VARIOUS LINKS BETWEEN WATER VAPOUR AND CONVECTION

Françoise Guichard (CNRM, Toulouse in France)

convection: atmospheric vertical motions associated with thermal instabilities and involving the formation of clouds (« moist convection »)
vertical tranport of heat, moisture, momentum...

(very wide subject, partial view)

deep convective cell
D ~ H ~ 10 km
|w| ~ 10 m.s^{-1} (leeking)

non-precipitating cumulus

cloud streets

photo from Scorer

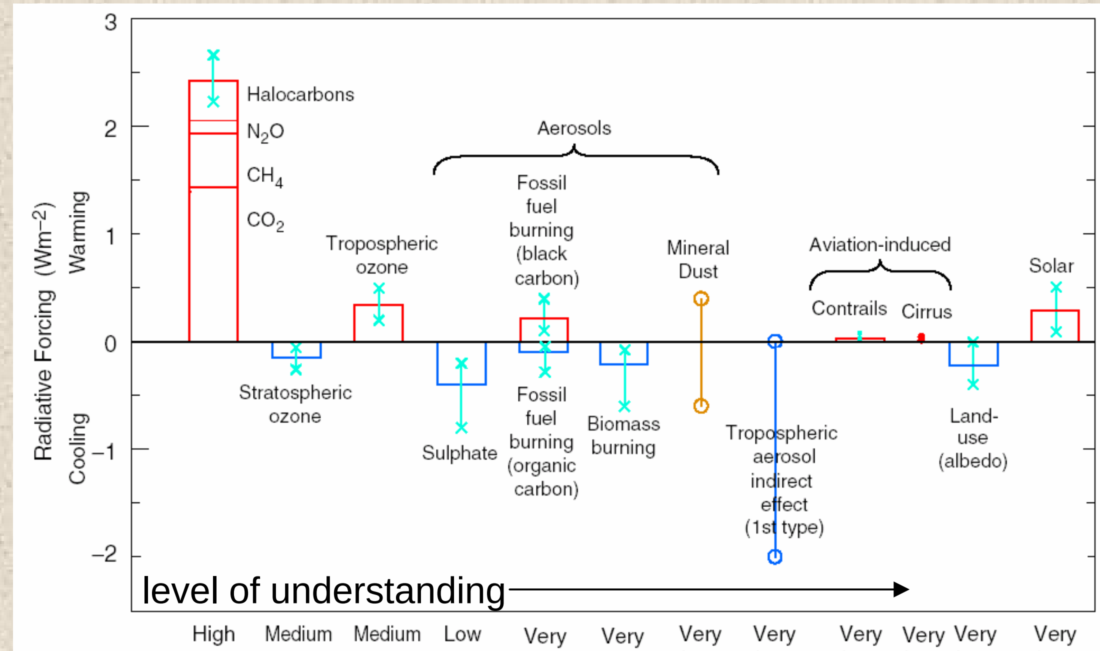
photos from the NOAA historic library

+ mesoscale organization (e.g. lines)

Why is water vapour so important for climate?

IPCC 2001

IPCC: inter-governmental panel on climate change



« A major feedback accounting for the large warming predicted by climate models in response to an increase in CO_2 is the increase in atmospheric water vapour....

H_2O : 1st greenhouse gas !

Water vapour feedback, as derived from current models, approximately doubles the warming from what it would be for fixed water vapour. »

It is likely that total atmospheric water vapour has increased several per cent per decade over many regions of the Northern Hemisphere.

... A pattern of overall surface and lower-tropospheric water vapour increases over the past few decades is emerging from the most reliable data sets, although there are likely to be time-dependent biases in these data and regional variations in the trends.

source of uncertainty & controversy / climate studies (1/2)

atmospheric moisture : a prognostic variable in climate models
the difficulty : microphysical, turbulent & convective transport of moisture are subgrid-scale in GCM, they are parameterized (not easy task!)
lack of understanding about: when, where, how (organization, structure/z)...

Lindzen (1990, BAMS) : « Some coolness concerning global warming »

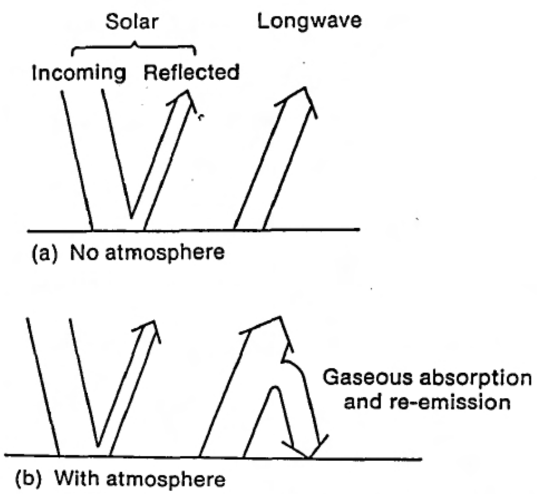


FIG. 5. Schematic illustration of the greenhouse effect showing (a) no atmosphere, where longwave radiation escapes directly to space, and (b) an absorbing atmosphere, where longwave radiation from the surface is absorbed and reemitted both downward, and upward, maintaining radiative balance at the top of the atmosphere.

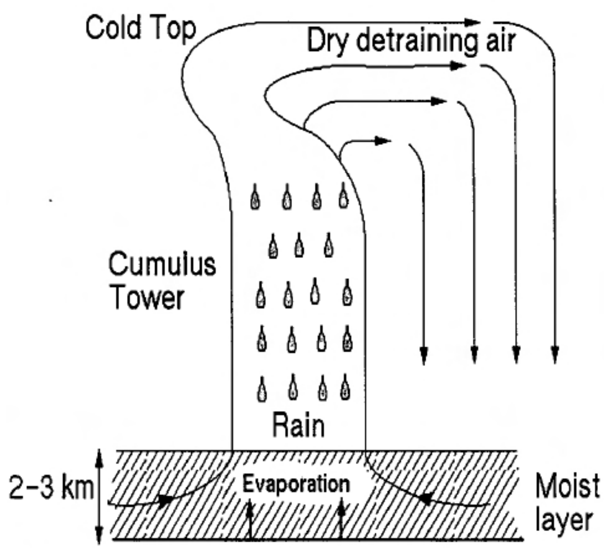


FIG. 7. Schematic illustration of cumulus tower wherein moisture evaporated from the surface and converged into cumulus convection is rained out, leaving dry air to detrain into the environment.

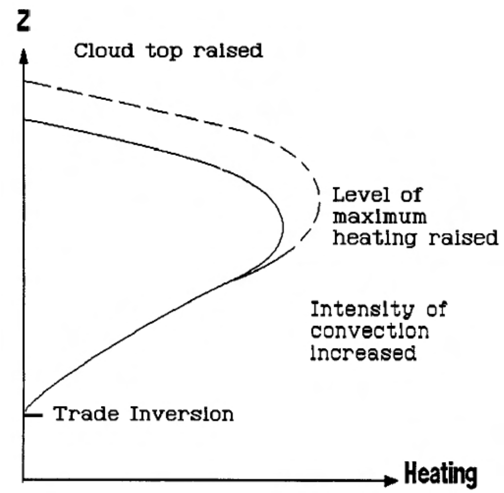


FIG. 8. Schematic illustration of cumulus heating distribution under (solid line) normal conditions, and (dashed line) under conditions of anomalous warming. Warming leads the following effects: 1) cloud tops are raised leading to dryer detrained air; 2) convective intensity increases which leads to the dryer air being pushed down more effectively; and 3) there is an increase in the height at which there is maximum cumulus heating, thus bypassing more infrared absorbers in the atmosphere.

with dryer air leading to OLR increase (outgoing longwave radiation at the top of the atmosphere)
To my knowledge, no solid evidence of the significance of this mechanism from observations (complex system, multiple interactions/feedbacks among processes)

source of uncertainty & controversy / climate studies (2/2)

11 years later
the same guy
Lindzen & co-
authors
(2001, BAMS) :

« Does the earth
has an
adaptative iris? »

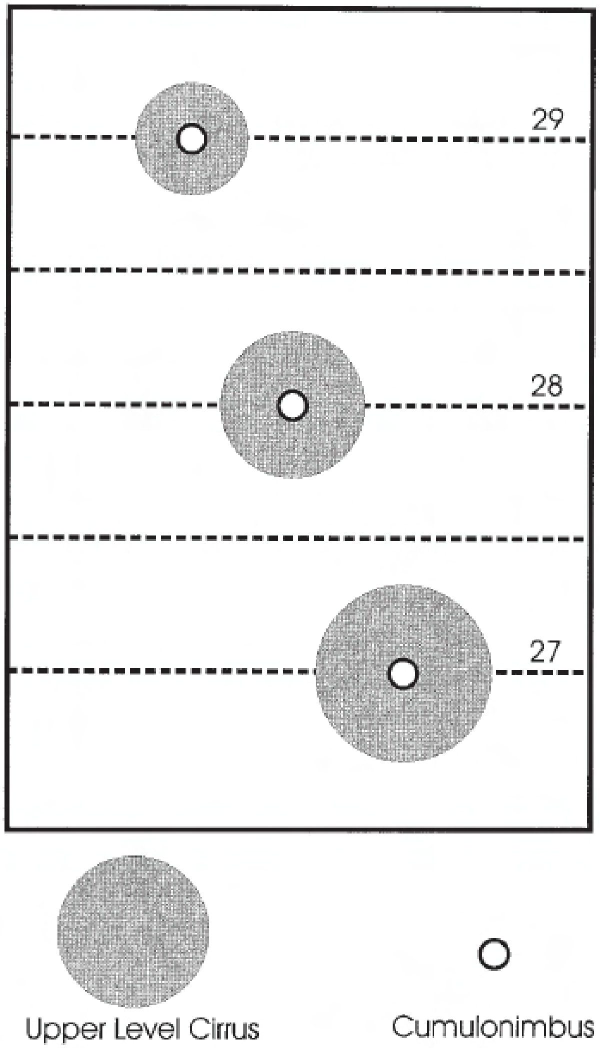


FIG. 3. Schematic illustrating change in cloud-weighted SST due to cloud systems moving from the central position to colder and warmer regions. Dotted horizontal lines correspond to isotherms. Units are nominally °C.

*Already comments,
replies to comments,
reply to reply...
again, not much
evidence so far
in favor of this
mechanism*

OUTLINE

- ❑ a few definitions

- ❑ some measurement techniques

  with illustrations of water vapour variability at different scales

- ❑ interactions of the water vapour field with convection
  - o *convective transport of moisture*
  - o *sensitivity of the atmospheric stability to moisture*
  - o *small scale variability and convective initiation*
  - o *life cycle/propagation of squall-lines*
  - o *role of dry intrusions for tropical convection*
  - o *intraseasonal variability, an example*
  - o *modelling issues*

- ❑ summary

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a few definitions

specific humidity (q or q_v) : mass of water vapour per unit mass of moist air

$$q_v = \rho_{vapour} / \rho_{air}$$

very large range of variations ~ 0-25 g/kg of air

water vapour mixing ratio (r or r_v) : mass of water vapour per unit mass of dry air

air : mixture of ideal gases

$$\rho_{air} = \rho_{vapour} + \rho_{dry\ air}$$

$$r_v = \frac{q_v}{1-q_v} (\approx q_v)$$

relative humidity (RH)

saturation vapour pressure (p_{vs}) = function (T)

$$P_{vs}(T) = 10^{\left(\frac{0.7859+0.03477T}{1.+00412T}\right)}$$

$$P_v / P = r_v / (r_v + \varepsilon)$$

$$\varepsilon = R_a / R_v \approx 0.622$$

$$RH = \frac{r_v}{r_{vs}}$$

saturation deficit $= r_{vs} - r_v$

r_{vs} : max possible value of r_v

r_{vs} strongly depends on T : r_{vs}(T=0°C) ≈ 4 gkg^{-1}
r_{vs}(T=37°C) ≈ 42 gkg^{-1}

(overall, r_v usually decreases with height, with exceptions)

precipitable water (PW) : mass of water vapour in an atmospheric column

$$PW = \int_{z_0}^{z_{top}} \rho\, q_v dz$$

PW ~ 50 kg.m^{-2} in the moist Tropics

*+ a number of variables, e.g. (**quasi-)conserved** under moist convective processes : θ_e , θ_l ...*

dry air

$$P = \rho_d R_d T$$

P : pressure
ρ_d : density of dry air
R_d : dry air gaz constant [R_d = 287 J.kg^{-1}.K^{-1}]
T : temperature

moist air, introduction of the **virtual temperature T_v**

$$P = \rho R_m T = \rho [(1- q_v - q_h) R_d + q_v R_v] T = \rho R_d T_v$$

R_m : specific gas constant for the mixture
q_h : mass of hydrometeor /unit mass of air

$$T_v = [1 - (1 - 1/\varepsilon) q_v - q_h)] T$$

[$\varepsilon = R_d / R_v \sim 0.622$]

$$T_v \sim (1 + 0.608 q_v - q_h) T$$

comment:

evaporation of δq_h , $\delta T_v \sim (1 + \varepsilon - L/(c_p T)) . T. \delta q_h \sim - 10 T. \delta q_v$
loading by evaporation of precipitation very efficient
formation of strong downdraughts (strong negative buoyancy, w << 0)
(fct hydromet. fall speed, i.e. involves microphysics)

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measurement techniques

1) radiosondes

the most common, in operational use (~1000 stations around the world)

5 decades of use

high resolution (~a few mb) vertical profiles of T, RH, wind & pressure (up to 30 km)

although the most robust technique, still accuracy issues

undersampling of time & space variability

(also dropsondes)

2) **other in situ data** (surface, along flight legs...)

3) **LIDAR** active remote sensing

~ to radar except operating with laser radiation

ground based or on board lidars (research instrum.,a few around the world)

4) **information from refractivity data** [n = function(T,q,...)]

(e.g. 2D field from radar measurement, possibly a promising technique for weather forecasting according to the recent experiment IHOP))

5) **GPS** [global positioning system, delay = fct(atmos. moisture)], PW

6) **radiometers, interferometers** passive remote sensors (r_v (z), dz ~ 50 m)

7) **satellite data** (passive & combinations with future active sensors)

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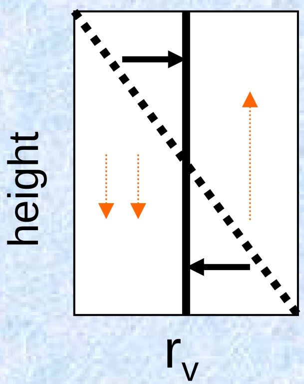
convective transport of moisture

very broadly speaking: source of water located at the surface
convective processes transport surface moist air upward and upper dryer air downward (for typical r_v vertical stratifications)

« dry » convection (i.e. without H_2O phase changes) affects in this way the lower atmospheric moisture field (typically the first 1-2 kilometres above the surface) – « convective boundary layer »



: convective motions (smaller arrows for downward motions because of the disymetrie between narrower stronger updraughts than weaker downdraughts)

indicate how convection modifies r_v profiles (vertical mixing)

hypothetic initially stratified r_v profile (e.g. early morning over land)

modifications of the profile due to convective motions alone (well mixed as commonly found over tropical ocean and daytime hours over land)

moist non-precipitating convection : a bit more complex, but basically same type of functionning except for some water storage in clouds (in the form of liquid droplets or ice cristals), as eventually these clouds disappear without producing any precipitation.
for instance fair-weather cumulus clouds (typical life time of one cloud ~ 15-30 min)

precipitating convection : often similar signature of r_v convective transport (drying of the lower troposphere and moistening of the upper troposphere), even though the phenomenon involves more processes and interactions among them; note however that the occurrence of convective rainfall acts to dry the atmospheric column (it does not mean that the atmosphere is dryer than it was once precipitating convection has occurred!).

