Convection parameterisations

Part I

WaVaCS summerschool
Autumn 2009
Cargese, Corsica

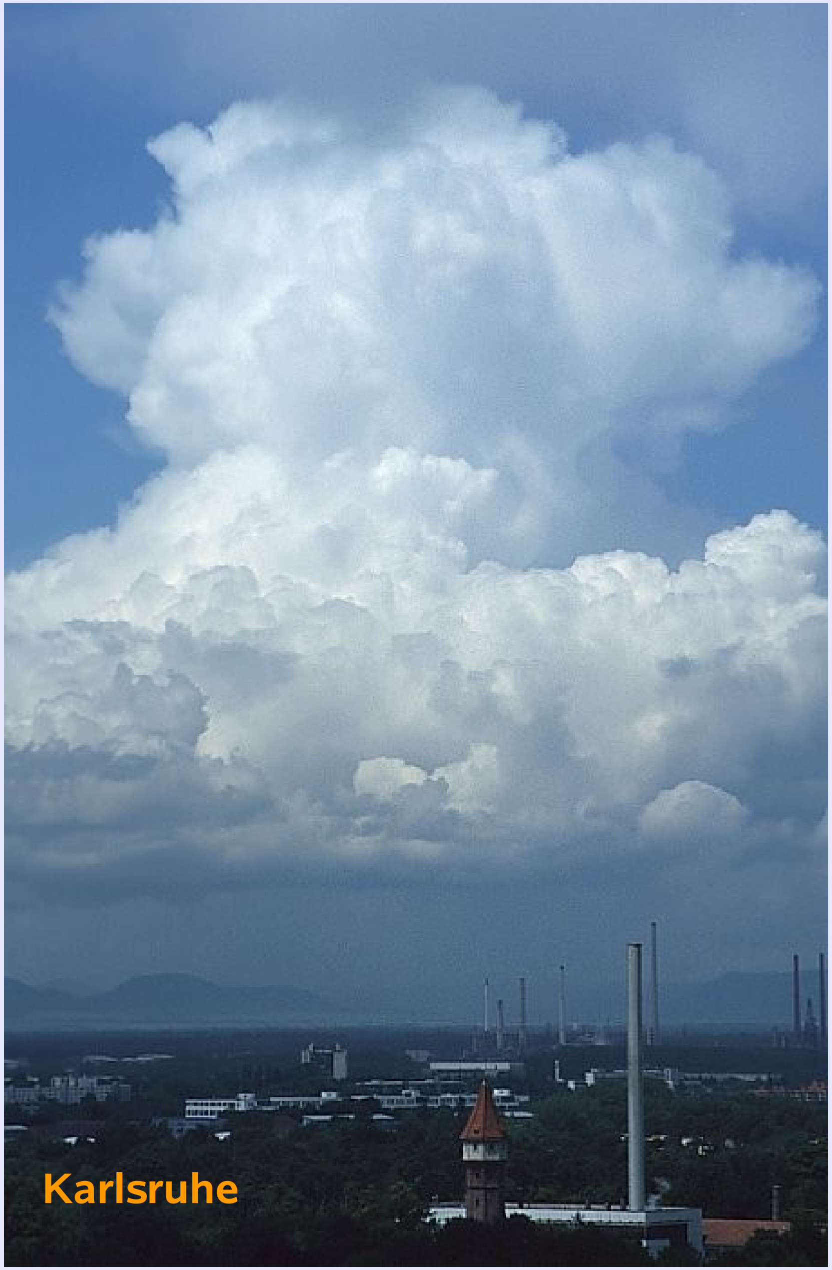
Holger Tost

Max Planck Institute for Chemistry, Mainz, Germany

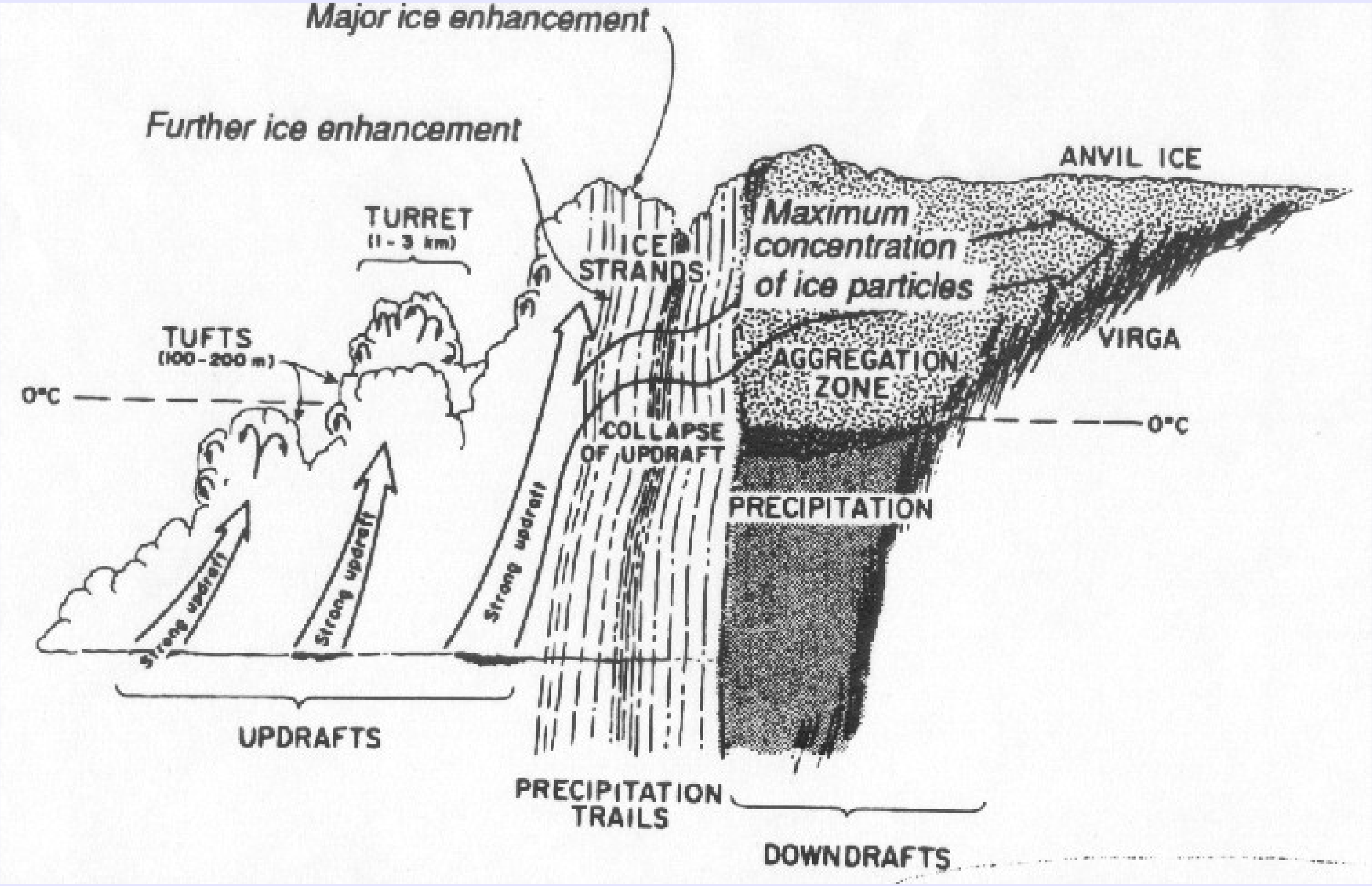
Overview

- What is a parameterisation and why using it?
- Fundamentals of convection parameterisations
- A little parameterisation application
- Examples of convection schemes for larger scale models
- Differences of convection schemes and implications for large scale modelling

(From the Karlsruher Wolkenatlas)

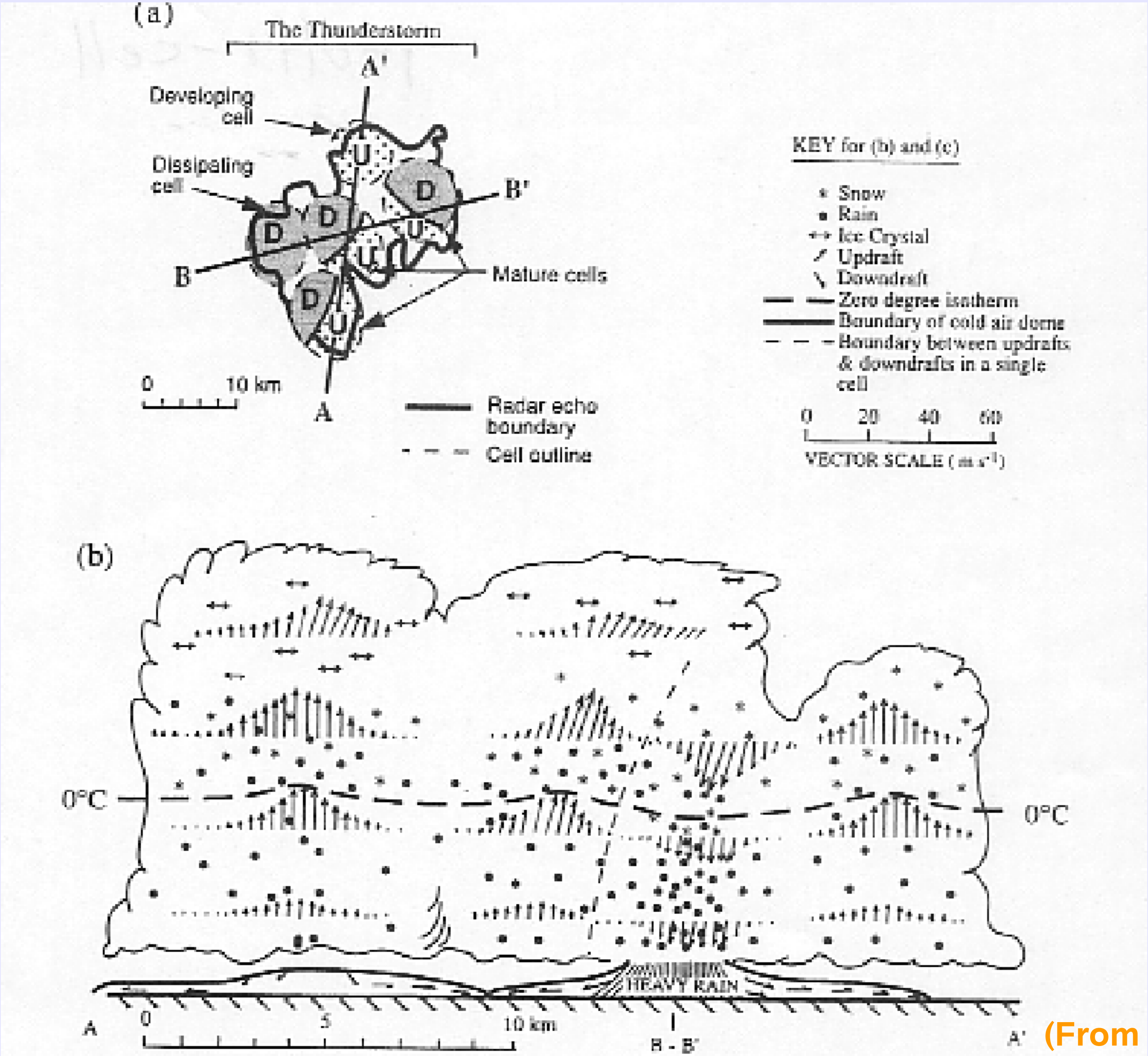


Schematic for single cell convection



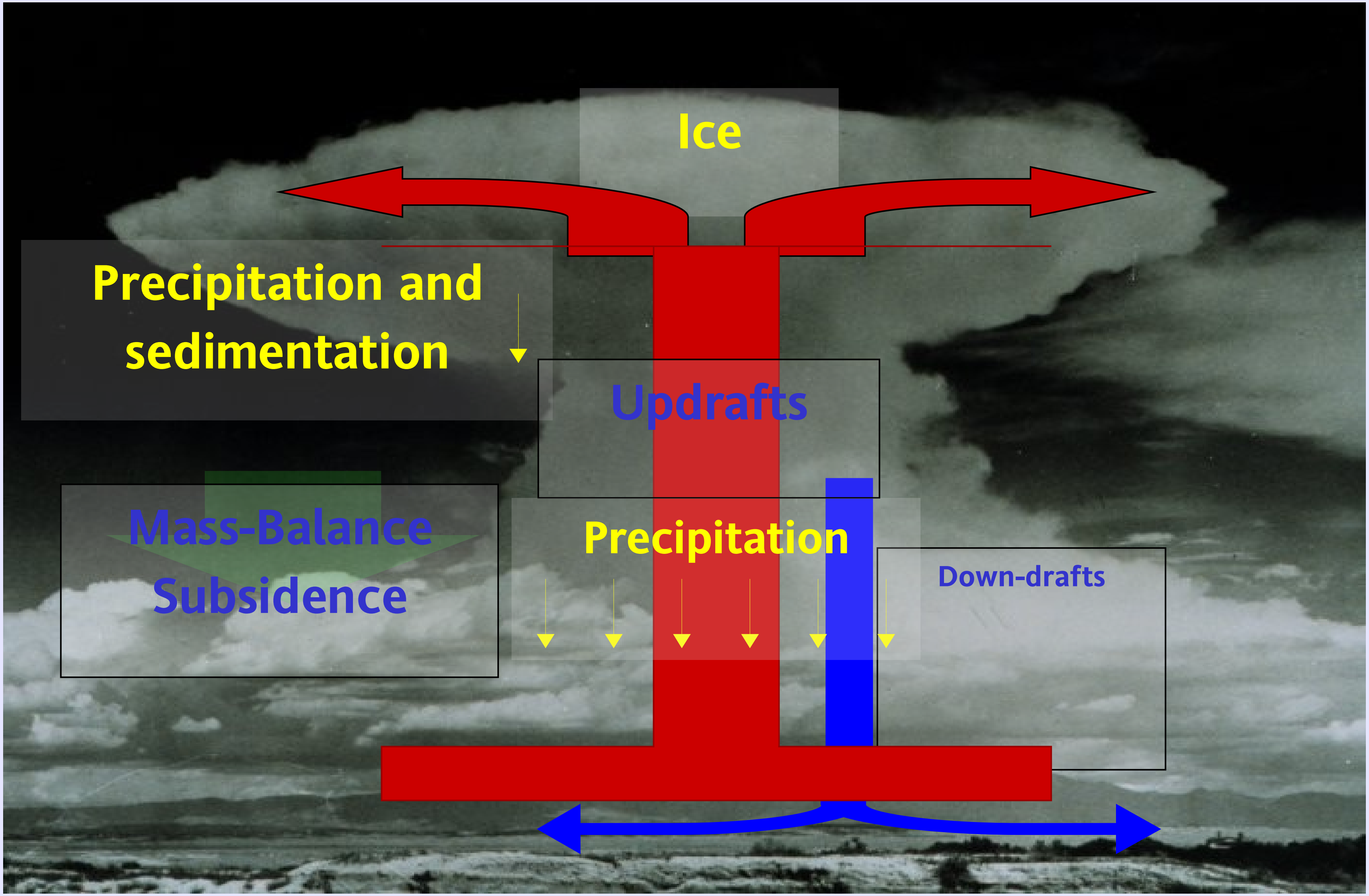
(From Houze, 1993)

