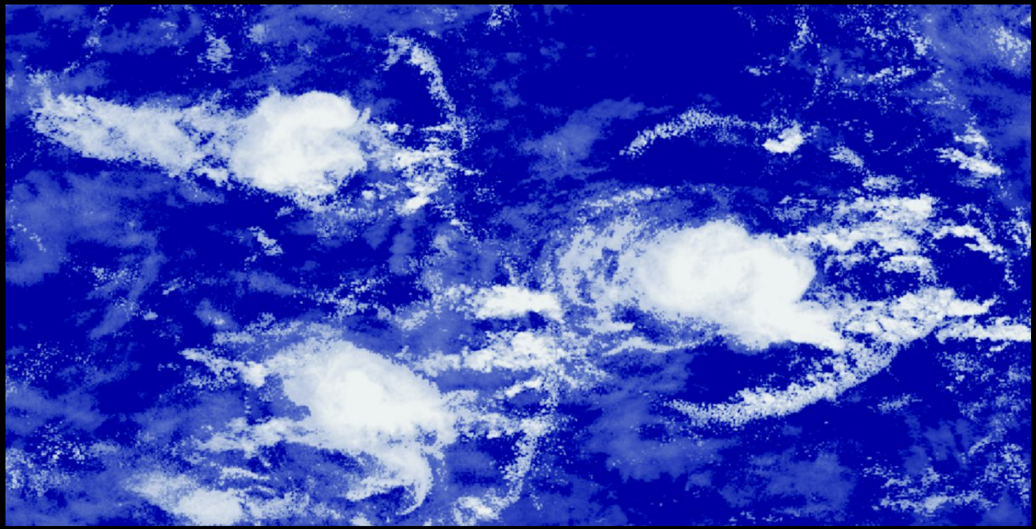
Large Eddy Simulation (LES) & Cloud Resolving Model (CRM)

Françoise Guichard & Fleur Couvreux

CNRM (CNRS & Météo-France, Toulouse, France)



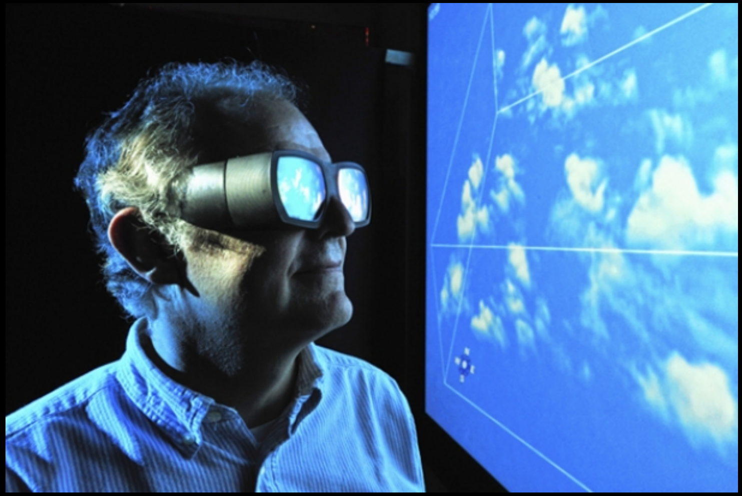
Khairoutdinov et al. (2009)

moist convection over ocean
$L_x = L_y = 200$ km, $L_z \sim 20$ km
$\Delta x = \Delta y = 100$ m ($\sim \Delta z$)

estimated visible albedo

OLR, NICAM model ($\Delta x = 7$ km, 2007)
Satoh, Miura, Tomita & coll.

Harm Jonker watching virtual clouds
National Geographic (2012)



Large Eddy Simulation (LES) & Cloud Resolving Model (CRM)

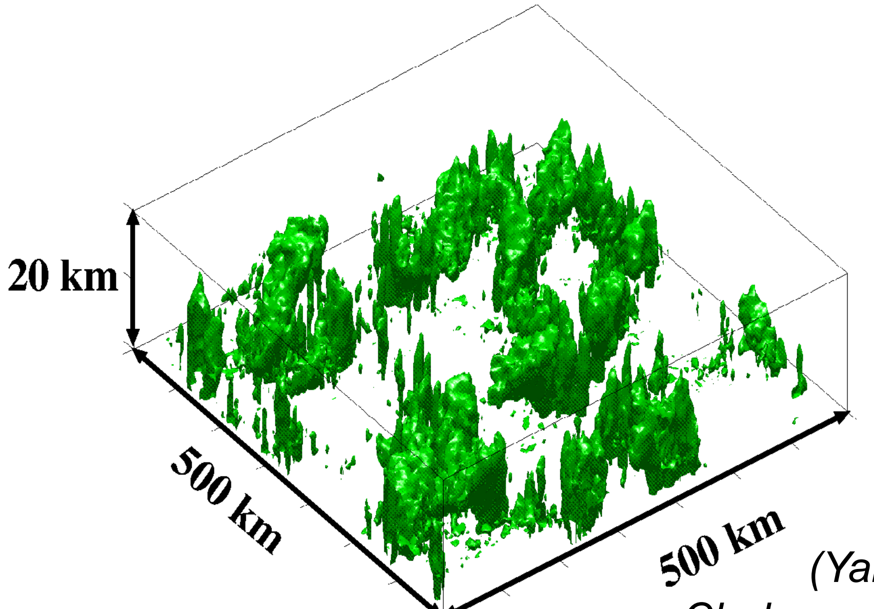
Both : numerical models able to explicitely simulate convective moist phenomena: mesoscale, transient, turbulent, cloudy, 3D, throughout their life cycle or part of it, over a limited area.

Acronym LES more broadly and widely used in fluid dynamics (Smagorinsky 1963)
CRM limited to atmospheric science (mid 90's, GEWEX GCSS)

CRMs existed before being given a name (e.g. Krueger 1988, Gregory and Miller 1989)

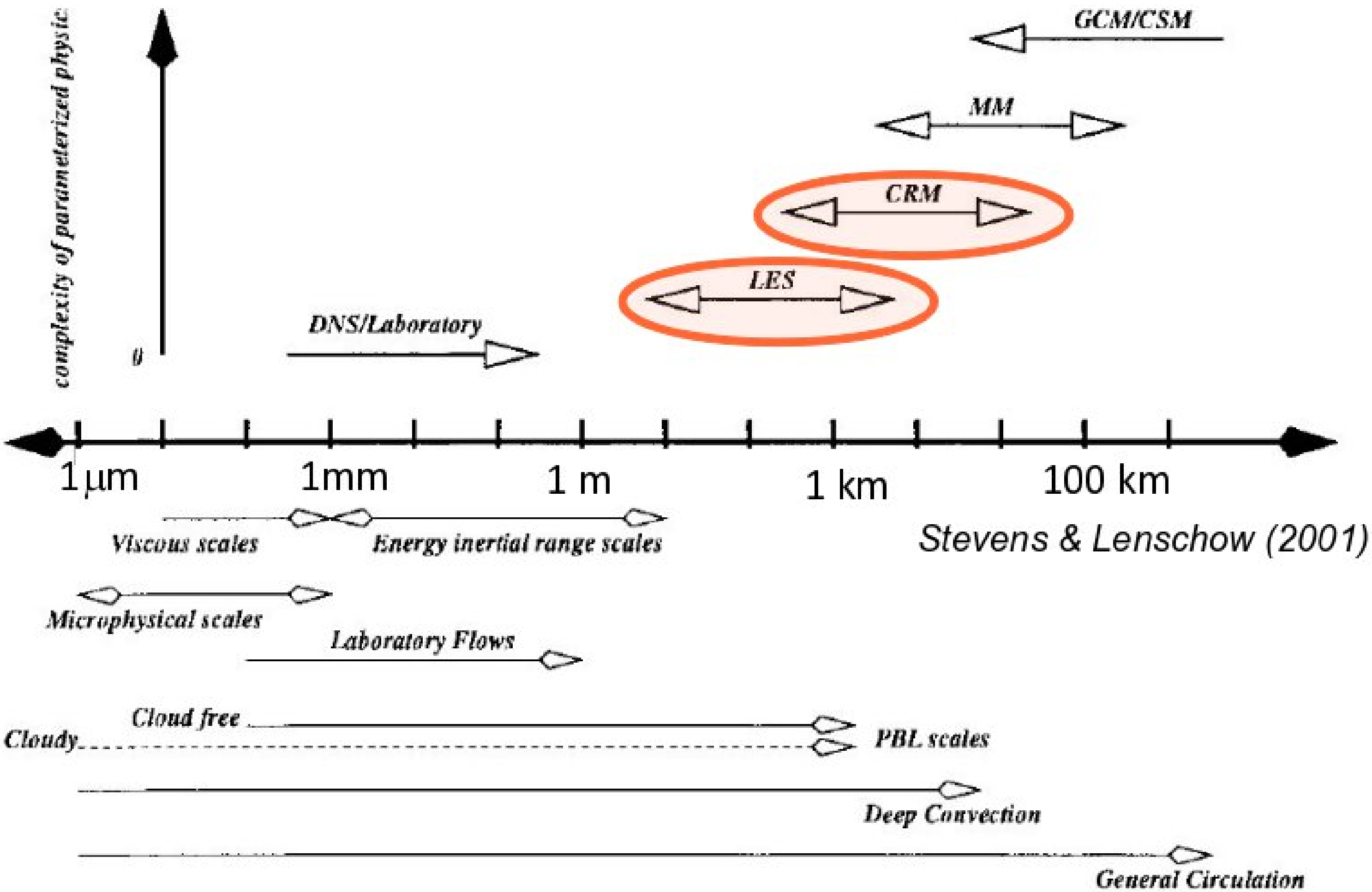
You will also find other expressions in the litterature :
CEM : cloud ensemble model (Xu & Randall 1996)
[CRM designed as extension of LES to the simulation of deep convection]
Convection Permitting Model *(more recent, NWP evolution)*