BUDGETS

$$\underbrace{\frac{\partial \overline{\alpha}}{\partial t}}_{\text{eulerian evolution}} = \underbrace{-\overline{u}_i\left(\frac{\partial \overline{\alpha}}{\partial x_i}\right)}_{\text{large-scale advection}} \underbrace{- \frac{1}{\rho}\frac{\partial}{\partial x_i}\left(\rho\overline{\alpha' u'_i}\right)}_{\text{turbulent/convective transport}} + \underbrace{S_\alpha}_{\text{diabatic source/sink of } \alpha}$$

$\alpha = T$: latent heat release Q^*, radiation Q_{rad}

$\alpha = q_v$: condensation/evaporation...Q

equation for heat

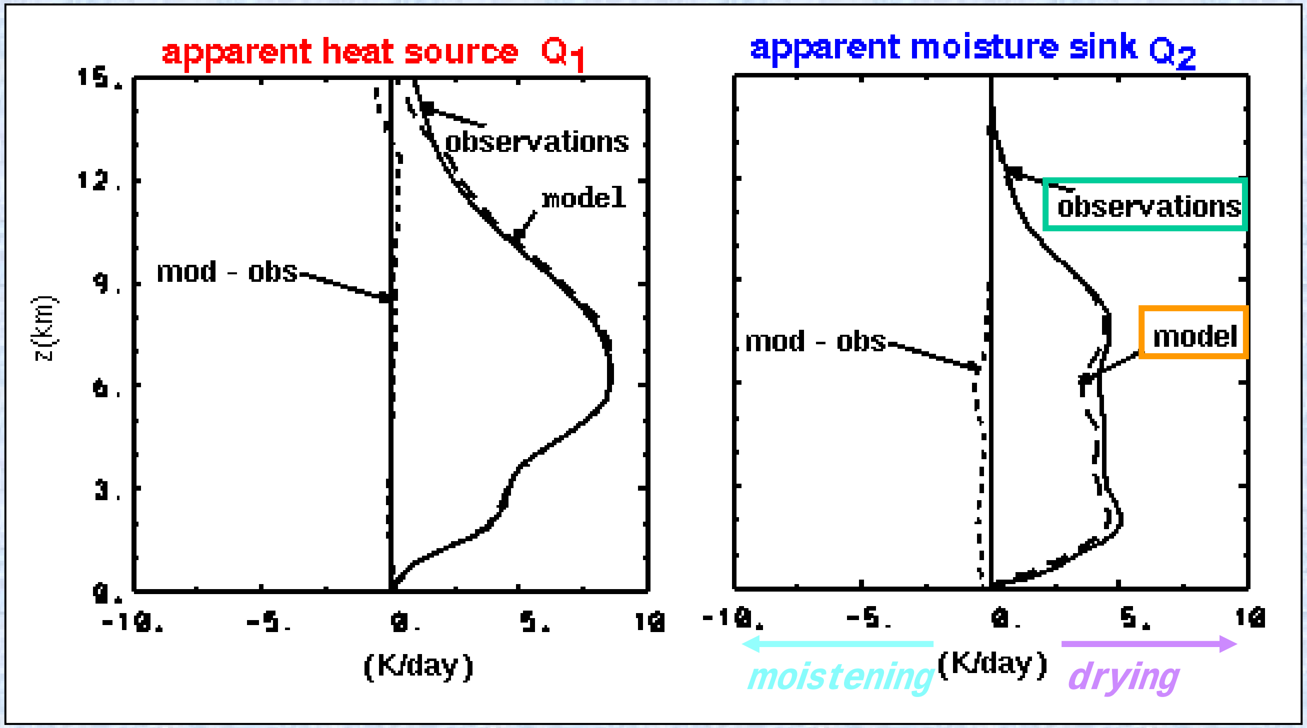
$$\pi\frac{\partial \overline{\theta}}{\partial t} = -\pi\,\overline{u}_i\left(\frac{\partial \overline{\alpha}\,\overline{\theta}}{\partial x_i}\right) \underbrace{- \frac{\pi}{\rho}\frac{\partial}{\partial x_i}\left(\rho\overline{\theta' u'_i}\right) + Q^* + Q_{rad}}_{\text{apparent heat source, refered to as } Q_1}$$

equation for moisture

$$-\frac{L}{c_p}\frac{\partial \overline{q}_v}{\partial t} = +\frac{L}{c_p}\overline{u}_i\left(\frac{\partial \overline{\alpha}\,\overline{q}_v}{\partial x_i}\right) \underbrace{+ \frac{L}{\rho c_p}\frac{\partial}{\partial x_i}\left(\rho\overline{q_v' u'_i}\right) + Q}_{\text{apparent moisture sink, refered to as } Q_2}$$

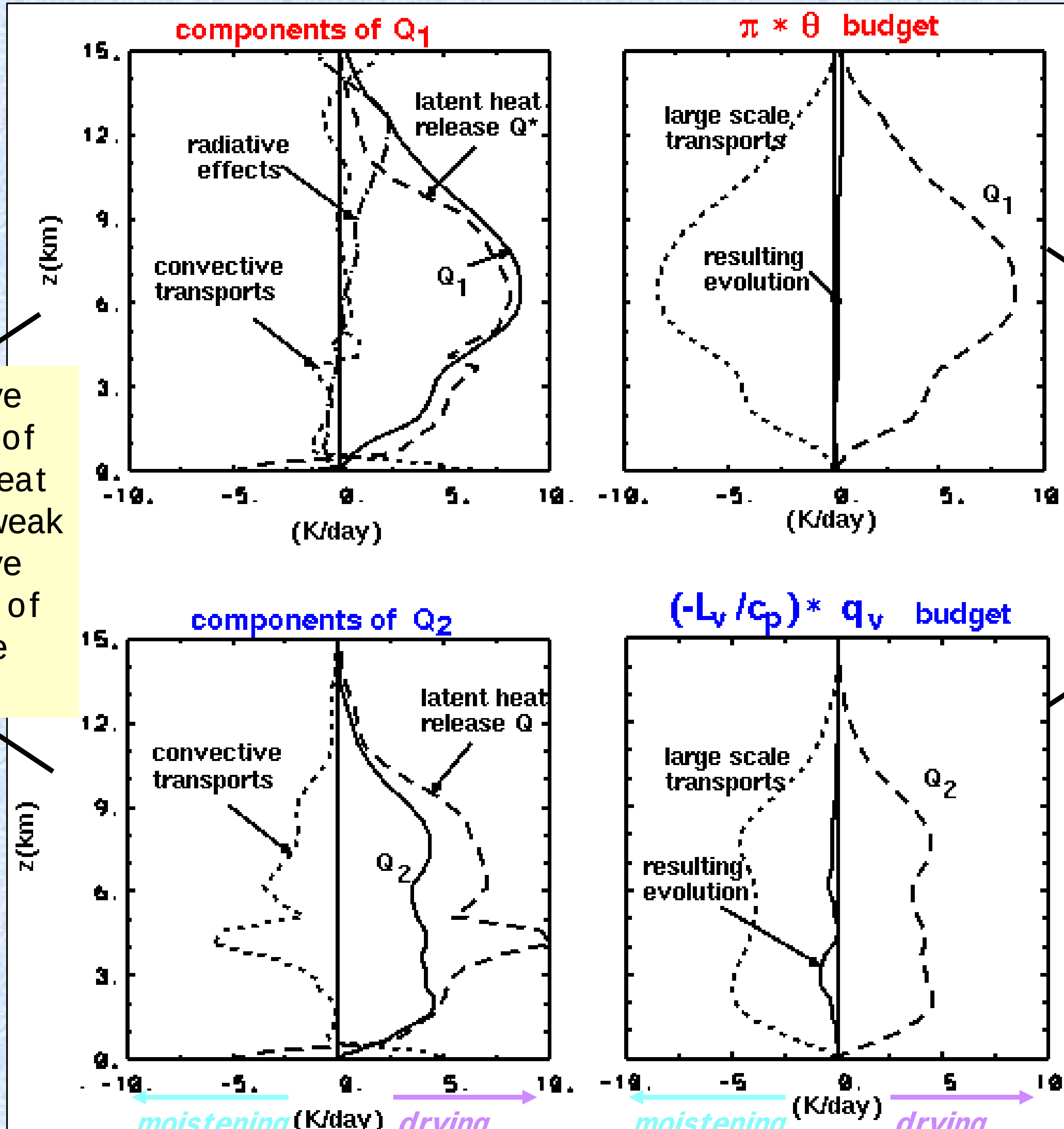
with $\pi = (P/P_0)^{(R/cp)}$ [Exner function] ρ : density c_p: heat capacity L: latent heat

<u>usefulness of the framework</u>: quantitatively compare θ and q_v budgets in a consistent way (terms of eqns expressed in the same units: $K.s^{-1}$) [note that 1 K. day^{-1} ~ 2.5 $g.kg^{-1}.day^{-1}$]



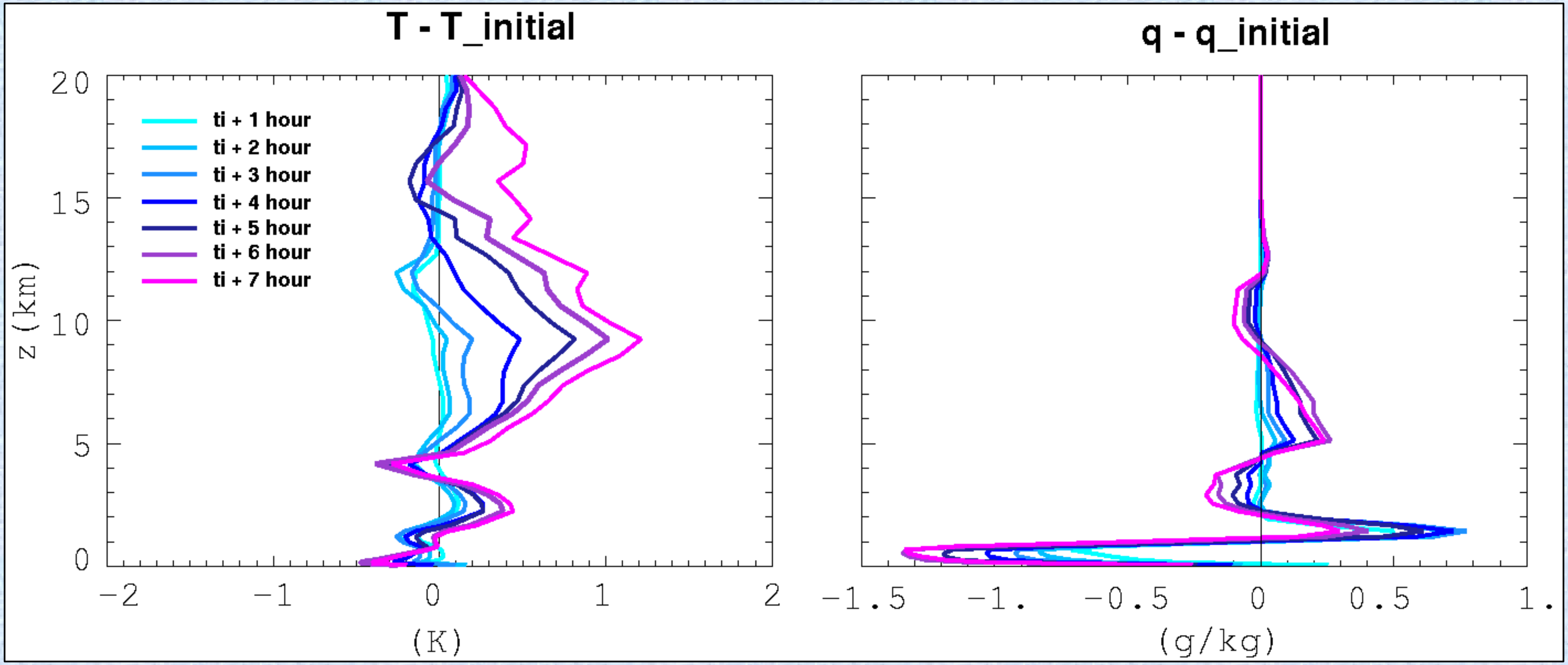
7-day mean vertical profiles of Q_1 & Q_2 under convective period over the tropical Pacific warm pool (TOGA-COARE experiment)

curve « observations » : budget analysis deduced from a network of soundings & other obs...
curve « model » : obtained from a limited area cloud resolving model (resol /x ~ 1km), using boundary conditions derived from observations



convective transport of sensible heat relatively weak
convective transport of moisture larger

for time scales > 1 day, typically a balance between Q1/Q2 and large-scale motions



departure of T and q mean profiles from initial ones in a convective situation (oceanic squall line simulation, Redelsperger et al. 2000)

relatively weak departures compared to Q_1 & Q_2 values, on the order of several tenth of K.day^{-1}
cooling/drying of the lowest levels, heating/moistening above 5 km
note than there is not a net drying of the column even though Q_2 corresponds in this case to a drying.

