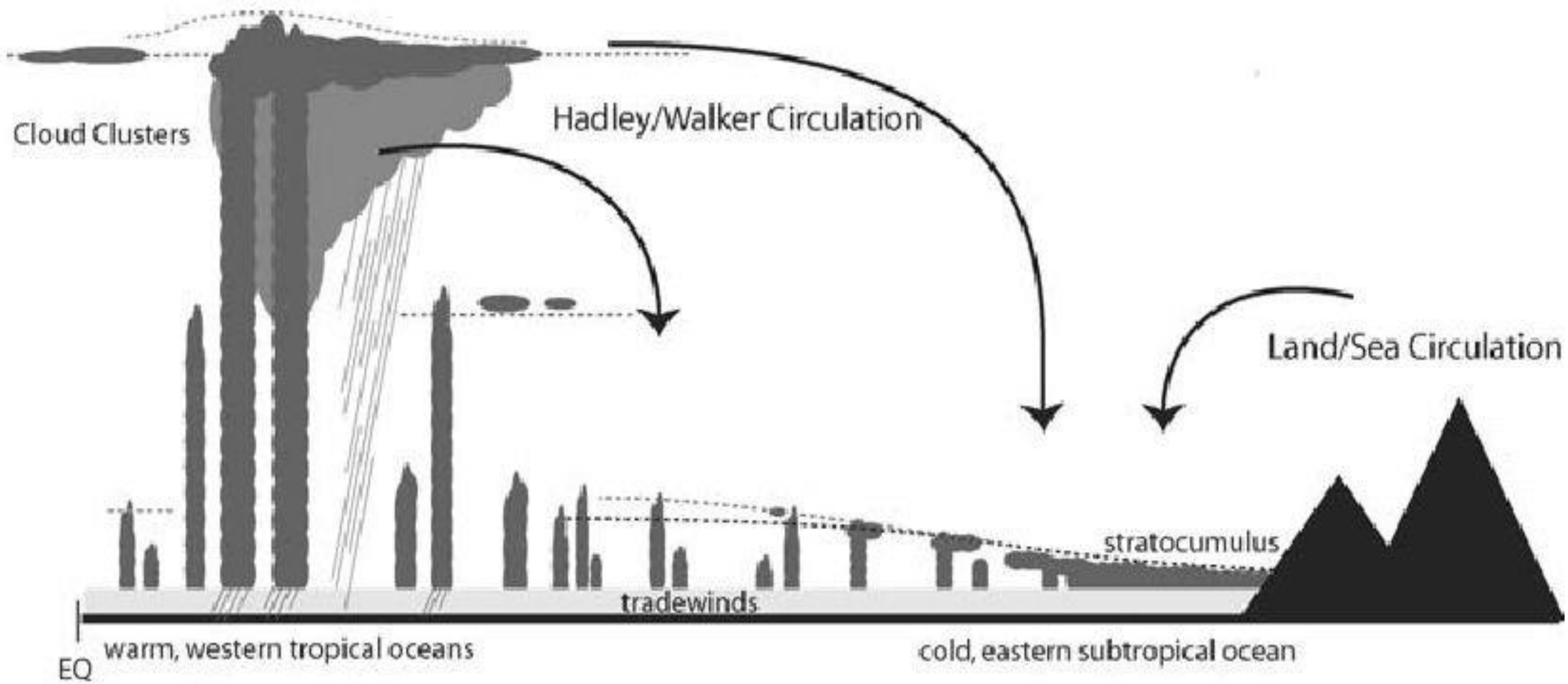


Figure 1 Cloud regimes in thermally direct circulations. Adapted from Arakawa (1975).

- cloud processes are a key to understand general circulation of the atmosphere;
- inadequate understanding of clouds is considered a largest gap in knowledge of our climate system.

Stratocumulus clouds

- essential element in Earth's radiation budget, covering ~ 20% of the globe;
- simple geometry (plain parallel cloud in below capping inversion),
- despite this, mixing processes at Sc top not well understood.

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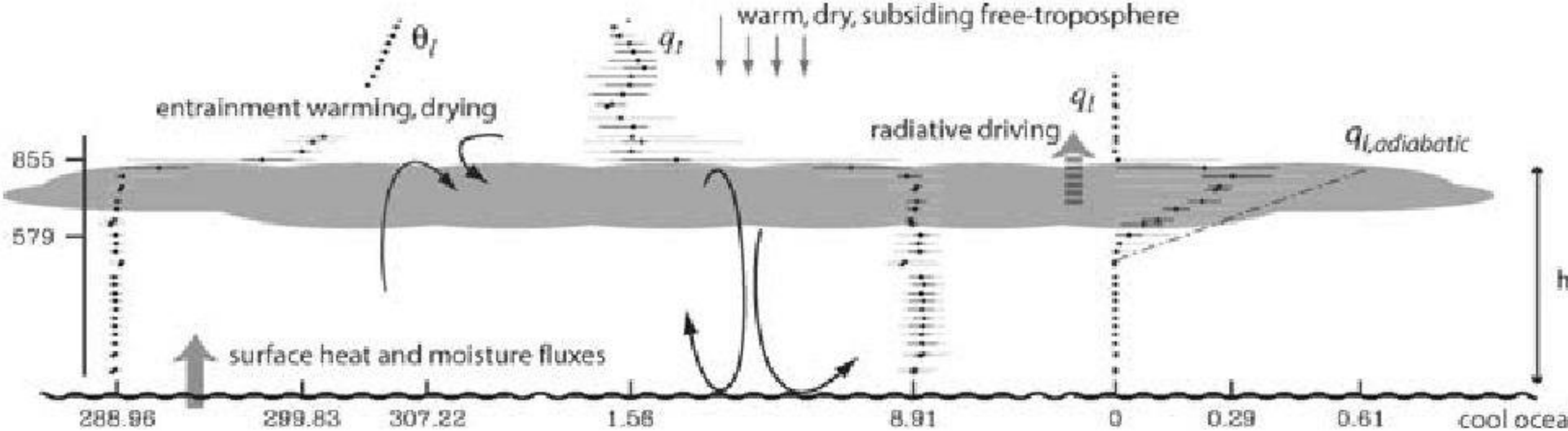
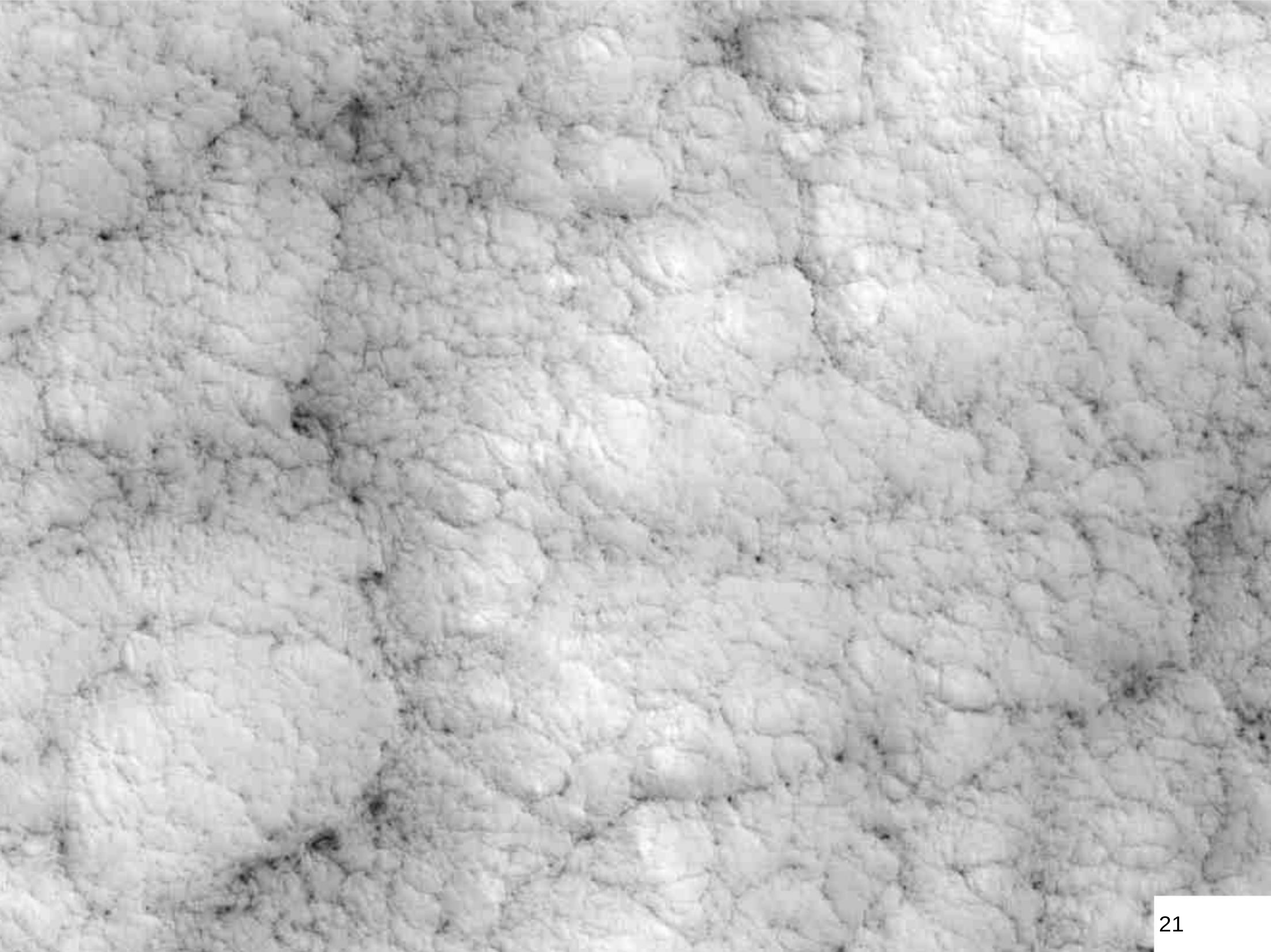
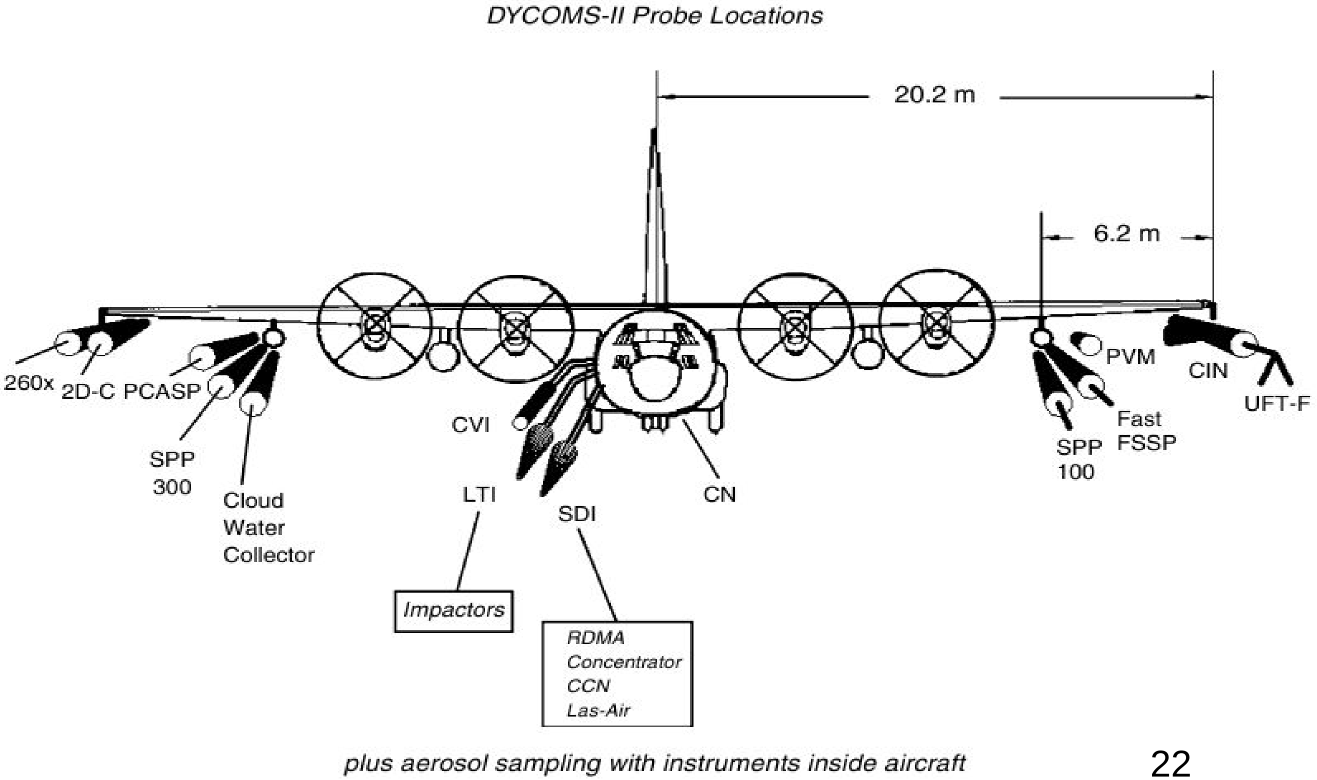


Figure 4 Cartoon of well-mixed, nonprecipitating, stratocumulus layer, overlaid with data from research flight 1 of DYCOMS-II. Plotted are the full range, middle quartile, and mean of θ_l, q_t, and q_l from all the data over the target region binned in 30-m intervals. Heights of cloud base and top are indicated, as are mixed layer values and values just above the top of the boundary layer of various thermodynamic quantities. The adiabatic liquid water content is indicated by the dash-dot line.

Stevens, 2005





In-situ measurements in Stratocumulus clouds: DYCOMS II.

Stevens et al., 2003, BAMS

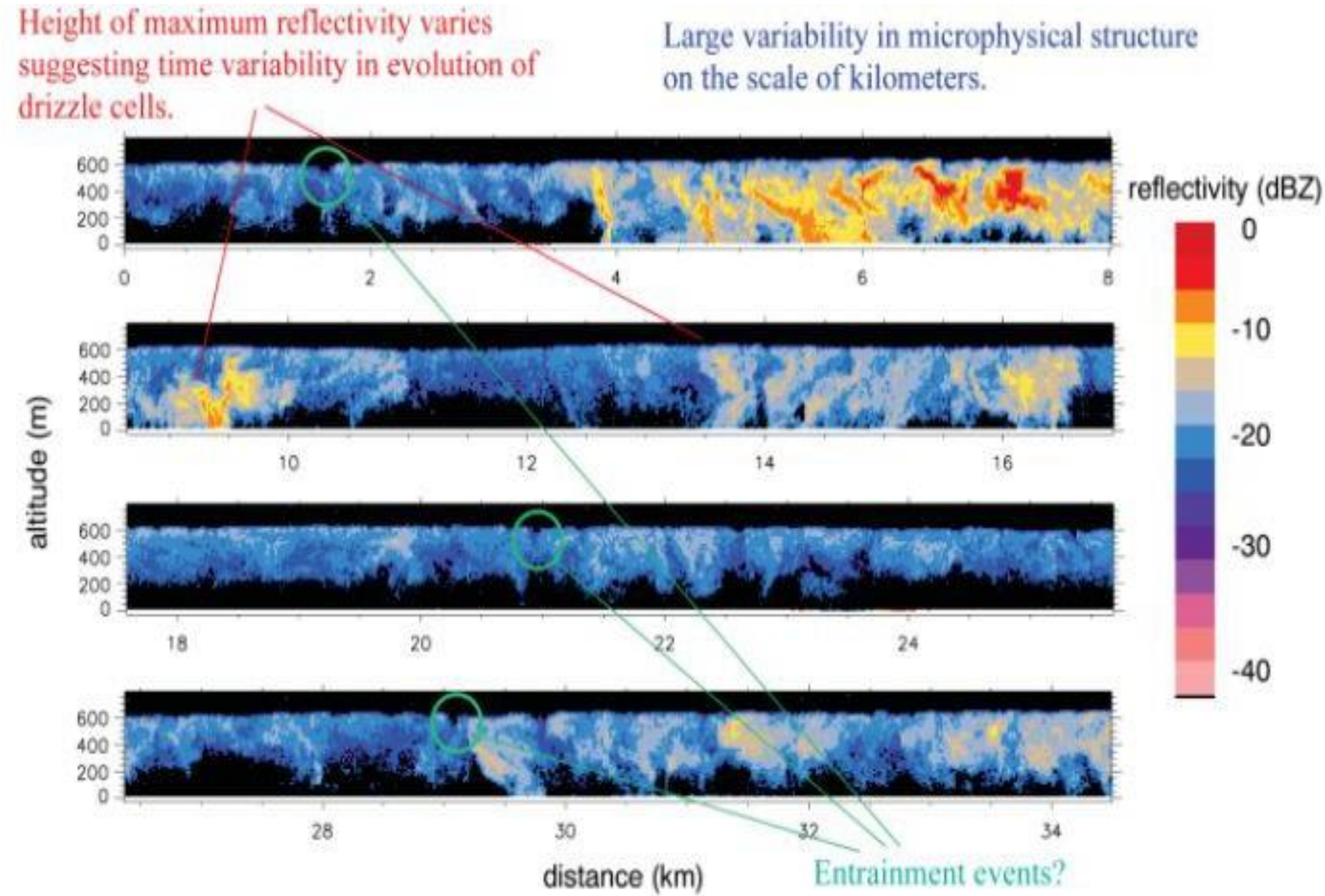


FIG. 5. Radar reflectivity for a segment of RF03. The axis scales are 1:1.

Airborne cloud radar observations of drizzle (red areas) in stratocumulus

Stevens et al., 2003

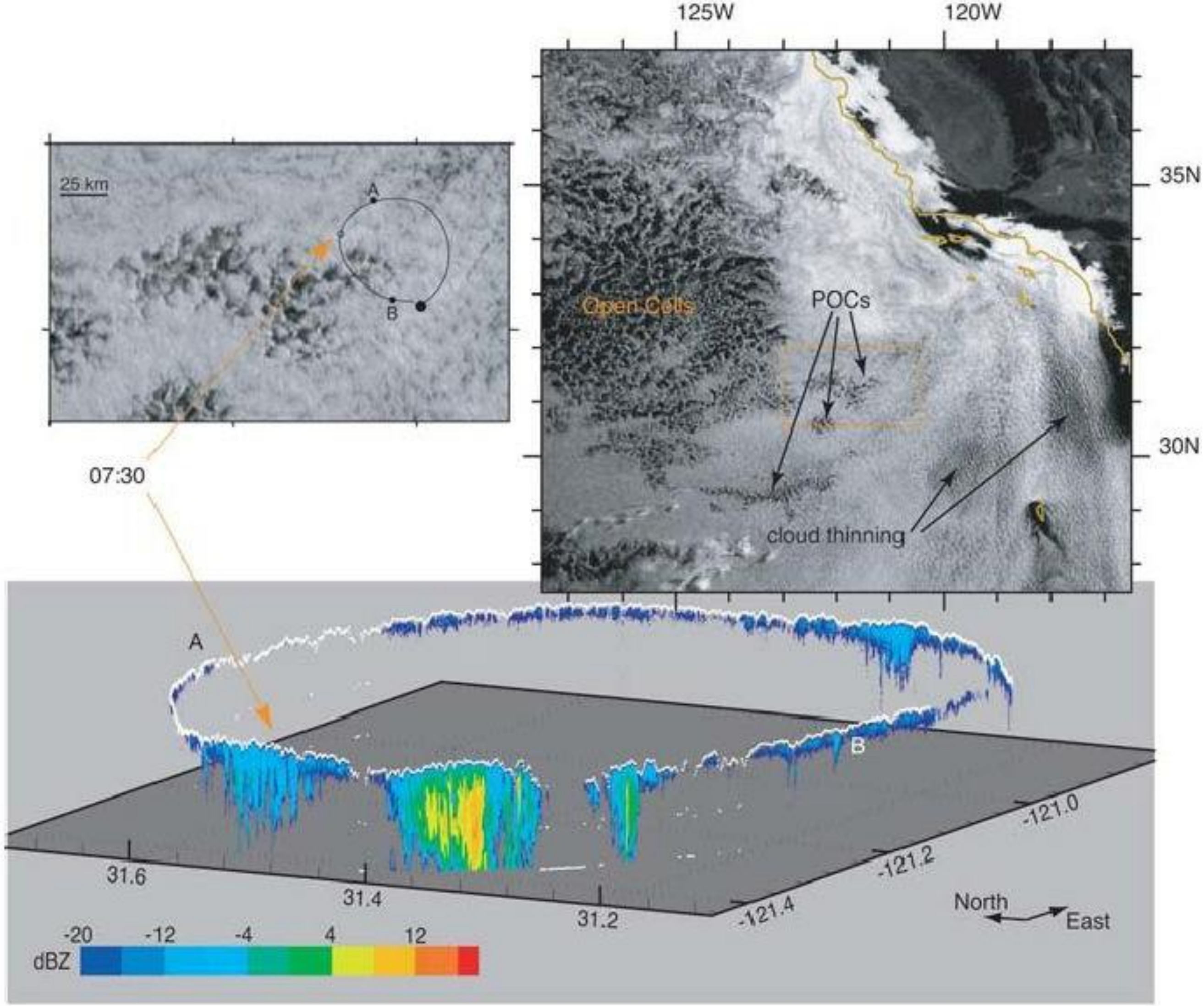


FIG 3. (top right) Channel 1 (0.6 μm) reflectance over the northeast Pacific from *GOES-10* at 0730 LT (1430 UTC) for 11 Jul 2002. (top left) Zoomed image of reflectance field from boxed region in regional image; overlaid on this image is a flight segment from RF02 that spans the time of the overpass and from which radar and lidar data is presented in top left panel. The zoomed image highlights a tilde-shaped POC boxed in the image. (bottom) Time–height radar reflectivities filled, with cloud top height as estimated by downward-looking lidar shown by white line. Regions where lidar detects no cloud are shown by a lidar trace at the surface. The time for which the satellite image is valid is indicated on the flight tracks.

Stevens et al., 2005

JAS, 1980

Cloud Top Entrainment Instability

J. W. DEARDORFF

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(Manuscript received 15 December 1978, in final form 8 May 1979)

Conditional Instability of the First Kind Upside-Down

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Department of Meteorology, Massachusetts Institute of Technology, Cambridge 02139

(Manuscript received 23 March 1979, in final form 14 August 1979)

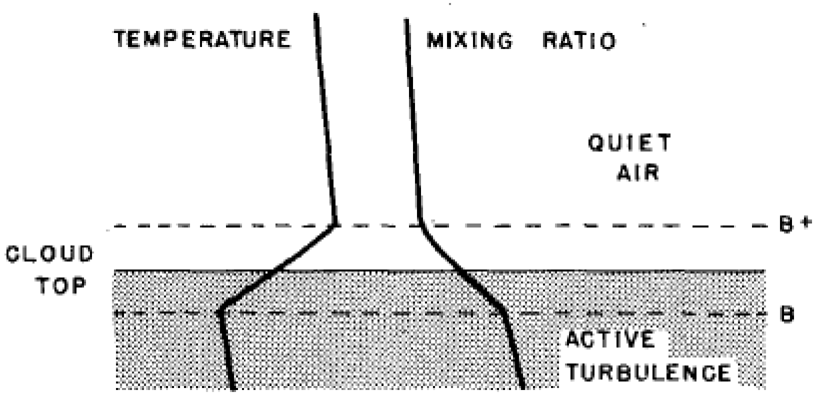


FIG. 1. Schematic diagram of the distributions of temperature and mixing ratio near cloud top. The stippled area represents cloudy air.

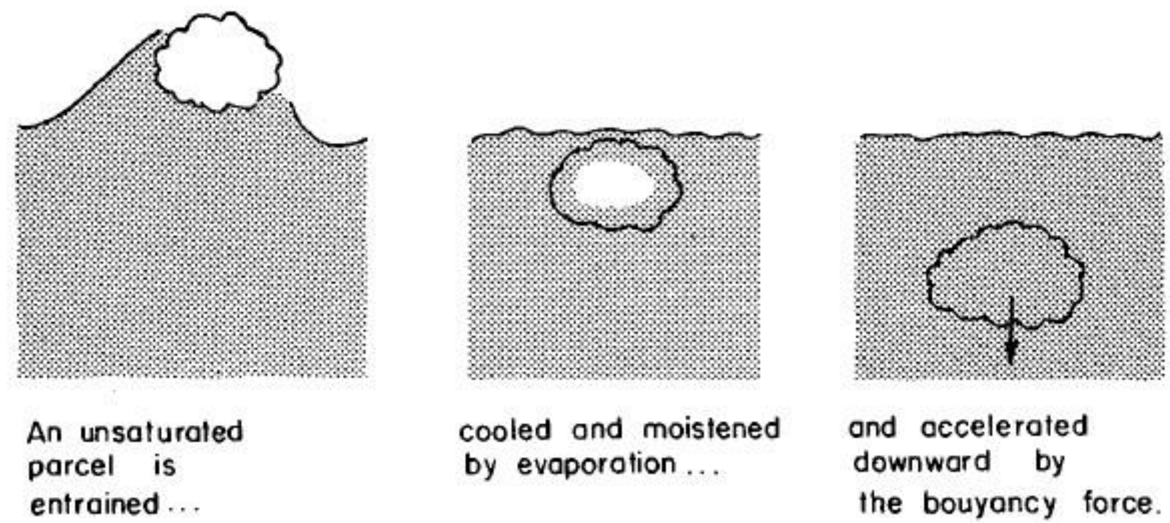
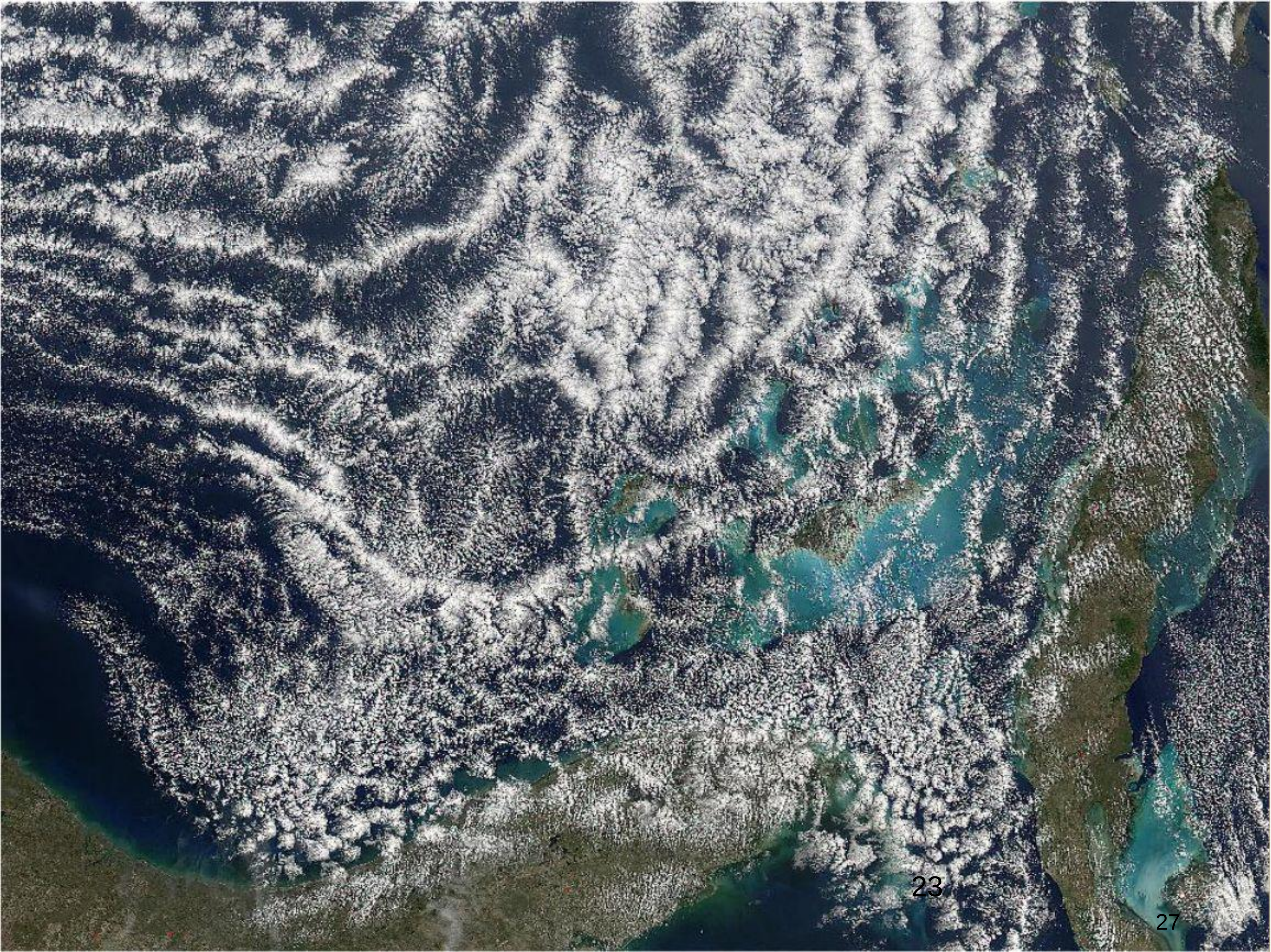


FIG. 4. A schematic illustration of the "parcel" interpretation of CIFKU. The stippled area represents cloudy air.

How do Stratocumulus clouds persist?

Cumulus clouds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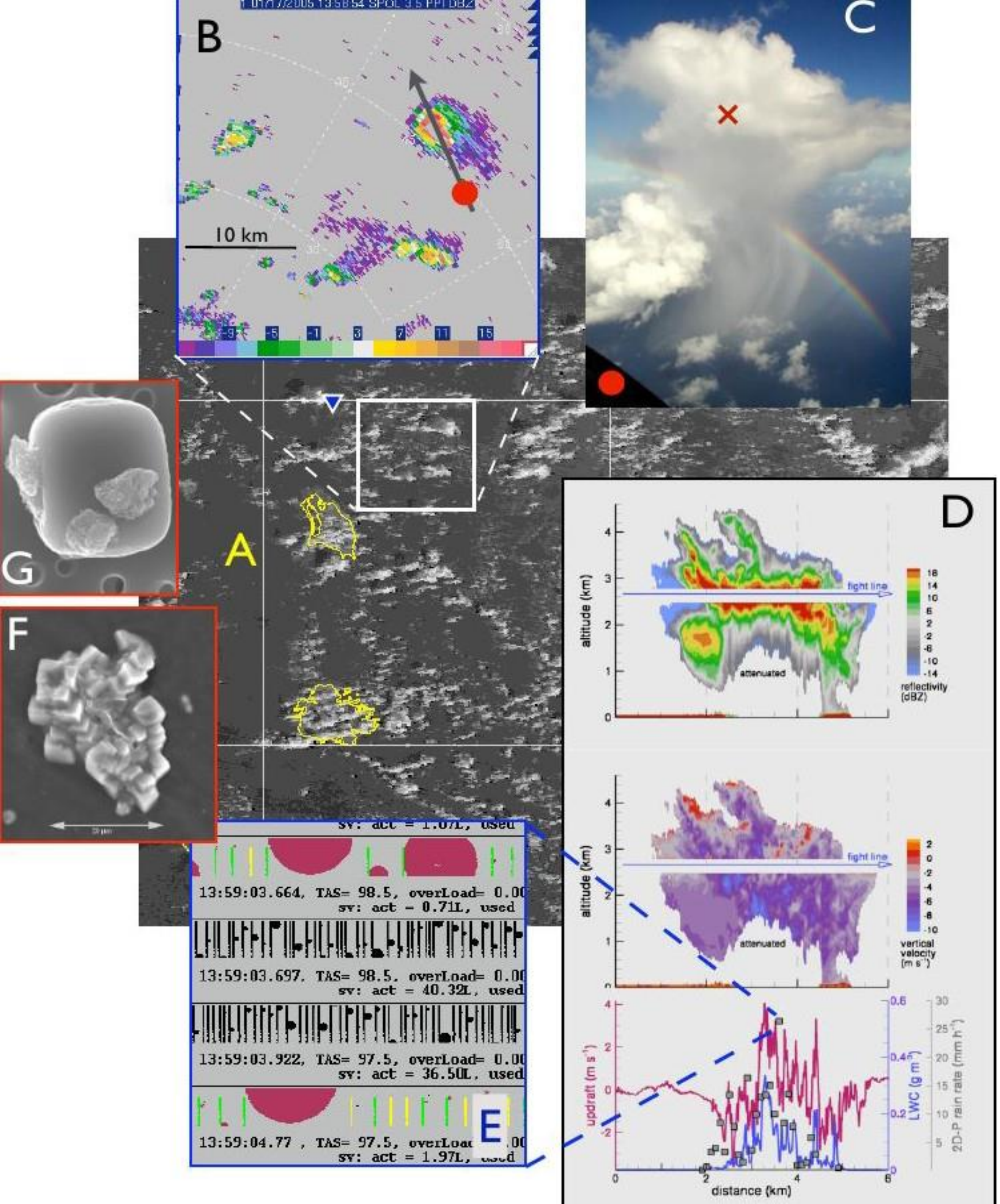
Courtesy B.Stevens



Observations on many scales of a precipitating small cumulus

(17 January, 13:59 UTC).

A: Satellite image from DMSP recorded 10 minutes before penetration by the Wyoming King Air.
B: SPol radar image at 3.5◦ elevation; the cloud is about 46 km from the radar.
C: Photograph taken from a position marked with the red dot in B. The cross marks the approximate location of the aircraft penetration at 2630 m altitude.
D: Vertical sections of radar reflectivity and of Doppler velocity from the Wyoming Cloud Radar and plots of the in situ updraft, liquid water content and rain rate measurements. Note that the high rain rates and large drops are within the updraft.
E: Millimeter sized drops seen at two different magnifications from imaging probes on the King

Air. Also shown in F/G are scanning electron microscope images such as were made from data collected on NSF/NCAR C130 sub-cloud circles: 2 µm sea-salt particle collected by the total aerosol sampler (F); giant sea-salt particle (20 µm scale) collected with the giant nuclei sampler (G). The location of the Research Vessel Seward Johnson is marked with a blue triangle in A.

Rauber et al., 2007

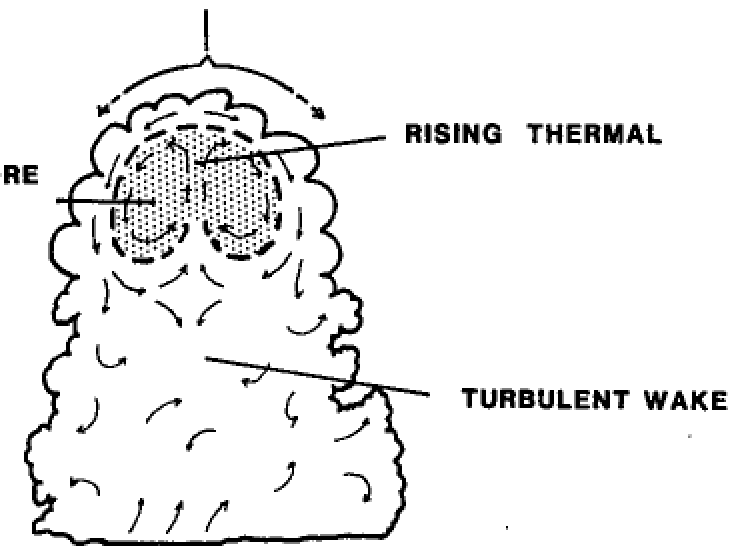


FIG. 14. Schematic model of a cumulus cloud showing a shedding thermal that has ascended from cloud base. Continuous entrainment into the surface of the thermal erodes the core, and the remaining undiluted core region continues its ascent, leaving a turbulent wake of mixed air behind it. See text for further discussion.

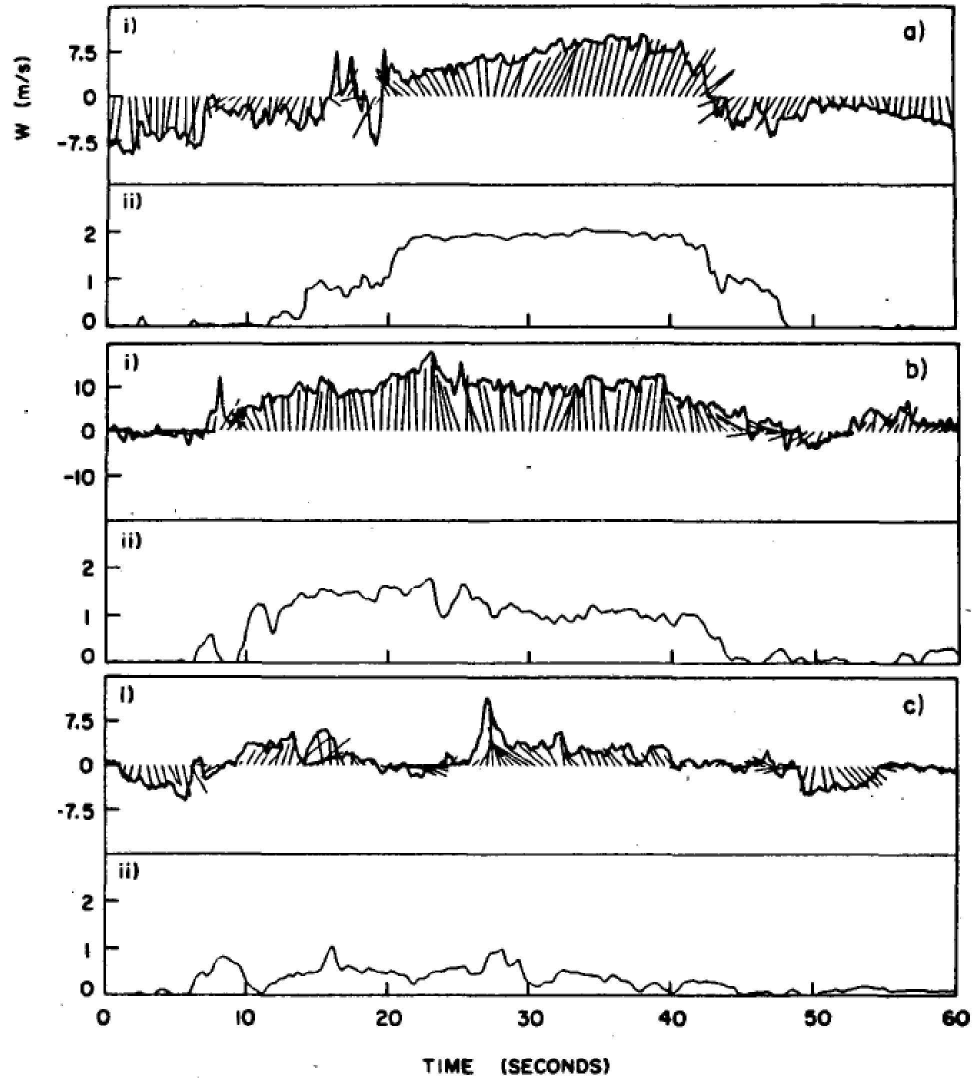


FIG. 17. Wind velocity (i) and liquid water content (ii) for three KA penetrations from 1625 to 1633 MDT in the 19 July 1981 cloud: (a) 472 mb, (b) 514 mb and (c) 527 mb. The wind vectors are formed from the vertical wind and the wind along the flight path and are drawn to scale.

Conceptual sketch of cumulus and supporting data.

Blyth et al., 1988

Numerical simulations of small scales of cloud mixing with the environment.

Simplified set of equations of cloud dynamics, thermodynamics and microphysics :

$$D/Dt \equiv \partial/\partial t + \mathbf{v}\cdot\boldsymbol{\nabla}$$

$$B \equiv g\left[\frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v_0}) - q_c\right], \qquad (2)$$

$$\frac{D\mathbf{v}}{Dt} = -\boldsymbol{\nabla}\pi + \mathbf{k}B + \nu\nabla^2\mathbf{v}, \qquad (1a)$$

$$\boldsymbol{\nabla}\cdot\mathbf{v} = 0, \qquad (1b)$$

$$\frac{DT}{Dt} = \frac{L}{c_p}C_d + \mu_T\nabla^2 T, \qquad (1c)$$

$$\frac{Dq_v}{Dt} = -C_d + \mu_v\nabla^2 q_v, \qquad (1d)$$

$$\frac{Dq_c}{Dt} = C_d. \qquad (3)$$

π – normalized pressure fluctuation
C_d – condensation rate
q_v, q_c – specific humidity, liquid water content
B – normalized buoyancy

$$C_d = \int f\frac{dm}{dt}\,dr,$$

$$\frac{D^* f}{D^* t} = -\frac{\partial}{\partial r}\left(f\frac{dr}{dt}\right) + \eta,$$

$$D^*/D^*t \equiv \partial/\partial t + (\mathbf{v} - \mathbf{k}v_t)\cdot\boldsymbol{\nabla}$$

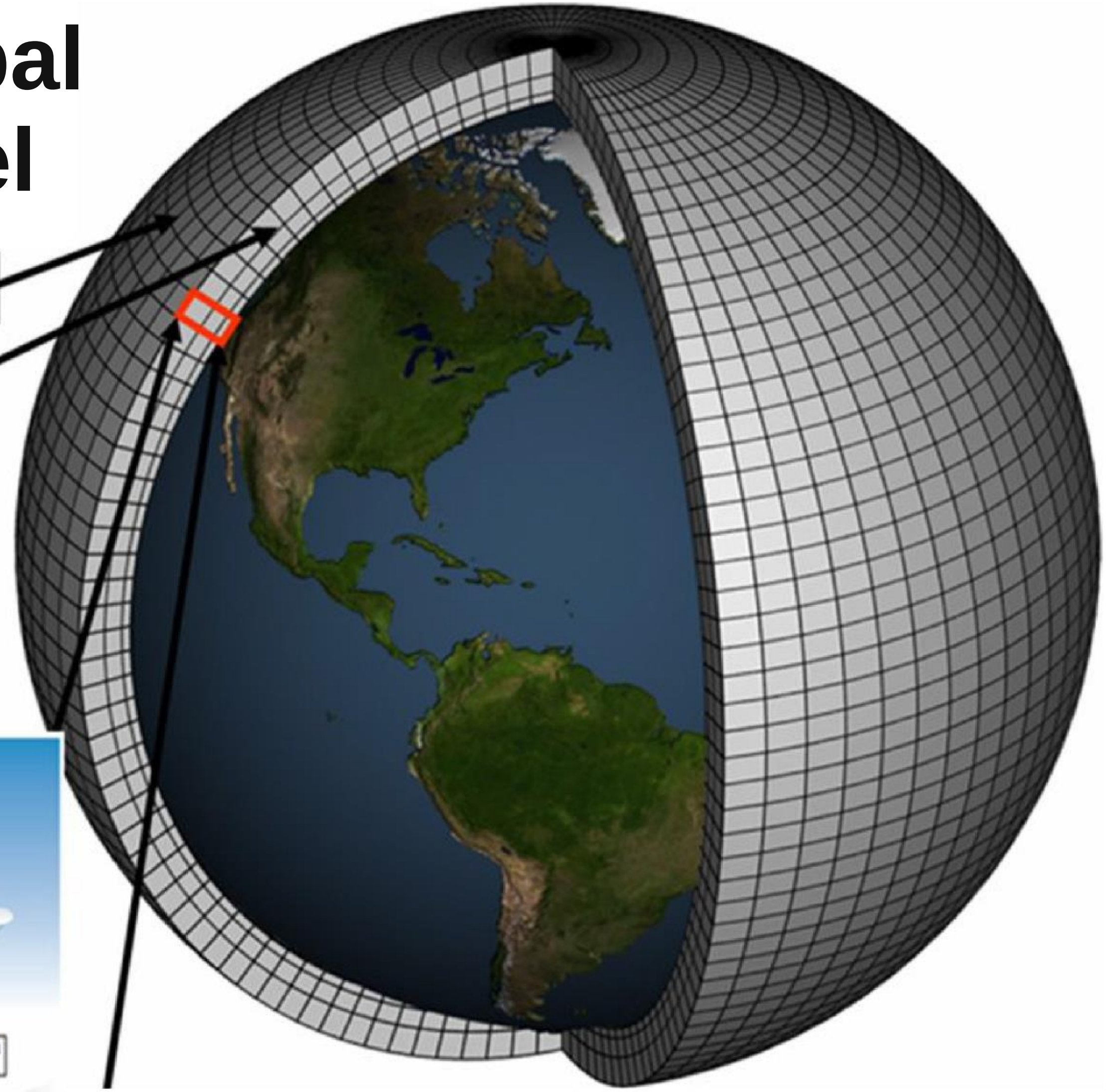
$f(\mathbf{x}, r, t)dr$ is the number of cloud droplets in a unit mass of air (viz. the mixing ratio) of the radius between r and $r + dr$, at a given point $(\mathbf{x}, t)$ in space and time.

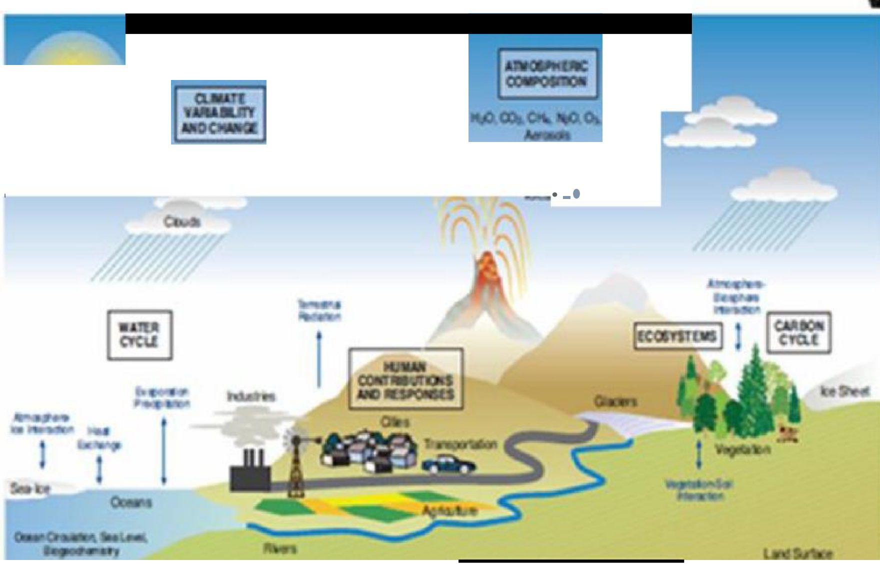
Andrejczuk et al., 2004, 2006, 2009, Malinowski et al., 2008

Schematic for Global A mosphericModel

Horizontal Grid (Latitude-Longitude)

Vertical Grid (Height or Pressure)





JAS, 1974

Interaction of a Cumulus Cloud Ensemble with the Large-Scale Environment, Part I

AKIO ARAKAWA AND WAYNE HOWARD SCHUBERT[1]

Dept. of Meteorology, University of California, Los Angeles 90024

(Manuscript received 10 August 1973, in revised form 7 November 1973)

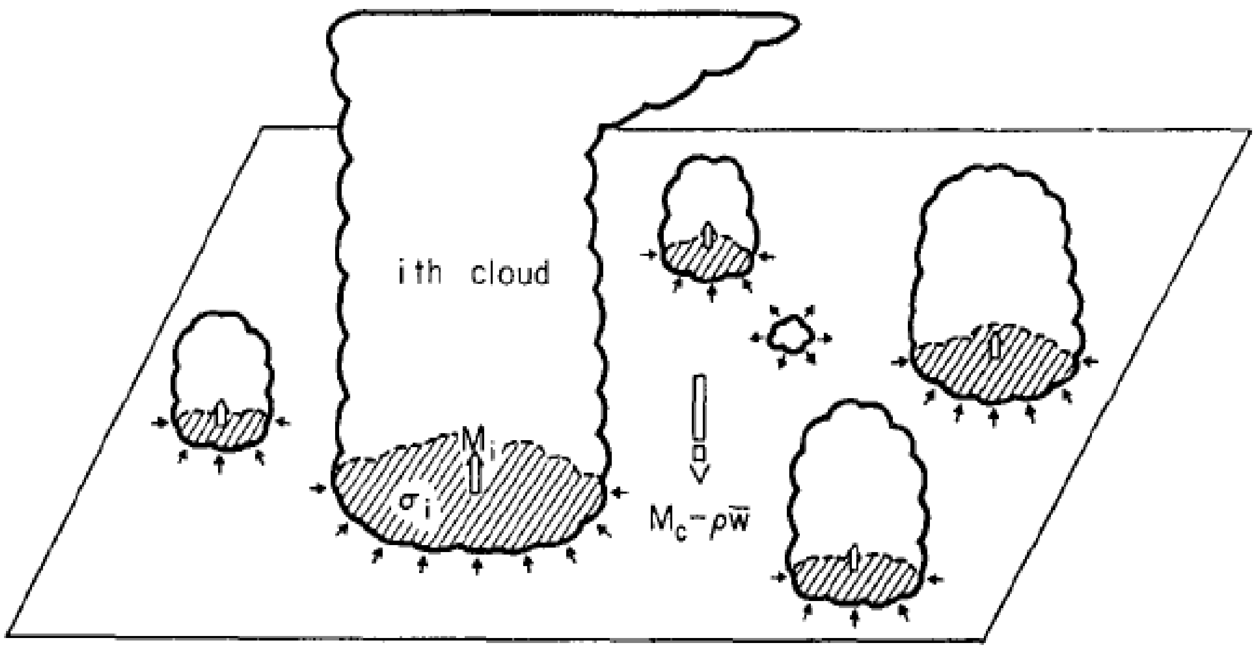


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

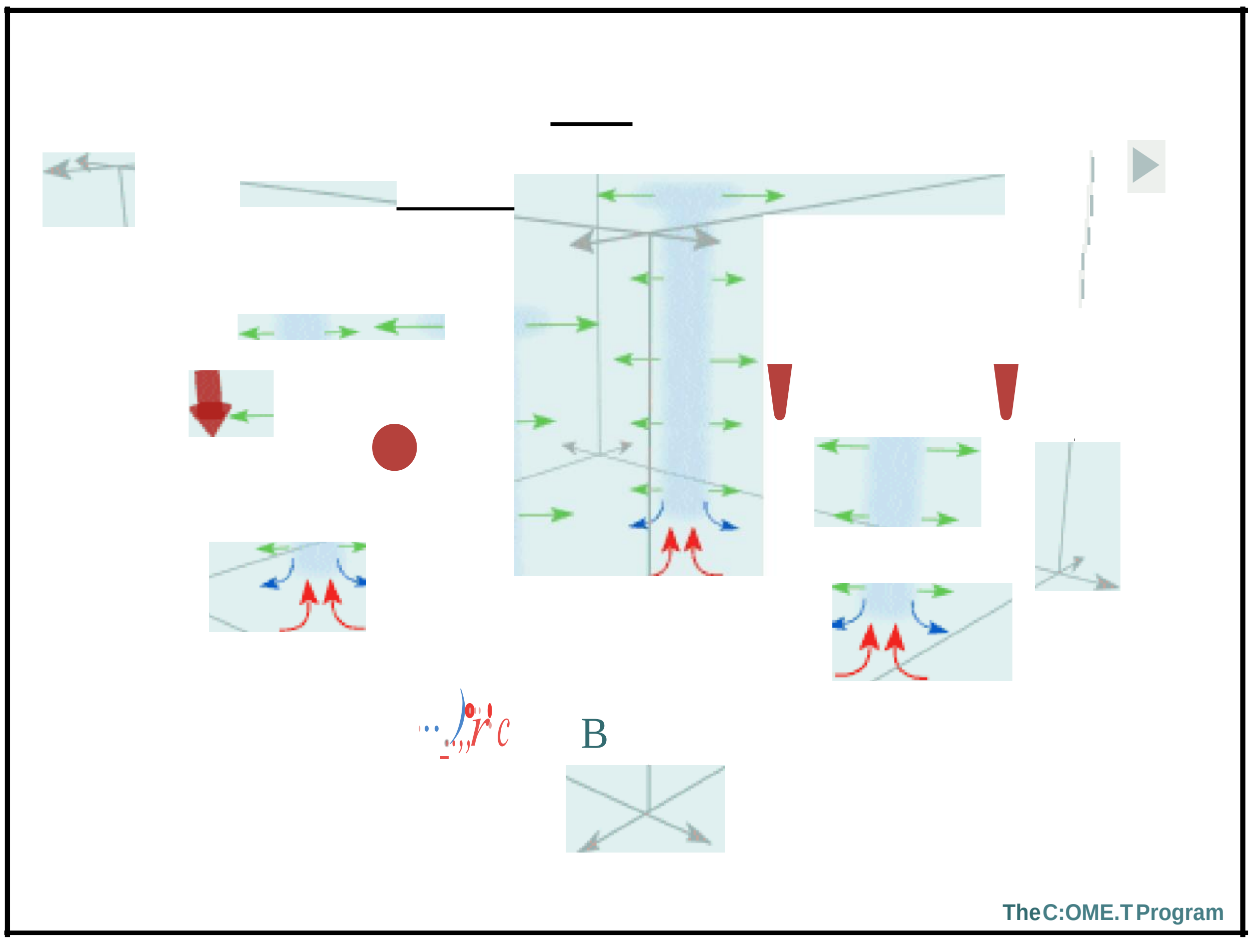
Vertical mass flux in the ensemble of clouds depends on entrainment and detainment rates.

This concept appeared very successful until recent years.

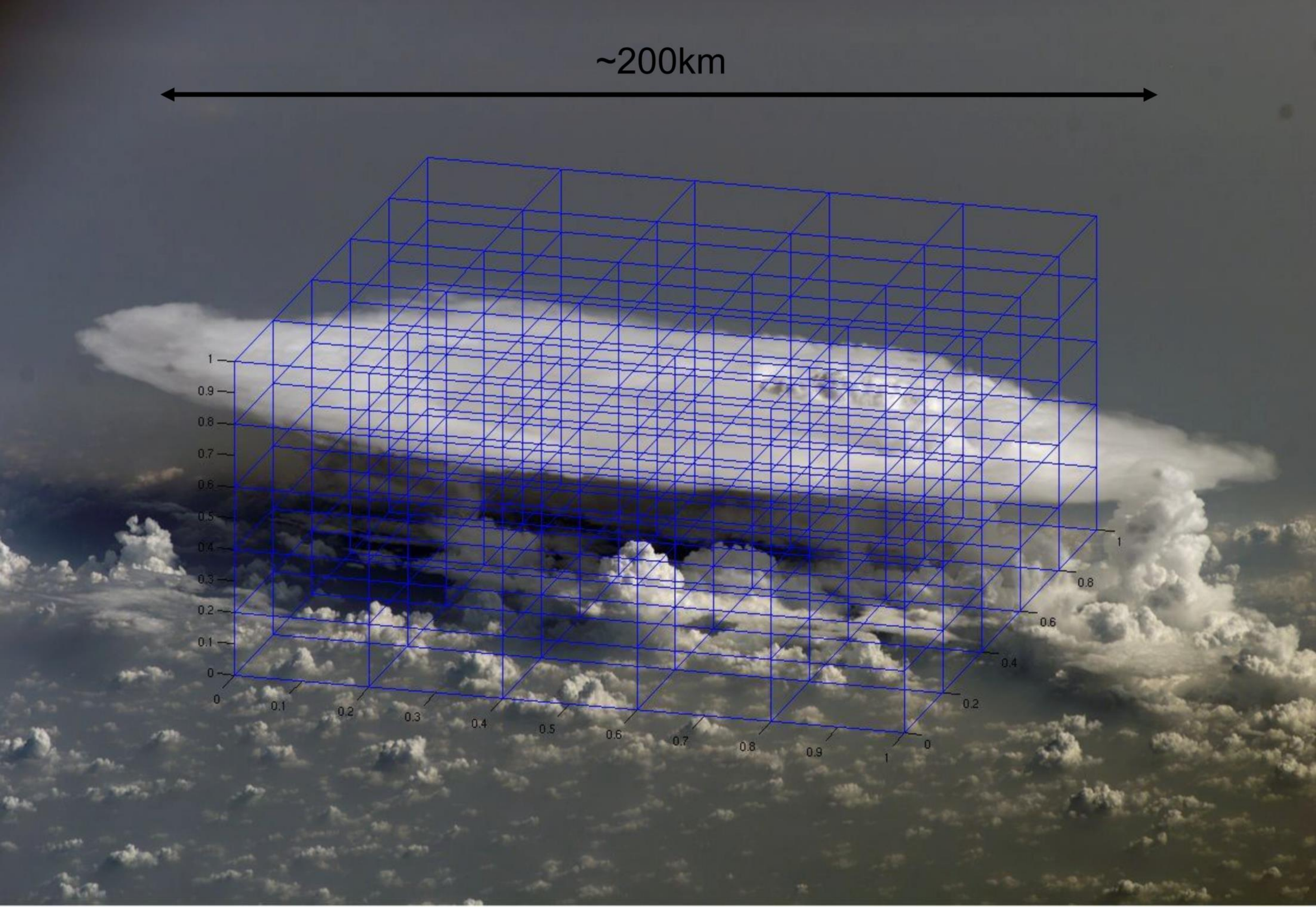
!

Convective parameterizations simply rearrange heat and moisture.

Most schemes today are mass-flux schemes



- Air enters updraft
- 1-d cloud model calculates parcel properties, including precip
- Cloud detrains
- Convecti've downdraft dumps into low levels might evaporate some preclp
- Compensating subsidence warms and dries grid column



ISS016E027426

In modern global models gridboxes are too fine for classical flux sch es.

Conclusion:

Don't believe that new generation of models will quickly improve weather forecast or climate projections.

Despite recent developments we are proud of,
our incomplete understanding of base physics and differences in “virtual reality” of the model and world outside are limiting factors.

Without understanding turbulence across its whole range of scales we are not able to understand clouds...

and weather… and climate…

Readings

1. Textbooks:

Yau, M.K. and R. R. Rogers: “A Short Course in Cloud Physics”, Third Edition (International Series in Natural Philosophy), Butterworth-Heinemann, 15th May 1996

Cotton, W.R., G. Bryan and S.C. van de Heever: “Storm and Cloud Dynamics”, Volume 99 International Geophysics, 2nd Edition, Academic Press, 15th October 2010

2. Papers:

Stevens, B.: Atmopsheric moist convection, Annu. Rev. Earth. Pl. Sc., 33, 605–643, doi:10.1146/annurev.earth.33.092203.122658, 2005.

Turner, J. S.: Turbulent entrainment: the development of the entrainment assumption, and its application to geophysical flows, J. Fluid. Mech., 173, 431–471, doi:10.1017/S0022112086001222, 1986.

Wood, R.: Stratocumulus clouds, Mon. Weather Rev., 140, 2373–2423, doi:10.1175/MWR-D-11-00121.1, 2012.

Yano, J.-I.: Basic convective element: bubble or plume? A historical review, Atmos. Chem. Phys., 14, 7019-7030, https://doi.org/10.5194/acp-14-7019-2014, 2014.

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Stevens, B., Lenschow, D.H., Vali, G., Gerber, H., Bandy, A., Blomquist, B., Brenguier, J.-L., Bretherton, C.S., Burnet, F., Campos, T., Chai, S., Faloona, I., Friesen, D., Haimov, S., Laursen, K., Lilly, D.K., Loehrer, S.M., Malinowski, S.P., Morley, B., Petters, M.D., Rogers, D.C., Russell, L., Savic-Jovcic, V., Snider, J.R., Straub, D., Szumowski, M.J., Takagi, H., Thornton, D.C., Tschudi, M., Twohy, C., Wetzel, M., Van Zanten, M.C., 2003, Dynamics and Chemistry of Marine Stratocumulus – DYCOMS-II, Bulletin of the American Meteorological Society, 84 (5), pp. 579-593+548.
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Rauber, R.M., Stevens, B., Ochs III, H.T., Knight, C., Albrecht, B.A., Blythe, A.M., Fairall, C.W., Jensen, J.B., Lasher-Trapp, S.G., Mayol-Bracero, O.L., Vali, G., Anderson, J.R., Baker, B.A., Bandy, A.R., Brunet, E., Brenguier, J.L., Brewer, W.A., Brown, P.R.A., Chuang, P., Cotton, W.R., Di Girolamo, L., Geerts, B., Gerber, H., Göke, S., Gomes, L., Heikes, B.G., Hudson, J.G., Kollias, P., Lawson, R.P., Krueger, S.K., Lenschow, D.H., Nuijens, L., O'Sullivan, D.W., Rilling, R.A., Rogers, D.C., Siebesma, A.P., Snodgrass, F., Stith, J.L., Thornton, D.C., Tucker, S., Twohy, C.H., Zuidema, P., 2007, Rain in shallow cumulus over the ocean: The RICO campaign, Bulletin of the American Meteorological Society, 88 (12), pp. 1912-1928.
Trenberth, K.E., Fasullo, J.T., Kiehl, J., 2009, Earth's global energy budget, Bulletin of the American Meteorological Society, 90 (3), pp. 311-323.

1st training school of COMPLETE
June 19-22, 2017
Torino, Italy

COMPLETE

Introduction to turbulence

- Szymon MALINOWSKI

UNIVERSITY
OF WARSAW

COMPLETE 1st school

Torino

Introduction to turbulence

June 20, 2017
Szymon Malinowski

2. Introduction to turbulence **41**

WIKIPEDIA:

In fluid dynamics, turbulence or turbulent flow is a flow regime characterized by chaotic and suspectedly stochastic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time....

In turbulent flow, unsteady vortices appear on many scales and interact with each other....

Nobel Laureate Richard Feynman described turbulence as "the most important unsolved problem of classical physics."

AMS Glossary:

1. Irregular fluctuations occurring in fluid motions.

It is characteristic of turbulence that the fluctuations occur in all three velocity components and are unpredictable in detail; however, statistically distinct properties of the turbulence can be identified and profitably analyzed. Turbulence exhibits a broad range of spatial and temporal scales resulting in efficient mixing of fluid properties. Analysis reveals that the kinetic energy of turbulence flows from the larger spatial scales to smaller and smaller scales and ultimately is transformed by molecular (viscous) dissipation to thermal energy. Therefore, to maintain turbulence, kinetic energy must be supplied at the larger scales.

2. Random and continuously changing air motions that are superposed on the mean motion of the air.

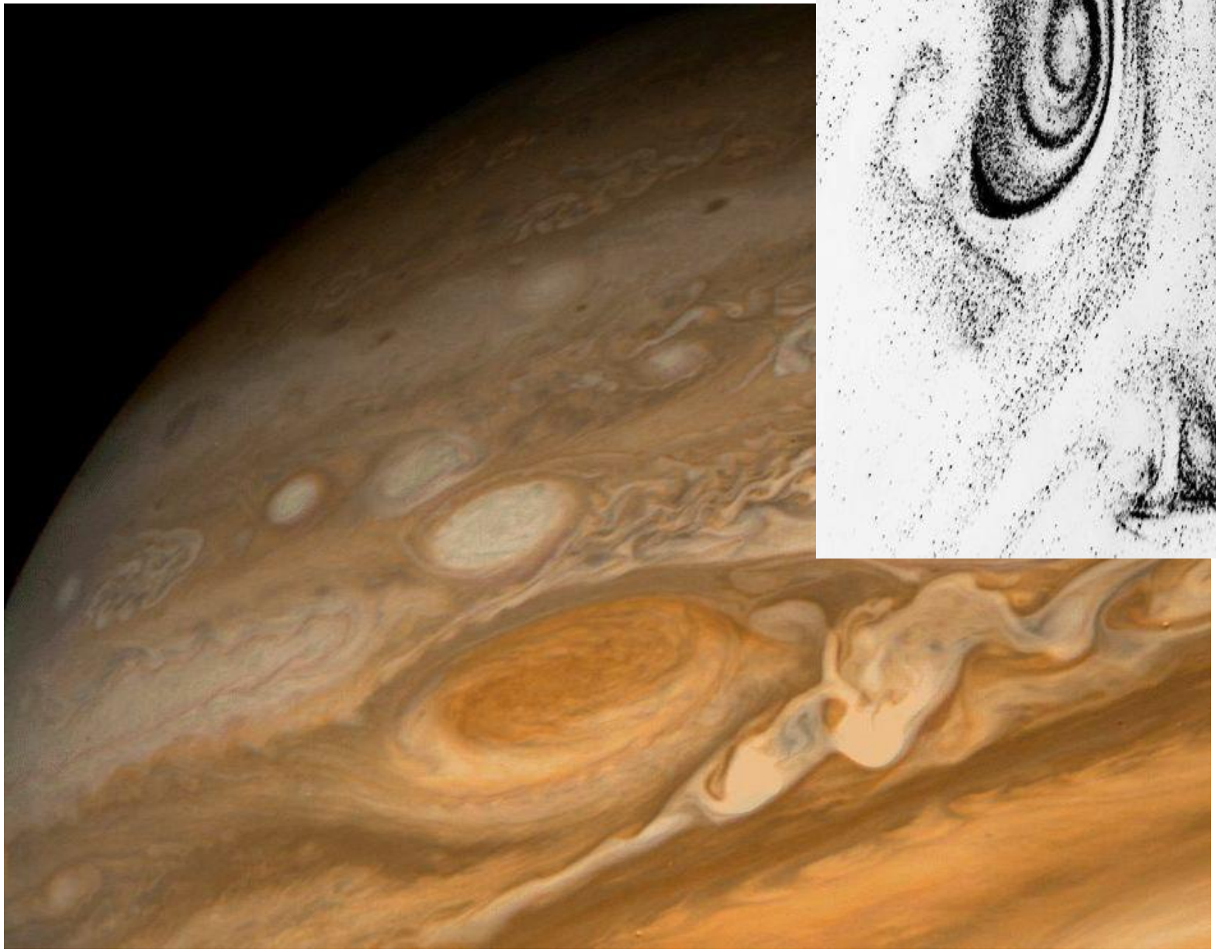
Properties of turbulent flows:

they obey a wide range of spatial and temporal scales;

nonlinear advective effects play an important role;

unpredictability;

irreversibility.