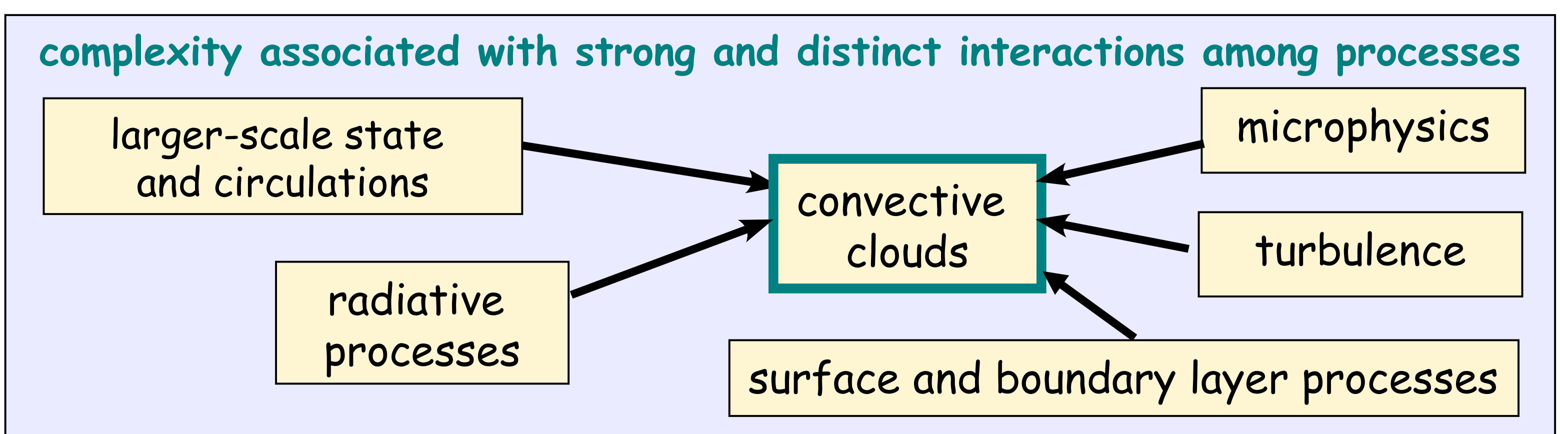
LES and CRM : cousins
Non-hydrostatic fine scale models
* ***LES** finer grid (~ 100 m or less)*
  *for **shallow clouds** (cumulus, stratocumulus)*
* ***CRM** coarser grid (~ 1 km)*
  *for **deep precipitating convective clouds***
    - *more complicated microphysics*
    - *different sub-grid parametrizations for sub-grid scale processes*
    - *employed with more varied initial and lateral boundary conditions*

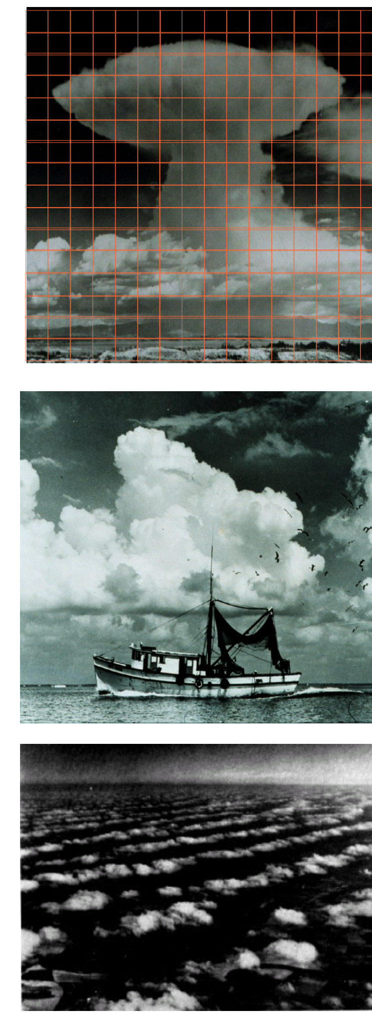


(Yano, Chaboureau)

SCALES : where LES/CRM stands within a panoply of atmos. models





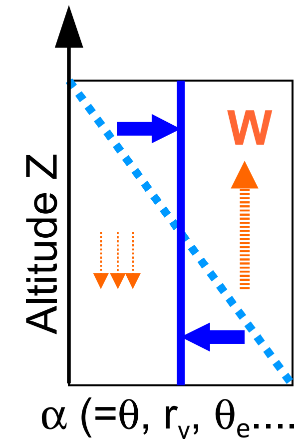


Photos from NOAA historical library

Large Eddy Simulation (LES) & Cloud Resolving Model (CRM)

Convective clouds : transient vertical motions arising at small scale

w : vertical velocity



Scale analysis :

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g$$

UW/L $\qquad P_0 / \rho H$

U=10 m/s , H = 10 km

Synoptic scale : L > 100 km w ~ 10^{-2} m/s dw/dt ~ 10^{-7} m (hydrostatic)

Cloud scale : L < 10 km w ~ 10 m/s dw/dt ~ 10^{-2} m

even if small, vertical acceleration cannot be neglected

From physical considerations, Dw/Dt is a major expression of convection

Non-hydrostatic dynamics**: introduction of a **prognostic equation for w

Nowadays : LES of squall lines, 2 km (x) x 2km (y) grid size of NWF models
NICAM (global CRM)
MMF (Multiscale Modelling framework, 2D CRM in each GCM column)
1^{st} DNS of CBL, Jonker et al.

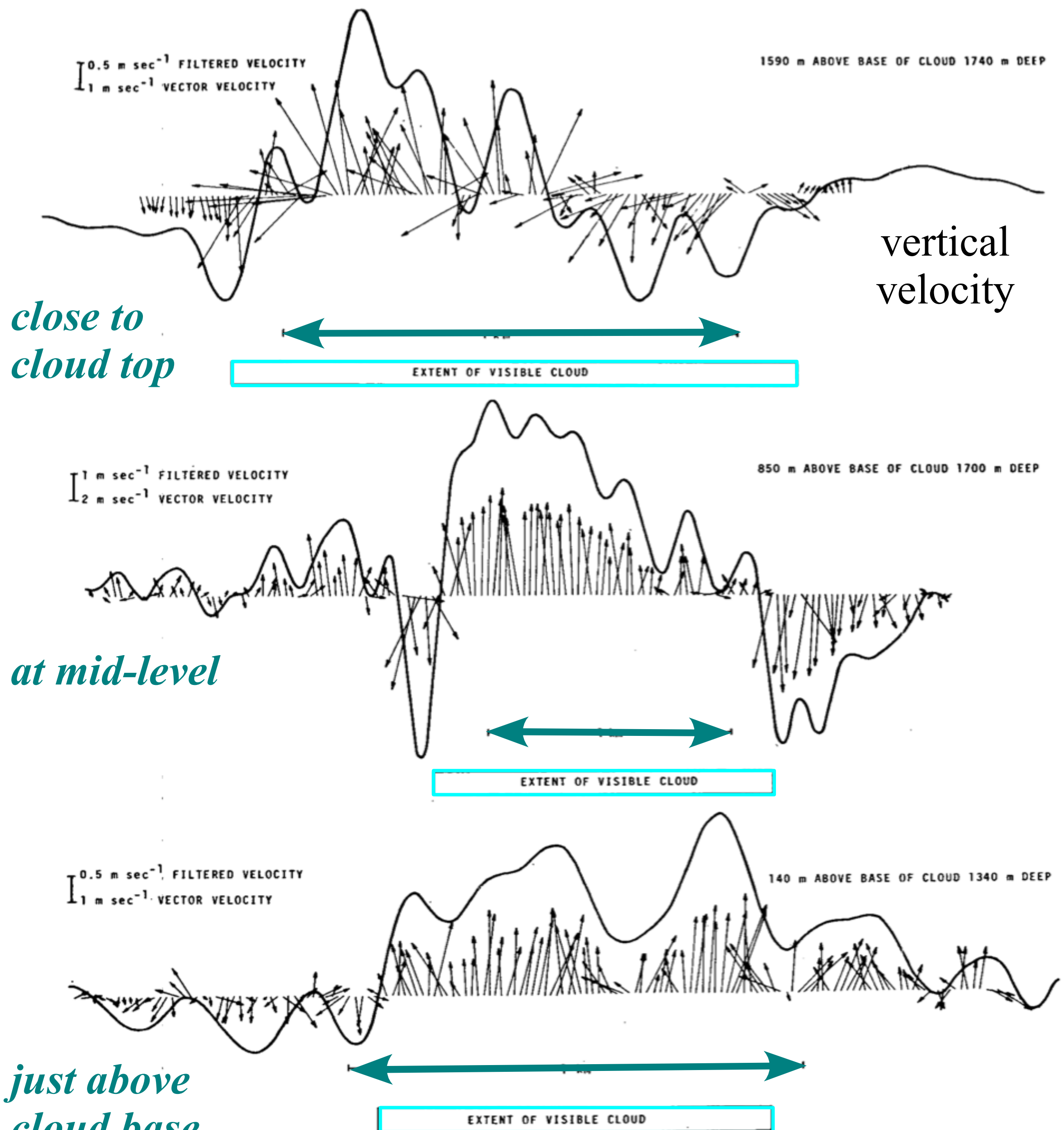
emergence of new names, acronyms likely (beyond superparametrization)

The evolution since 1970's is very impressive

* computer power
* but also a lot of work dedicated to improve models (on-going process)