Schematic for multi cell convection



(From Houze, 1993)

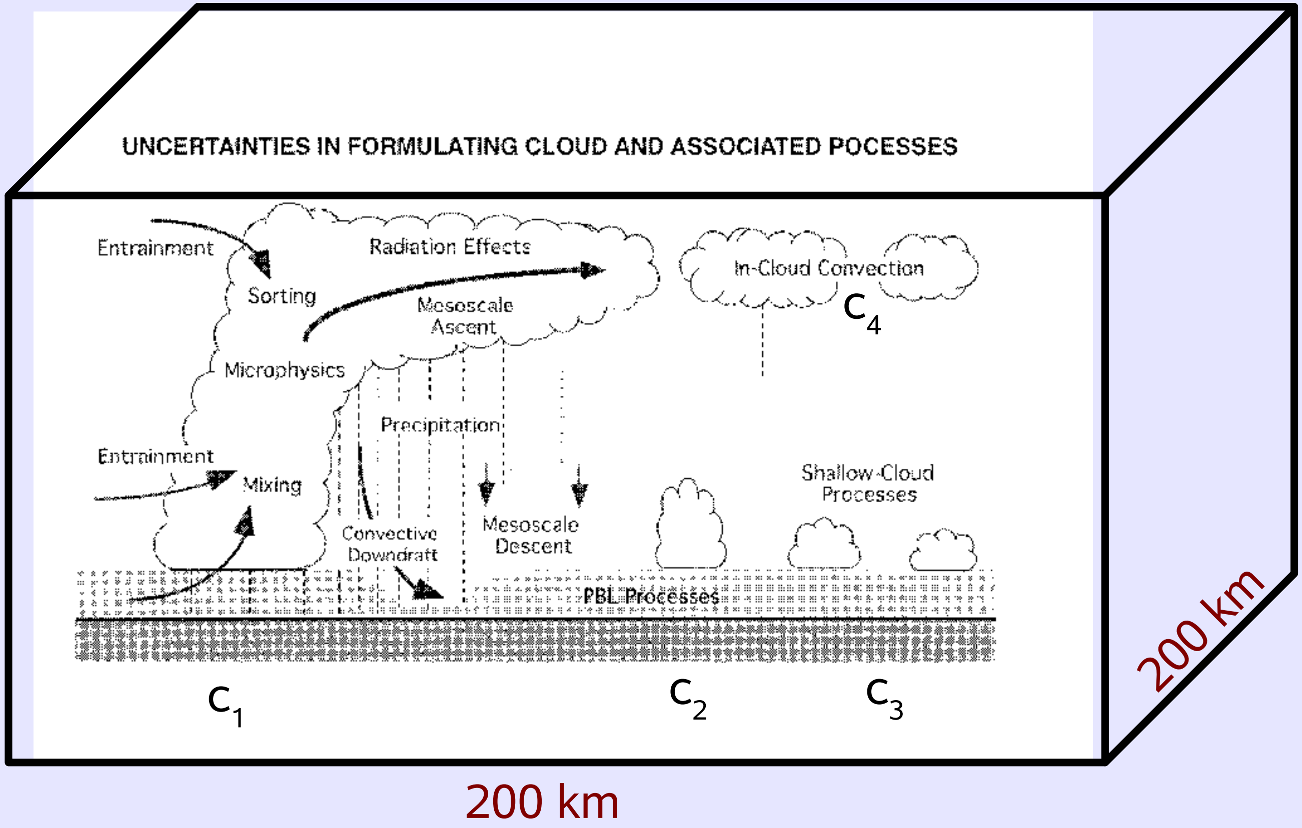
Processes in a convective cell



Characteristics of convective clouds

- Relatively small horizontal extensions (10 km), but can organise into larger convective systems
- Large vertical extent (whole troposphere)
- Complicated dynamical and transport processes
- Cloud microphysical components
- Both local and large – scale impacts
- Each cloud is different !

Convection – a modellers nightmare



- several individual different clouds in one model grid box (column)
- all clouds influence the column properties

total effect of all clouds = effect of c_1 + effect of c_2 + effect of c_3 + effect of c_4

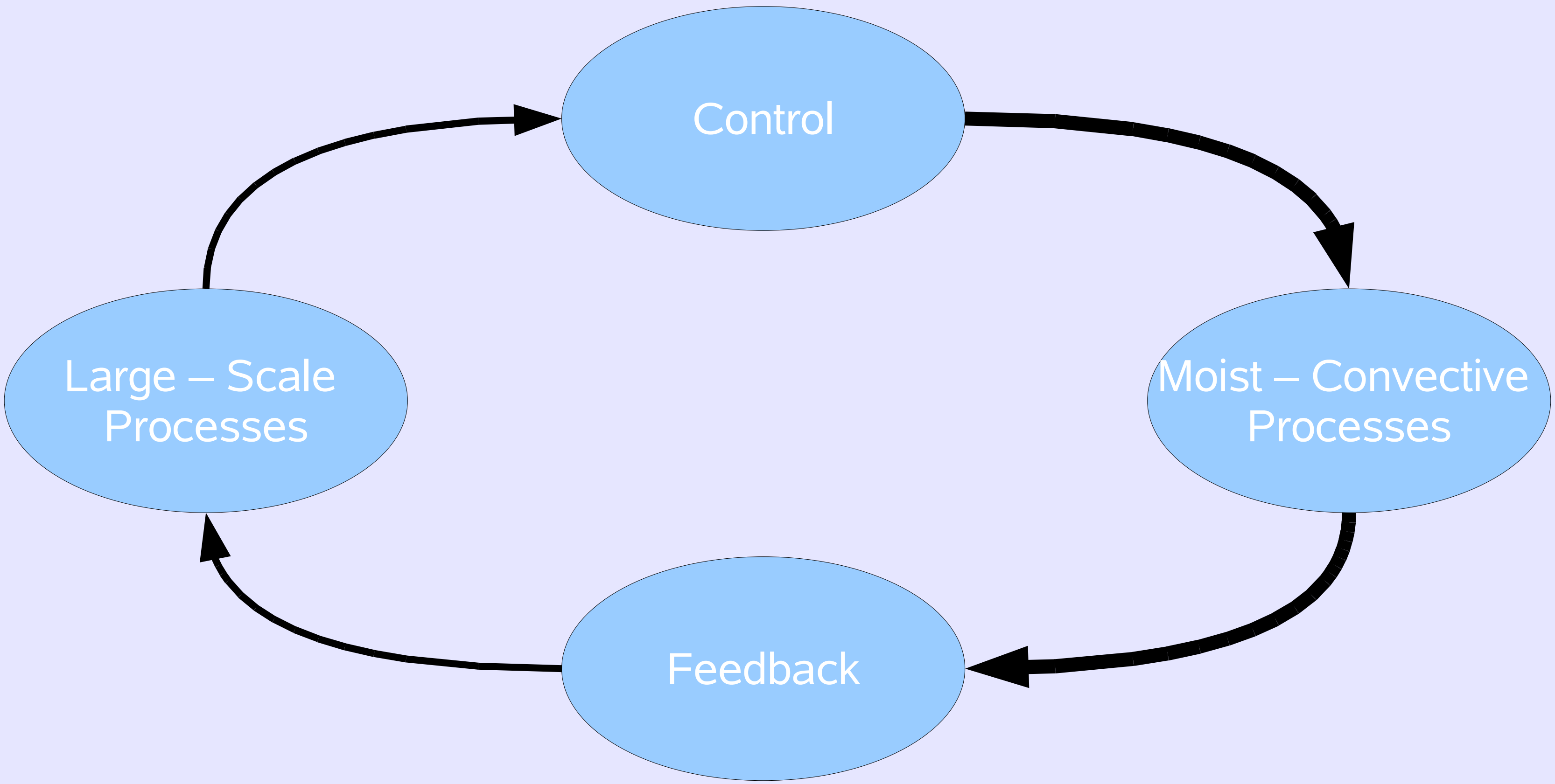
Convection – parameterising the effects

- individual clouds within a grid column cannot be resolved
- all clouds affect the grid column properties

=> *A convection parameterisation should capture the **effects** of all subgrid – scale clouds within a grid column.*

- not simulating individual subgrid – scale clouds, but using a more statistical approach

Convection – feedback loop



What to use for parameterisations?

- Linking subgrid scale events (disturbances of the grid mean value) to the **grid mean value** with the help of physical and mathematical concepts
- **Closure assumptions** to find a sufficient small number of equations, that govern the statistics of the system
  - Closure assumptions must not lose the predictability of large – scale fields.
  - Closure assumptions must be valid quasi – universally.

(Arakawa, 1993)

Thermodynamics of convection (I)

- 2 main equations:
  - one for large – scale potential temperature

$$c_p \left[\frac{\partial \bar{\theta}}{\partial t} + \bar{\vec{v}} \cdot \nabla \bar{\theta} + \bar{\omega} \frac{\partial \bar{\theta}}{\partial p} \right] = \left[\frac{p_0}{p} \right]^{R/cp} Q_1$$

Q_1 = apparent heat source

  - one for the water vapour budget

$$L \left[\frac{\partial \bar{q}}{\partial t} + \bar{\vec{v}} \cdot \nabla \bar{q} + \bar{\omega} \frac{\partial \bar{q}}{\partial p} \right] = -Q_2$$

Q_2 = apparent moisture sink

Thermodynamics of convection (II)

- Q_1 and Q_2 contain grid scale and subgrid scale processes
- with some simplifications:

$$Q_{1C} \equiv Q_1 - Q_R = L\bar{C} - \frac{\partial \overline{\omega' s'}}{\partial p}$$

$$-Q_2 = -L\bar{C} - \frac{\partial \overline{\omega' Lq'}}{\partial p}$$

$$Q_{1C} - Q_2 = \frac{-\partial \overline{\omega' h'}}{\partial p}$$

Q_R	=	radiation heating
Q_{1C}	=	part of Q_1 due to condensation and transport processes
C	=	rate of net condensation
s	=	dry static energy
	=	$c_p T + gz$
h	=	moist static energy
	=	s + L q

Thermodynamics of convection (III)

- simplifying the effects of the large scale (known):

$$\frac{\partial T}{\partial t} = \left(\frac{\partial T}{\partial t}\right)_{LS} + \frac{1}{c_p} Q_1 \qquad \text{with: } \left(\frac{\partial T}{\partial t}\right)_{LS} = -\left(\frac{p}{p_0}\right)^{R/c_p} \left(\vec{\bar{v}} \cdot \nabla \bar{\theta} + \bar{\omega} \frac{\partial \bar{\theta}}{\partial p}\right)$$

$$\frac{\partial q}{\partial t} = \left(\frac{\partial q}{\partial t}\right)_{LS} - \frac{1}{L} Q_2 \qquad \text{with: } \left(\frac{\partial q}{\partial t}\right)_{LS} = -\left(\vec{\bar{v}} \cdot \nabla \bar{q} + \bar{\omega} \frac{\partial \bar{q}}{\partial p}\right)$$

- 2 equations, 4 unknown quantities: $\frac{\partial T}{\partial t}, Q_1, \frac{\partial q}{\partial t}, Q_2,$

=> ***Closure assumptions*** required!

Closure assumptions (I)

- mainly 3 commonly used types:
  (classification after Arakawa (1993))
  - type I: coupling net warming and net moistening, constraints on the large – scale states

$$\frac{\partial T}{\partial t}, \frac{\partial q}{\partial t}$$

  - type II: coupling of Q_1 and Q_2, constraints on the moist – convective processes

$$Q_{1,} Q_2$$

  - type IV: coupling of Q_1 and Q_2 with the large scale terms, i.e. a direct coupling between large – scale and moist – convective processes

$$Q_{1,} Q_{2,} \left(\frac{\partial T}{\partial t}\right)_{LS}, \left(\frac{\partial q}{\partial t}\right)_{LS}$$

Example1: Large – scale condensation (I)

- example of type I closure:
  - if $\left(\frac{\partial q}{\partial t}\right)_{LS} > \left(\frac{\partial q_{sat}}{\partial t}\right)_{LS} = \left[\gamma \frac{c_p}{L}\left(\frac{\partial T}{\partial t}\right)_{LS}\right]$ is true, then

$with: \gamma \equiv \left(\frac{L}{c_p}\right)\left(\frac{\partial q_{sat}}{\partial T}\right)_p$

$$q - q_{sat} = 0 \; \forall \; t$$

  - differentiating in time yields a relation of $\frac{\partial q}{\partial t}$ and $\frac{\partial q_{sat}}{\partial t}$

Example1: Large – scale condensation (II)

- no convective transport, no radiative heating

=> all changes in temperature due to changes in condensation

- example of type II closure: $Q_1 - Q_2 = 0$
- using the previous equations and the type I closure:

$$\gamma Q_1 + Q_2 = \left(\frac{\partial q}{\partial t}\right)_{LS} - \gamma c_p \left(\frac{\partial T}{\partial t}\right)_{LS}$$

$$Q_1 = Q_2 = \frac{1}{1+\gamma}\left[\left(\frac{\partial q}{\partial t}\right)_{LS} - \gamma c_p \left(\frac{\partial T}{\partial t}\right)_{LS}\right]$$

Example1: Large – scale condensation (III)