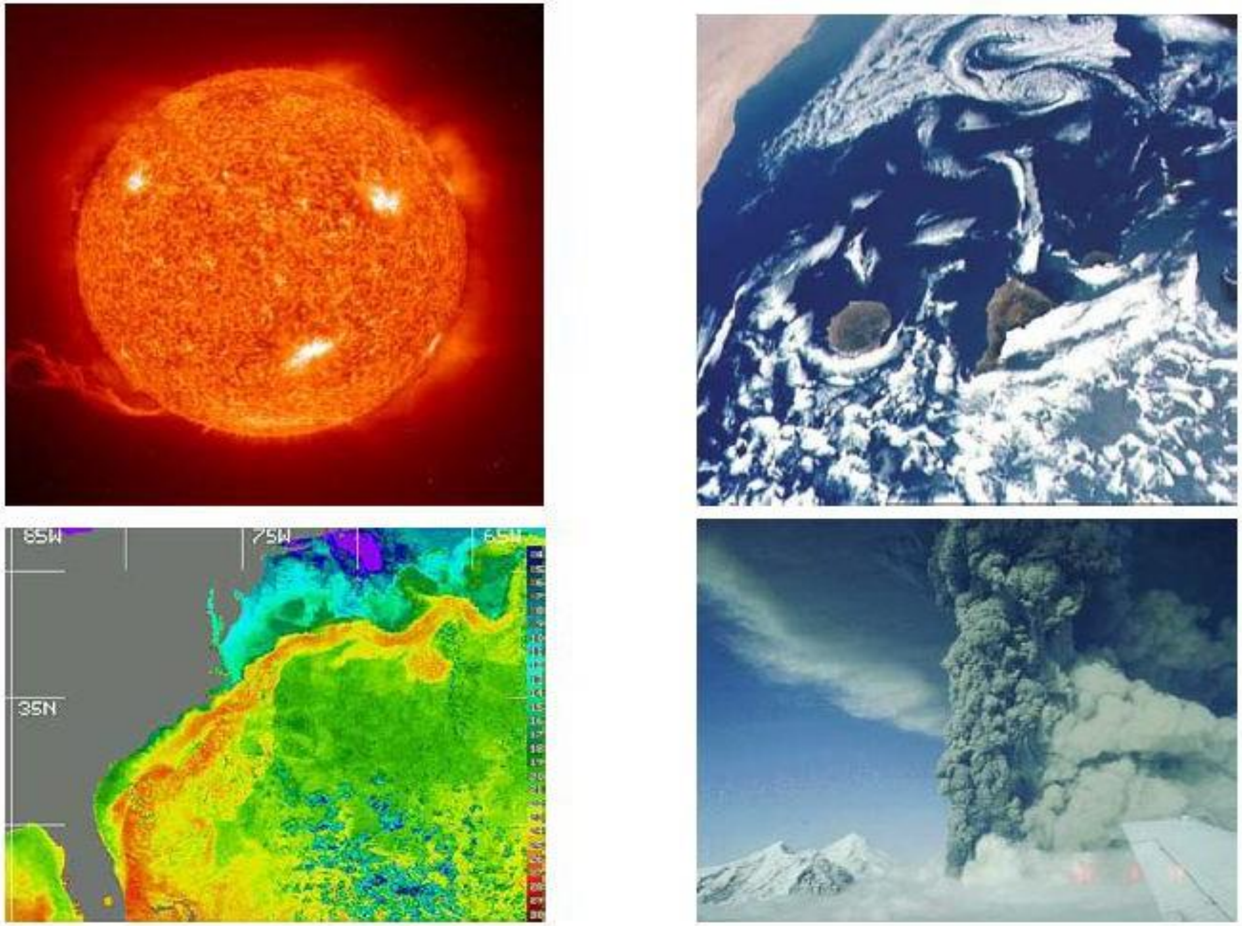


Figure 1.1: Examples of turbulent flows at the surface of the Sun, in the Earth's atmosphere, in the Gulf Stream at the ocean surface, and in a vulcanic eruption.

Other important properties of turbulent flows:

vortex stretching is an important feature ;
energy cascade from large to small scales can be observed.

ON THE DY AMICAL THEORY OF INCOIVIPRESSIBLE VISCOUS FLUIDS AND THE DETERMINA'£ION OF THE CRITERION.

[*From the* "Philosophical Transactions of the Royal Society," 1895.]

(*Read* May 24, 1894.)

In 1850, after Joule's discovery of the Mechanical Equivalent of Heat, Stokes showed, by transforming the equations of mot io - with arbitrary stresses-so as to obtain the equations of ("Vis-viva") energy, that this equation contained a definite function, which represented the difference between the work done on the fluid by the stresses and the rate of increase of the energy, per unit of volume, which function, he concluded, must, according to Joule, represent the Vis-viva converted into heat.

This conclusion was obtained from the equations irrespective of any particular relation between the stresses and the rates of distortion. Sir G. Stokes, however, translated the function into an expression in terms of the rates of distortion, which expression has sincebeen named by Lord Rayleigh the *Dissipation-Function.*

2. In 1883 I succeeded in proving, by means of experiments with colour bands-the results of which were communicated to the Society•- tha.t when water is caused by pressure to flow through a uniform smooth pipe, the motion of the water is *direct, i.e.*, parallel to the sides of the pipe, or *sinuous, i.e.*, crossing and re-crossing the pipe, according as $U_{,,,,}$ the mean velocity of the water, as measured by dividing Q, the discharge, by , the area of the section of the pipe, is below or above a certain val ue given by

$$K\mu,/Dp;$$

where D is the diameter of the pipe, p the density of the water, and J{ a numerical constant, the value of which according to my experiments, and, as I was able to show, to all the experiments by Poiseuille and Darcy, is fol' pipes of circular section between

1900 and 2000,

or, in other words, steady direct motion in round tubes is stable or unstable according as

$$p\frac{IJUm}{\mu,} > 1900 \text{ or } < 2000,$$

the number K being thus a criterion of the possible maintenance of sinuous or eddying motion.

3. The experiments also showed tha.t K was equally a criterion of the law of the re.sistance to be overcome-which changes from a resistance proportional to the velocity, and in exact accorda.nce wit-h the theoretical results obtained from the singular solution of the equation, when. direct motion changes to sinuous, *i.e.*, when

$$\frac{PDUm}{\mu}=K.$$

4. **In** the same paper I pointed out that the existence of this sudden change in the law of motion of fluids between solid surfaces when

$$DUm=\frac{f:K}{p}$$

proved the dependence of the manner of motion of the fluid on a raelation between the product of the dimensions of the pipe multiplied by the velocity of the fluid, and the product of the molecular dimensions multiplied by the molecular velocities which determine the value of

$$\mu,$$

for th-e fluid, also that the equations of motion for viscous fluid contained evidence of this relation, Boussinesq incompressible equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \underbrace{(\mathbf{u} \cdot \nabla)\mathbf{u}}_{inertia} = -\frac{1}{\rho_0}\nabla p + \underbrace{\nu \nabla^2 \mathbf{u}}_{friction} + \left[\underbrace{b\hat{z}}_{buoyancy} - \underbrace{f\hat{z} \times \mathbf{u}}_{Coriolis} \right], \tag{1.2}$$

$$\left[\frac{\partial b}{\partial t} + \underbrace{(\mathbf{u} \cdot \nabla)b}_{advection} = \underbrace{\kappa \nabla^2 b}_{diffusion} \right], \tag{1.3}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{1.4}$$

p –pressure, $\mathbf{u}$ – velocity, t – time, ρ - density, b – buoyancy, f– Coriolis parameter, - ν viscosity, κ – thermal conductivity.

These equations can be supplemented with pressure scalar equation, formally similar to (1.3), but not influencing momentum equations.

Pathways towards solutions of equations
or at least towards some properties of these solutions:

- analytical solutions of exact equations for selected flows and range of parameters;
- analytical solution of approximated equations;
- direct numerical simulations DNS;
- looking for some statistical properties of solutions (more soon);
- dimensional analysis.

Deri,ṙiation of RANS Equations

The basic tool required for the derivation of the RANS equation .. :fro1n the instantaneous Navier- Stoke equations is the *Rgynolds decornposition*. Reynolds deco1nposition ref:ers to eparation of the flow variable (like velocity *u)* into the mean (time-averaged) co1nponent **(U)** and the fluctuating co1nponent (**.[Z]** Thu , *U*)..

$$u(x = \underline{u(x)} + u^{1}(x$$

ill

where,X = x Y z is the position vector.

The following ru les will be useful while deriving the RANS. Iff,andg are two flow variables (like density (p) veloc ity *(u)*, pressure *(p)* etc.) and s is one of the independent variables (x; *z*, or *t)* then

$$f = \bar{f}$$

$$\overline{f+g} - \bar{f} + \underline{g}$$

$$\bar{J}g = \bar{J}\underline{g}$$

$$J g =\!\!|\!\!= \underline{fg}$$

$$\overline{lJJ/\partial s} = \frac{\overline{8f}}{\partial s}$$

Kinetic Energy Budgets

$$KE = \frac{1}{2}\mathbf{u}.\mathbf{u} \tag{3.3}$$

$$\text{KE of mean or large-scale flow} = KE_{mean} = \frac{1}{2}\overline{\mathbf{U}}.\overline{\mathbf{U}} \tag{3.4}$$

$$\text{KE of turbulent or fluctuating flow} = KE_{turb} = \frac{1}{2}\overline{\mathbf{u}'.\mathbf{u}'} \tag{3.5}$$

KE of the mean flow, x component

We begin with the Boussinesq equations, to derive equations for the evolution of KE_{mean}. Consider the portion due to each velocity component separately. In the x-direction, multiply the evolution equation for $\overline{U}$ by $\overline{U}$:

$$\frac{\partial}{\partial t}\left(\frac{\overline{U}^2}{2}\right) + \overline{\overline{U}\overline{\mathbf{U}}.\nabla\overline{U}} + \overline{\overline{U}\mathbf{u}'.\nabla u'} = -\frac{\overline{U}}{\rho_0}\frac{\partial\overline{P}}{\partial x} + \nu\overline{U}\nabla^2\overline{U} + f\overline{U}\overline{V} \tag{3.6}$$

Now $\overline{U}(\overline{\mathbf{U}}.\nabla\overline{U}) = \overline{\mathbf{U}}.\nabla(\overline{U}^2/2)$;
$\overline{U}\overline{(\mathbf{u}'.\nabla u')} = \nabla.(\overline{\mathbf{u}'u'}\overline{U}) - \overline{u'\mathbf{u}'}.\nabla\overline{U}$
and $\overline{U}\nabla^2\overline{U} = \nabla^2(\overline{U}^2/2) - \nabla\overline{U}.\nabla\overline{U}$.

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{U}^2}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial x}(\overline{PU}) + \nu\nabla^2(\frac{\overline{U}^2}{2}) - \nabla.(\overline{\mathbf{u}'u'U})$$
$$-\nu\nabla\overline{U}.\nabla\overline{U} + \overline{\mathbf{u}'u'}.\nabla U$$
$$+f\overline{UV} + \frac{\overline{P}}{\rho_0}\frac{\partial \overline{U}}{\partial x} \quad (3.7)$$

The first three terms on the right hand side describe redistribution of mean KE within the volume:

$-\frac{1}{\rho_0}\frac{\partial}{\partial x}(\overline{PU})$: pressure work

$\nu\nabla^2(\frac{\overline{U}^2}{2})$: transport by viscous stresses

$-\nabla.(\overline{\mathbf{u}'u'U})$: transport by Reynolds stresses.

When integrated over a volume with no flux of KE in or out, these terms are zero.

The 4th and 5th terms represent net sources/sinks of mean KE:

$-\nu\nabla\overline{U}.\nabla\overline{U}$: loss of KE to dissipation;

$\overline{\mathbf{u}'u'}.\nabla U$: transfer of mean KE to the fluctuating/turbulent part of the flow.

The 6th and 7th terms represent transfer of kinetic energy from the $\overline{U}$-component of the flow to the $\overline{V}$- and $\overline{W}$- components.

Kinetic energy of the mean flow, y and z components

We can write down similar equations for the time-evolution of $\overline{V}^2$ and $\overline{W}^2$:

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{V}^2}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial y}(\overline{PV}) + \nu\nabla^2(\frac{\overline{V}^2}{2}) - \nabla.(\overline{\mathbf{u}'v'}\overline{V})$$
$$-\nu\nabla\overline{V}.\nabla\overline{V} + \overline{\mathbf{u}'v'}.\nabla\overline{V}$$
$$-f\overline{UV} + \frac{\overline{P}}{\rho_0}\frac{\partial\overline{V}}{\partial y} \tag{3.8}$$

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{W}^2}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}(\overline{PW}) + \nu\nabla^2(\frac{\overline{W}^2}{2}) - \nabla.(\overline{\mathbf{u}'w'}\overline{W})$$
$$-\nu\nabla\overline{W}.\nabla\overline{W} + \overline{\mathbf{u}'w'}.\nabla\overline{W}$$
$$+\overline{Wb} + \frac{\overline{P}}{\rho_0}\frac{\partial\overline{W}}{\partial z} \tag{3.9}$$

The $\overline{V}^2$ equation contains terms analogous to the $\overline{U}^2$ equation, while the $\overline{W}^2$ equation lacks the coriolis term (since we have assumed Coriolis is aligned with the vertical), but includes a buoyancy term, through which large scale potential energy is converted to kinetic energy.

Kinetic energy of the mean flow

If we sum these three equations, to obtain the evolution equation for $1/2\overline{\mathbf{U}}.\overline{\mathbf{U}}$, and rewrite it in Einstein notation, we have

$$\left(\frac{\partial}{\partial t}+\overline{U}_j\frac{\partial}{\partial x_j}\right)\frac{\overline{U}_i^2}{2}=\frac{\partial}{\partial x_j}\left(-\frac{\overline{P}}{\rho_0}\overline{U}_j\delta_{i,j}+\nu\frac{\partial}{\partial x_j}\frac{\overline{U}_i^2}{2}-\overline{u_j'u_i'}\overline{U}_i\right)$$
$$-\nu\left(\frac{\partial\overline{U}_i}{\partial x_j}\right)^2+\overline{u_j'u_i'}\frac{\partial}{\partial x_j}\overline{U}_i+\overline{W}\overline{b} \qquad (3.10)$$

where the first three terms on the right hand side are once again the transport terms: pressure work, transport by viscous stresses and transport by Reynolds stresses. The 4th term is again the dissipation, and the 5th term represents the transfer of kinetic energy between the mean flow and the turbulent fluctuating flow. This term is known as the Shear production term, since the shear in the mean flow (finite gradients in $\overline{U}_i$) leads to production of turbulent kinetic energy. The final term on the right hand side is the large-scale buoyancy production term.

Note that the terms $\overline{P}/\rho_0\partial\overline{U}_i/\partial x_i$, which transfer kinetic energy between the different components of the flow $\overline{U},\overline{V},\overline{W}$ vanish from the equation for the total, due to the divergence relation $\nabla.\mathbf{U}=0$. The Coriolis term similarly does not influence the total kinetic energy, but only its transfer between $\overline{U}$ and $\overline{V}$ components.

Turbulent Kinetic Energy (kinetic energy of fluctuations), x component

To find the evolution equation for the x-component of the turbulent kinetic energy (TKE) multiply $\partial u'/\partial t = \partial U/\partial t - \partial \overline{U}/\partial t$ by u' and take the spatial average:

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{u'^2}}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial x}\overline{u'p'} + \nu\nabla^2\frac{\overline{u'^2}}{2} - \nabla.\left(\frac{\overline{\mathbf{u}'u'^2}}{2}\right)$$
$$-\nu\overline{\nabla u'.\nabla u'} - \overline{u'\mathbf{u}'.\nabla U}$$
$$+f\overline{u'v'} + \frac{1}{\rho_0}\overline{p'\frac{\partial u'}{\partial x}} \tag{3.11}$$

Comparing with the equation for $\overline{U}^2/2$ we see that once again, there are three transport terms: pressure work, transport by viscous stresses and transport by Reynolds stresses, and loss of TKE to dissipation. The shear production terms appears once again, but with the opposite sign to that in eqn 3.7 - hence this term represents no net loss of KE but a transfer between mean and turbulent components.

Turbulent Kinetic Energy (kinetic energy of fluctuations), y and z.

The analogous equations for $\overline{v'^2}$ and $\overline{w'^2}$ are:

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{v'^2}}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial y}\overline{v'p'} + \nu\nabla^2\frac{\overline{v'^2}}{2} - \nabla.\left(\frac{\overline{\mathbf{u}'v'^2}}{2}\right) - \nu\overline{\nabla v'.\nabla v'} - \overline{v'\mathbf{u}'}.\nabla\overline{V} - f\overline{u'v'} + \frac{1}{\rho_0}\overline{p'\frac{\partial v'}{\partial y}} \tag{3.12}$$

$$\left(\frac{\partial}{\partial t} + \overline{\mathbf{U}}.\nabla\right)\frac{\overline{w'^2}}{2} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}\overline{w'p'} + \nu\nabla^2\frac{\overline{w'^2}}{2} - \nabla.\left(\frac{\overline{\mathbf{u}'w'^2}}{2}\right) - \nu\overline{\nabla w'.\nabla w'} - \overline{w'\mathbf{u}'}.\nabla\overline{W} + \overline{w'b'} + \frac{1}{\rho_0}\overline{p'\frac{\partial w'}{\partial z}} \tag{3.13}$$

The $\overline{w'^2}$ equation contains an additional term: the buoyant production of kinetic energy, representing conversion from potential to kinetic energy.

Turbulent Kinetic Energy (TKE) equation

Adding the contributions due to the 3 velocity components and rewriting in Einstein notation we have

$$\left(\frac{\partial}{\partial t} + \overline{U}_j \frac{\partial}{\partial x_j}\right) \frac{\overline{u_i'^2}}{2} = \frac{\partial}{\partial x_j}\left(-\frac{1}{\rho_0}\overline{u_i' p'}\delta_{ij} + \nu \frac{\partial}{\partial x_j}\frac{\overline{u_i'^2}}{2} - \overline{u_j' u_i' u_i'}\right)$$
$$-\nu \overline{\left(\frac{\partial u_i'}{\partial x_j}\right)} - \overline{u_j' u_i'} \frac{\partial}{\partial x_j}\overline{U}_i + \overline{b' w'} \qquad (3.14)$$

Hence TKE is generated by (a) shear production,

$$P = -\overline{u_j' u_i'} \frac{\partial}{\partial x_j}\overline{U}_i \qquad (3.15)$$

and (b) buoyant production

$$B = \overline{b' w'} \qquad (3.16)$$

and lost through dissipation

$$\epsilon = \nu \overline{\left(\frac{\partial u_i'}{\partial x_j}\right)^2} \qquad (3.17)$$

The buoyant production term may be either positive (generation of kinetic energy, loss of potential energy) or negative (loss of KE, increase in PE).

Stationary turbulence

Now we see the importance of turbulence to the total energy of the system. The viscous terms in the KE of the mean flow can be quite small, so that most KE loss from the mean flow might be due to transfer to the turbulence via the shear production term. Then once in the turbulent regime the KE may either be dissipated, or converted to potential energy via the buoyancy term.

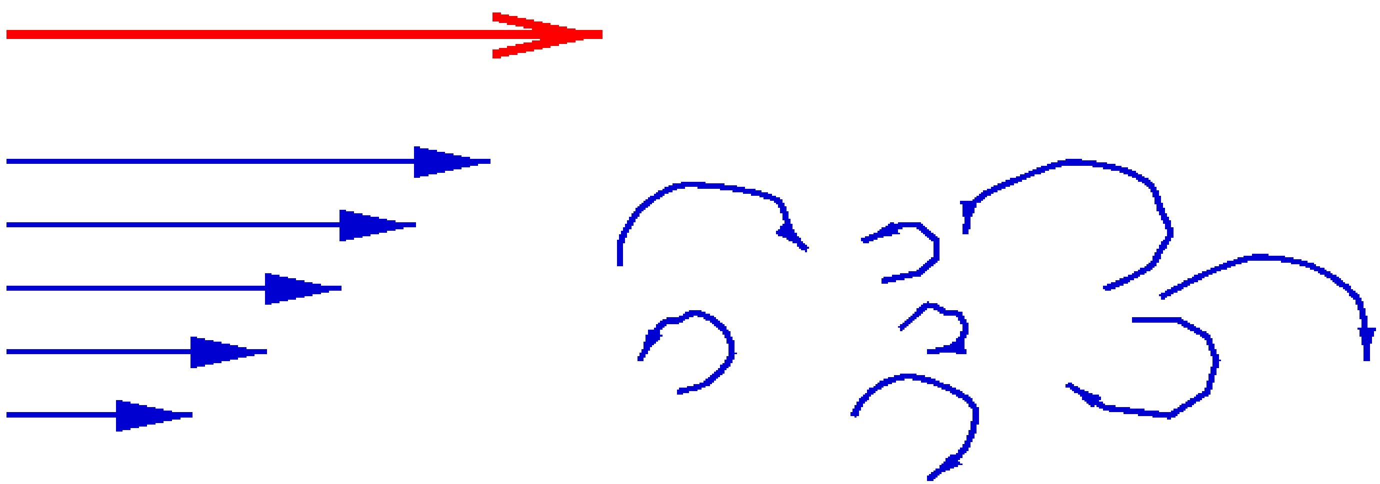
Note that the TKE equations are far from isotropic. Shear production reflects any isotropy in the mean flow, while buoyant production appears only in the $\overline{w'^2}$ equation. The pressure interaction terms (and coriolis terms) transfer the TKE between different velocity components.

If (a) the Turbulence is stationary $(D/Dt(KE) = 0)$, and (b) we integrate over a volume bounded by surfaces through which there are no energy fluxes, then there is a balance between production and dissipation of TKE:

$$P + B = \epsilon \qquad (3.18)$$

Pure Shear flow

If the large-scale flow consists of a pure shear flow of the form $(U, V, W) = (U(z), 0, 0)$ with no buoyancy forcing, then the TKE shear production term becomes $\overline{u'w'}\partial \overline{U}/\partial z$, and it appears only in the $\overline{u'^2}$ equation. Hence the large-scale flow directly generates TKE only in the x-direction. $\overline{v'^2}$ and $\overline{w'^2}$ are then generated by transfer of TKE from the x-direction via the pressure interaction terms.

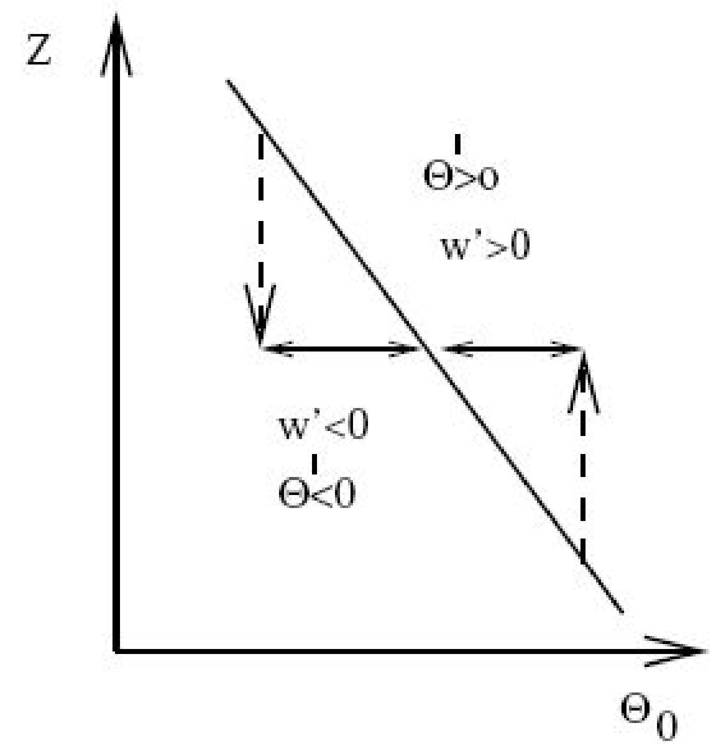


Pure convective flow

If there is no large-scale flow, and turbulence is generated entirely through buoyancy forcing, $P = 0$. The source of TKE is $\overline{w'b'}$, and TKE is directly generated only in the z-direction. Again, $\overline{u'^2}$ and $\overline{v'^2}$ are then generated by transfer of TKE via the pressure interaction terms.

BPL - produkcja lub ubytek wskutek sił wyporu

$BPL = \overline{(w'\Theta')}(\frac{g}{\theta_0})$



For turbulence to be isotropic: (a) Coriolis and buoyancy must be unimportant and therefore neglected (b) There must be no large-scale shear in any direction. If turbulence is homogeneous, then there are no spatial gradients in any averaged quantities. Hence for isotropic, homogeneous turbulence, the kinetic energy equation reduces to:

$$\frac{\partial}{\partial t}\frac{\overline{u_i'^2}}{2} = -\nu\overline{\left(\frac{\partial u_i'}{\partial x_j}\right)^2} \tag{4.1}$$

or

$$\frac{d}{dt}E = -\epsilon \tag{4.2}$$

Turbulent kinetic energy E is therefore a conserved quantity of the motion, known as a **quadratic invariant**. The variance of a passive tracer is another quadratic invariant: e.g.

$$\frac{d}{dt}\frac{\overline{T'^2}}{2} = -\kappa\overline{\nabla T'.\nabla T'} \tag{4.3}$$

TKE changes only by viscous dissipation. Of course this in unsustainable - a source of kinetic energy is needed. TKE sources (shear production, buoyant production) are NOT isotropic and homogeneous. We sidestep this contradiction by assuming that for large Reynolds numbers, although isotropy and homogeneity are violated by the mechanism producing the turbulence, they still hold at small scales and away from boundaries. Then the turbulence production can be represented simply by a forcing term F, assumed to be isotropic and homogeneous:

$$\frac{d}{dt}E = -\epsilon + F \tag{4.4}$$

TKE changes

TKE dissipation

TKE production

In stationary turbulence production is balanced by dissipation

Turbulent Kinetic Energy, second order moments – phenomenology

Adding the contributions due to the 3 velocity components and rewriting in Einstein notation we have

$$\left(\frac{\partial}{\partial t} + \overline{U}_j \frac{\partial}{\partial x_j}\right)\frac{\overline{u_i'^2}}{2} = \frac{\partial}{\partial x_j}\left(-\frac{1}{\rho_0}\overline{u_i' p'}\delta_{ij} + \nu\frac{\partial}{\partial x_j}\frac{\overline{u_i'^2}}{2} - \overline{u_j' u_i' u_i'}\right)$$

Transport

$$-\nu\overline{\left(\frac{\partial u_i'}{\partial x_j}\right)^2} - \overline{u_j' u_i'}\frac{\partial}{\partial x_j}\overline{U}_i + \overline{b'w'} \qquad (3.14)$$

Hence TKE is generated by (a) shear production,

$$P = -\overline{u_j' u_i'}\frac{\partial}{\partial x_j}\overline{U}_i \qquad (3.15)$$

and (b) buoyant production

$$B = \overline{b'w'} \qquad (3.16)$$

and lost through dissipation

$$\epsilon = \nu\overline{\left(\frac{\partial u_i'}{\partial x_j}\right)^2} \qquad (3.17)$$

The buoyant production term may be either positive (generation of kinetic energy, loss of potential energy) or negative (loss of KE, increase in PE).

Stull's textbook

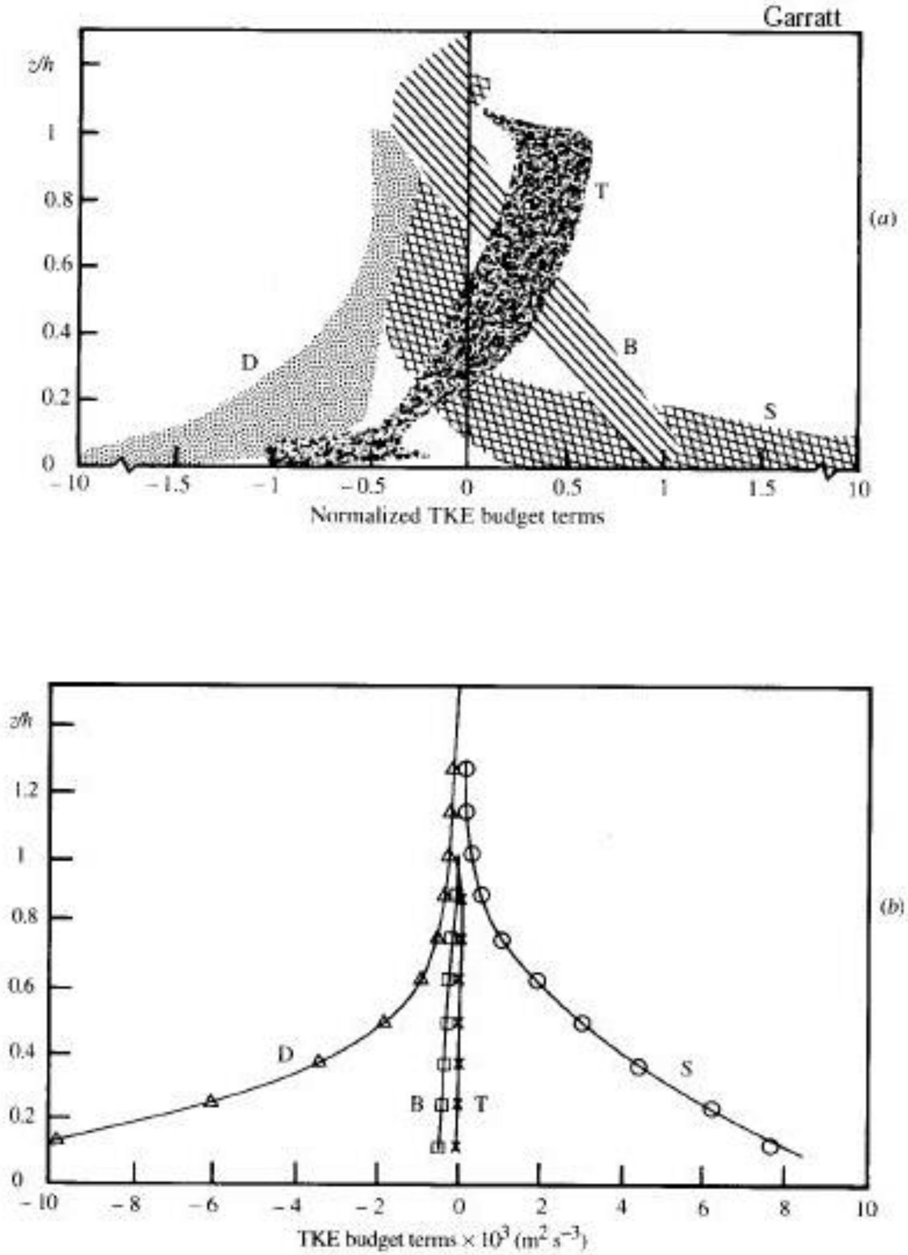


Fig. 2.4 Terms in the TKE equation (2.74b) as a function of height, normalized in the case of the clear daytime ABL (a) through division by w_*^3/h; actual terms are shown in (b) for the clear night-time ABL. Profiles in (a) are based on observations and model simulations as described in Stull (1988; Figure 5.4), and in (b) are from Lenschow *et al.* (1988) based on one aircraft flight. In both, B is the buoyancy term, D is dissipation, S is shear generation and T is the transport term. Reprinted by permission of Kluwer Academic Publishers.

Simplified set of equations of cloud dynamics, thermodynamics and microphysics :

$$D/Dt \equiv \partial/\partial t + \mathbf{v}\cdot\boldsymbol{\nabla}$$

$$B \equiv g\left[\frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v_0}) - q_c\right], \qquad (2)$$

$$\frac{D\mathbf{v}}{Dt} = -\boldsymbol{\nabla}\pi + \mathbf{k}B + \nu\nabla^2\mathbf{v}, \qquad (1a)$$

$$\boldsymbol{\nabla}\cdot\mathbf{v} = 0, \qquad (1b)$$

$$\frac{DT}{Dt} = \frac{L}{c_p}C_d + \mu_T\nabla^2 T, \qquad (1c)$$

$$\frac{Dq_v}{Dt} = -C_d + \mu_v\nabla^2 q_v, \qquad (1d)$$

$$\frac{Dq_c}{Dt} = C_d. \qquad (3)$$

π – normalized pressure fluctuation
C_d – condensation rate
q_v, q_c – specific humidity, liquid water content
B – normalized buoyancy

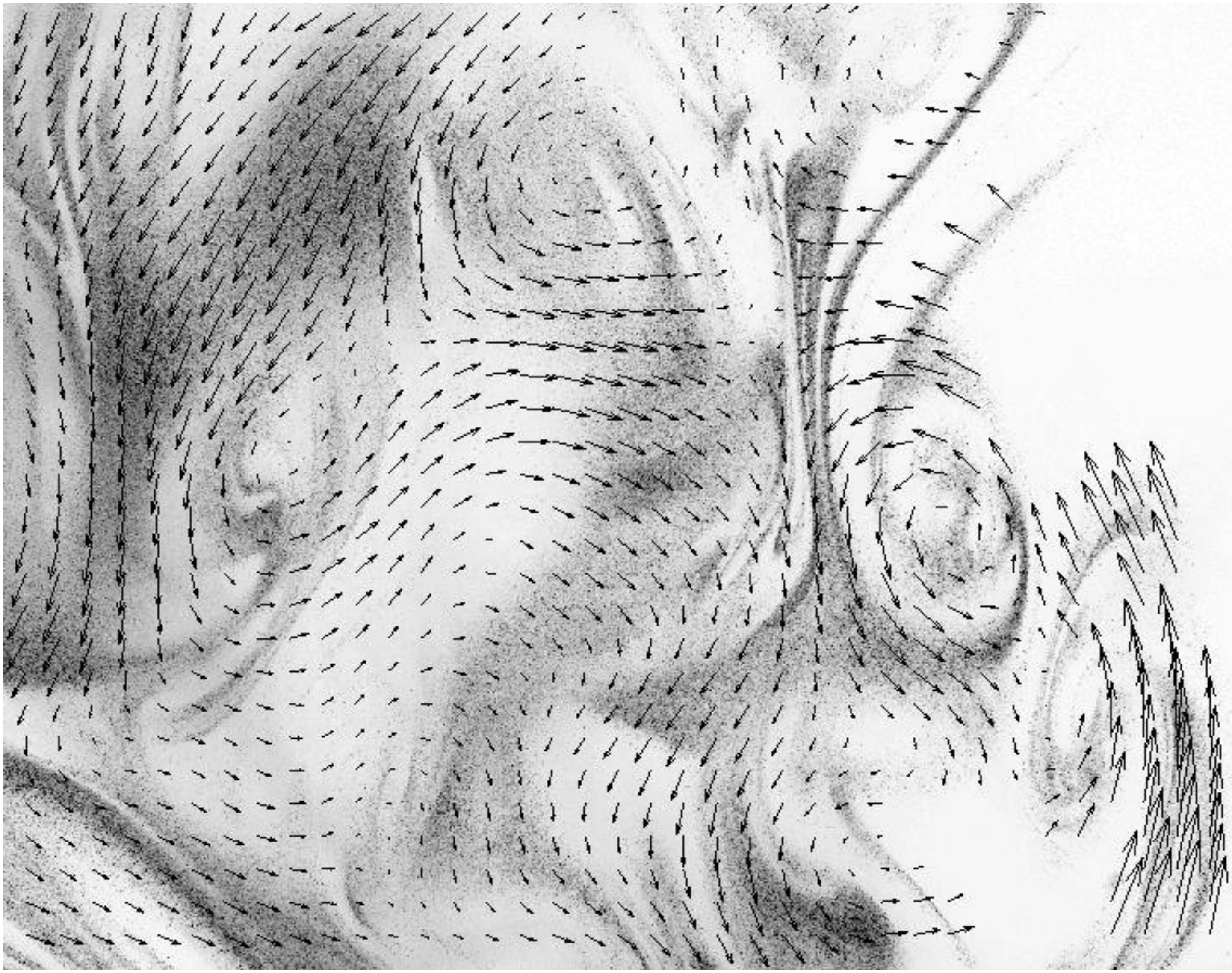
$$C_d = \int f\frac{dm}{dt}\,dr,$$

$$\frac{D^* f}{D^* t} = -\frac{\partial}{\partial r}\left(f\frac{dr}{dt}\right) + \eta,$$

$$D^*/D^*t \equiv \partial/\partial t + (\mathbf{v} - \mathbf{k}v_t)\cdot\boldsymbol{\nabla}$$

$f(\mathbf{x}, r, t)dr$ is the number of cloud droplets in a unit mass of air (viz. the mixing ratio) of the radius between r and $r + dr$, at a given point $(\mathbf{x}, t)$ in space and time.

Andrejczuk et al., 2004, 2006, 2009, Malinowski et al., 2008

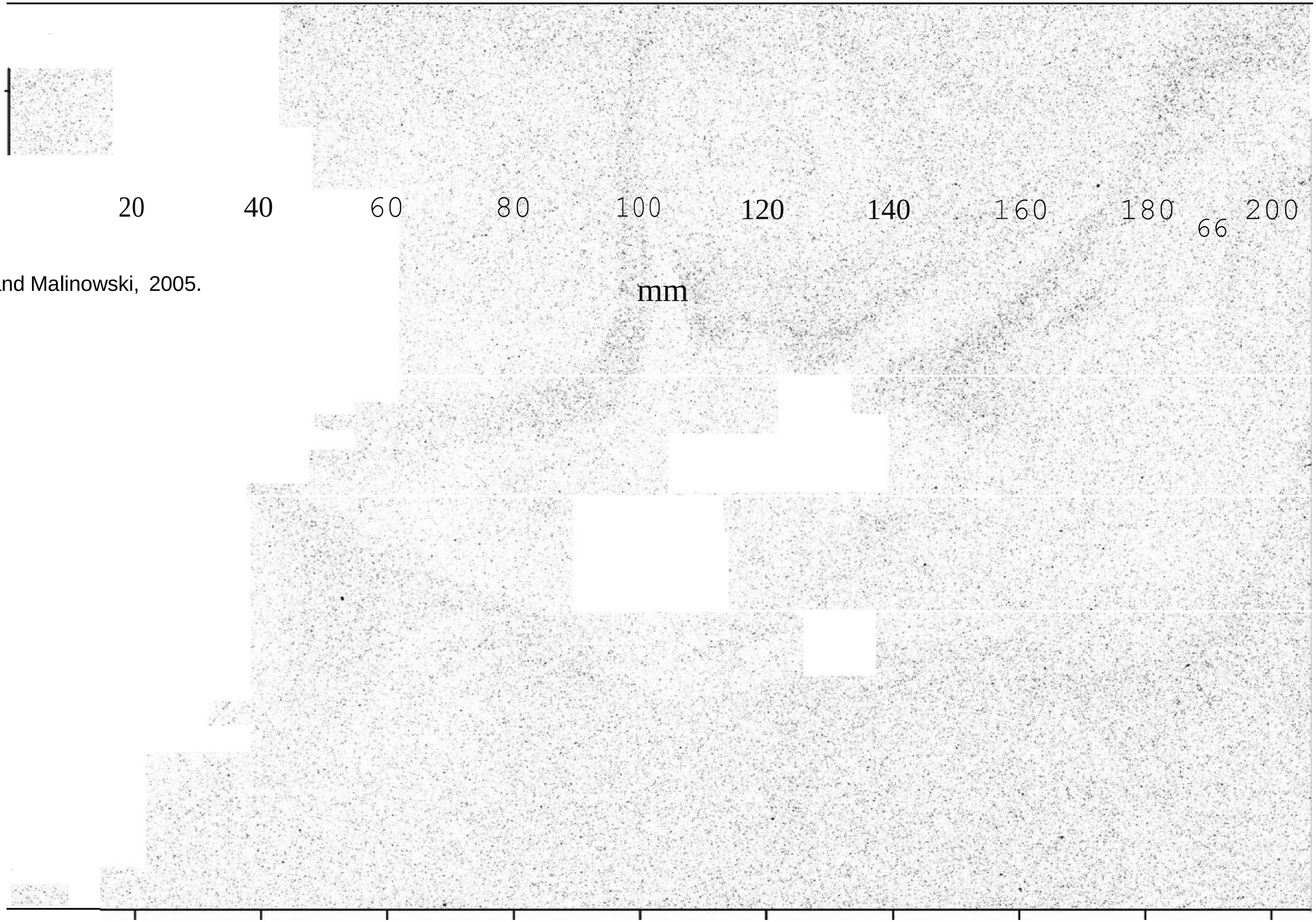


Microphysical effects of small-scale turbulence:

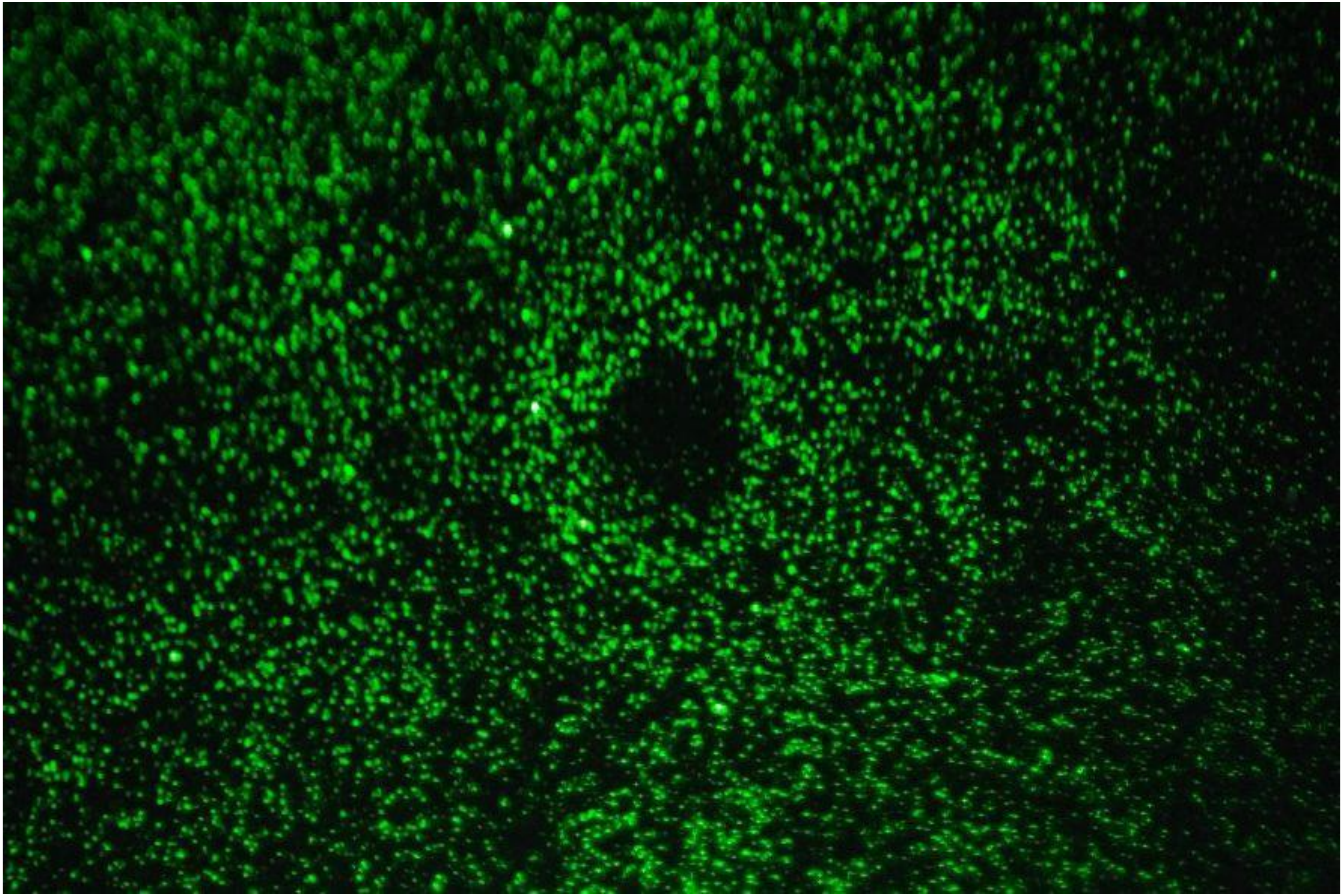
preferential concentration,

homogeneous vs. inhomogeneous mixing.

Preferential concentration weak turbulence in cloud chamber.



Jaczewski and Malinowski, 2005.



First experimental evidence of droplets expelled from vortex tubes in real clouds – Bodenschatz, Xu, Malinowski et al., 2011, Zugspitze cloud campaign – not published yet.

Short summary of clustering and collisions:

Observations of droplet clustering in real clouds remain ambiguous which has led some authors to question its importance in real clouds.

Moreover, DNS of sedimenting droplets has shown that turbulent enhancement of collision rates occurs primarily through changes to the droplet relative velocity and the collision efficiency.

Nevertheless, some argue that the vortex tubes that are associated with small-scale turbulence at high Reynolds numbers persist for long and droplets with a considerable range of St are able to spin out of the vortex.

The importance of intermittency in potentially increasing droplet clustering has also been raised by Falkovich et al. (2002) who based on theoretical arguments claim that clustering can increase collisions by a factor of 10.

Without a clear theoretical basis for the R_λ -dependence of clustering, which will remain valid in the large-R_λ limit, it is likely that these arguments will continue.

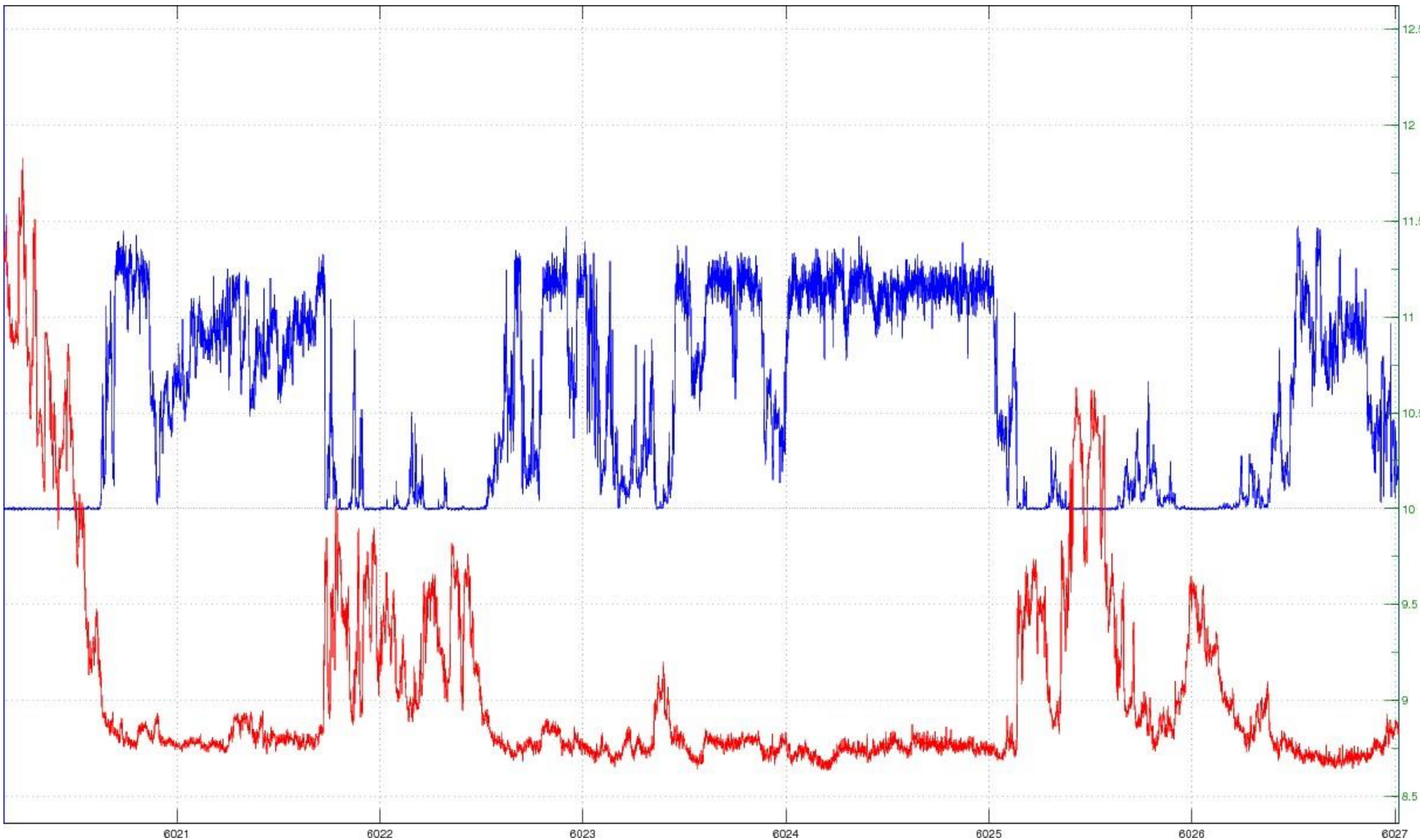
POST – Physics of Stratocumulus Top, California, 2008

aerosol (CCN)

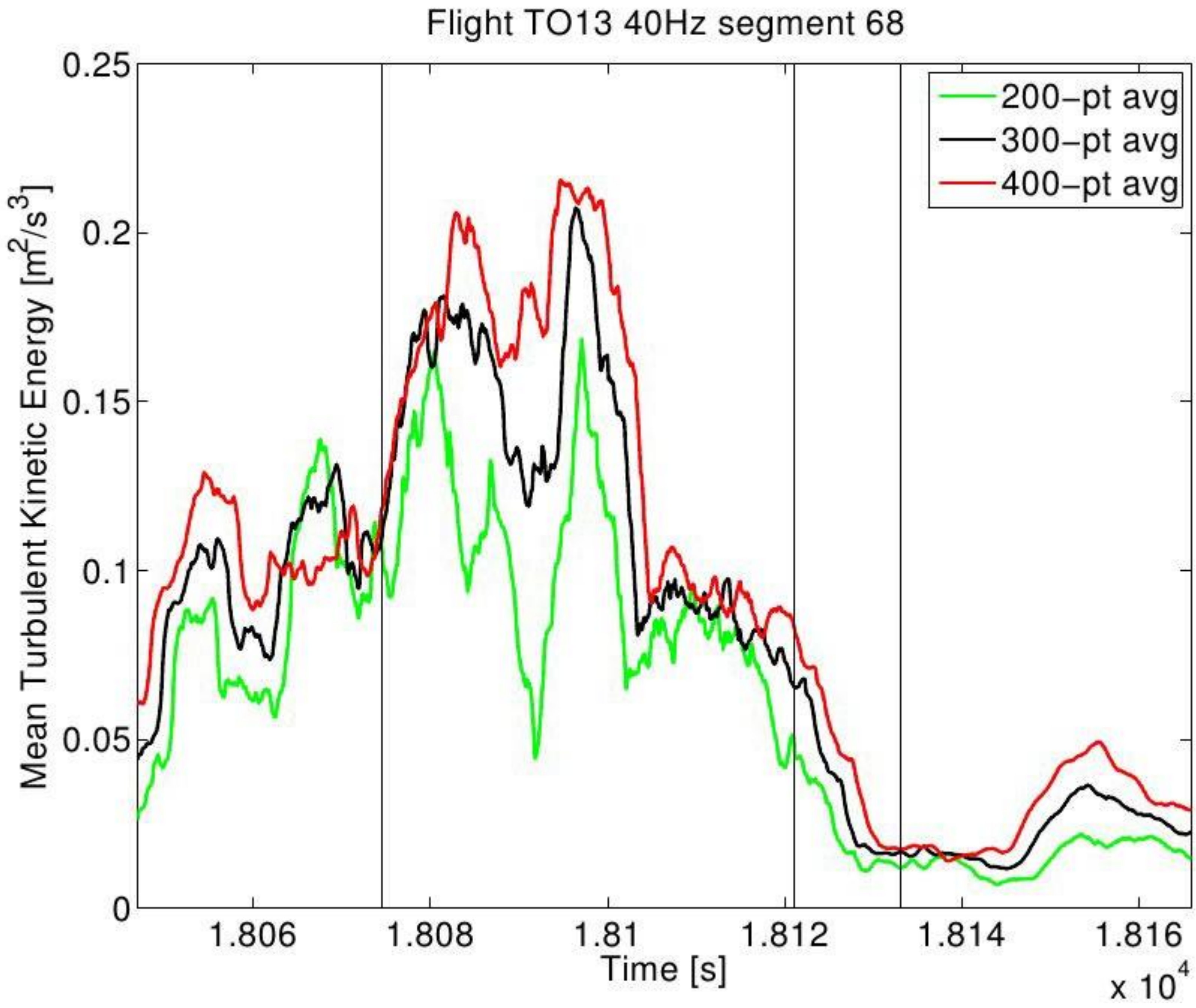
microphysics

temperature,
humidity,
liquid water,
turbulence,

droplet counting



Blue – LWC, red – temperature, spatial resolution – 5 cm, fluctuations on ~350m distance.



Airborne data in clouds: Estimates of TKE depend on averaging!

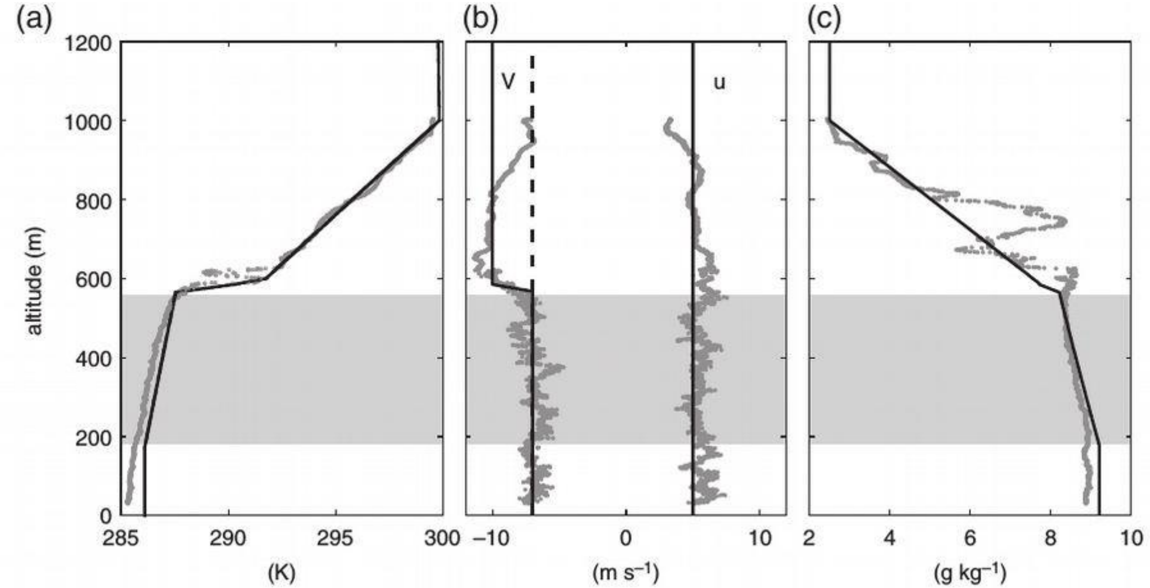
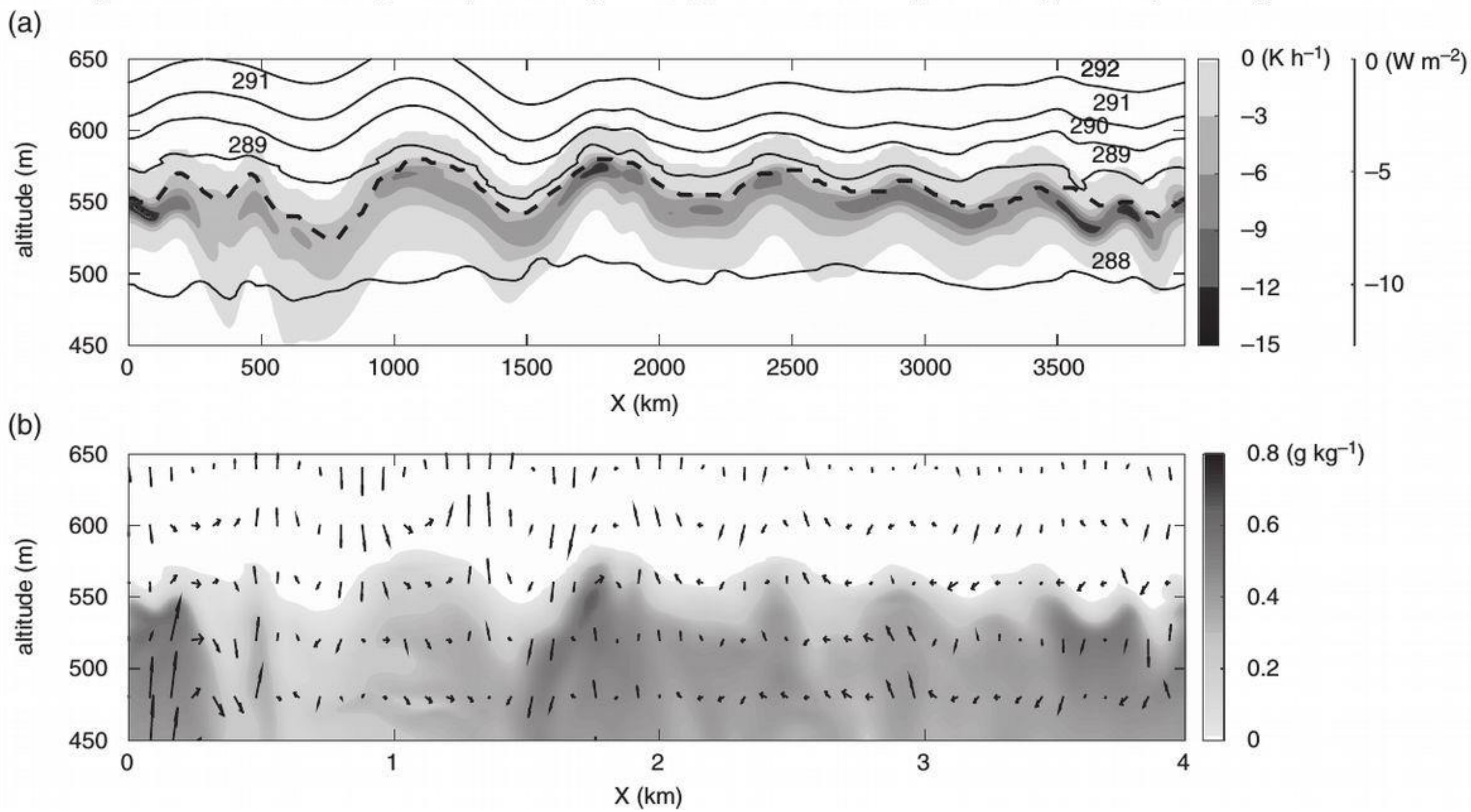


Figure 2. Initial (black lines) and measured (grey lines) profiles. The dashed black line in the central panel marks the initial wind profile for cases without wind shear. Grey boxes indicate the region with cloud water. Panel (a) shows potential temperature, (b) horizontal wind components and (c) water-vapour mixing ratio.



Q. J. R. Meteorol. Soc. 142: 3222–3233, October 2016 B DOI:10.1002/qj.2903

TKE in the stratocumulus topped boundary layer – LES simulations based on the measurements

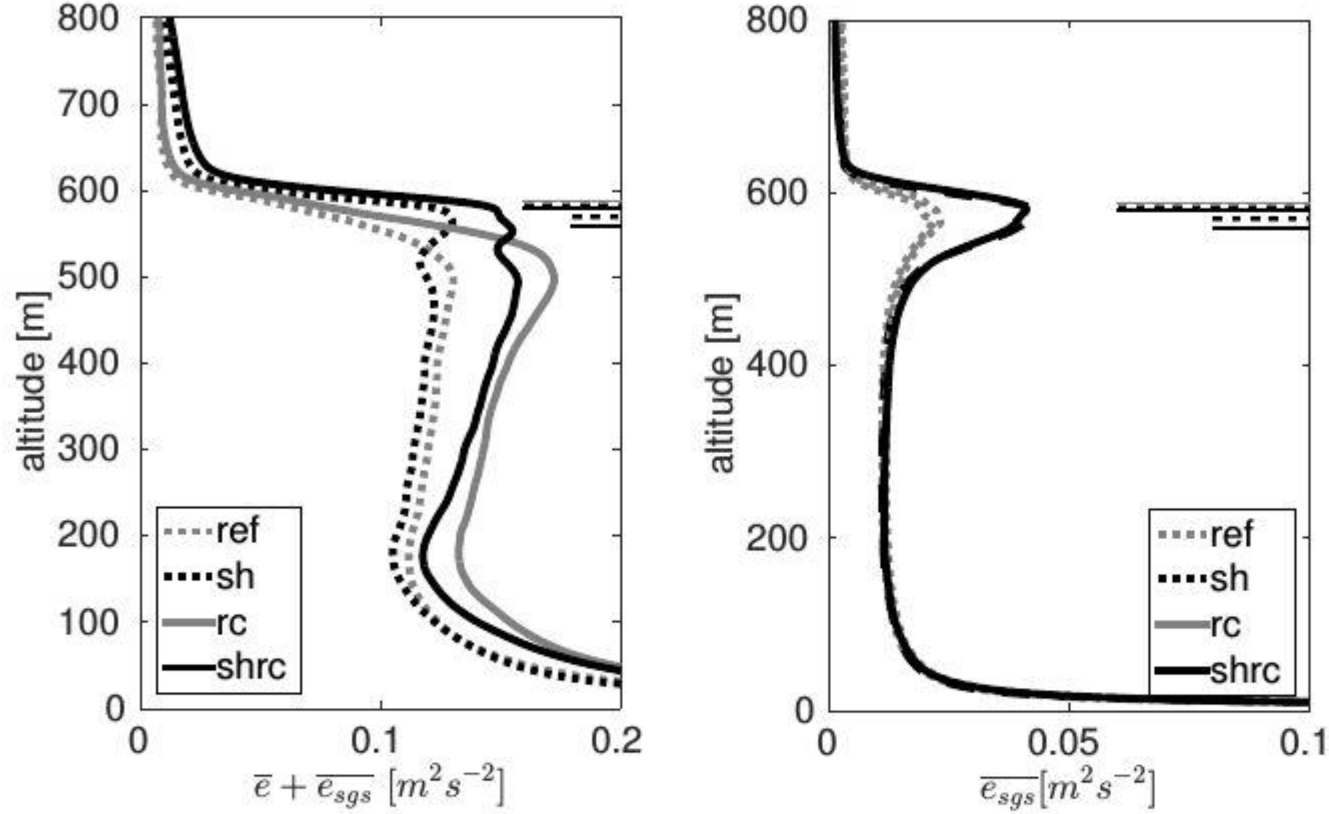


Figure 11. Resolved plus SGS TKE (left panel) and SGS TKE (right panel). The colour code is as in Figure 4. Short horizontal lines indicate cloud top and long horizontal lines marks the level of maximum gradient of liquid water potential temperature.

Comment: shear dominant TKE in the top of STBL allows to undertstand why cloud entrainment instability concept does not work and Sc clouds survive for a long time...