The early days of LES/CRM

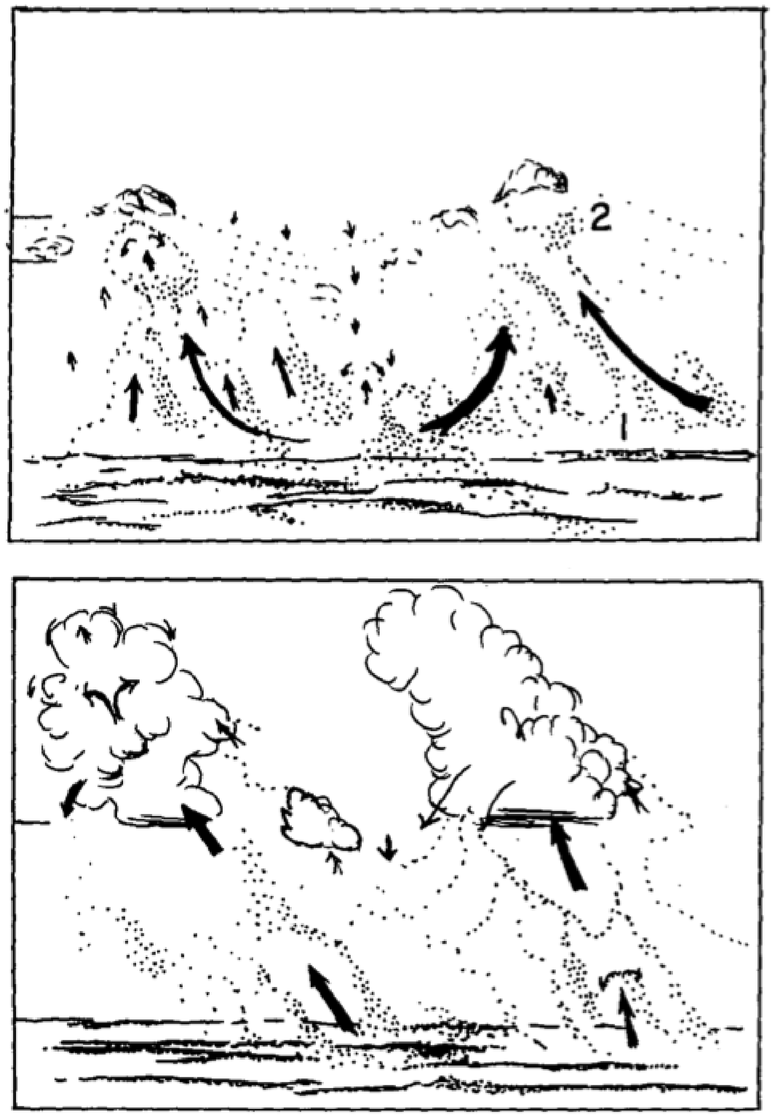
Aircraft in-cloud flights, shallow cumulus



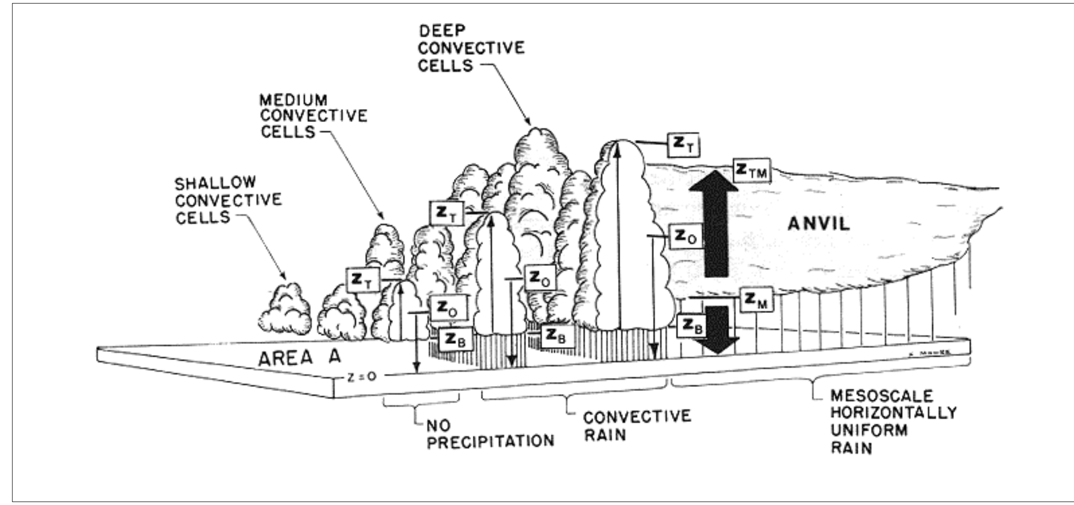
Warner (1970)

highly turbulent
down to less than 100 m

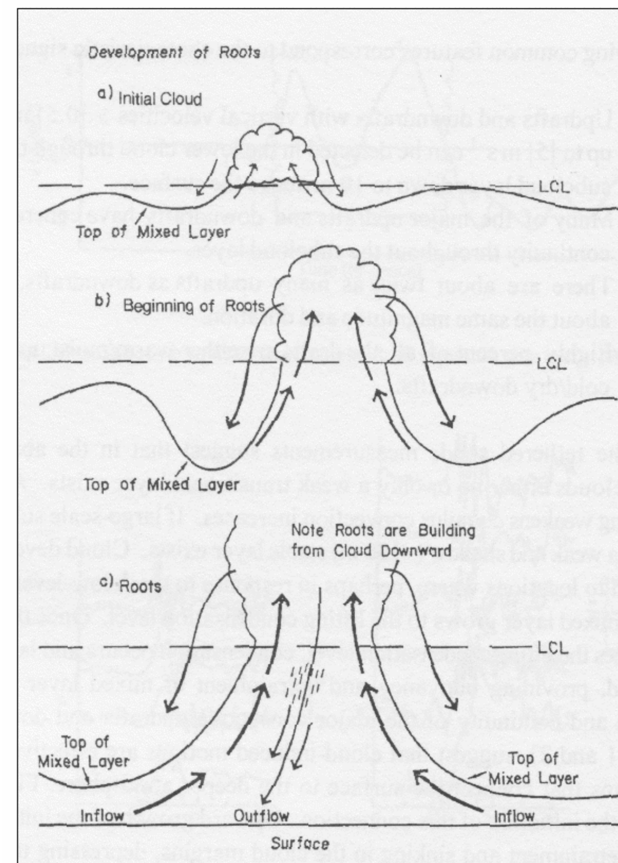
Conceptual models inferred from analyses of field campaign data



Schematic of two distinct cloudy convective boundary layers
(Lemone et Pennell 1976)
GATE experiment (1974)



(Houze 1980, Houze and Betts 1981)



(Garstang 1980, Garstang et Fitjarrald 1999)

Mitigated perceptions on CRM ancestors in the late 60's

« A contrasting approach is exemplified by the brave attempts at much more sophisticated models (e.g., Ogura, 1963; Murray and Hollinden, 1966; Arnason, Greenfield, and Newburg,1968) which integrate the full hydrodynamic equations of motion (...) in a series of time steps.

So far, none of these have achieved sufficiently realistic relationships between vertical growth, buoyancy, size,velocity, and temperature for useful prediction in modification experiments.

Among the major problems are the intractability of formulating turbulent entrainment, the limitations imposed by working within confined boundaries, errors and fictitious results introduced by finite differencing schemes, and the restriction to two-dimensional or axisymmetric coordinates. »

Simpson et Wiggert (1969)

However

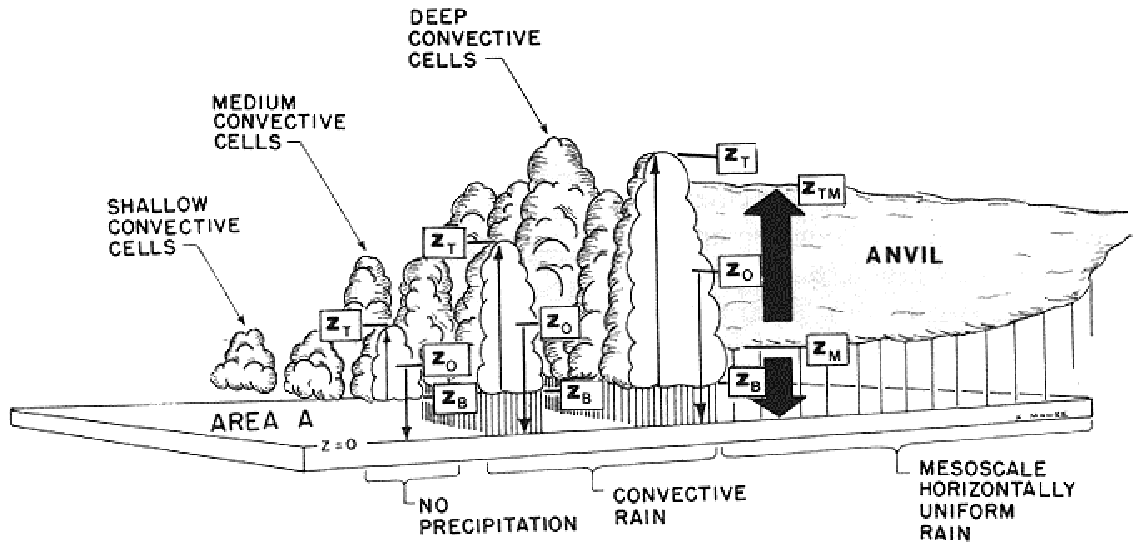
in view of the numerous questions raised by convective clouds...
scales, patterns, budgets, fluxes, rain, life cycle...

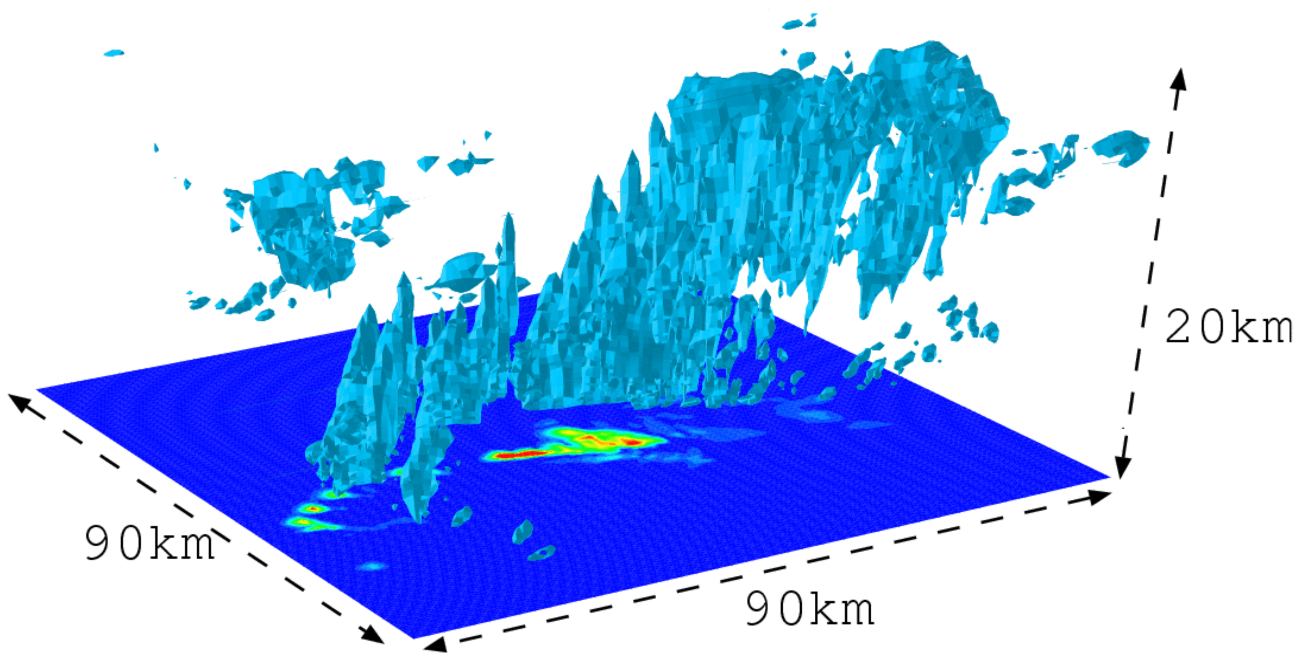
only limited insight from analytical approaches
precious guidance inferred from observations but too limited

LES/CRM : attractive approach for some + motivation, dedicated work, and results

1980's in France : listings & suitcases, ECMWF computer, taxis story...