- resulting equations:

$$\frac{\partial T}{\partial t} = \frac{1}{1+\gamma}\frac{1}{c_p}\left(\frac{\partial h}{\partial t}\right)_{LS}$$

$$\frac{\partial q}{\partial t} = \frac{\gamma}{1+\gamma}\frac{1}{L}\left(\frac{\partial h}{\partial t}\right)_{LS}$$

$$with: \left(\frac{\partial h}{\partial t}\right)_{LS} \equiv c_p\left(\frac{\partial T}{\partial t}\right)_{LS} + L\left(\frac{\partial q}{\partial t}\right)_{LS}$$

Example2: Moist convective adjustment (I)

- “simplest” convection scheme (still used in GCMs) (Manabe et al., 1965)
- applied in conditionally unstable regions ($\Gamma > \Gamma_m$) and super – saturated regions
  - controversial, since subgrid scale clouds require 100% RH for grid box mean
- adjusts moisture to saturation and Γ to the moist adiabatic lapse rate (Γ_m)
- constraint: energy conservation in the whole convective reagion:
  - type II closure

$$\int_{p_T}^{p_B} (Q_1 - Q_2)\, dp = 0$$

Example2: Moist convective adjustment (II)

- if the 2 following statements hold:
  - a) (as previously): $\left(\frac{\partial q}{\partial t}\right)_{LS} > \left(\frac{\partial q_{sat}}{\partial t}\right)_{LS} = \left[\gamma \frac{c_p}{L}\left(\frac{\partial T}{\partial t}\right)_{LS}\right]$
  - b)

$$\frac{\partial}{\partial p}\left(\frac{\partial h_{sat}}{\partial t}\right)_{LS} = \frac{\partial}{\partial p}\left[\frac{1}{1+\gamma} c_p \left(\frac{\partial T}{\partial t}\right)_{LS}\right] > 0$$

- then $q - q_{sat} = 0$ and $\frac{\partial h_{sat}}{\partial p} = 0$

used: $\frac{\partial h_{sat}}{\partial p} \gtreqless 0 \; as \; \Gamma \gtreqless \Gamma_m$

- time derivatives of these 2 equations yield a closure of type I

Example2: Moist convective adjustment (III)

- energy conservation implying mass conservation can be rewritten:

$$\int_{p_T}^{p_B} (Q_1 - Q_2)\, dp = 0 \longrightarrow [\![Q_1]\!] - [\![Q_2]\!] = 0$$

$[\![\ ]\!]$ denote the vertical mean with respect to mass

- using similar steps as in Example1 results in:

$$\frac{\partial T}{\partial t} = \frac{1}{1+\gamma} \frac{1}{c_p} \left[\!\!\left[\left(\frac{\partial h}{\partial t} \right)_{LS} \right]\!\!\right]$$

$$\frac{\partial q}{\partial t} = \frac{\gamma}{1+\gamma} \frac{1}{L} \left[\!\!\left[\left(\frac{\partial h}{\partial t} \right)_{LS} \right]\!\!\right]$$

$$with: \left(\frac{\partial h}{\partial t} \right)_{LS} \equiv c_p \left(\frac{\partial T}{\partial t} \right)_{LS} + L \left(\frac{\partial q}{\partial t} \right)_{LS}$$

Example2: Moist convective adjustment (IV)

- Equations as for Example1, but including the vertical mean over the convective layer
- 2 conditions (used in the closure assumptions) must be fulfilled for convection to occur:

$$\frac{\partial}{\partial p}\left[(1+\gamma)c_p\left(\frac{\partial T}{\partial t}\right)_{LS}\right]>0$$

$$\left(\frac{\partial q}{\partial t}\right)_{LS}=-\gamma\frac{c_p}{L}\left(\frac{\partial T}{\partial t}\right)_{LS}>0$$

=> Concept of ***large – scale forcing***

Example2: Moist convective adjustment (V)

- can create unrealisitcally high rain rates due to the saturation requirement
- some modifications like a weaker adjustment (at e.g. 80% RH)
- convection occurs only in a fraction of the grid cell
- prototype of a large family of convection schemes, including Arakawa – Schubert, Hack, Betts – Miller, ……

Example3: Kuo's scheme (I)

- used in NWP models (after Kuo, 1974) with some modfications
- modified adjustment scheme

$$Q_1 = (1-b)\frac{T_c - T}{[\![T_c - T]\!]} L \left[\!\!\left[\left(\frac{\partial q}{\partial t}\right)_{LS}\right]\!\!\right]$$

$$L\left(\frac{\partial q}{\partial t}\right)_{LS} - Q_2 = b\frac{q_c - q}{[\![q_c - q]\!]} L \left[\!\!\left[\left(\frac{\partial q}{\partial t}\right)_{LS}\right]\!\!\right]$$

T_c	=	temperature of a model cloud
q_c	=	humidity of a model cloud
b	=	moistening parameter
$[\![\,]\!]$	=	vertical mean over the convective layer

Example3: Kuo's scheme (II)

- derived from the closure assumptions:

$$\frac{Q_1}{c_p} = \alpha_T (T_c - T)$$

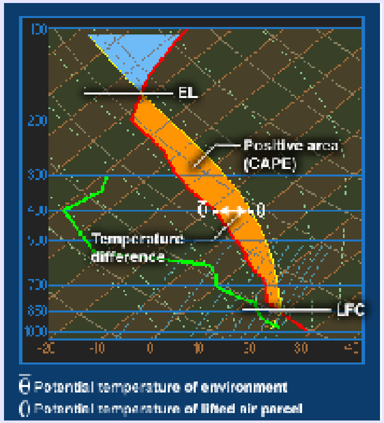
$$\left(\frac{\partial q}{\partial t}\right)_{LS} - \frac{Q_2}{L} = \alpha_q (q_c - q) \quad \text{or} \quad -\frac{Q_2}{L} = \alpha_q (q_c - q)$$

- type IV closure
- α_T and α_q can be determined from $[\![Q_1]\!] - [\![Q_2]\!] = 0$ and are independent of height

Trends in Convection scheme developments

Quasi - Equilibrium

- *Moist – convective quasi equilibrium as the basis for parameterisability* (Arakawa, 2004)
  - Agreements:
    - Under which conditions are what quantities suitable for quasi – equilibrium for the prediction of weather and climate ?
    - usage of cloud work functions
      (rate of convective kinetic energy per unit cloud – base mass flux)
    - usage of CAPE (convective available potential energy)



$$CAPE = \int_{z_1}^{LNB} g \frac{\theta - \theta_a}{\theta} dz$$

with: z_1 = LFC
(level of free convection)
or
z_1 = surface
LNB = level of neutral buoyancy

Quasi - Equilibrium

- Quasi – equilibrium concept implies:
  - condensation strongly coupled with the dynamical processes => condensational heat is not an external heat source to the dynamics
  - condensational heat not necessarily produces CAPE, since heating and temperature are not correlated by default
  - cumulus heating = cumulus adjustment
    = passive response to other processes

Closures

- Diagnostic closure schemes
  - based on large – scale moisture or mass convergence or vertical advection of moisture at the same time(step)
  - based on quasi – equilibrium
    - relate cumulus effects with large – scale processes at the same instant
    - explicit definition of moist – convective equilibrium states and a sequence of equilibria with the large – scale
      - large – scale -> deviations from equilibrium
      - cumulus convection -> restoration of equilibrium

Closures

- (Virtually) Instantaneous Adjustment Schemes
  - explicit adjustment towards equilibrium state with implicit forcing
    - adjustment occurs in the same timestep
- Relaxed and/or triggered Adjustment Schemes
  - as above, but:
    - adjustment occurs only partially (relaxed) or only if certain conditions are fulfilled (triggered)
    - with short relaxation times similar to instantaneous adjustment schemes
      - more generated disequilibrium -> more convection
    - with long relaxation times
      - more existing disequilibrium -> more convection

Closures

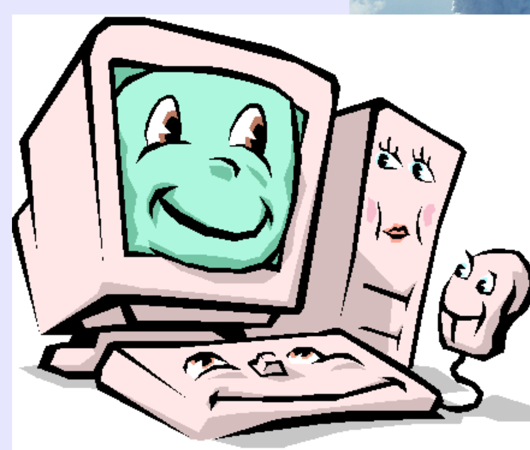
- Prognostic closure schemes
  - adjustment by time integration of explicitly formulated transient processes
- Stochastic closure schemes
  - introducing stochastic elements in other closure types => increasing variance of precipitation

$$\frac{\partial T}{\partial t} = \frac{1}{1+\gamma}\frac{1}{c_p}\left(\frac{\partial h}{\partial t}\right)_{LS}$$

$$\frac{\partial q}{\quad} = \frac{\gamma}{\quad}\frac{1}{\quad}\left(\frac{\partial h}{\partial t}\right)_{LS}$$

$$with: \quad L\left(\frac{\partial q}{\partial t}\right)_{LS}$$

FROM THEORY TO PRAXIS



Simulating convection

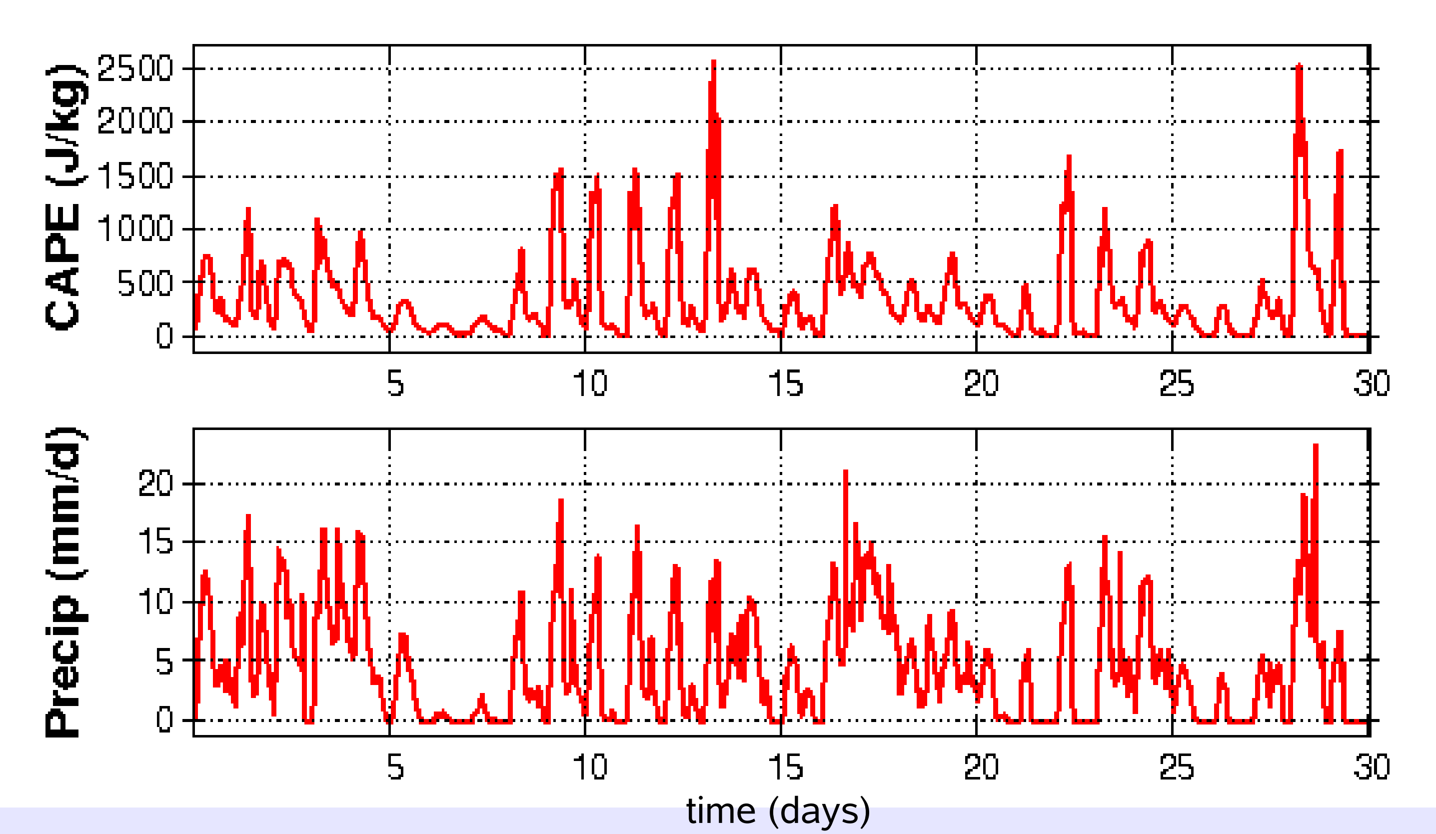
Single column model

- single column model using a convection parameterisation
- Zhang – McFarlane convection scheme (Atmosphere – Ocean,1995)
- driven by external data from a 3D model (more a diagnostic calculation of convection)