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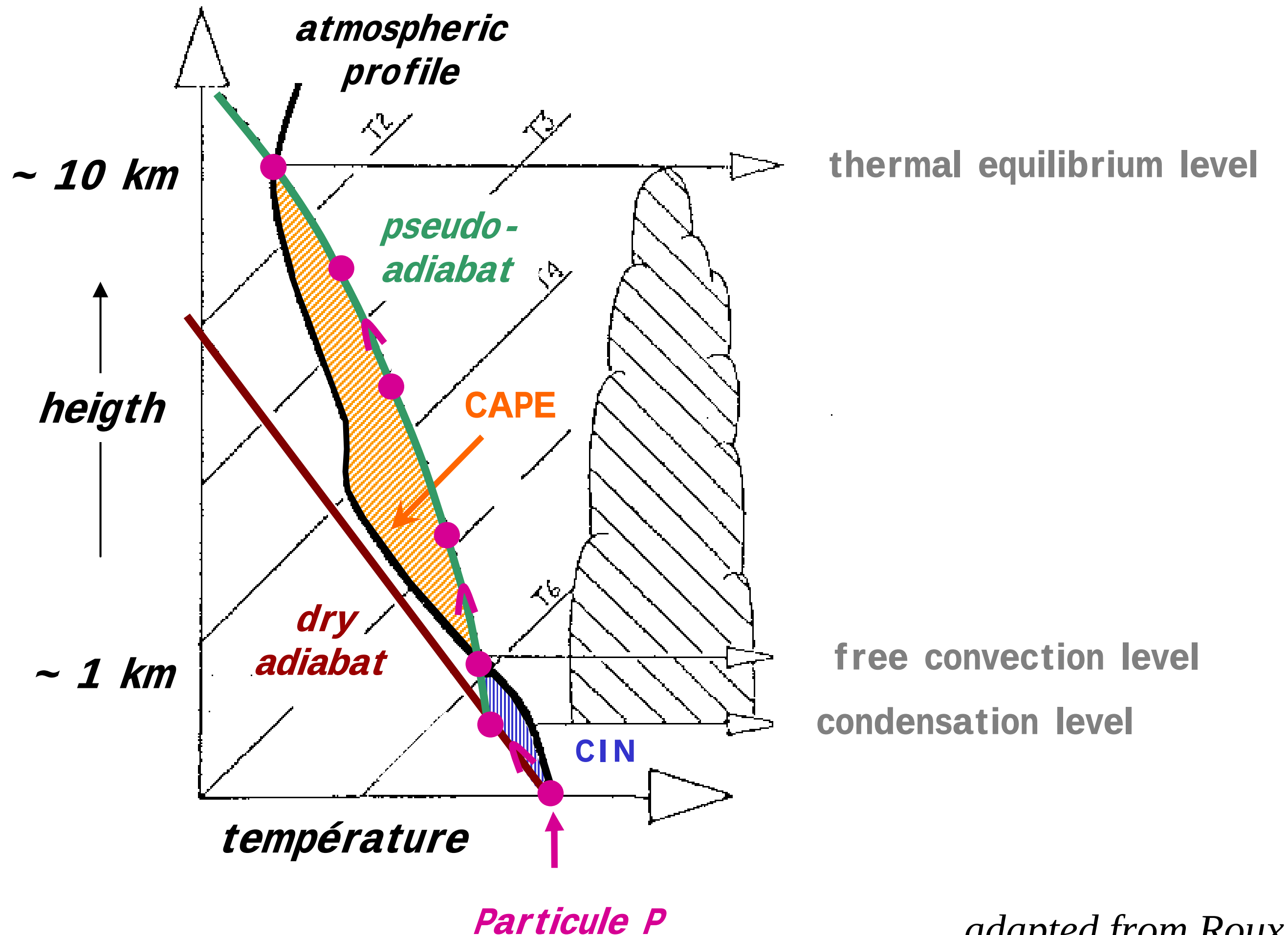
CONDITIONAL INSTABILITY (parcel theory)



adapted from Roux (1991)

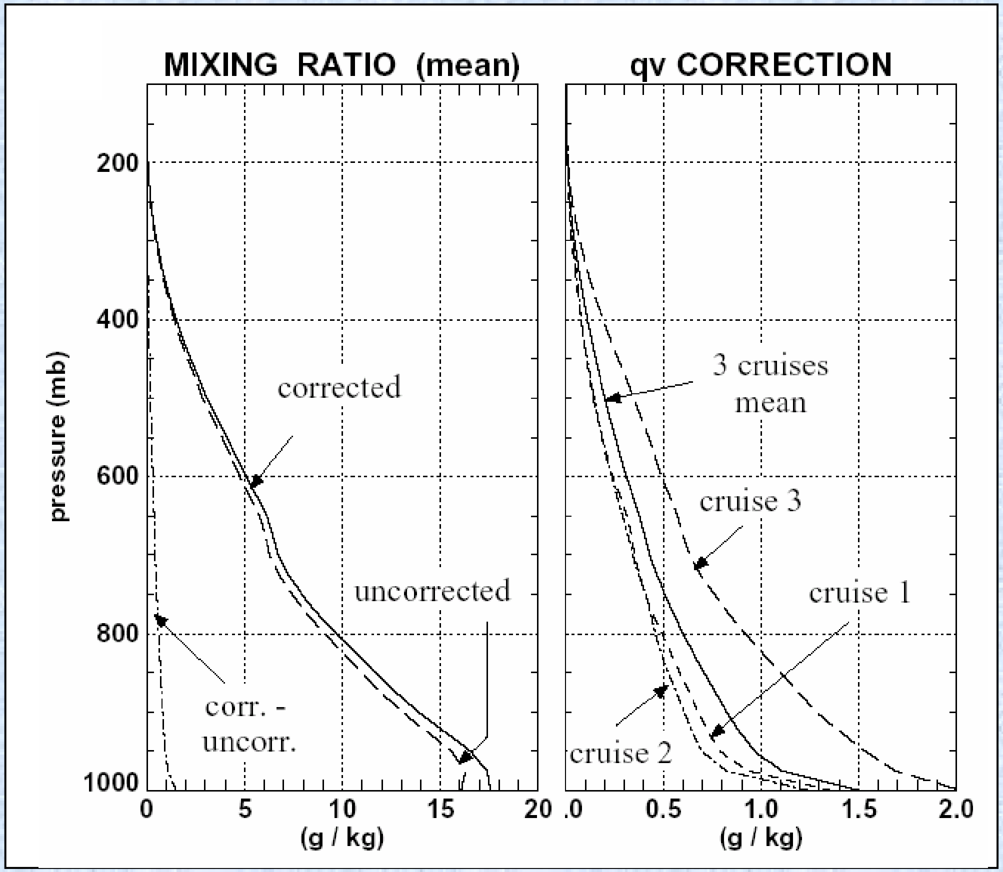
CAPE (Convective Available Potential Energy) : e*nergy that could be relased by the ascent of P*

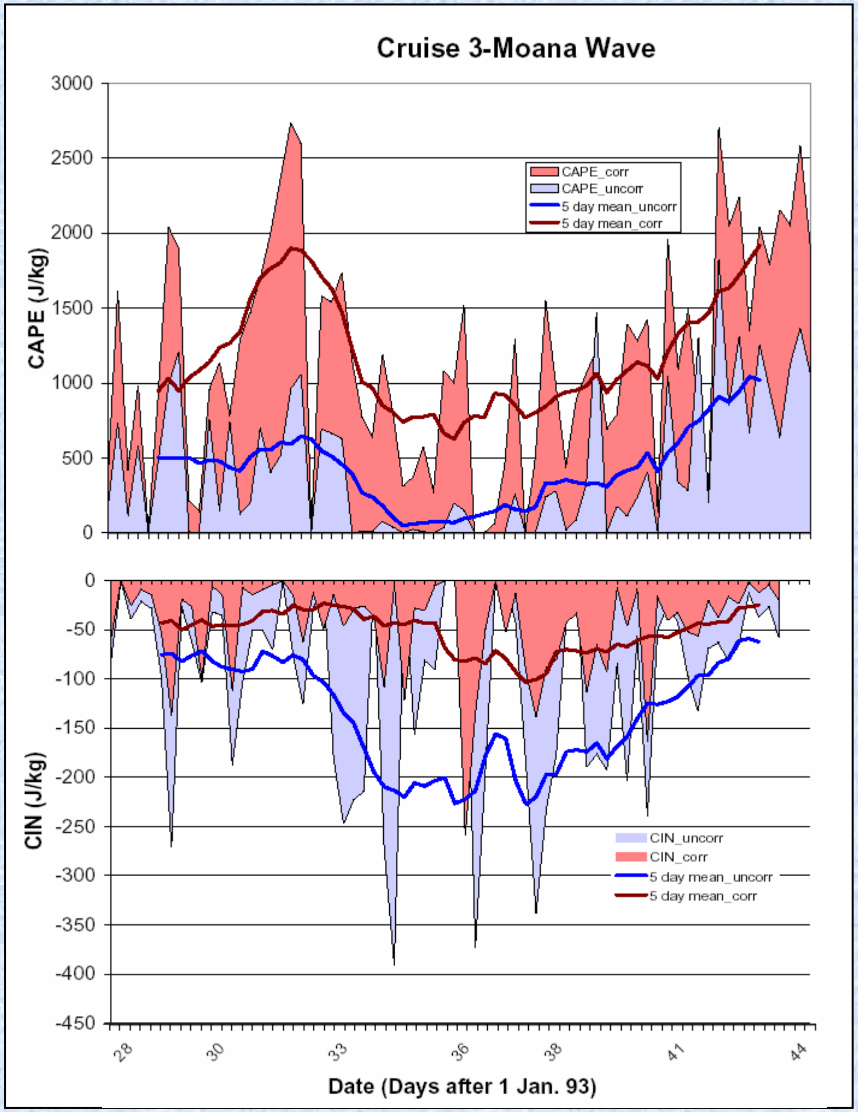
CIN (Convective INhibition) : *energy barrier for P*

w_{max}=sqrt(2xCIN)
caution: this is a « rough estimation »

Sensitivity of atmospheric stability to relatively « small » errors in humidity measurements

sounding data from the warm pool (tropical Pacific)
TOGA-COARE experiment





Guichard et al. (2000)

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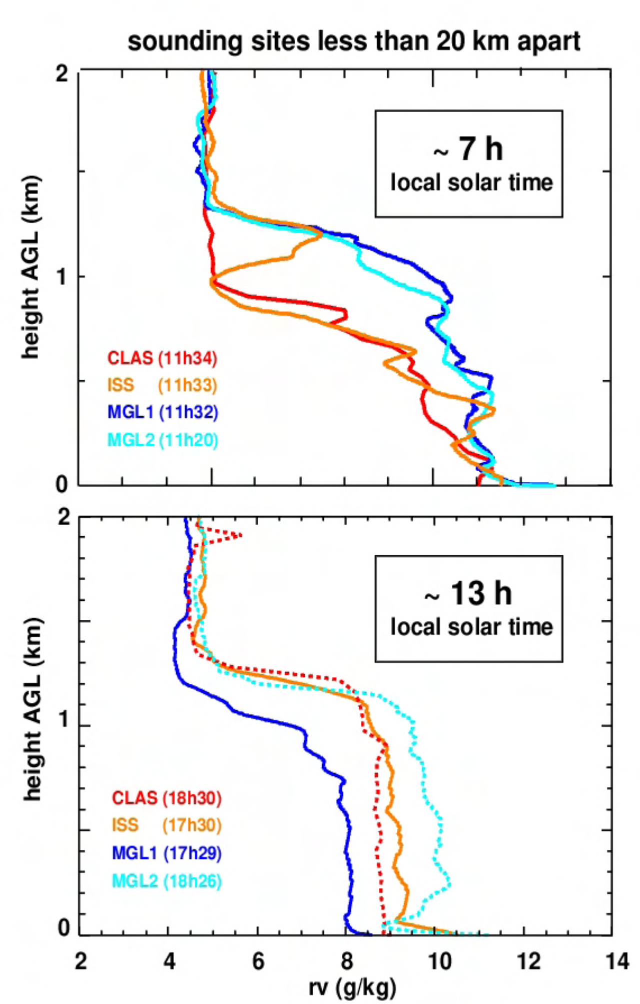
small scale variability of moisture and convective initiation



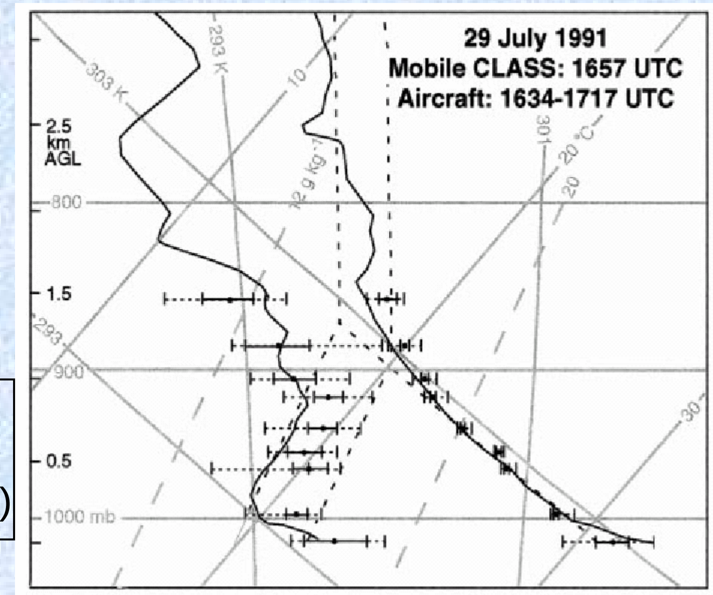
morning: layered vertical structures, with differences among soundings fct(z)
midday: well mixed r_v profiles on the vertical in BL but large fluctuations (~ 2g.kg^{-1})

Couvreux et al. (2004)
IHOP experiment
(Southern Great Plains, USA)

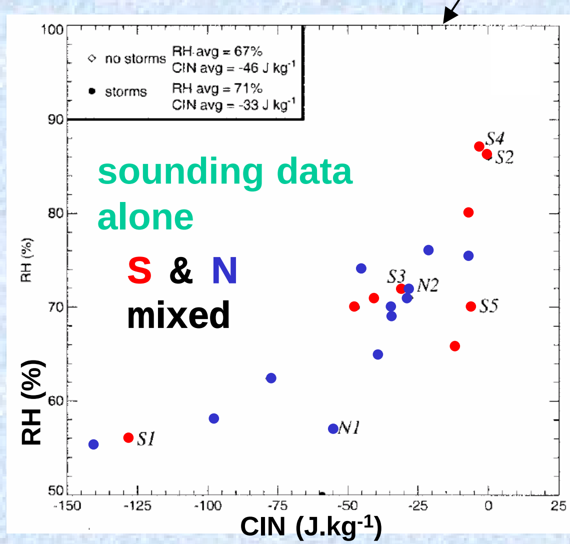
Weckwerth (2000)
CAPE experiment
(in Florida, USA)

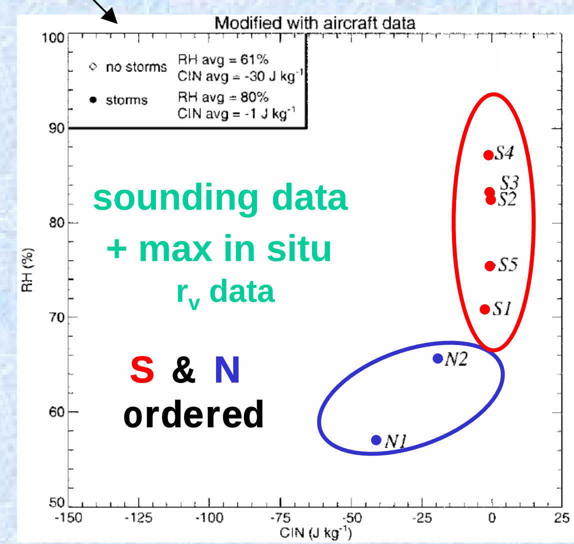
difference between **stormy** & **no stormy** days?

soundings with range of fluctuations from in situ measurements (flight data)