Far from taken from granted 40 years ago


DEEP CONVECTIVE CELLS
MEDIUM CONVECTIVE CELLS
SHALLOW CONVECTIVE CELLS
z_T
z_{TM}
ANVIL
z_O
z_M
z_B
AREA A
z = 0
NO PRECIPITATION
CONVECTIVE RAIN
MESOSCALE HORIZONTALLY UNIFORM RAIN


20km
90km
90km

LES & CRM : some distinct features about their origins

LES (70's)
More clearly defined theoretical grounds than CRM
Resolves larger-scale eddies with a grid size within the inertial range
aim to estimate turbulent fluxes, numerics : perhaps more care conservation issues
Filtering of smaller-scale motions, represented by parametrizations (3D)

Clear atmospheric convective boundary layers (Deardorff 1972)

Refined, modified to simulate shallow cumulus clouds (Sommeria 1976)
prog. equations for q_v and q_c , u, v, w, θ
anelastic hypothesis, eqn continuity, eqn state
refined turbulence scheme
moist adjustment (condens, evap), no rain
initiation with a sounding + small random noise

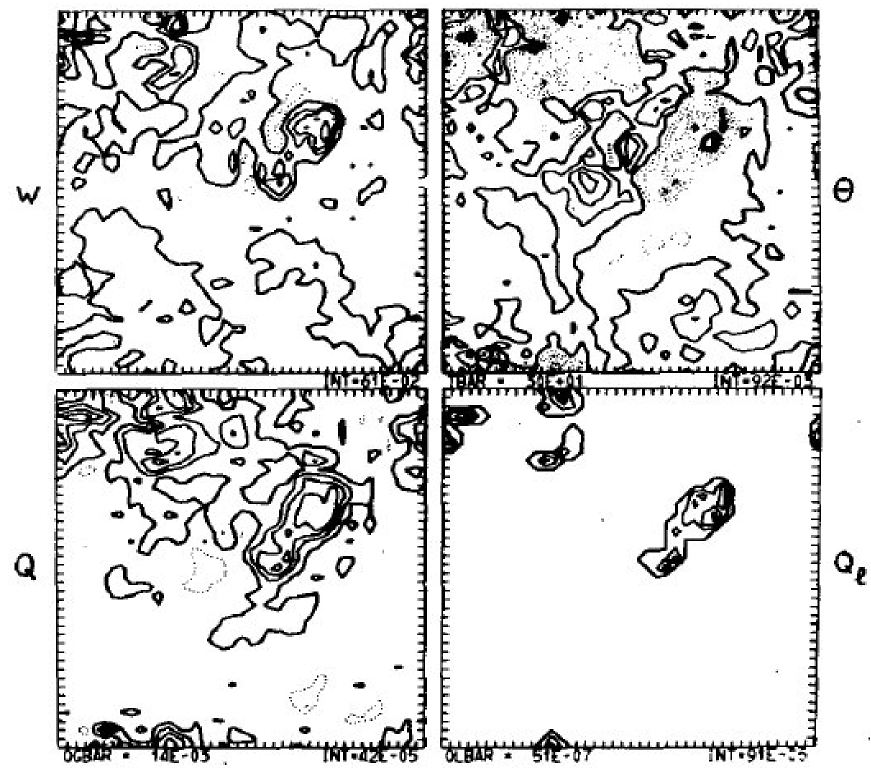


Fig. 13. Horizontal cross section at level 775 m (time 3.71 hour) relative to the variables w, θ, q and q_l.

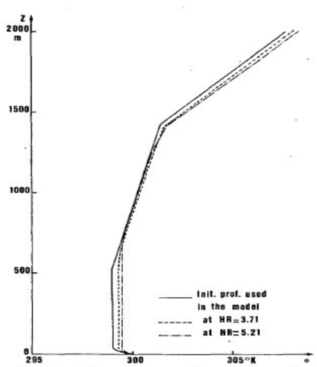
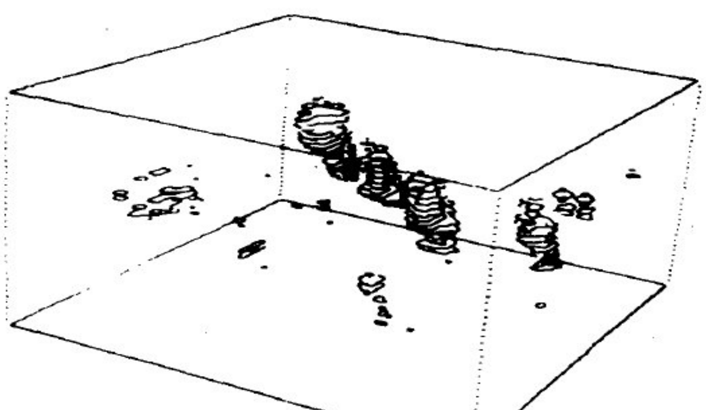


Fig. 2. Evolution of the potential temperature profile (time 0 to 5.21 hour).



2 km x 2 km x 2 km

Fig. 16. Perspective view of clouds.

LES & CRM : some distinct features about their origins

LES (70's)
Comparison with observations
statistical, fluxes, budgets (Sommeria and LeMone1978)

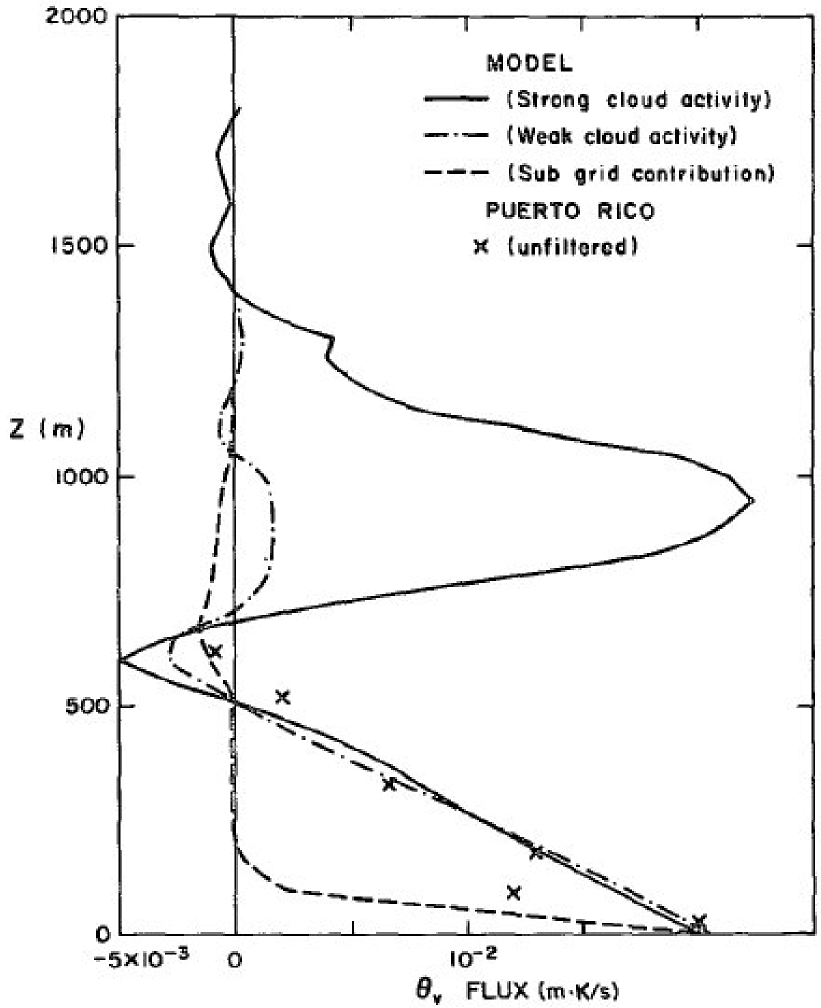


Fig. 14. Comparison of the flux of virtual potential temperature in the model and in the Puerto Rico experiment.