TKE budget in STBL

$$\frac{\partial e}{\partial t} + w\frac{\partial e}{\partial z} = \frac{g}{\theta_v}\overline{w'\theta_v'} - \left(\overline{u'w'}\frac{\partial u}{\partial z} + \overline{v'w'}\frac{\partial v}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} - \varepsilon \qquad (3)$$

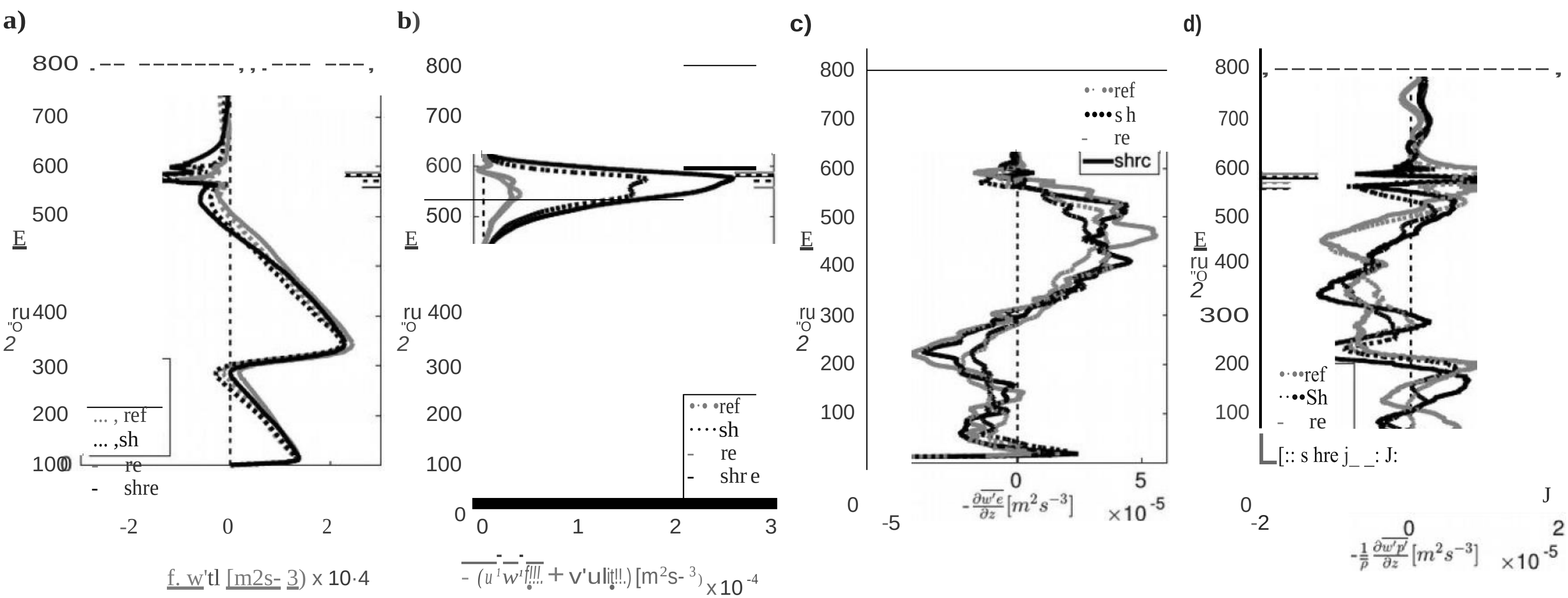
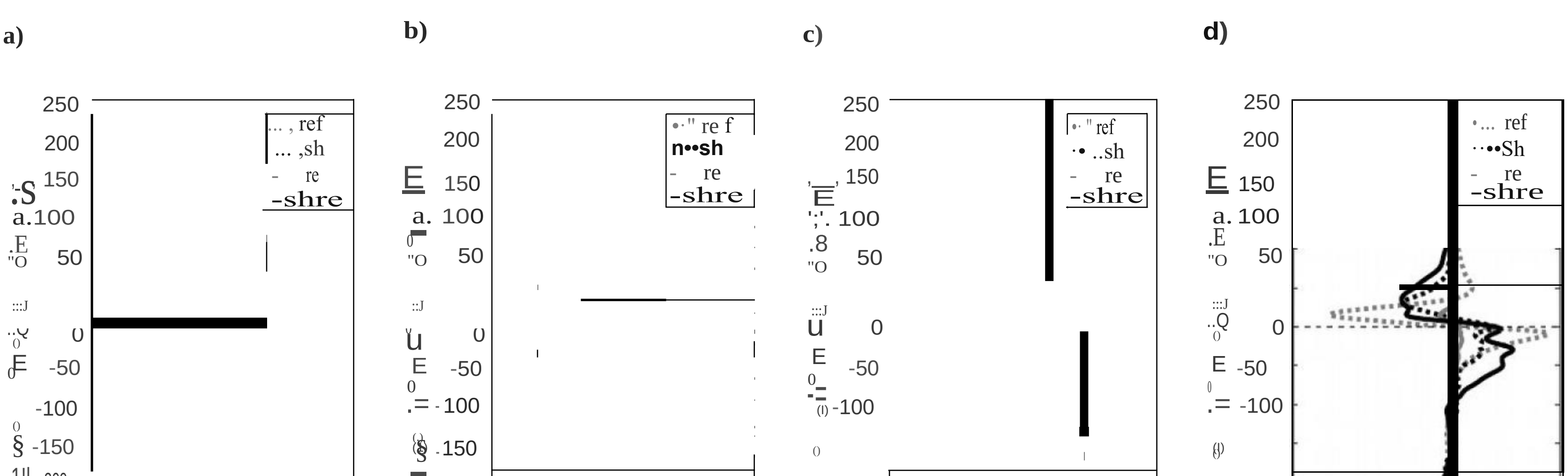


Figure 12. Time-averaged TKE budget te1ms ca lculated for the last hour of the simu latio ns. C olo ur code as in Figure 4. Short horizontal lin es indicate cloud top and lon f hori zontal li nes marks th e leve l of maximum gradient of hquid water potential temperan1re.



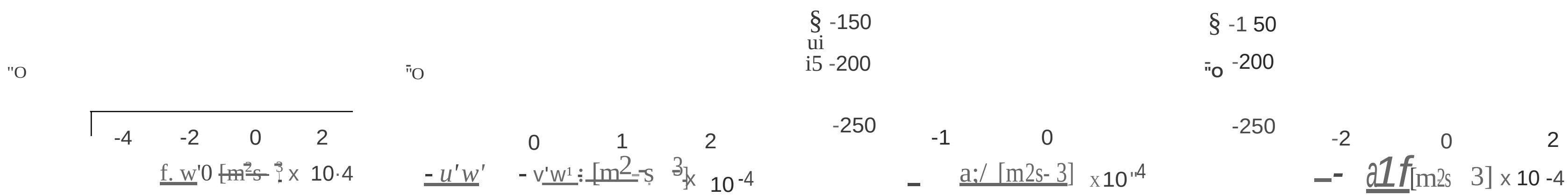
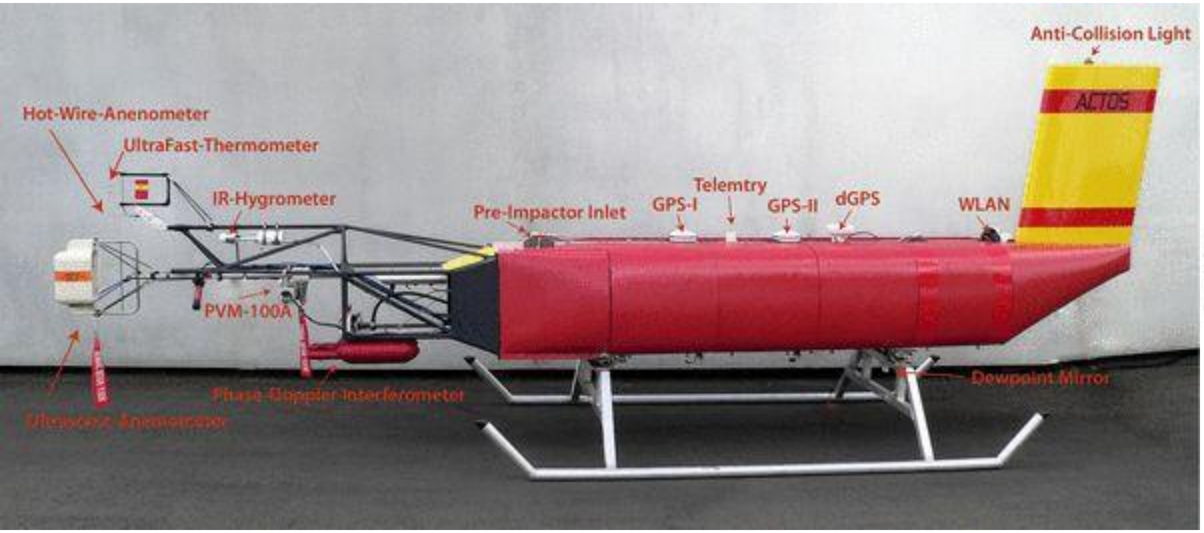


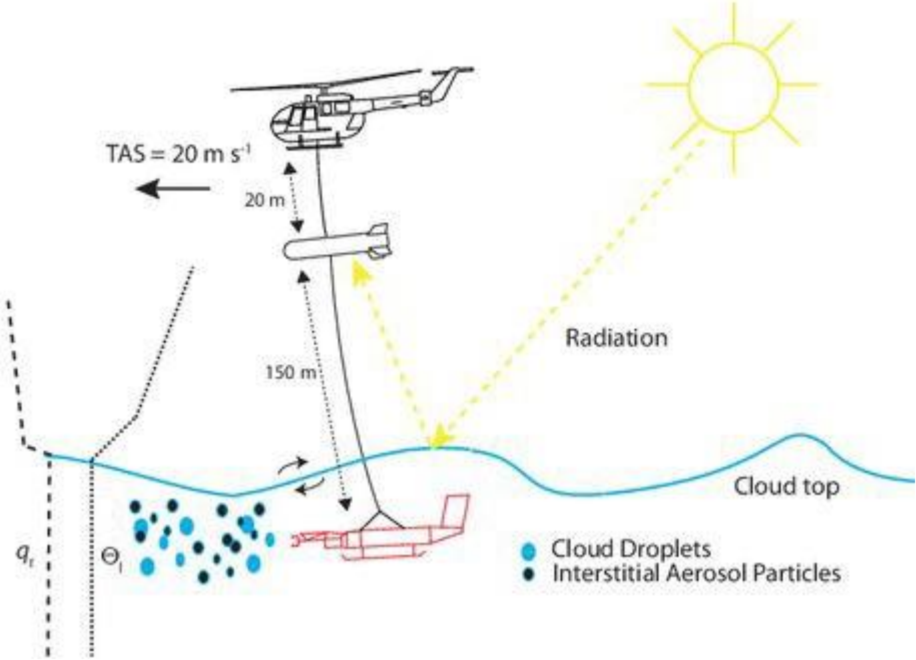
Figure 13. Time-averaged TKE budget terms calculated for the last hour of the simulations and normalised to the cloud top. Colour code as in Figure 4.

Airborne

Cloud Turbulence Observation System

ACTOS





TKE dissipation ate estimated from the balloon-borne measurements.

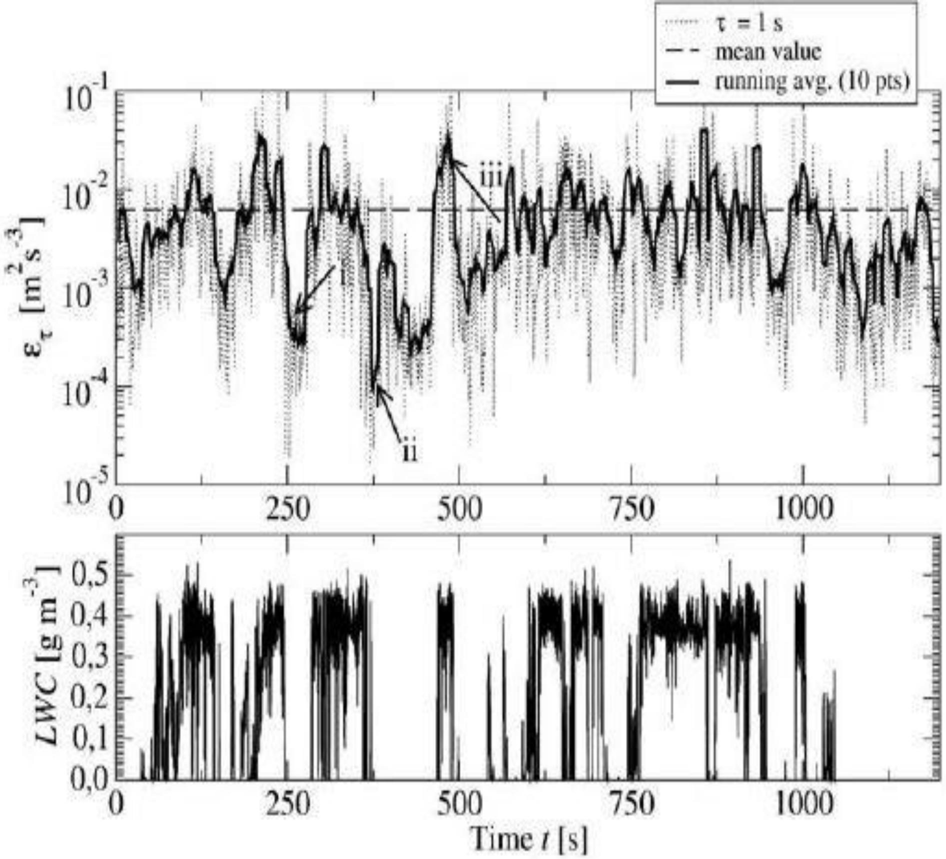


FIG. 8. (top) Time series of local energy dissipation rate ε_τ and (bottom) LWC of BBC2 data. The integration time τ for ε_τ is 1 s; a running average over 10 points is included.

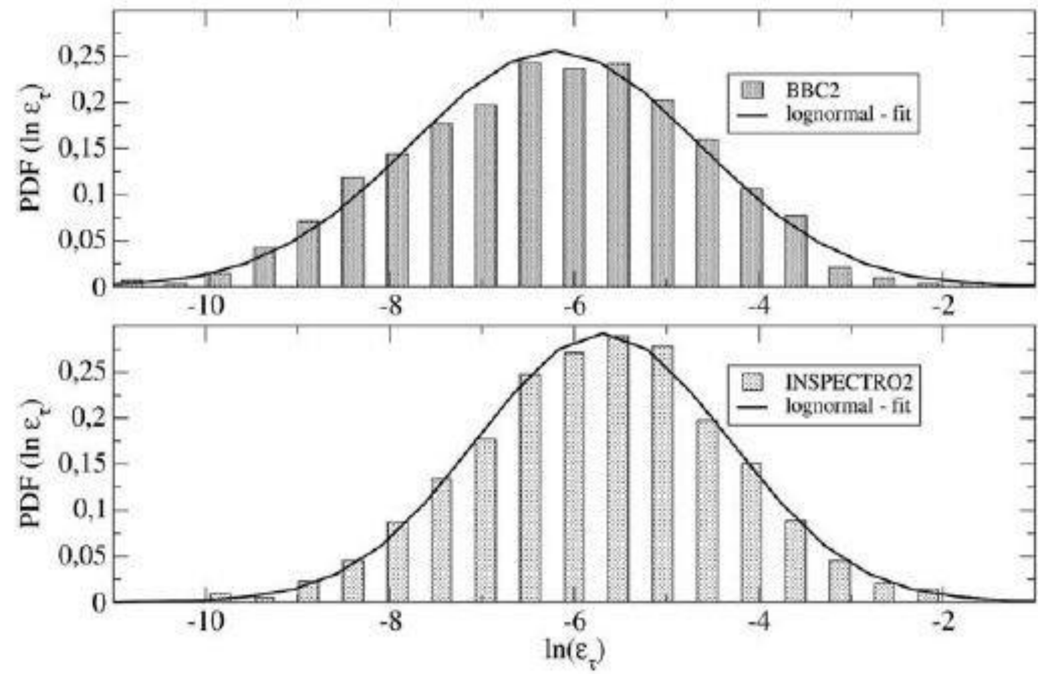


FIG. 11. PDF of natural logarithm of local energy dissipation rates ε_τ. A Gauss fit is included for reference.

The following parameters characterize warm turbulent clouds and give some indication of their variability.

Mean ε, can **vary** from **~10 cm^2s^{-3}** in stratiform clouds to **~2000 cm^2s^{-3}** in cumulonimbus clouds (e.g. Caughey et al., 1982; MacPherson and Isaac, 1977).

R_λ, **varies** from **~5000** in stratiform clouds to **~20,000** in strong deep convective clouds (e.g. Shaw, 2003; Khain et al., 2007);

$\varepsilon \sim 3\ cm^2s^{-3}$ and $R_\lambda \sim 5000$ for stratocumulus (Siebert et al., 2010)

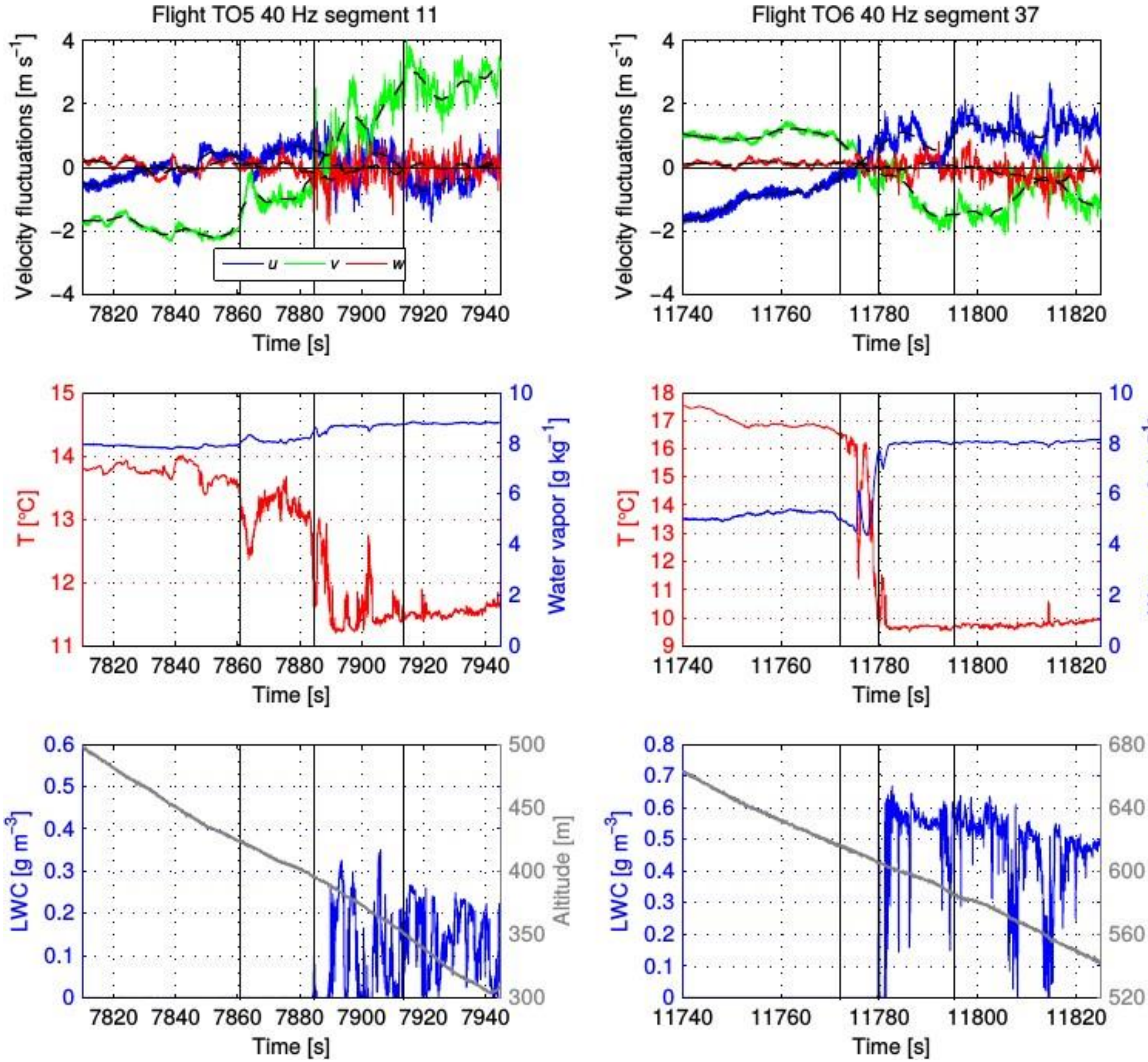
$\varepsilon \approx \sim 30\ cm^2s^{-3}$ and $R_\lambda \sim 4 \times 10^4$ for small cumulus (Siebert et al., 2006).

The **maximum LWC** are in convective clouds with very strong updrafts and not exceed **4–5 g m^{-3}**; **typically** in cumulus **0.1–2 g m^{-3}** depending on the stage of development (Pruppacher and Klett, 1997, §2.1.3).

Most estimates of cloud parameters come from a limited number of measurements at low resolution; only recently (Siebert et al., 2006; Siebert et al., 2010) have higher-resolution ($\sim$20cm) measurements.

Devenish et al., 2011

Stratocumulus top penetrations

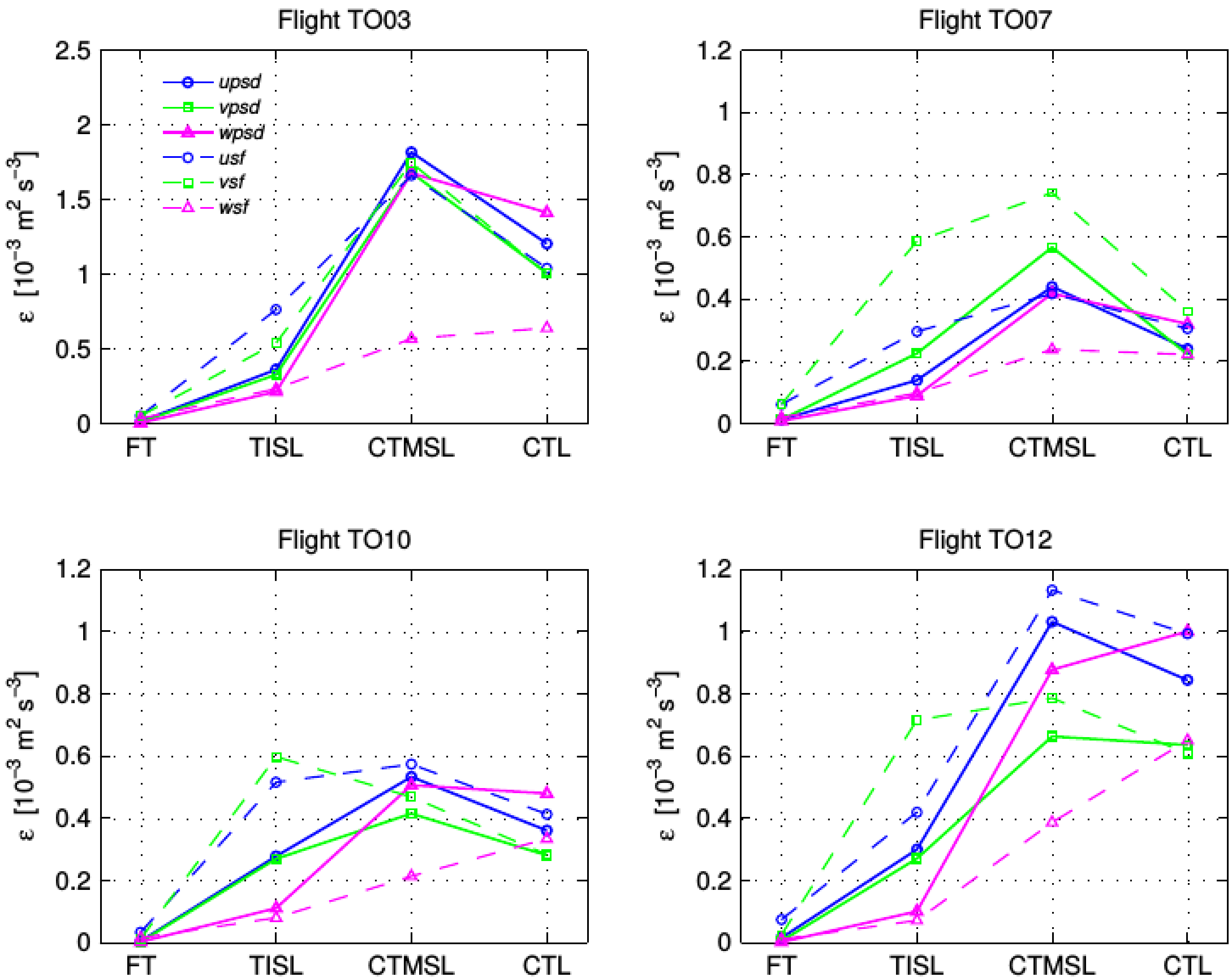


In top panels three components of wind velocity (u, v, w) are presented in blue, green and red.
Thick dashed lines represent centered running averages over 300 data points;
black vertical lines are those resulting from the algorithmic layer division;
layers (from the left): free troposphere (FT), turbulent inversion sublayer (TISL), cloud top mixing sublayer (CTMSL), cloud top layer (CTL).

In the middle panels corresponding temperature and humidity records are shown.

In the lowest panel liquid water content and aircraft altitude are shown.

www.atmos-chem-phys.net/16/9711/2016/
doi:10.5194/acp-16-9711-2016



Estimates of the TKE dissipation rate ε in sublayers for four selected flights.

Continuous lines denote estimates based on the power spectral density, dashed lines indicate estimates from second-order structure functions, and circles, squares and triangles indicate u, v and w velocity fluctuations, respectively.

METEOROLOGY GLOSSARY
AMERICAN METEOROLOGICAL SOCIETY
glossary of meteorology

ENTRAINMENT

1) In meteorology, the mixing of environmental air into a preexisting organized air current
(in our case convective cloud)
so that the environmental air becomes part of the current.

2) The process by which turbulent fluid within a mixed layer
(in our case stratocumulus topped boundary layer)
incorporates adjacent fluid that is nonturbulent, or much less turbulent; thus entrainment always proceeds toward the nonturbulent layer.

Importance of entrainment:

- cloud dilution;
- cloud dissipation and decay;
- evaporative cooling.

Possible influence of entrainment

- cloud dynamics;
- cloud radiative properties;
- precipitation formation.

Indirect effects:
- influence on transport processes within the atmosphere;
- influence on a life cycle of cloud fields;
- key interactions in climate system.

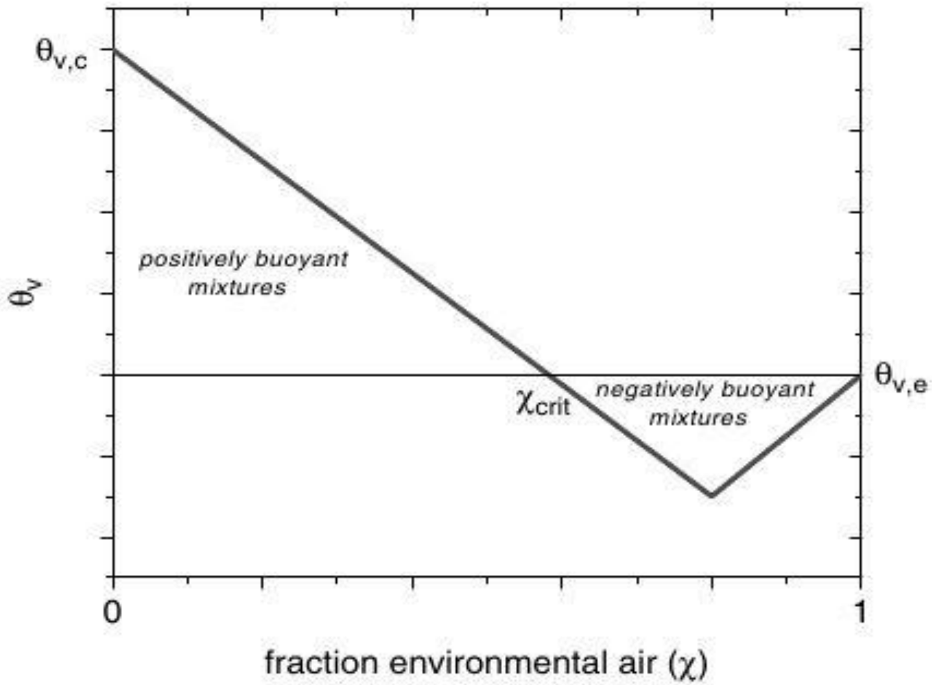


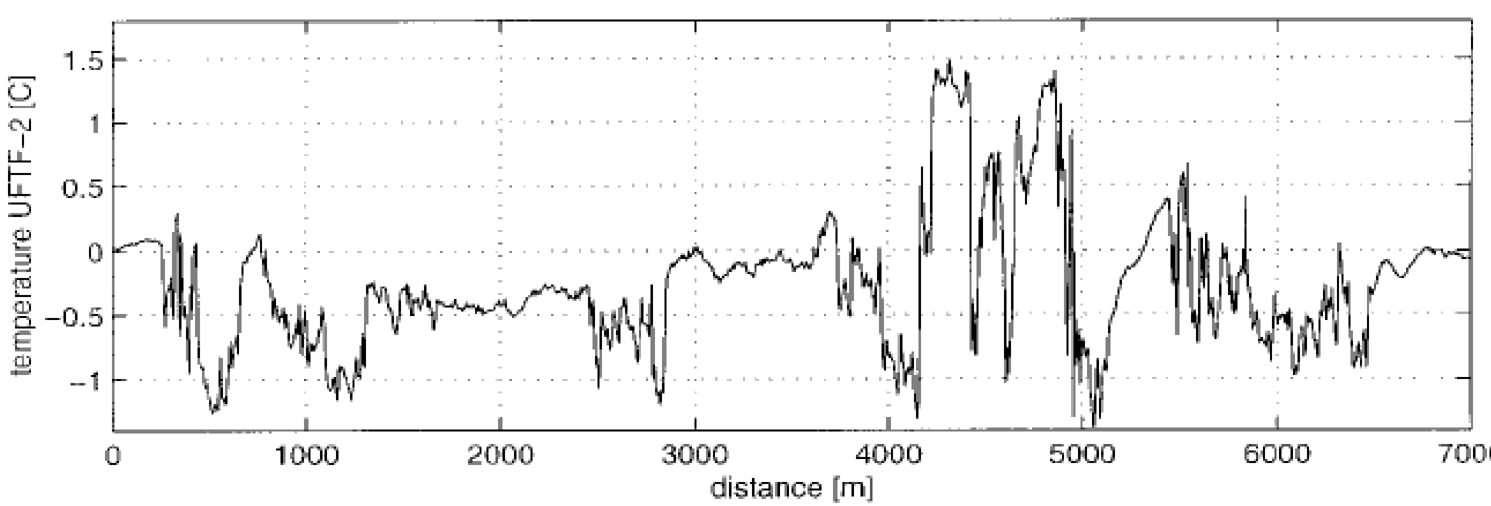
Figure 4. The virtual potential temperature of a mixture of cloudy air with environmental air as a function of the fraction, χ, of environmental air. The virtual potential temperatures of the cloudy and environmental air are θ_{vc} and θ_{ve}, respectively. χ_{crit} is the fraction environmental air necessary to make the cloudy air just neutrally buoyant.

De Rooy et al., 2013, QJRMS

$$B \equiv g\left[\frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v_0}) - q_c\right],$$

Buoyancy reversal possible due to mixing with unsaturated environmental air.

Haman et al., 2001, JAOT



JAS 2008

Subsiding Shells around Shallow Cumulus Clouds

THIJS HEUS AND HARM J. J. JONKER
Department of Multi-Scale Physics, Delft University of Technology, Delft, Netherlands

(Manuscript received 18 October 2006, in final form 5 June 2007)

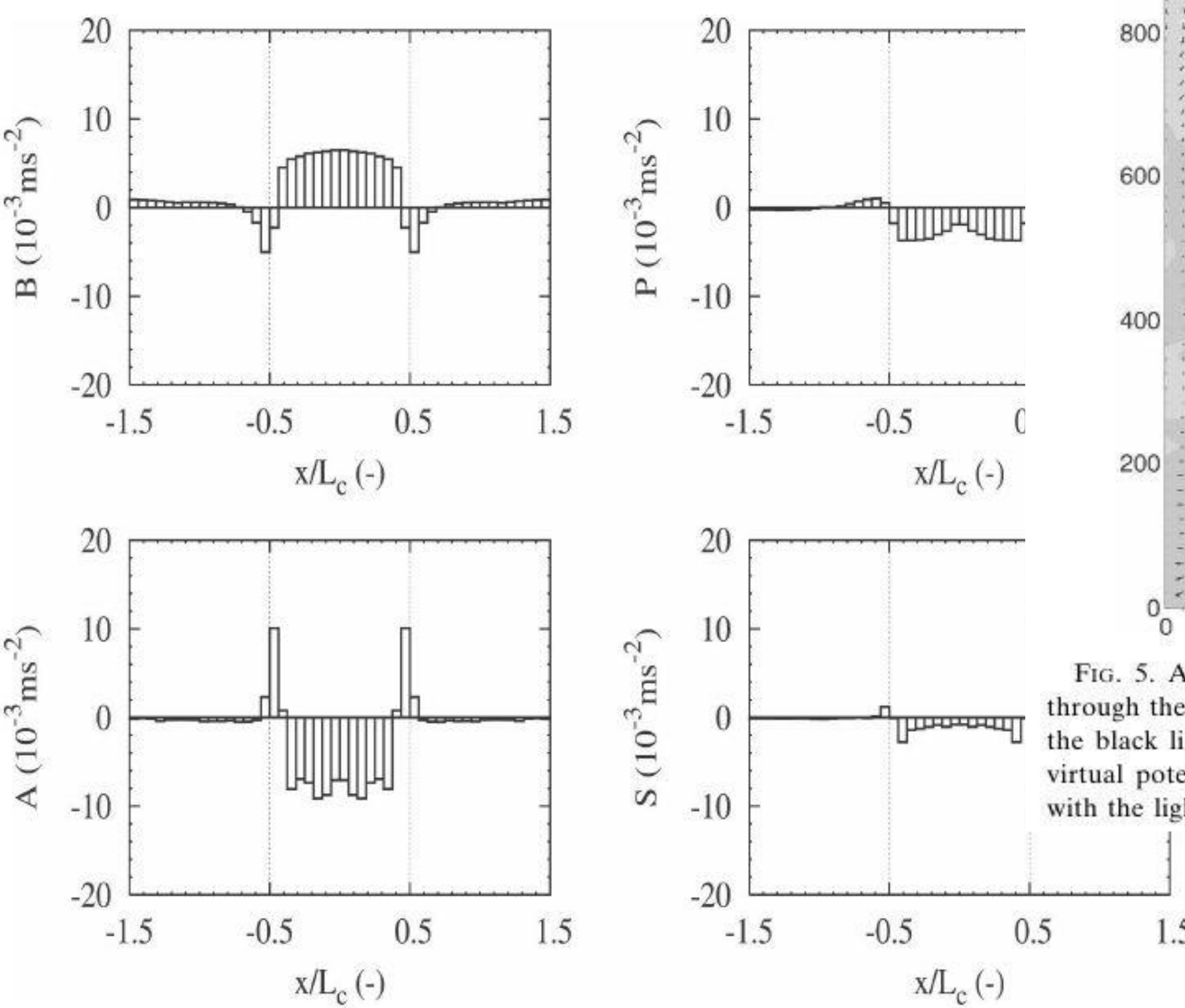


FIG. 2. The individual terms of the vertical momentum Eq. (1): (top left) buoyancy B, (top right) vertical pressure gradient P, (bottom left) advection A, and (bottom right) subgrid diffusion S, plotted against the distance to cloud center x (normalized with cloud size L_c).

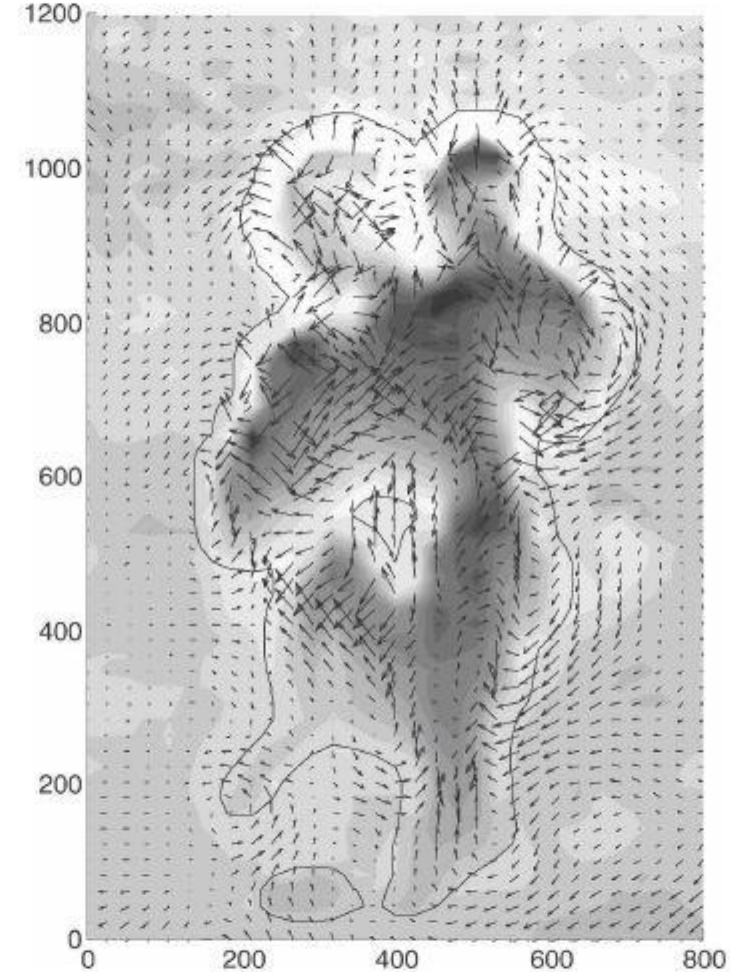
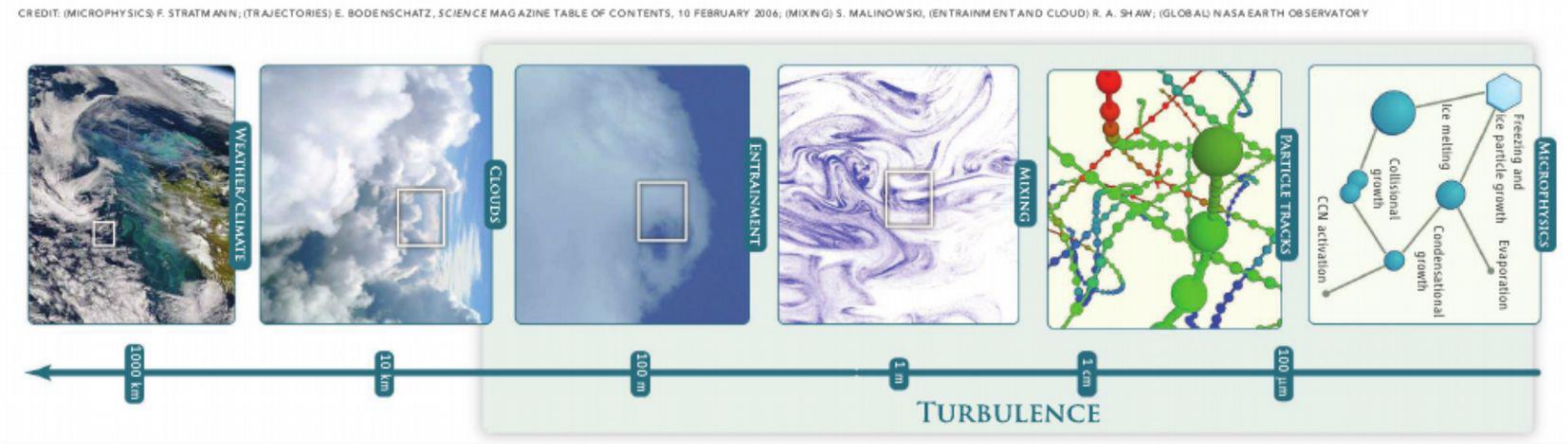


FIG. 5. A y–z plane cross section (with distances in meters) through the center of mass of a cloud. Cloud edge is denoted by the black line, the vectors signify the in-plane velocity, and the virtual potential temperature excess is displayed in gray tones, with the lighter areas more negatively buoyant.

There are “shells” of moist cold air separating Cumulus clouds from their environment.

SUMMARY AND CONCLUSIONS:



Clouds are dispersions of drops and ice particles embedded in and interacting with a complex turbulent flow. They are highly nonstationary, inhomogeneous, and intermittent, and embody an enormous range of spatial and temporal scales. Strong couplings across those scales between turbulent fluid dynamics and microphysical processes are integral to cloud evolution.

Turbulence drives entrainment, stirring, and mixing in clouds, resulting in strong fluctuations in temperature, humidity, aerosol concentration, and cloud particle growth and decay. It couples to phase transition processes (such as nucleation, condensation, and freezing) as well as particle collisions and breakup. All these processes feed back on the turbulent flow by buoyancy and drag forces and affect cloud dynamical processes up to the largest scales.

Bodenschatz et al., Science, 2010.

The last decades have seen the emergence of new views into the "inner workings" of both clouds and turbulent flows.
For example, **high-resolution measurements** of temperature, liquid water content, aerosol physical and chemical properties, and airflow **reveal fascinating small-scale cloud structures,** invisible with earlier technology.

Laboratory experiments and **numerical simulations** are allowing us to study details of cloud microphysics, the **fine structure of turbulence**, turbulent **Lagrangian dynamics**, **interactions and collisions between droplets**.

Scale-resolving simulations merging computational methods from both cloud and turbulence communities are yielding new insights into the wide **variety of circulation regimes**.

These new tools, experimental and computational, have begun to make it possible to explore the full complexity of microphysical and fluid-dynamical interactions within clouds.

We can now begin to address:

¬How does **turbulence influence phase transition processes** like condensation, evaporation, activation, and freezing taking place inside clouds?

¬How does t**urbulence influence particle-particle interactions** like collisions, coalescence efficiencies, ice aggregation, and drop- or ice-breakup?

¬How do **microphysical processes feed back on the turbulence** through latent-heat release, energy injection at small scales, and buoyancy reversal?

¬How do **small scale processes propagate to and couple to the larger scales**, such as, cloud dynamics, precipitation formation, and radiative properties?

Additional readings

1. Textbooks:

Frisch, U.: “Turbulence: The Legacy of A. N. Kolmogorov”, Cambridge University Press, 30 Oct. 1995

Stull, R.B.: “An introduction to Boundary Layer Meteorology”, Springer Science & Business Media, 6 Dec. 2012

Wyngaard, J.C.: “Turbulence in the Atmosphere”, Cambridge University Press, 28 Jan. 2010

2. Papers:

Bodenschatz, E., Malinowski, S. P., Shaw, R. A., and Stratmann, F.: Can we understand clouds without turbulence?, Science, 327, 970–971, doi:10.1126/science.1185138, 2010.

Devenish, B.J., Bartello, P., Brenguier, J.-L., Collins, L.R., Grabowski, W.W., Ijzermans, R.H.A., Malinowski, S.P., Reeks, M.W., Vassilicos, J.C., Wang, L.-P., Warhaft, Z., 2012: Droplet growth in warm turbulent clouds, , Q. J. Roy. Meteorol. Soc. 138, 1401-1429, part B. DOI: 10.1002/qj.1897

Grabowski, W. W., and L. -P. Wang, 2013: Growth of cloud droplets in a turbulent environment. Annual Review of Fluid Mechanics, 45, 293-324, doi:10.1146/annurev-fluid-011212-140750.

Siebert, H., Gerashchenko, S., Lehmann, K., Gylfason, A., Collins, L. R., Shaw, R.A., Warhaft, Z., 2010: Towards understanding the role of turbulence on droplets in clouds: In situ and laboratory measurements. Atmos. Res., 97, Sp. Iss. SI, 426-437 p. doi:10.1016/j.atmosres.2010.05.007

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Cloud microphysics

- Hanna PAWLOWSKA

UNIVERSITY
OF WARSAW

Why do we study cloud microphysics?

- A matter of scales
- Interactions

A matter of scale

100 μm

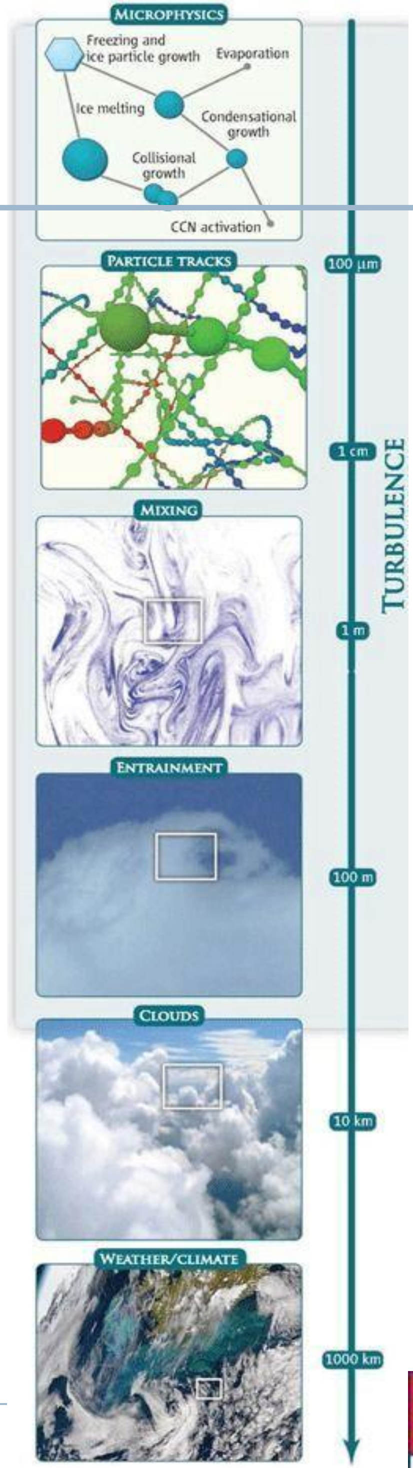
1 cm

1 m

100 m

1 km

1000 km



E Bodenschatz et al. Science 2010;327:970-971

A matter of scale

100 µm

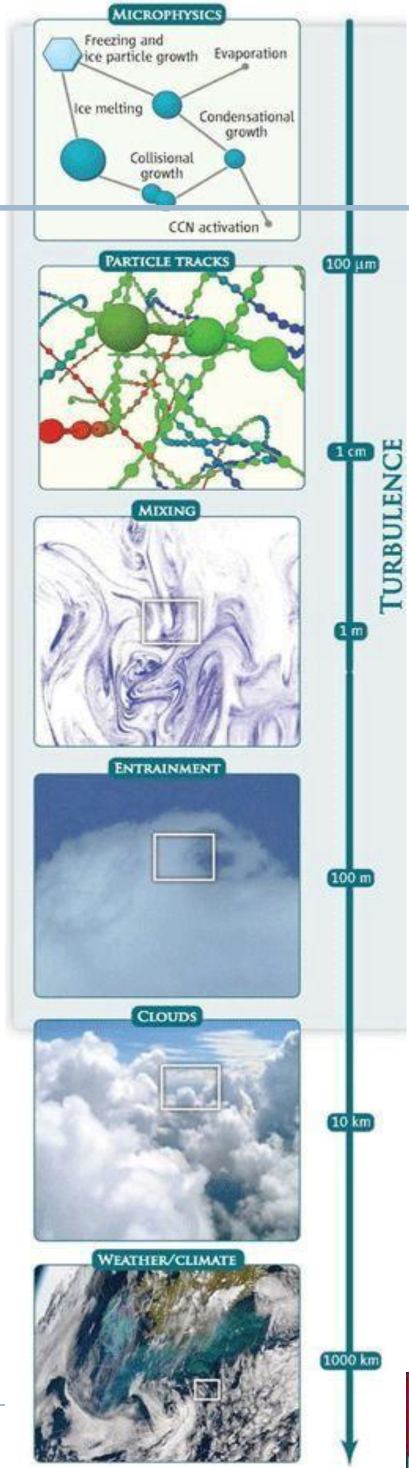
1 cm

1 m

100 m

1 km

1000 km



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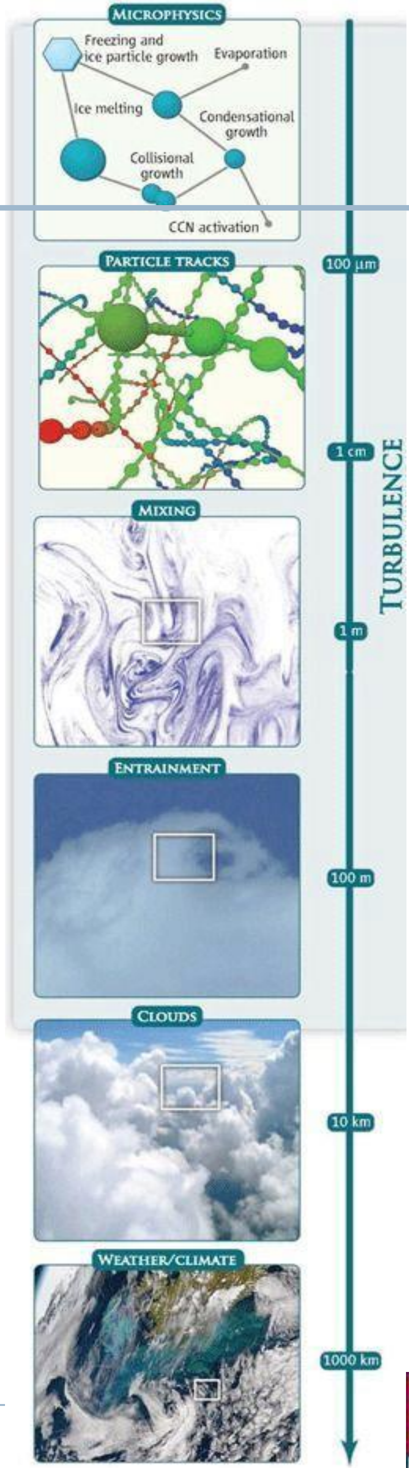

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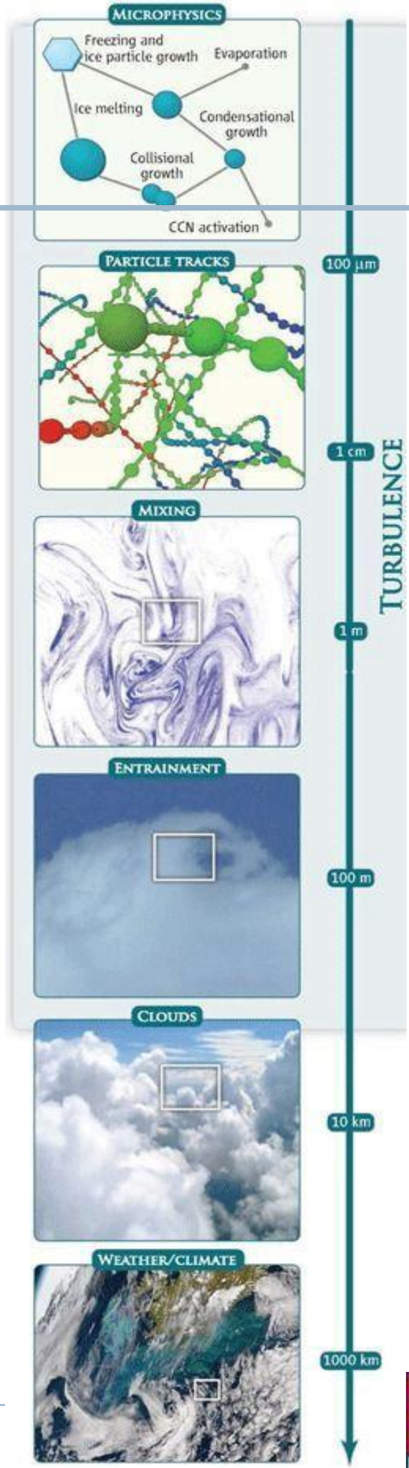

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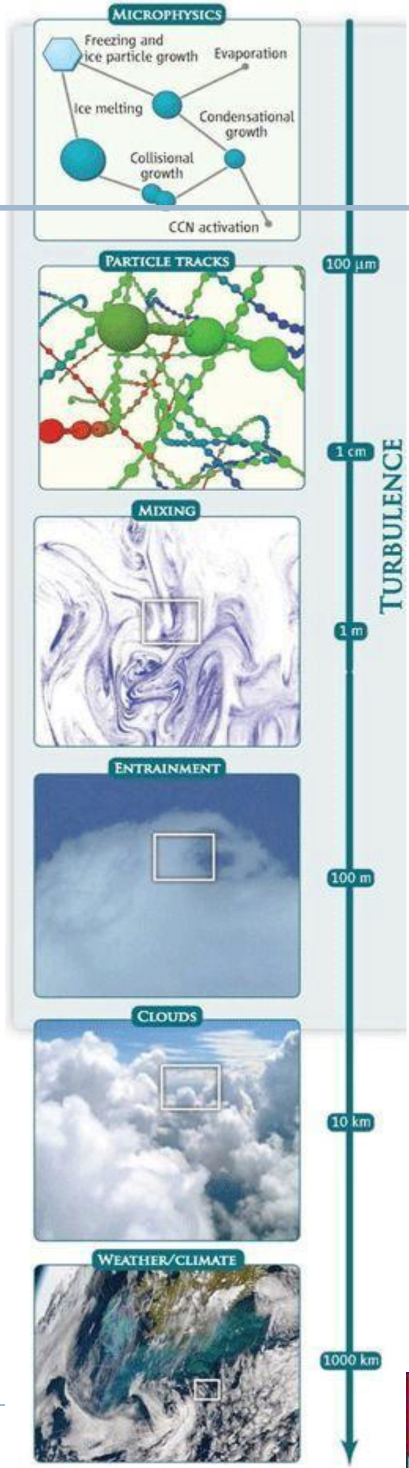
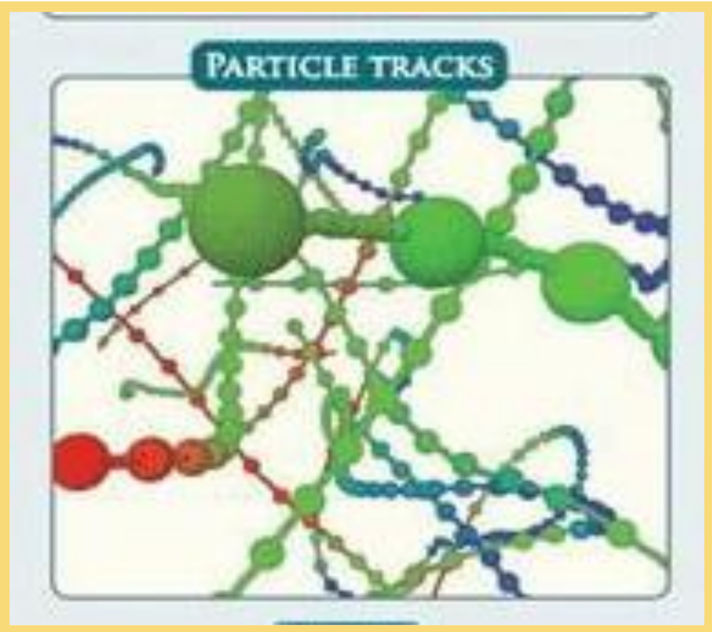


E Bodenschatz et al. Science 2010;327:970-971

Science AAAS

A matter of scale



100 µm

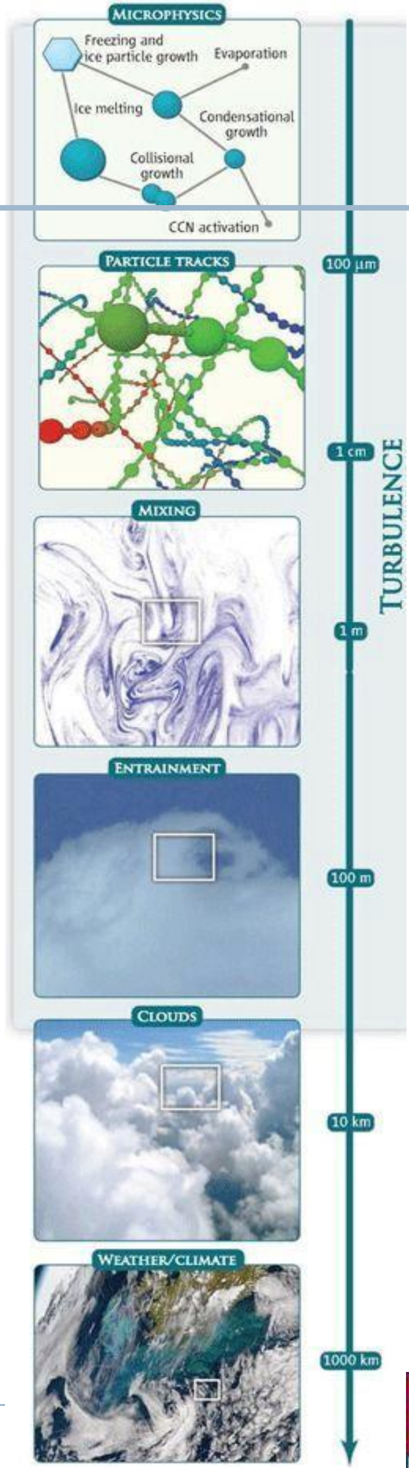
1 cm

1 m

100 m

1 km

1000 km



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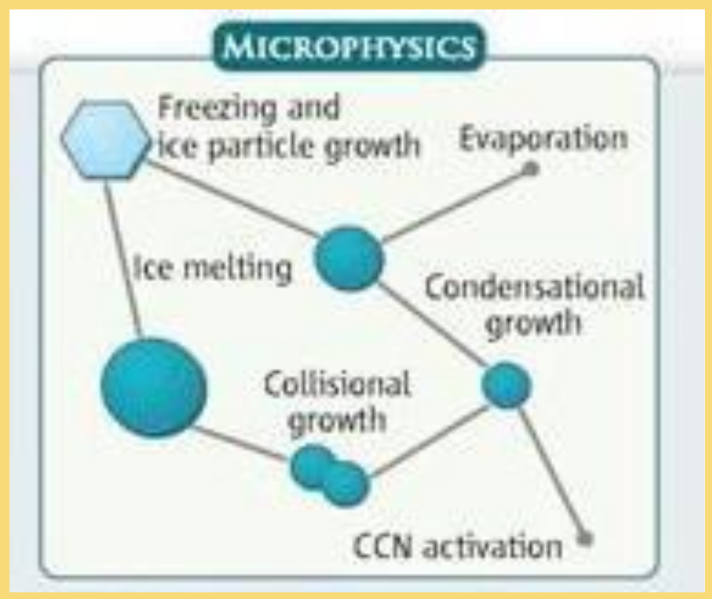
A matter of scale



100 μm

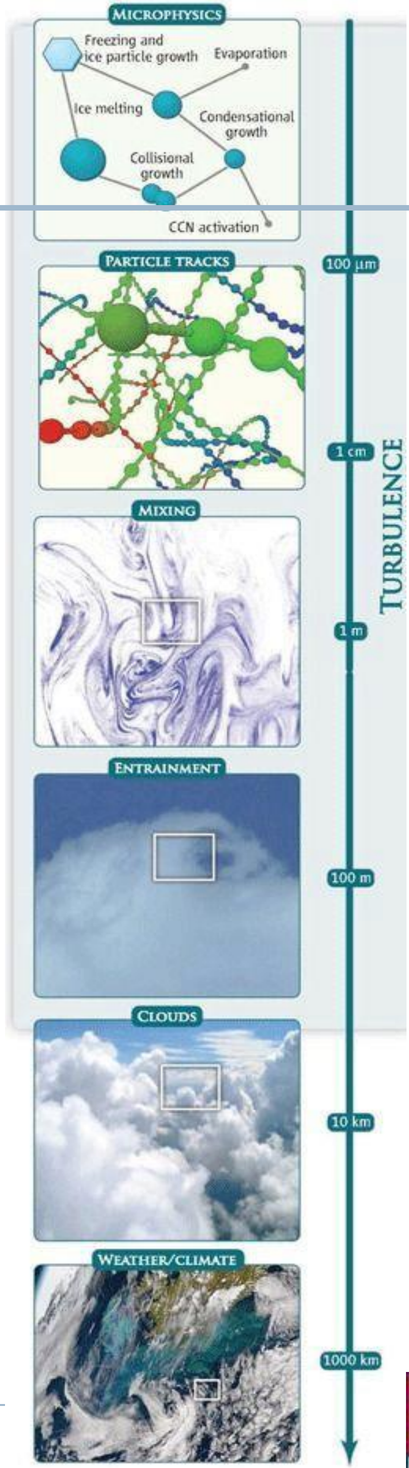
1 cm

1 m

100 m

1 km

1000 km

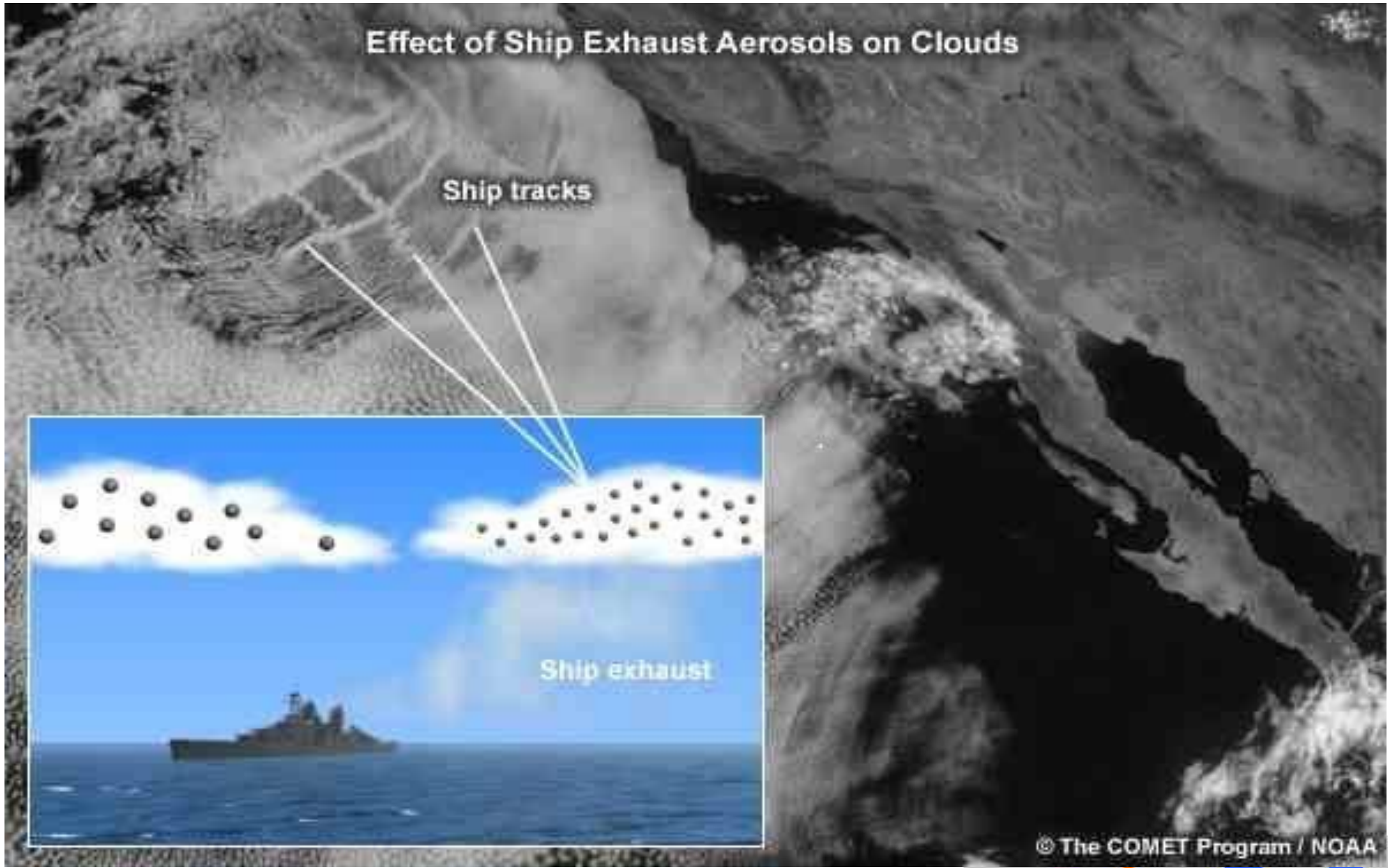


E Bodenschatz et al. Science 2010;327:970-971

Interactions

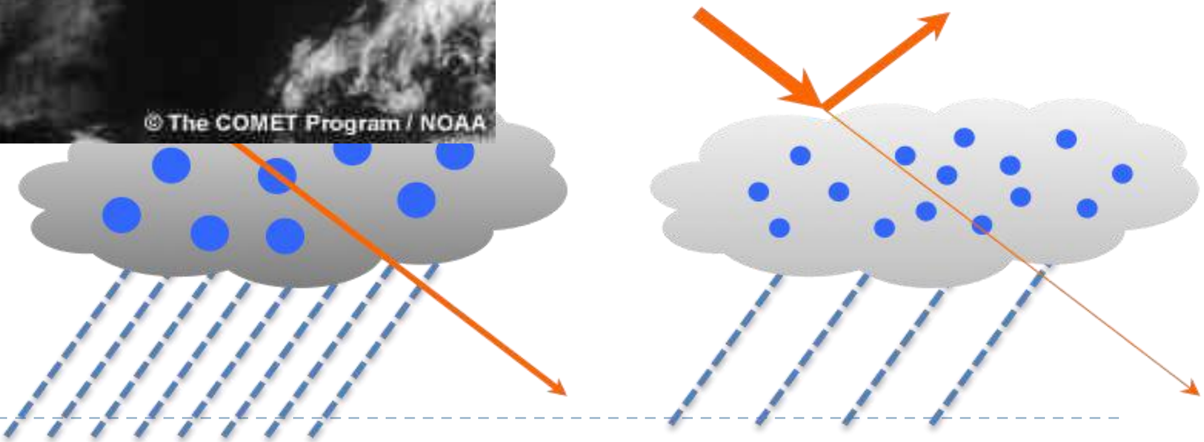
- Interaction with radiation
  - Scattering of light, absorption of thermal radiation
  - Indirect effects
- Thermal interaction
  - Redistribution of heat and moisture
- Hydrological interaction
  - Rain formation
- Chemical interactions
  - Removal and generation of aerosols and gases

Interaction with radiation – aerosol indirect effect



Albedo depends on cloud optical thickness.

Cloud optical thickness depends on cloud microphysics – spectrum of cloud particles.