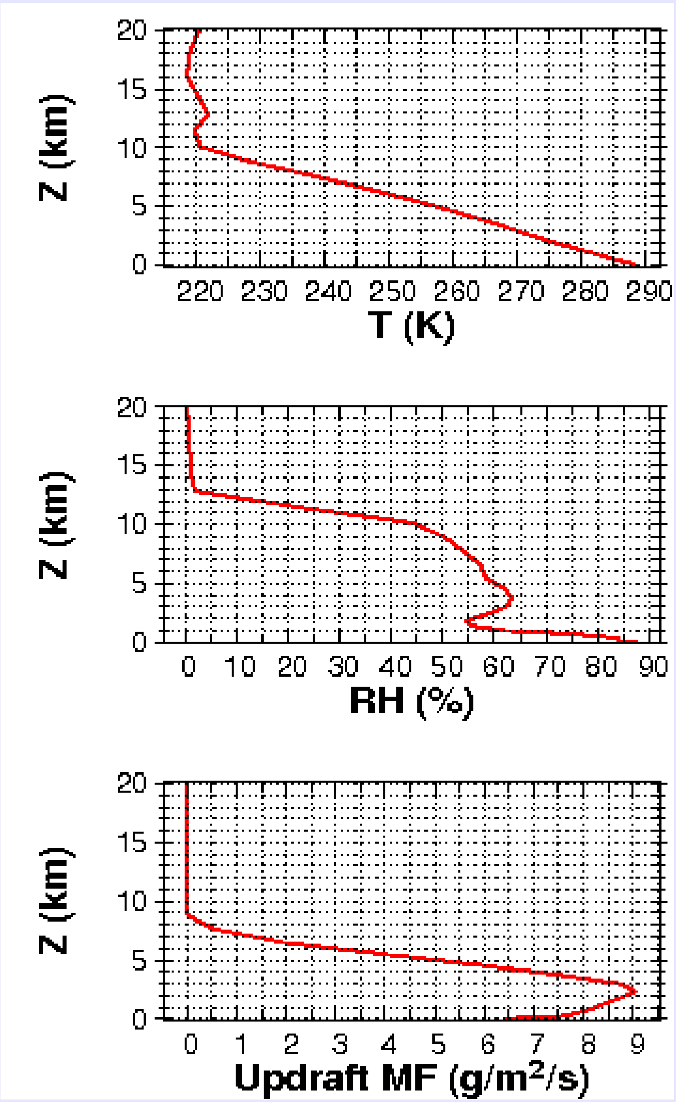
Case1:
Mid – latitude continental convection

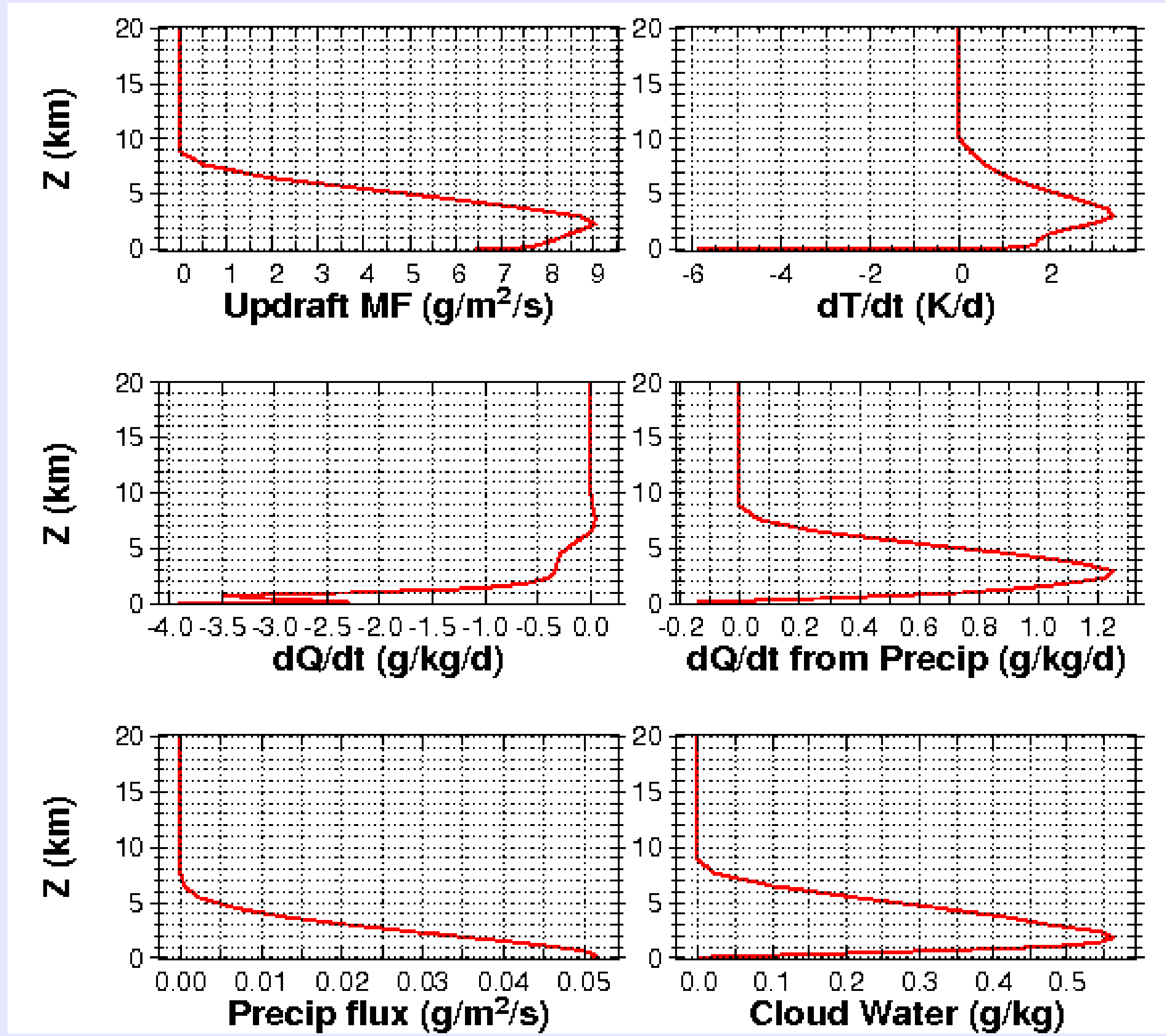
Case1:
Mid – latitude continental convection

- summer conditions over southern Germany
- one month of data



Case1: Mid – latitude continental convection

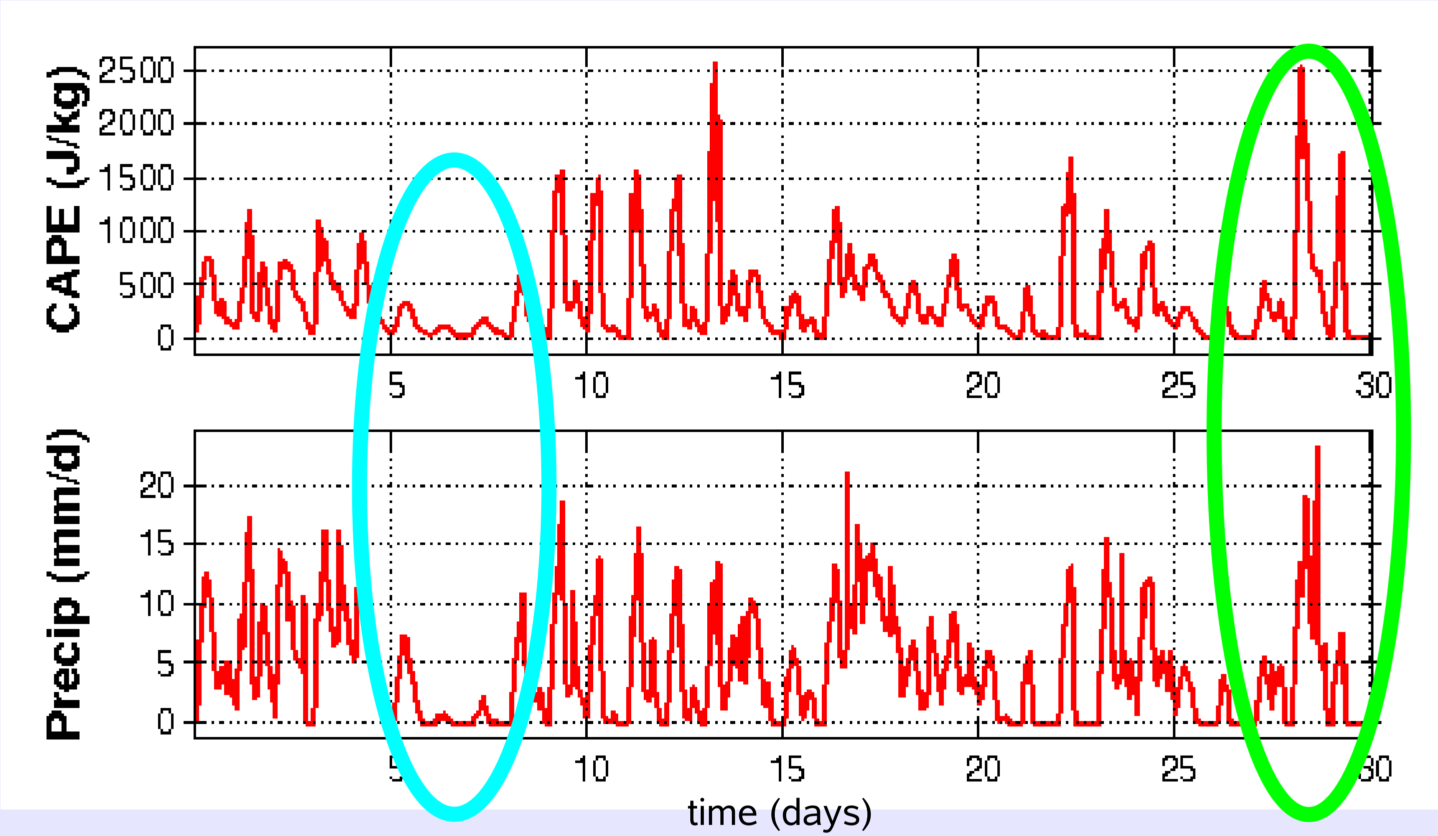




vertical profiles (30 days time averaged)

Case1:
Mid – latitude continental convection

- 2 completely different periods
- What is responsible for this ?

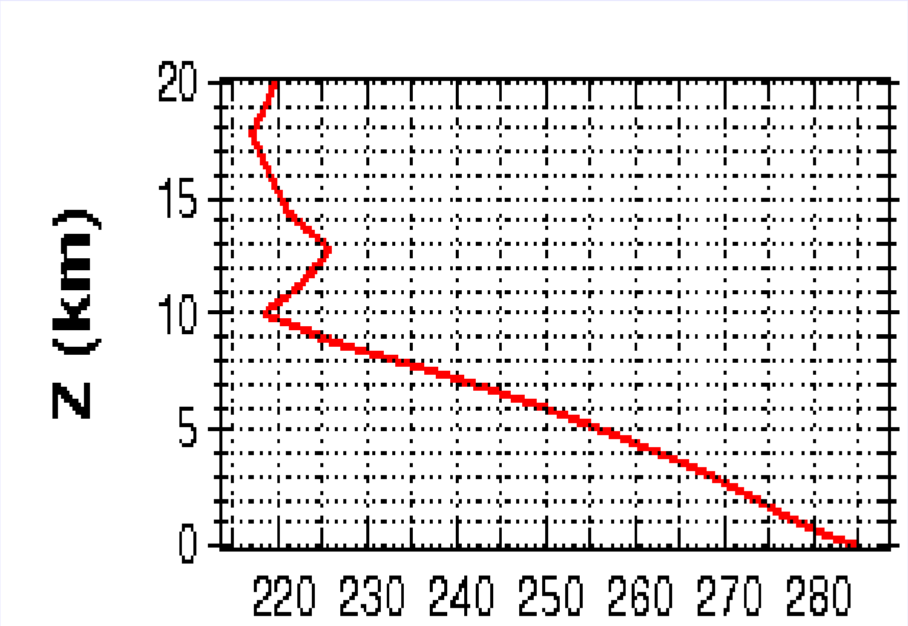


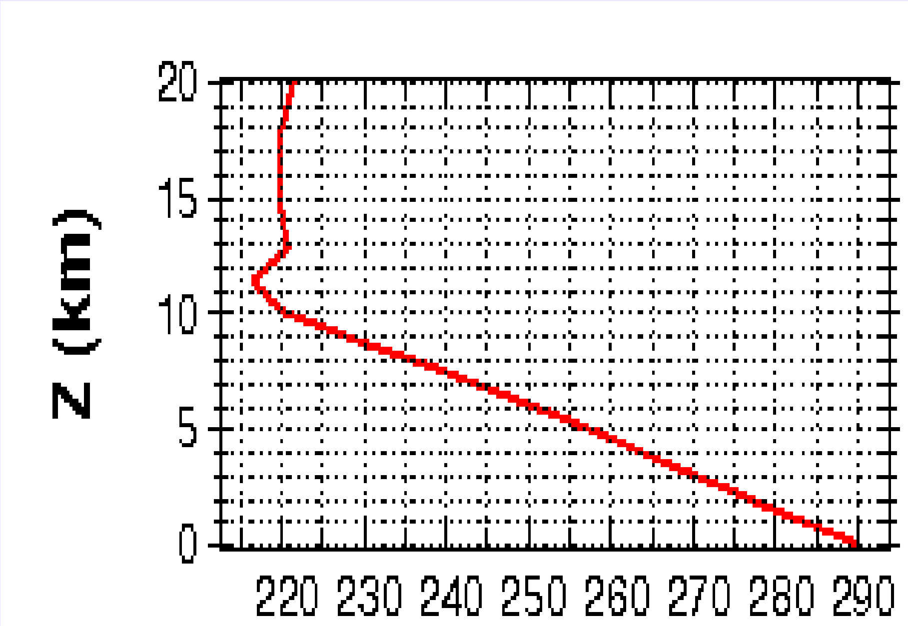
Case1:
2 different periods

- absolute Temperature ?
- Profile and Lapse rate ?

Case1:
2 different periods

- absolute Temperature ?
- Profile and Lapse rate ?