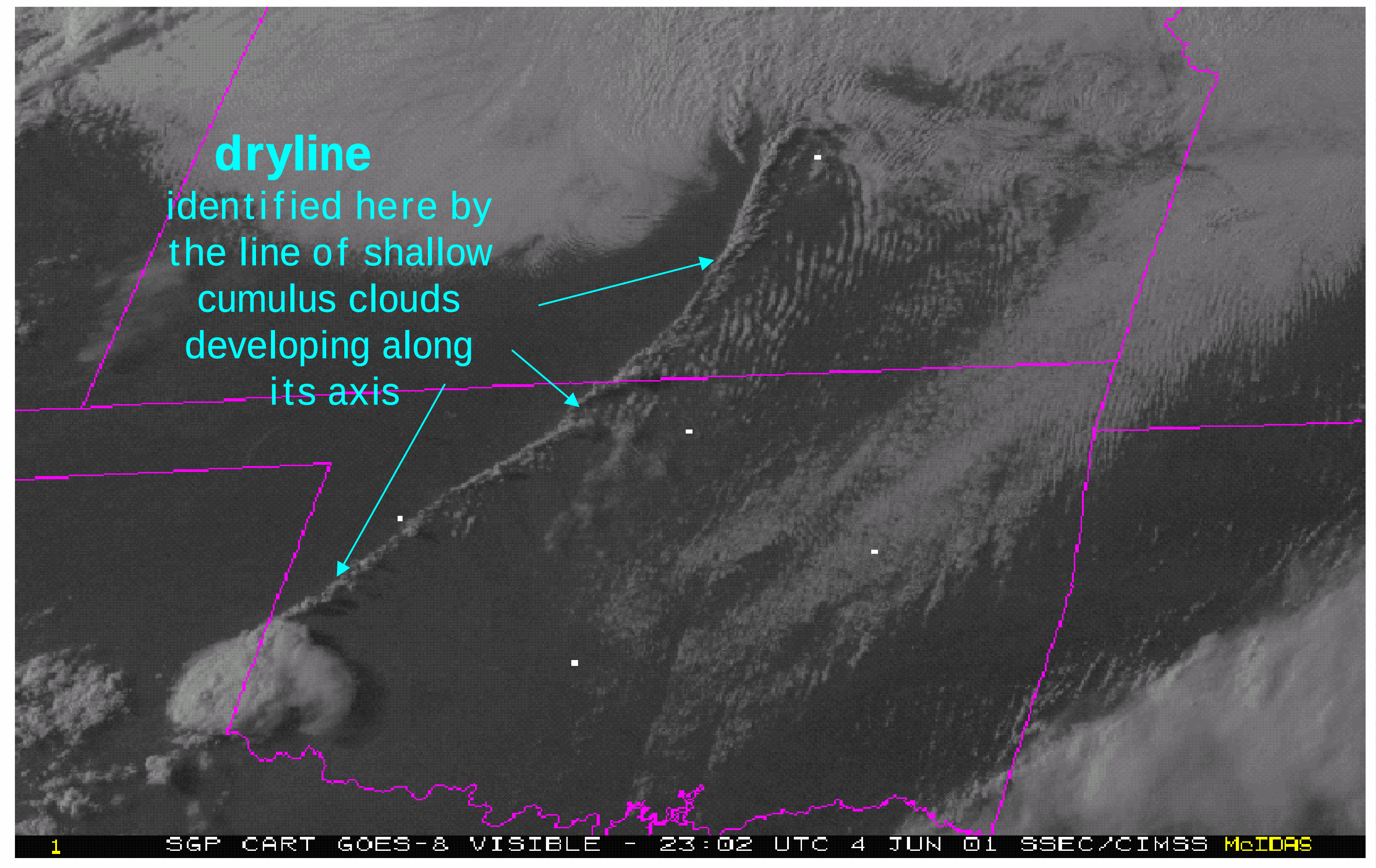
∃ parameters for distinguishing stormy from no stormy days ?





At mesoscale scale, what is well know and not as well : the example of the dryline of the Southern Great Plains (SGP, USA)

the dryline : a sharp (< 10 km) mesoscale moisture gradient, a few hundreds of km long often present during spring to early summer over the SGP



deep convection, if it occurs is likely to be initiated in the close vicinity of the dryline (Rhea 1966)
knowing exactly where along this line, and why, is still a matter of research

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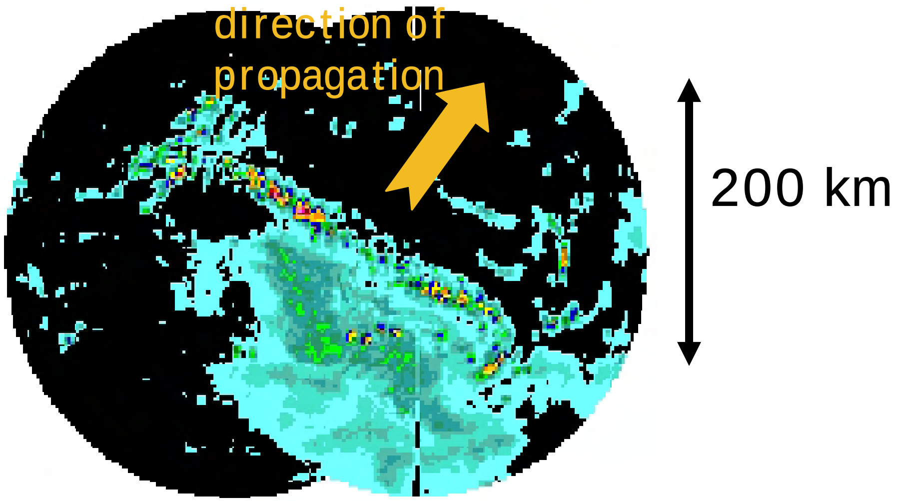
moisture and convective organization (life cycle, propagation speed...)

a piece of squall line as seen from the surface

experiment COPT81, Ivory Cost, (photo S Chauzy)

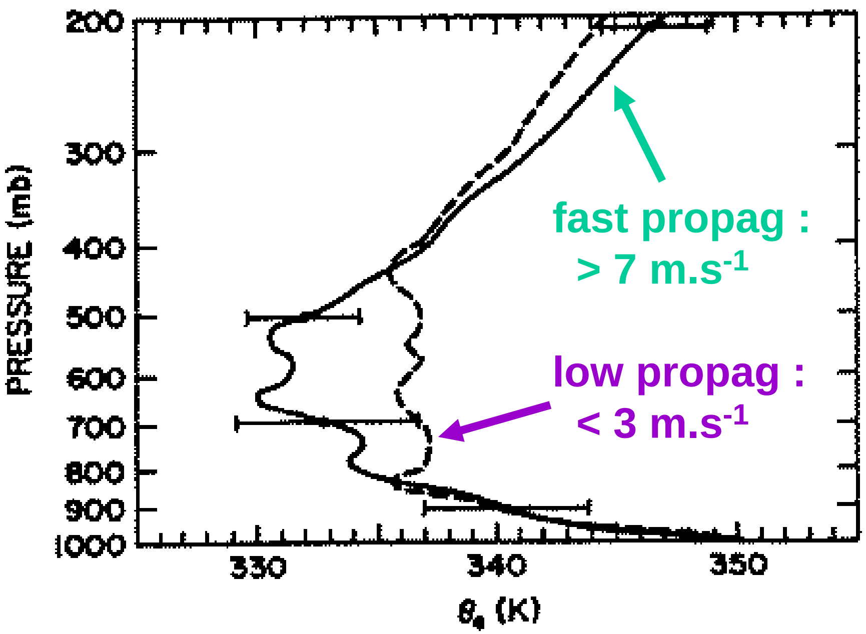


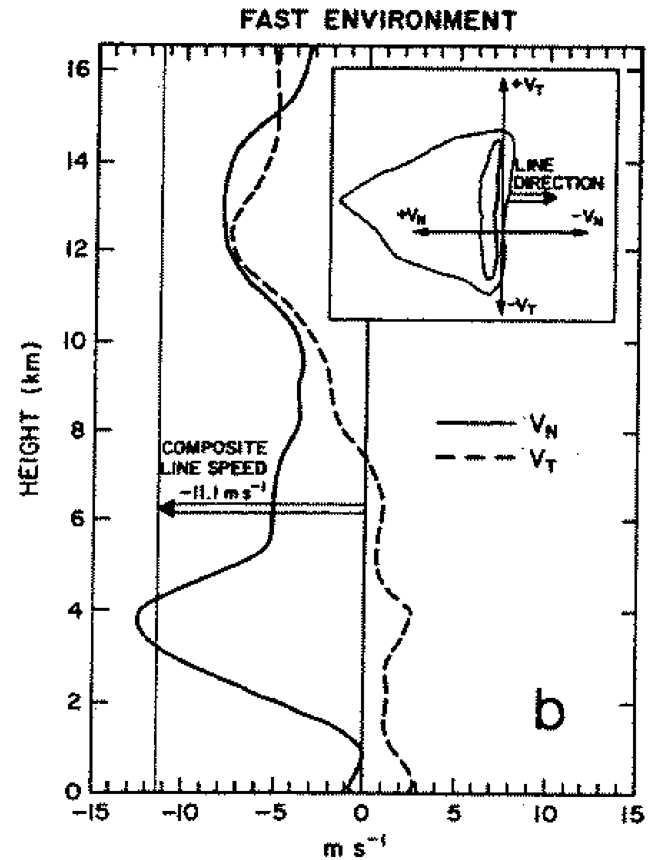
squall line as seen from surface radar

moisture and convective organization (life cycle, propagation speed...)

Barnes and Sieckman (1984)

mesoscale convective systems (MCS): covering more than 100 000 km^2





MCS propagating faster characterized by a dryer mid-troposphere (also stronger shear).

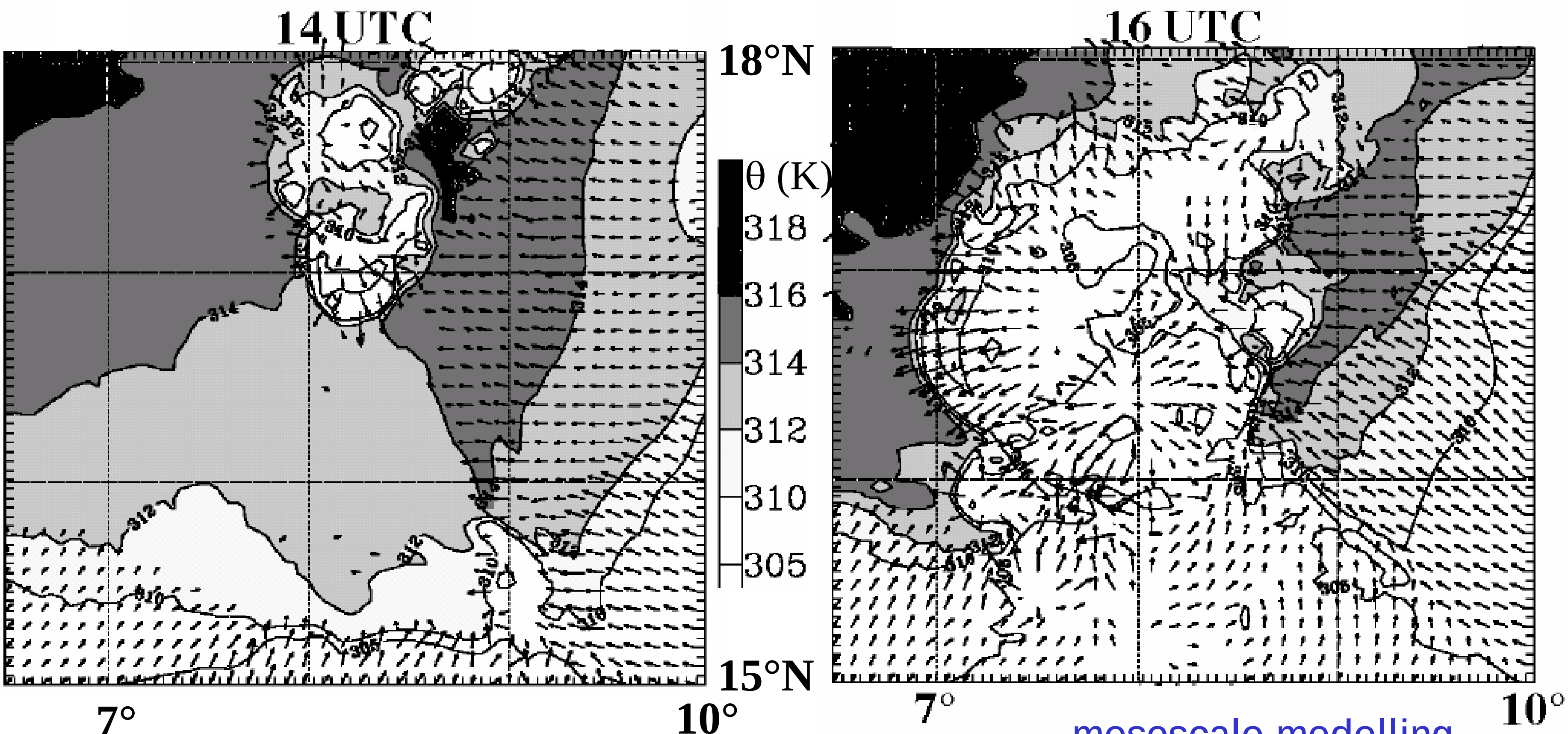
proposed mechanism: drier air promotes the formation of strong downdraughts feeding a cold pool; the strength and propagation speed of the cold pool will depends on the properties of the downdraughts: if strong enough, rapid propagation and lifting of the air ahead of the gust front (also role of the shear). you can get a quasi-stationary mesoscale system.

integration of this mechanism in a convection parametrization: discuss with J.-Y. Grandpeix

an example of fast moving squall line

Diongue et al. (2002)

early stage, T & wind at ~40 m AGL, formation & propagation of the cold pool



simulation results (horizontal resolution : 5 km)

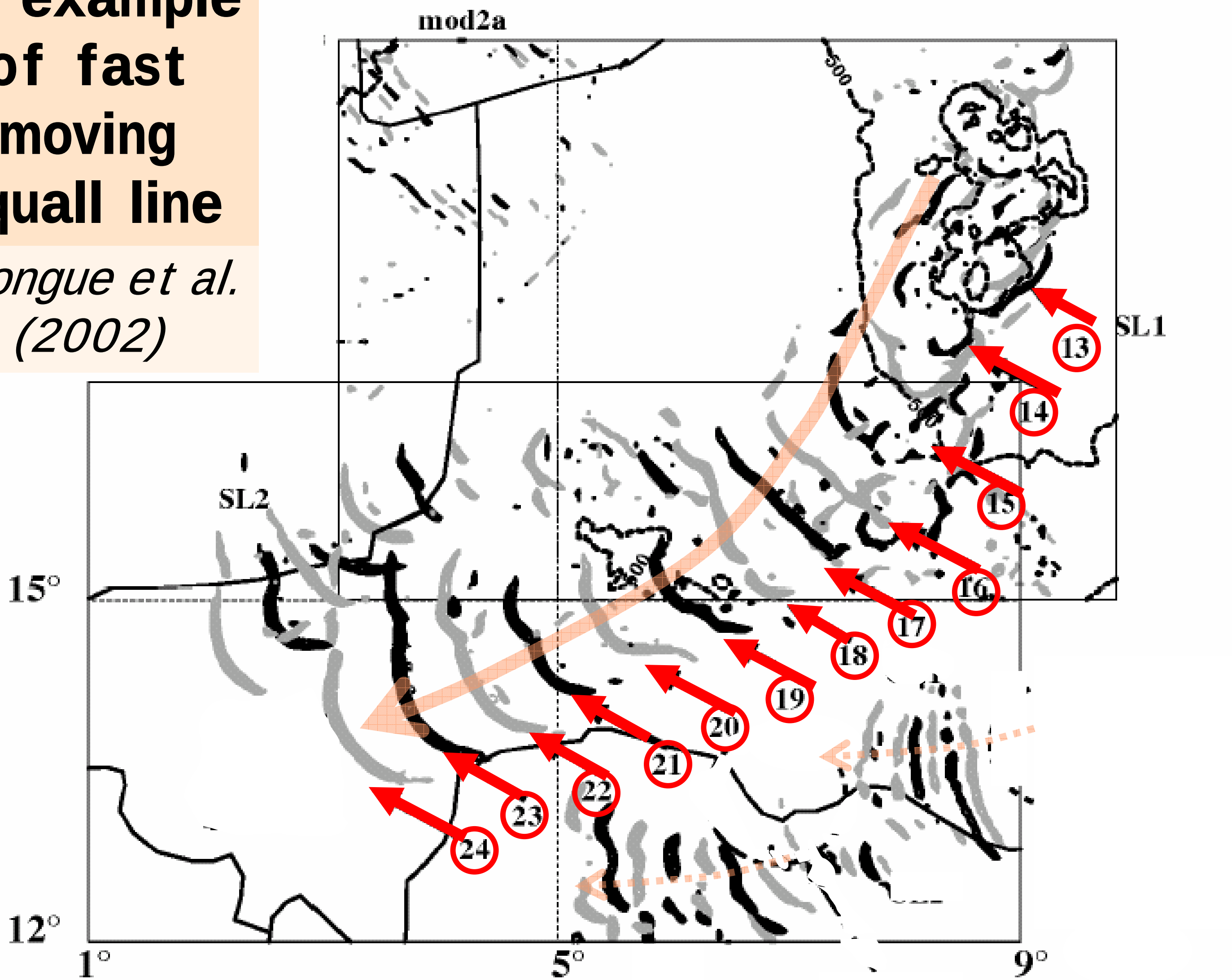
30 m/s

mesoscale modelling initiated with ECMWF analysis

recent history in the eighties, objective of « explicit » modelling: simulation of the mature stage only, initiation from a line of cold bubbles to mimic the cold pool (mean atmospheric properties not favourable to the development of such system)