Pockets of open cells: aerosol-cloud-precipitation interaction

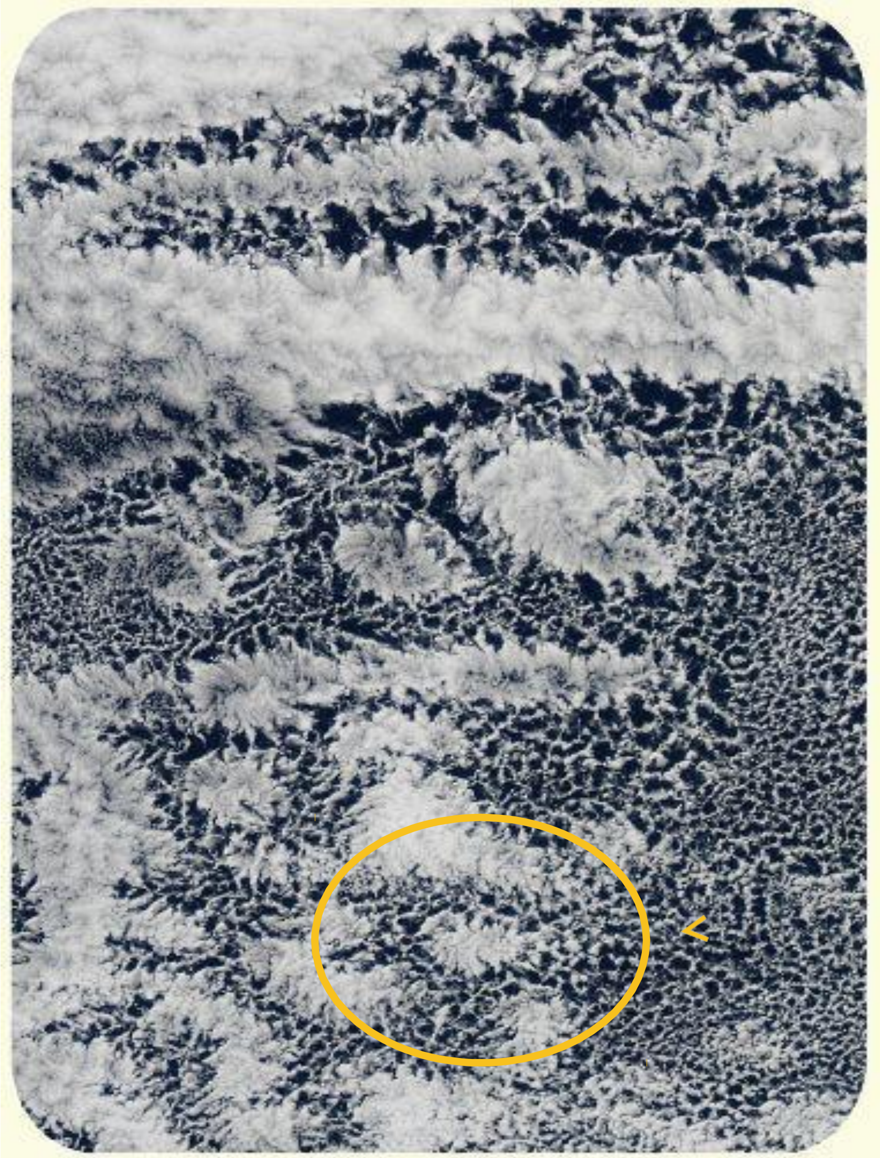


Photo: NASA, 17 April 2010, East Pacific

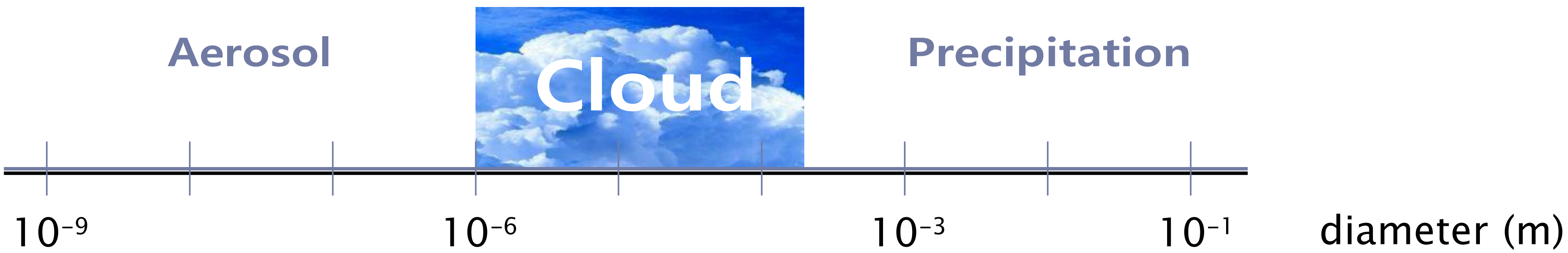
What is cloud microphysics?

- Cloud is a medium composed of water and/or ice particles immersed in a field of water vapor

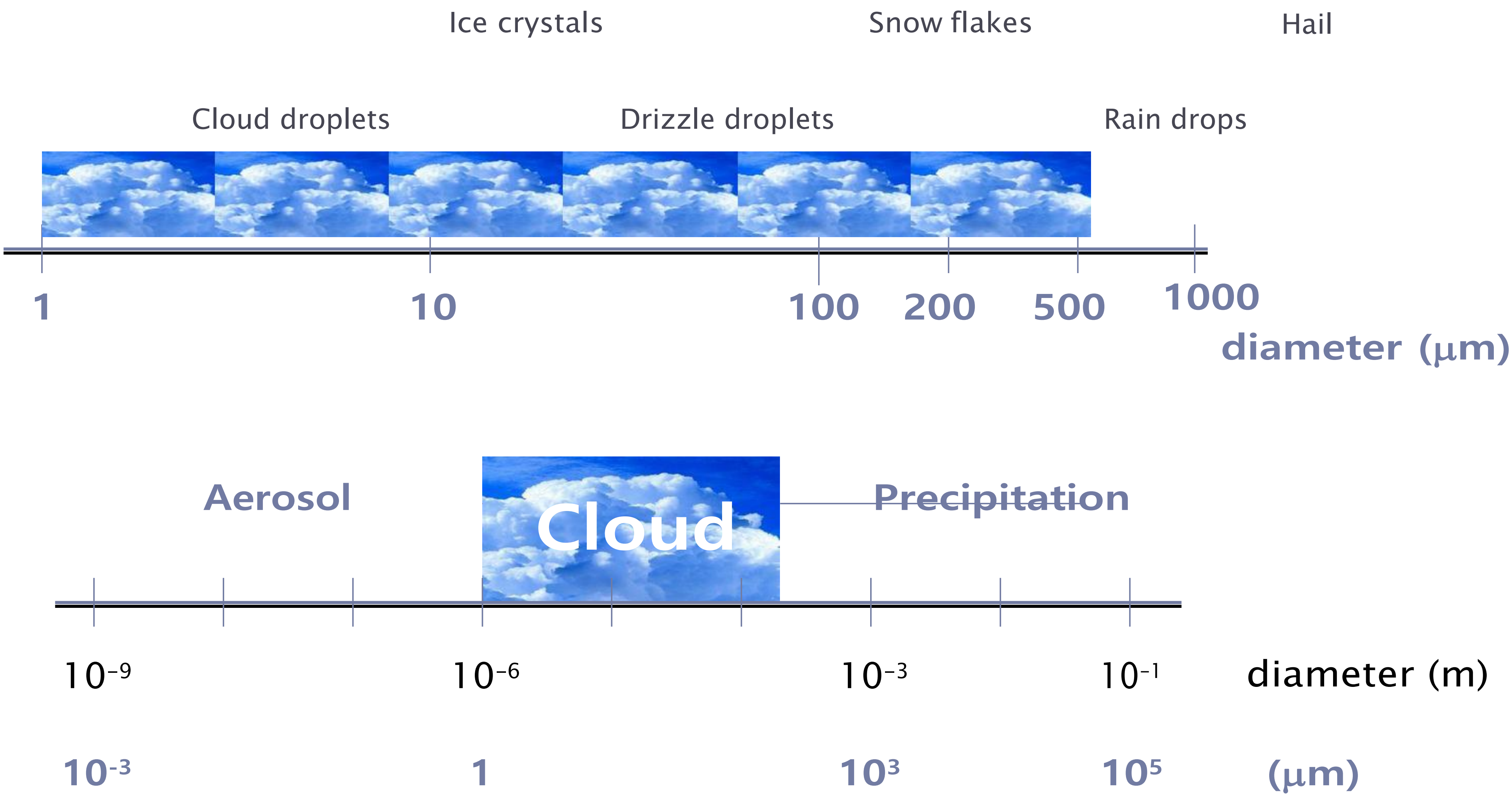
- Description of formation and evolution of cloud particles is a main goal of what is called ‘cloud microphysics’

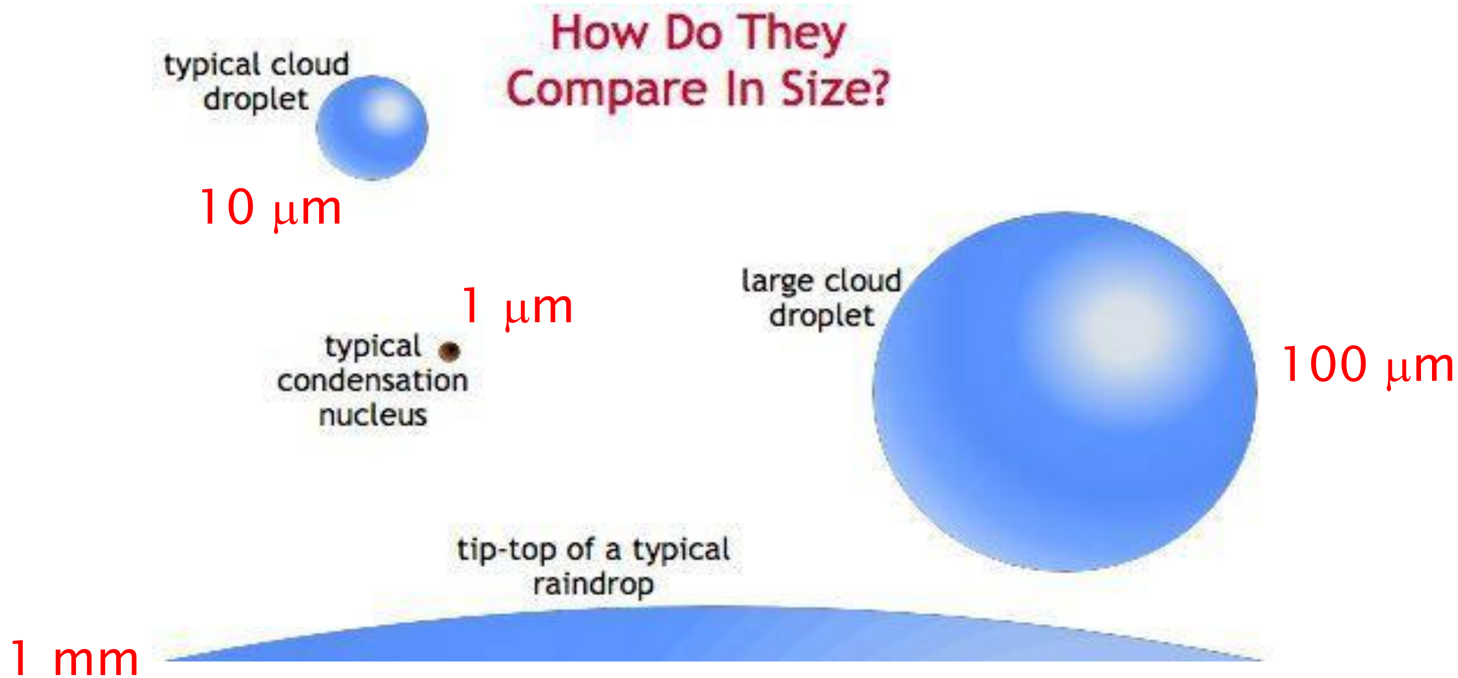
- Spatial coordinates, sizes, and/or shapes of each cloud particle at any instant of time would provide the most exhaustive information on a cloud

Sizes of cloud particles



Sizes of cloud particles



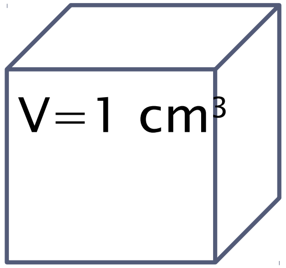


Cloud particles are divided according to their sizes (diameter):

- Cloud droplets: 1–30 μm
- Drizzle drops: 30 – 600 μm
- Rain drops: > 600 μm

This division reflects processes involved in those particle's formation.

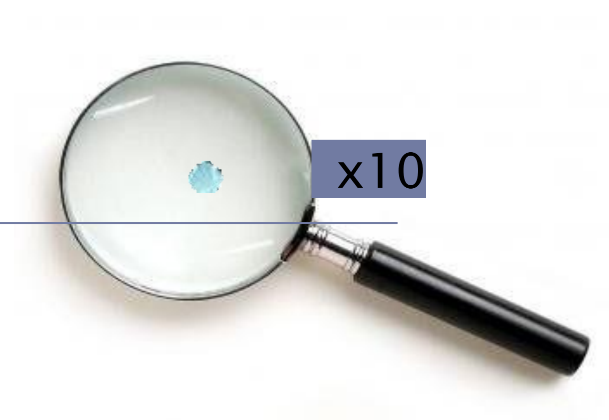
Cloud droplets, drizzle, rain drops
Concentration, size, distance between drops



1 cm

Cloud droplets: N=125 cm^{-3}
r=10 μm
d=2 mm

r=10 μm



2 mm

Drizzle drops: N=0.1-1 cm^{-3}
r=100 μm
d~ 1 cm

1 cm

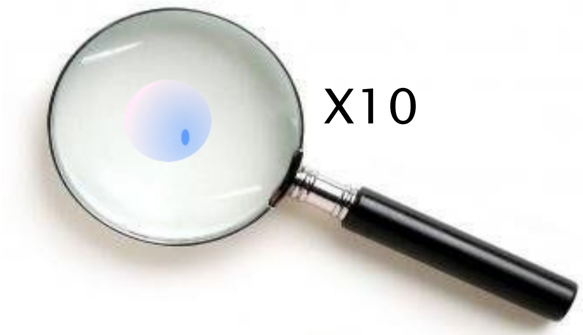
Rain drops: N=1 dcm^{-3}

r=1000 μm=1 mm

d=10 cm

Hailstone… record

The largest recorded hailstone in the United States by diameter 8 inches (20 cm) and weight 1.93 pounds (0.88 kg). The hailstone fell in Vivian, South Dakota on July 23, 2010.



Raindrop, r= 1 mm

Image: NOAA

How to describe cloud microphysical properties?

- Particle size distribution (PSD)
- Moments of PSD (concentration, mean radius, mean volume radius…)
- Integrated cloud characteristics (liquid water path, cloud optical thickness)

Spatial coordinates, sizes, and/or shapes of each cloud particle at any instant of time provide the most exhaustive information on a cloud.

Is position of any single cloud particle important for description of cloud microphysics?

NO!!!!!

Because any identical cloud won't happen any more.

For description of populations of cloud's particles we need to define distribution functions.

Warm clouds

Cloud processes span over wide ranges of scales

- Lower limit:
  - cloud droplets sizes – micrometers
  - distance between cloud droplets – milimeters, centimeters

  Investigation of cloud processes in such scales in natural clouds is very difficult if not impossible
- Upper limit:
  - cloud macroscale – hundreds of meters to tens or hundreds of kilometers

  Characterization of clouds in macroscale is a challenge because
  - it should reflect mean cloud properties and
  - it should reproduce well their global radiative and/or dynamical properties

Characteristics of cloud microphysics refer to a given volume or mass of air

Particle size distribution (PSD)

Particle size distribution (particle spectrum) provides information of a number of particles of a given size in a given volume of a cloud.

(N_i, r_i) –number of particles, N_i (cm^{-3}), in a unit volume having radius r_i (μm).
The most often N_i is a number of particles having radii in a bin size (r_i, $r_i+\Delta r_i$).

$n_i = N_i / \Delta r_i$ is particle number density ($cm^{-3}\ \mu m^{-1}$).

For many purposes the particle density function is expressed by a continuous analytical function n(r), where
n(r)dr is the number of particles in the infinitesimal size interval (r,r+dr).
In fact (n_i, r_i) is also a continuous size distribution.

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In fact (n_i, r_i) is also a continuous size distribution.

Cloud microphysical parameters

$$M_j = \sum_i r_i^j N_i = \int_o^\infty r^j n(r) dr$$

j^th moment of the particle size distribution

	Name of parameter		Application	
M_0	concentration	$N = M_o$		
M_1	mean radius	$\bar{r} = \frac{1}{N} M_1$		
M_2	mean surface radius	$r_s = \left(\frac{1}{N} M_2\right)^{1/2}$ $r_v = \left(\frac{1}{N} M_3\right)^{1/3}$	Extinction [m^-1]	$\sigma_{ext} = Q_{ext} \pi N r_s^2$ $LWC = \frac{4}{3} \pi \rho_w N r_v^3$
M_3	mean volume radius		Liquid water content Mixing ratio	$Z \propto M_6$
M_6	9No name		Radar reflectivity	

Effective radius

A parameter used to define optical properties (aerosol, cloud particles)

$$\boxed{r_e = \frac{r_v^3}{r_s^2}}$$

Liquid water content

$$LWC = \frac{4}{3}\pi\rho_w N r_v^3 \quad \Rightarrow \quad r_v^3 = \frac{3LWC}{4\pi\rho_w N}$$

Extinction

$$\sigma_{ext} = Q_{ext}\pi N r_s^2 \quad \Rightarrow \quad r_s^2 = \frac{\sigma_{ext}}{Q_{ext}\pi N}$$

Effective radius links cloud microphysical properties (*LWC*) with cloud optical properties (σ_{ext})

$$\sigma_{ext} = \frac{3}{4}\frac{Q_{ext}}{\rho_w}\frac{LWC}{r_e}$$

Integrated cloud characteristics

Liquid water path

$$LWP = \int_{h_{base}}^{h_{top}} LWC \cdot dh$$

Optical thickness

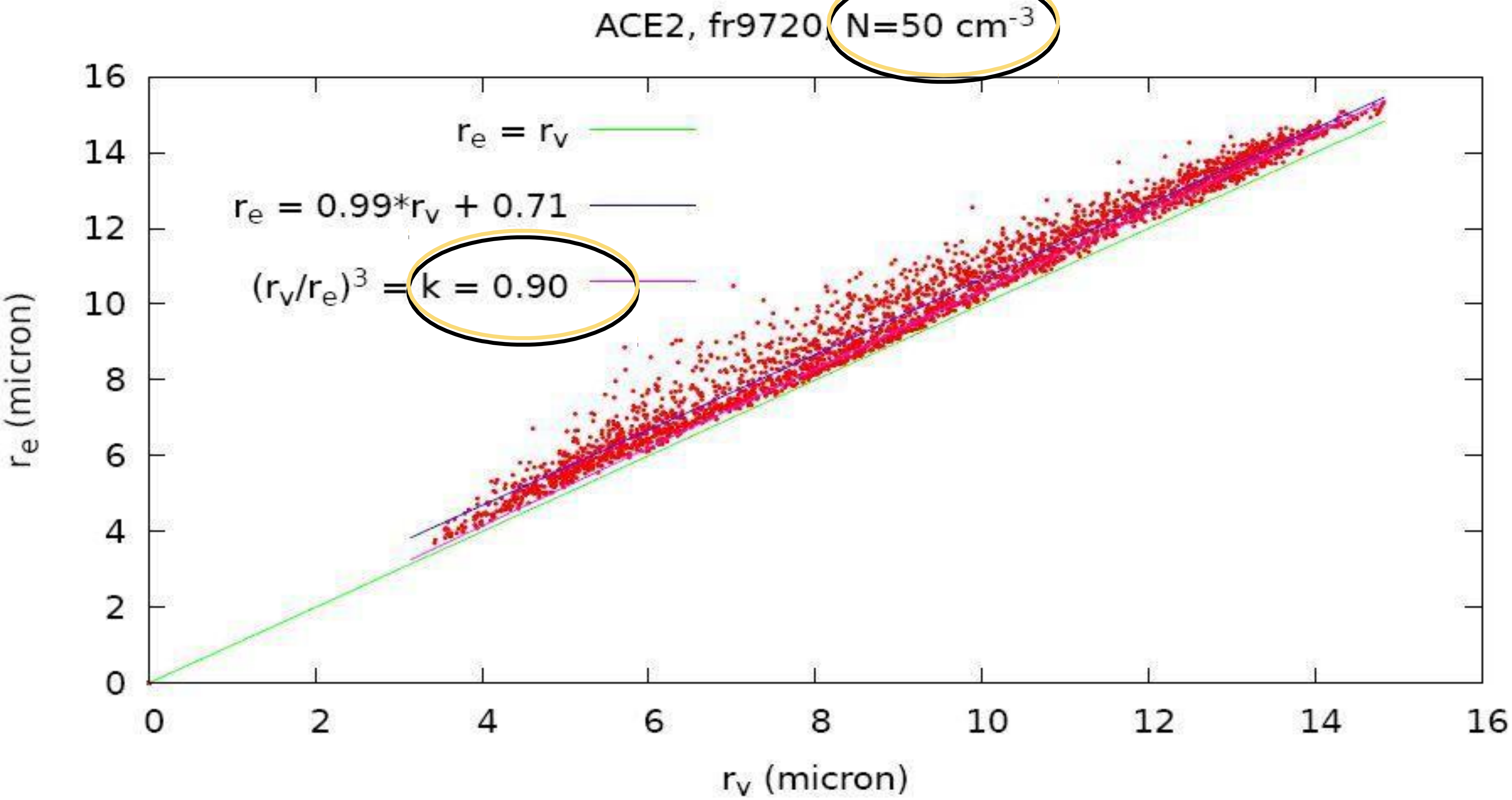
$$\tau = \int_{h_{base}}^{h_{top}} \sigma_{ext} dh = \pi Q_{ext} \int_{h_{base}}^{h_{top}} N r_s^2 dh$$

$$r_s^2 = \frac{r_v^3}{r_e}$$

$$\tau = \frac{3Q_{ext}}{4\rho_w} \int_{h_{base}}^{h_{top}} \frac{LWC}{r_e} dh$$

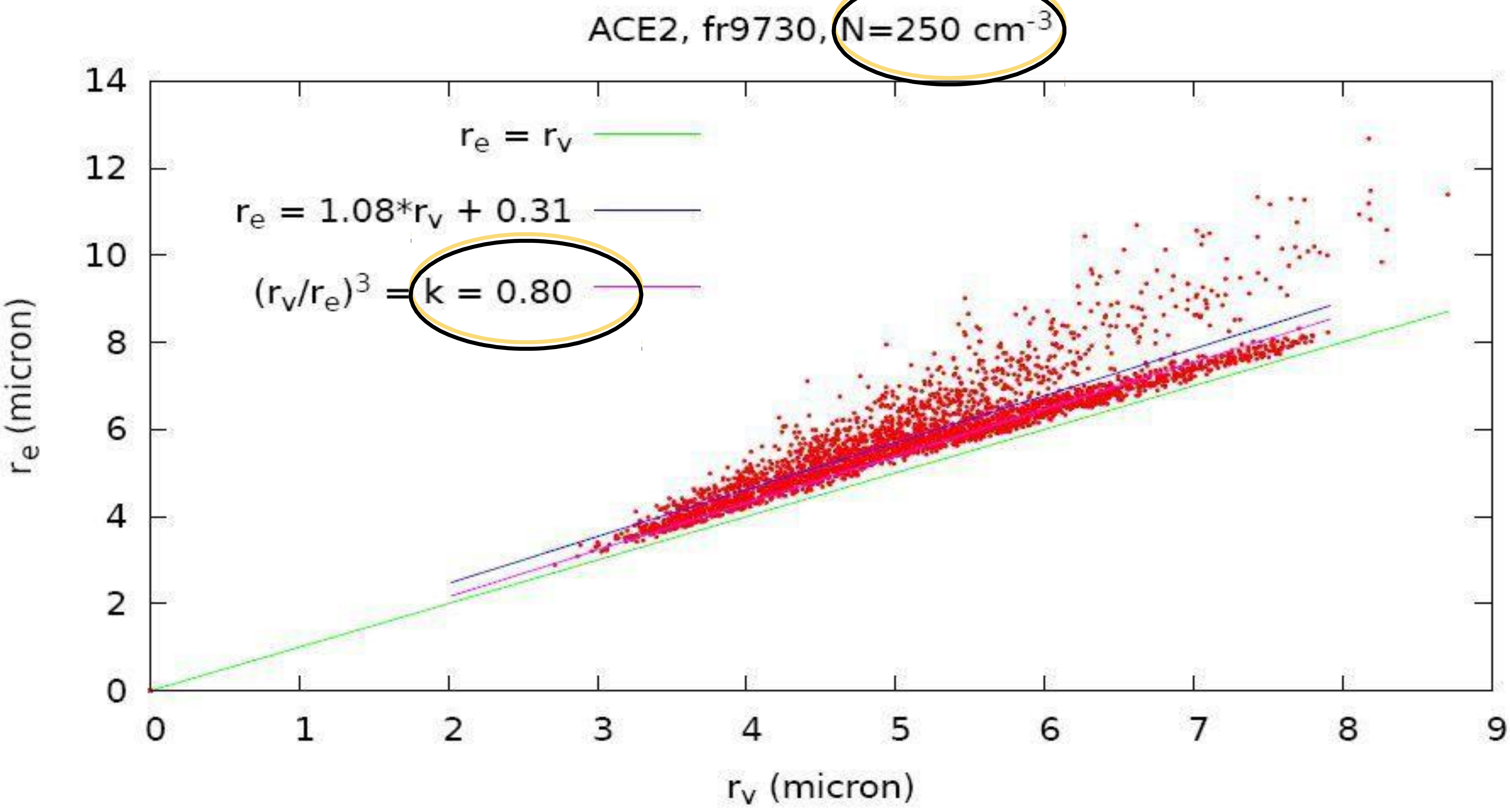
if $r_e = const$ $\tau = \frac{3Q_{ext}}{4\rho_w} \frac{LWP}{r_e}$

Effective radius (r_e) versus mean volume radius (r_v); $r_e > r_v$



ACE2: Aerosol Characterization Experiment; Stratocumulus over Canary Islands

Effective radius (r_e) versus mean volume radius (r_v)



Microphysics processes

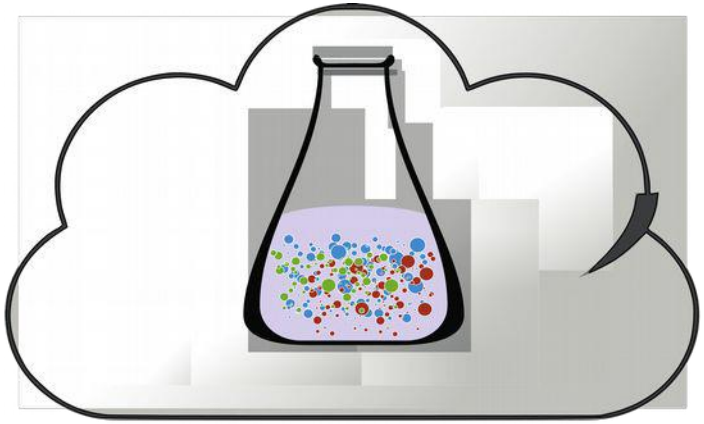
- Warm rain processes
- Ice processes

Warm cloud processes

- Heterogeneous nucleation, activation
- Condensational growth
- Rain formation

Warm cloud processes
aerosol-cloud-precipitation

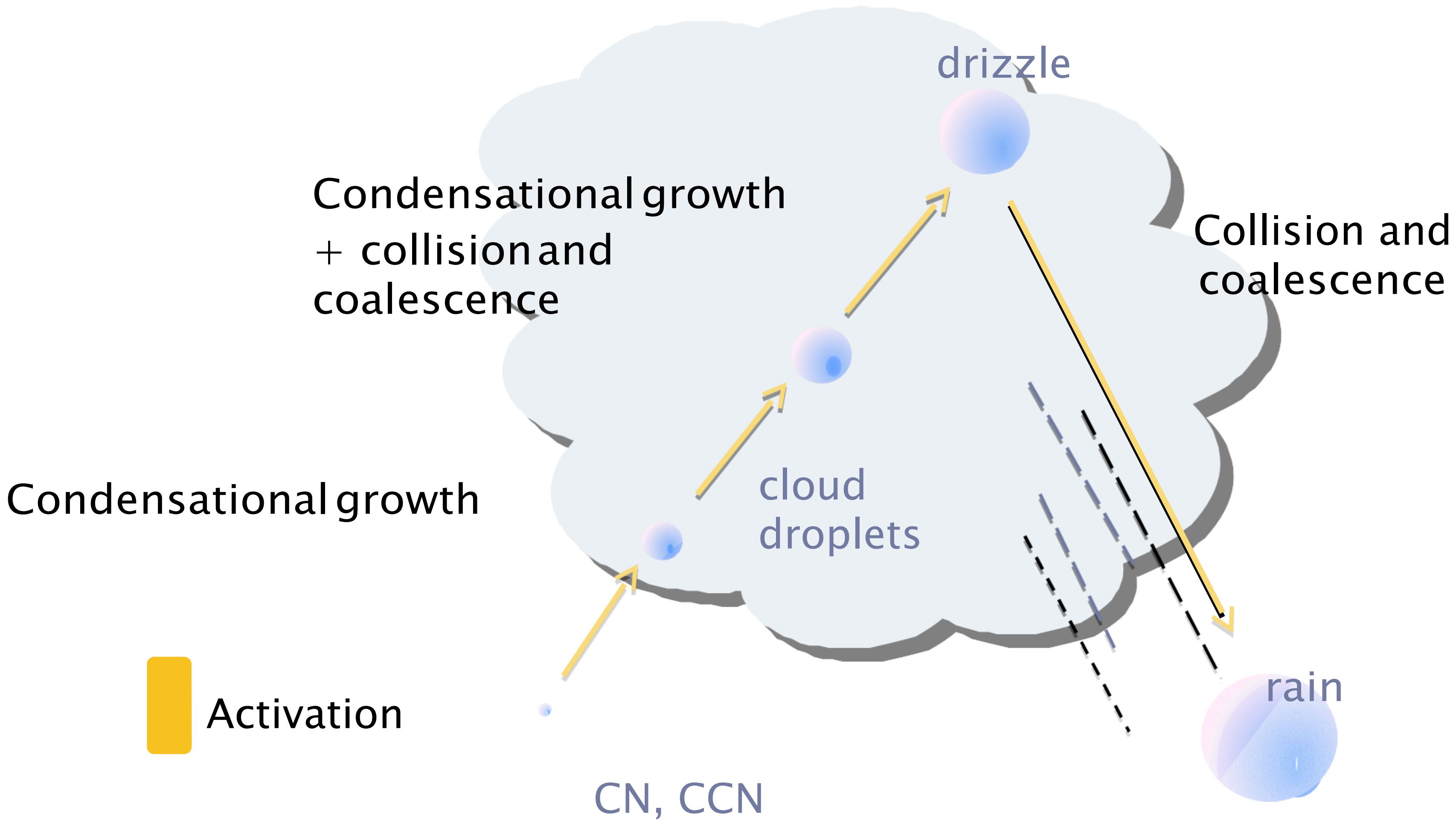
Heterogeneous
nucleation;
CCN activation



Diffusional growth;
condensational growth
Collision/coalescence
Drizzle formation

Rain
CCN washout

Warm cloud processes

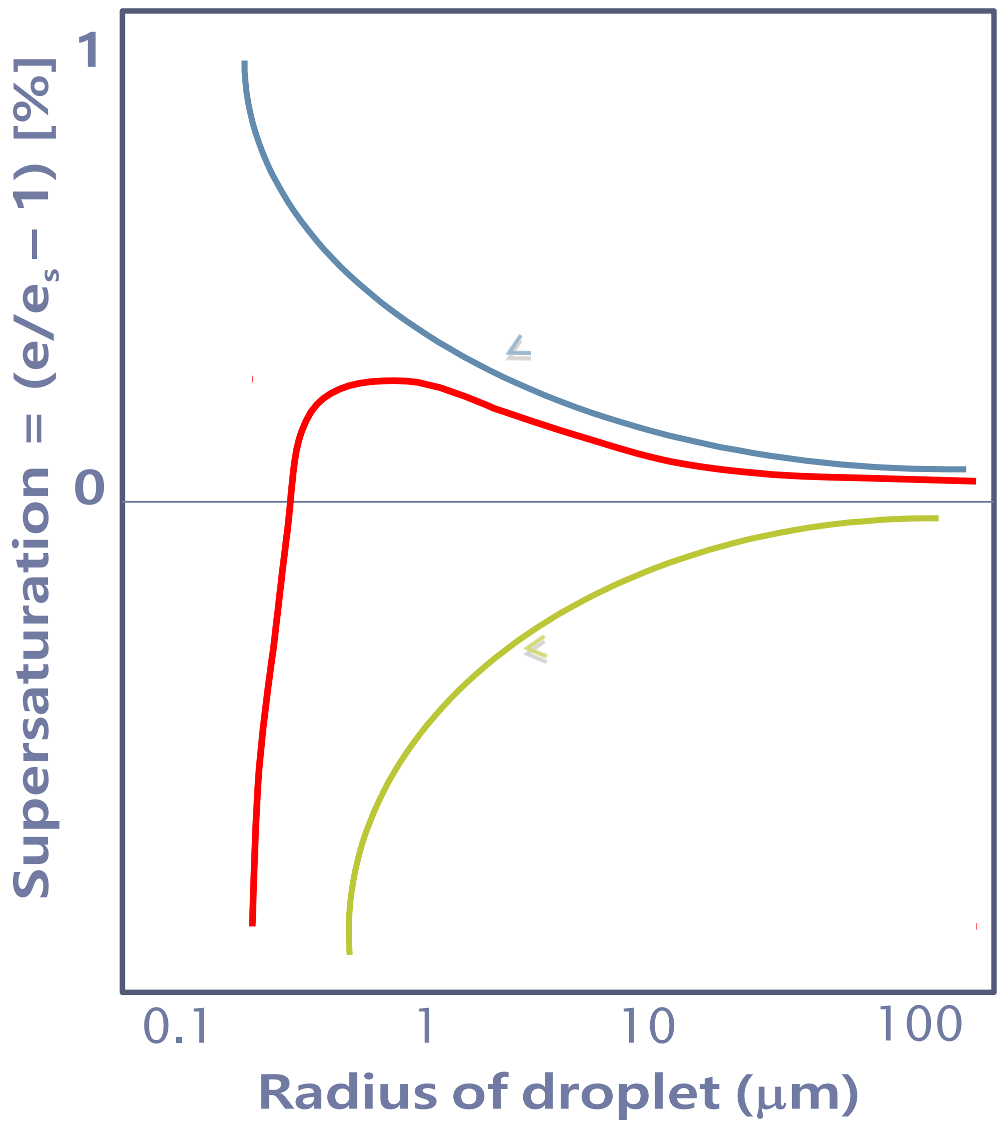


0,1 1 10 100 1000 μm

Droplet activation; cloud condensation nuclei

- Activation – process by which droplets (several microns in size) are formed (or activated) from primarily submicron particles; also called heterogeneous nucleation or just nucleation
  - Process illustrates the conditions required for growth to droplets
  - The approach used assumes that this formation is an equilibrium process
- Cloud condensation nuclei (CCN) – those particles which have large enough radii and enough solute content to activate to particles at a prescribed supersaturation

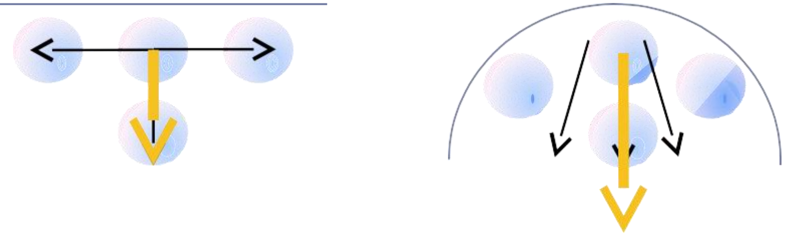
Saturation equilibrium over droplets



Curvature term / Kelvin term ~1/r

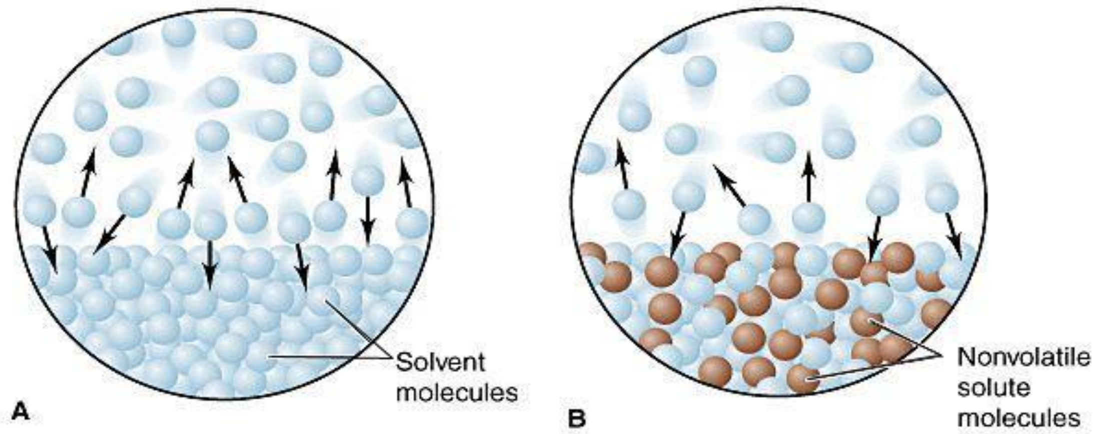
surface tension effect over curved surface

Water vapor is oversaturated; S~1/r

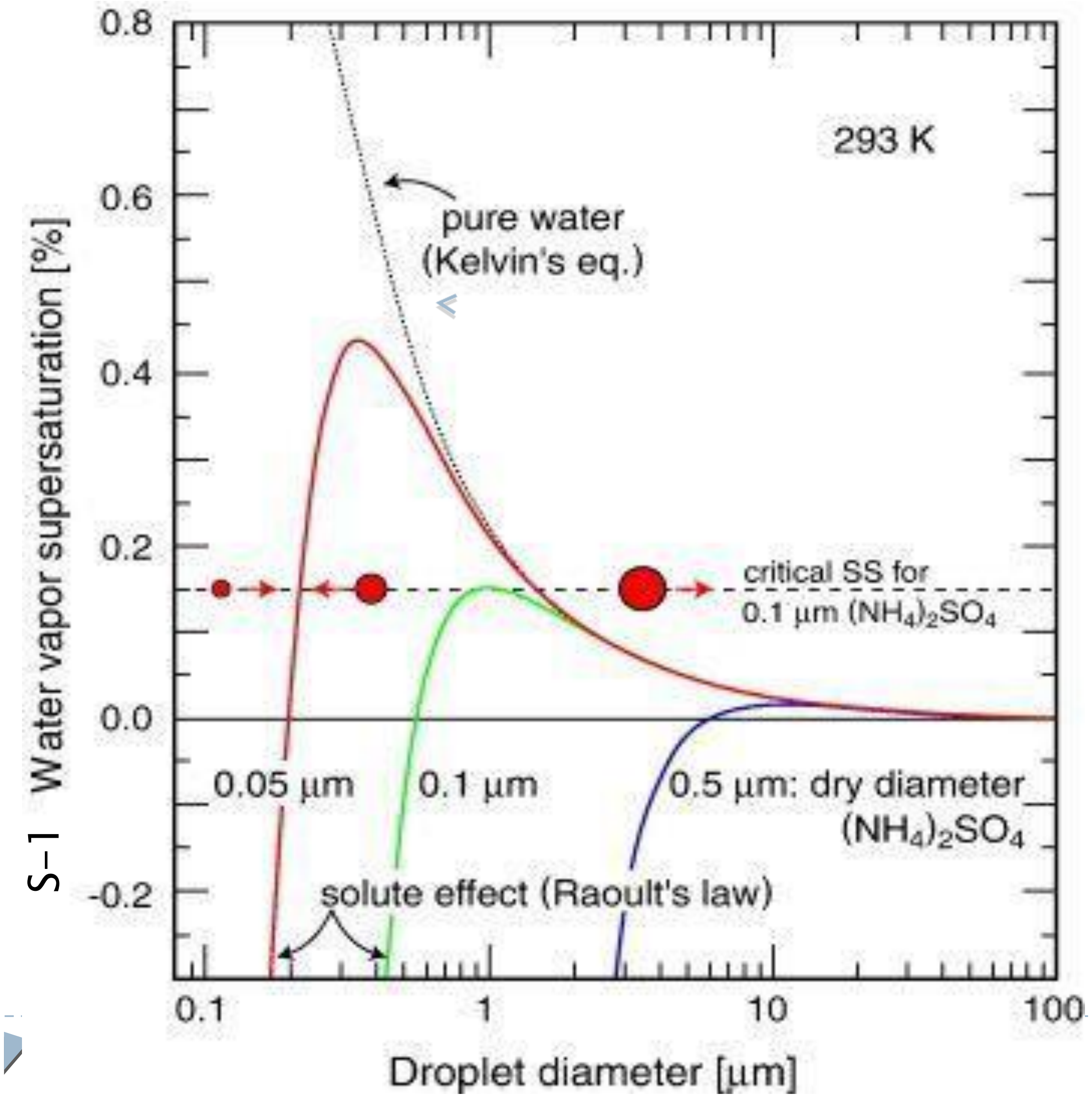


Sollute term / Raoult term ~-1/r^3

Effect of decrease of saturation equilibrium due to the presence of



Activation – Köhler curves



The activation of CCN is fairly accurately described by the theory developed by Köhler in the first quarter of the twentieth century .

Curvature term / Kelvin term

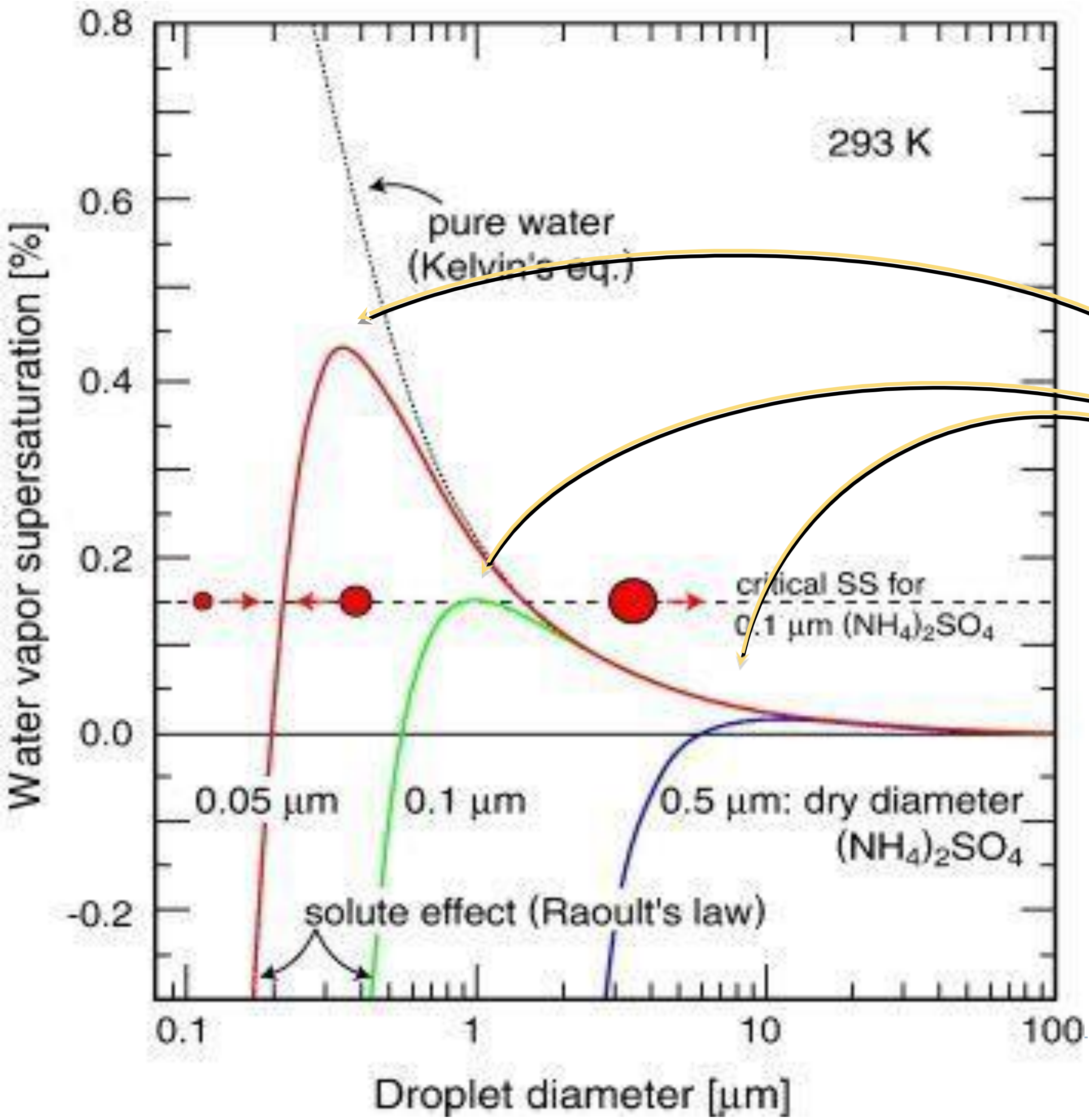
$$S(r,T,B) = exp\left(\frac{A(T)}{r} - \frac{B}{r^3}\right)$$

$$A = \frac{2\sigma}{\rho_l R_v T}$$

B depends on chemical composition

Sollute term / Raoult term

Activation – Köhler curves



For not too small droplets a good aproximation of saturation is

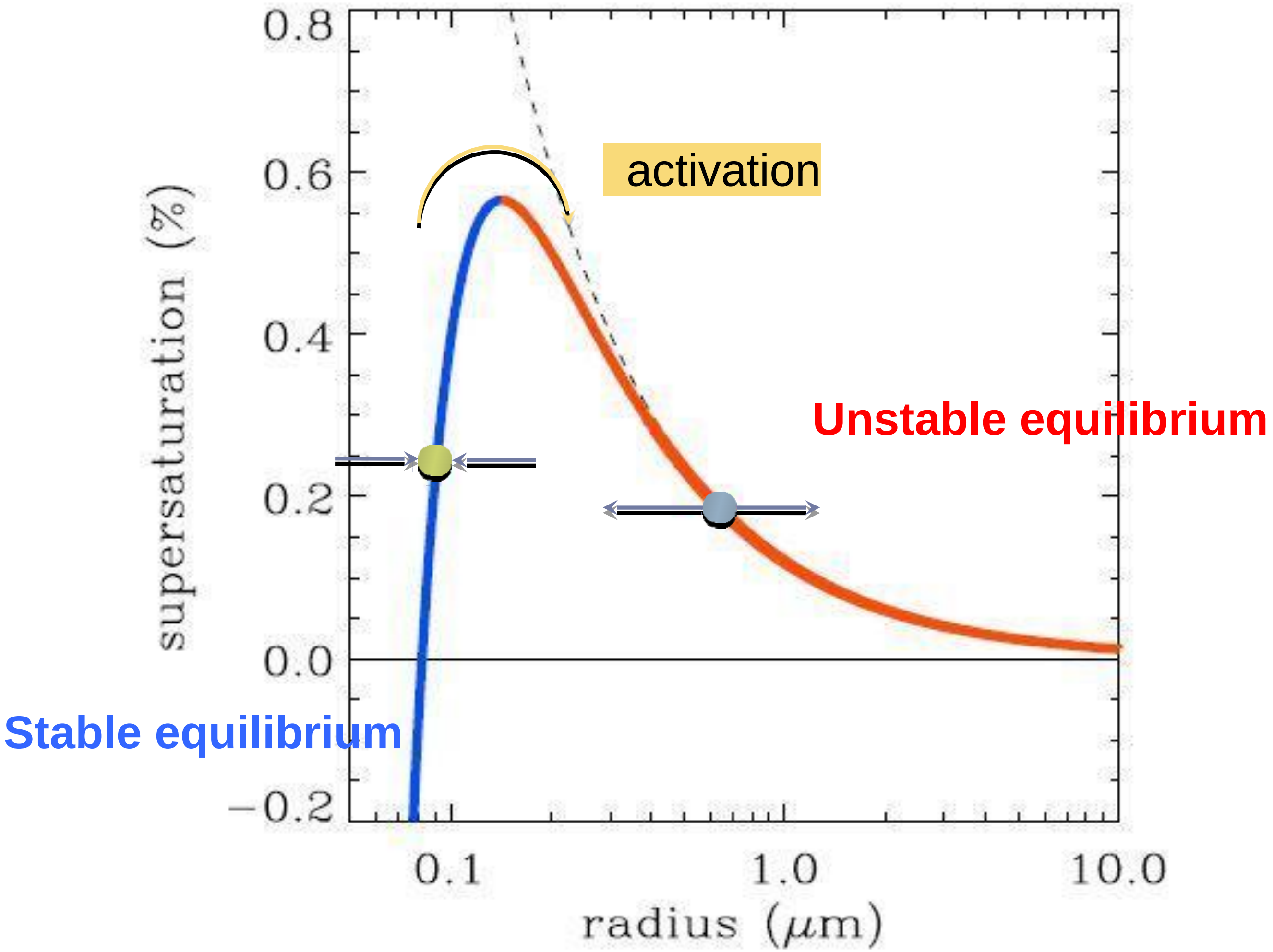
$$S = 1 + \frac{A}{r} - \frac{B}{r^3}$$

Maximum supersaturation

$$\frac{dS}{dr} = 0$$

$$r = \sqrt{\frac{3B}{A}}, \quad S_{max} = \sqrt{\frac{4A^3}{27B}}$$

Activation


0.8
0.6
0.4
0.2
0.0
−0.2
supersaturation (%)
activation
Unstable equilibrium
Stable equilibrium
0.1
1.0
10.0
radius (μm)

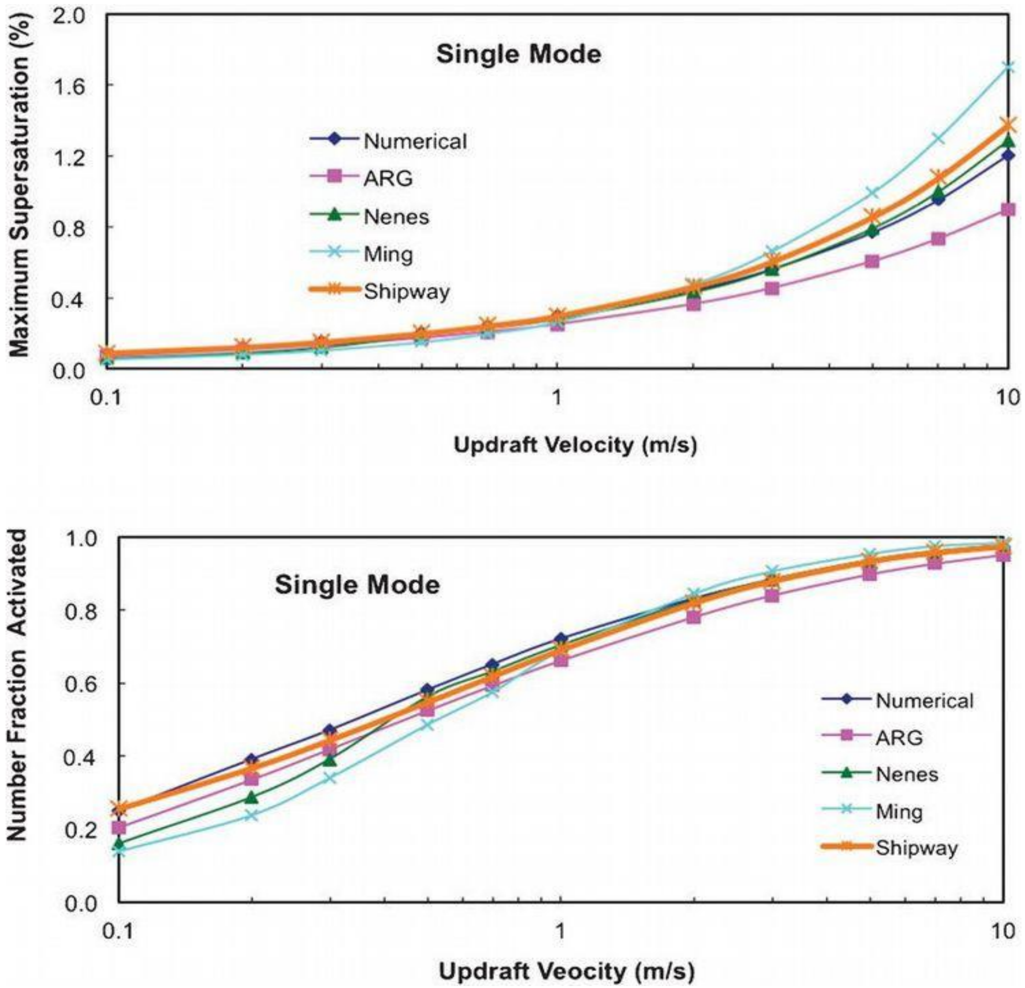
Activation – where it happens ?

- Droplets tend to originate at cloud base where an updraught typically produces a peak in the supersaturation.
- CCN activation is generally confined to the first 30–50 m above the cloud base *except in vigorous convective clouds with vertical velocities of order of 10 m/s, where the supersaturation can reach levels higher than 1%.*

- The peak value of the supersaturation determines the fraction of available CCN that are activated
- **CCN activation spectrum depends on the supersaturation and available CCN**

- The droplet concentration depends on the CCN activation spectrum
  - *Clouds growing in a continental or polluted environment typically show higher droplet concentrations than those growing in a marine or pristine environment*

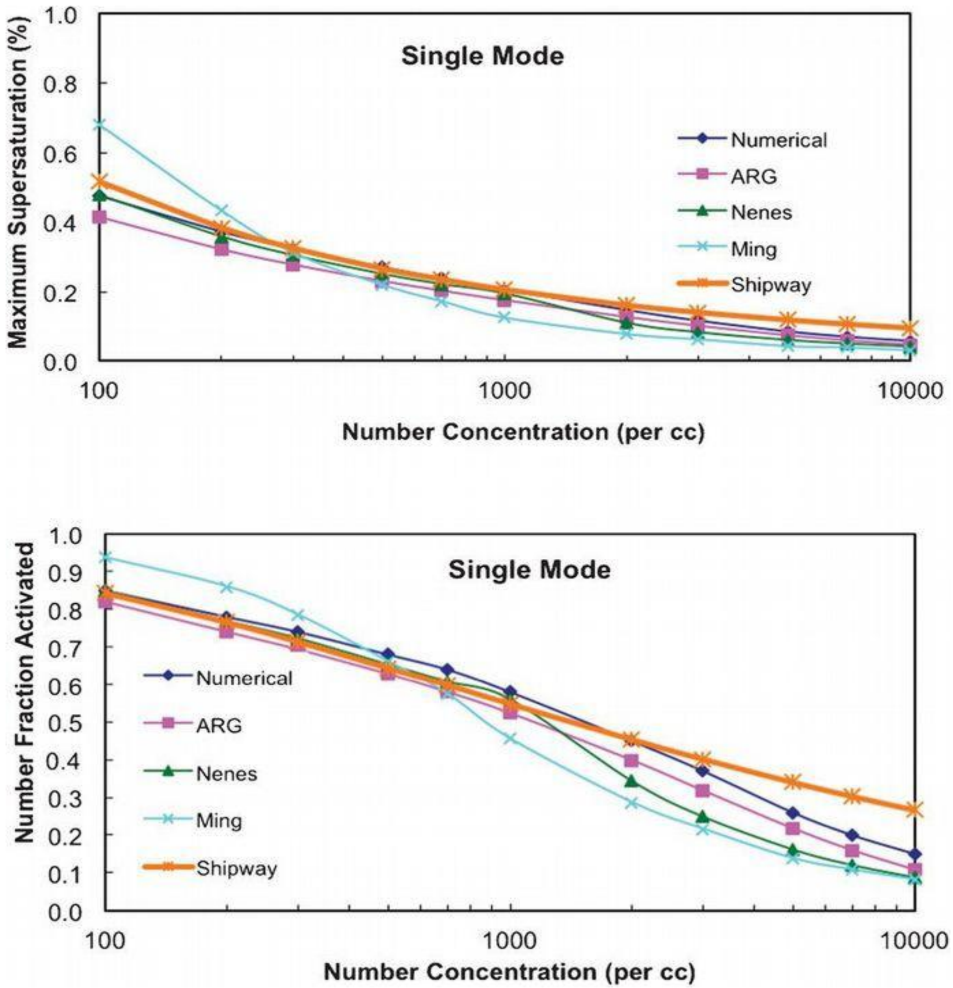
How many of the aerosol are activated?



Ghan et al, 2011

Figure 3: Parameterized and simulated maximum supersaturation and (bottom) number fraction activated as functions of updraft velocity for a single lognormal aerosol mode with N_a = 1000 cm^{-3}, number mode radius = 0.05 μm, geometric standard deviation = 2, and composition of ammonium sulfate. Curves show different parametrization methods.

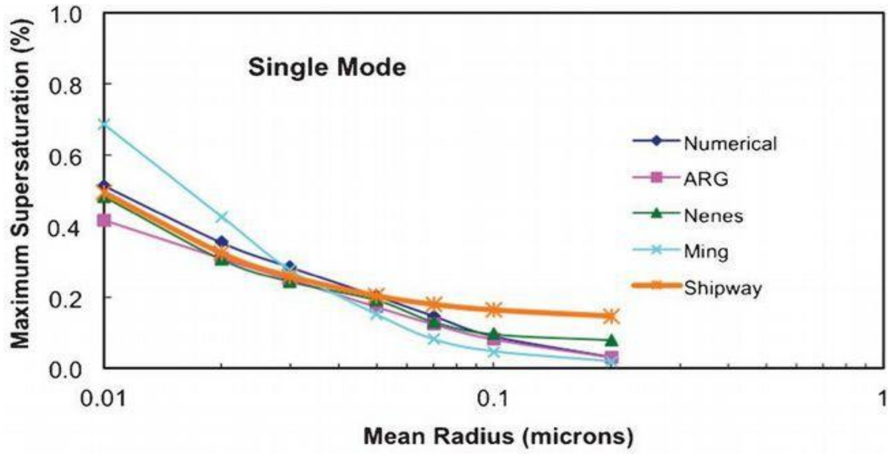
How many of the aerosol are activated?

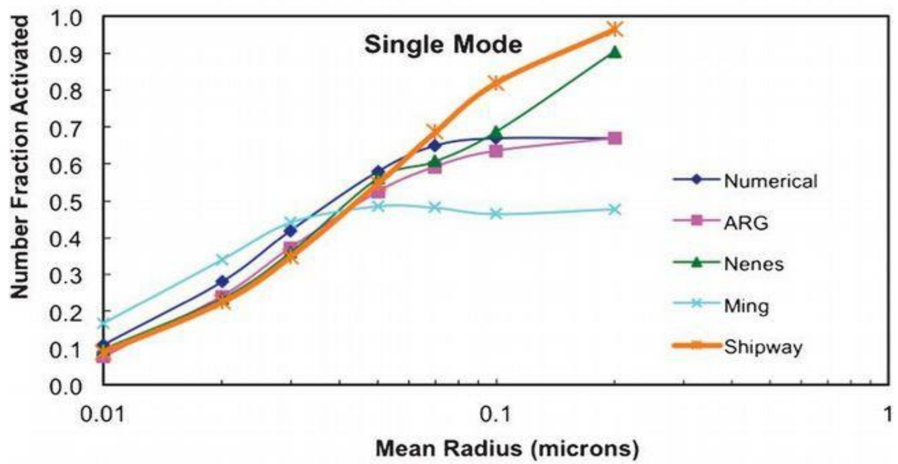


Ghan et al, 2011

Figure 4. As in Figure 3, but as a function of aerosol number concentration for a fixed updraft velocity of 0.5 m s^{-1}. The baseline number concentration is 1000 cm^{-3}.

How many of the aerosol are activated?





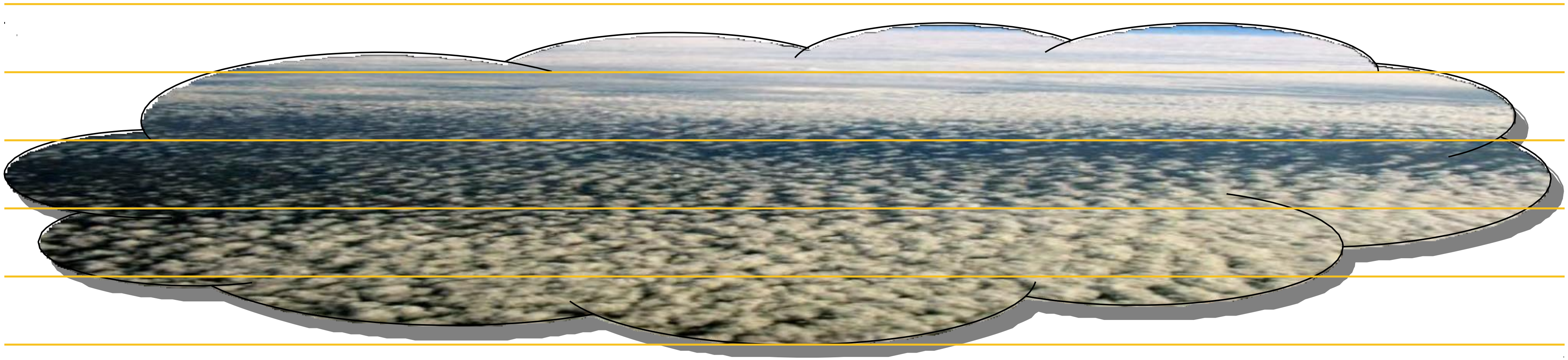
Ghan et al, 2012

Figure 5. As in Figure 3, but as a function of number mode radius for a fixed updraft velocity of 0.5 m s^{-1}. The baseline number mode radius is 0.05 μm. Supersaturation does not reach a maximum in the numerical simulations for mode radius larger than 0.2 μm

Second Aerosol Characterization Experiment (ACE2)

June-July 1997,

Stratocumulus clouds over the Atlantic

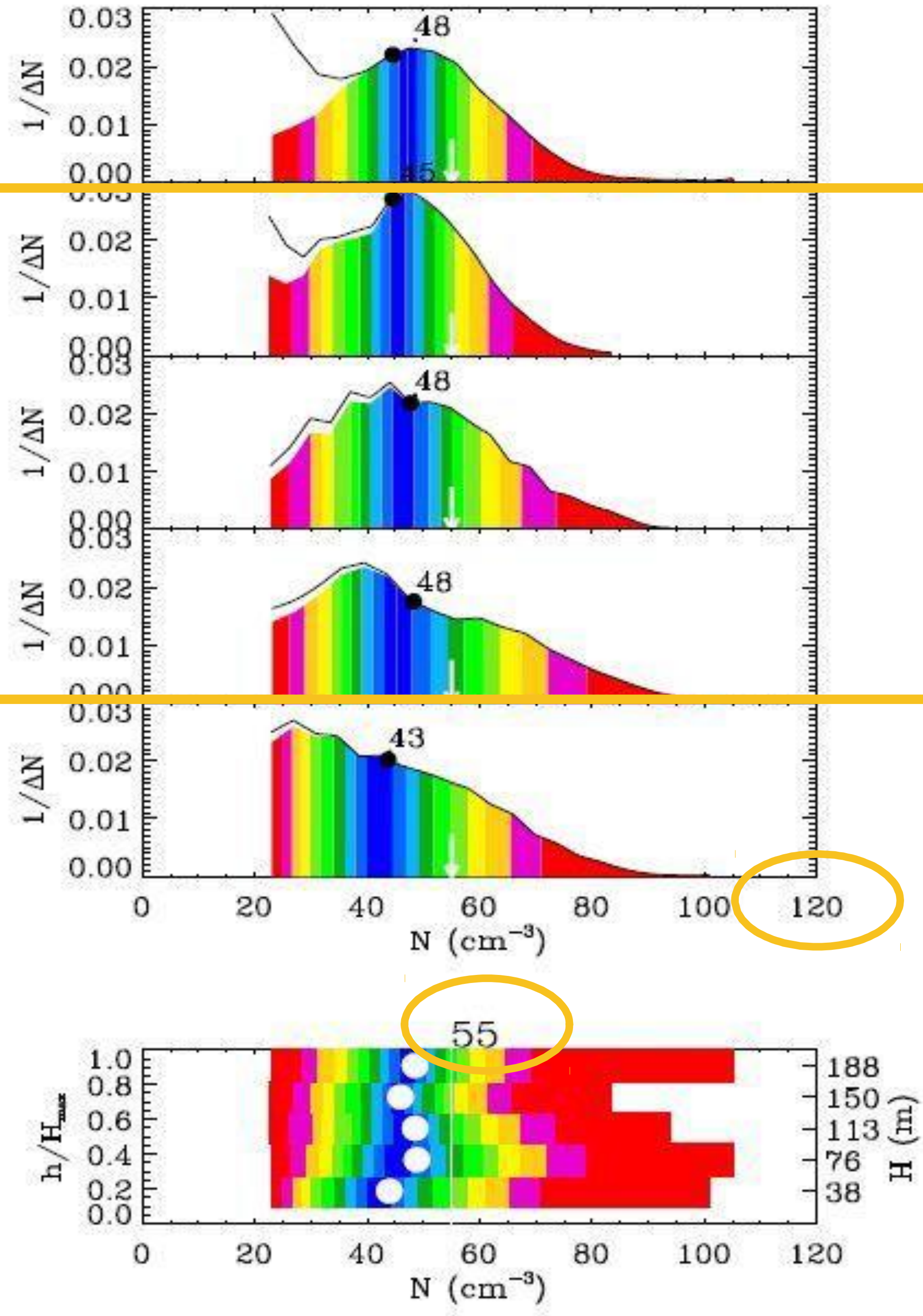


Cloud divided into 5 layers.