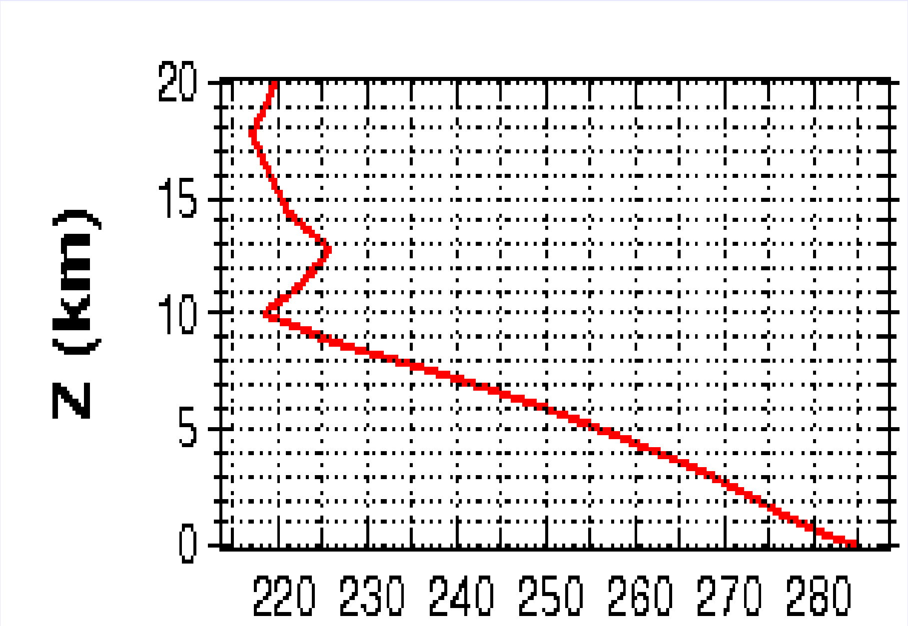


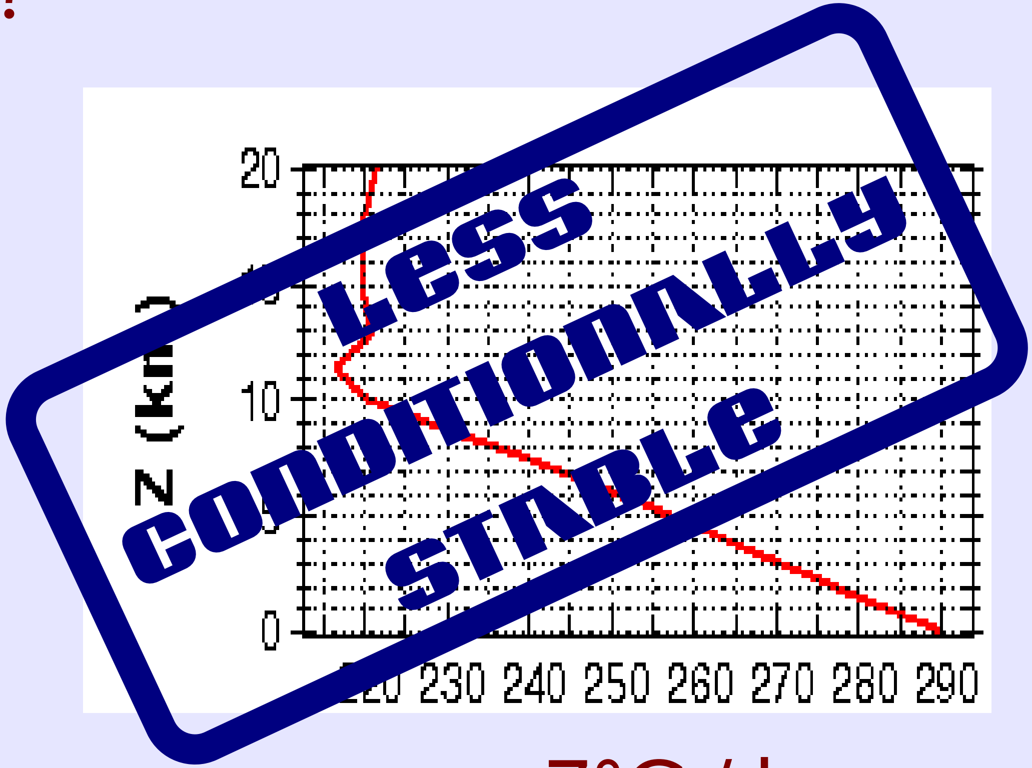
6.5°C / km 7°C / km

(typical moist adiabatic lapse rate 6.5°C/km)

Case1:
2 different periods

- absolute Temperature ?
- Profile and Lapse rate ?





6.5°C / km 7°C / km

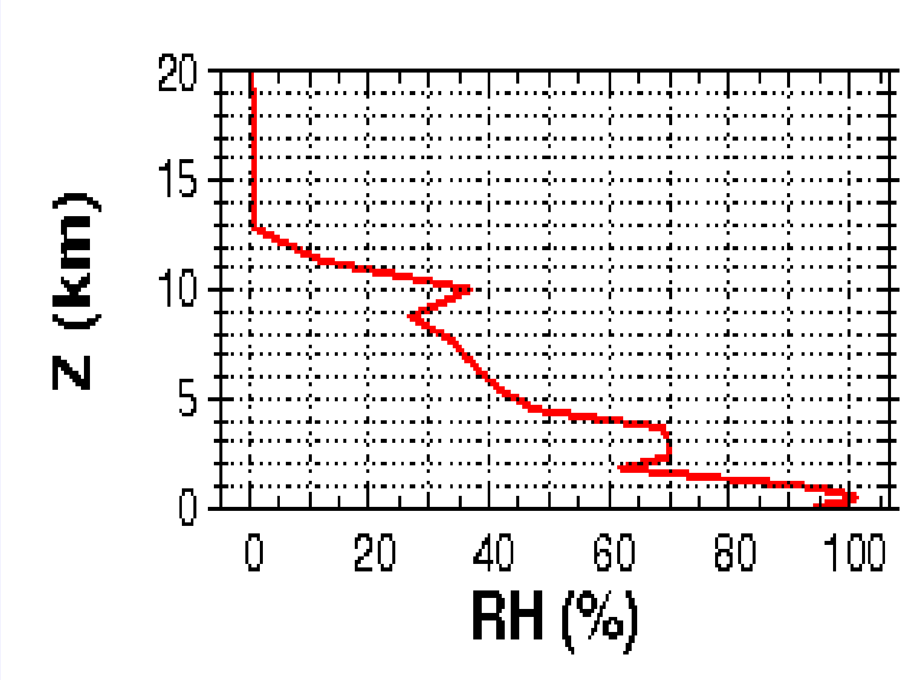
(typical moist adiabatic lapse rate 6.5°C/km)

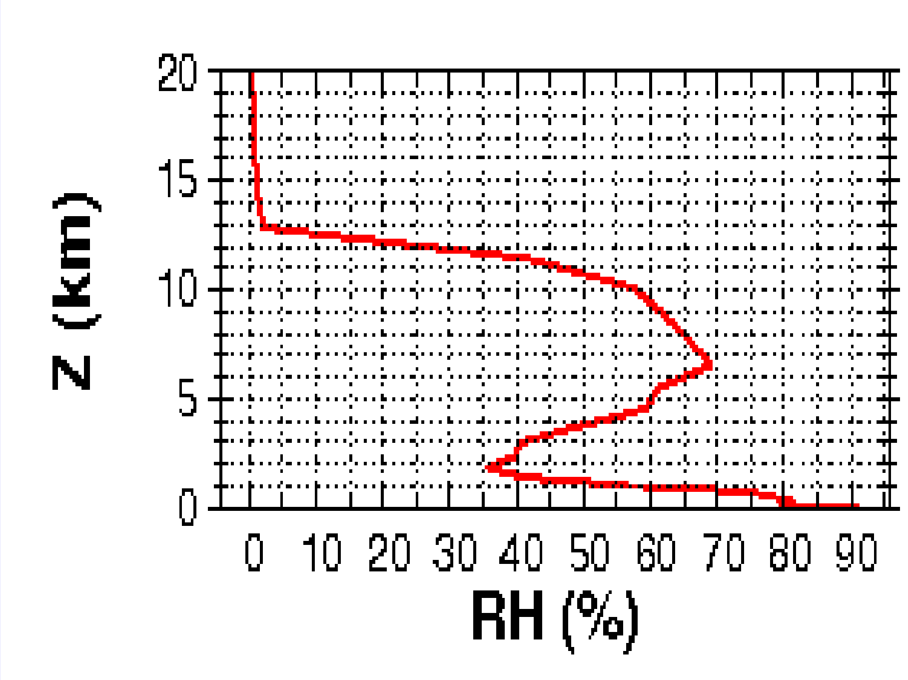
Case1: 2 different periods

- Moisture?

Case1: 2 different periods

- Moisture?

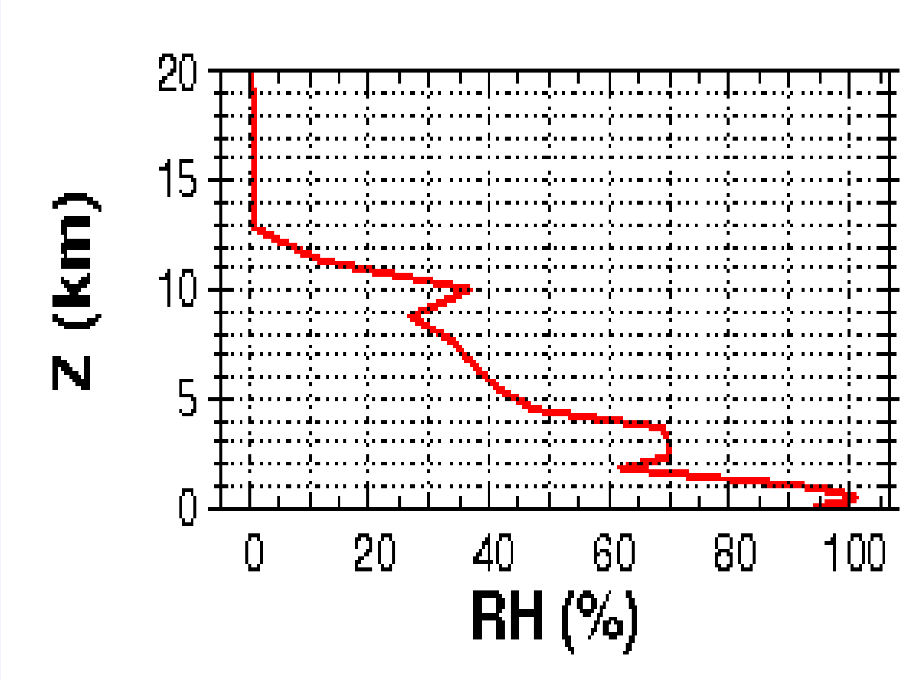


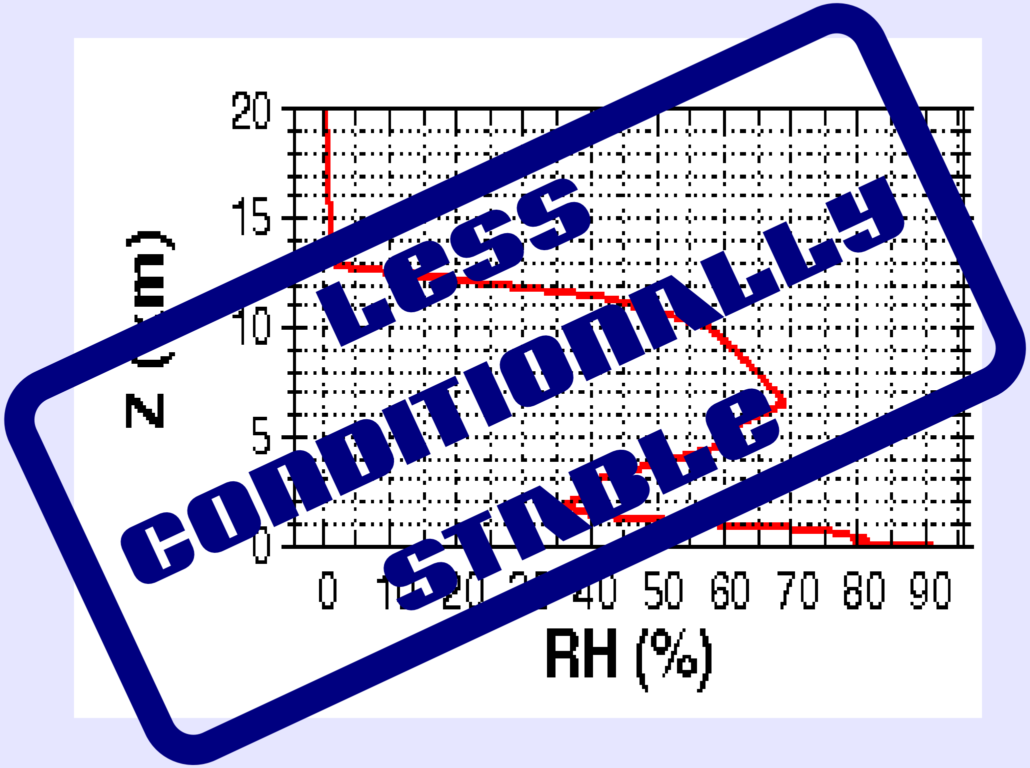


- substantially enhanced mid and upper tropospheric humidity
(with similar or even higher T, RH is higher because of higher specific humidity)

Case1:
2 different periods

- Moisture?