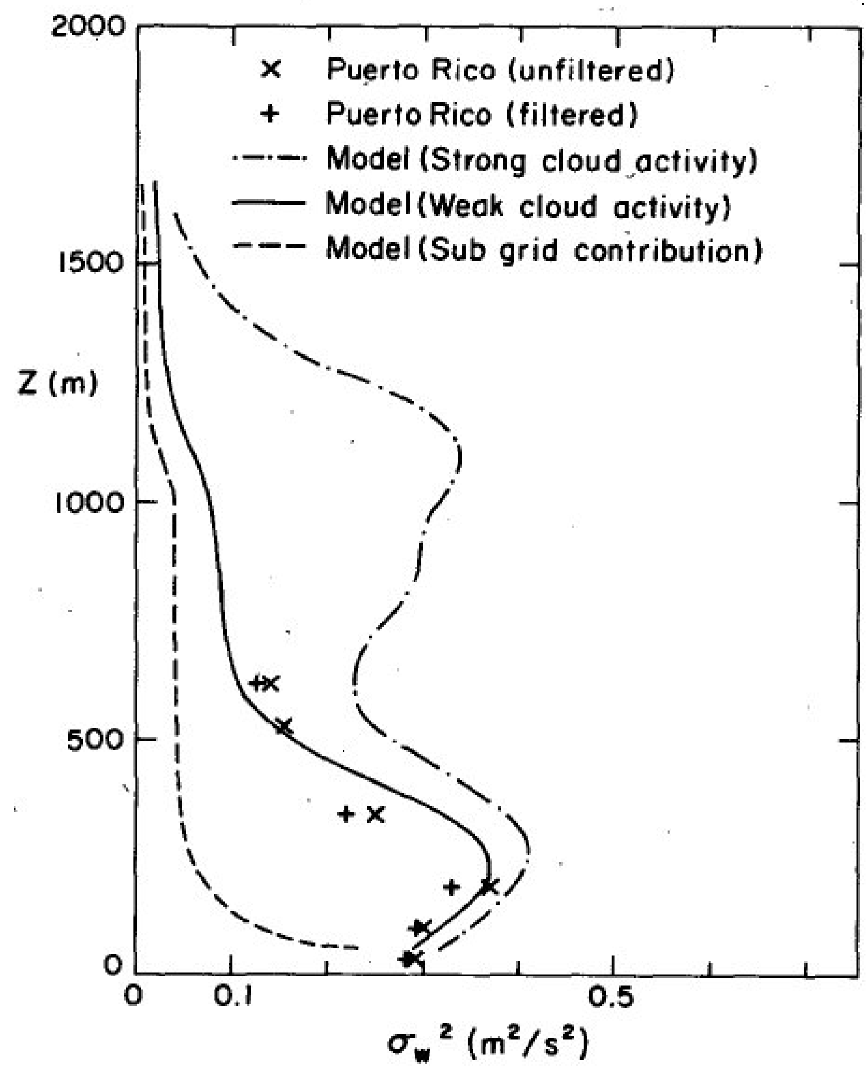


Fig. 10. Comparison of the variances of the vertical component of the velocity in the model and Puerto Rico experiment.

LES turning to CRM (80's)

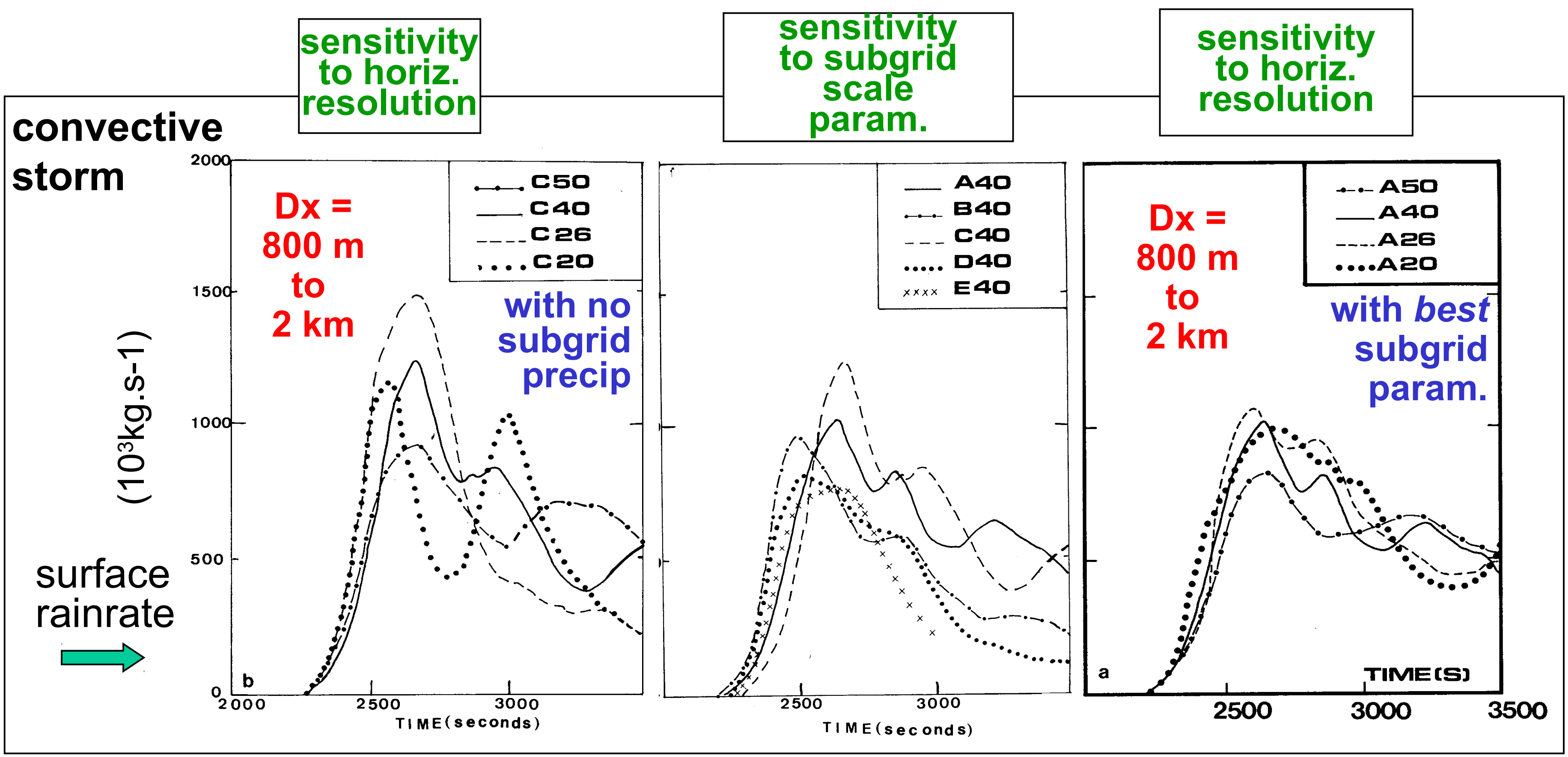
Introduction of (warm) rain processes

Kessler type : autoconversion, accretion (q_c to q_r)

sedimentation of rain drops (terminal velocity v_t, precipitation flux $\rho\, v_t\, q_r$)

consideration of the interactions between subgrid-scale motions and microphysics

Krueger (1988) (3rd order closure), Redelsperger and Sommeria (1986) (prog. Eqn. TKE)

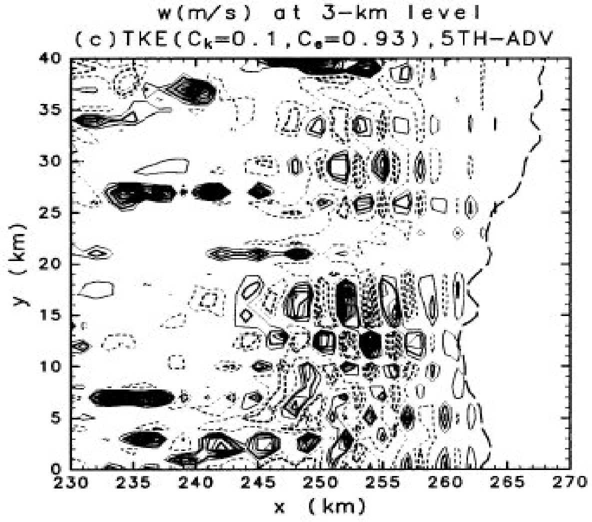


LES & CRM : some distinct features about their origins

CRM (70's, 80's)
aim to better understand the phenomenology of deep convective cells and events, their structure, intensity, motion (mesoscale circulations associated with transient convective features...)
(Miller and Pearce 1974, Wilhelmson 1974)

*« Three dimensional modeling currently requires sacrifices in the representation of physical processes and in the scales of resolution which must be made through **careful consideration on one's modeling goals**. It s not currently feasible, for example, to model storm evolution with a grid that lies well within the inertial subrange with a domain three or four times the storm size... » (Klemp and Wilhelmson 1978)*

More numerical filtering than in LES type runs
(cf also Takemi & Rotunno 2003)