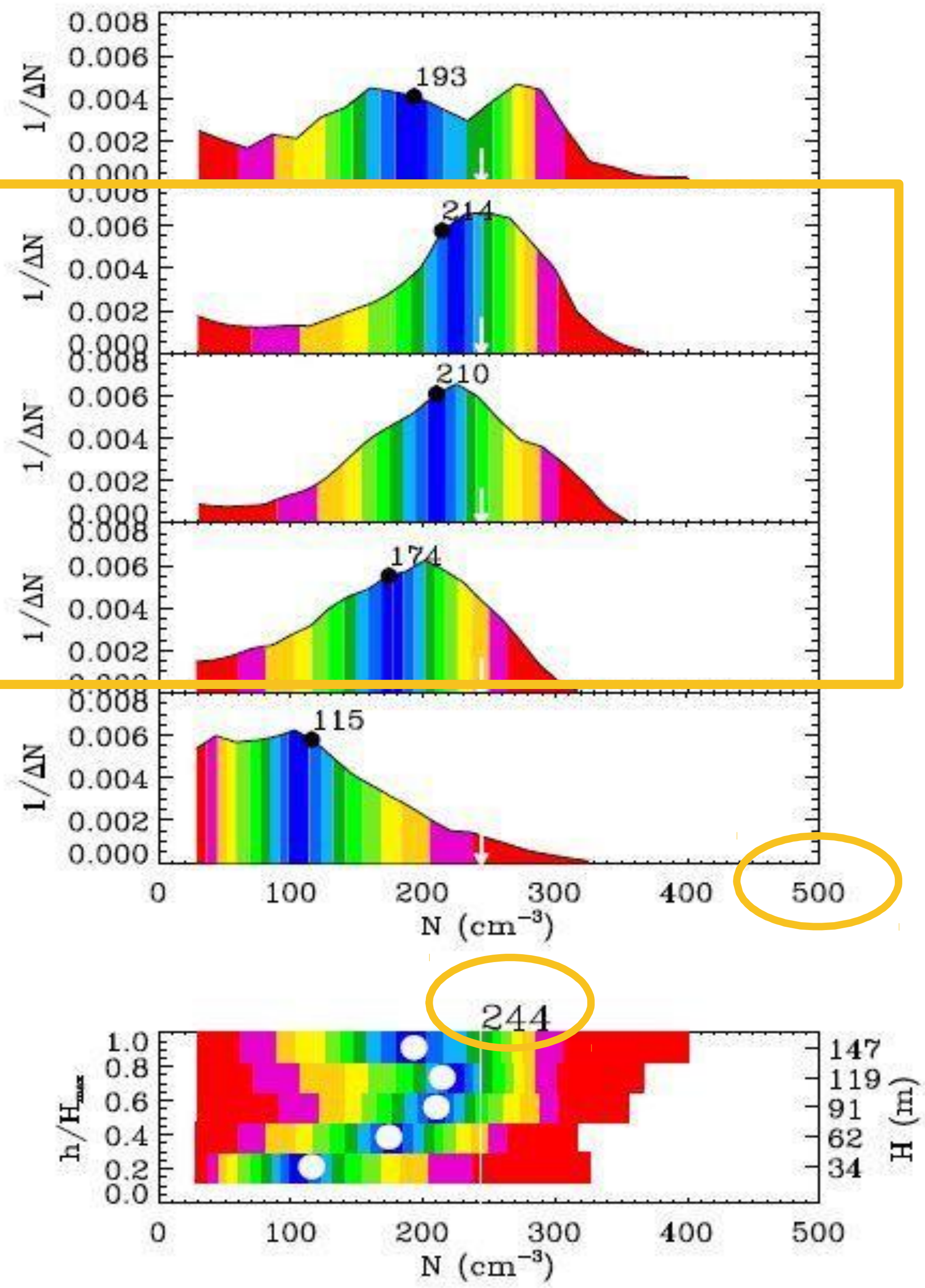
Cloud droplet concentration reflects fairly well the activation process at the cloud base.

Concentration

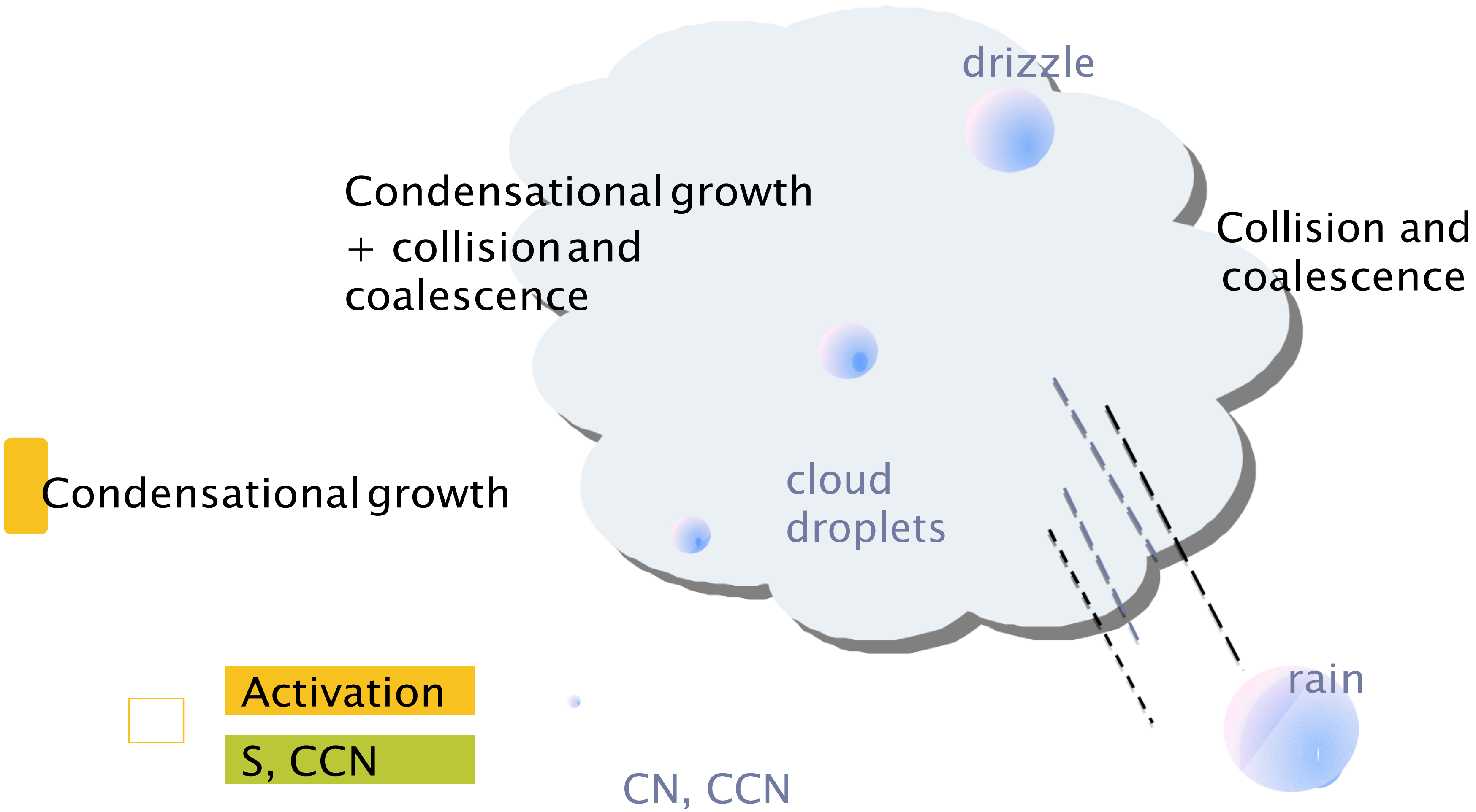
PRISTINE



POLLUTED



Warm cloud processes

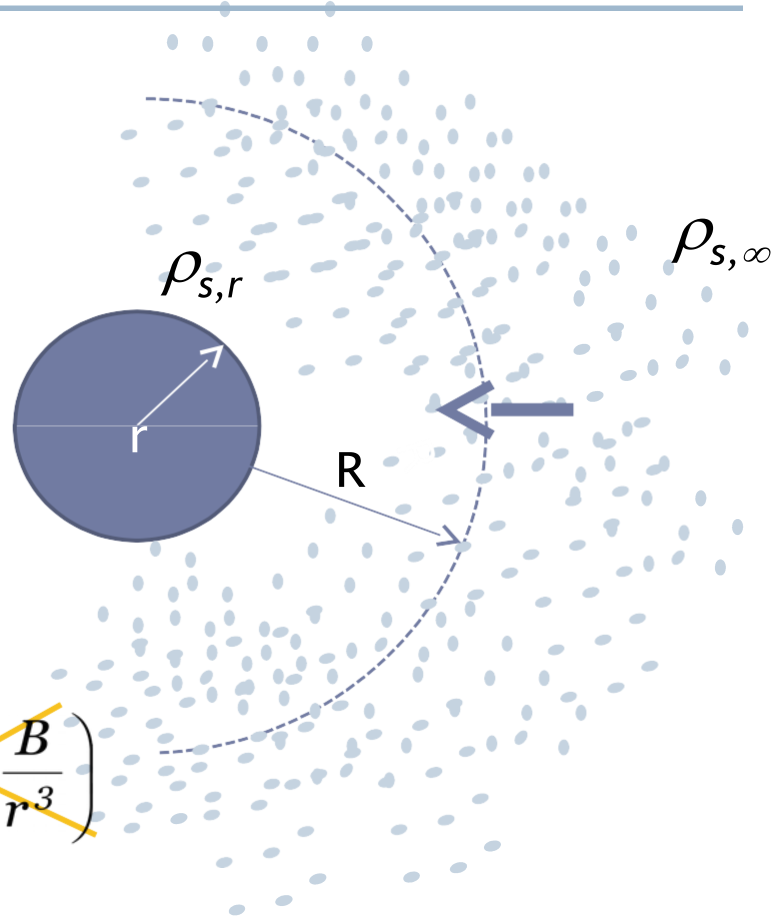


0,1 1 10 100 1000 μm

Condensational growth

- Activated droplets grow by vapor diffusion (D_v – diffusivity)

$$\frac{dr}{dt} = \frac{D_v}{r\rho_l}\left(\rho_{v,\infty} - \rho_{s,r}\right)$$

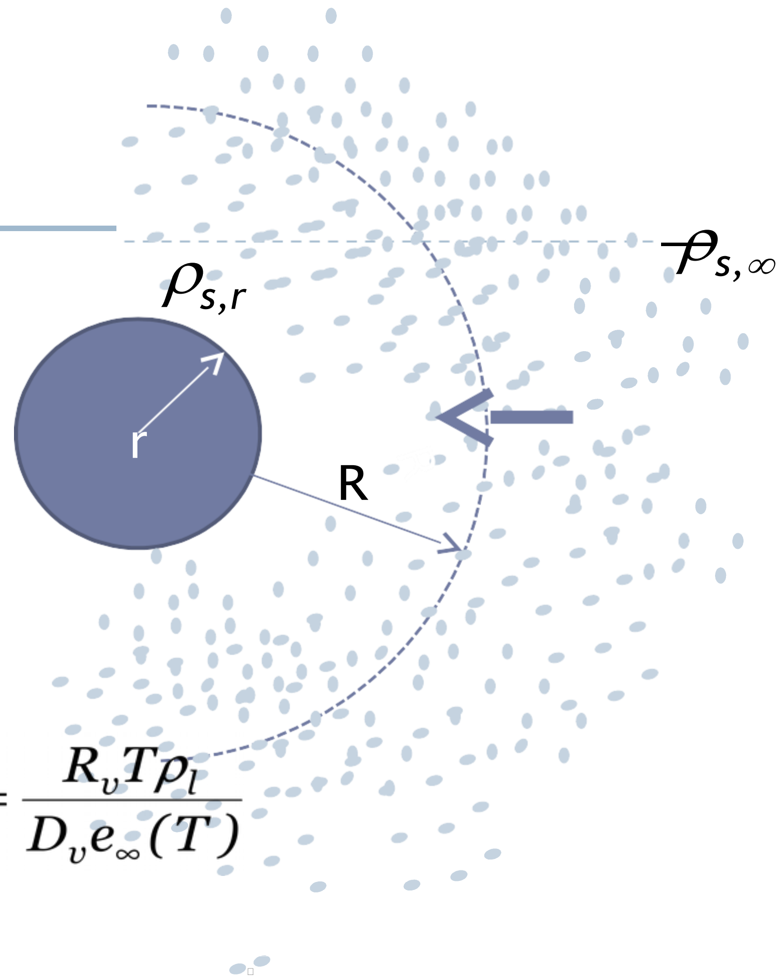


- With the help of the ideal gas law, the equation may be written in terms of the saturation vapor pressure

$$\frac{dr}{dt} = \frac{1}{r}\frac{D_v}{R_v T\rho_l}\left(e_\infty - e_r\right) = \frac{1}{r}\frac{D_v e_\infty}{R_v T\rho_l}\left(S - 1 - \cancel{\frac{A(T)}{r} + \frac{B}{r^3}}\right)$$

- For large enough drops the curvature and sollute corrections for the supersaturation vapor pressure are neglected

Condensational growth



- As water vapor molecules condense on the droplet's surface, latent heat is released, which warms the growing droplet. The equation for condensational growth takes the form:

$$\frac{dr}{dt} = \frac{1}{r}\frac{S-1}{F_D + F_K} \qquad F_K(T) = \frac{\lambda\rho_l}{KT}\left(\frac{\lambda}{R_v T} - 1\right) \qquad F_D(T) = \frac{R_v T \rho_l}{D_v e_\infty(T)}$$

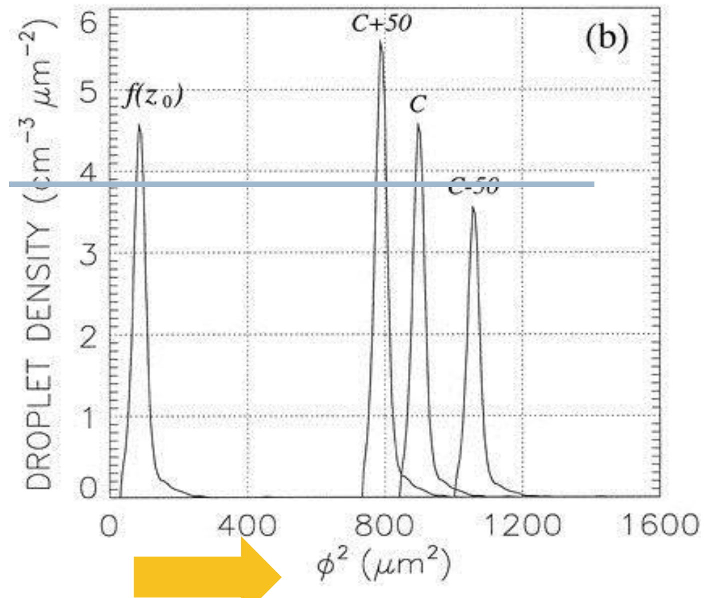
F_D depends on the vapor diffusivity,
F_K depends on the thermal conductivity

The growth rate is primarily determined by the degree of supersaturation.

Condensational growt

$$\frac{dr}{dt} = C\frac{(S-1)}{r} \quad , \quad C = \frac{1}{F_D + F_K}$$

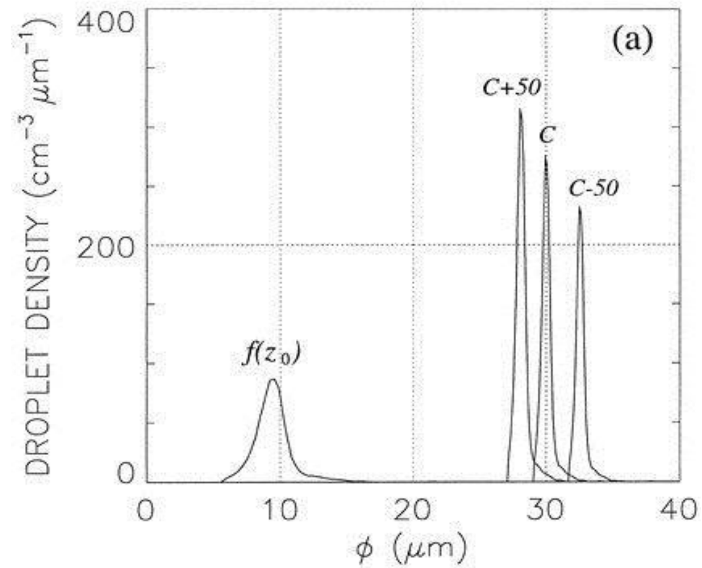
$$\frac{dr^2}{dt} = 2C(S-1)$$



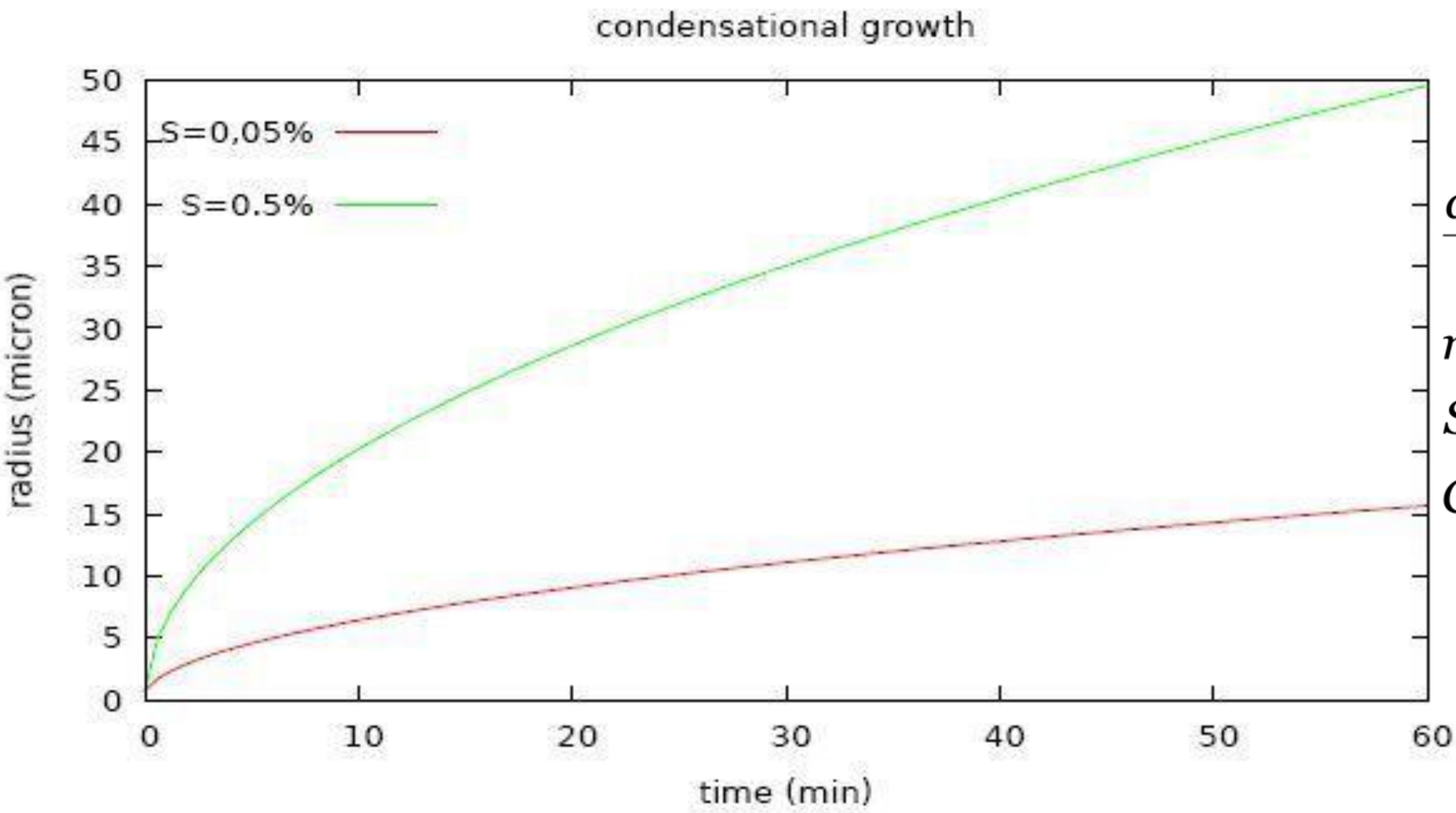
For given thermodynamic conditions the rate of growth of the drop's surface (~r^2) is constant, and depends only on the supersaturation.

In an equally supersaturated environment smaller drops grow faster (their radius grow faster) than bigger drops.

Condensational growth implies that droplet spectrum becomes narrower higher in the cloud.



Figures: Brenguier and Chaumat, JAS 2001



$$\frac{dr^2}{dt} = 2C(S-1)$$

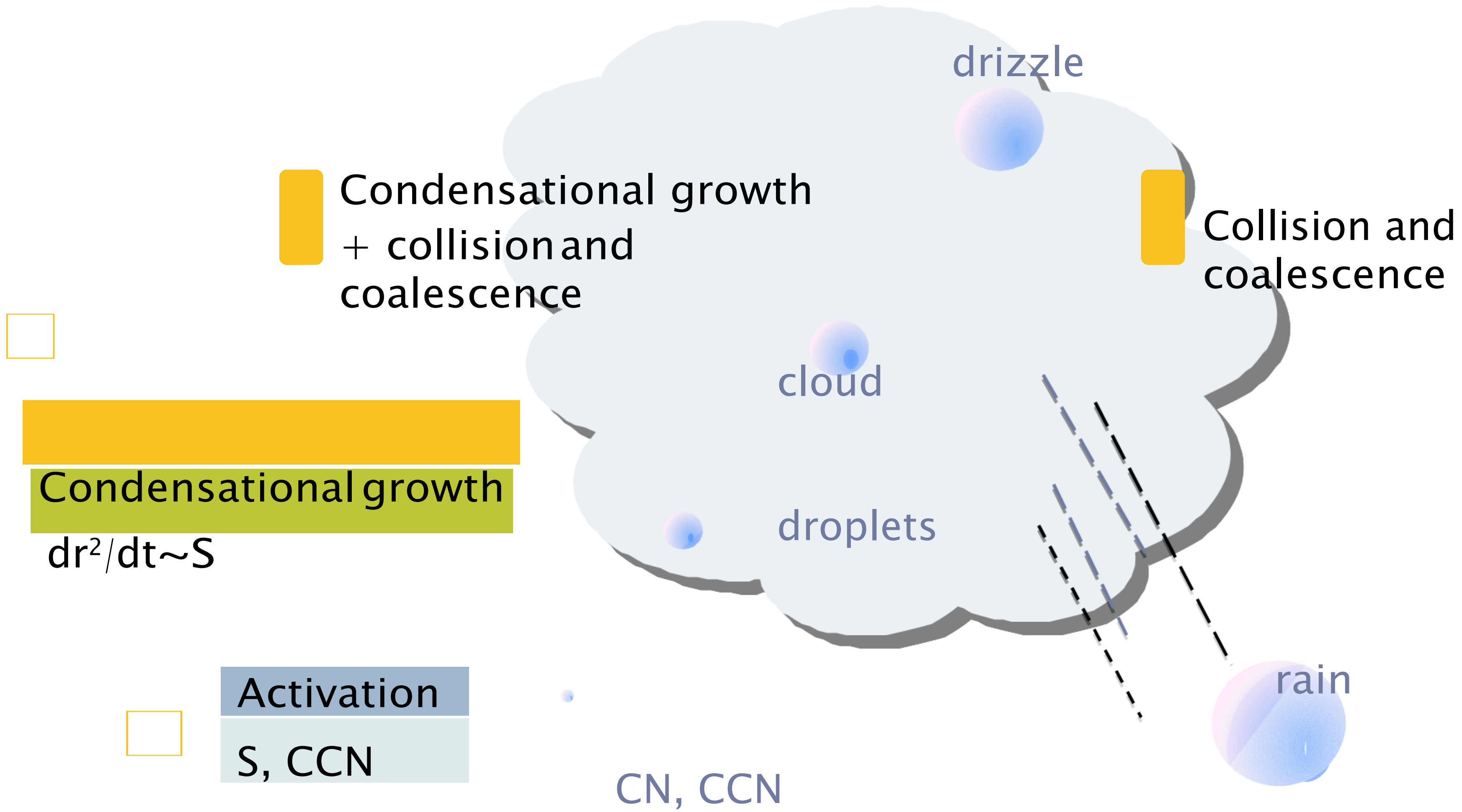
$$r = \sqrt{r_o^2 + 2C(S-1)\cdot t}$$

$$S = 0{,}05\%$$

$$C = 68.2\mu^2 s^{-1}$$

In realistic cloud conditions, growth by water-vapor diffusion seldom produces droplets with radii close to 20 μm because of the low magnitude of the supersaturation field and the time available for the growth (~10^3 s; 17 min).

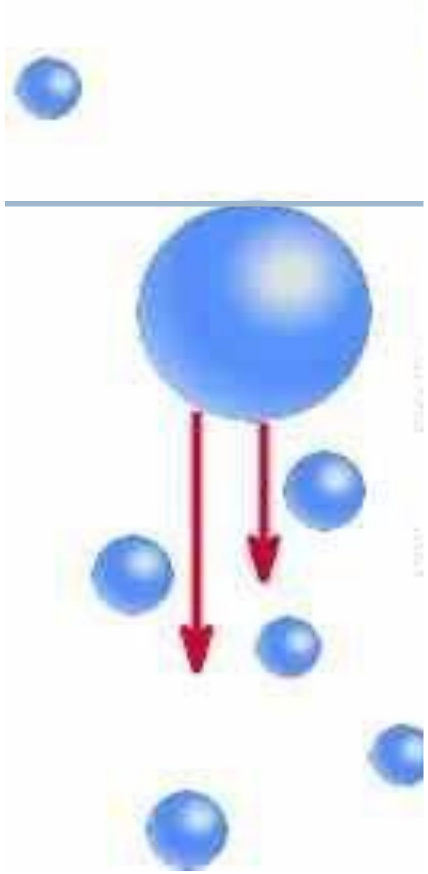
Warm cloud processes

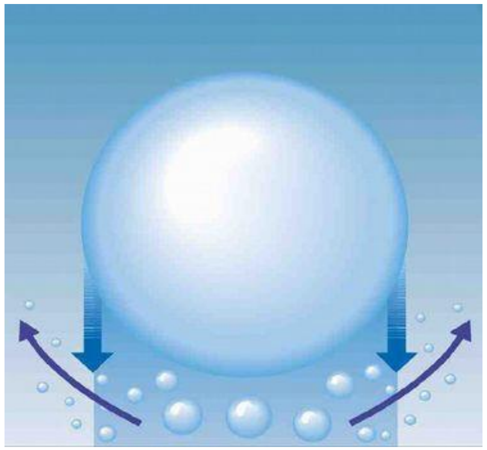


0,1 1 10 100 1000 μm

Collision

- *Collisions may occur through differential response of the droplets to gravitational, electrical, or aerodynamics forces*
  - *Gravitational effects dominate in clouds: large droplets fall faster then smaller ones, overtaking and capturing a fraction of those lying in their path*





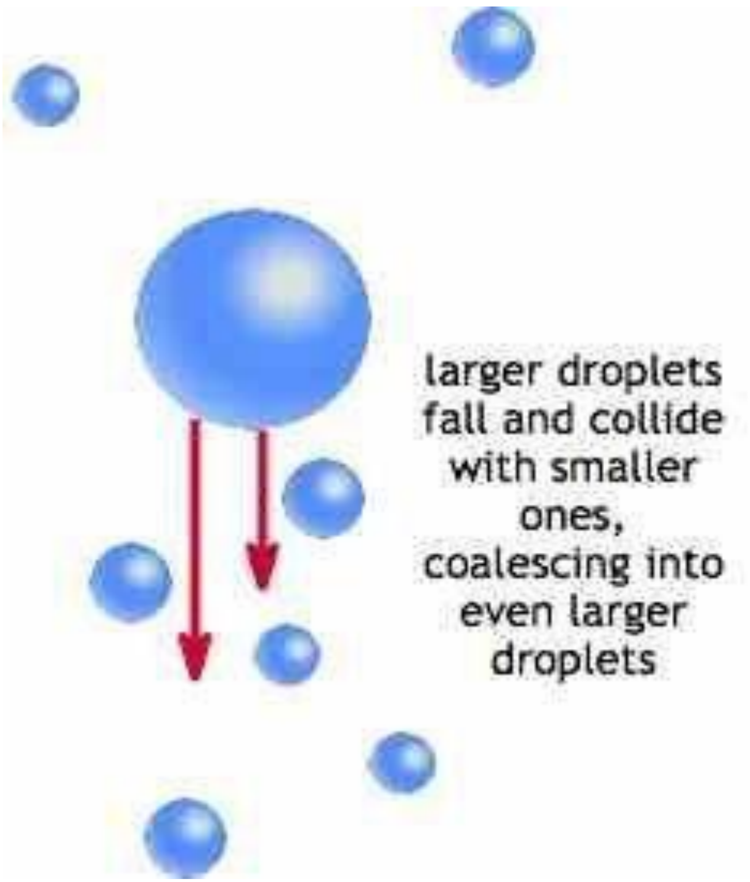
Small droplets can also be swept aside

If drops have the same size, no overtaking or collision

Coalescence, collection efficiency

- Collision does not guarantee coalescence.
- For drops smaller than 100 μm the most probable types of interactions are :
  - they may bounce apart
  - they may coalesce and remain permanently united
- The ratio of the number of coalescences to the number of collisions is called the coalescence efficiency
- The growth of the drop by the collision-coalescence process is governed by the collection efficiency, which is the product of collision efficiency and coalescence efficiency

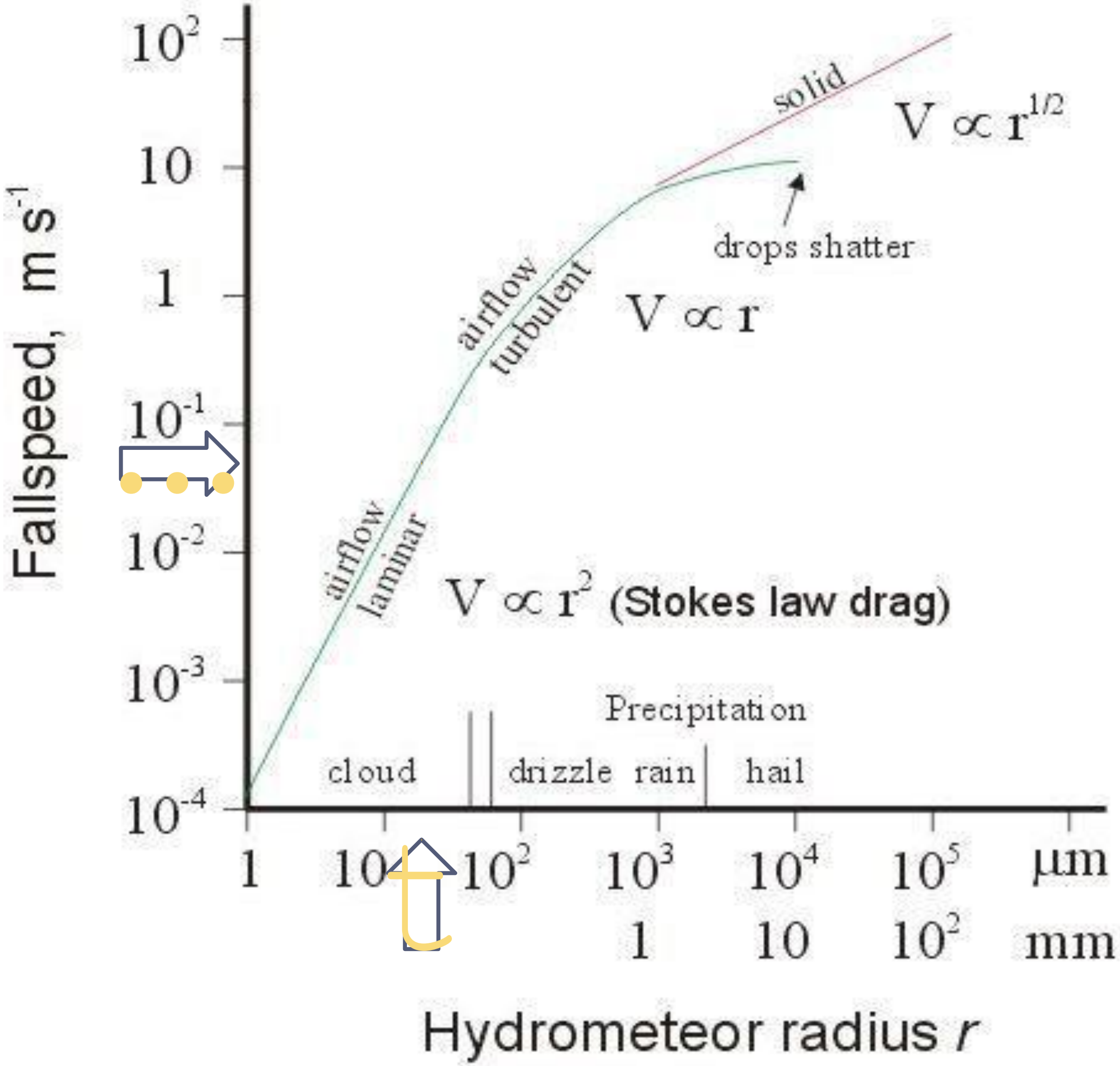
Gravitational collision-coalescence



The textbook explanation of rain formation in ice-free clouds: gravitational collision-coalescence…

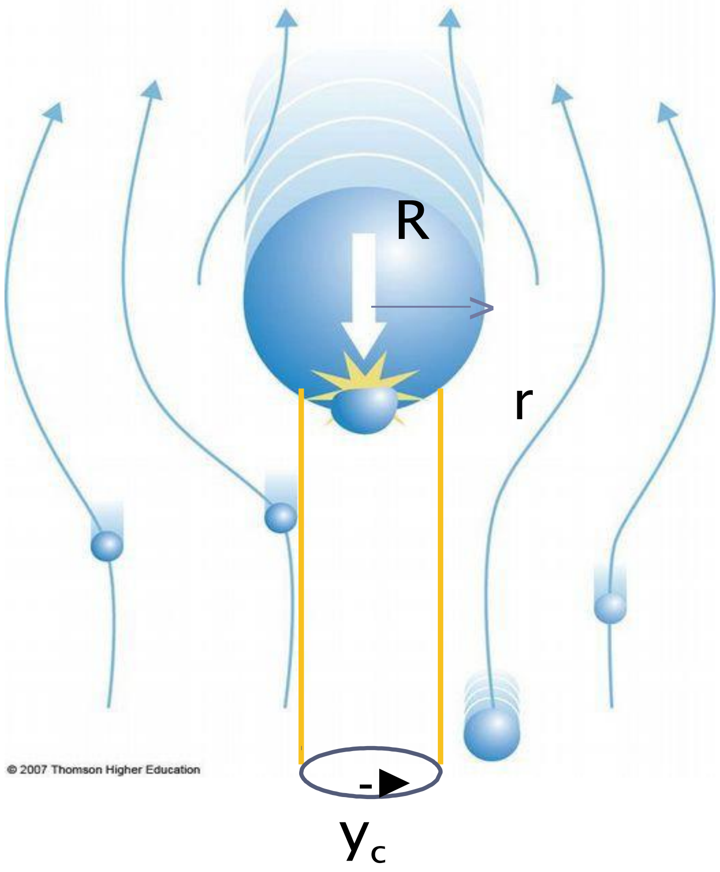
For this mechanism to be efficient the differential fall spead has to be large…..

Cloud particle fall speed

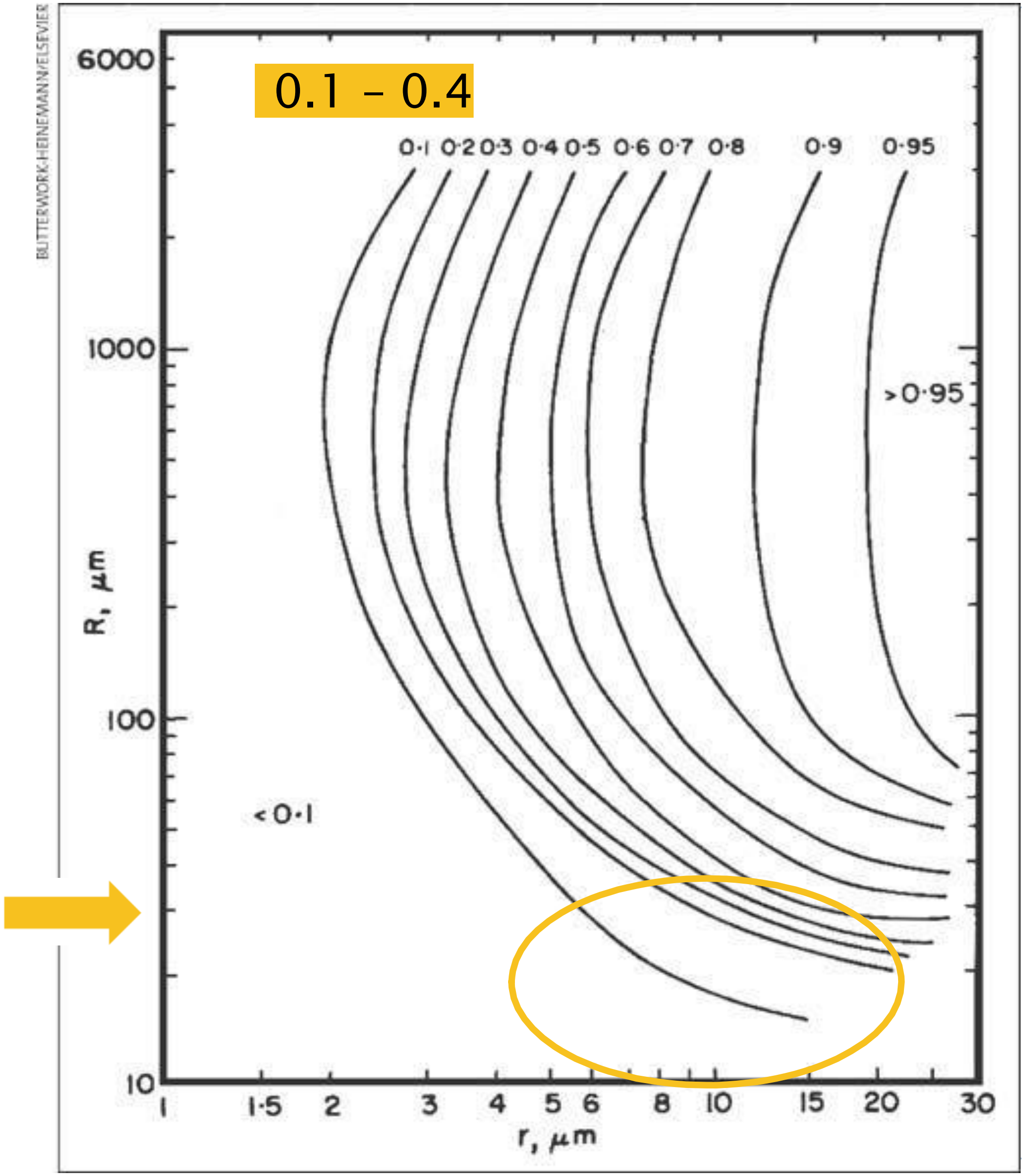


Adapted from McIlveen (1992)

Collision efficiency for the gravitational case



$$E_c = \frac{y_c^2}{(R+r)^2}$$



Condensational growth
Collision-coalescence (accretion) growth

Gravitational collisions between cloud droplets are effective when the droplet radius reaches approximately 40 μm

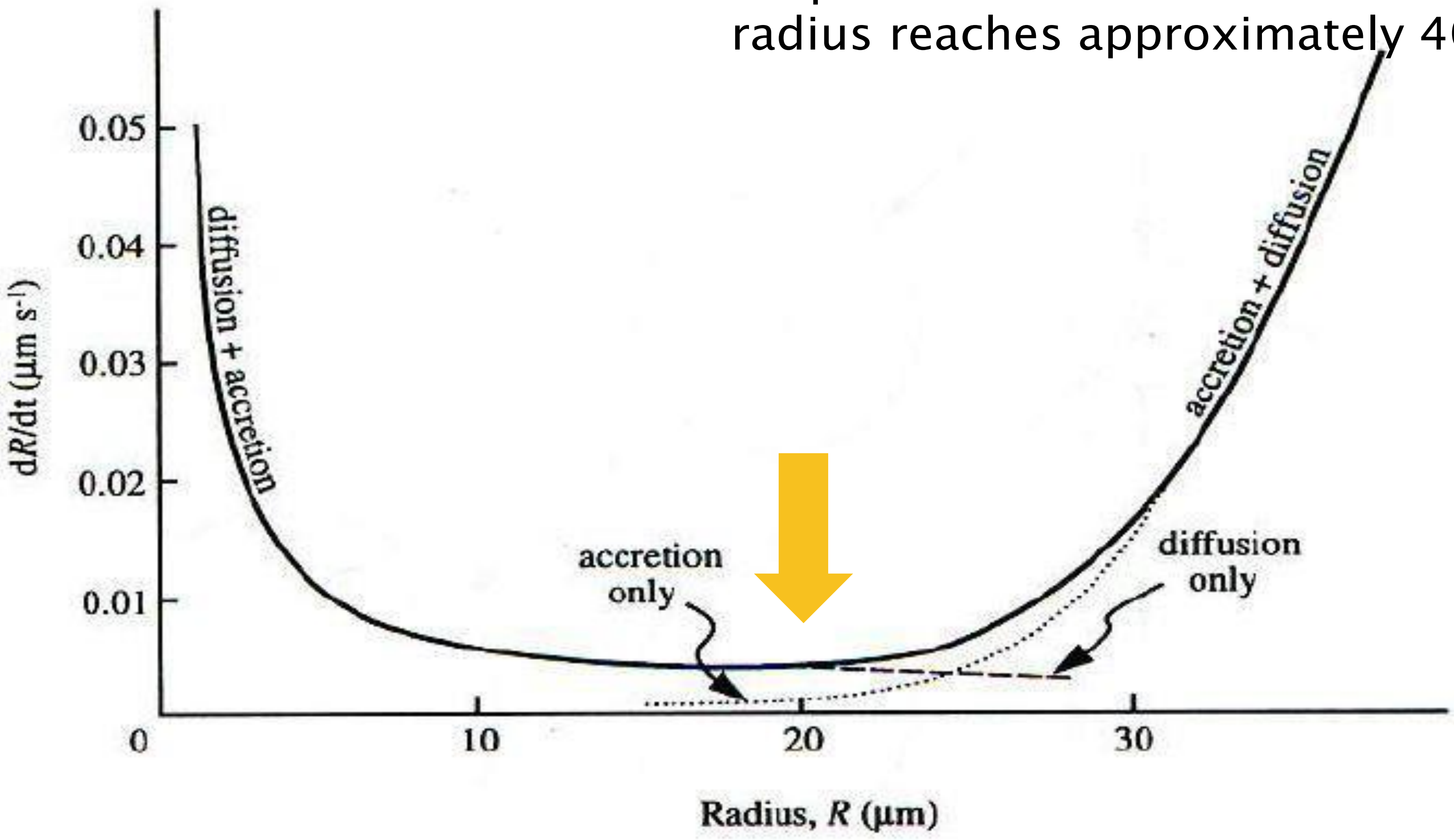


Figure 8.6 Drop growth rate by condensation and accretion. The dashed line represents growth by diffusion only, and the dotted line represents growth by accretion only, while the solid curve represents the combined growth rate. Condensational growth rate decreases with increasing radius, while accretional growth rate increases with increasing radius.

Warm cloud processes

- Condensational growth + collision and coalescence

- Collision and

Gravitational turbulence

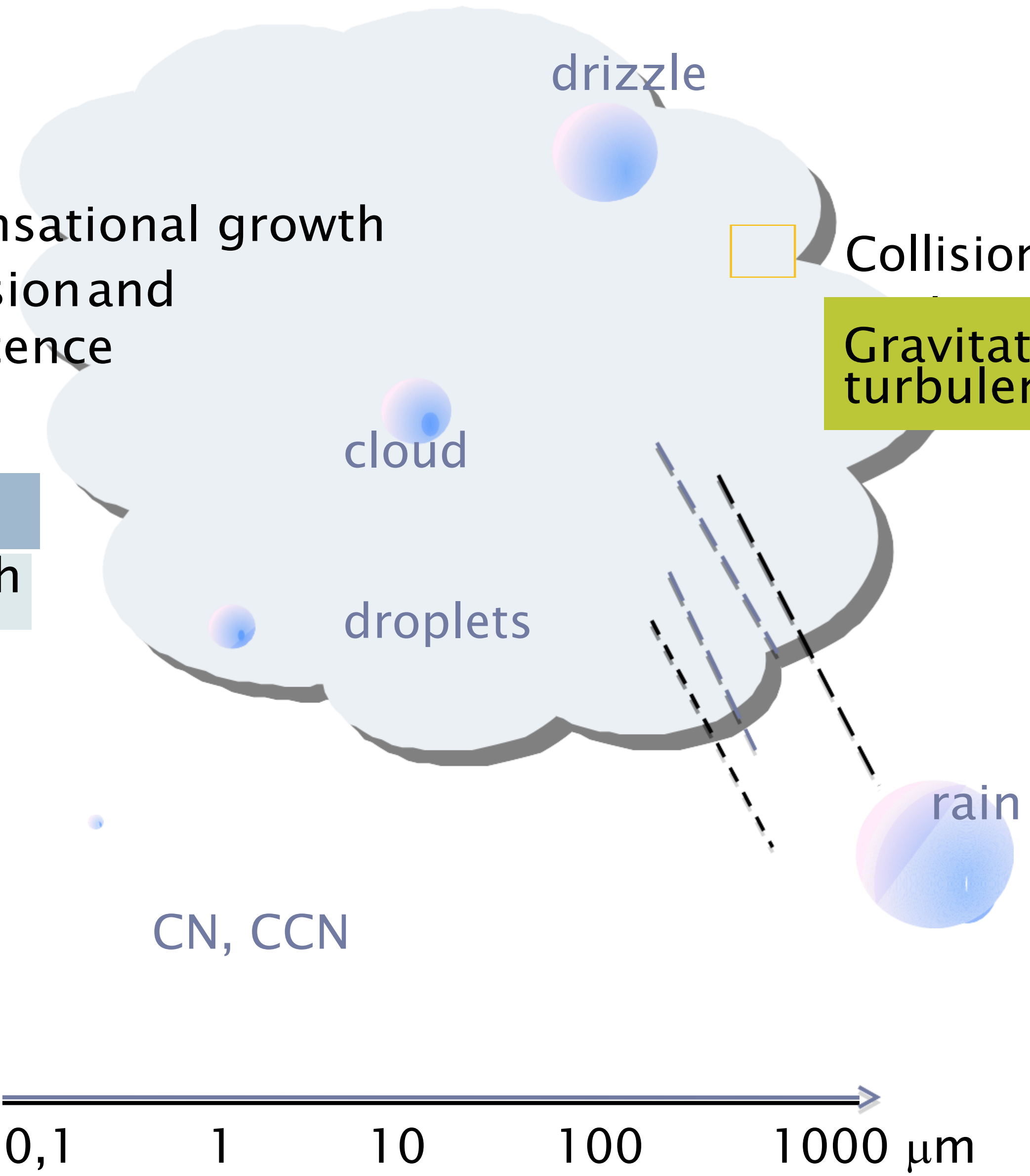
-

Condensational growth

$dr^2/dt \sim S$

- Activation

S, CCN



OPEN ISSUES

- In-cloud activation
- Spectrum broadening by entrainment/mixing processes
- Impact of small-scale turbulence on collision/coalescence

Warm cloud processes

OPEN ISSUES

In-cloud activation

Condensational growth
+ collision and
coalesce n

Narrow cloud droplet spectrum

Gravitational collision
not efficient

Collision and

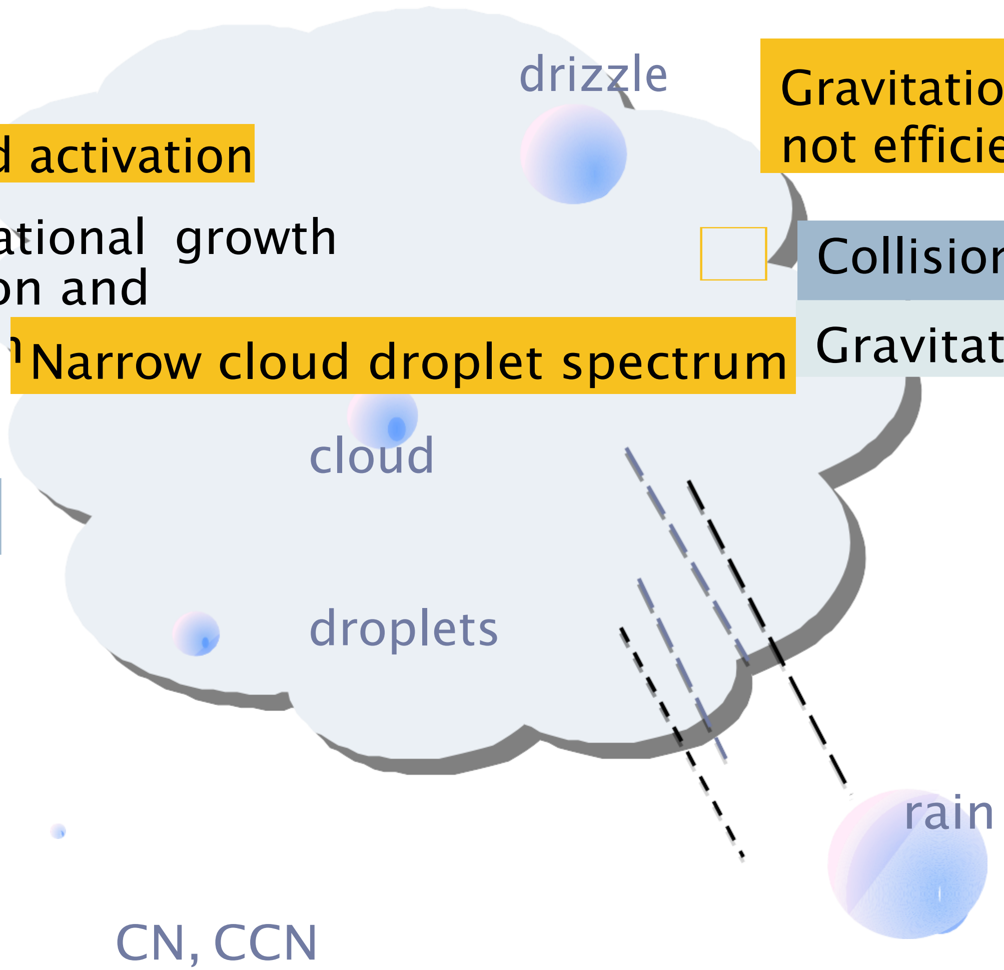
Gravitational

Condensational growth

$dr^2/dt \sim S$

Activatio

S, CCN



0,1 1 10 100 1000 μm

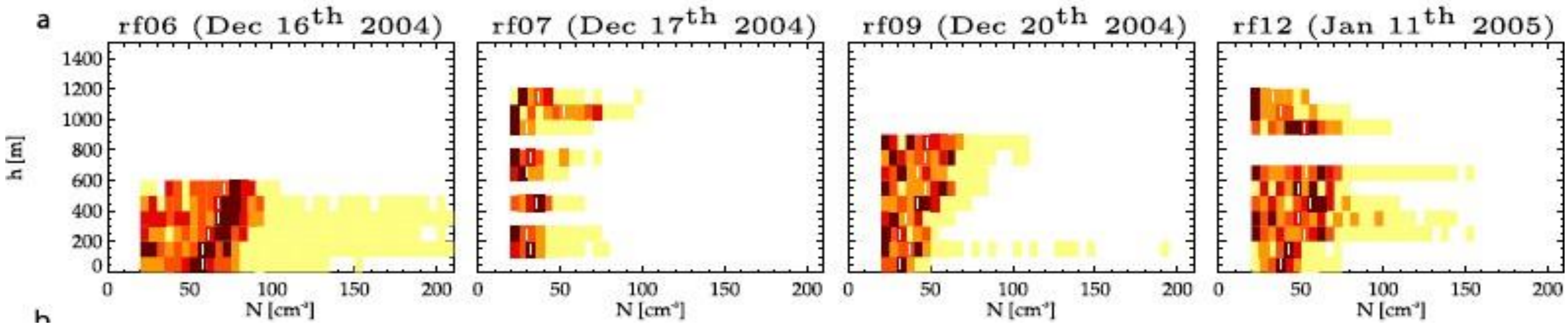
In-cloud activation

Table 3. Microphysics of the seven Cu at five different levels shown in Fig. 2, with mean values of LWC (liquid water content) and its sample standard deviation for three horizontal data resolutions, total droplet concentration N, and mean volume radius r_v. The latter two parameters correspond to 10-m resolution data. The subscript a indicates expected adiabatic values.

Level	LWC_a (g/m³)	LWC (g/m³)	s (10 cm) (g/m³)	s (50 cm) (g/m³)	s (1000 cm) (g/m³)	N (No/cc)	s [N] (No/cc)	r_{va} (μm)	r_v (μm)	s (r_v) (μm)
1	.605	.284	.084	.078	.063	95	12	11.4	9.2	2.0
2	1.00	.427	.142	.136	.128	97	22	13.5	10.6	3.1
3	1.42	.520	.160	.153	.145	112	25	15.2	10.2	1.7
4	2.11	.536	.196	.184	.173	116	11	17.3	10.6	2.4
5	2.46	.331	.142	.135	.125	54	35	18.2	11.9	3.7

Gerber et al., JMSJ, 2008

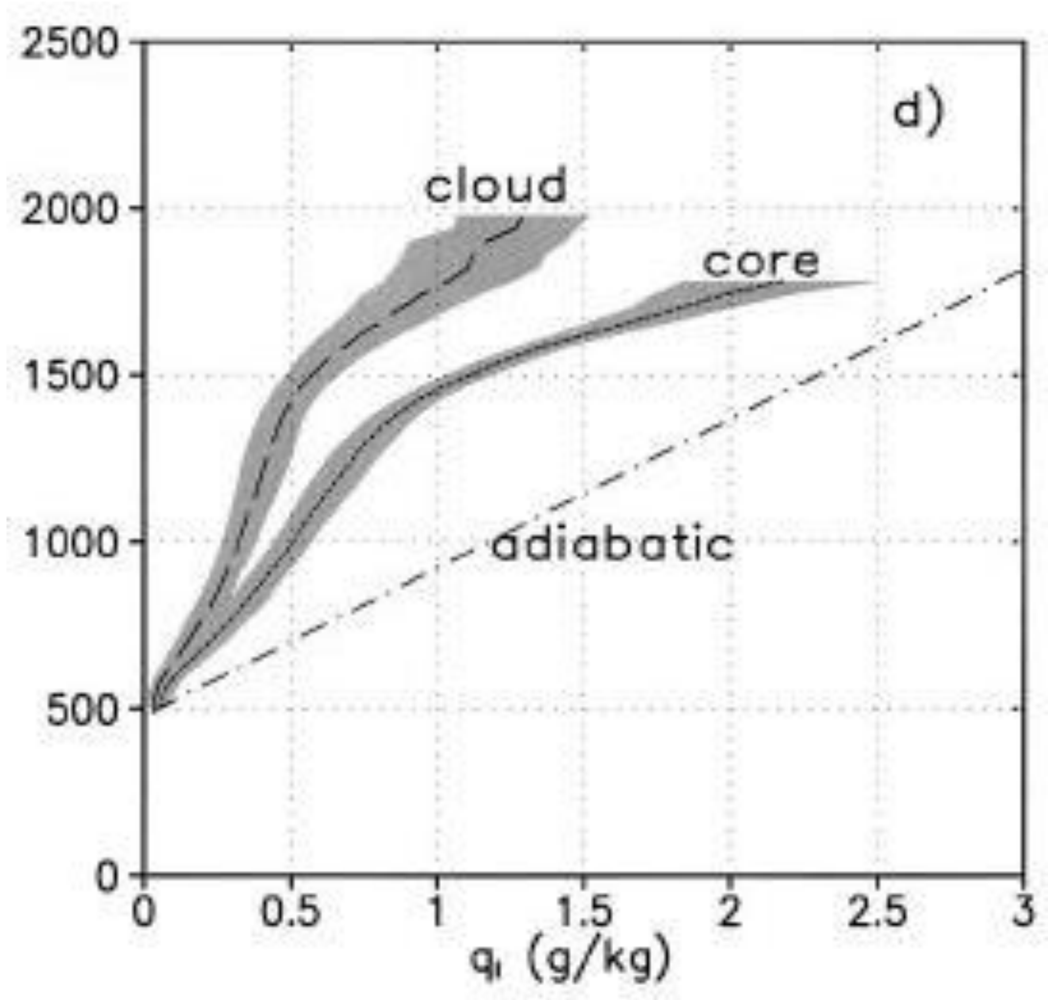
ARABAS ET AL.: OBSERVATIONS OF CU MICROPHYSICS



Arabas et al. GRL 2009

Shallow convection during RICO (Rain in Cumulus over the Ocean)

How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?

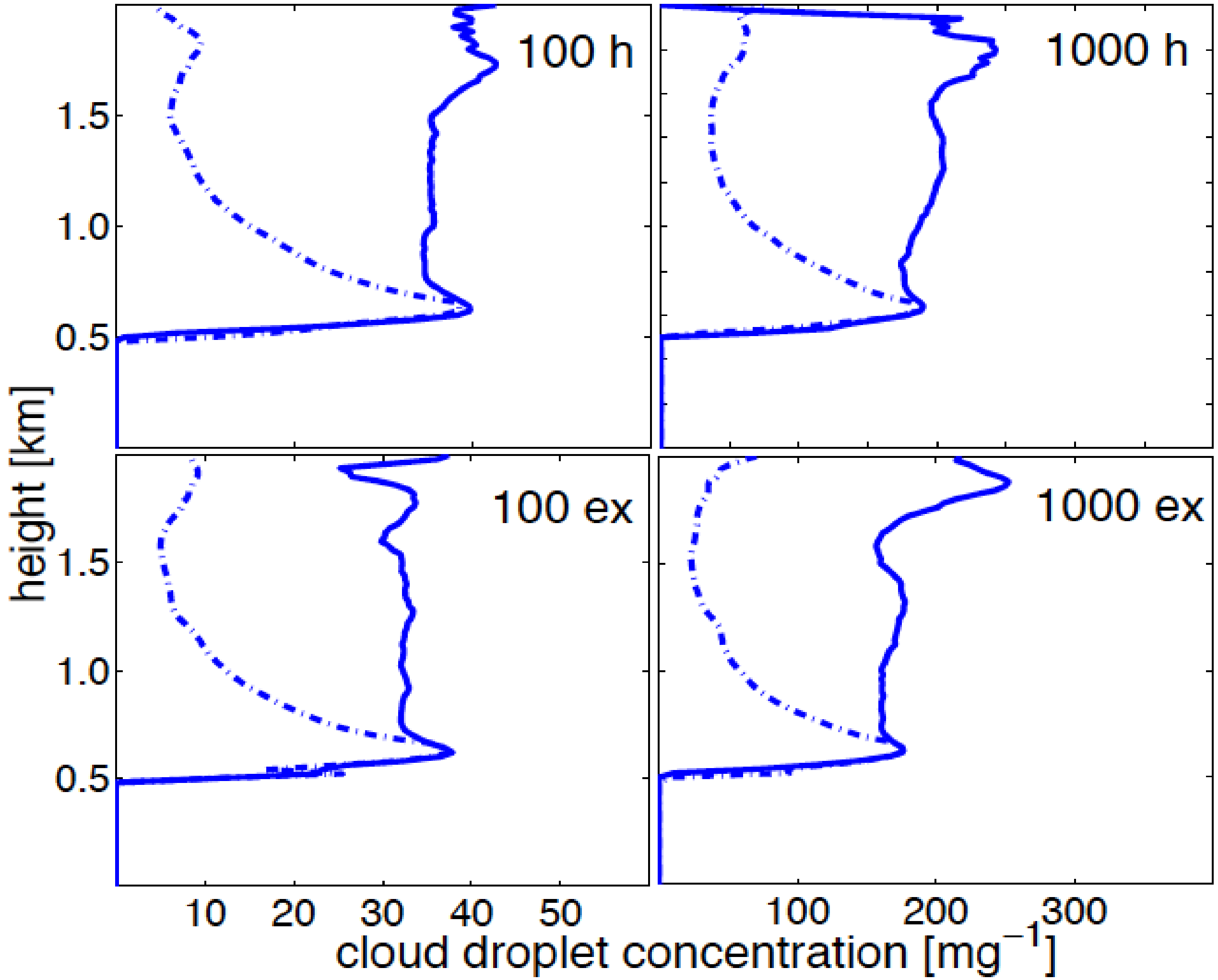


How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?

In-cloud activation

(i.e., activation above the cloud base)!

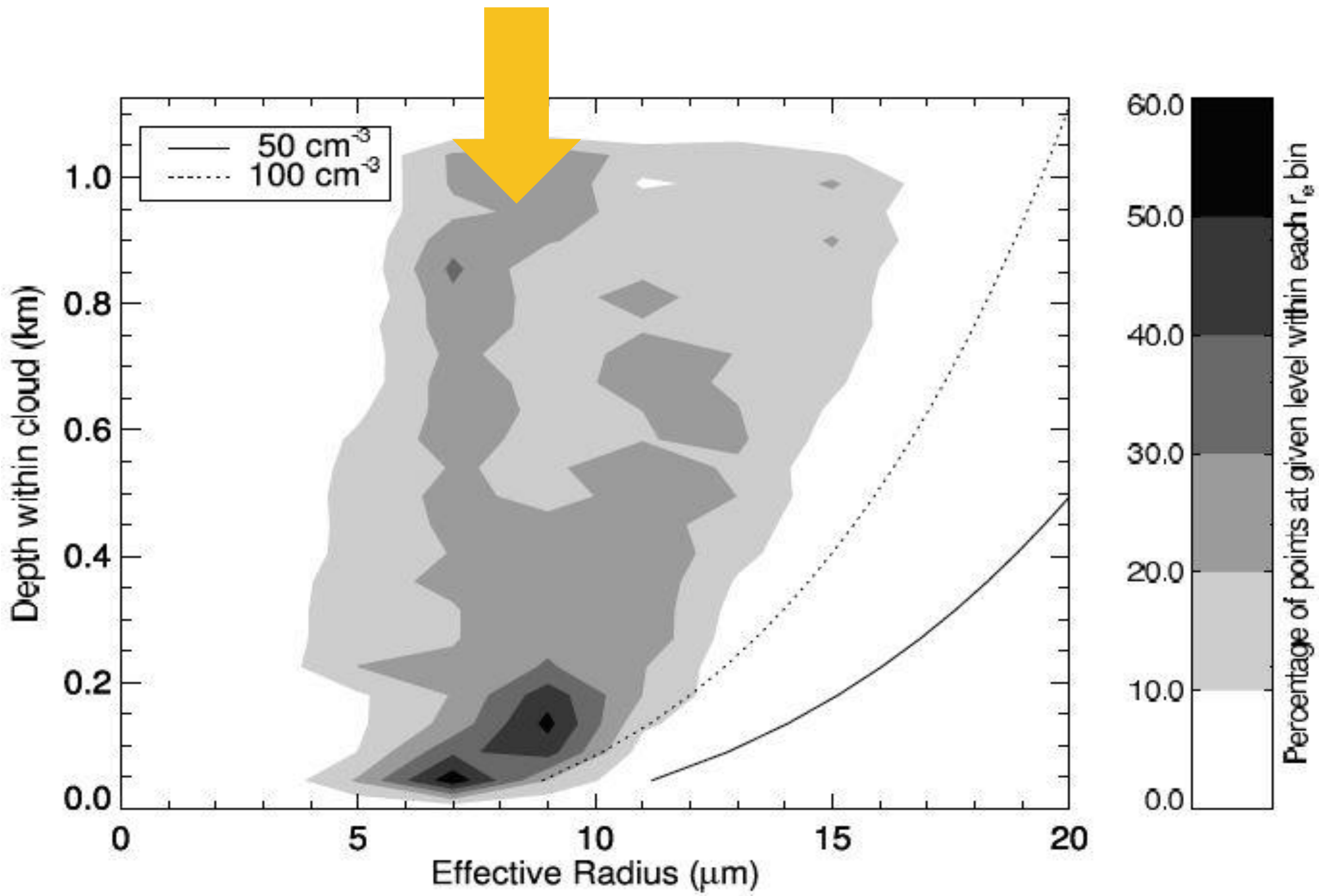
In-cloud activation



LES modelling with 2-moment microphysics.

Slawinska et al., JAS 2011

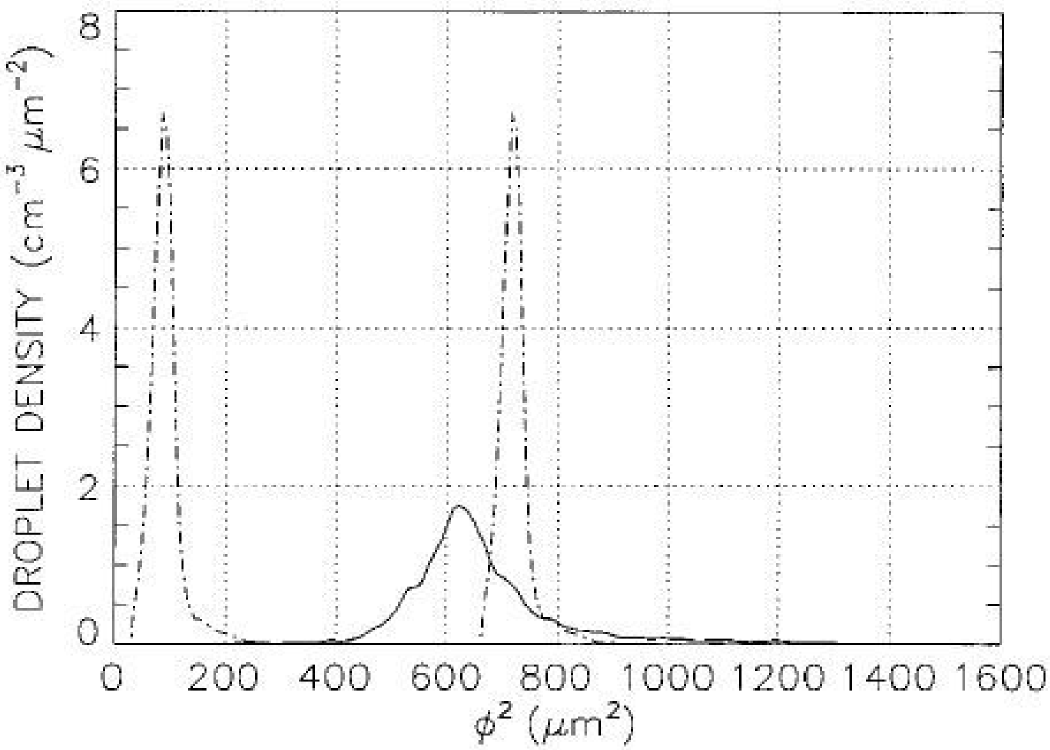
In-cloud activation…???