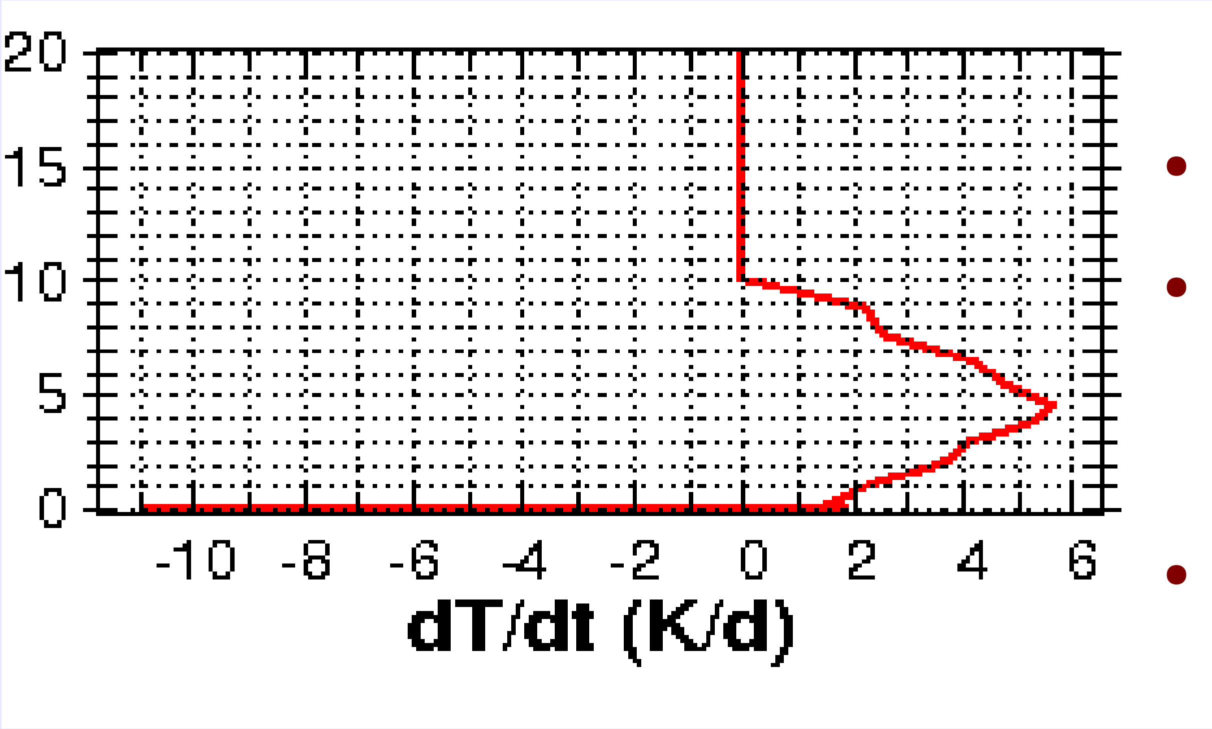


- substantially enhanced mid and upper tropospheric humidity
(with similar or even higher T, RH is higher because of higher specific humidity)

Case1:
2 different periods

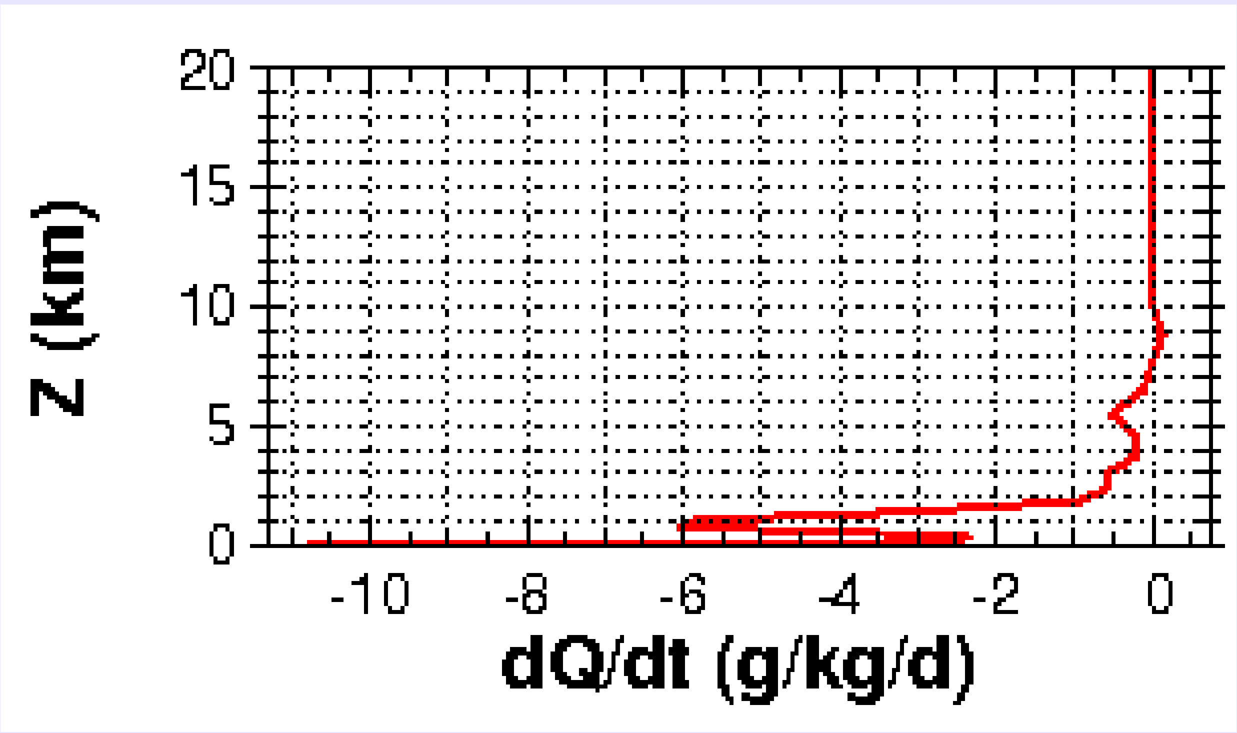
- Both temperature profile (lapse rate) and enhanced moisture in the middle and upper troposphere destabilise the atmosphere and favour convective activity in the 2nd period
- CAPE as a measure for this:
  - 1st period: ca. 62 J/kg
  - 2nd period: ca. 880 J/kg
- Convective precipitation:
  - 1st period: 0.2 mm/day
  - 2nd period: 8.2 mm/day

Case1:
2nd period – convective "adjustment"



- convection peaks at 10 km
- warming of the whole troposphere (maximum warming at 5 km)
- substantial cooling of the surface by precipitation and downdrafts

Case1: 2nd period – convective “adjustment”

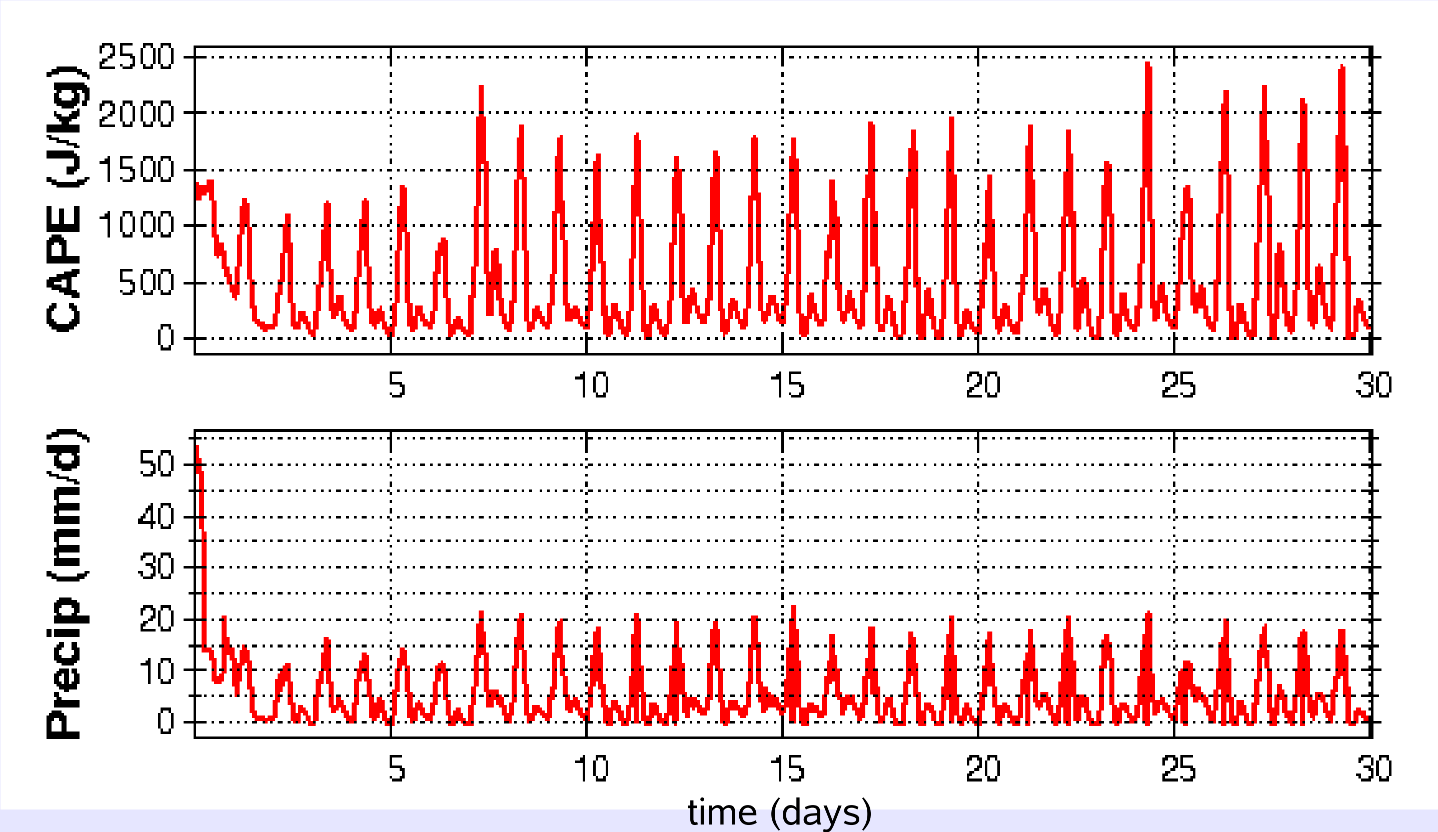


- drying of the lower and middle troposphere by production of cloud water and precipitation and subsidence for dry upper tropospheric air
  - compensated partly by evaporation of falling precipitation into sub – saturated regions
- slight moistening at 9 km (upper troposphere)

Case2:
Tropical continental convection

Case2: Tropical continental convection

- conditions over Central Africa
- daily convective activity of similar strength
- shorter convective events

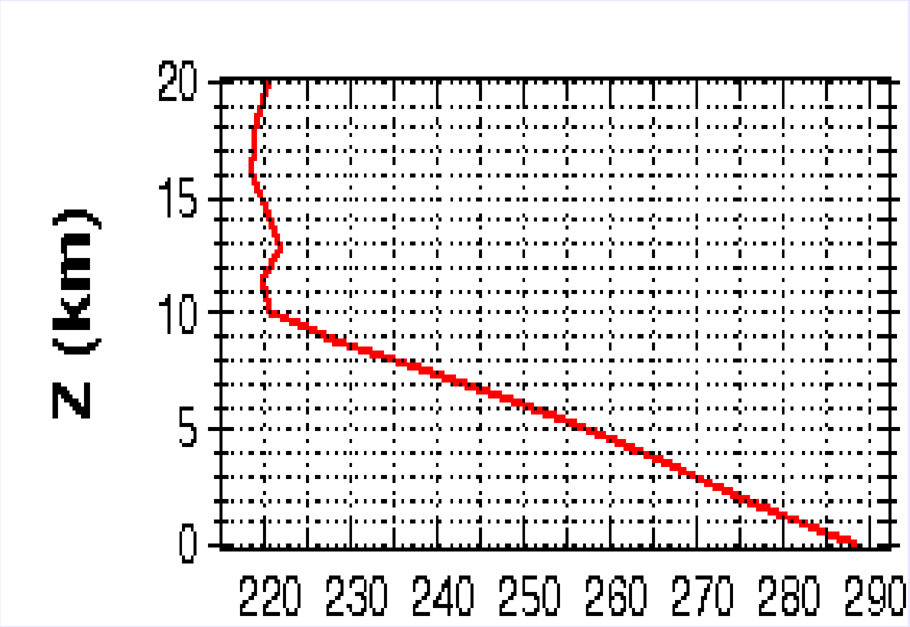


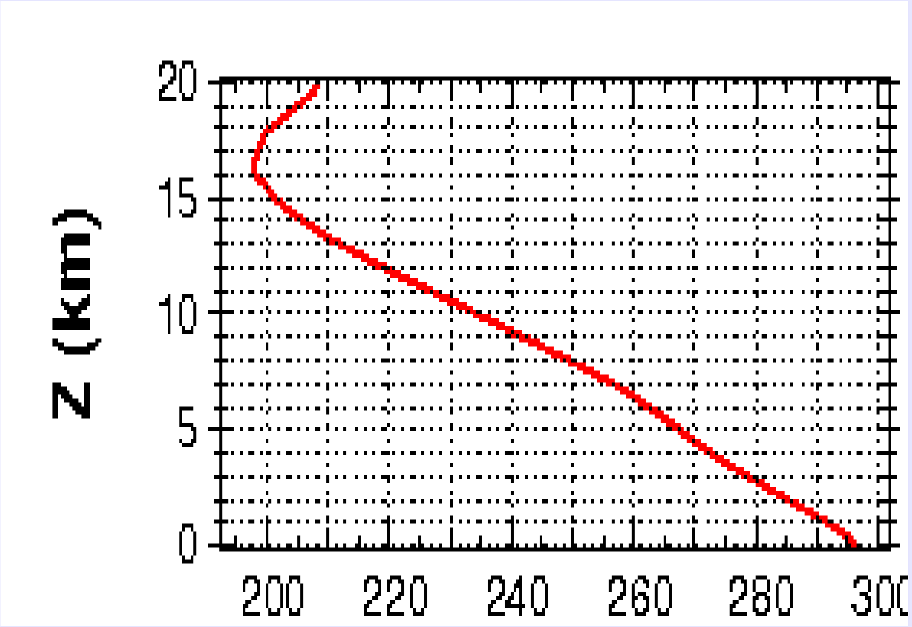
Case2:
Differences between Africa and Germany

- absolute Temperature ?
- Profile and Lapse rate ?

Case2:
2 different regions

- absolute Temperature ?
- Profile and Lapse rate ?