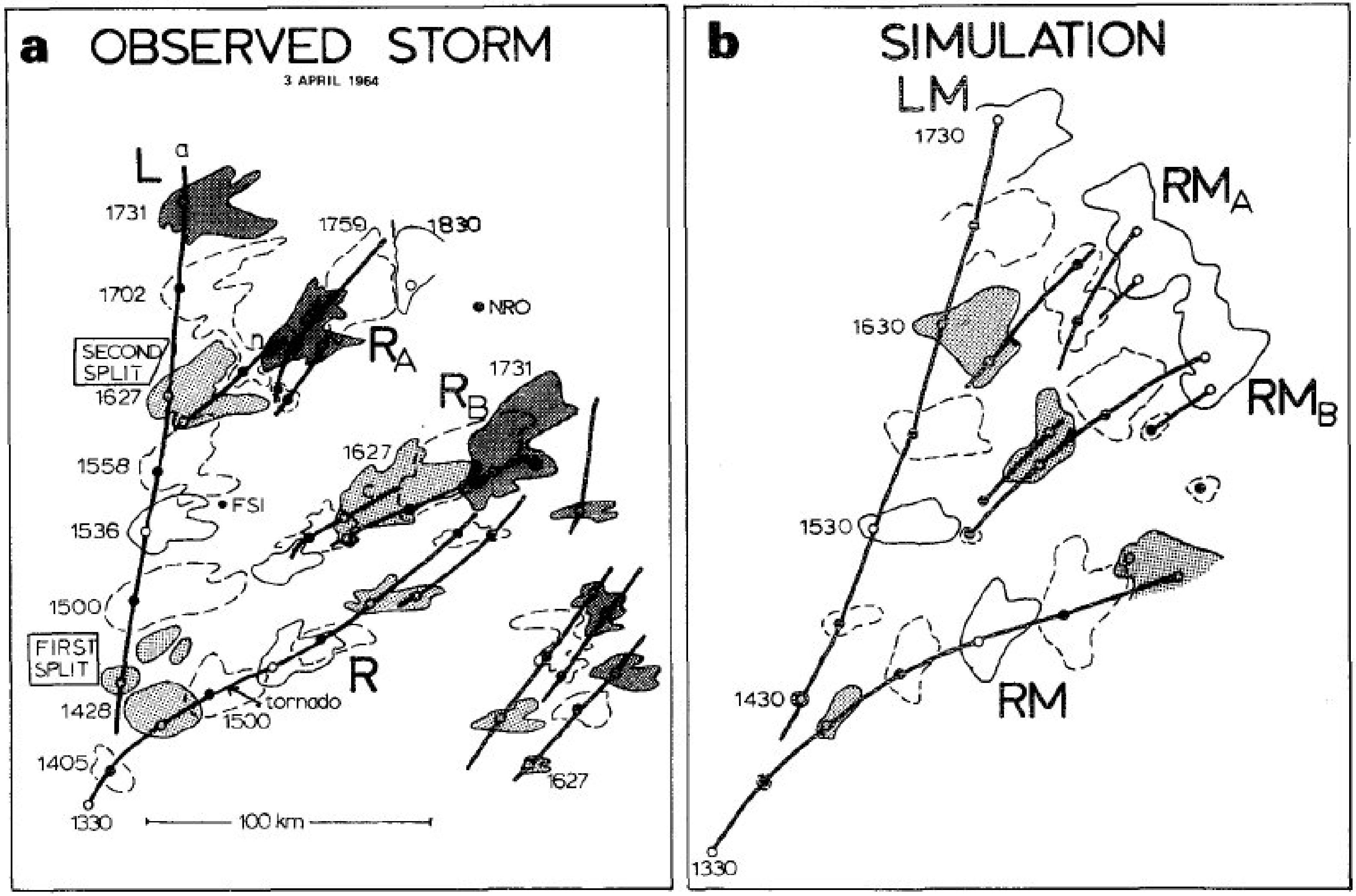


Fig. 1. The (a) observed and (b) modeled storm development on 3 April 1964. Observed reflectivities > 12 dBZ at 0° and modeled rainwater contents > 0.5 g kg⁻¹ at z = 0.4 km are enclosed by alternating solid and dashed contours about every 30 min. Maxima in these fields are connected by solid lines. The storms are labeled and at several times the contoured regions are stippled for better visualization of the storm development. Labels for the modeled storms are the same as the corresponding observed storms except for the inclusion of M. The scale shown in (a) applies in (b).

Wilhelmson and Klemp (1981)

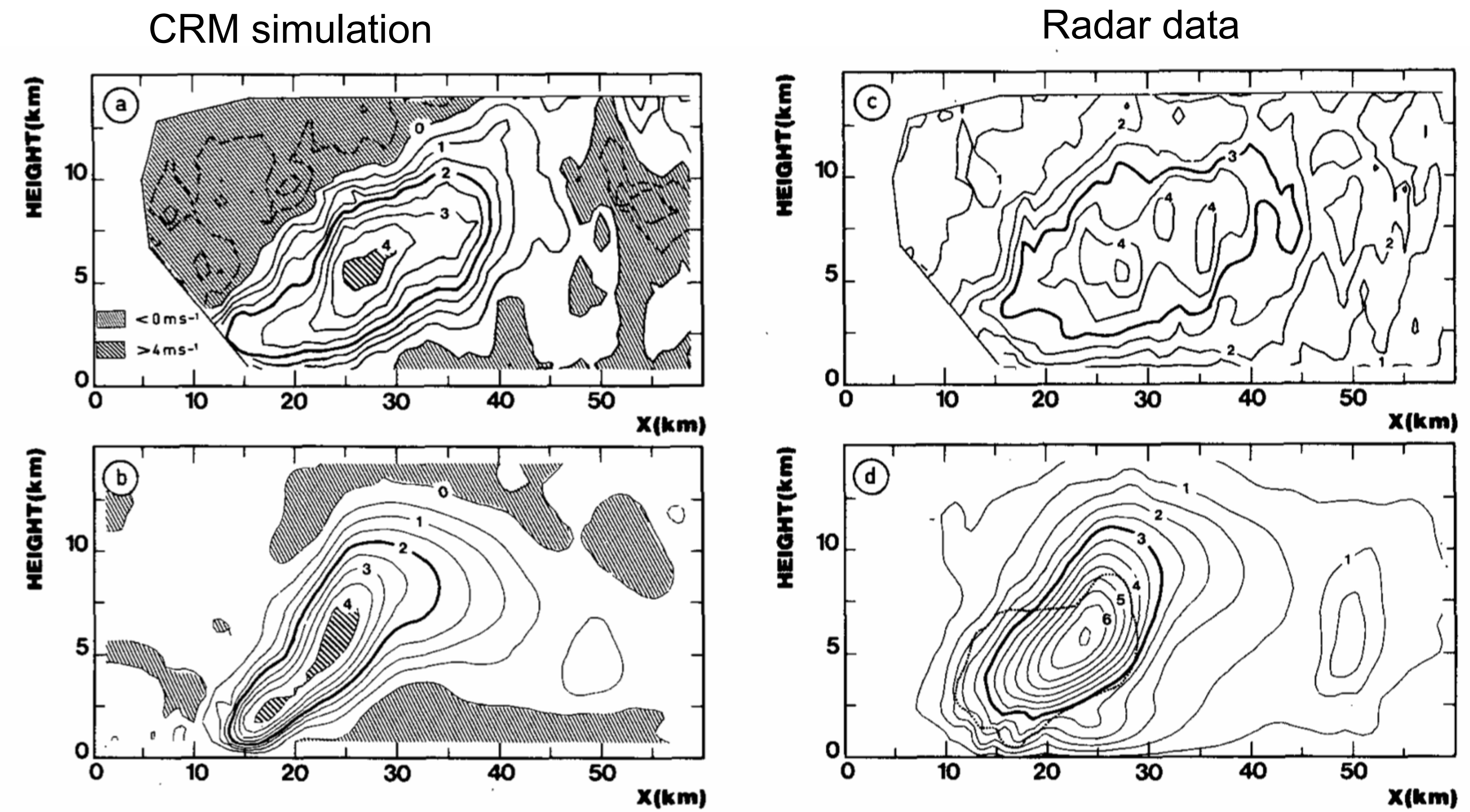
Initial conditions for simulation: a sounding + warm bubble

Study the role of wind shear in storm splitting

Even if this example indicates remarkable match to reality, academic studies, basic mechanisms

Mature quasi-stationary squall-line

Archetype of mesoscale convective system (MCS) , wind shear
multicellular system: individual deep cells grow and die quickly (~ 1h) but the MCS lives much longer (several hours) – interesting properties for observations and to some extend modelling



Mean and standard deviation of vertical velocity (average over ~ 50 km, 30 min)
(Lafore et al. 1988)

EXPLICIT CONVECTIVE CLOUD MODELLING

1980's

1990's

2000's

REFERENCE	DIM	Lx	dx	DUREE	RAD	ICE	ENVIRONNEM[T]
	3D	30 km	1 km	6 h	non	non	Tropical
	3D	20 km	500 m	4 h	non	non	*Tropical*
	3D	*40 km*	*1 km*	*1 h*	*non*	*non*	*Tropical*
	3D	*70 km*	*1 km*	*7 h*	*non*	*non*	*COPT81*
	2D	256 km	1 km	9 h	non	non	Tropical
	2D	512 km	2 km	5 jours	non	oui	Tropical
	2D	*500 km*	*1 km*	*8 h*	*non*	*oui*	*COPT81*
	2D	768 km	1.5 km	52 jours	oui	oui	Conv-Rad-Equil
	2D	*120 km*	*1km*	*3 jours*	*oui*	*non*	*Tropical*
	2D	512 km	2 km	18 jours	oui	oui	GATE
	2D	900 km	1 km	7 jours	oui	oui	GATE
	3D	*90 km*	*1 km*	*10 h*	*oui*	*oui*	*'COARE'*
	3D	400 km	2 km	7 jours	oui	oui	GATE
	3D	100 km	2 km	70 jours	oui	oui	Conv-Rad-Equil
	2D	200 km	2 km		non	oui	aquaplanète
	2D	*512 km*	*2 km*	*7 jours*	*oui*	*oui*	*COARE*
	3D	270 km	125 m	3 h	non	non	ligne de grains
	3D	*512 km*	*2 km*	*2 jours*	*oui*	*oui*	*COARE*
	2D	*256 km*	*2 km*	*4 jours*	*oui*	*oui*	*ARM (continental)*
	3D	154 km	100 m	6h	non	oui	continental LBA
	3D	global	3.5 km	7 days	oui	oui	GLOBE

1990' : introduction of new processes: ice microphysics, radiative processes
use of field campaigns for guidance (advection) GATE (1974), COPT81
longer duration simulations, wider domains = > 2D configurations (costl)

2000' : increase of resolution (CRM => LES), back to 3D
convection over land, more evaluation, use as guides for parametrizations
new types de modèles (global CRM, MMF), new types of configurations, questions

Ingredients of LES/CRM

In brief (as in 2013), CRM and LES include

Set of equations (defined as deviation from a reference state)

Equation of state

Prognostic equations for the 3 components of motions (*u, v, w*) *(dynamics)*

Prognostic equations for a set of temperature and water variables
e.g. ($\theta, r_v, r_w, r_r, r_i, r_s, r_g$) , alternatives: ($\theta_l$, q_t) … (≠ choices in ≠ models)

Equation of continuity (conservation of mass)
removal of acoustic waves (via anelastic hypothesis)

$$\frac{\partial \rho_0 u_j}{\partial x_j} = 0$$

Involves parametrizations (various degrees of complexity)

Microphysics (liquid or liquid and ice)
Subgrid scale turbulence (various complexity)
Radiative processes (from none to simple to plane //)
Surface processes (lower boundary) : from prescribed surface fluxes, to simple bulk formulation over ocean with prescribed SST to more complex coupling with an ocean mixed layer model or a land surface model)

Numerical choices: discretization (grid), numerical schemes (equations) & filters, order of operations (fast versus slow processes, care with advection of scalars...)