an example of fast moving squall line

Diongue et al. (2002)



w > 1m.s-1 600m AGL

2.n hours

2.n+1 hours

initiation
11h-16h

mature phase
16h-24h

« quasi-stationary » behaviour during several hours

cover 1000 km in 15 hours, propagation speed of 17 m.s-1

note : modes of convective organization: still a lot to understand

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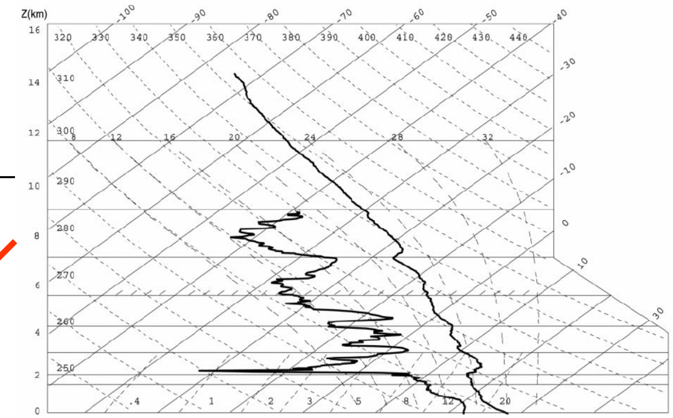
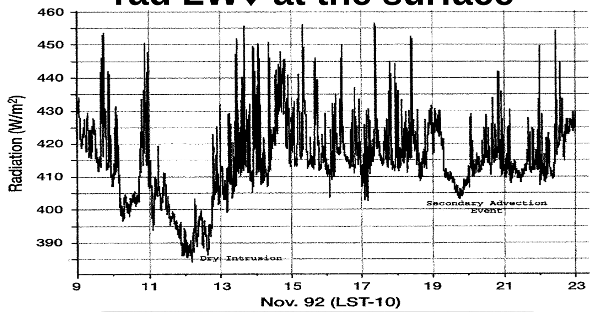
dry intrusions in the Tropics

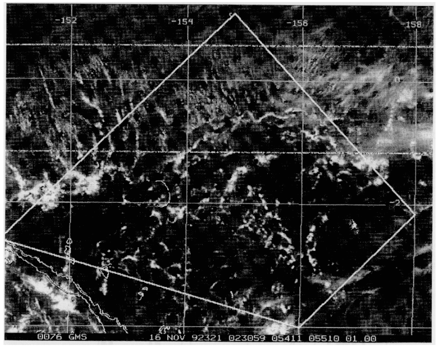
not rare, tongues of dry air from higher-latitudes
suppression of convective activity
(from local arguments ~10 days for recovery)

Parsons et al. (2000)
Redelsperger et al (2002)

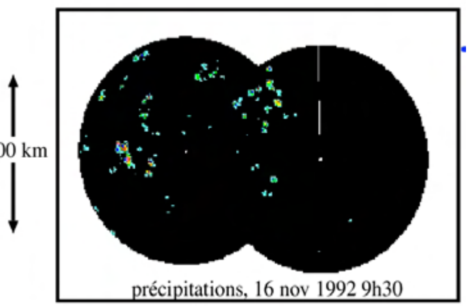


rad LW↓ at the surface

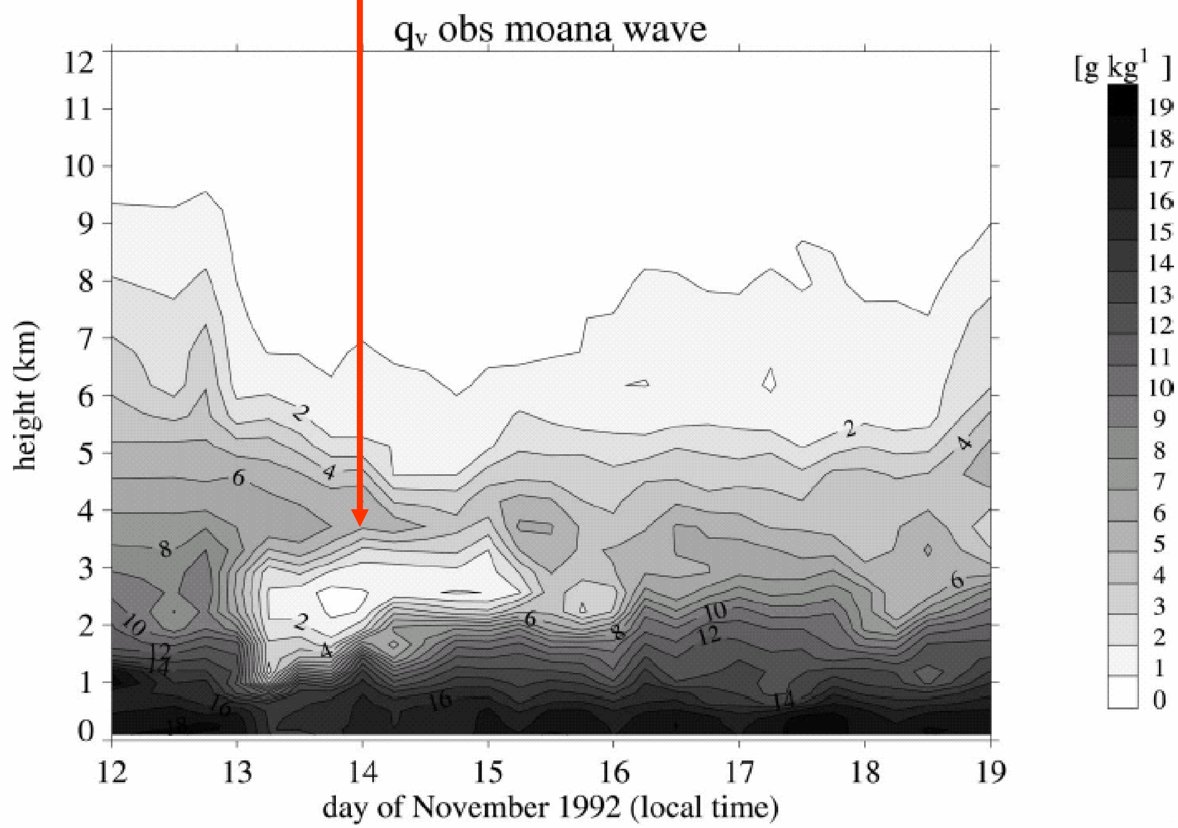




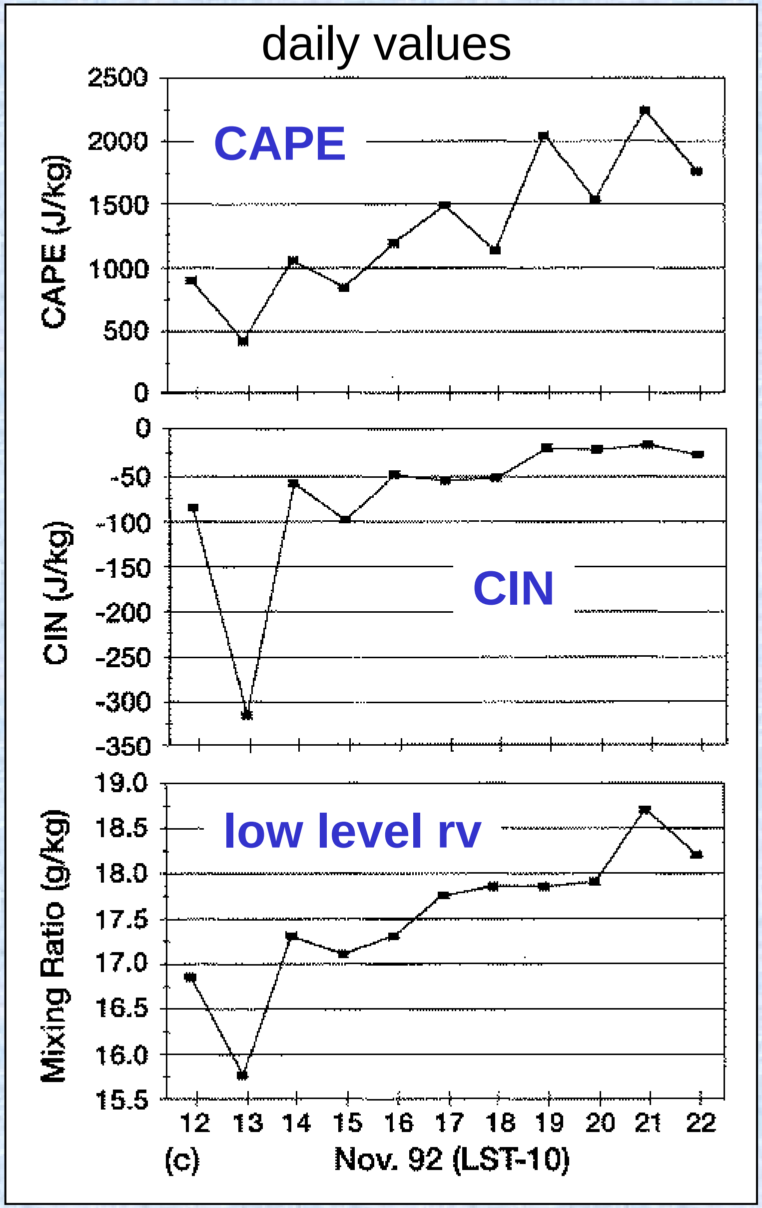
~ 500 km

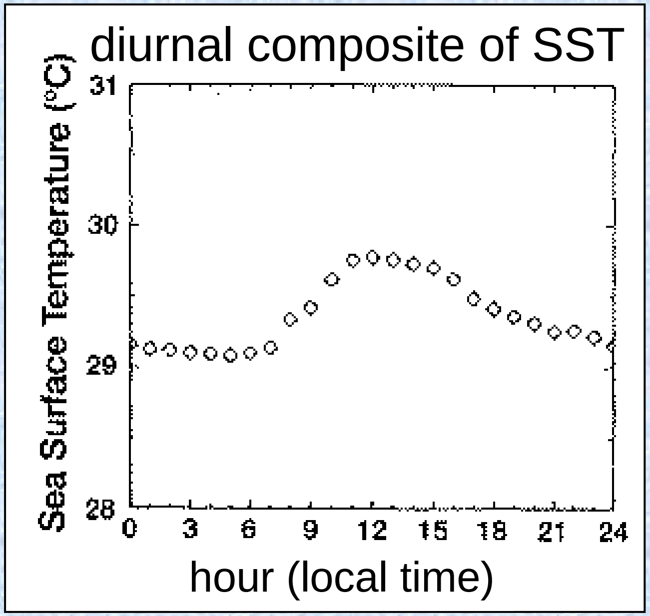


COARE experiment
equatorial Pacific
warm pool



Parsons et al. (2000) , case study analysis (continued)





progressive:

increase of CAPE

(quite large value after 10 days)

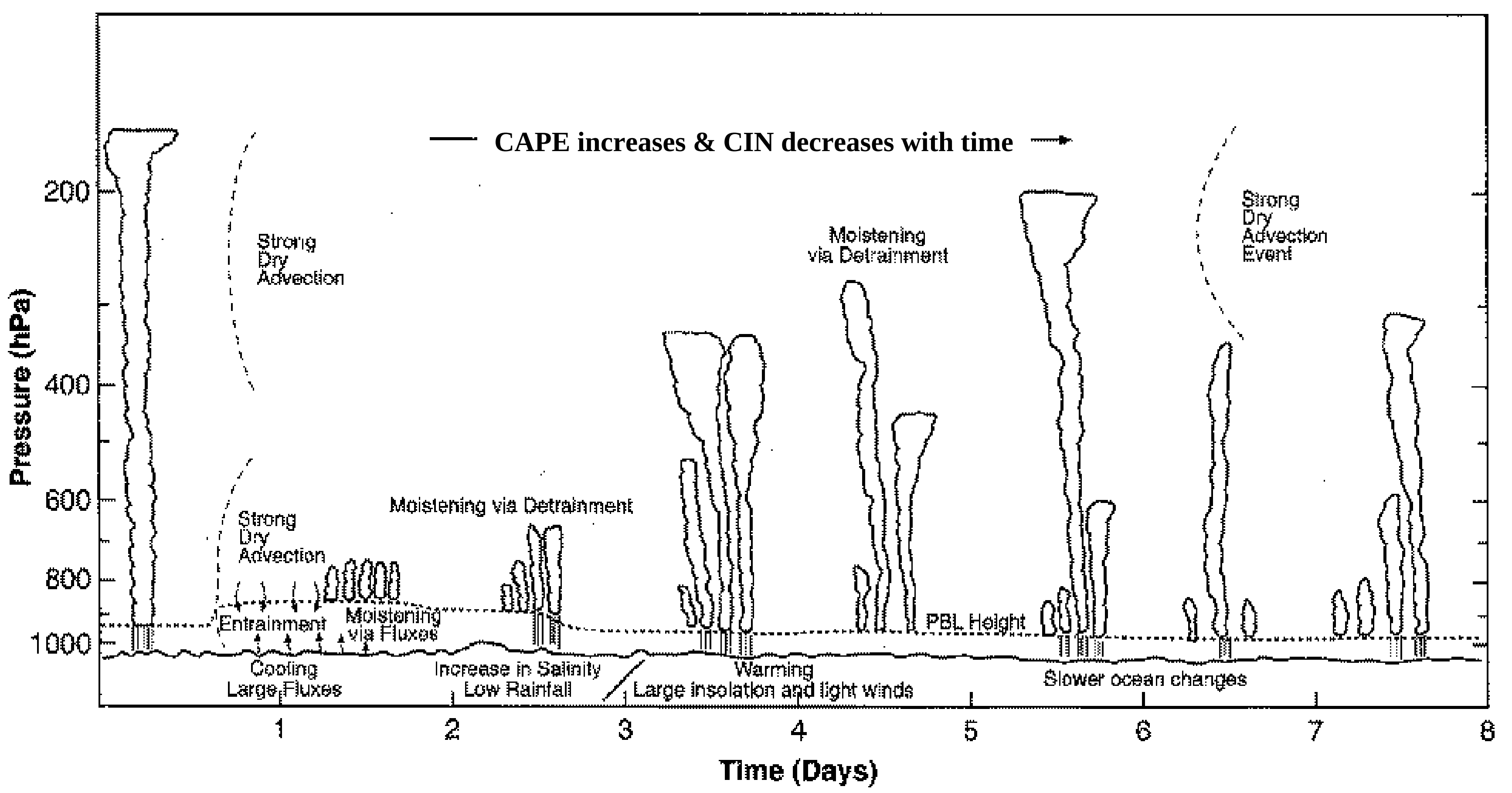
decrease of CIN

recharge of the atmosphere

(changes in the diurnal cycle)