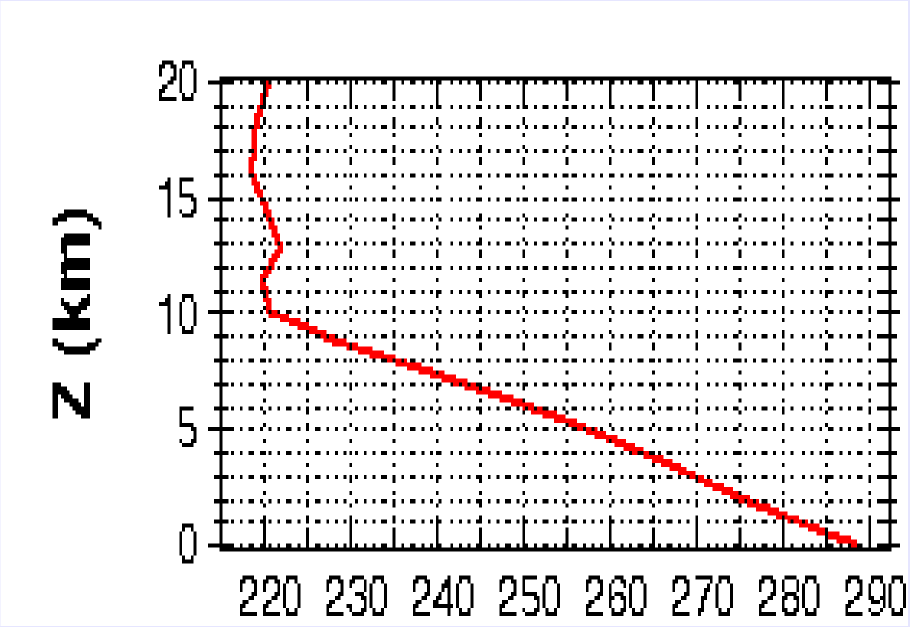
6.5°C - 7°C / km

6°C - 6.5°C / km

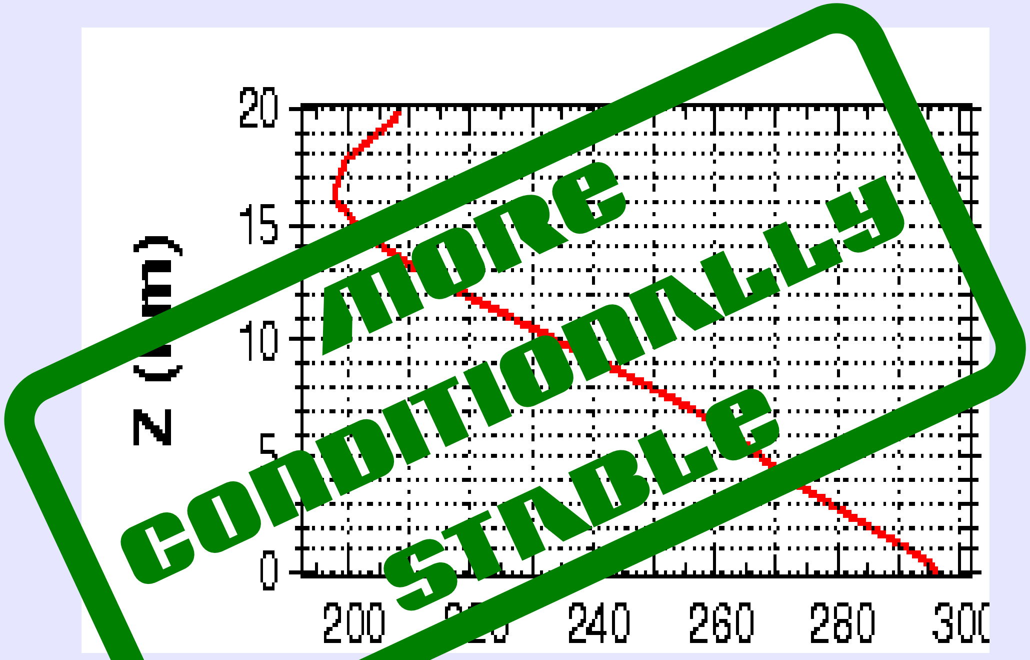
- higher tropopause
- warmer lower and middle troposphere

Case2:
2 different regions

- absolute Temperature ?
- Profile and Lapse rate ?



6.5°C - 7°C / km



6°C - 6.5°C / km

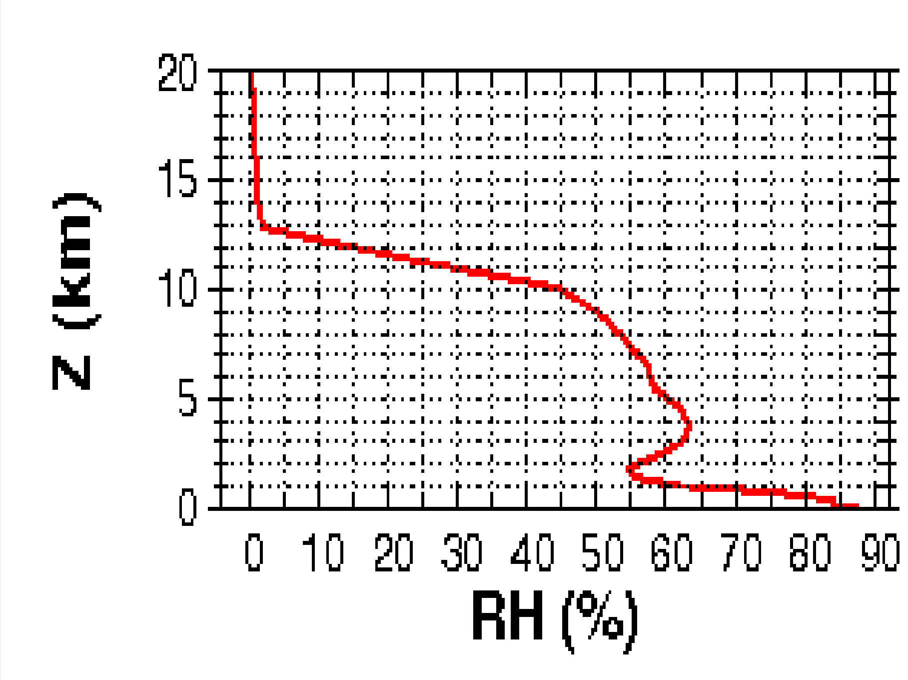
- higher tropopause
- warmer lower and middle troposphere

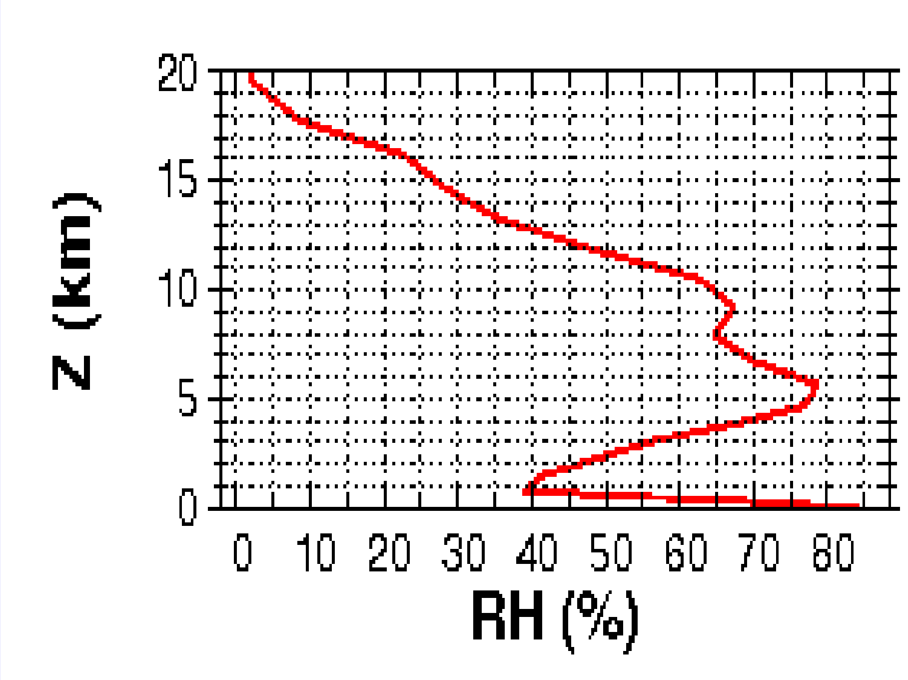
Case2:
2 different regions

- Moisture?

Case2:
2 different regions

- Moisture?

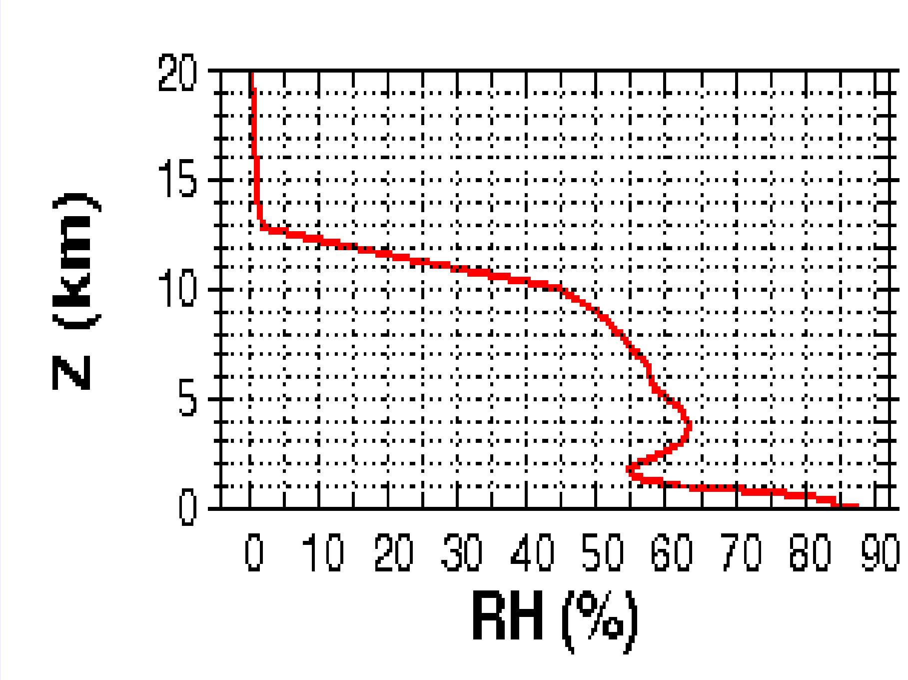


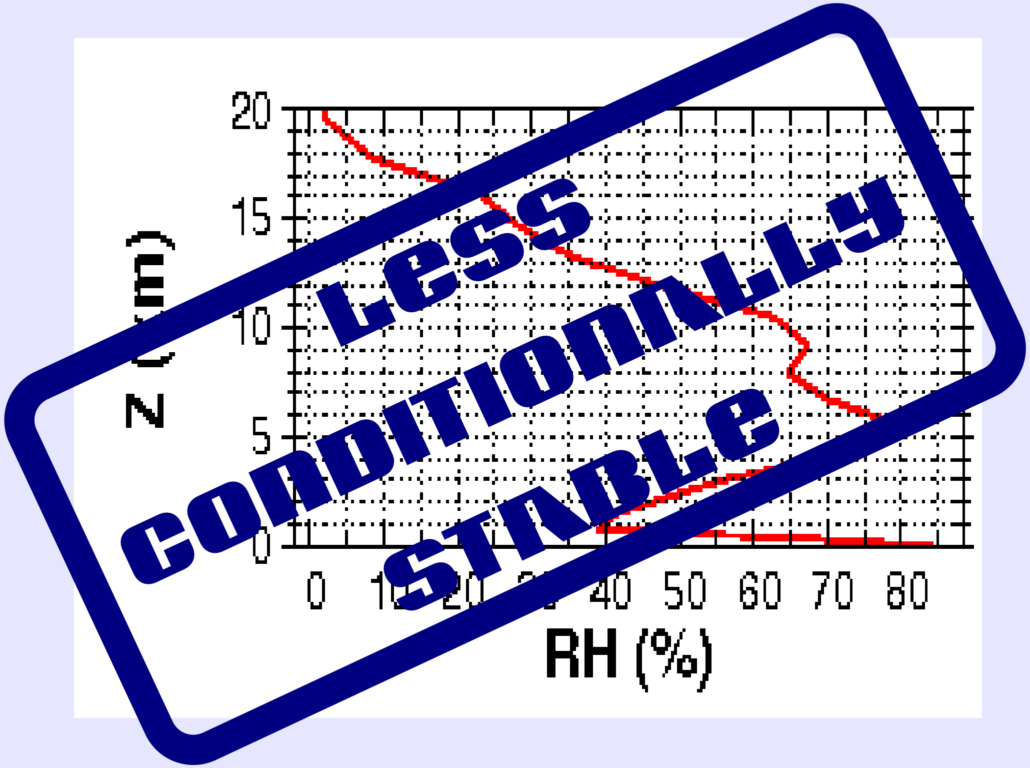


- substantially enhanced mid and upper tropospheric humidity
(with substantially higher T, RH is higher because of substantially enhanced specific humidity)

Case2:
2 different regions

- Moisture?





- substantially enhanced mid and upper tropospheric humidity
  (with substantially higher T, RH is higher because of substantially enhanced specific humidity)

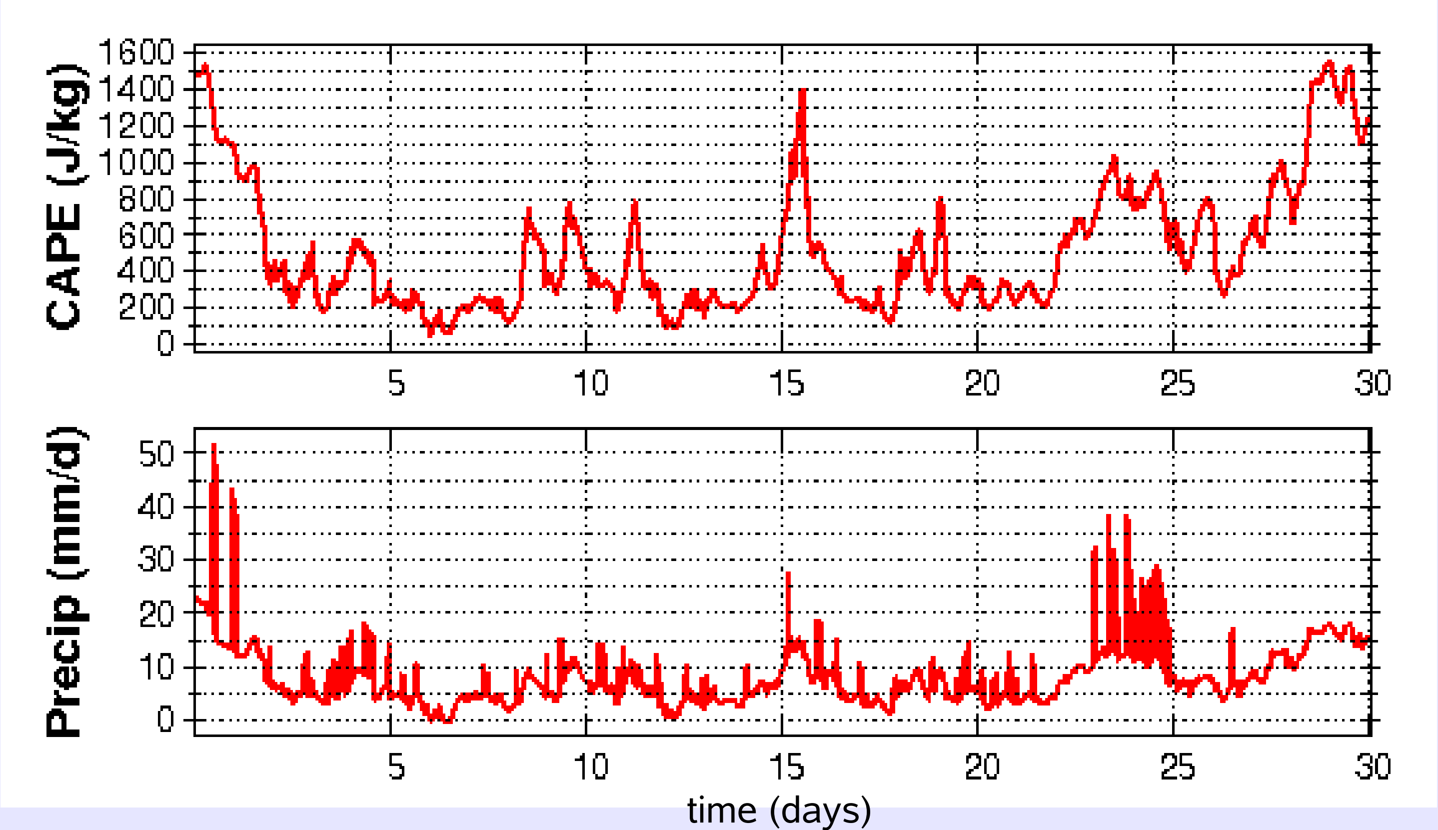
Case2:
2 different regions

- Substantially enhanced moisture in the middle and upper troposphere destabilise the atmosphere and favour convective activity
- CAPE:
  - Germany: ca. 355 J/kg
  - Africa: ca. 509 J/kg
- Convective precipitation:
  - Germany: 4.4 mm/day
  - Africa: 5.5 mm/day
- Germany has more episodic convective activity
  (determined by the stronger large – scale forcing of synoptic weather systems)