Grabowski, W.W. and S. A. McFarlane, 2007: Optical properties of shallow tropical cumuli derived from ARM ground-based remote sensing, *Geophys. Res. Let*.

Spectral broadening

The observations show broad droplet spectra while the idealized model of droplet growth in an adiabatic convective cell predicts narrow spectra.



The r^2 (Φ^2) distribution (solid line) for measurements during SCMS. Comparison with the adiabatic reference (dot-dashed line). The initial reference spectrum is represented by a dot-dashed line on the left.

Figures: Brenguier and Chaumat, JAS 2001

Spectral broadening through different growth histories

- Simulation of a small cumulus, illustrating the idea of cloud-droplet growth through large-eddy hopping.
- The figure shows the cloud water field and a small subset of droplet trajectories arriving at a single point at the upper part of a cloud.
- The trajectories are colored according to the liquid water content encountered.
- The variability of the vertical velocity across the cloud base already results in some differences in the concentration of activated cloud droplets at the starting point of the trajectories.
- There are also relatively small-scale changes in color along the trajectories, highlighting variable environments in which the droplets grow.

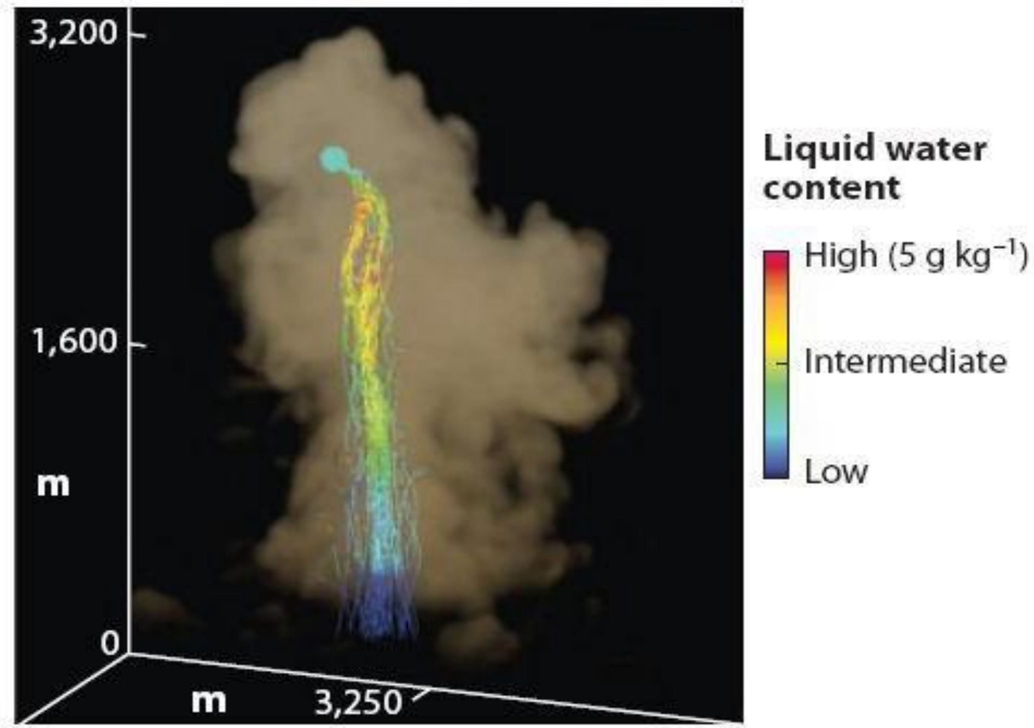
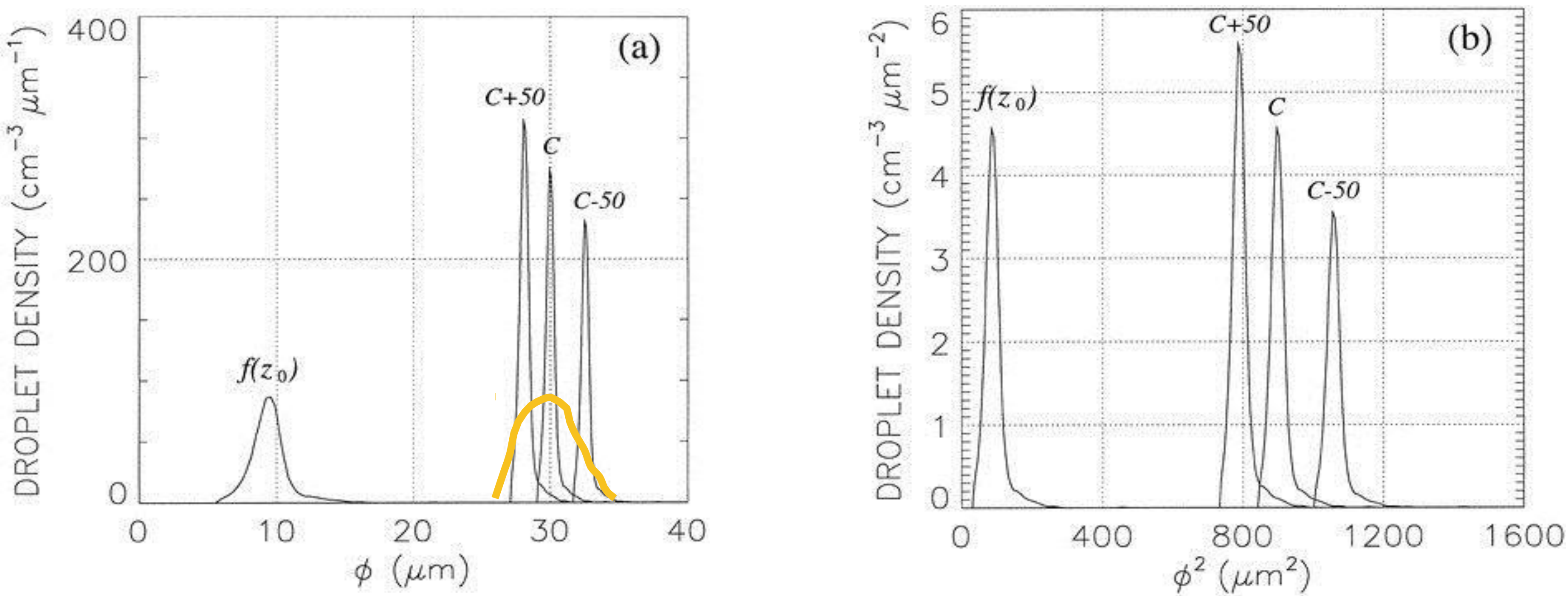


Figure courtesy of S. Lasher-Trapp

Spectral broadening



Spectrum evolution in an adiabatic updraft. The curve labeled C is the corresponding spectrum after condensational growth. Curves labeled *C +50 and C -50 are the* resulting spectra for a total droplet concentration of *C ±50 cm*$^{-3}$.

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Figures: Brenguier and Chaumat, JAS 2001

Homogeneous and inhomogeneous mixing in cloud

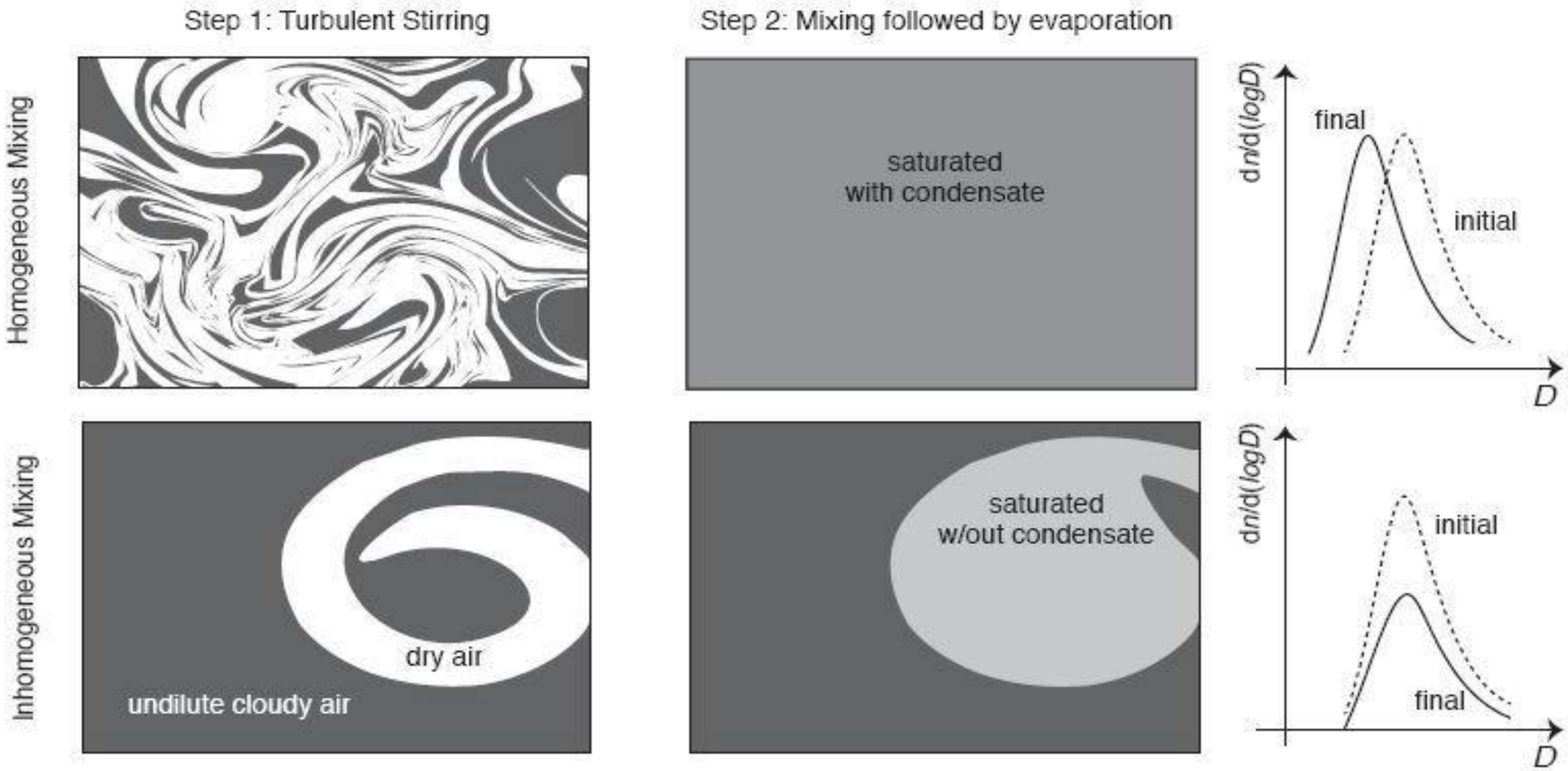
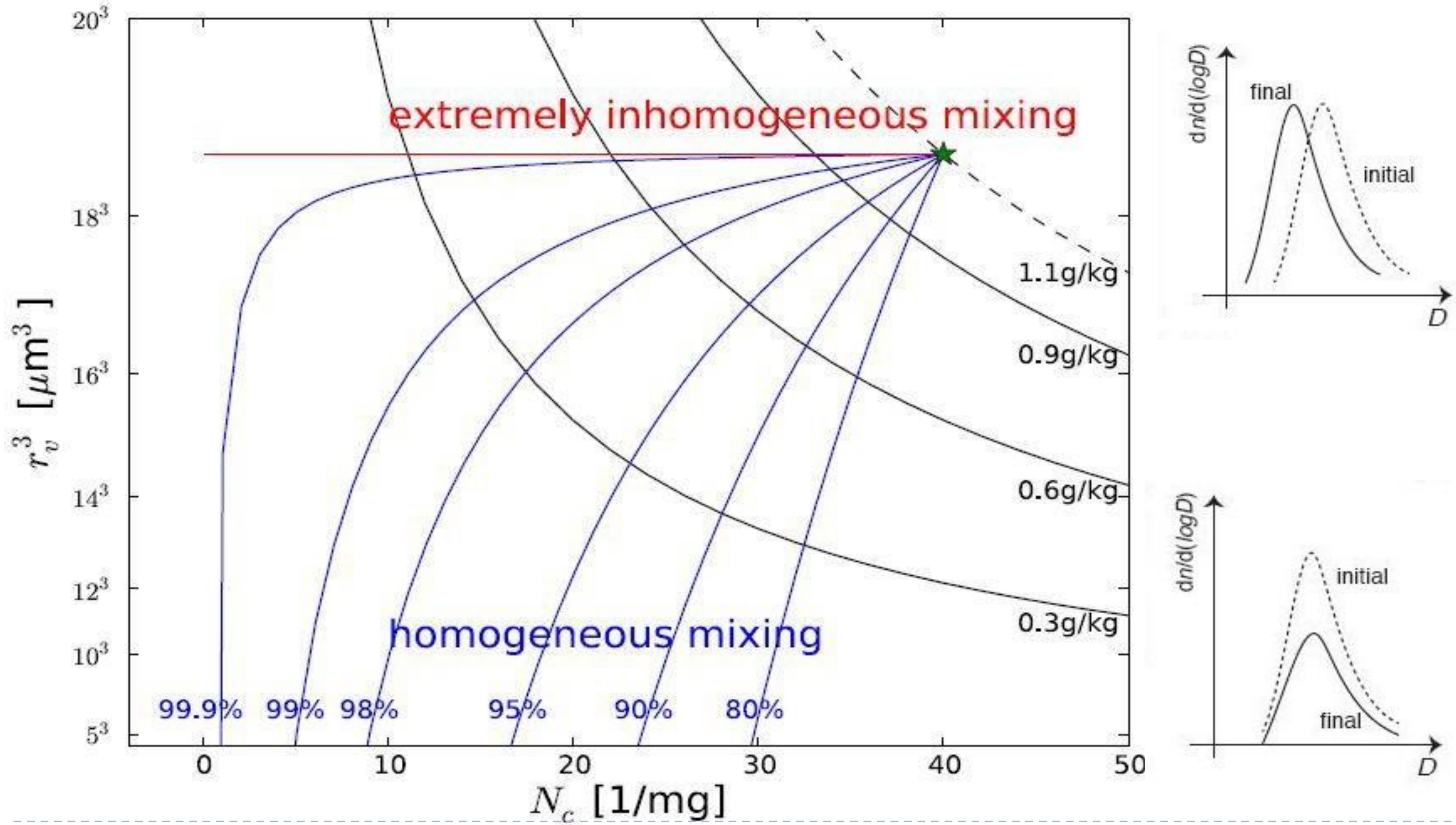


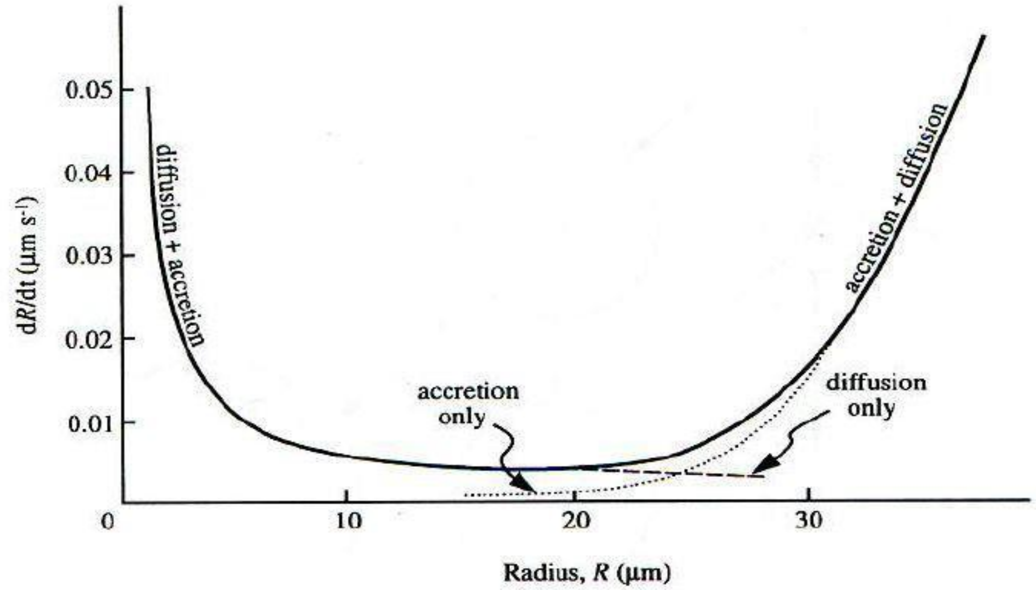
Figure: B. Stevens

Homogeneous and inhomogeneous mixing
Spectral broadening through different histories



The size-gap problem

- It is difficult to explain the rapid growth of cloud droplets in the size range 15–40 μm in radius for which neither the diffusional mechanism nor the collision–coalescence mechanism is effective (i.e. the condensation–coalescence bottelneck or the size gap)



- Several mechanisms have been proposed, including:
  - Entrainment of dry air into the cloud
  - The effect of giant aerosol particles
  - Turbulent fluctuations of the water–vapor supersaturation
  - The turbulent collision–coalescence

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

- Turbulence modifies local droplet concentration (preferential concentration effect)

- Turbulence modifies relative velocity between droplets

- Turbulence modifies hydrodynamic interactions when two drops approach each other

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

- Turbulence modifies local droplet concentration (preferential concentration effect)

- Turbulence modifies relative velocity between droplets

- Turbulence modifies hydrodynamic interactions when two drops approach each other

Geometric collisions,
(no hydrodynamic interactions)

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence

- Turbulence modifies local droplet concentration (preferential concentration effect)

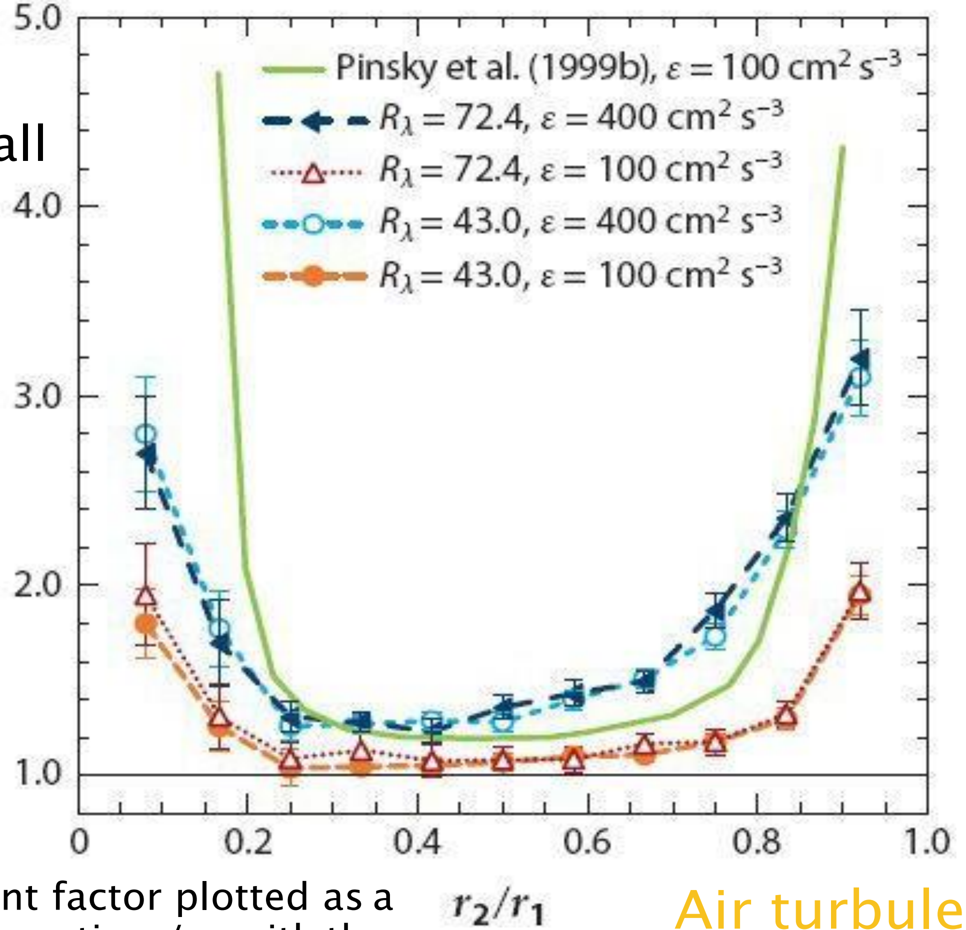
- Turbulence modifies relative velocity between droplets

- Turbulence modifies hydrodynamic interactions when two drops approach each other

Collision efficiency

The net enhancement factor (the ratio of the turbulent collection kernel and the hydrodynamic-gravitational collection kernel)

When $r_2/r_1 << 1$, the gravitational kernel may be small owing to small collision efficiency.



When r_2/r_1▪1, the gravitational kernel is small owing to the small differential sedimentation.

Grabowski and Wang, ARFM 2013

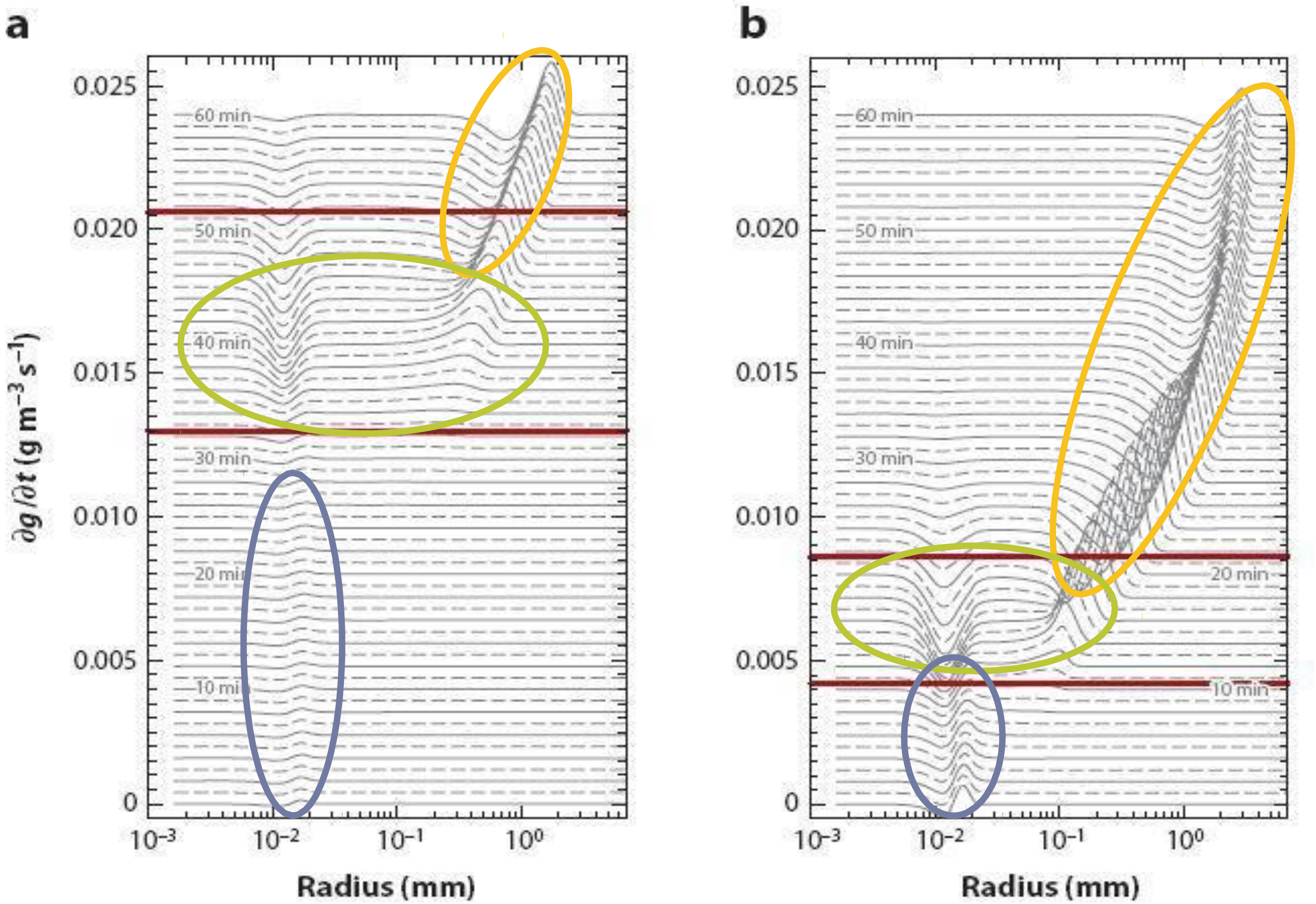
The net enhancement factor plotted as a function of the radius ratio r_2/r_1, with the larger droplet 30 μm in radius. ϵ is the flow viscous dissipation rate, and R_λ is the Taylor microscale Reynolds number of the simulated background turbulent airflow.

Air turbulence plays an important role in enhancing the gravitational collision kernel when the collision efficiency is small. It enhances collection kernel by a factor up to 5.

1- autoconversion

2 - accretion

3 - Hydrometeor self-collection (Berry and Reinhardt, 1974)



Without turbulence   With turbulence

Xue, Y., L.P. Wang, and W. W. Grabowski, 2008)

Summary

- Small-scale turbulence alone does not produce a significant broadening of the cloud-droplet spectrum during diffusional growth.
- The coupled small-scale and larger-scale turbulence, combined with larger-scale flow inhomogeneity, entrainment, and fresh activation of CCN above the cloud base , creates different growth histories for droplets. This leads to a significant spectral broadening.
- The effect of turbulence on the collision-coalescence growth is significant.
- Turbulence of moderate magnitudes leads to a significant acceleration of warm rain initiation.

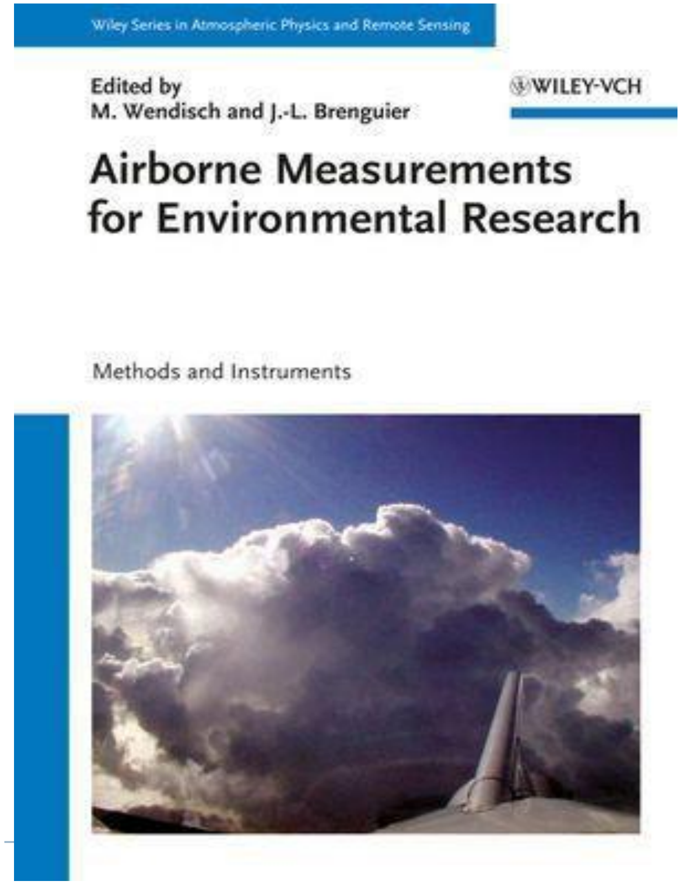
Observations, measurements

In-situ measurements

Remote sensing

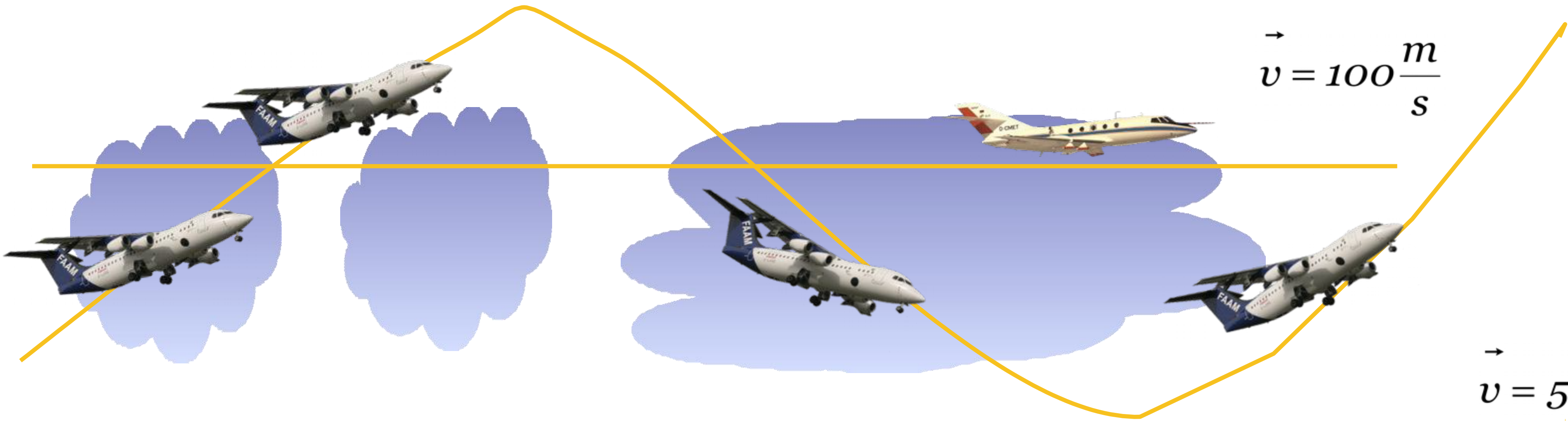
In-situ measurements

- Direct measurements in clouds
  - Instrumented aircrafts
  - Airborne laboratories (as ACTOS – Airborne Cloud Turbulence Observation System)



In-situ measurements
Instrumented aircrafts

EUFAR
European Facility
For Airborne
Research

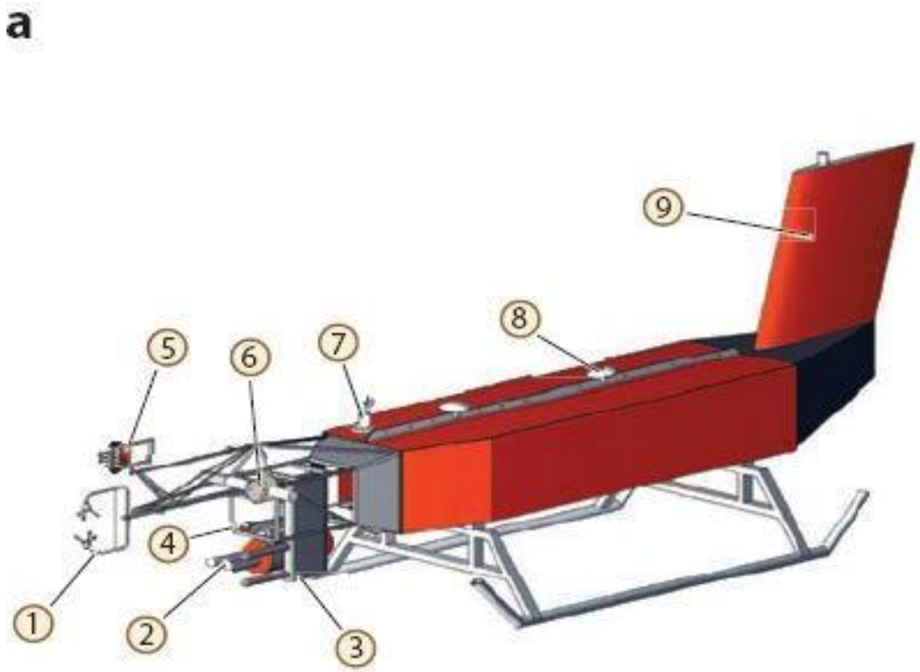


$$\vec{v} = 100\,\frac{m}{s}$$

$$\vec{v} = 5\,\frac{m}{s}$$

Vertical distance: 500 m, horizontal distance: 10 km

In-situ measurements
ACTOS – Airborne Cloud Turbulence Observation System



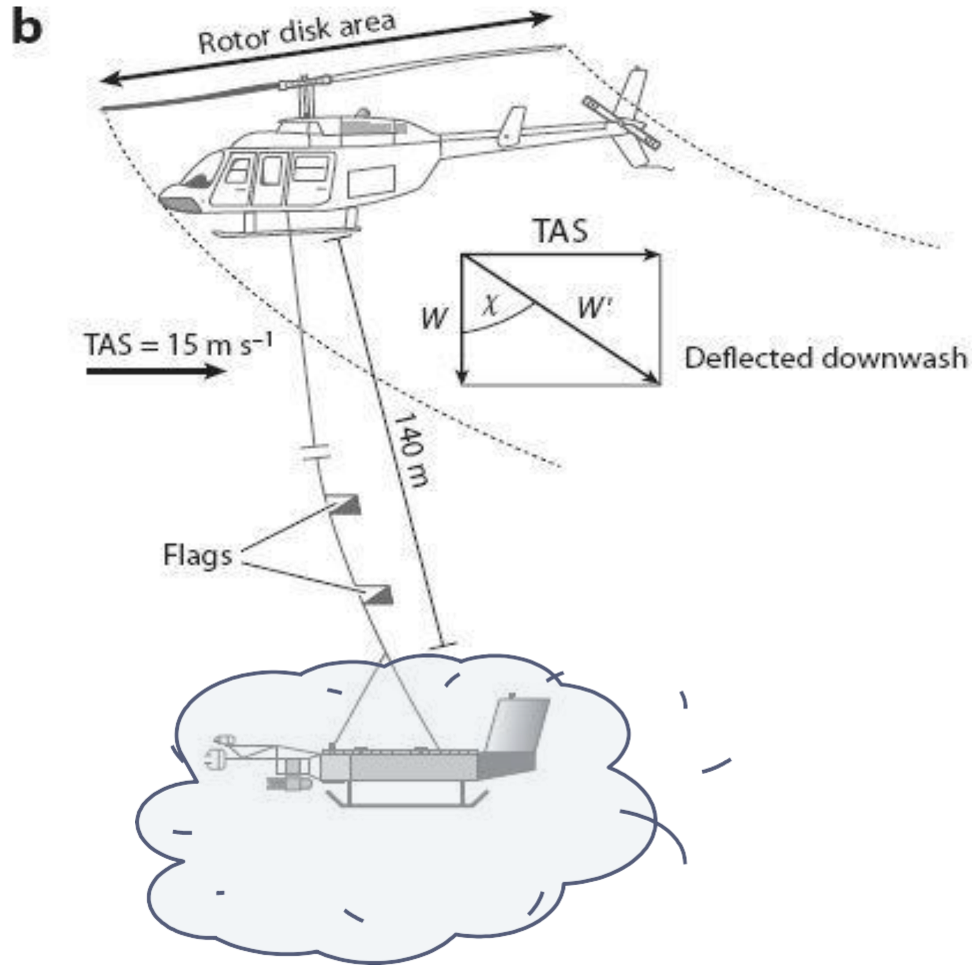


Figure: Siebert et al. 2006

Airborne measurements

Aircraft-borne

- Observing the wide range of scales from an aircraft is challenging because of the aircraft speed (~100 m/s)
- This requires instruments with extremly fast response time
- They need to be located close to each other to provide information about small-scale structures
- Possible to represent 'vertical cloud structure'
- Impossible to distinguish between causes and effects …. Example will be given

Helicopter-borne

- Significantly lower horizontal speed
- Much better resolution
- Instruments have to be located closly
- Limited flight ceiling (helicopter are not allowed to fly through clouds)
- Measurements don't represent large scale phenomena
- Very suitable to study turbulence processes

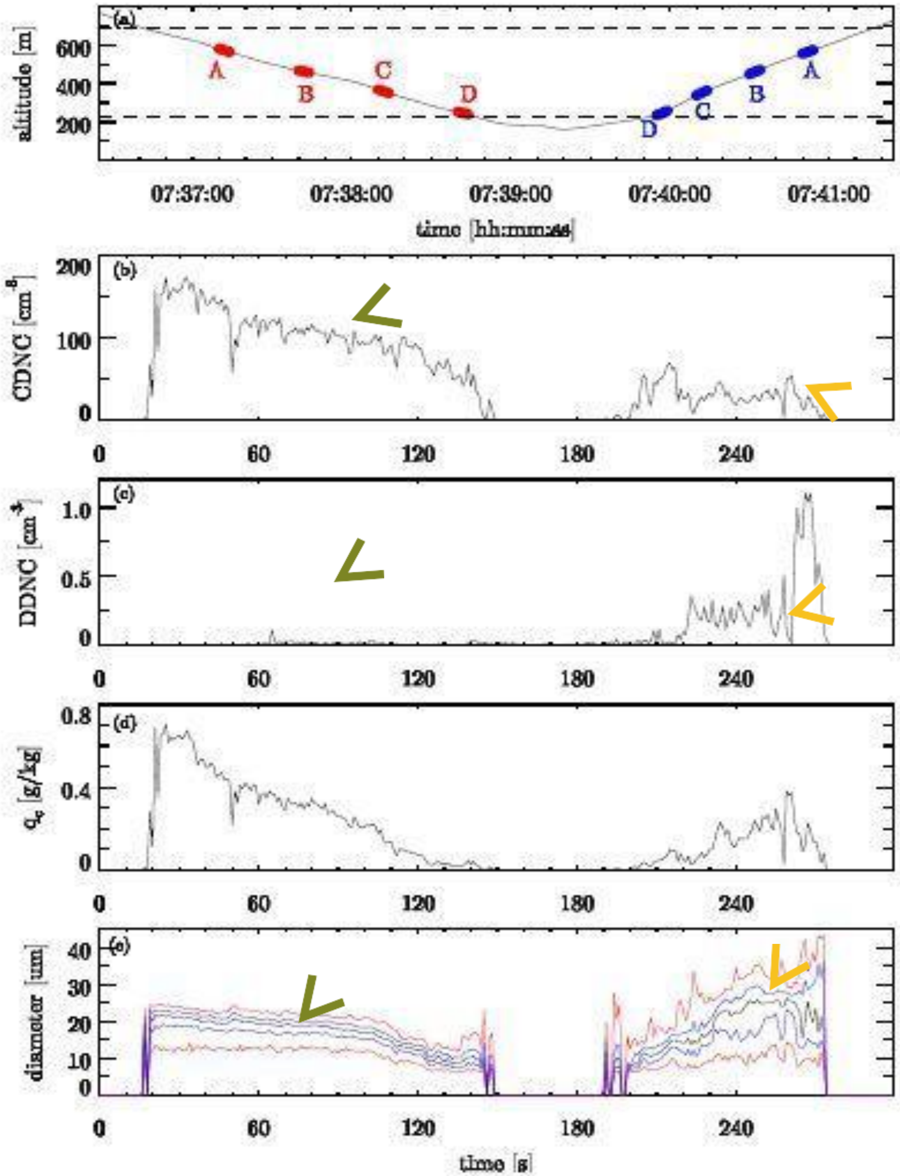
Cause and effect

Cloud droplets concentration

Drizzle drops concentration

Liquid water content

Droplets spectrum percentiles



High droplets concentration
No drizzle
Narrow spectrum

Low droplets concentration
Significant amount of drizzle
Wide spectrum

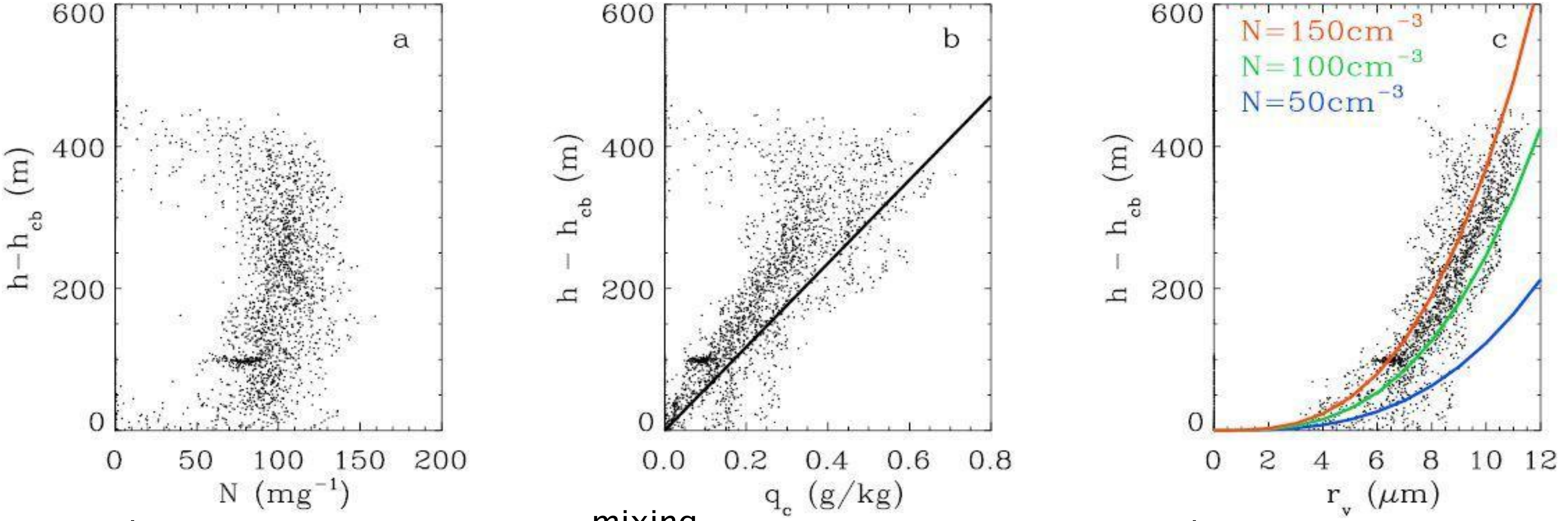
Time series of measurements taken during two ‘vertical traverses’ through stratocumulus layer during DYCOMS-II experiment

(2001)

- The vertical stratification of droplet size must be resolved because it is central to both the cloud albedo and the precipitation process

'Vertical' profiles

EUCAARI – IMPACT experiment
SCu over the North Sea, 2008



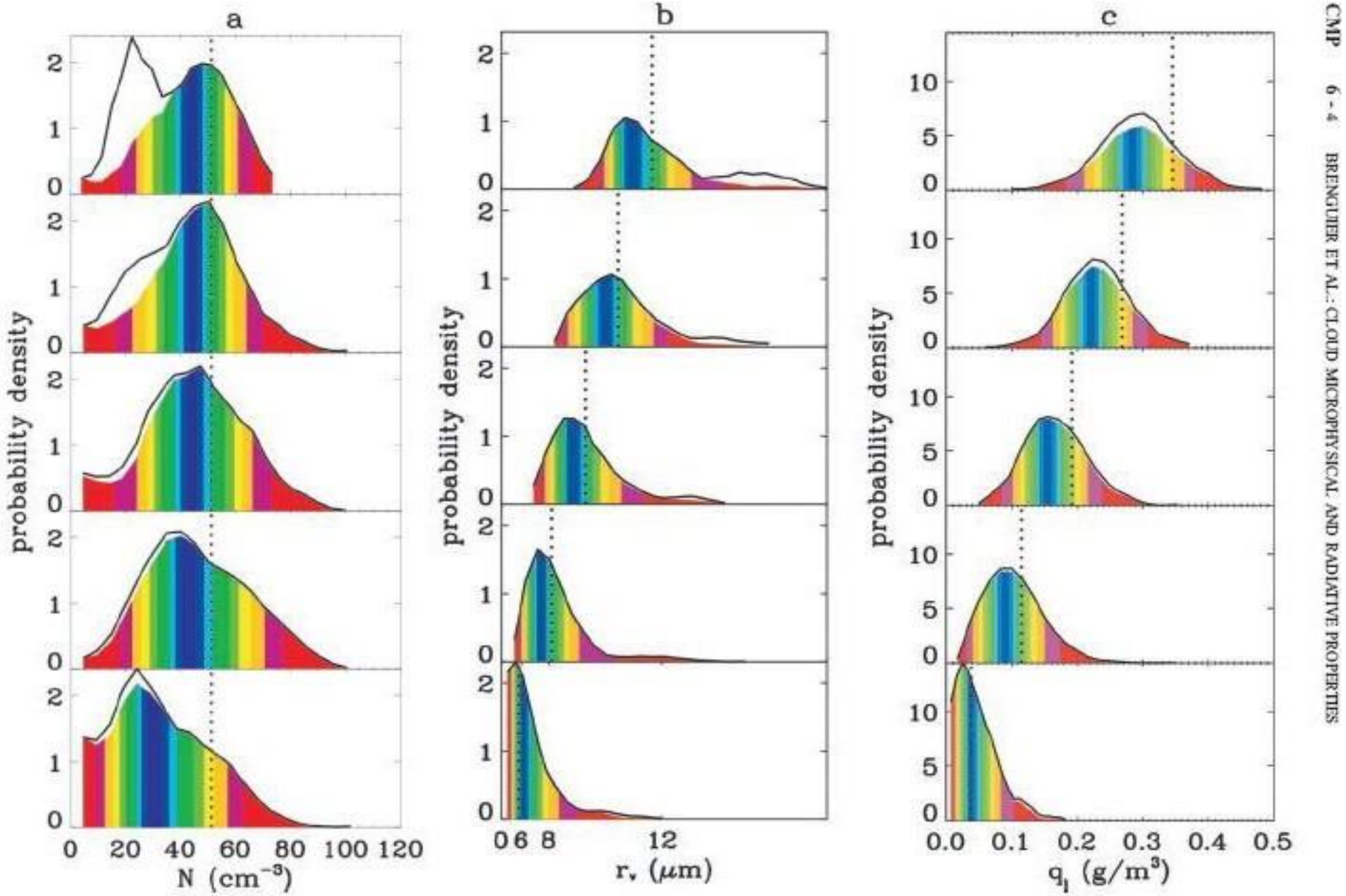
- Droplet concentration constant with height
- Small values near the cloud base are due to instrument limitation (it misses small droplets)
- Small values at the cloud top are due to entrainment and mixing

- Liquid water content increases with height (solid line adiabatic value)
- LWC values bigger than adiabatic belongs probably to cumulus that enter into Scu
- LWC depletion at the cloud top due to entrainment

Mean volume radius follows adiabatic profile for $N=100\ cm^{-3}$

Jarecka et al., JAS 2013

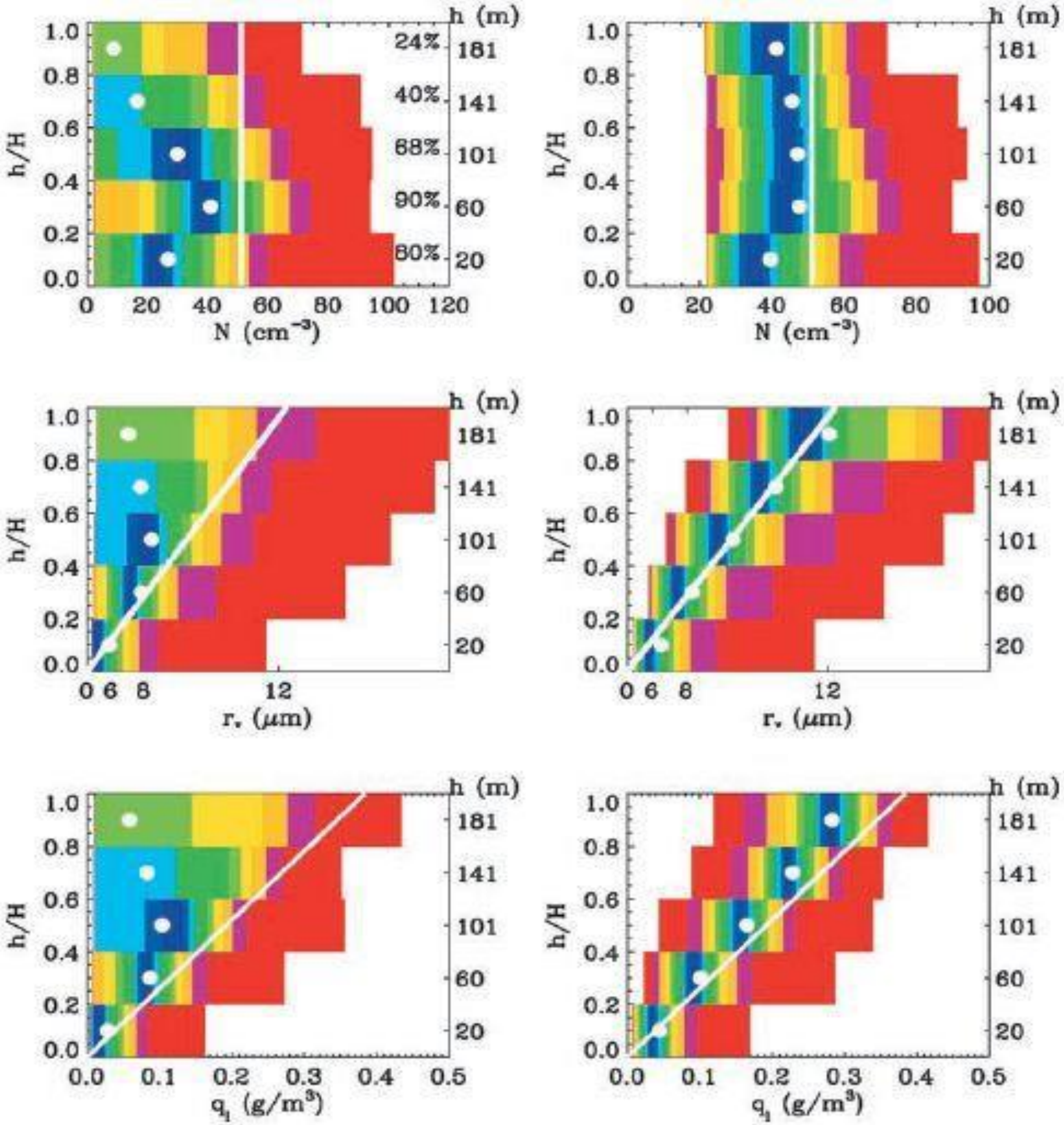
Scu during ACE 2



Brenguier et al., JGR 2003

Scu during ACE2

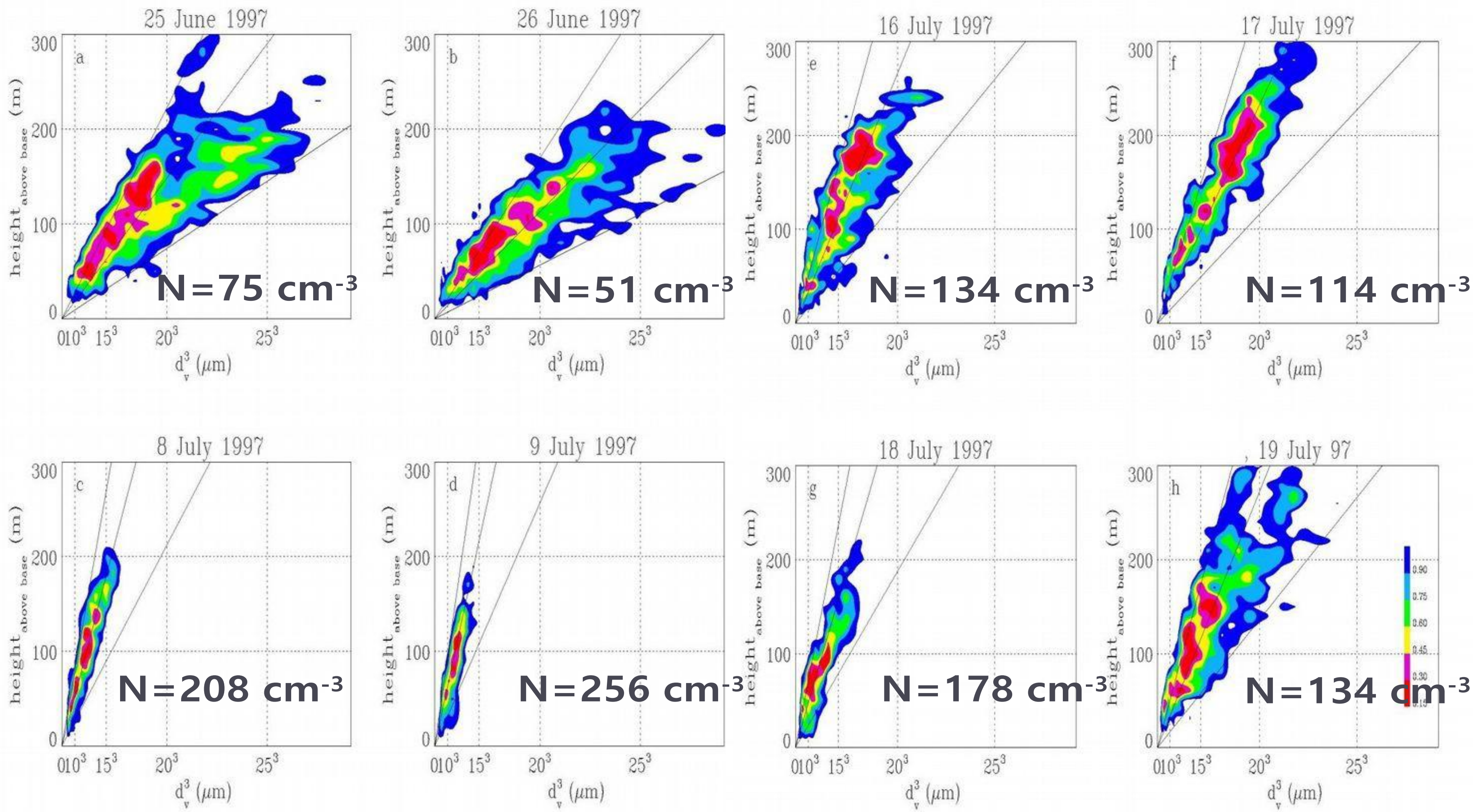
With drizzle



Without drizzle

Brenguier et al., JGR 2003

Scu, ACE 2, 'vertical' profiles



Shallow cumulus; RICO

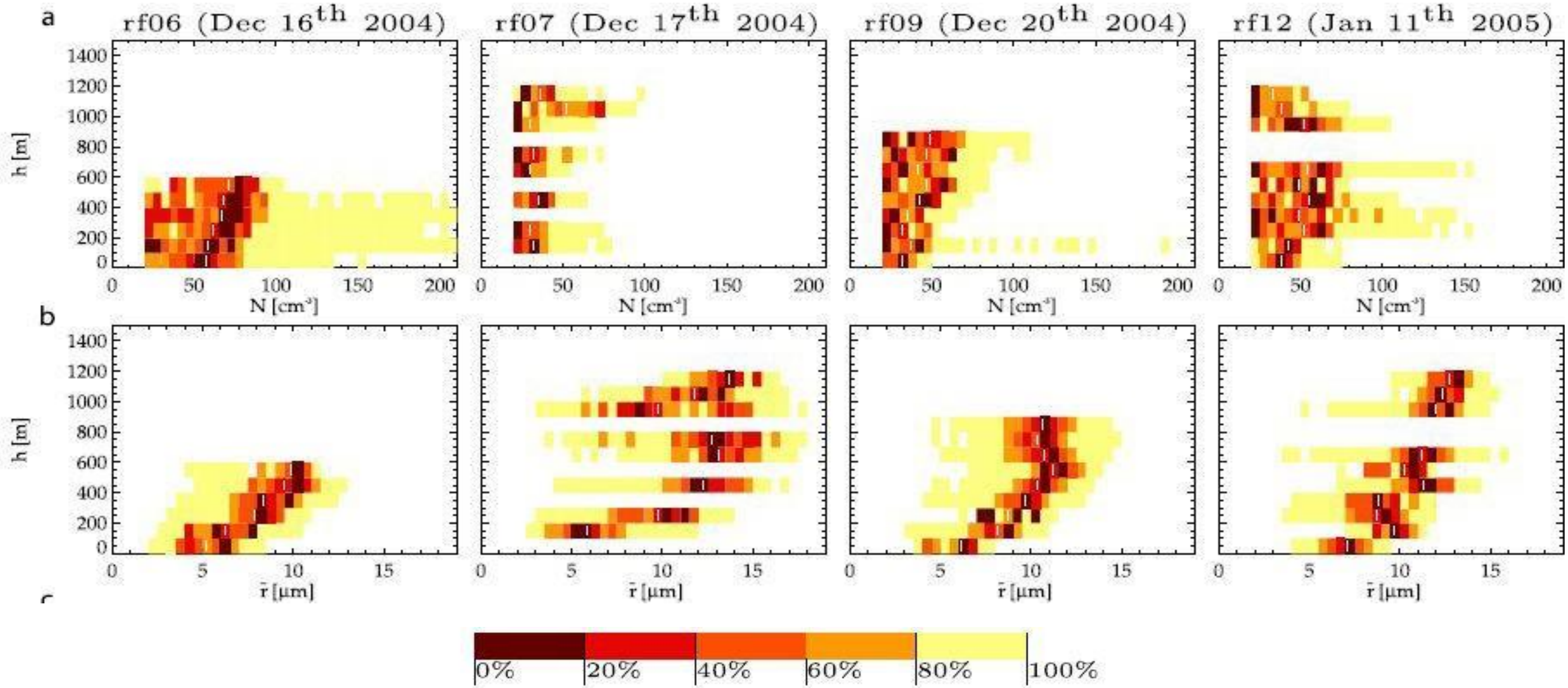


Figure 1. Statistics of droplet-spectrum and concentration measurements from RICO flights rf06, rf07, rf09, and rf12 as a function of height. (a) Droplet concentration N, (b) the mean radius $\overline{r}$, (c) the standard deviation of radius σ_r, and (d) the relative dispersion $d = \sigma_r/\overline{r}$. See text for details.

Arabas et al., GRL 2008

Shallow cumulus, RICO

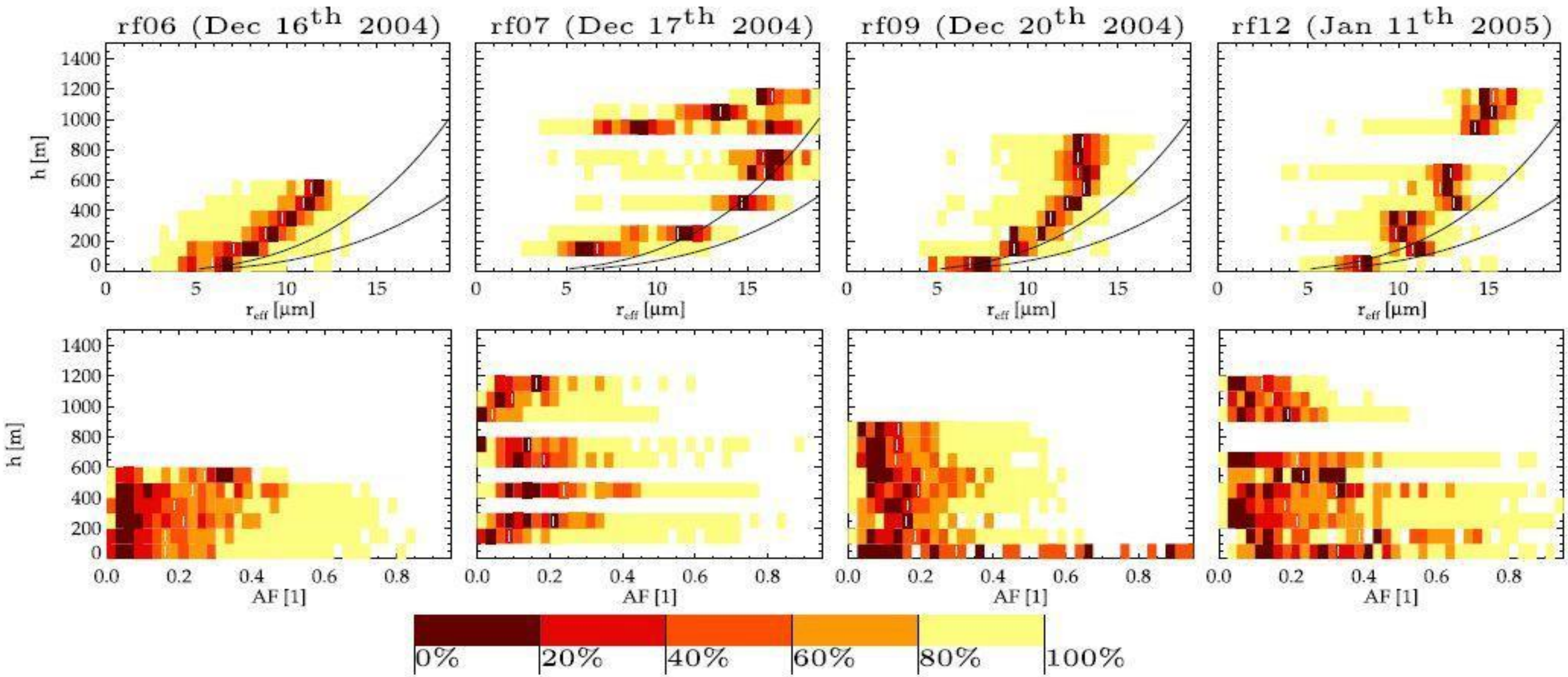


Figure 2. Same as Figure 1, but for the effective radius r_{eff} and adiabatic fraction *AF* values. Effective radius for adiabatic clouds with droplet concentrations of 50 and 100 cm^{-3} are shown by solid lines (larger r_{eff} values correspond to the concentration of 50 cm^{-3}).

Arabas et al., GRL 2008

Further reading:

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Pruppacher, H.R., Klett, J.D., 1997: Microphysics of Clouds and Precipitation, p. 954. Kluwer Academic Publishers.

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Xue, Y., Wang, L.-P., Grabowski, W.W., 2008, Growth of cloud droplets by turbulent collision-coalescence, Journal of the Atmospheric Sciences, 65 (2), pp. 331-356.

Politecnico di Torino
Department of Management and Production Engineering
Marco Cantamessa, Francesca Montagna

TRAINING ON INNOVATION AND ENTREPRENEURSHIP

Soft skills training

Training on innovation and entrepreneurship
21st and 22nd June 2017

Part 1: Understanding the phenomena that occur behind a technology-based project

Part 2: The role of technology-based entrepreneurship

Slide 73 – defining the concept of business model
Slide 75 – the business model canvas
Slide 85 – Getting deeper into CSs and VPs
Slide 99 – Competitive advantage
Slide 103 – Core competencies and capabilities
Slide 105 - Roadmapping

Teaching note and educational aims

Innovation Management is nowadays a recognized discipline that concerns scientific knowledge and professional skills. In the current economic environment, the transfer of scientific and technological results into developed products and services, which must be both profitable for businesses and useful to society, is not immediate and requires special capabilities. The capabilities and skills required are transversal and common to the different expressions of technology as well as to various industrial sectors.

Within this framework, the creation of new ventures requires to develop both entrepreneurial skills and competencies related to the analysis and evaluation of the economic value of technological innovations. Students therefore have to acquire competences to analyse and manage business decisions related to technological innovation in strategic and business terms. They have to get the phenomena that occur behind a technology-based venture, learning how to move from an idea to innovation, gaining an understanding of how to design business models and eventually become entrepreneurs.