+ choices of variables, and also height coordinate
≠ approximations in thermodynamics in ≠ models

When using a given CRM, read the documentation

A simple example (with Boussinesq approximation *($\rho_0(z)$ = cste)*

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0$$

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \overline{p_1}}{\partial x_i} + \beta(\overline{\theta_v} - \theta_r)\delta_{3i} + \nu\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - 2\epsilon_{ijk}\Omega_j\overline{u_k} \quad -\frac{\partial}{\partial x_j}\overline{u_i' u_j'}$$

$$\frac{\partial \overline{\theta}}{\partial t} + \overline{u_j}\frac{\partial \overline{\theta}}{\partial x_j} = \nu_\theta \frac{\partial^2 \overline{\theta}}{\partial x_j \partial x_j} + \quad S_\theta \quad -\frac{\partial}{\partial x_j}\overline{u_j' \theta'}$$

$$\frac{\partial \overline{q}}{\partial t} + \overline{u_j}\frac{\partial \overline{q}}{\partial x_j} = \nu_q \frac{\partial^2 \overline{q}}{\partial x_j \partial x_j} + \quad S_{qv} \quad -\frac{\partial}{\partial x_j}\overline{u_j' q'}$$

$$\frac{\overline{\rho}}{\rho_0} = -\frac{\overline{\theta_v}}{\theta_r}$$

S_θ : ***microphysics processes leading to cooling or warming*** *(condensation, evaporation, melting... , but e.g. not autoconversion)* ***and radiative processes***

S_{qv} : ***microphysical processes involving qv sources and sinks*** *(again condensation, évaporation... , but e.g. not melting nor riming)*

Microphysics

Bulk : Hydrometeors considered as being from one or another pre-defined categories below, single moment (q_α), double moment (q_α, N_α), bin resolving (different sizes)

Symbol	Mechanism	Sink	Source	Process
$RVHENI$	$r_v \Longrightarrow r_i$	r_v	r_i	heterogeneous nucleation
$RCHONI$	$r_c \Longrightarrow r_i$	r_c	r_i	homogeneous nucleation
$RRHONG$	$r_r \Longrightarrow r_g$	r_r	r_g	homogeneous nucleation
$RCBERI$	$r_c \Longrightarrow r_i$	r_c	r_i	Bergeron-Findeisen effect
$RVDEPI$	$r_v + r_i \Longrightarrow r_i$	r_v	r_i	deposition(sublimation)
$RVDEPS$	$r_v + r_s \Longrightarrow r_s$	r_v	r_s	deposition(sublimation)
$RVDEPG$	$r_v + r_g \Longrightarrow r_g$	r_v	r_g	deposition(sublimation)
$RIAUTS$	$r_i + r_i \Longrightarrow r_s$	r_i	r_s	autoconversion of pristine ice
$RIAGGS$	$r_i + r_s \Longrightarrow r_s$	r_i	r_s	aggregation of pristine ice
$RRCFRIG$	$r_i + r_r \Longrightarrow r_g$	r_r	r_g	raindrops contact freezing
$RICFRRG$	$r_i + r_r \Longrightarrow r_g$	r_i	r_g	raindrops contact freezing
$RCRIMSS$	$r_c + r_s \Longrightarrow r_s$	r_c	r_s	light riming of aggregates
$RCRIMSG$	$r_c + r_s \Longrightarrow r_g$	r_c	r_g	heavy riming of aggregates
$RSRIMCG$	$r_c + r_s \Longrightarrow r_g$	r_s	r_g	heavy riming of aggregates
$RRACCSS$	$r_r + r_s \Longrightarrow r_s$	r_r	r_s	accretion of rain and aggregates
$RRACCSG$	$r_r + r_s \Longrightarrow r_g$	r_r	r_g	accretion of rain and aggregates
$RSACCRG$	$r_r + r_s \Longrightarrow r_g$	r_s	r_g	accretion of rain and aggregates
$RCDRYG$	$r_c + r_g \Longrightarrow r_g$	r_c	r_g	dry growth of the graupels
$RIDRYG$	$r_i + r_g \Longrightarrow r_g$	r_i	r_g	dry growth of the graupels
$RRDRYG$	$r_r + r_g \Longrightarrow r_g$	r_r	r_g	dry growth of the graupels
$RSDRYG$	$r_s + r_g \Longrightarrow r_g$	r_s	r_g	dry growth of the graupels
$RCWETG$	$r_c + (r_g) \Longrightarrow r_r$	r_c	r_r & r_g	partial freezing & water shedding
$RRWETG$	$r_r + (r_g) \Longrightarrow r_g$	r_r	r_g	partial freezing & water shedding
$RIWETG$	$r_i + r_g \Longrightarrow r_g$	r_i	r_g	wet growth of the graupels
$RSWETG$	$r_s + r_g \Longrightarrow r_g$	r_s	r_g	wet growth of the graupels
$RIMLTC$	$r_i \Longrightarrow r_c$	r_i	r_c	melting
$RGMLTR$	$r_g \Longrightarrow r_r$	r_g	r_r	melting
$RSCVMG$	$r_s \Longrightarrow r_g$	r_s	r_g	conversion melting

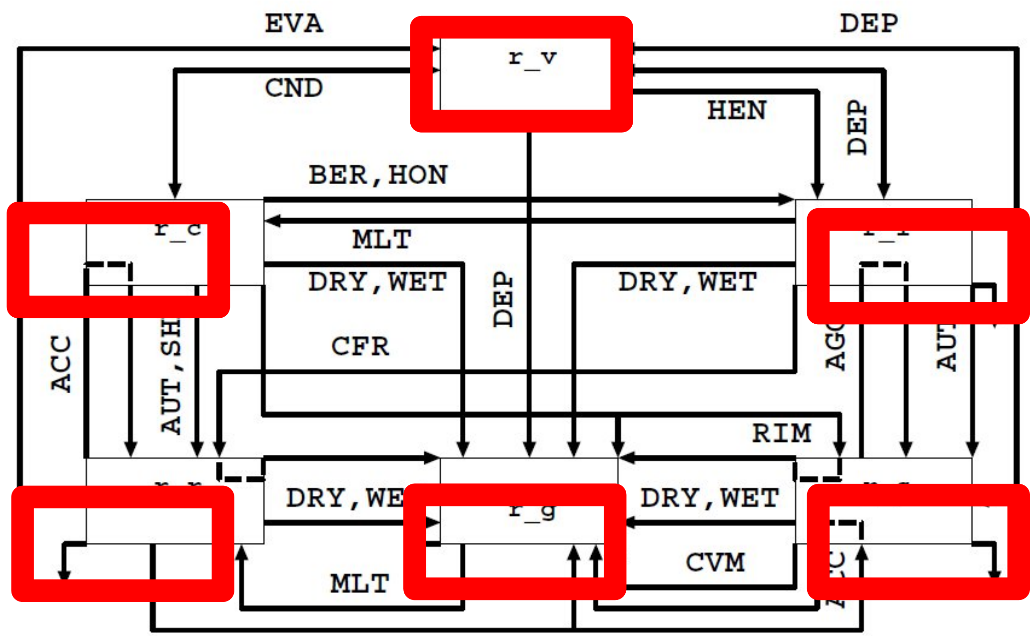


Figure 6.2: Diagram of the microphysical processes for mixed phase cloud in the present scheme.

$$m(D) = aD^b$$

$$v(D) = cD^d\,(\rho_{00}/\rho_{dref})^{0.4},$$

and other relationships

Parameters	r_i	r_s	r_g		r_r	r_c
a	0.82	0.02	19.6		524	524
b	2.5	1.9	2.8		3	3
c	800	5.1	124		842	$3.2\ 10^7$
d	1.00	0.27	0.66		0.8	2

Complex, numerous processes considered
some arbitrariness in design, still a number of weakly constrained constants, with sensitivity

Subgrid scale turbulence

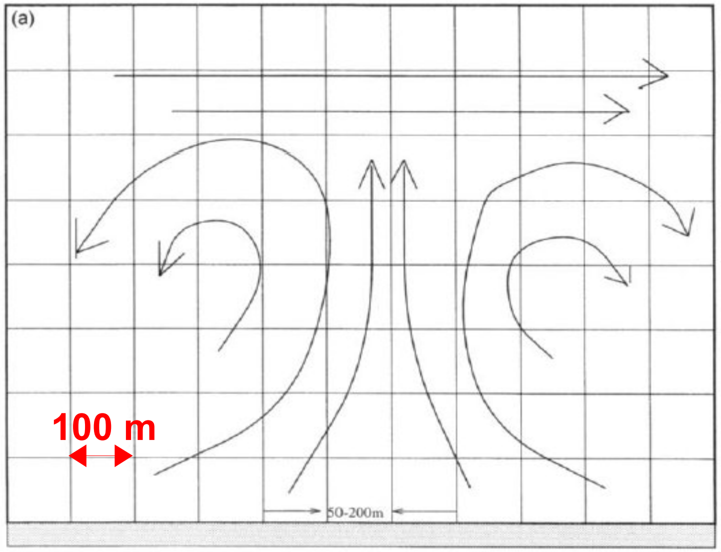
Closure problem

3D scheme (LES)

$$\overline{u'_i u'_j} = - K_m \ (\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i)$$

$$\overline{u'_i \alpha'} = - K_\alpha \ (\partial \bar{\alpha} / \partial x_i)$$

eddy diffusivity



$$K = l \sqrt{e}$$

l: mixing length, e: turbulent kinetic energy

$$l = (\Delta x . \Delta y . \Delta z)^{1/3}$$

consideration of stability, fct (R_i)

prognostic e

3rd order moment (rare)

Subgrid scale turbulence

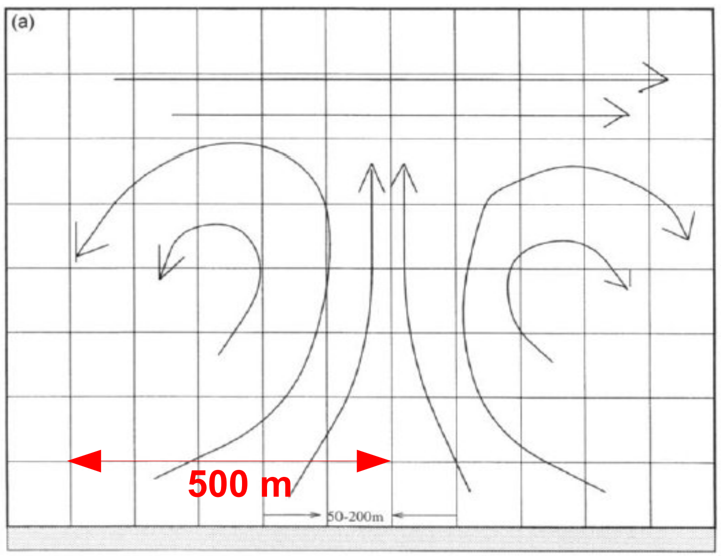
Closure problem

3D scheme (LES)

$$\overline{u'_i u'_j} = -K_m \left(\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i \right)$$

$$\overline{u'_i \alpha'} = -K_\alpha \left(\partial \bar{\alpha} / \partial x_i \right)$$

eddy diffusivity



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$$l = (\Delta x . \Delta y . \Delta z)^{1/3}$$

consideration of stability, fct (R_i)

prognostic e

3rd order moment (rare)