Parsons et al. (2000)

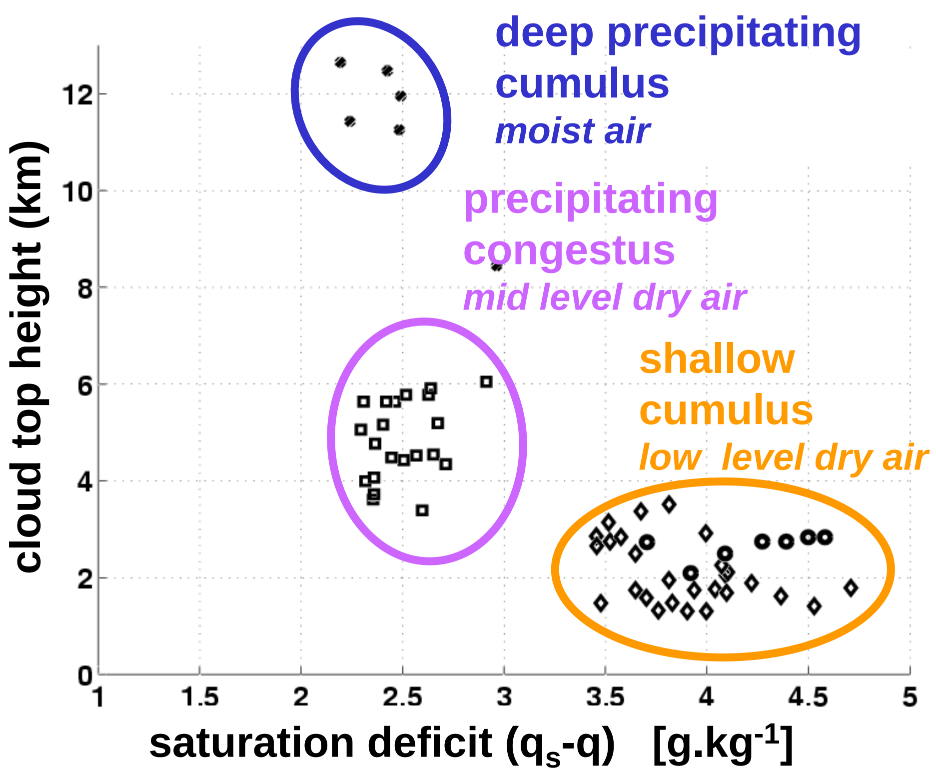
conceptual model of the recovery period following a dry intrusion



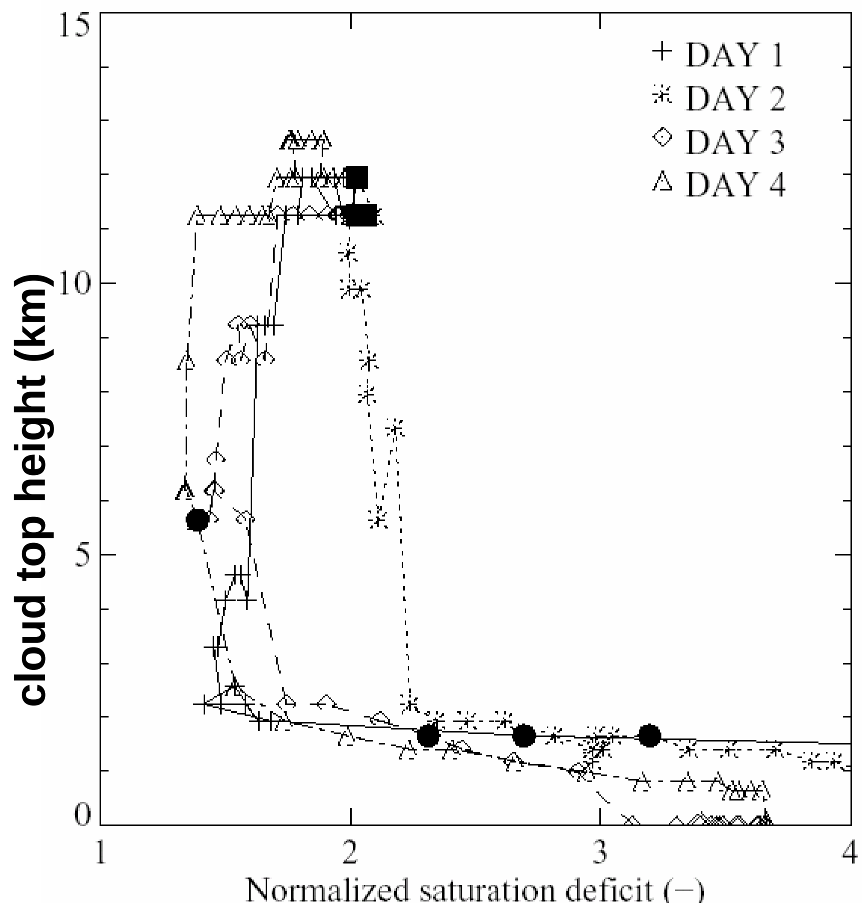
COARE experiment:
modification of the views about the working of tropical convection
idea that it is important to know why convection does not occur

Relationship between dry air & cloud top

modelling results
(explicit modelling, dx ~1 km)



Redelsperger et al (2002)



~ (qsat-q) / σ (qsat-q)

Chaboureau et al. (2004)

OUTLINE

- a few definitions

- some measurement techniques

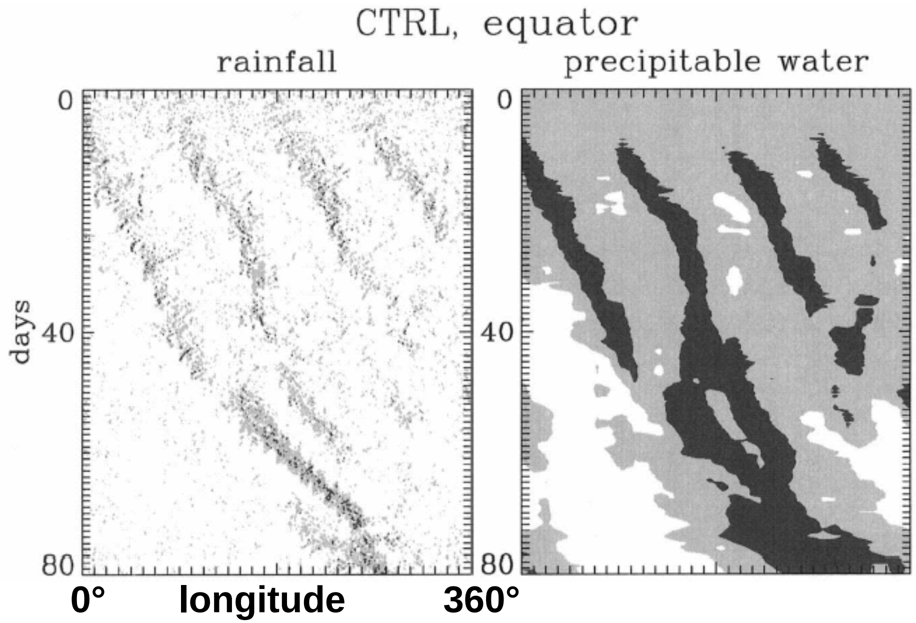
  with illustrations of water vapour variability at different scales

- **interactions of the water vapour field with convection**
  - *convective transport of moisture*
  - *sensitivity of the atmospheric stability to moisture*
  - *small scale variability and convective initiation*
  - *life cycle/propagation of squall-lines*
  - *role of dry intrusions for tropical convection*
  - *intraseasonal variability, an example*
  - *modelling issues*

- summary

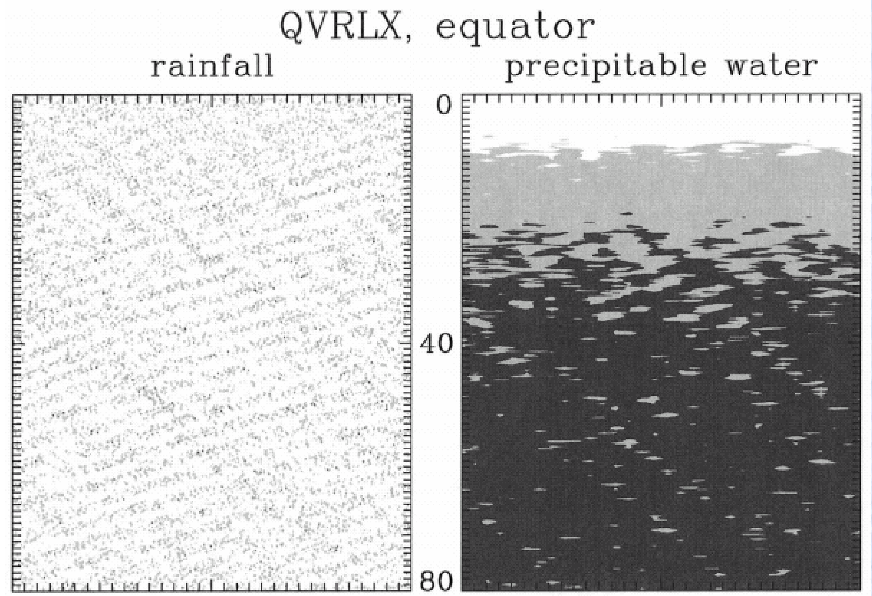
intraseasonal variability

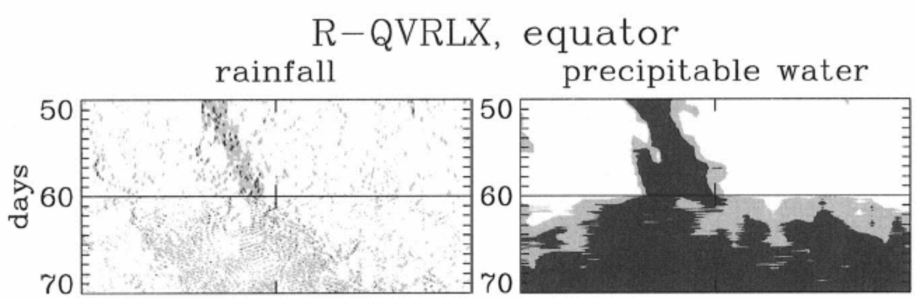
Grabowski (2003)



developement of MJO like coherent structures

how to remove them?





modelling study
inovative global model (CRCP)
with explicit convection

from this study & others, it seems that large-scale organization of convection in the Tropics involves moisture convection feedbacks

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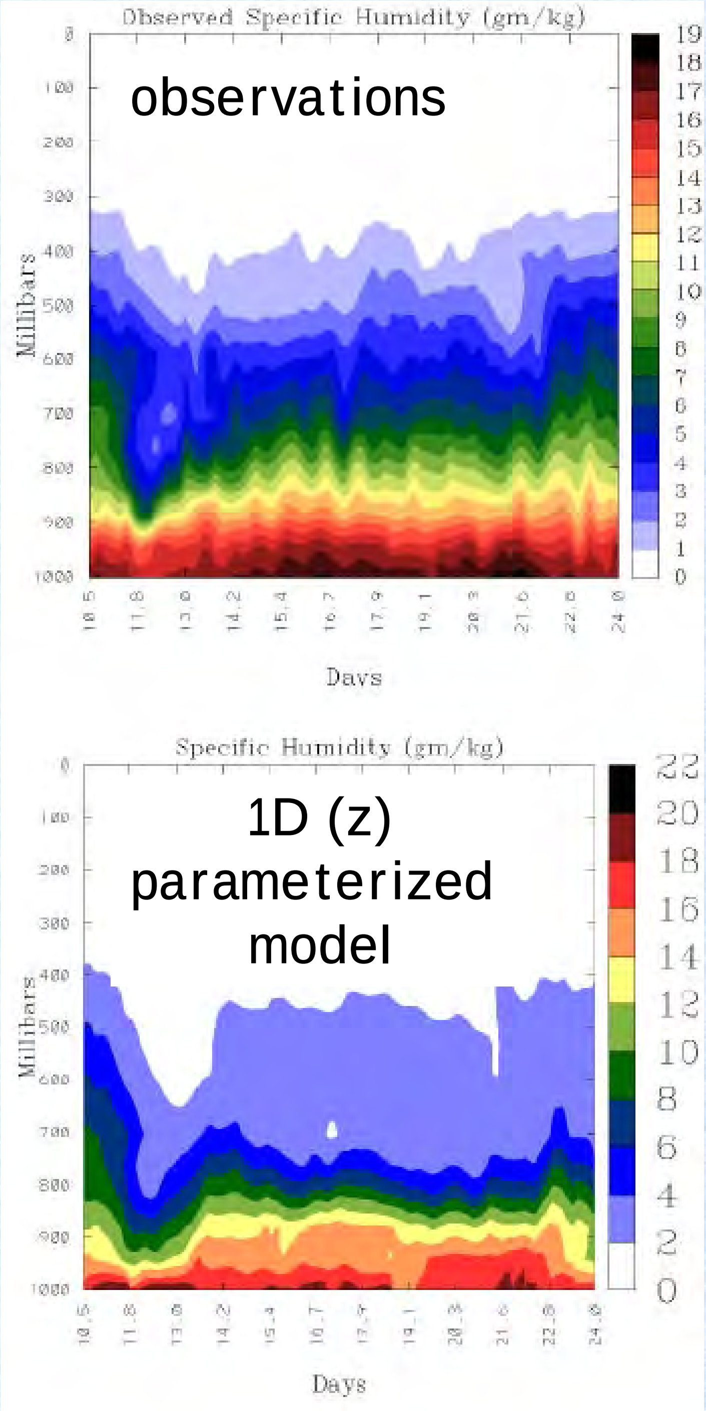
- summary

large-scale modelling issues

how does parametrized convection deals with such environmental conditions?