Course modules

- ***PART1*** **Understanding the phenomena that occur behind a technology-based project**

  F. Montagna

- ***PART2*** **The role of technology-based entrepreneurship**
- *M. Cantamessa*

Course Outline

PART1 Understanding the phenomena that occur behind a technology-based project

- Slide 5 - From invention to innovation
- Slide 18 - Where are we in the innovation pipeline?
- Slide 27 - S-curves
- Slide 31 - Understanding paradigms
- Slide 36 - Framing the innovation
- Slide 38 - Disruptive and sustaining innovations
- Slide 53 - Dynamics of innovation

PART2 The role of technology-based entrepreneurship

- Slide 60 - The role of technology-based entrepreneurship
- Slide 63- What is an entrepreneur? Can I be an entrepreneur?
- Slide 72 - What types of technology ventures can we think of?
- Slide 73 - Defining the concept of business model
- Slide 75 - The business model canvas
- Slide 85 - Getting deeper into CSs and VPs
- Slide 99 - Competitive advantage
- Slide 103 - Core competencies and capabilities
- Slide 105 - Roadmapping

Francesca Montagna

PART 1 – UNDERSTANDING THE PHENOMENA THAT OCCUR BEHIND A TECHNOLOGY-BASED PROJECT

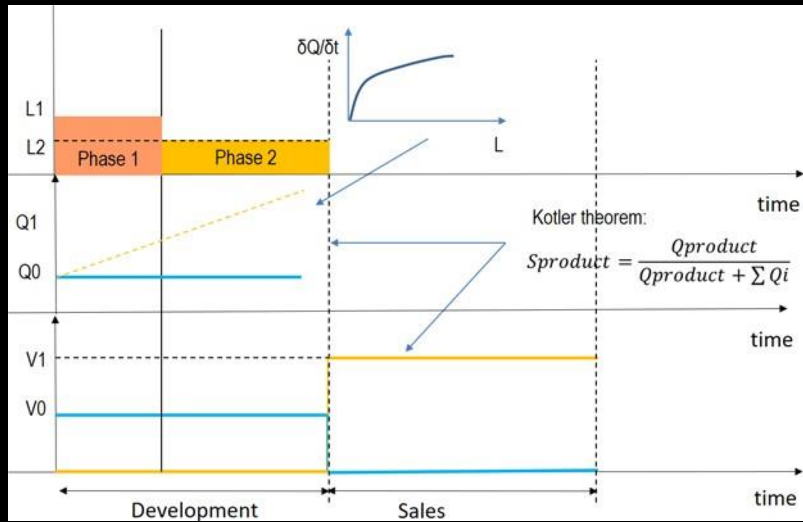
Josef Schumpeter
(* 1883, †1950)

Economics of Innovation

Josef Schumpeter
(* 1883, †1950)

$$s_i = \exp(p_i)\prod_k X_{ki}^{\beta_k}\xi_i$$

$$N(t) = M\,\frac{1-e^{-(p+q)t}}{1+\frac{q}{p}e^{-(p+q)t}}$$



$$\bar{C}(n) = \frac{1}{n}\int_0^n C(n')\,dn' = \frac{1}{n}\int_0^n C(1)\,n'^{-b}\,dn' = \frac{C(1)\,n^{1-b}}{n\,(1-b)} = \frac{C(1)}{1-b}\,n^{-b} = \frac{C(n)}{1-b}$$

Economics of Innovation

Josef Schumpeter
(* 1883, †1950)

$$Y=f\,(x1,\ x2,\ \ldots,\ xn)$$

Innovation = f (technological progress, competitive environment, market conditions)

Invention vs. innovation

From Merriam Webster Dictionary

- Def1: "**new** idea method of devise"
- Def2: "the **introduction** of something **new**"

Invention vs. innovation

Sir Humphry Davy
(1778-1829)

Thomas Alva Edison
(1847-1931)

Nikola Tesla
(1856-1943)

Joseph Wilson Swan
(1828-1914)

Alessandro Cruto
(1847-1908)

George Westinghouse
(1846-1914)

S.S. Columbia
May 1880

J.P. Morgan’s home, New York
June 1880

Holborn Viaduct, London
January 1882

Pearl Street Station, New York
September 1882

Invention / Technology (demonstrator) *Invention (prototype)*

Discovery *Product* *Innovation*

Basic research **Applied research** **Product development (pre- and post- competitive)** **Diffusion**

Here is a **technology**

Here are an **industry** and a **market**

$

t

If

"research and invention = using $ to generate ideas and knowledge"

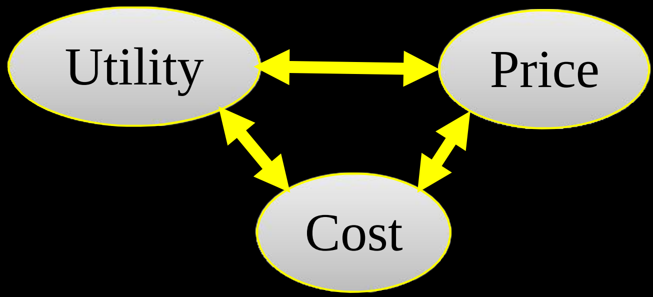
Then

"Innovation = using .... to generate ......"

Technological innovation

- Is the **economic** (i.e. commercial) **utilization** of an invention
- Innovation always implies two aspects: **technical** (related to the “product-in-use” and to its manufacturability); **economic** (related to the market)

GOAL:
“Develop products/services that will give customers a utility that is greater than the cost of production”



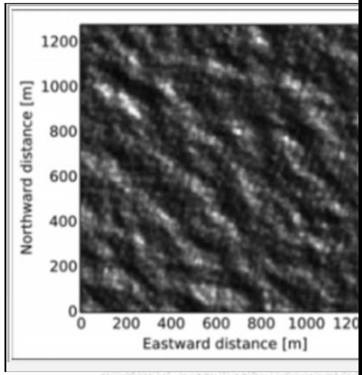
Data acquisition and gathering

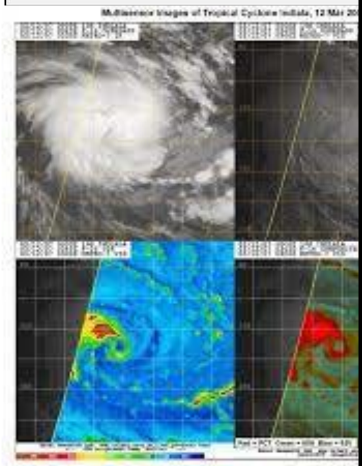
New sensor series
into long-term stable
applications

Flying probe series

Communication protocols

Data elaboration and modelling





Modelling techniques from different and new data sources that are enabled by technology

Machine learning

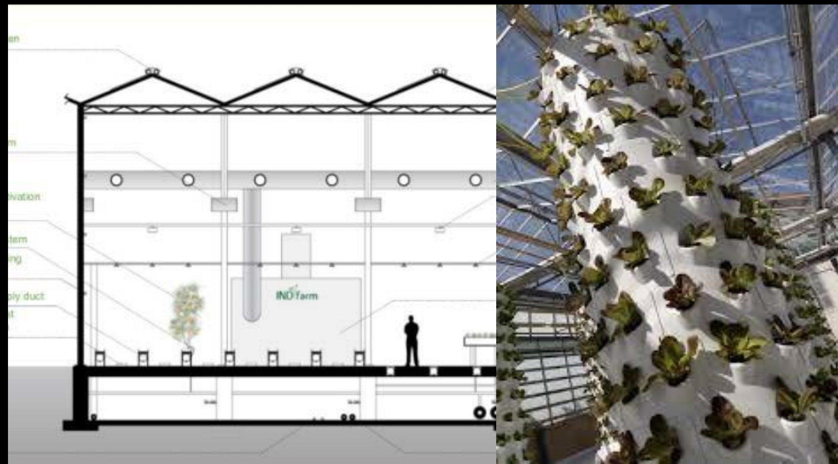
Forecasting, and nowcasting especially, require the integration of acquired data (e.g. Sat monitoring, infrared, wind tracking are integrated for T-storm tracking)

Big data

Meteo and IoT

Smart cities

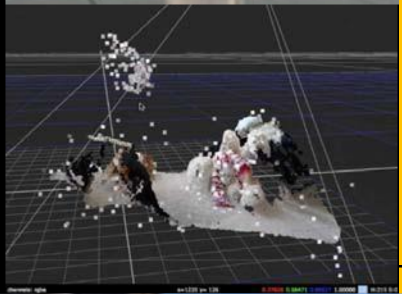
Greenhouses and indoor farming

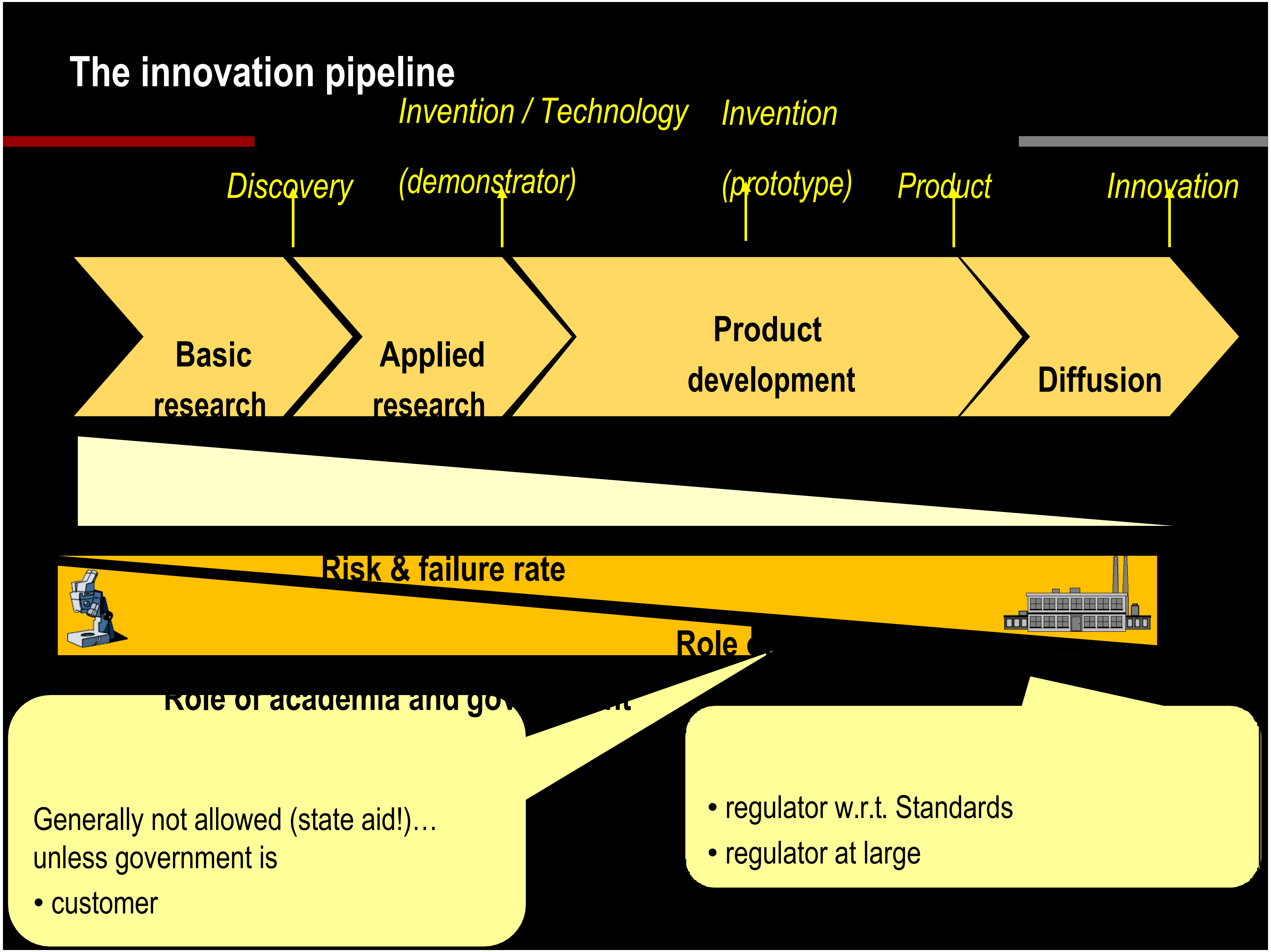


Distributed forecast devices

Meteo informed mobility

Technological innovation

	Utility	Costs	Price
			
			
			


The innovation pipeline
Invention / Technology
(demonstrator)
Invention
(prototype)
Discovery
Product
Innovation
Basic research
Applied research
Product development
Diffusion
Risk & failure rate
Role
Role of academia and gov
Generally not allowed (state aid!)…
unless government is
• customer
• regulator w.r.t. Standards
• regulator at large

- Schumpeterian innovator-entrepreneurs
- Schumpeter's large firms
- Chesbrough's Open Innovation networks
- Ramaswamy's co-creative customers (?)

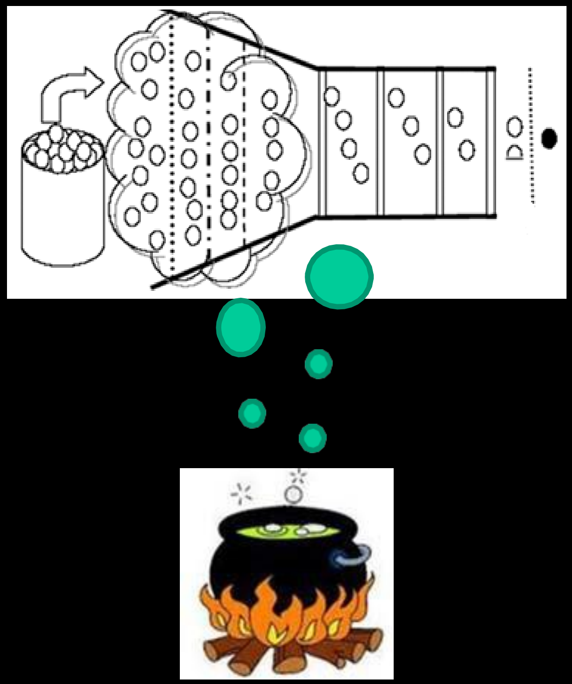
The innovation pipeline

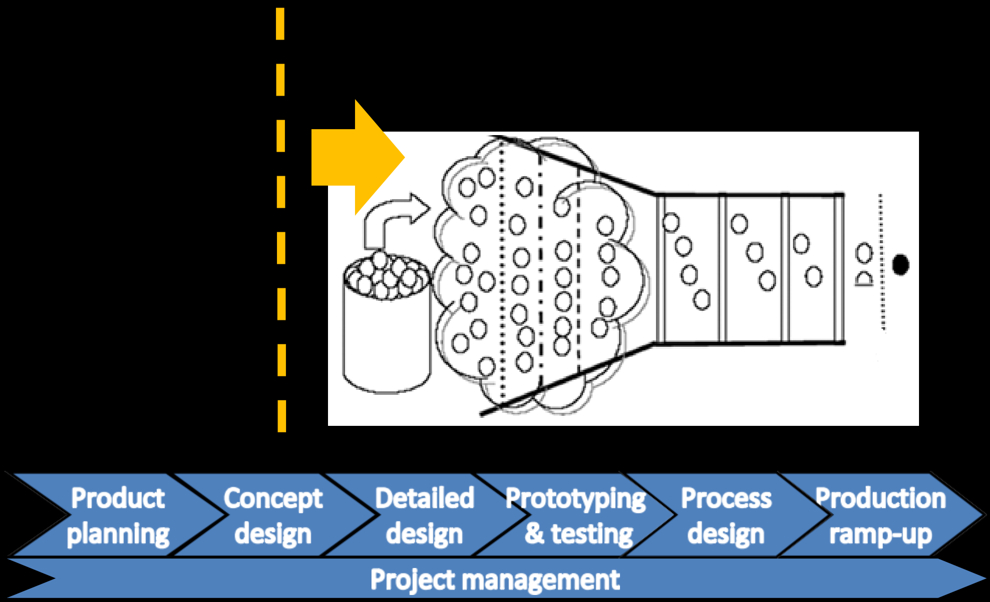
Is there any difference?

The innovation pipeline

The innovation pipeline

Is there any difference?





Impact on society

Impact on society

Negative externalities:

1 Technological displacement vs unemployment

2 Technology can shape the world… irreversible consequences

Impact on society

Negative externalities:

3 Technology is no longer a neutral (“innocent”) tool that humans use (or do not use) as means to a (consciously deliberated) goal

4 Technology shapes human behaviors

Technology push vs Demand pull Innovation

Technology push vs Demand pull Innovation

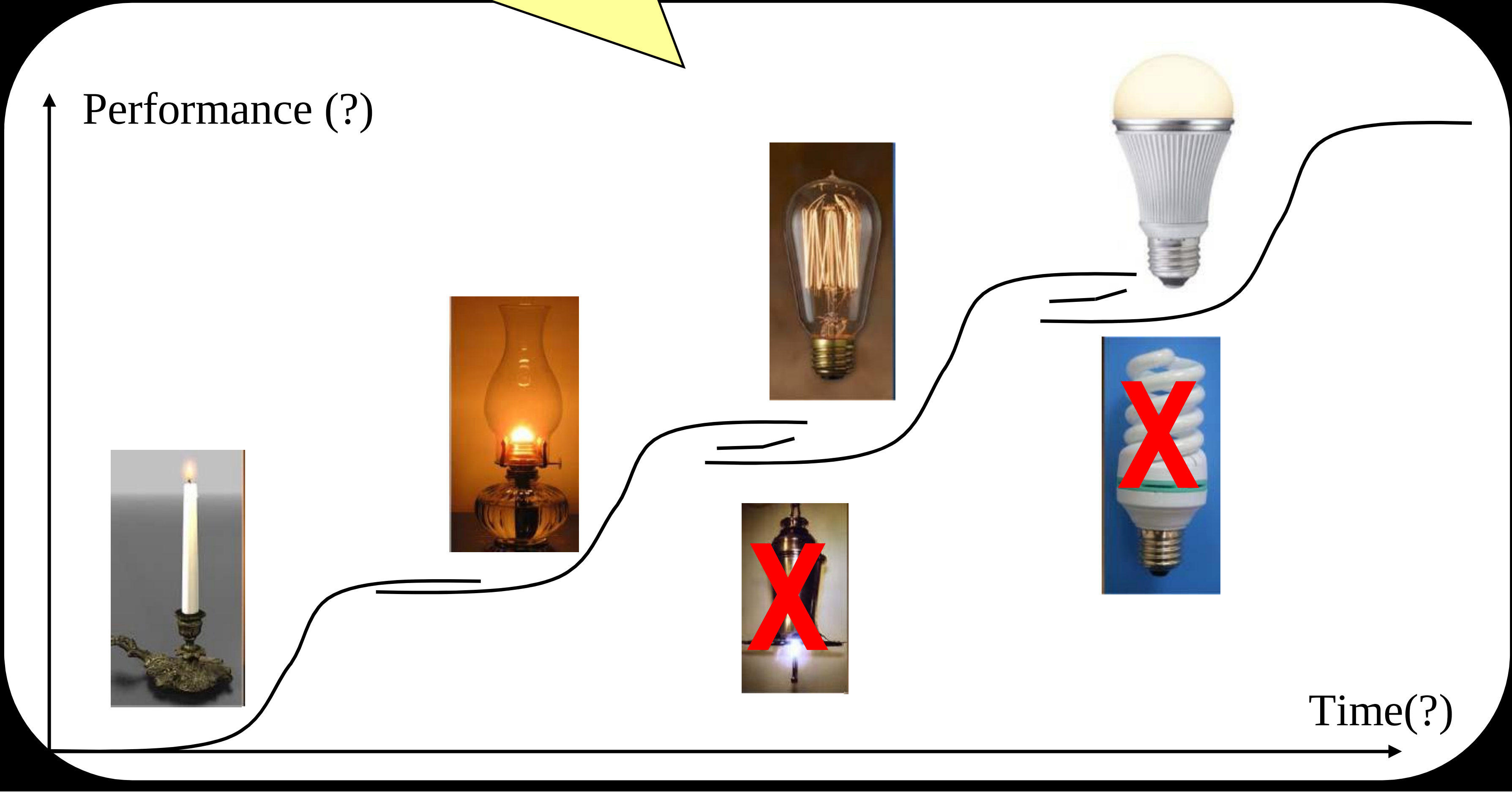
?

S-curve analysis

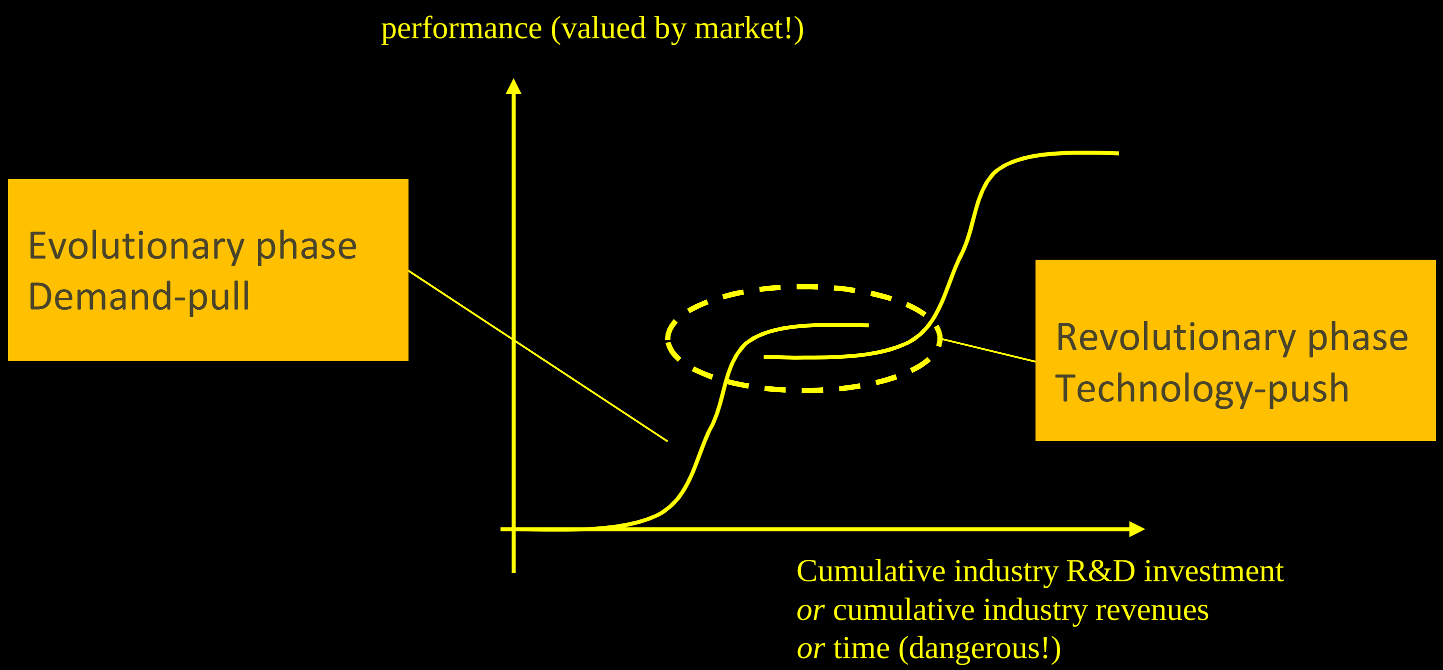
Does it look like a story characterized by continuous progress?

S-curve analysis

Not really! Innovation follows a continuous alternation of



Evolutionary vs Revolutionary progress



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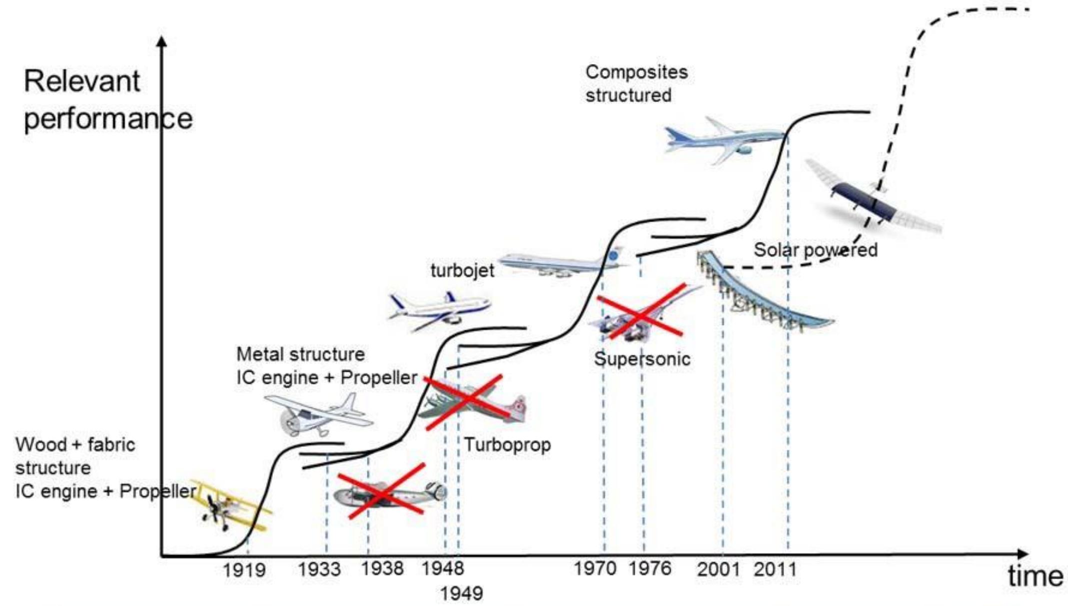
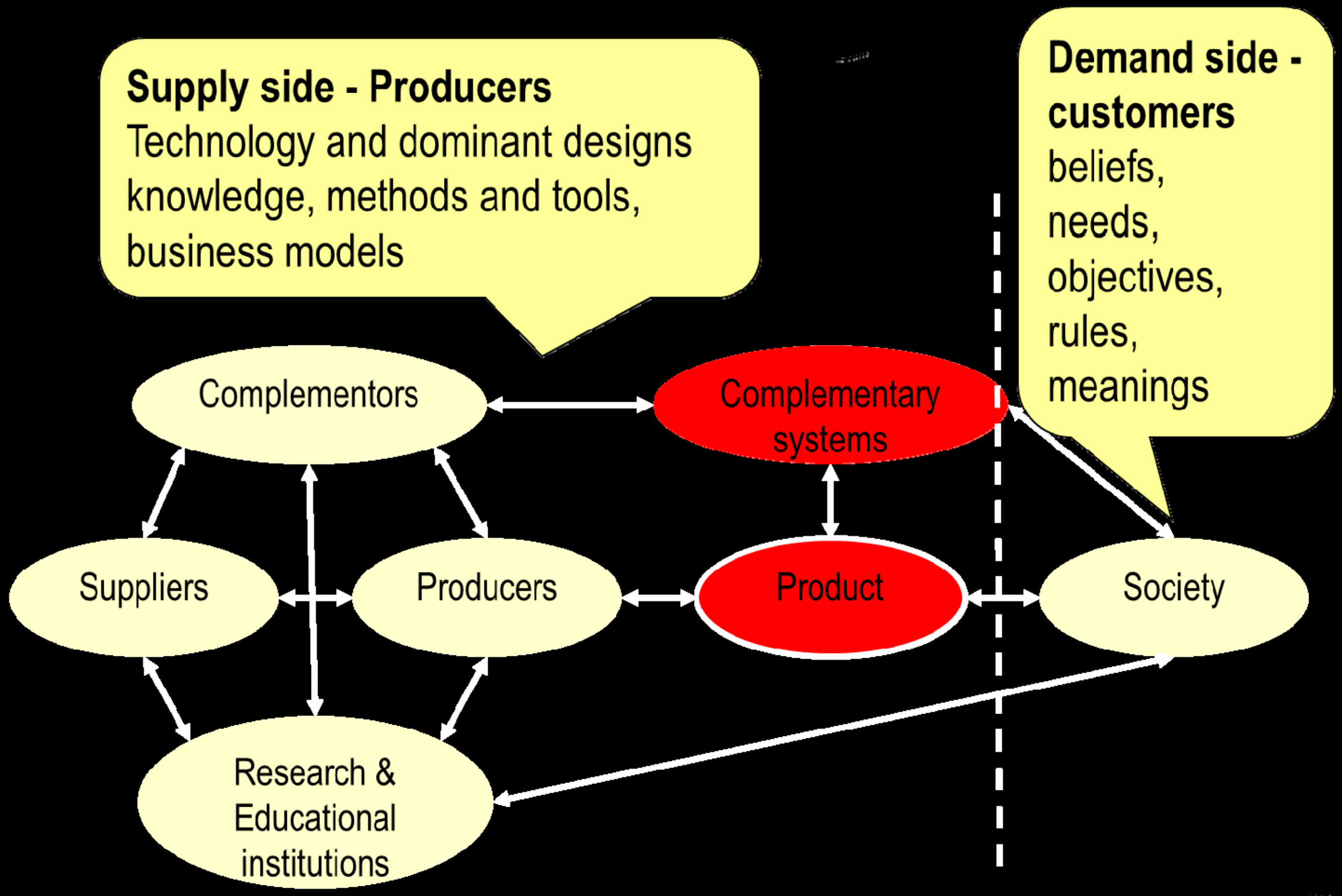
Performance matters but…



Airliner	Year	Airframe	Engines	Cruise speed (km/h)	Range (km)	Max pass.	Fuel eff. (km seat/l)
Flyer	1903	Wood + fabric	1 piston + propeller	48	-	1	-
Farman Goliath	1919	Wood + fabric	2 piston + propeller	120	400	14	13.4
FIAT C.R. 32	1933	Metal	1 piston + propeller	315	750	1	2.2
Douglas DC-3	1935	Metal	2 piston + propeller	333	2400	32	8.4
Boeing 314- flying boat	1938	Metal	4 piston + propeller	340	5900	74	23.5
Vickers Viscount 700	1948	Metal	4 turboprop	496	2220	48	15.3
De Havilland Comet	1949	Metal	4 turbojet	740	2400	44	3.56
Boeing 747-100, 200	1970	Metal	4 turbojet	893	12690	550	26.9
Concorde	1976	Metal	4 turbojet	2158	7222	120	6.4
Boeing 787	2011	Composites	2 turbofan	913	15400	440	36.6

Technological paradigm



- Dosi G, (1982) Technological paradigms and technological trajectories. A sug-gested interpretation of the determinants and directions of technical change, Research Policy, 11(3):147-162

Paradigms

What were the competing paradigms they proposed?
Which one won?
Why?

performance (valued by market!)

Technological limit

?

time

What are the competing paradigms?

Model	Technology	Main use	Meaning	Complement to
 				
				
				

Paradigms

P	**Politics** (general political environment, specific policies, regulatory frameworks, etc.)
E	**Economy** (macro and micro)
S	**Society** (cultural, demographical, etc.)
T	**Technology** (core and complementary)

Factors such as ethical, environmental, etc., can be inserted or added as new categories

Framing the innovation

Criterion (look at...)	An "evolutionary" innovation is called	A "revolutionary" innovation is called
Product and the technical tradeoffs that define it	Incremental innovation	Radical innovation
Producer and its organization	Competence enhancing innovation	Competence destroying innovation
Product architecture	Peripheral innovation	Core innovation
Business impact	Sustaining innovation	Disruptive innovation

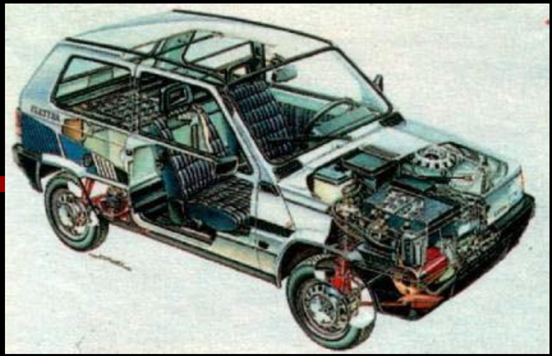
What kind of innovation is it?
It depends on who you are!

Framing the innovation

- Innovation and product architecture
  - It is generally harder to change architecture than technology
  - Innovations often are not incremental or modular (but incumbents tend to downplay them as such)

Relationships between components Reference technologies	Do not change	Change
Change	Modular innovation	Radical innovation
Do not change	Incremental innovation	Architectural innovation

- Henderson R, Clark KB, (1990) Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Administrative Sciences Quarterly, 35: 9–30.



Relationships between components / Reference technologies	Do not change	Change
Change	Modular innovation	
Do not change	Incremental	

Radical innovation

Arch

itectural
innovation

Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- How can innovations be *disruptive* (i.e. why do *incumbent* firms fail to face them)?

1. The old technology does not keep pace with growing or new customer needs, while the new one does

   AND

   incumbents have misaligned resources and organizational inertia (*competency traps*)

Disruptive and sustaining innovations

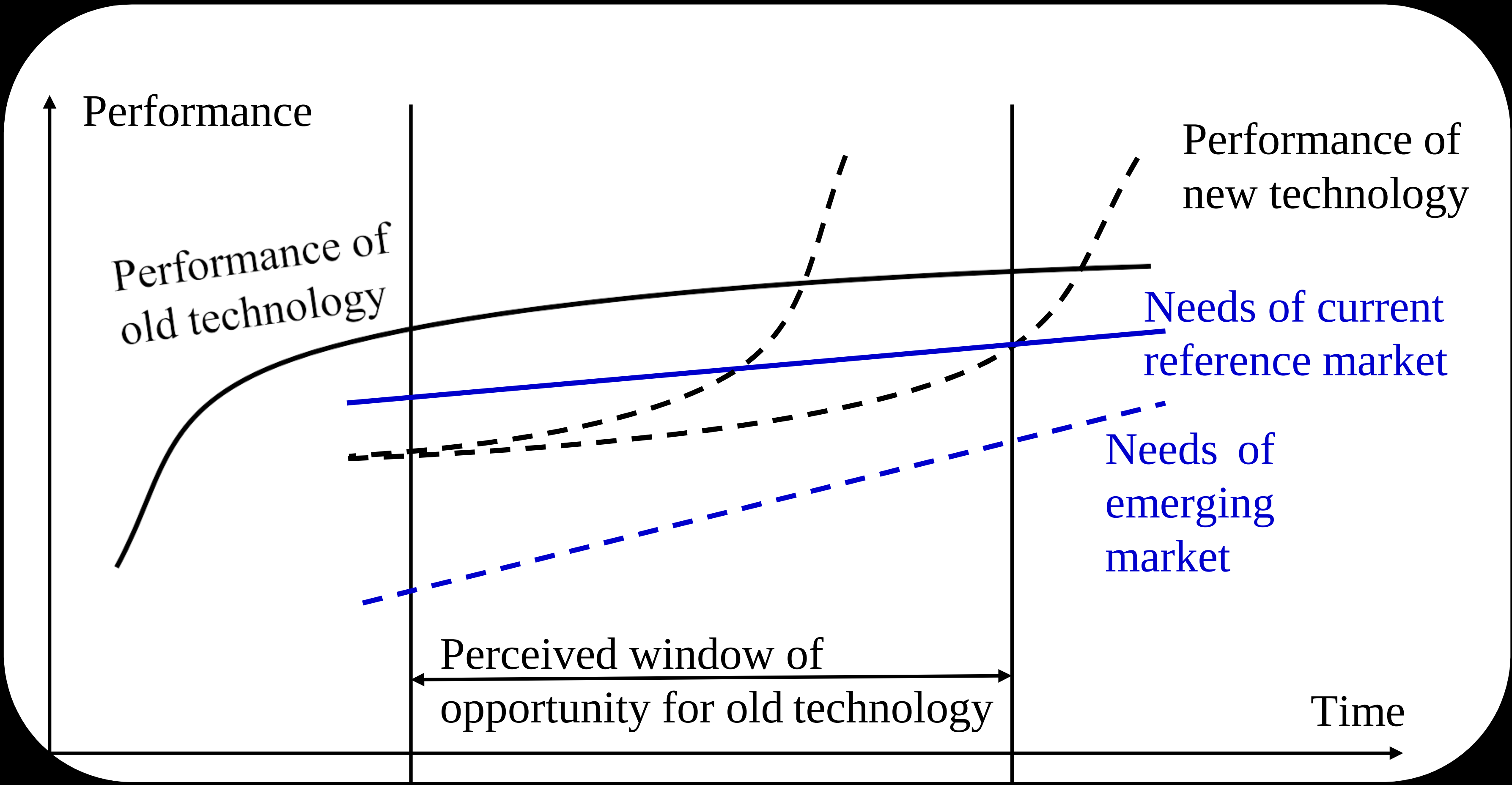
- Radical innovations sometimes are disruptive and sometimes not
- How can innovations be *disruptive* (i.e. why do *incumbent* firms fail to face them)?

Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- How can innovations be *disruptive* (i.e. why do *incumbent* firms fail to face them)?

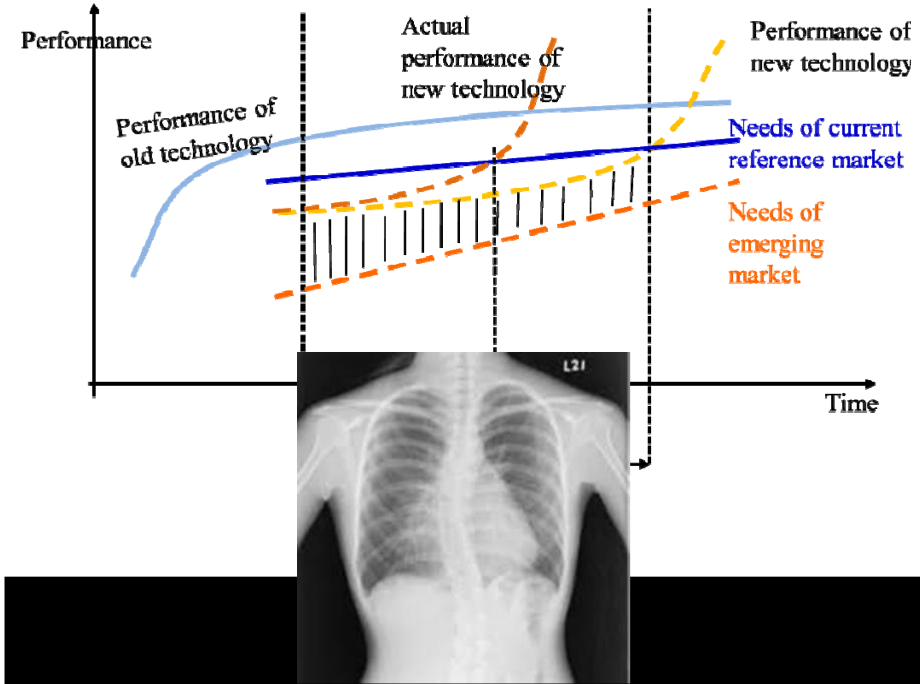
2. Focus on reference markets and customers (Christensen).

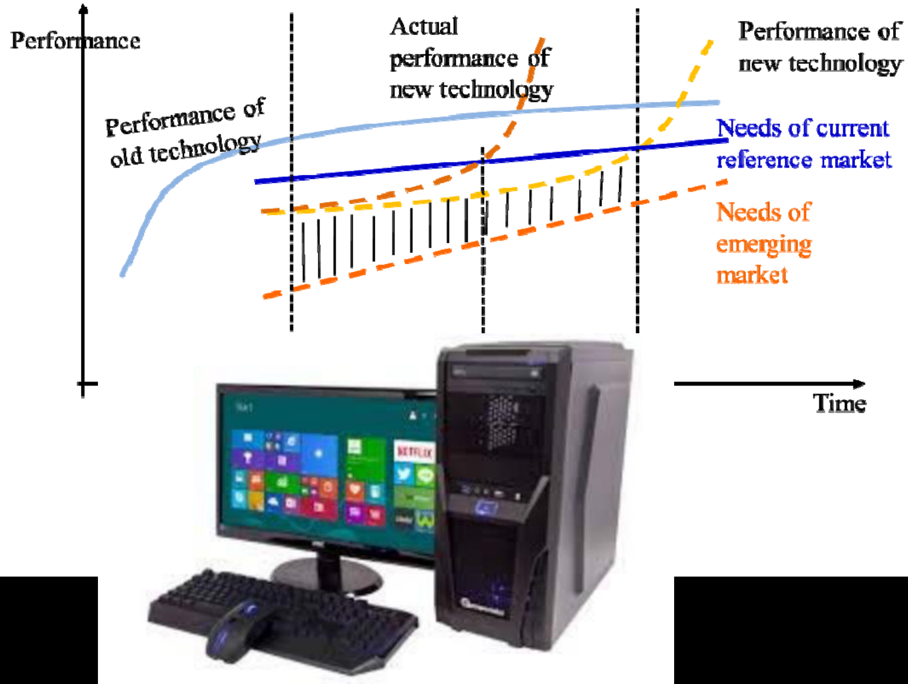
Disruptive and sustaining innovations



- Christensen CM, (1997). The innovator's dilemma: When new technologies cause great firms to fail. Harvard Business School Press, Boston.

Disruptive and sustaining innovations





Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- How can innovations be *disruptive* (i.e. why do *incumbent* firms fail to face them)?

2. Focus on reference markets and customers (Christensen).

   Where is the problem?

   - resource allocation and project selection are driven by observable market demand
   - “don’t kill the cash cow but milk it” attitude
   - no envisioning of the future
   - middle managers can test new technology and try championing innovative projects… but can’t “change the givens”

Disruptive and sustaining innovations

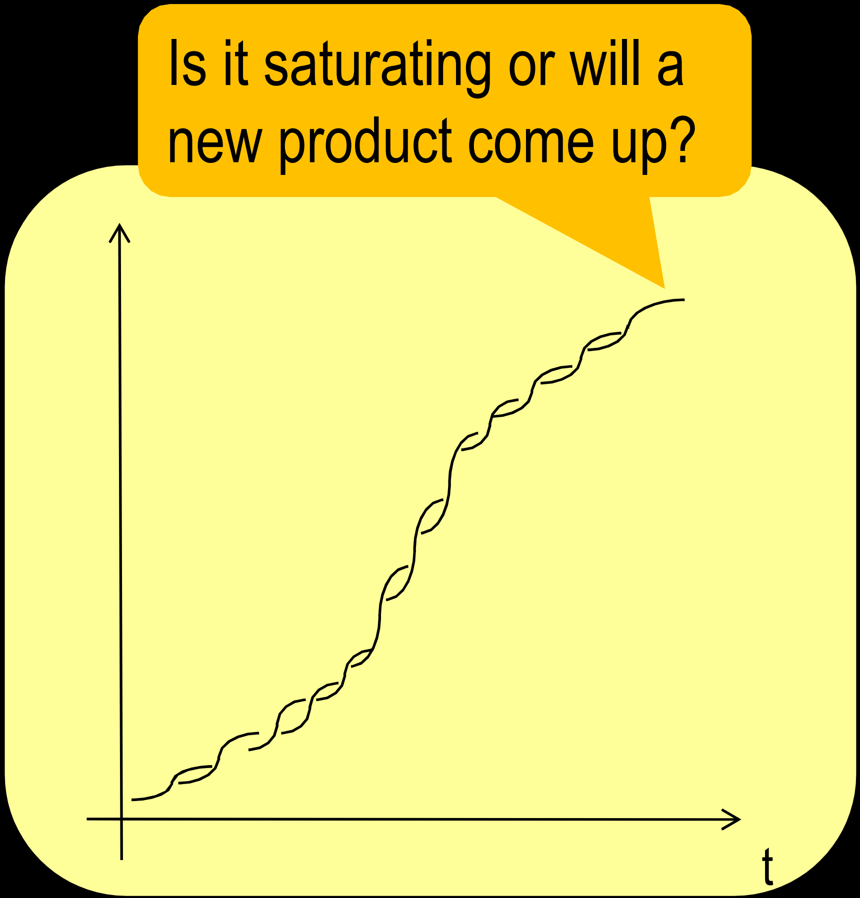
?

Disruptive and sustaining innovations

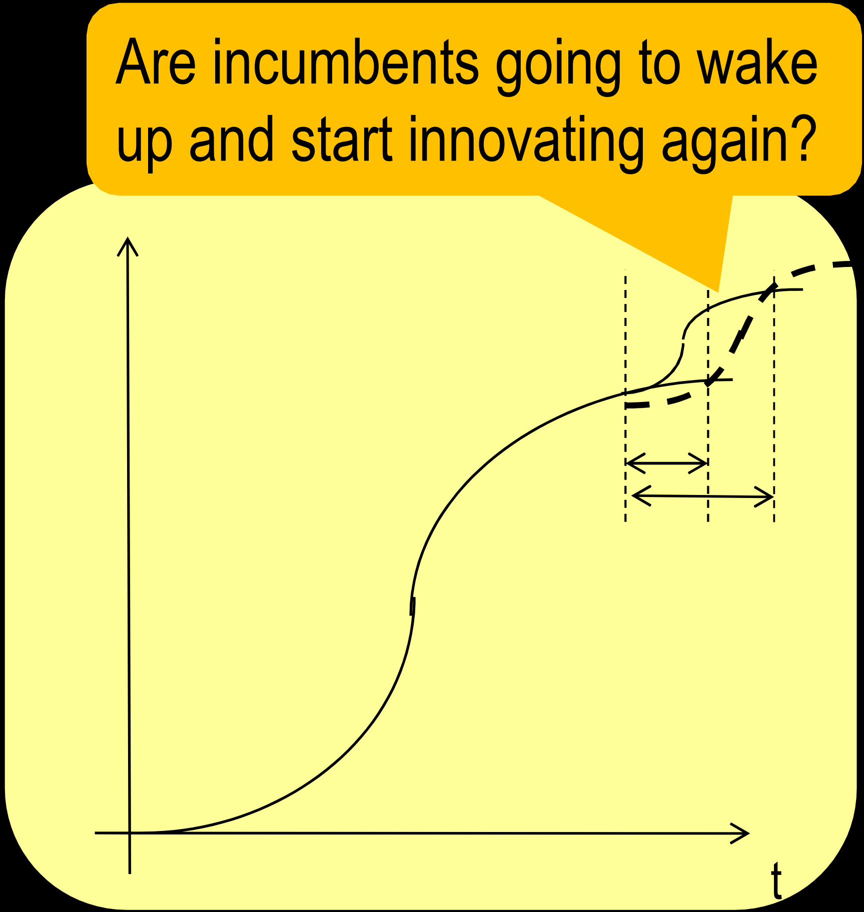
- Radical innovations sometimes are disruptive and sometimes not
- Why can innovations *not become* disruptive (i.e. why do incumbents win over innovating new entrants)?

3. There are risks in using “maturing” S-curves as forecasting tools, (Christensen)

Disruptive and sustaining innovations



Nested s-curves



Sailing ship effect

- Geels FW, (2005) Technological transitions and system Innovations: A co-evolutionary and socio-technical analysis.

Edward Elgar Publishing, Northamp-ton.

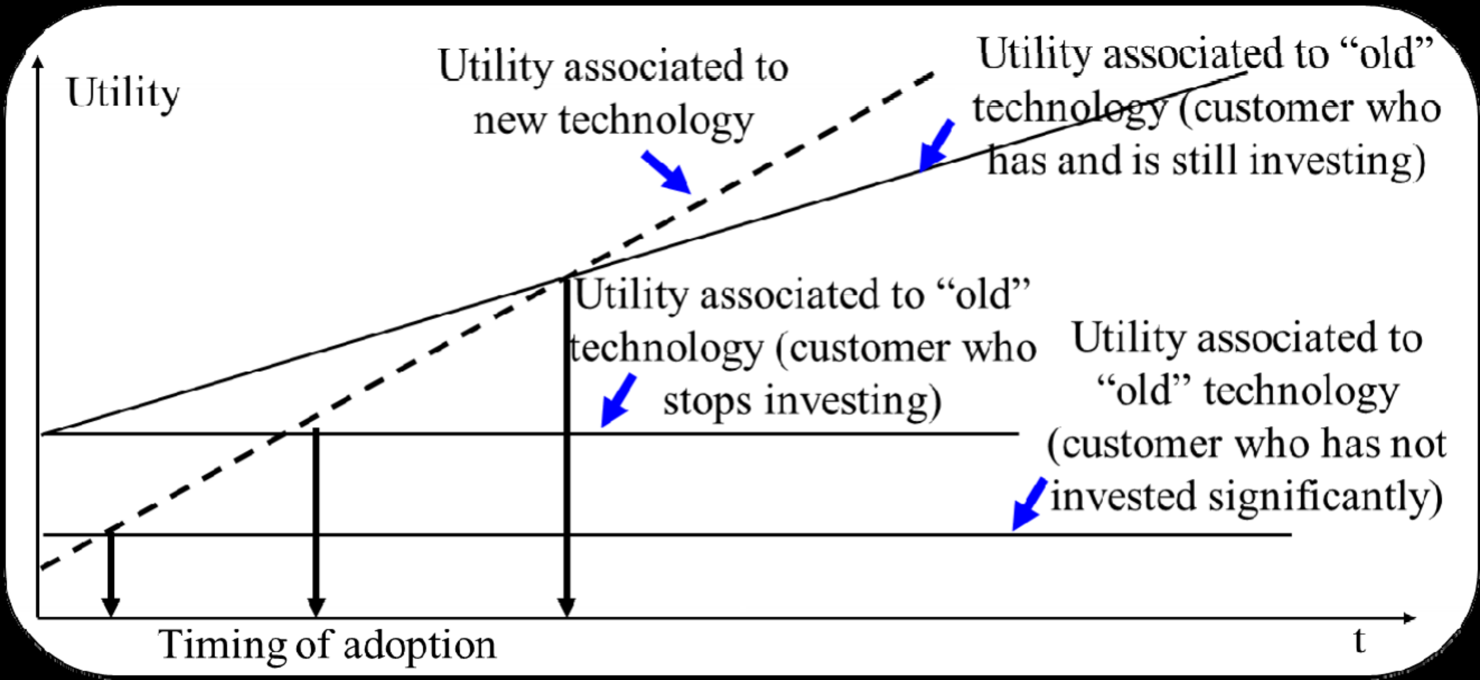
Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- Why can innovations *not become* disruptive (i.e. why do incumbents win over innovating new entrants)?

4. The market might reject it
   - a coherent and sustainable paradigm does not emerge
   - the market is locked in the old technology (theory of localized technological change)

Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- Why can innovations *not become* disruptive (i.e. why do incumbents win over innovating new entrants)?



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Disruptive and sustaining innovations

Disruptive and sustaining innovations

- Radical innovations sometimes are disruptive and sometimes not
- Why can innovations *not become* disruptive (i.e. why do incumbents win over innovating new entrants)?

5. Incumbents might have significant advantages
    - Incumbents might successfully imitate entrants
    - Entrants might not be able to secure complementary assets
        - If generic, incumbents might own them
        - If specialized or co-specialized, who is going to build them?

Disruptive and sustaining innovations

Suppose you are an incumbent. What could your strategy be, in order to avoid being disrupted by radical innovation?

Disruptive and sustaining innovations

Suppose you are an entrant.
What could your strategy be, in order to disrupt incumbents?

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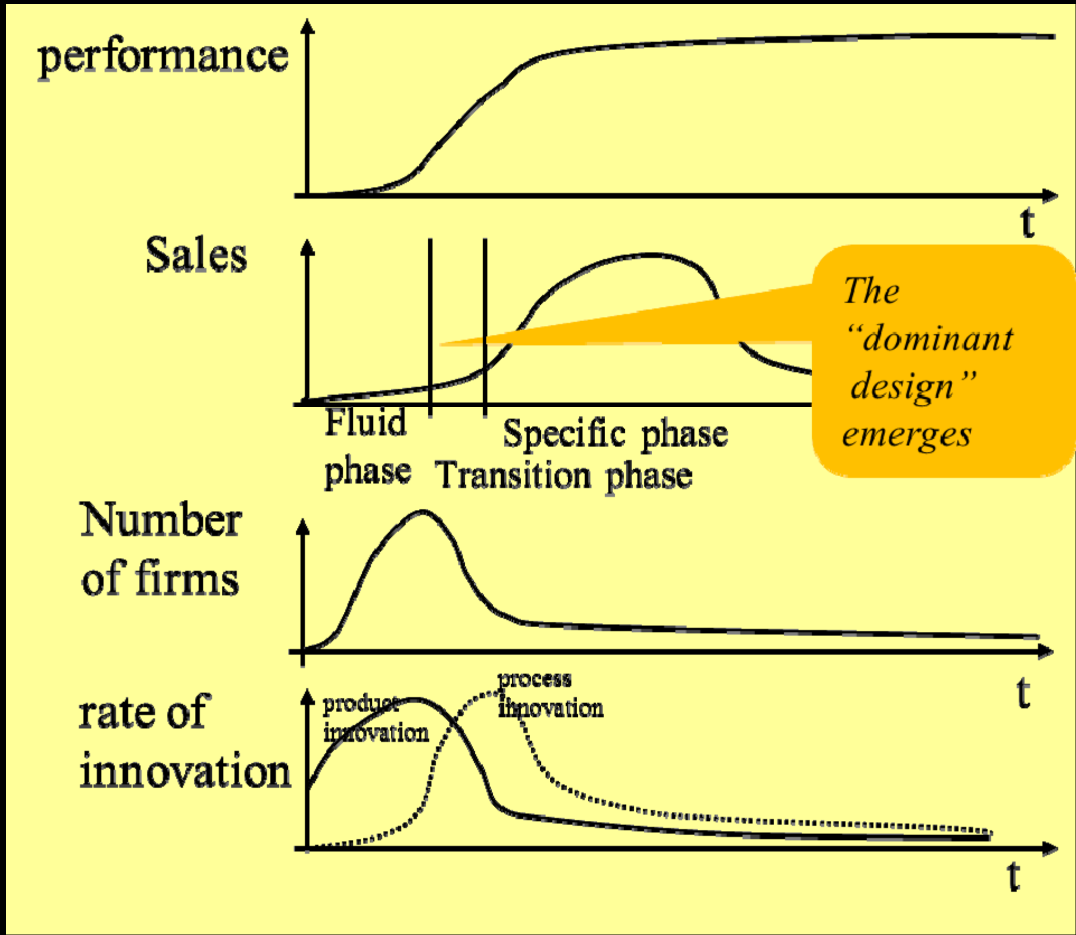
Dynamics of Innovation

- Performance s-curves and diffusion s-curves

Dynamics of Innovation



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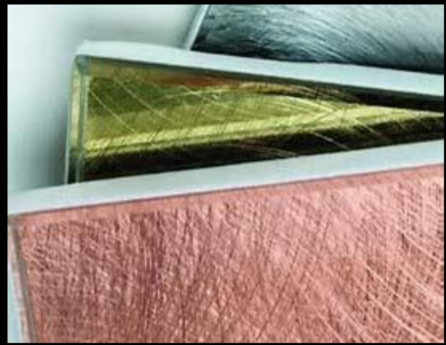
Dominant design

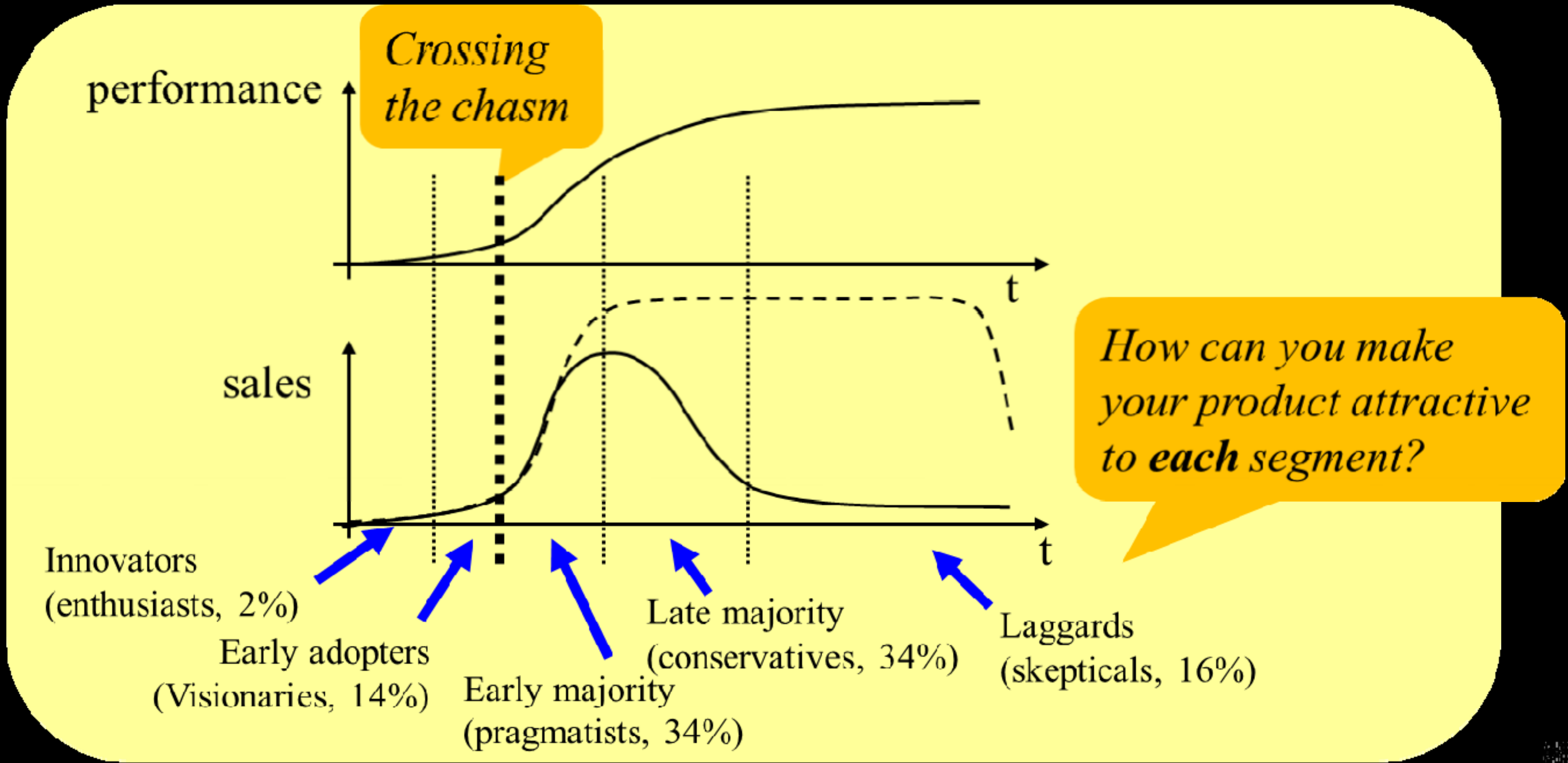
Does dominant design always emerge?

Domnant designs in process industries?



Domnant designs in process services?

Dynamics of Innovation



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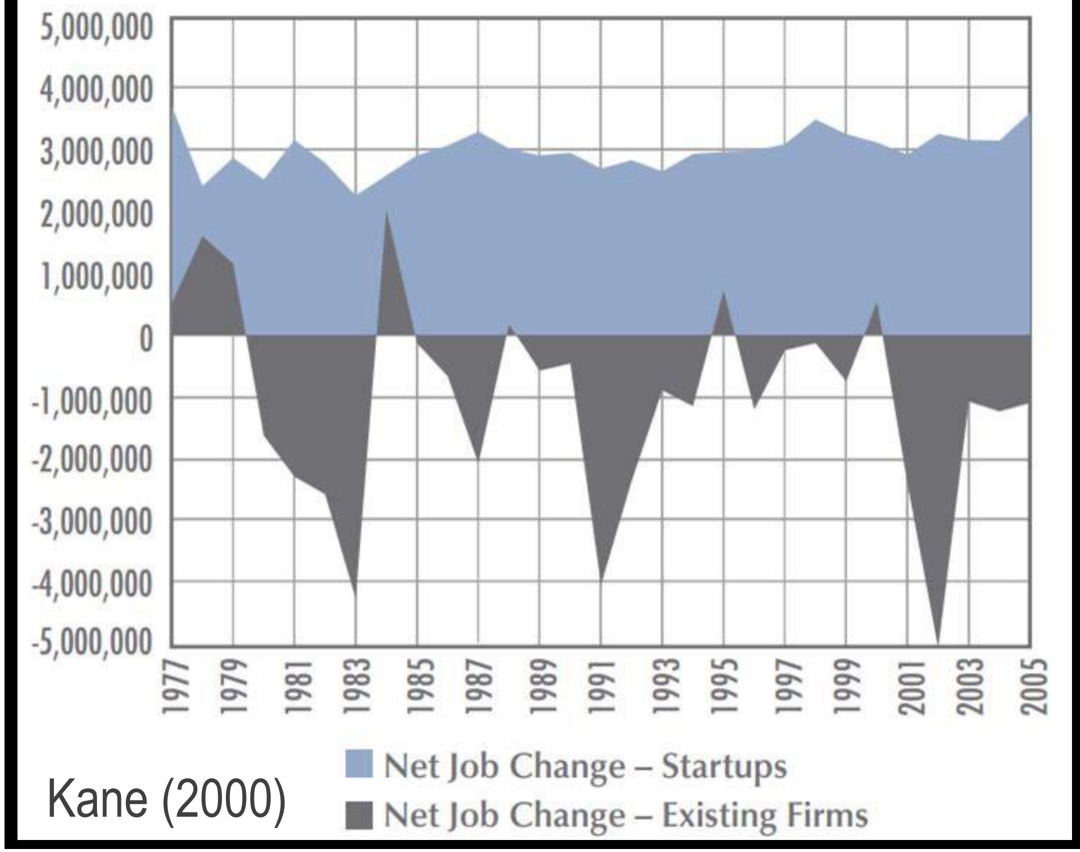
Marco Cantamessa

PART 2 – THE ROLE OF TECHNOLOGY-BASED ENTREPRENEURSHIP

The role of technology-based entrepreneurship

- Startups are key to the economy because of

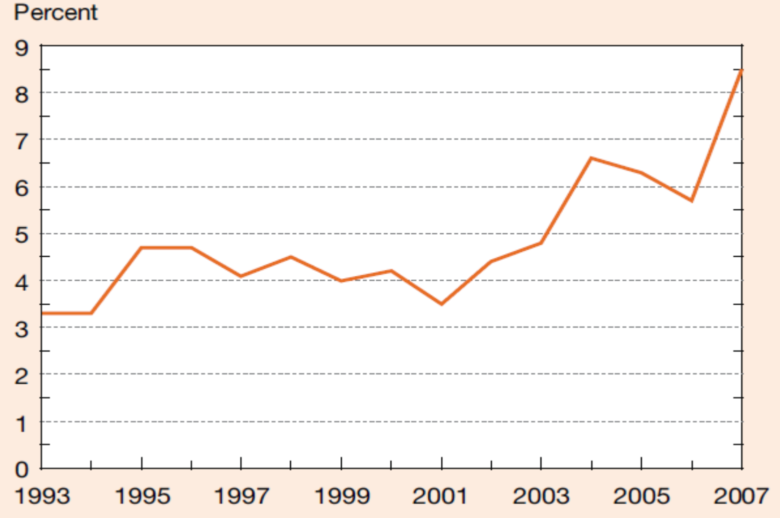
growth
→job creation



Kane (2000)

sales to other firms
→Open Innovation

Figure 4-22
R&D contracted out in United States by manufacturing companies as ratio of company-funded and -performed R&D: 1993–2007



SOURCE: National Science Foundation, Division of Science Resources Statistics, Survey of Industrial Research and Development (annual series). See appendix table 4-39.

Science and Engineering Indicators 2010

The role of technology-based entrepreneurship

- Technology transfer occurs through
  - Licensing
  - Consulting
  - Hiring
  - Startup creation

What is an entrepreneur?

Let’s look at entrepreneurs as a profession and as an attitude

The term «entrepreneur» comes from French and Latin

Imprendere comes from
In → moving towards
Pre → before
Hendere → grabbing with the hand

Entrepreneur as a hunter (of what?)

What is an entrepreneur?

« ... individuals who exploit market opportunity through technical and/or organizational innovation» - Joseph Schumpeter, 1965

« This defines entrepreneur and entrepreneurship - the entrepreneur always searches for change, responds to it, and exploits it as an opportunity » - Peter Drucker, 1985

What are the key words here?

What is an entrepreneur?

William Baumol

- Innovative vs. replicative entrepreneurs and their attitude to «knowable» and «Knightian» risk
- Entrepreneurship can be productive (innovative), improductive (rent seeking), destructive

Entrepreneurial orientation

- Innovativeness
- Risk propensity
- Proactiveness

… what about ambition and greed?

What is an entrepreneur?

From a psychological perspective

- The existence of «entrepreneurial personality traits» is debatable (good news!)
  - need for achievement,
  - self-efficacy (i.e., the belief in your own ability to succeed)
  - innovativeness,
  - stress tolerance / resilience,
  - need for autonomy,
  - proactiveness / passion.
- In broader terms, entrepreneurship can be seen as a «nexus between individuals, opportunities and resources» (Zachary and Mishra, 2011)

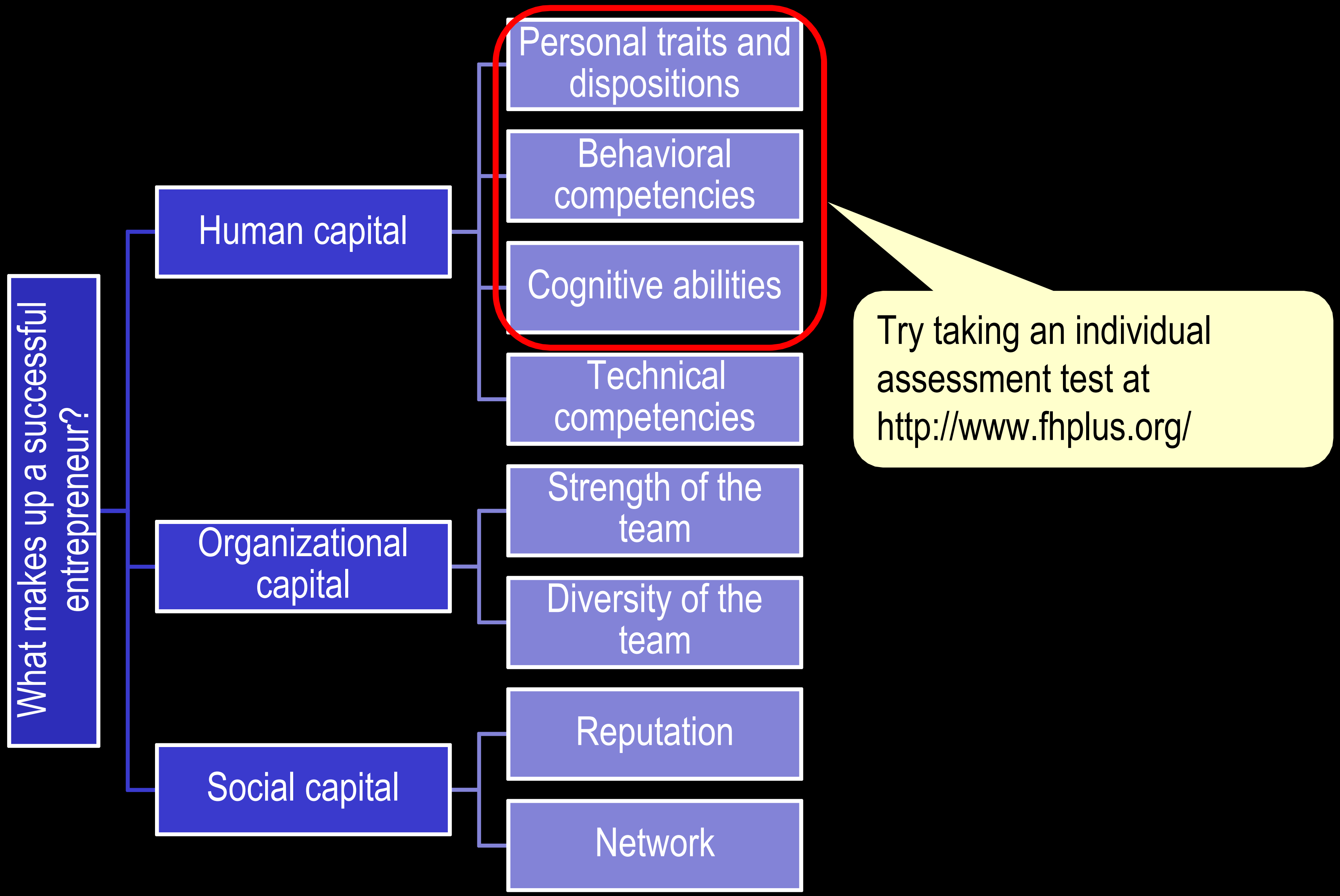
What is an entrepreneur?