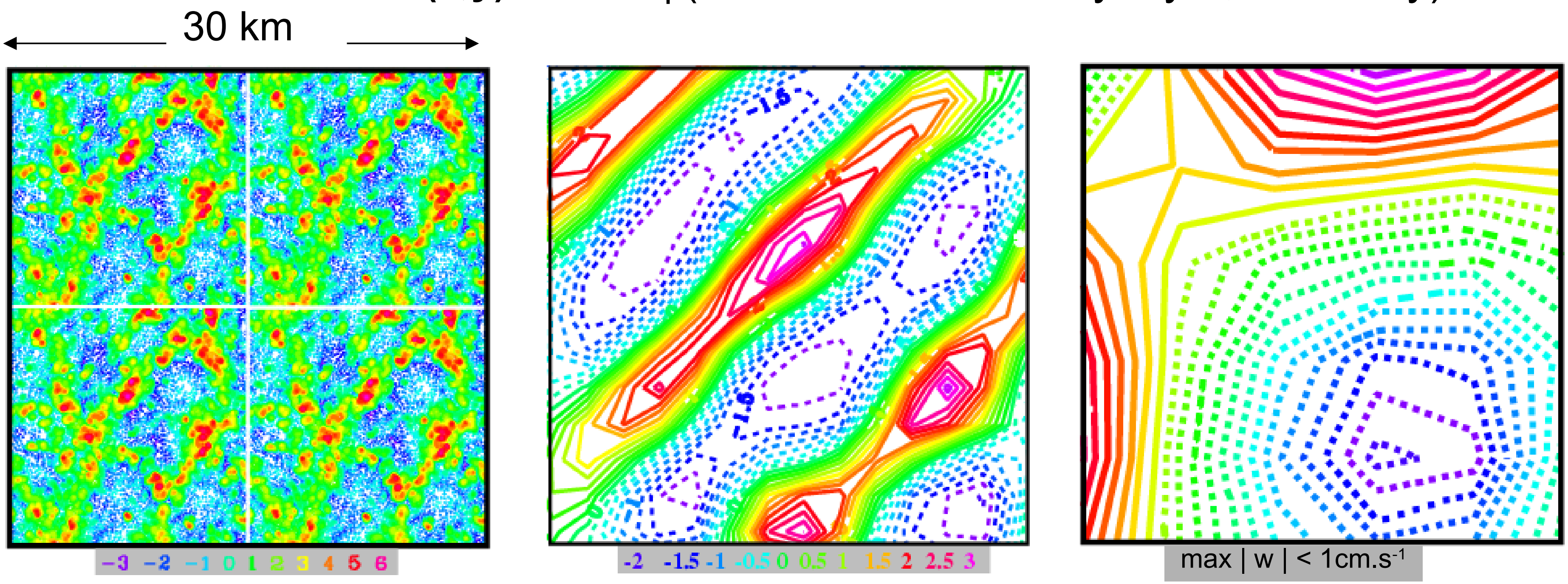
1D scheme

$$\overline{w'\phi'} = -K \frac{\partial \bar{\phi}}{\partial z}$$

From a physical point of view, $l \neq (\Delta x . \Delta y . \Delta z)^{1/3}$

Sharing work between resolved and parametrized turbulence...

w(x,y) at 0.6 z_i (convective boundary layer, clear sky)



Δx = 100 m

classical organization (open cells)

Δx = 2 km

1D turbulence scheme

development of spurious organizations

here resolved motions react to (compensate for) too weak subgrid transport, in their own way...

Δx = 10 km

1D turbulence scheme

expected behaviour with this resolution

adapted from Couvreux (2001)

« Scale-aware » parametrizations issues related to NWP models

Radiative processes

from simple formulations

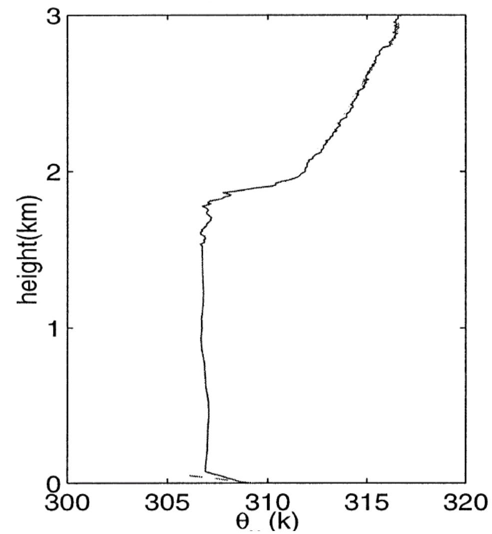
to more complex two-stream models
plane // (as in GCM), independent columns, several spectral bands
Formulation involving and using q_w ,q_i , r_e
(microphysical-radiative coupling)

expensive, not computed at all time step

When moving to smaller scales, the underlying hypotheses become debatable

Initial conditions

Sounding or more academic profiles
applied homogeneously on the horizontal
$u(z)$, $v(z)$, $T(z)$, $q_v(z)$
$q_w=0$



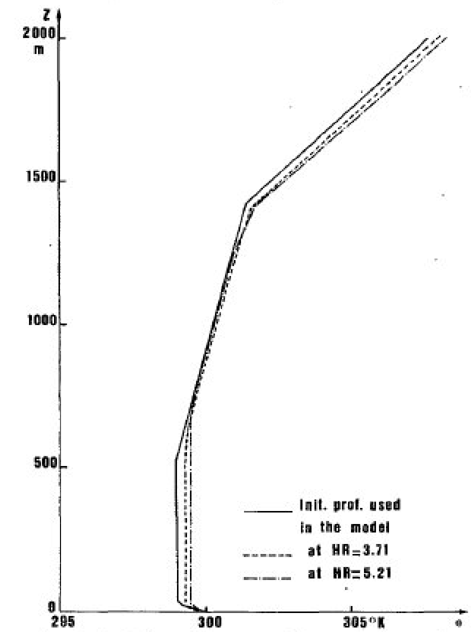


FIG. 2. Evolution of the potential temperature profile (time 0 to 5.21 hour).

Examples of θ (z)

surface :

SST (ocean)
Ocean mixed layer model
Radiative ppties albedo, emissivity
Land surface models

+ An initial kick to initiate motions
  - * Small randow noise in the low levels
  - * Warm, cold, bubble(s) (!)
    mimic warm raising cell, convective cold outflow...
    why?
    « the system quickly forget about the initial bubbles » : what does it mean?

Boundary conditions

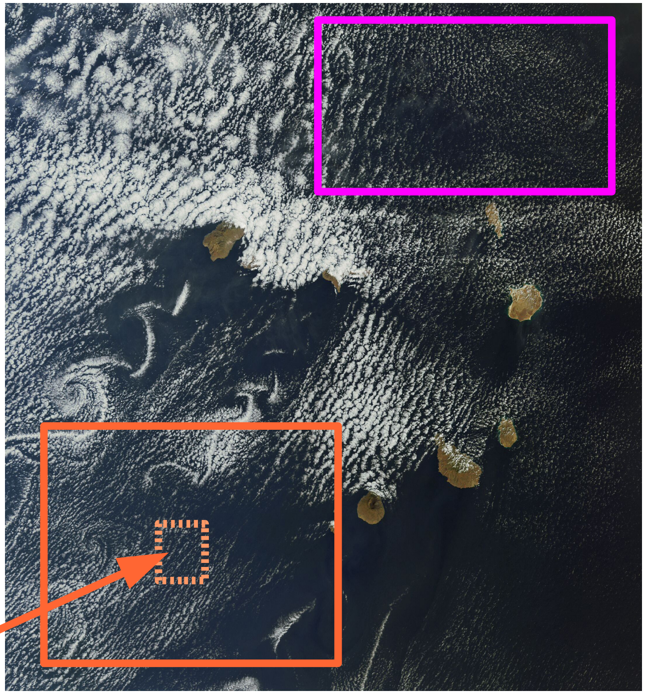
upper boundary : radiative layer, sponge layer
Lower boundary : SST, LSM, sfc ppties...

Lateral boundaries

Wall : solid boundary

Open : atmosphere responsive to convection
(no resistence)

Cyclic →



Well suited for a small piece of a large homogeneous cloud field
what about domain mean vertical velocity w(t,z) then?

with hypothesis scale separation (see derivation in e.g. Grabowski et a. 1996)
→ *formulation of a large-scale advection term*

$$\frac{\partial\bar{\theta}}{\partial t} + \overline{u_j}\frac{\partial\bar{\theta}}{\partial x_j} = S_\theta - \frac{\partial}{\partial x_j}\overline{u_j'\theta'} + \left(\frac{\partial\bar{\alpha}}{\partial t}\right)_{LS}$$

Allows e.g. to take into account large-scale subsidence in LES Simulations of stratocumulus

with $$\left(\frac{\partial\bar{\alpha}}{\partial t}\right)_{LS} = -U\left(\frac{\partial\alpha}{\partial x}\right) - V\left(\frac{\partial\alpha}{\partial y}\right) - W\left(\frac{\partial\alpha}{\partial z}\right)$$

$U,\ V,\ W,\ \alpha$: large-scale horizontally homogeneous variables

Summary and final remarks for today

LES & CRM : recent history

60's : first attemps, bases (seriously limited by computing power)
70's : first models (warm clouds, a few hours, small domain)
80's : improving models (more physics, better numerics)
90's : evaluations with observations, larger domains, 2D
00's: more and more used for wider variety of purpose (basic questions, guide development of GCM parametrization...), + much more computing power *(it is not going to stop)*

LES & CRM : specific features

* Fine-scale, limited area models, allowing to simulate explicitely mesoscale dynamics associated with convective clouds.
* These models use parametrizations to represent subgrid processes (turbulence, microphysics, radiative processes).
* Unlike GCMs: explicit coupling between convective motions & physical processes (strength)

LES & CRM : now a few 10's around the world (?)

These models are **not black boxes**

Whether you develop part of, or use, such a model in order to answer a specific question
may need to pay some attention to :
the formulation of the model (thermodynamics)
its parametrizations, their couplings
its boundary conditions
choose of grid size...
when something is unclear, read documentation, ask people around...