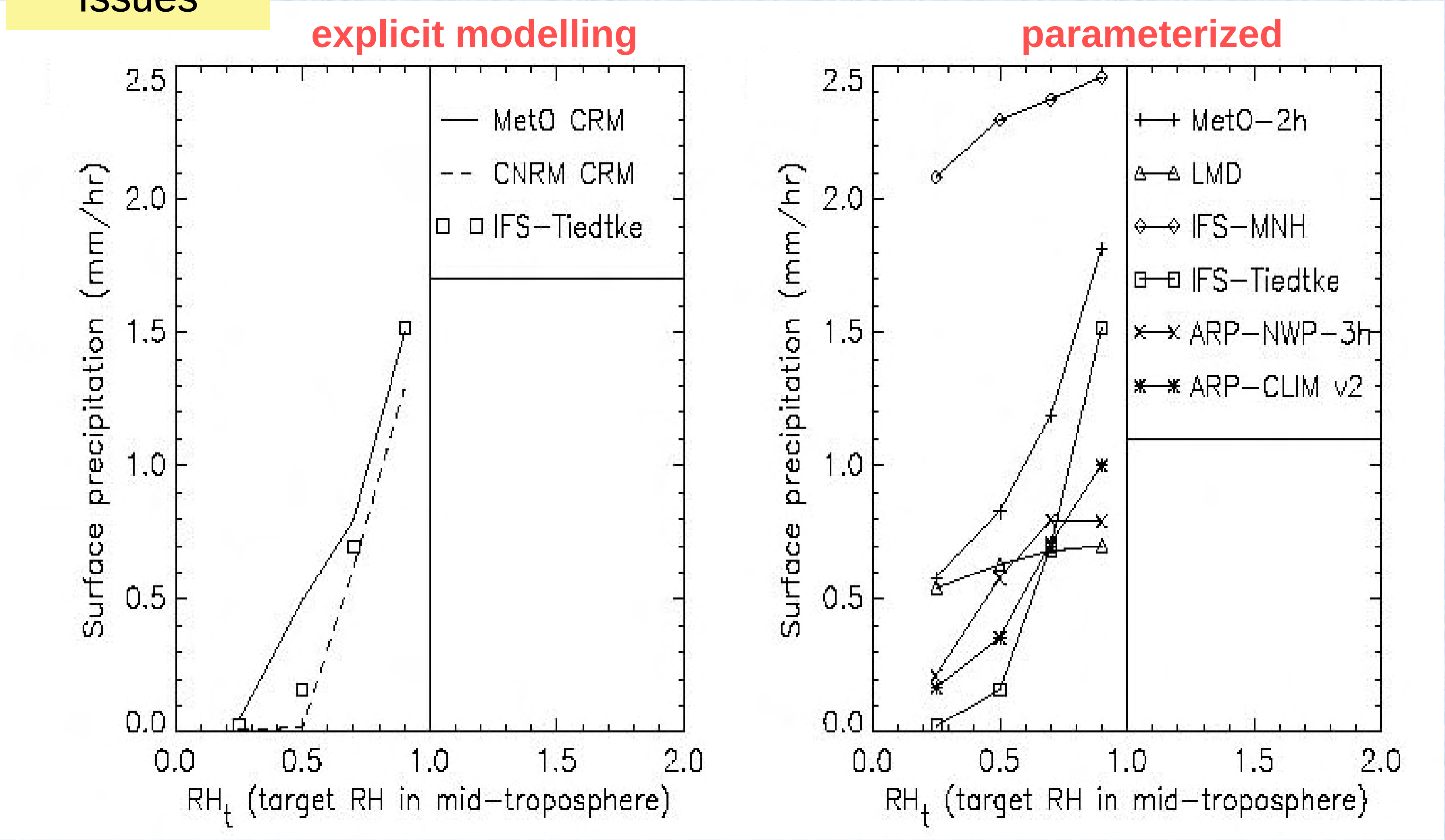


instead of a progressive recovery of the moisture profile (remoistening of the free troposphere), the 1D model tends to remove moisture rapidly via precipitation and then remains dry.

Redelsperger et al. (2000)

large-scale modelling issues

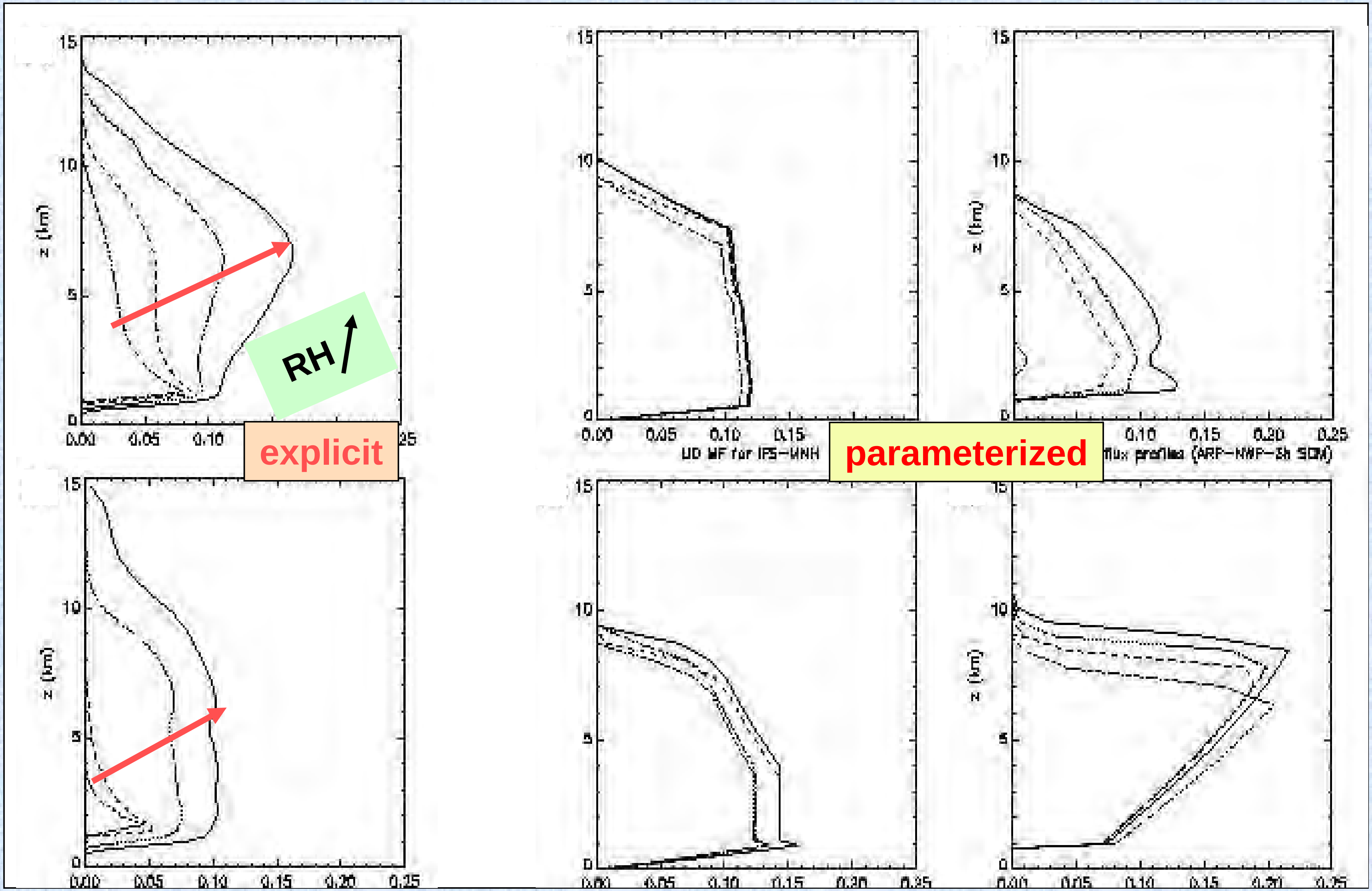
Surface precipitation rates as function of RH



Derbyshire et al. (2004)

large-scale modelling issues

upward convective mass flux



transition of regime, *Derbyshire et al. (2004)*

OUTLINE

- ❑ a few definitions

- ❑ some measurement techniques

  with illustrations of water vapour variability at different scales

- ❑ **interactions of the water vapour field with convection**
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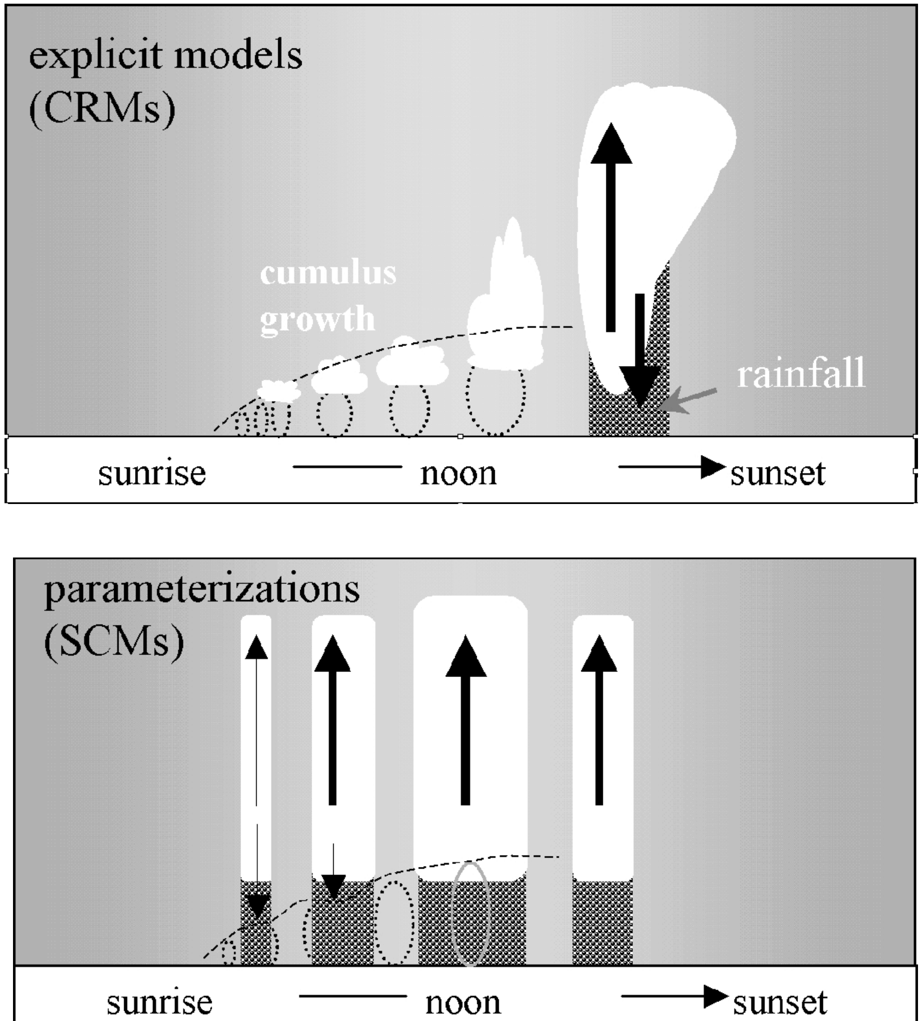
- ❑ summary

SUMMARY

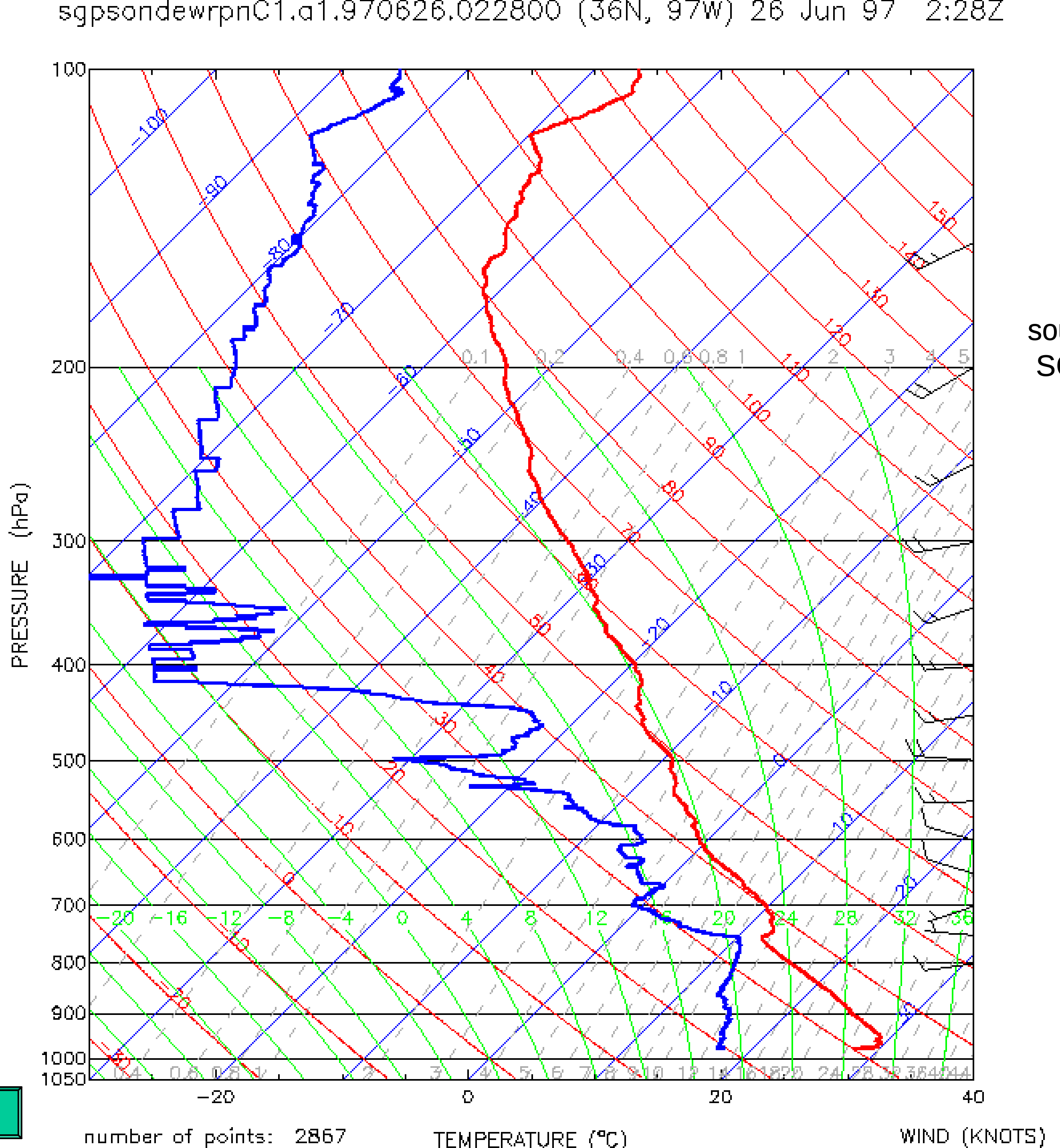
- strong time and space scale fluctuations of moisture
- still measurement issues
- large impact on stability (convective) parameters (e.g., CAPE & CIN)
- a key parameter for convective processes (initiation, maintenance, suppression)
- various mechanisms of interaction between convection & humidity
  (some yet to be found possibly)
- dry free tropospheric air can suppress deep precipitating convection for several days, e.g. relatively long recovery periods after dry intrusion in the Tropics
  preconditionning of the atmosphere via moistening by cumulus congestus
  impact on the timing and characteristics of convection
  (diurnal cycle / intraseasonal variability, e.g., MJO - more from W. Grabowski)
- mid-level dry air is a factor explaining the fast propagation of squall line (generation of strong convective downdraughts & cold pool)
  note: it may limit the life cycle of mesoscale convective systems in other parts of the world .
- modelling issues: sensitivity of convection to moisture and moisture small-scale variability needs to be improved in GCMs (more info from J.-Y. Grandpeyx) (transient states)

humidity plays a role in the diurnal cycle of convection too (next talk)