From a psychological perspective

- There appears to be a distinctive «entrepreneurial cognition» (Mitchell et al., 2007)…. can you learn it?

Thinking in terms of opportunities, not of solutions	Capability of leveraging others' competencies	Frequent falling into cognitive biases (especially overconfidence)
Significant use of heuristics	Low propensity to engage in counterfactual analysis	Flexibility in using • causal reasoning (objective → required resources) • effectual reasoning (resources → achievable objective)

Can I be an entrepreneur?



Can I be an entrepreneur?

Why should I think of launching a tech startup?

Can I be an entrepreneur?

What kind of tech startup?

Can I be an entrepreneur?

How do I finance it?

Try connecting the boxes

Labor-intensive services (consultancy)

Capital-intensive services

Tech transfer entity

IP-based product startup

Fabless product startup

Fools, Friends & Family

Bootstrapping

Public R&D&I funding

Debt

Equity or co-development funding from customers

Vertically integrated product startup

Equity from Business Angels, Accelerators or Venture Capitalists

Defining business models

- The concept of business models arises in the early XXI Century
  - firms operating in the «Internet economy»
  - innovations that are difficult to otherwise classify (e.g., low-cost airlines)
- The business model as the «format» with which technological innovation is delivered to the market

Defining business models

- The business model as
  - a «conceptual, rather than financial, model of a business» (Teece) (i.e., what elements make up the business? Are they coherent?)
    → a precursor to a strategy document or a business plan
  - a description of supply side and demand side elements
  - Can be used to analyze or to (re)design a firm or a business unit

Strategic Choices

Customer (target market, scope)
Value Proposition
Capabilities/competences
Pricing
Competitors
Offering
Branding
Differentiation

Value Network

Suppliers
Customer information
Customer relationship
Information flows
Product/service flows

Create value

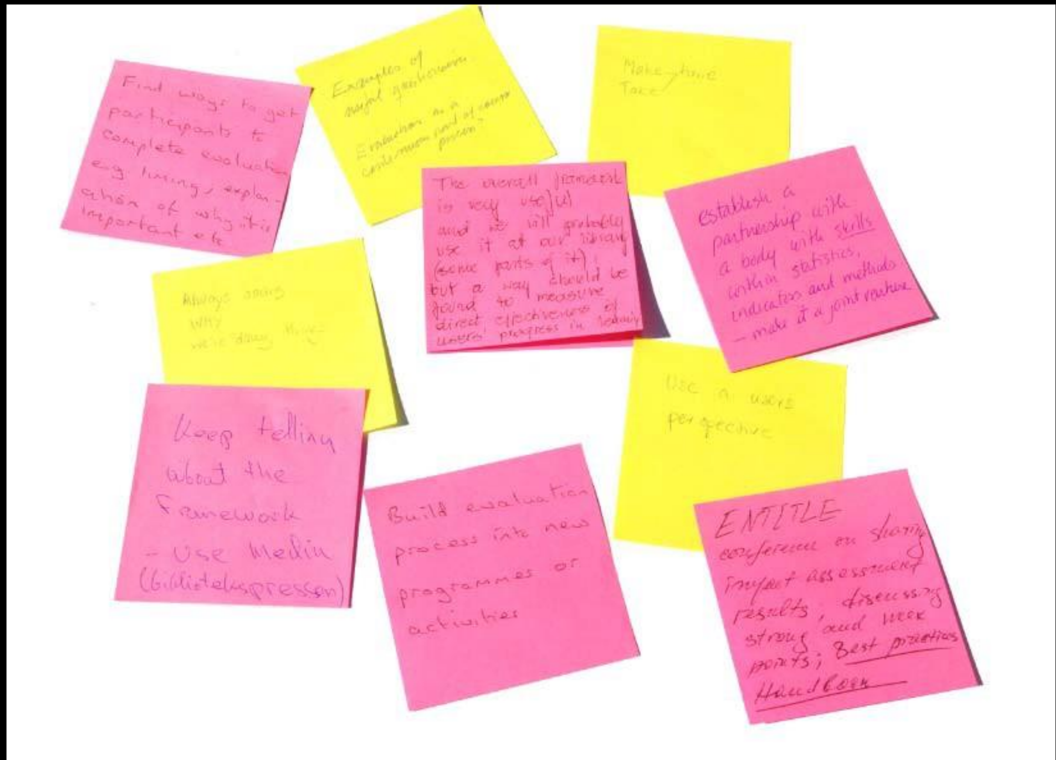
Resources/Assets
Processes/Activities

Capture Value

Costs
Financial aspects
Revenues

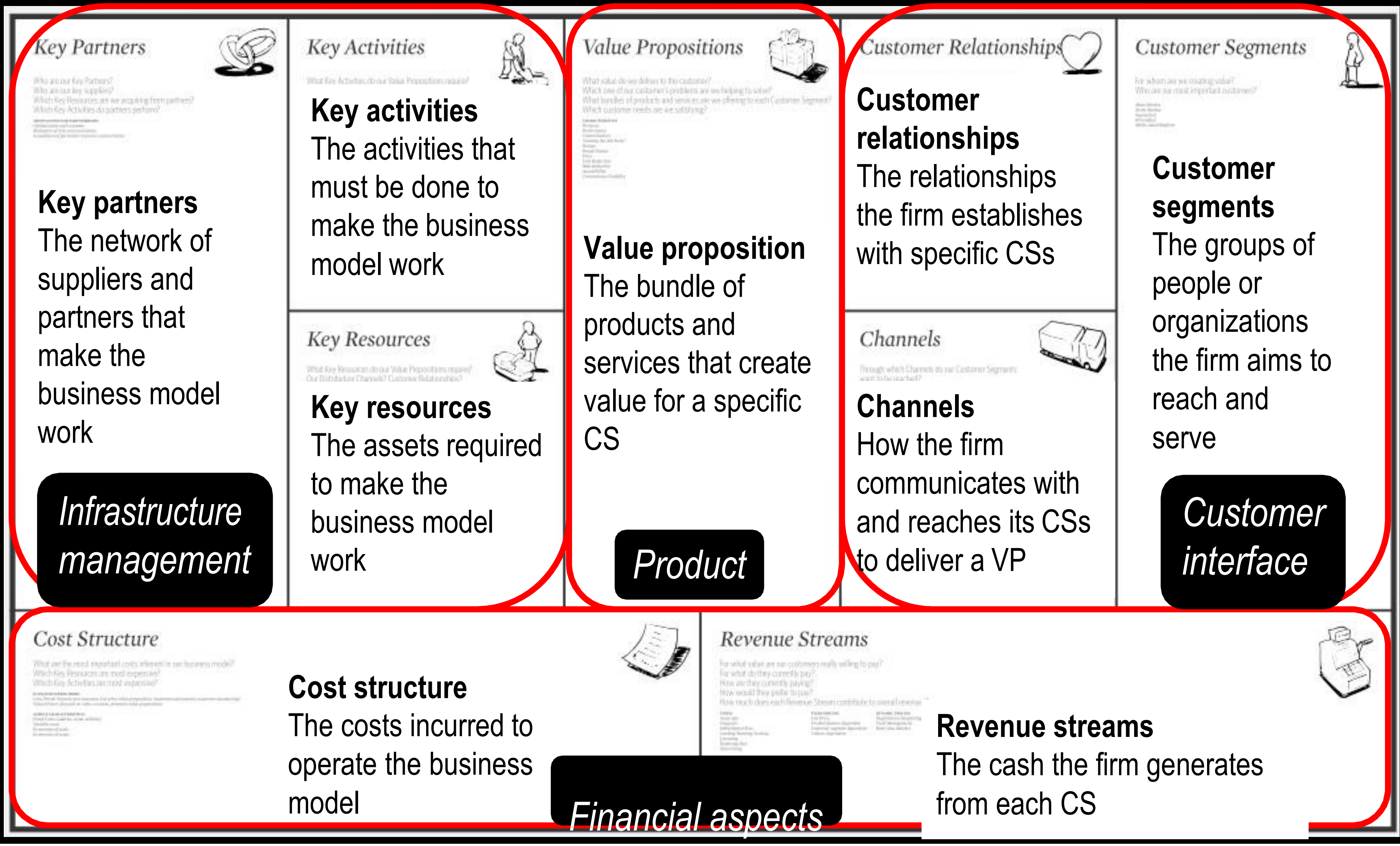
Defining the concept

- Defining a business model requires specific technology



The business model canvas

- … and Osterwalder's business model canvas (www.businessmodelalchemist.com)



The business model canvas

- Is there a sharp definition of who will be served (and who will not)?
- What are the needs of these CSs (e.g., better, faster, cheaper)?
- Is there a roadmap from the beach-head to the mainstream market (innovators → early adopters → early majority)?
- What is the size of the market?
- What is their willingness-to-pay?
- Is the definition of CS based on a hunch, or did we actually speak to customers?

Customer segments
The groups of people or organizations the firm aims to reach and serve

The business model canvas

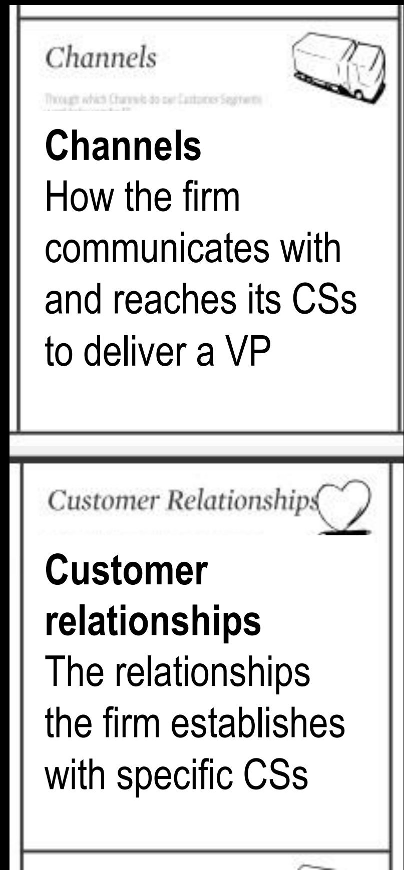
Value proposition
The bundle of products and services that create value for a specific CS

- Is the VP defined in terms of the features or in terms of benefits?
- Is each VP well connected to each CS?
- Is the attractiveness of the VPs clear?

The business model canvas

- Do the Channels cover the entire lifecycle, from initial awareness to after-sales support?
- Are the Channels coherent with VPs and CSs?

- Are the CRs able to fully engage CSs
- Are CRs complementary to the Channels?
- Are the CRs appropriate to VPs and CSs?



The business model canvas

Key activities
The activities that must be done to make the business model work

- Are the KAs that are relevant to deliver the VPs all listed?
- Is there a clear distinction between core and non-core activities?

The business model canvas

Key partners
The network of suppliers and partners that make the business model work

Key resources
The assets required to make the business model work

- Are KRs and KPs coherent with the KAs?
- What type of KRs are they?
  - physical vs. intangible vs. human
  - fixed vs. current
  - generic vs. specific vs. co-specialized among themselves
- How should these KRs be acquired (buy, make, ally)?
- Are KPs adequate to ensure KRs and KAs?
- What type of relationships tie us to KPs?

The business model canvas

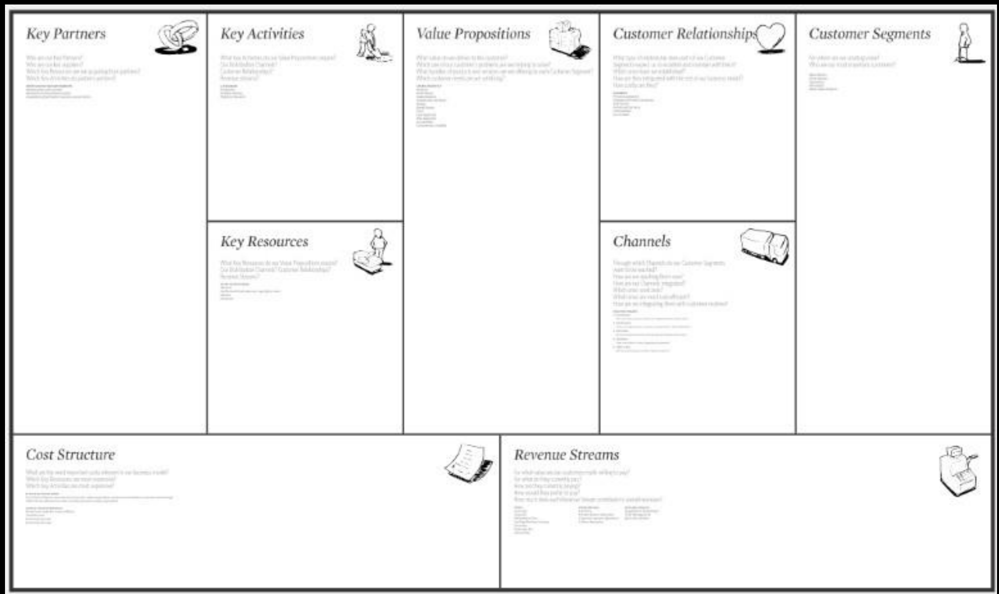
- What is the cost structure, divided among?
  - Fixed costs
  - Semi-fixed costs
  - Variable costs
- Can you envisage?
  - Economies of scale
  - Economies of scope
  - Economies of learning
- What is the revenue model and how will it evolve?
  - Transactions vs. recurring
  - Fixed vs. subject to discounts
  - Fixed vs. proportional to value
  - Sale vs. rental vs. ESCo
  - Static vs. dynamic pricing
- Given the size of CSs, what revenue can be expected?

Cost structure
The costs incurred to operate the business model

Revenue streams
The cash the firm generates from each CS

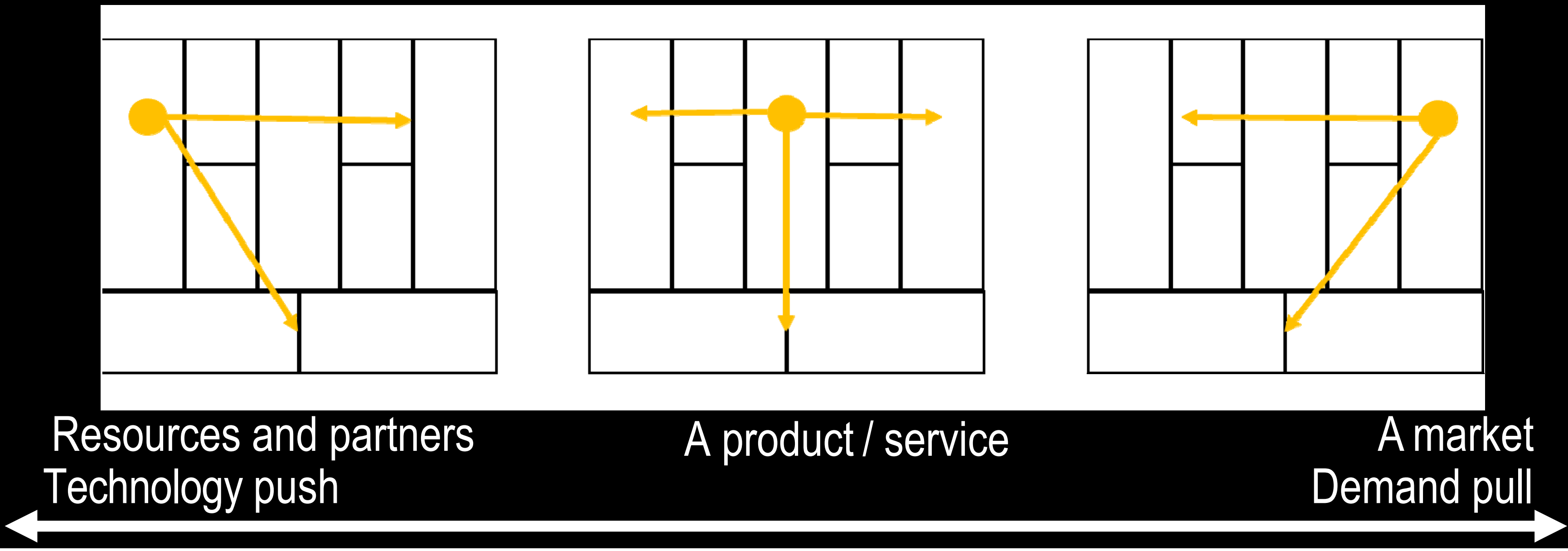
The business model canvas

- Try doing it! Pick one…
  - Analyze the business model for your favorite restaurant
  - Build a business model around your hobby
  - Build a business model around the needs of 5 yr. old kids
  - Build a business model around a cow (or some other apparently useless asset)



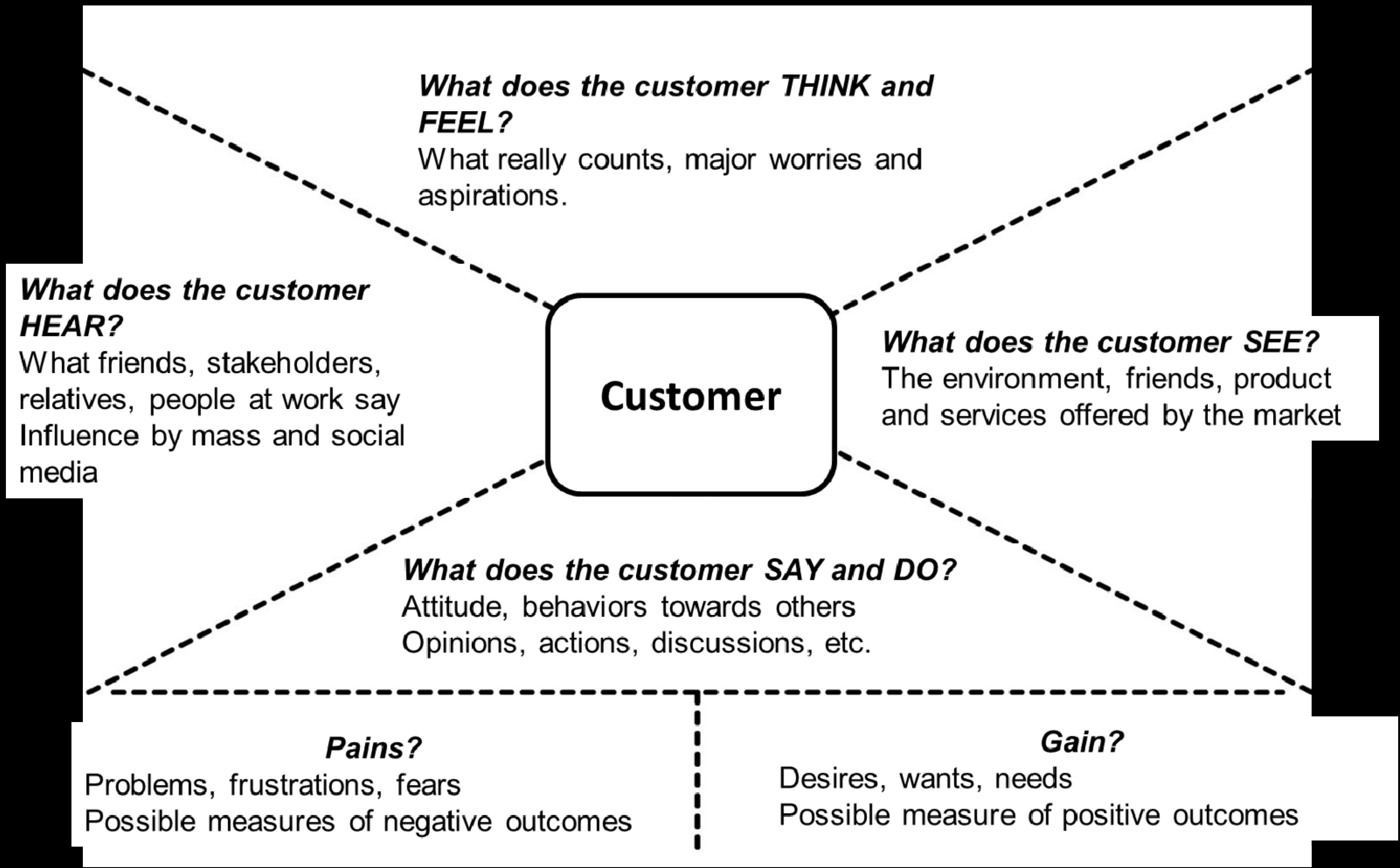
The business model canvas

- Can we benchmark our canvas against competitors' ones?
- What are the possible future scenarios, and which business model would be most suitable in each?
- Can we "unbundle" the firm, focus on one of the three key processes (innovation, production, sales) and outsource the other ones?
- What is the core of the firm, around which we can pivot?



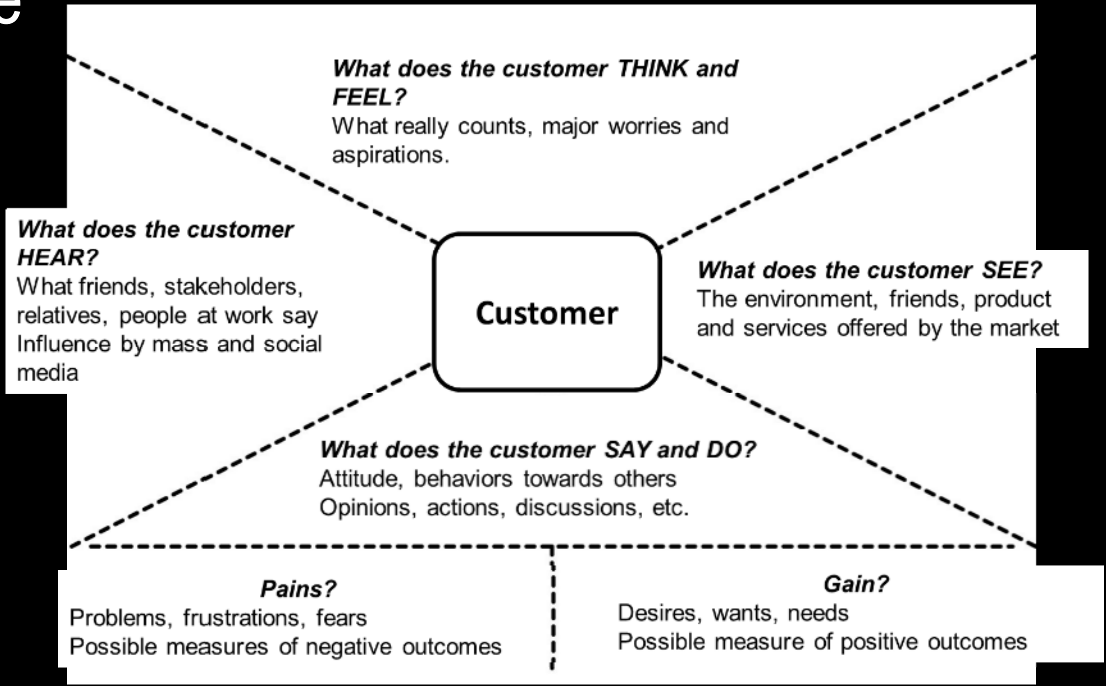
Getting deeper

- Understanding customers (the empathy map)



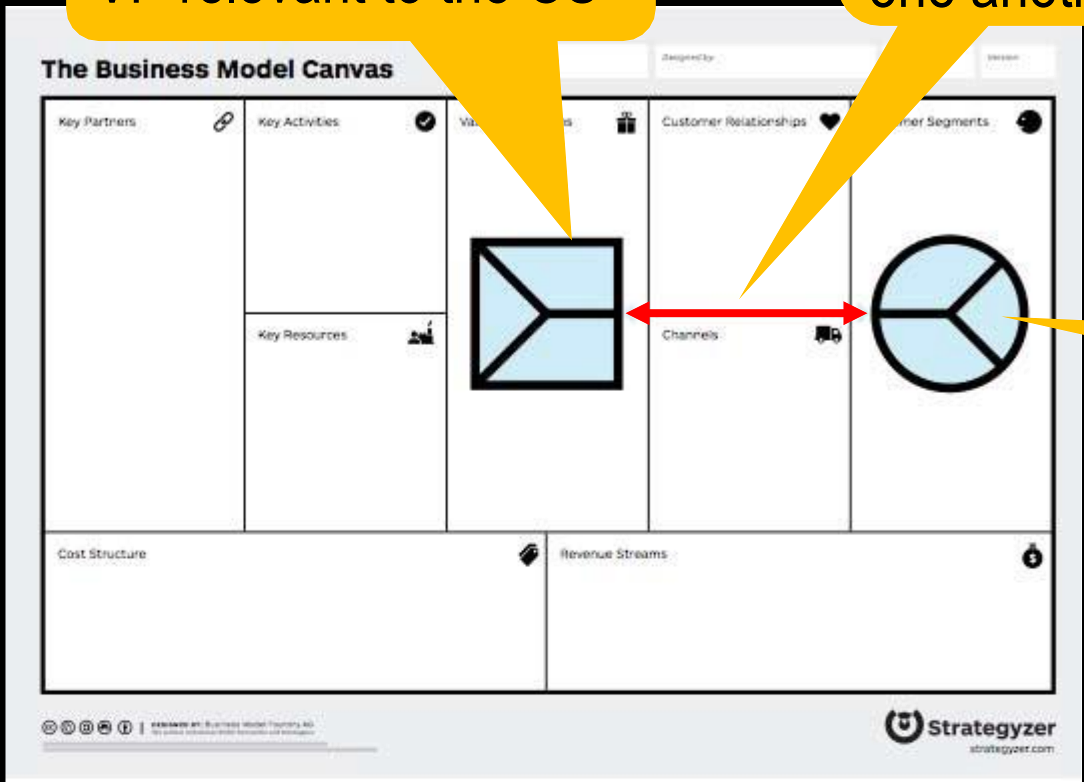
Getting deeper

- Try doing it! Pick one topic, and role-play with analysts interviewing a customer…
  - Urban mobility
  - Checking up your health
  - A day at the seaside



Getting deeper

- Understanding CSs and developing meaningful VPs (The Value Proposition Map)

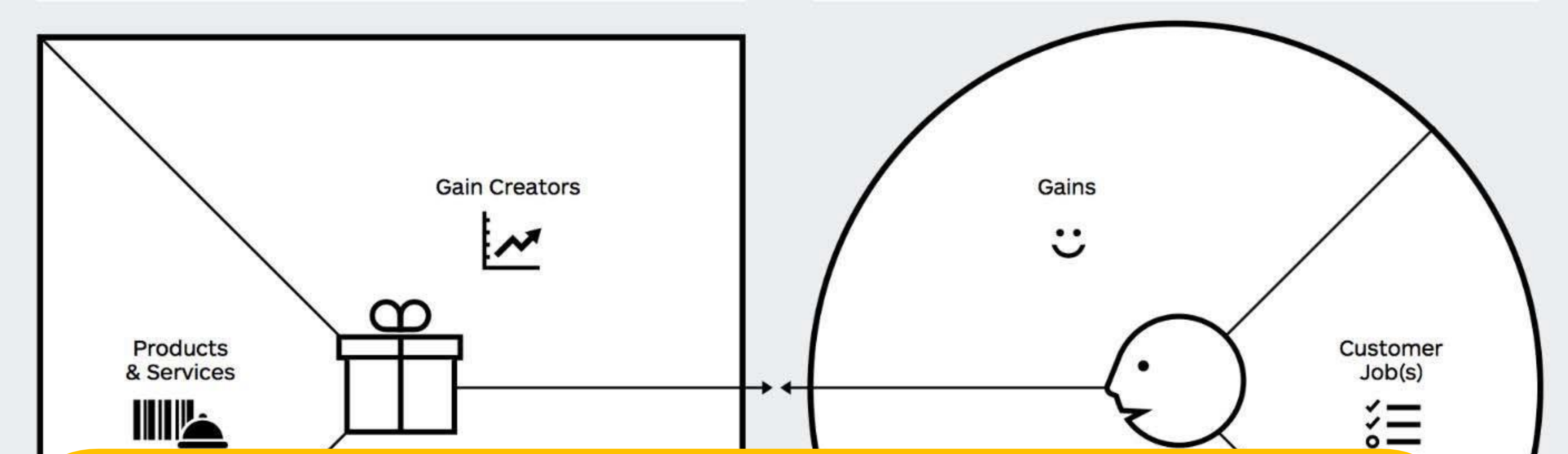


Value map for each VP relevant to the CS

Check that they fit with one another

Customer profile for each CS

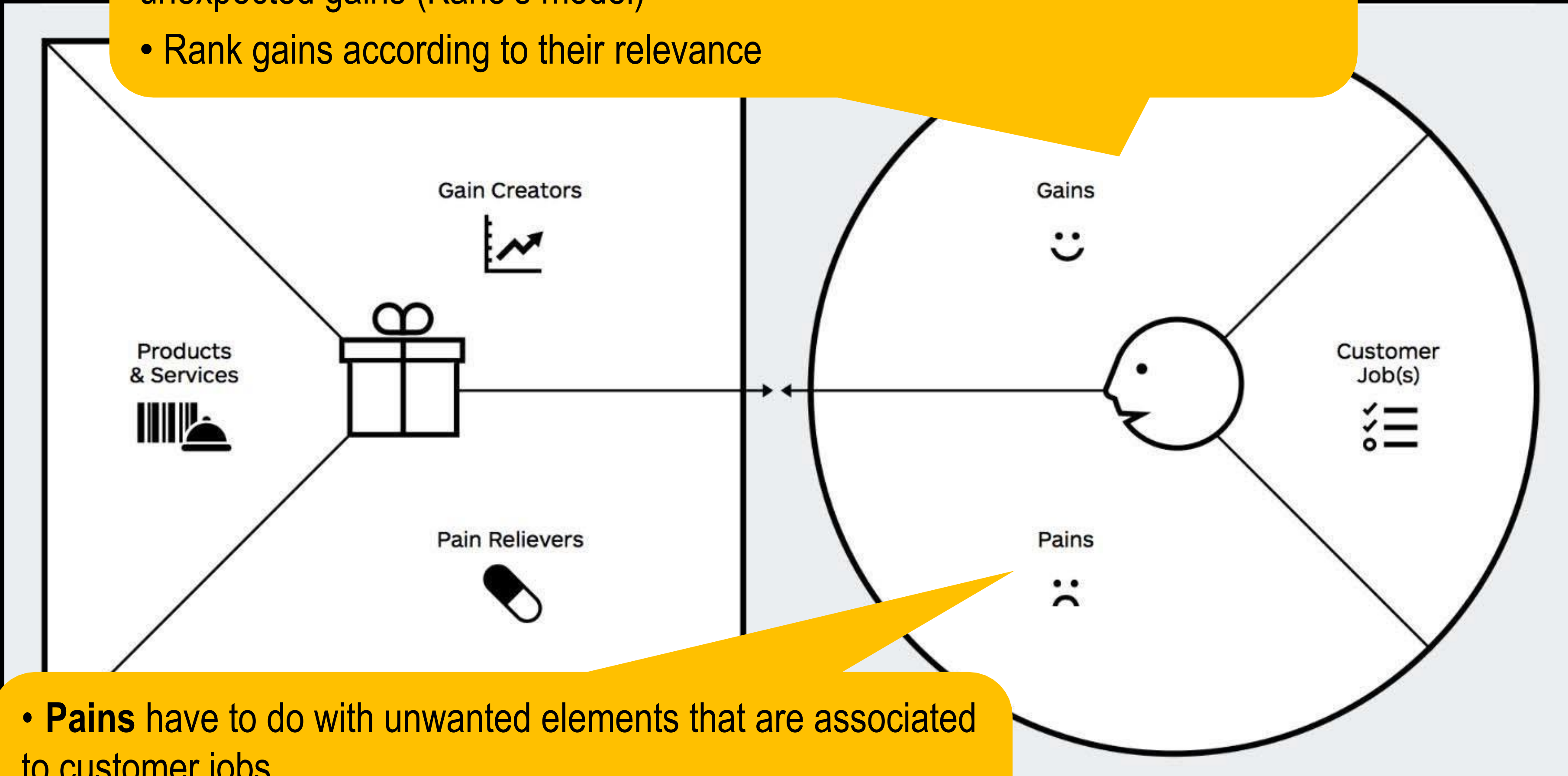
Getting deeper



- **Customer jobs** have to do with what customers are trying to do
- Jobs *lead* to outcomes («gains» if positive, «pains» if negative)
- Distinguish among functional vs. social vs. emotional jobs
- Understand job context(s)… the same CS may behave differently according to context
- Drill deeper by asking «why?»
- Work on interrelated CSs (e.g., customers that cover complementary roles in the purchasing process, complementors, components of double-sided markets)
- Rank jobs considering importance (does it matter?), tangibility (can people feel the problem?), dissatisfaction (are people unhappy?), potential (volume or willingness to pay?)

Getting deeper

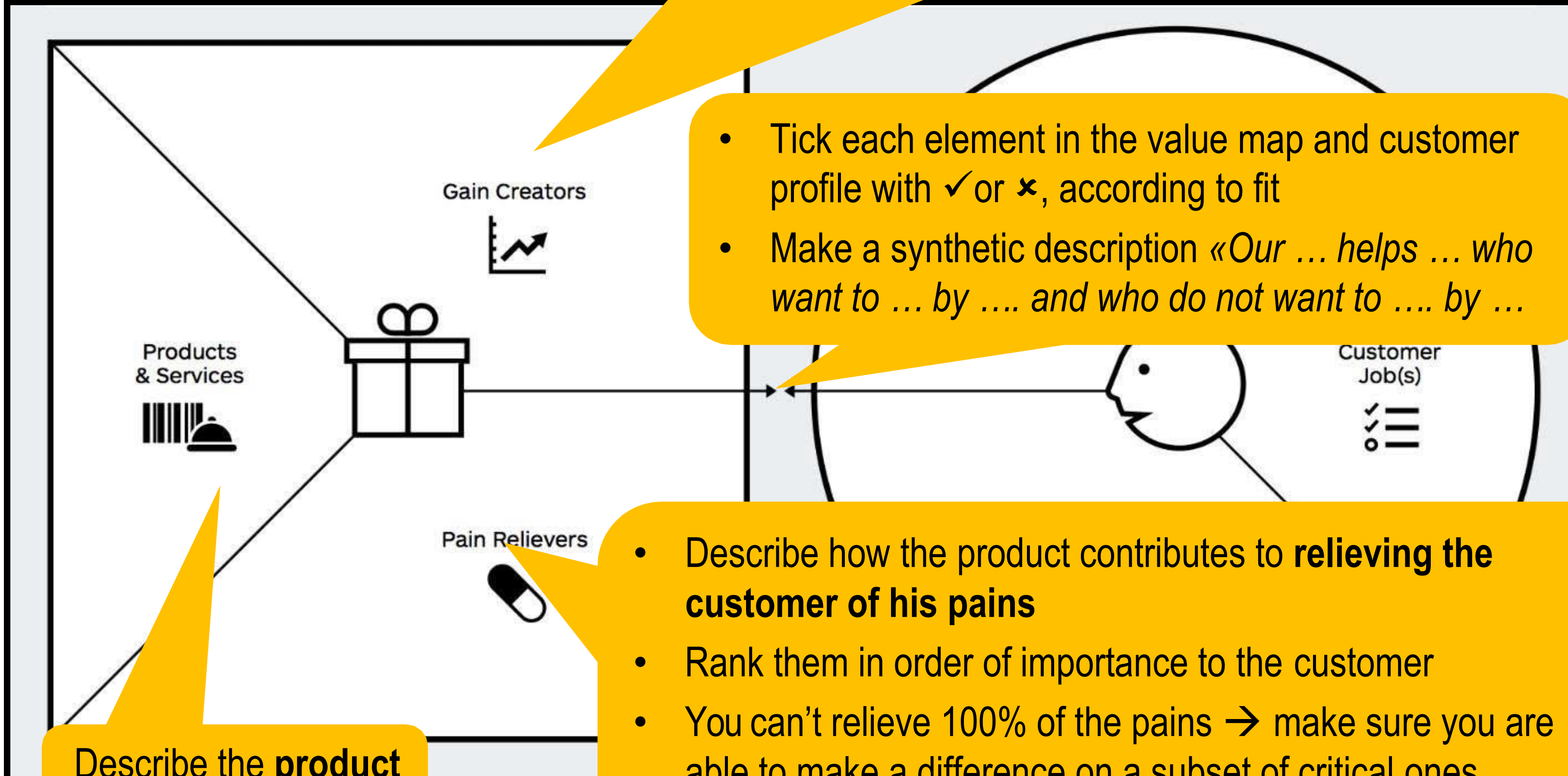
- **Gains** have to do with wanted elements that are associated to customer jobs
- Distinguish among required gains, expected gains, desired gains, unexpected gains (Kano's model)
- Rank gains according to their relevance



- **Pains** have to do with unwanted elements that are associated to customer jobs
- Distinguish among undesired outcomes, obstacles, risks
- Rank pains according to their severity

Getting deeper

- Describe how the product contributes to **creating customer gains**
- Rank them in order of importance to the customer
- You can't create 100% of the desired gains → make sure you are able to make a difference on a subset of important ones
- Take out unnecessary gain creators and simply the product



- Tick each element in the value map and customer profile with ✓ or ×, according to fit
- Make a synthetic description *«Our … helps … who want to … by …. and who do not want to …. by …*

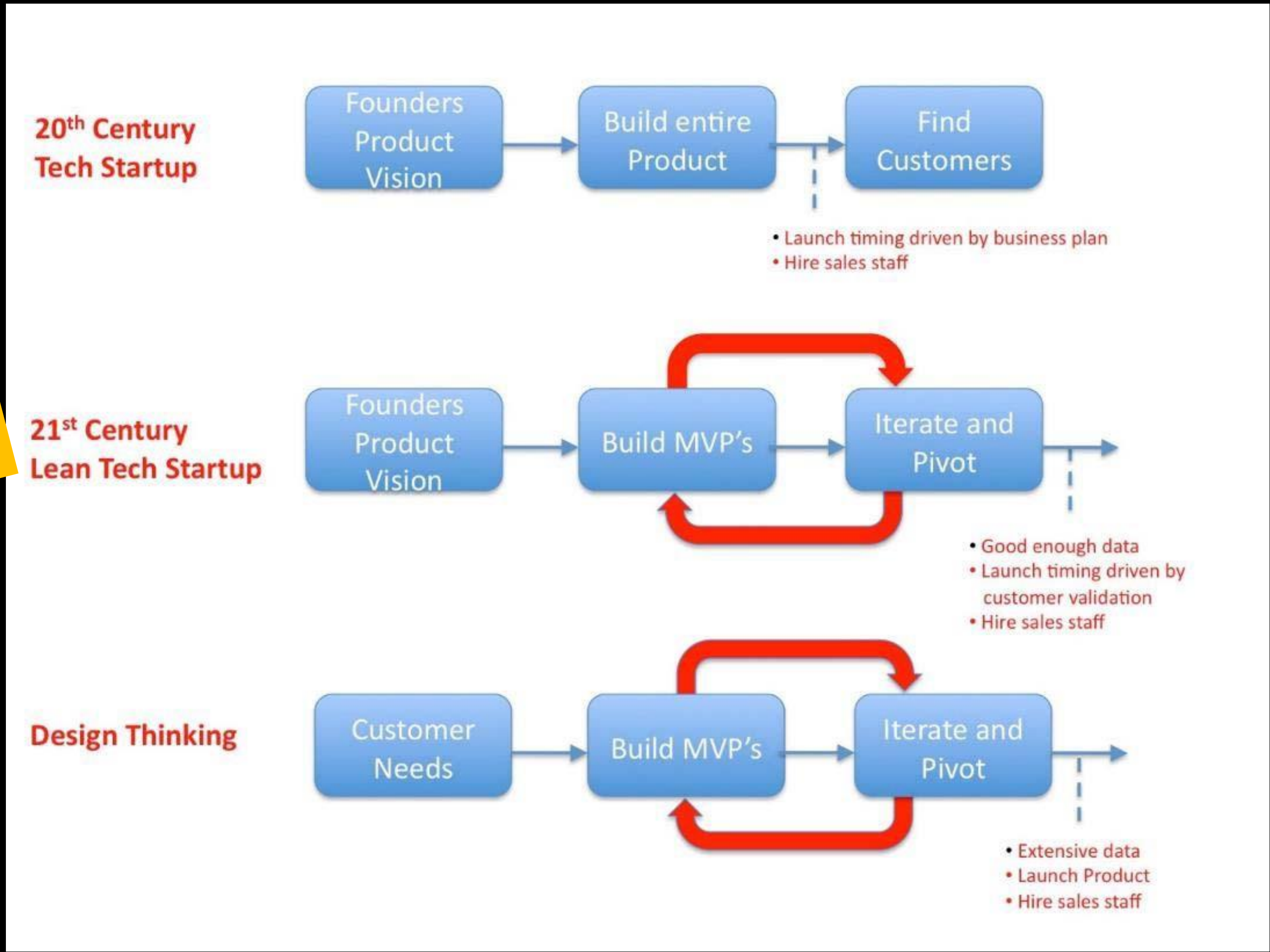
Describe the **product** and its features

- Describe how the product contributes to **relieving the customer of his pains**
- Rank them in order of importance to the customer
- You can't relieve 100% of the pains → make sure you are able to make a difference on a subset of critical ones
- Take out unnecessary pain relievers and simplify the product

Getting deeper

- Three approaches to develop the startup are possible

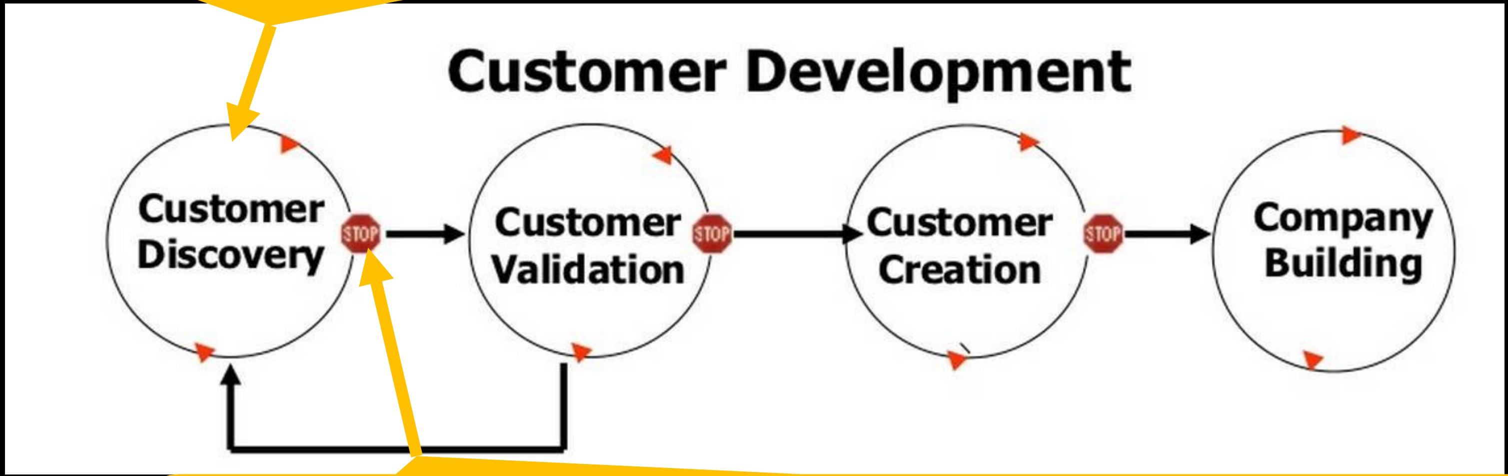
The «lean startup» approach is based on the concept of «customer development»



Getting deeper

- Developing customers

• Get out of your building, talk to customers, collect facts and generate hypothesis
• Since customers are conquered 1 by 1, «develop your concept for the few»
• Understand the orgchart behind purchasing processes



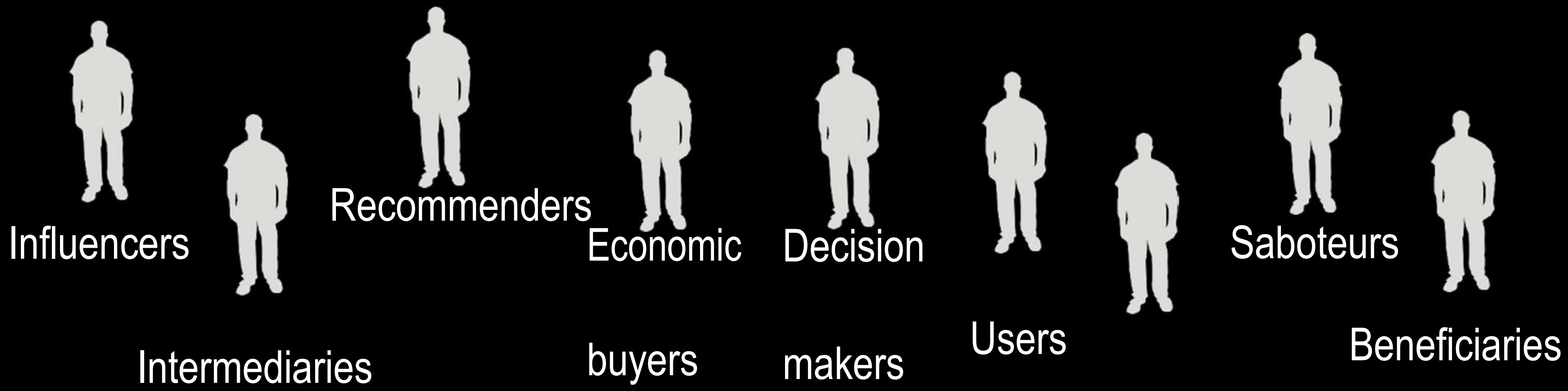
• Have you understood customers' problems?
• Does your product solve them? How will their «typical day» change?
• Have you understood how much will they pay for it?
• Have you figured out how actors influence each other during the purchasing process?

Getting deeper

- Getting information from customers is very important
  - Look for existing data and insights (secondary research)
  - Interview people
  - Stay close to customers and observe them
  - Be a customer yourself
  - Co-create with customers
  - Perform experiments (see later)

Getting deeper

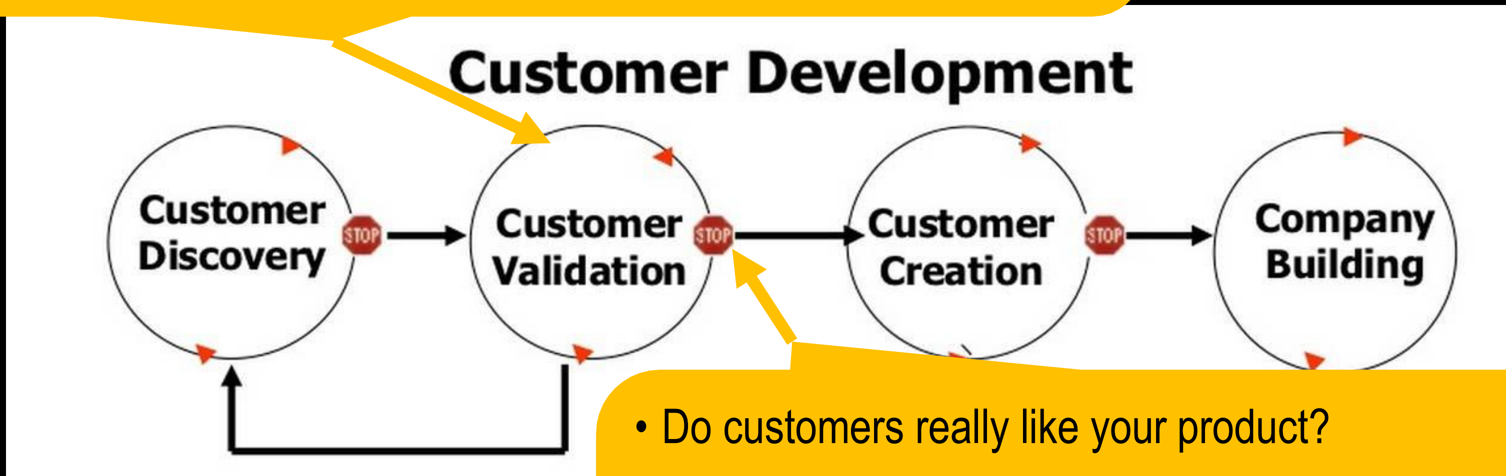
- In B2B sales, procurement is a complex process that occurs in a complex organization
- Each actor can be viewed as a CS… how can you “align the stars” so that you get a “yes” from each?
  - Try creating VPs that all of them may view as positive or at least acceptable → design the product
  - Play on reciprocal influences → design the sales process



Getting deeper

- Developing customers

- Use prototypes and Minimum Viable Products to test hypothesis
- Perform A/B experiments
- Debug things that customers don't like and their root causes
- Develop a repeatable sales process



- Do customers really like your product?
- Do you have a good understanding of the sales cycle and a proven sales process?
- Do you have orders?
- Is the model financially sustainable?

Getting deeper

- Prototypes and MPV can be of different nature

Representation of VPs

- Data sheets or brochures
- Storyboards
- Landing pages or product boxes
- Videos

Functional MVP

- Preliminary functional prototypes
- Wizard of Oz prototypes (real front end, fake back-end)

Life-size MVPs

- Near-final prototypes
- Mock sales and pilots
- Presales

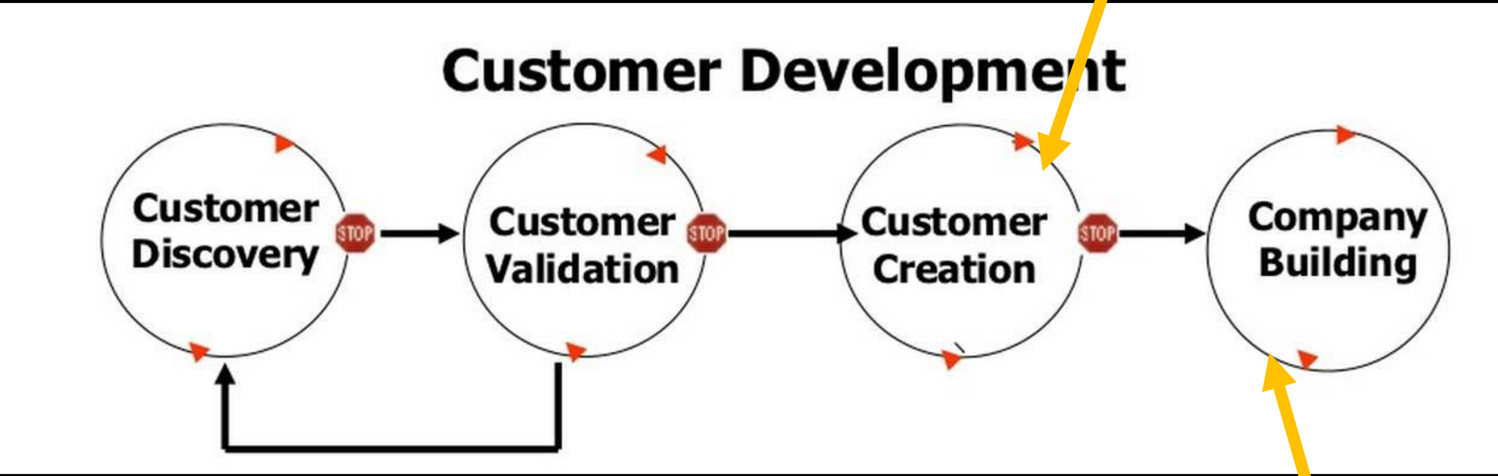
Innovation games

- Design the product box and try selling it
- Buy a feature

Getting deeper

- Developing customers

• Scale up your customer creation process by using «growth engines»
• Learn how to progress along the curve from innovators to early adopters and then to the early majority



• Rebuild the company….
It's not a startup any more

The elements that make up strategy

- Let’s work on a metaphor… strategy and navigation
  - Destination («where do we want to go?»)
  - Map («what is the environment from here to there?»)
  - Weather («what is going to happen from here to there?»)
  - Means («what is available to bring me there?»)
  - Crew («who and how capable are we?»)
  - Provisions («how can we sustain ourselves?»)
- What elements are fixed or variable in the short vs. medium term?

Competitive advantage

- A rough summary of Porter's theory of competitive advantage

Term	Meaning	Implication
Industry	Firms do not operate in vacuum, but in industries and value chains	Study your industry and its value chain carefully
Profitability	Industries can be more or less attractive, depending on their structural profitability	Try to enter profitable industries and steer away from unprofitable ones
Five forces	A firm's profitability is eroded by «forces» exerted by competitors, customers, suppliers, entrants, other industries	Get to know these forces, and steer your firm in order to reduce their impact
Competitive advantage	A firm has competitive advantage if it is more profitable than its peers. Competitive advantage arises if the firm has structured itself in order to reduce the influence of the five forces	See above
Sustainable competitive advantage	A firm's competitive advantage is sustainable if it is able to avert the 5 forces, and prevent imitation from less competitive firms	Look for unique, difficult to imitate, appropriable sources of competitive advantage (e.g., patents, proprietary standards or platforms)
Generic strategies	A firm can pursue competitive advantage by either lowering costs or looking for differentiation	Make up your mind

Competitive advantage

- Intellectual Property (IP) strategy

Form	Pros	Cons

Competitive advantage

- Common pitfalls in IP strategy

Inadvertent disclosure (make proper use of NDAs)	Doing everything by yourself
Leaving everything to the patent attorney	Patenting what could be kept secret
Not studying Freedom to Operate carefully	Thinking one patent is enough

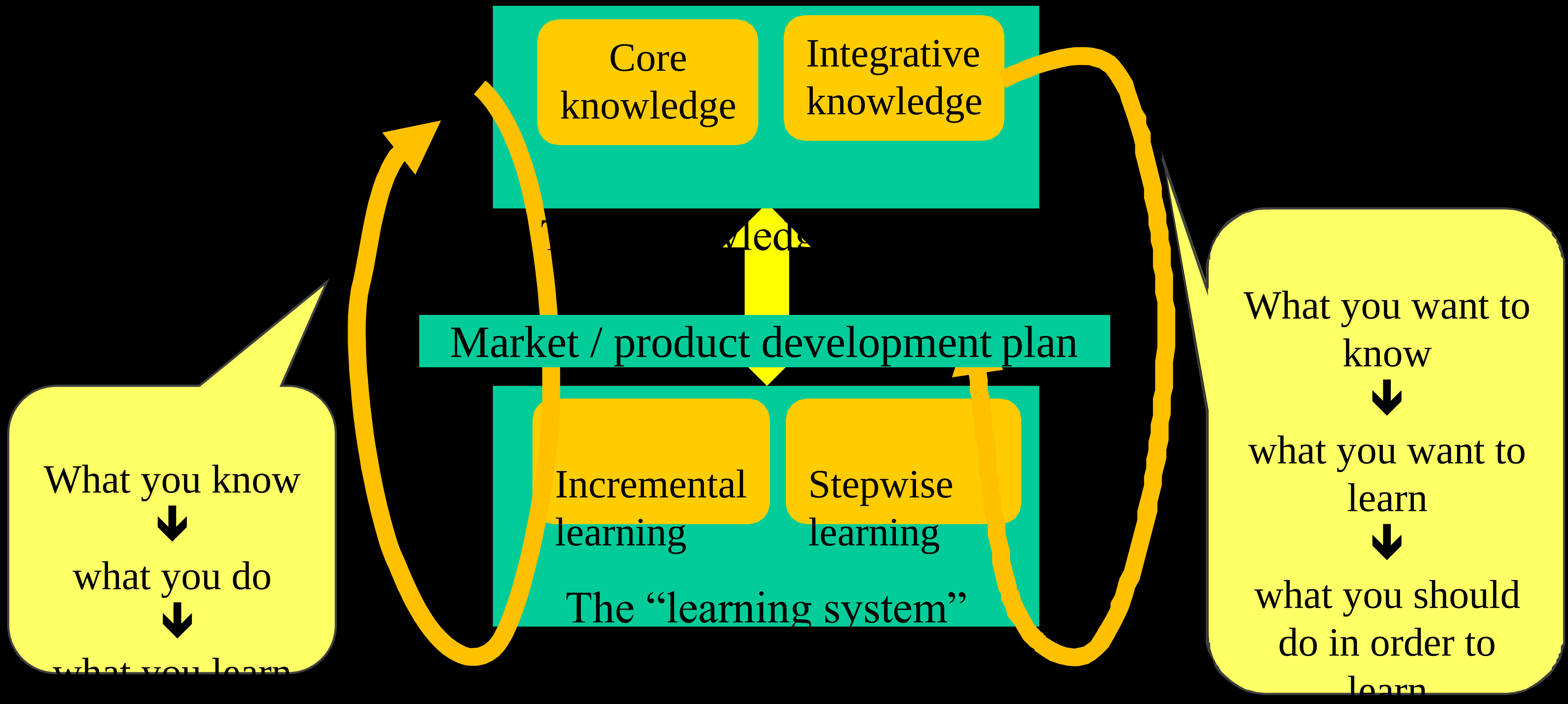
Competitive advantage

- Standard: "*set of specifications that provide value to the product* <u>*because of its conformity to the standard*</u>"
  - A standard is there if "were the product different, it would be of lesser economic value because of non-conformity (and NOT because of lesser performance!)"
  - If standards are applicable, success requires specific strategies
    - Winner takes all
    - Lock-in

    } → Potential monopolies
  - Strategies include
    - Lobbying
    - Speed
    - Penetration pricing
    - Licensing

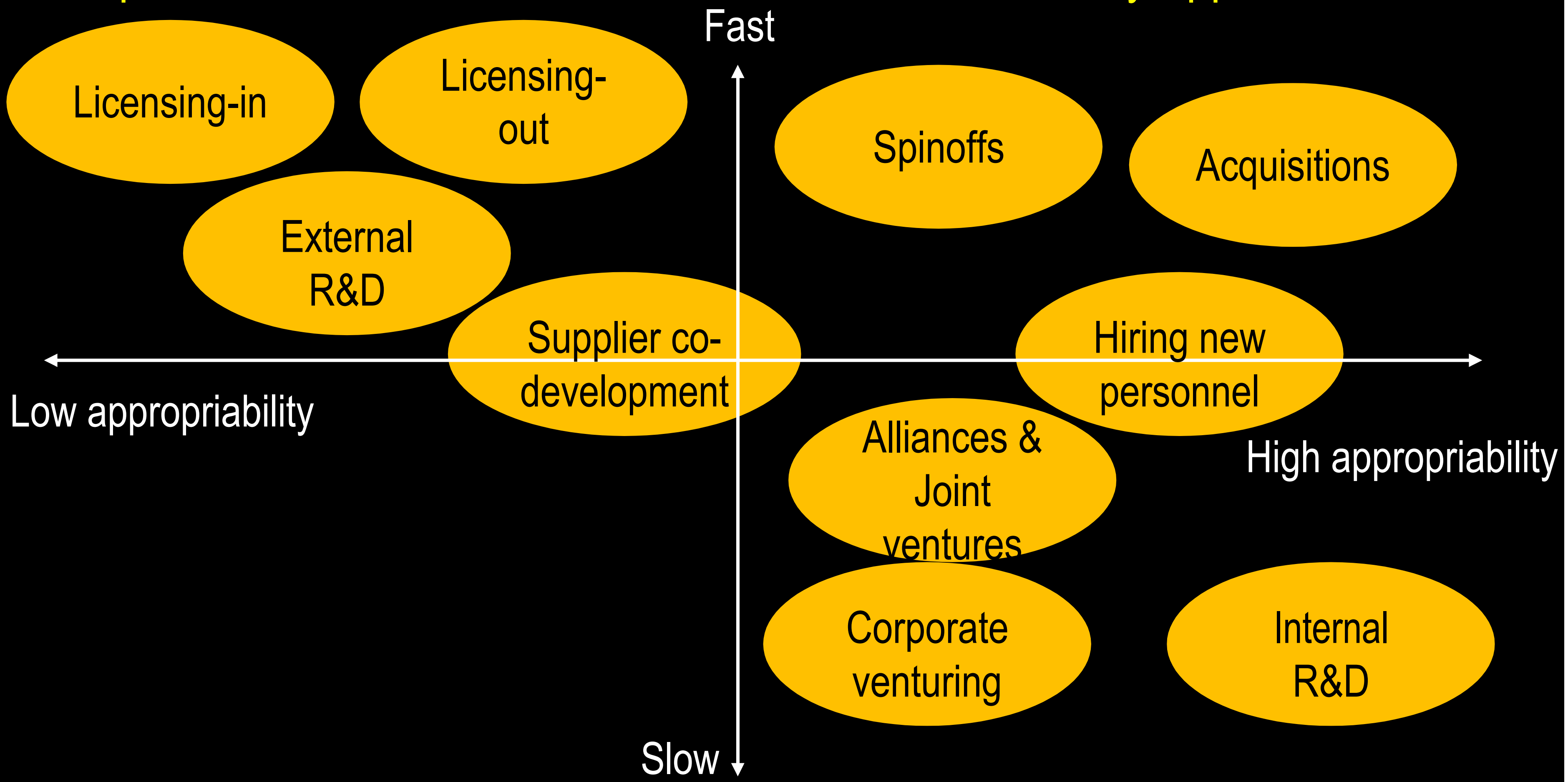
«Core competencies» and capabilities

- The firm is a set of resources and routines (→competencies)
- The firm's strategy must rotate around core competencies and their evolution



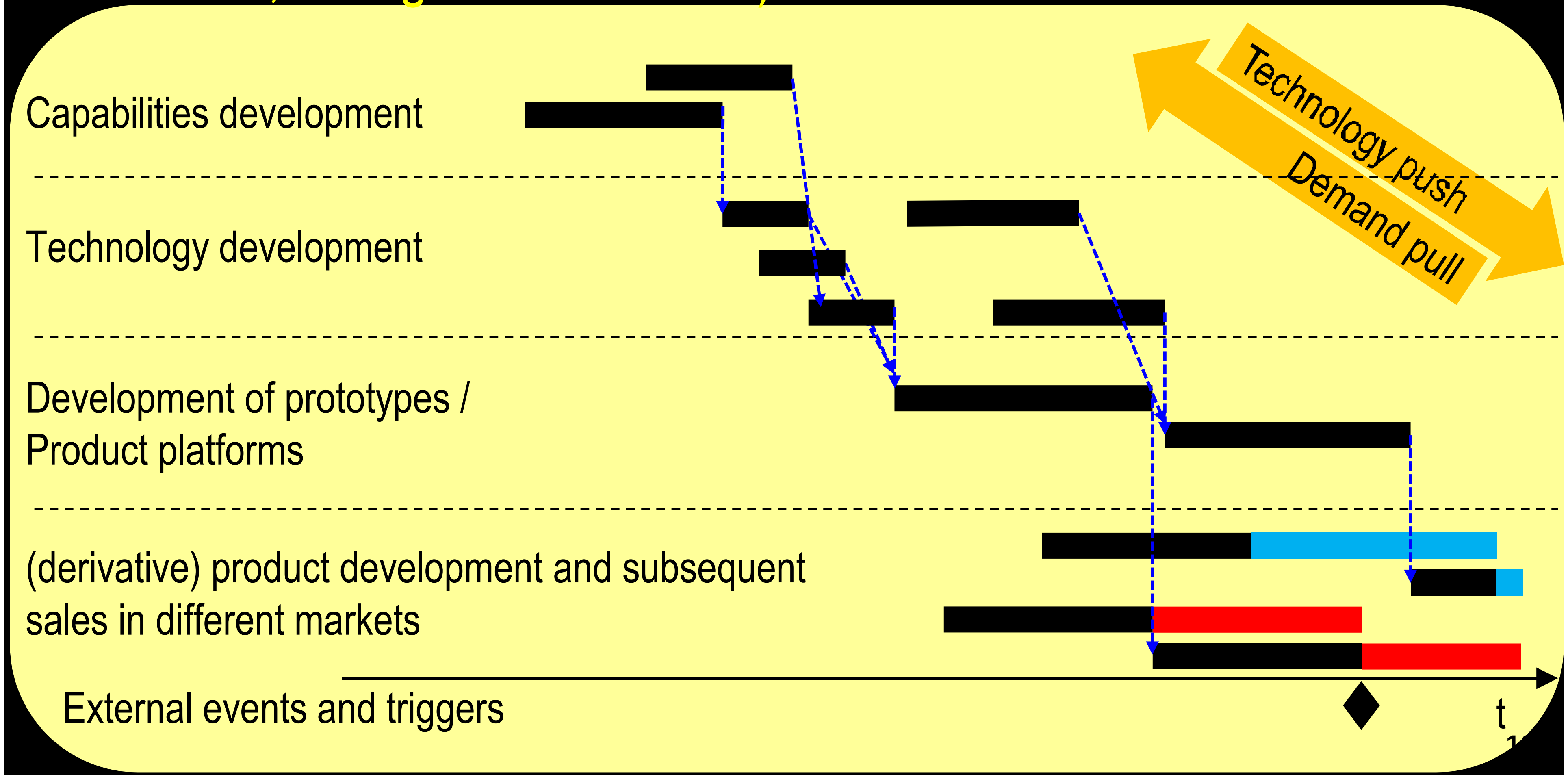
"Core competencies" and capabilities

- There is a variety of means (the main tradeoff is speed vs. appropriability)
- A dilemma between appropriateness of choice vs. execution capability
- "Open innovation" is an umbrella term that covers many approaches



Roadmapping

- Technology roadmapping allows making a picture of an innovation strategy (check for coherence with respect to results, timing and resources)



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