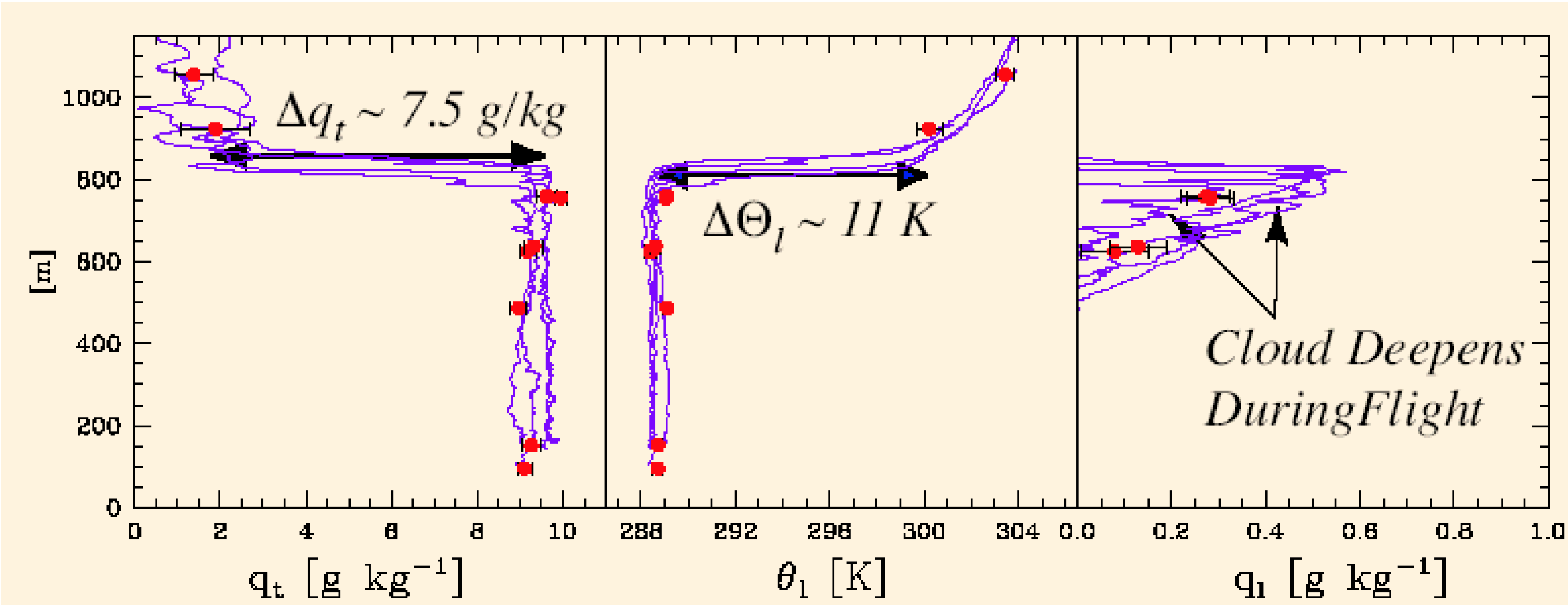
Guichard et al. (2004)

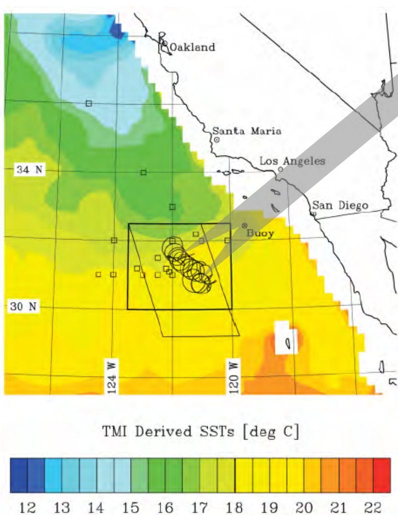
the end



sounding data at the ARM-SGP site (Southern Great Plains, USA)

see 4-day « animation » ppt file





typical structure in stratocumulus area

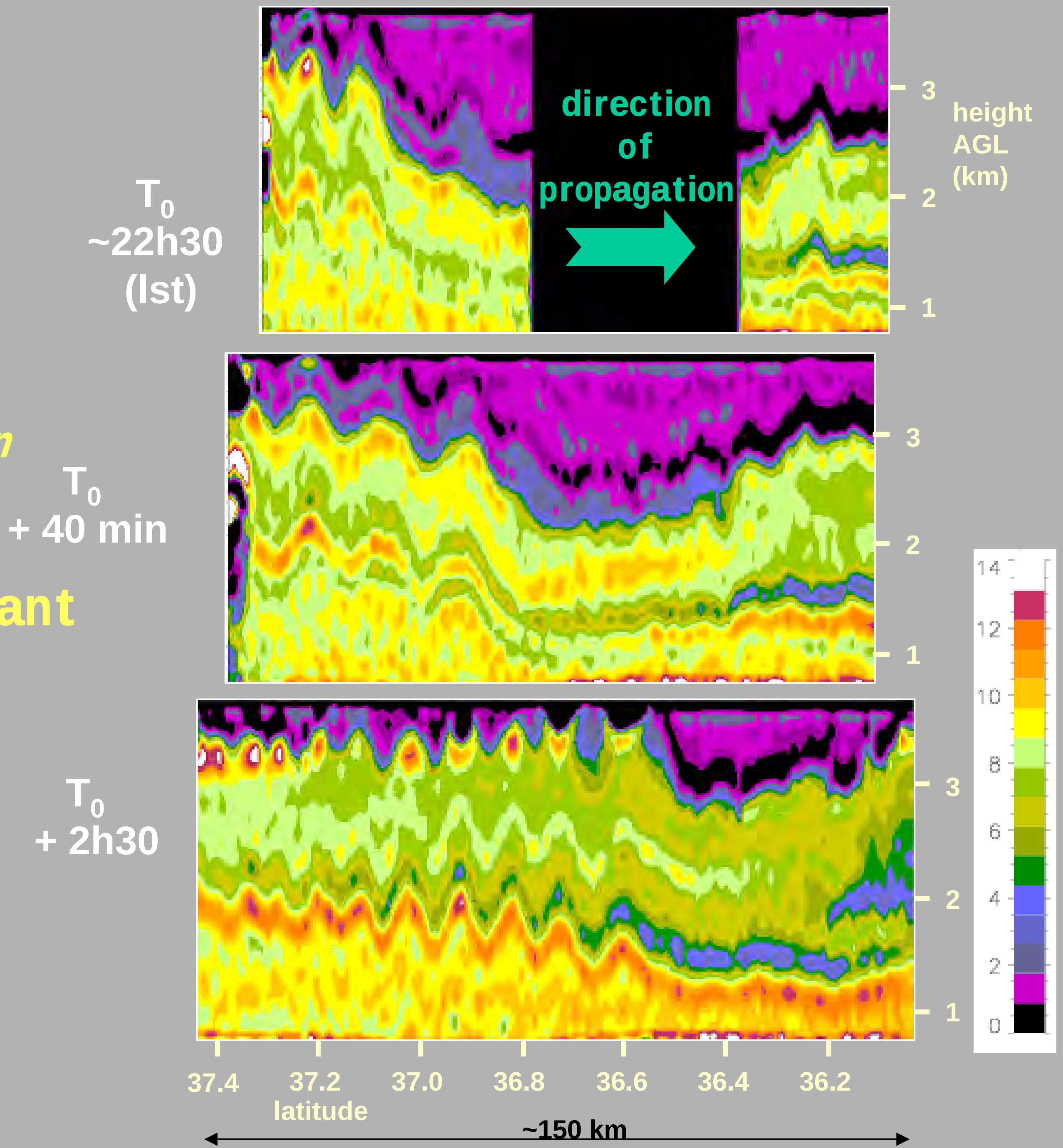
Stevens et al. (2002)

mixing ratio
r_v (x,z)
measured
by the lidar
LEANDRE2

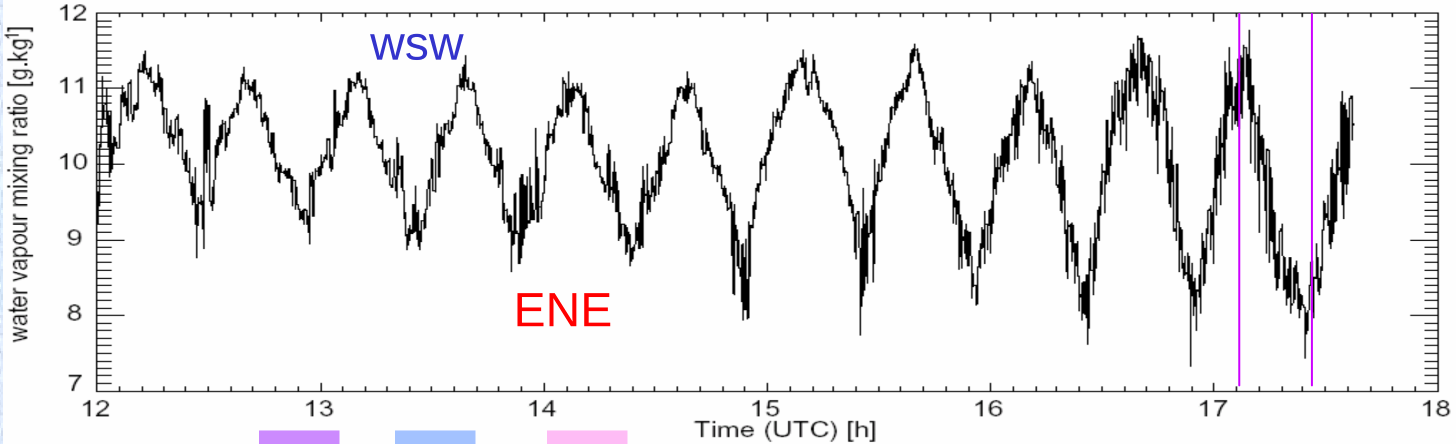
propagation/evolution of a bore

courtesy C. Flamant
IHOP experiment

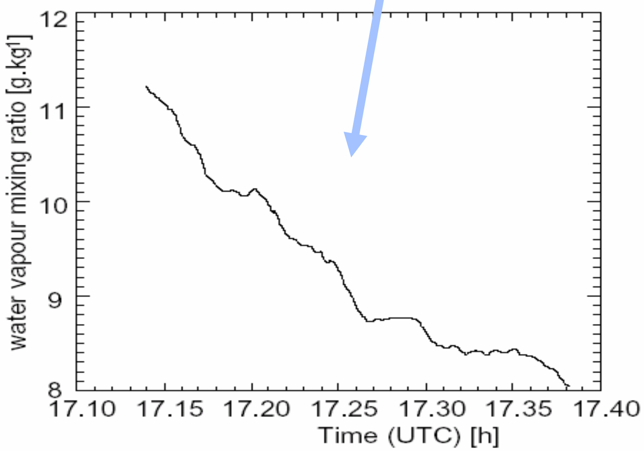
see also
Weckwerth
et al. (2004)

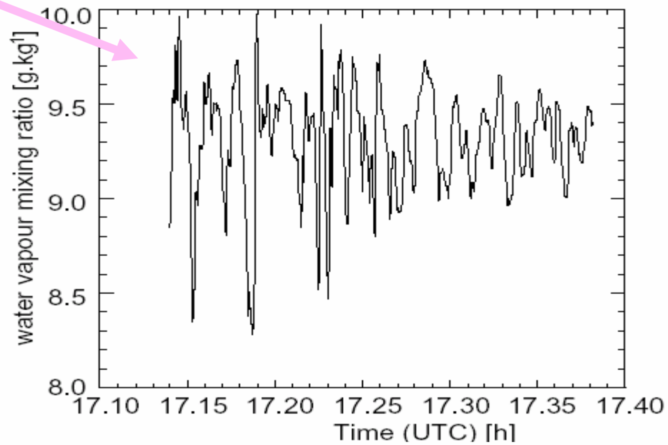


in situ flight data, ~ 350 m AGL (in the boundary layer after 1300 UTC)

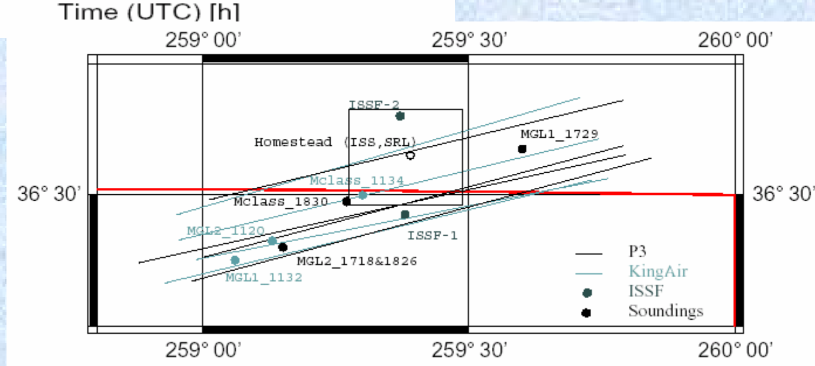


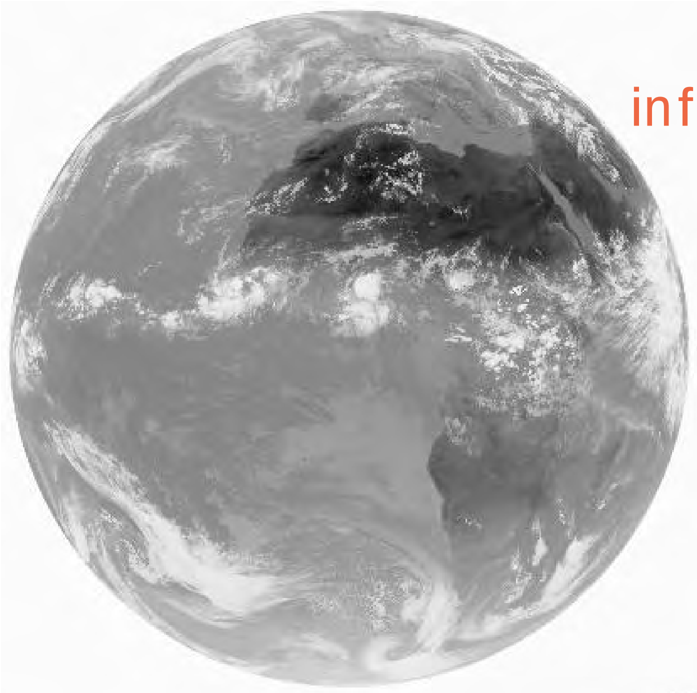
$$r_v = \overline{r_v} + r_v'$$





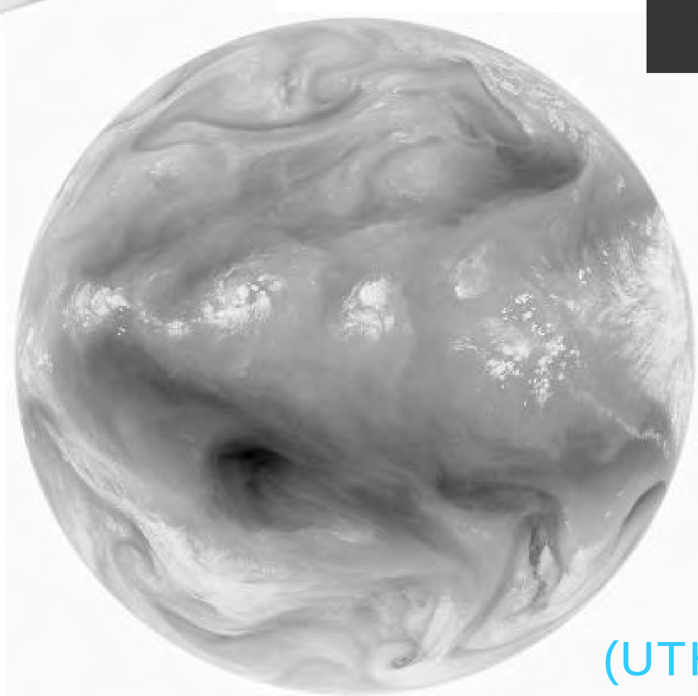
Couvreux et al. (2004)





infrared

visible



water vapour
(UTH: upper tropospheric humidity)

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