Case3:
Tropical oceanic convection

Case3: Tropical oceanic convection

- conditions over the Pacific warm pool
- daily convection, episodic very strong events
- very short convective peaks, but almost continuous rain

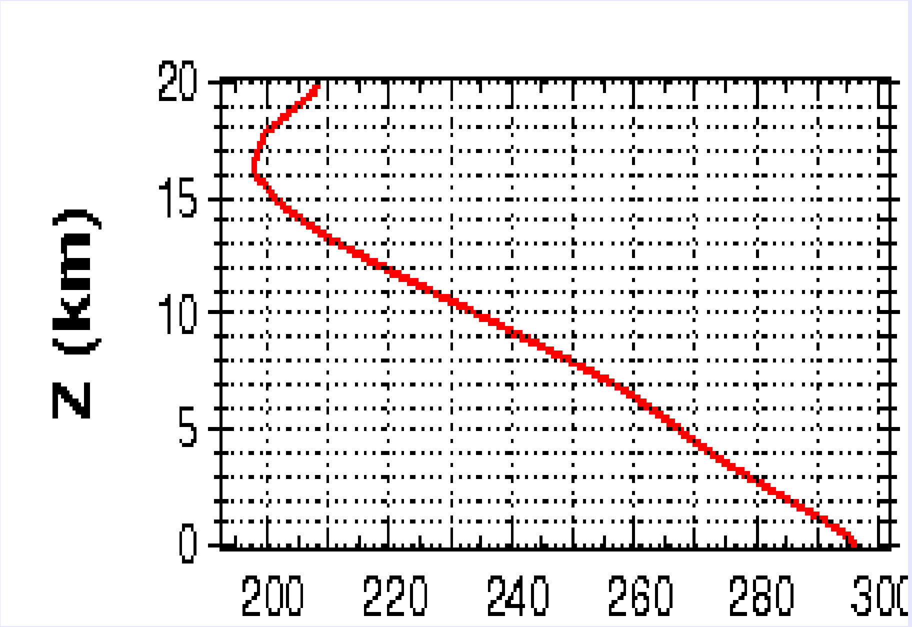


Case3:
Differences between land and ocean

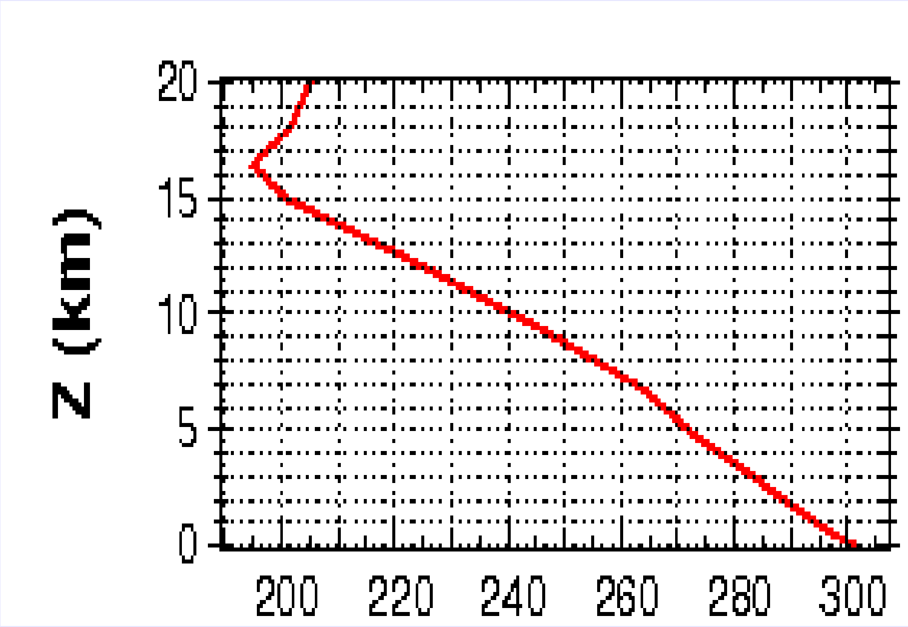
- absolute Temperature ?
- Profile and Lapse rate ?

Case3:
land and ocean

- absolute Temperature ?
- Profile and Lapse rate ?



6°C - 6.5°C / km

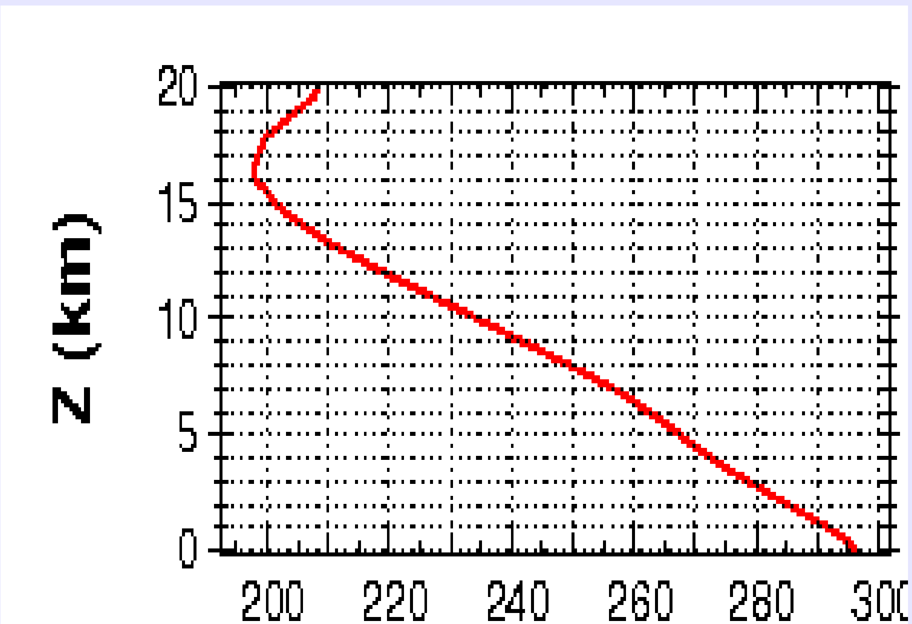


5.5°C - 6°C / km

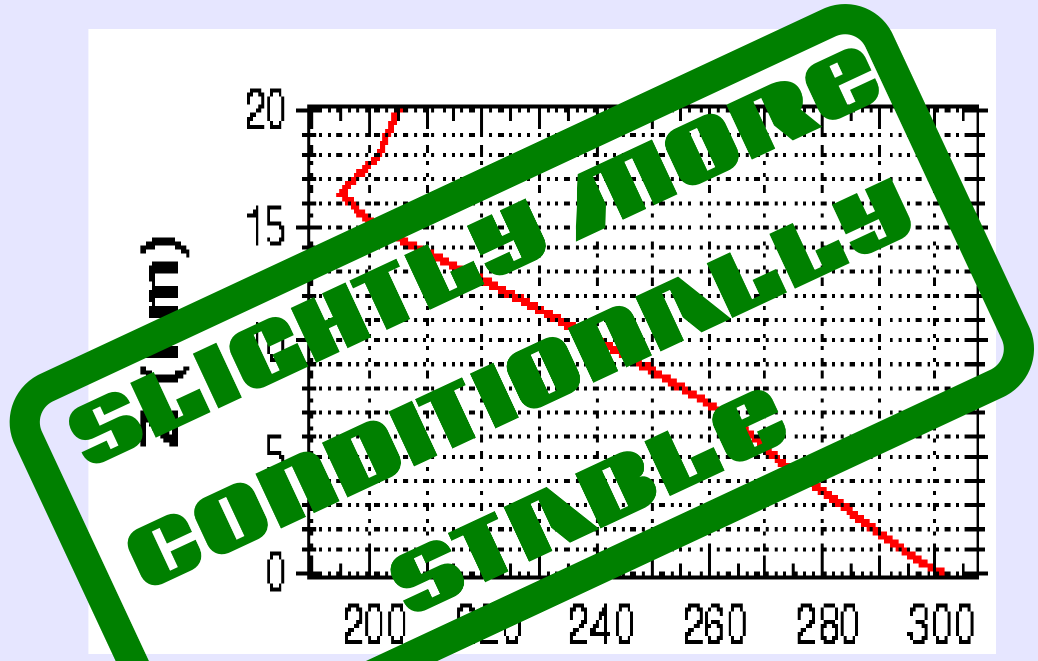
- slightly warmer lower and middle troposphere

Case3:
land and ocean

- absolute Temperature ?
- Profile and Lapse rate ?



6°C - 6.5°C / km



5.5°C - 6°C / km

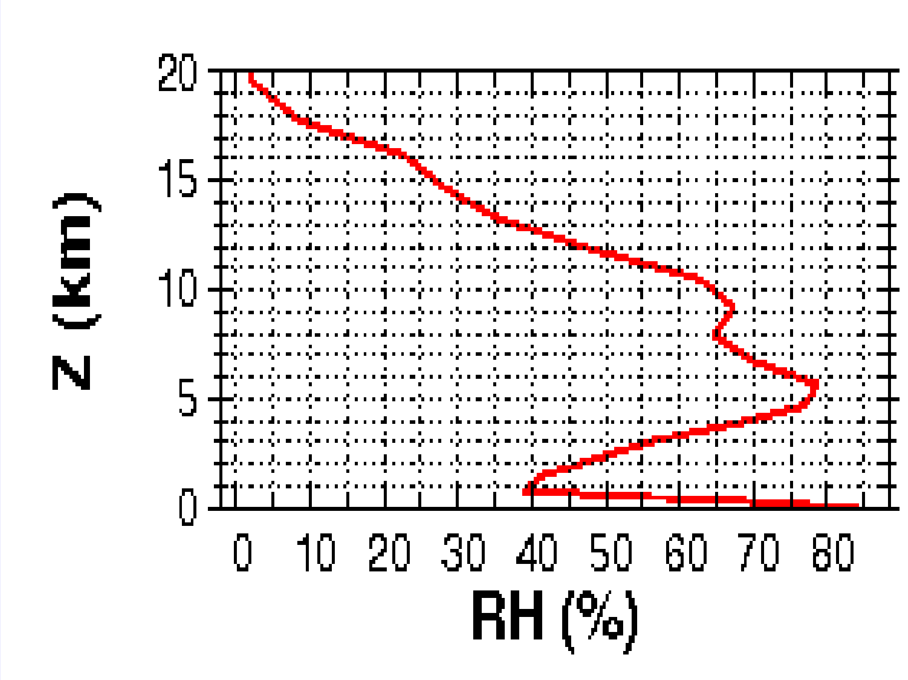
- slightly warmer lower and middle troposphere

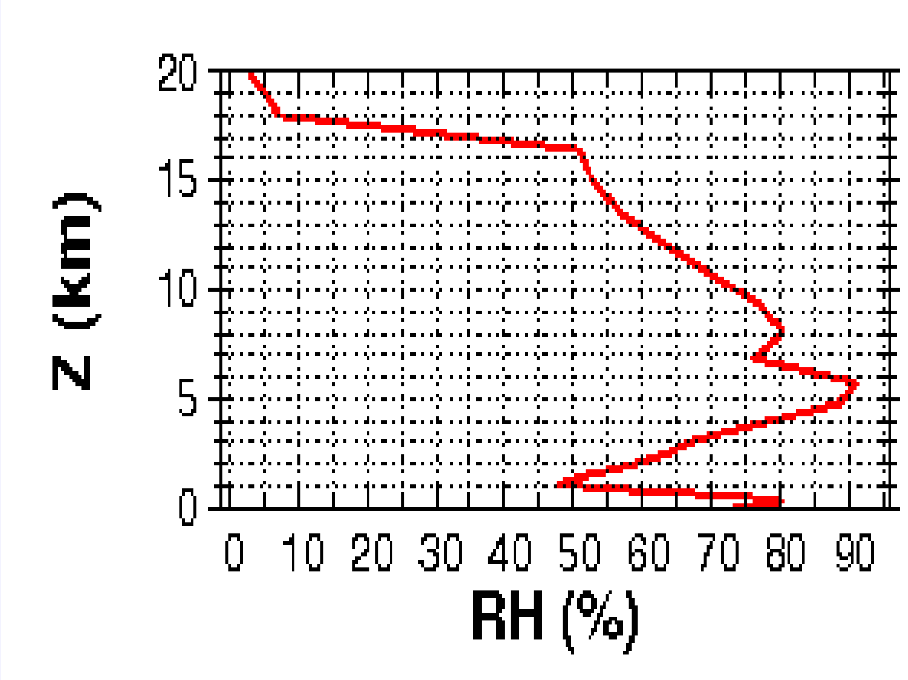
Case3: land and ocean

- Moisture?

Case3:
land and ocean

- Moisture?

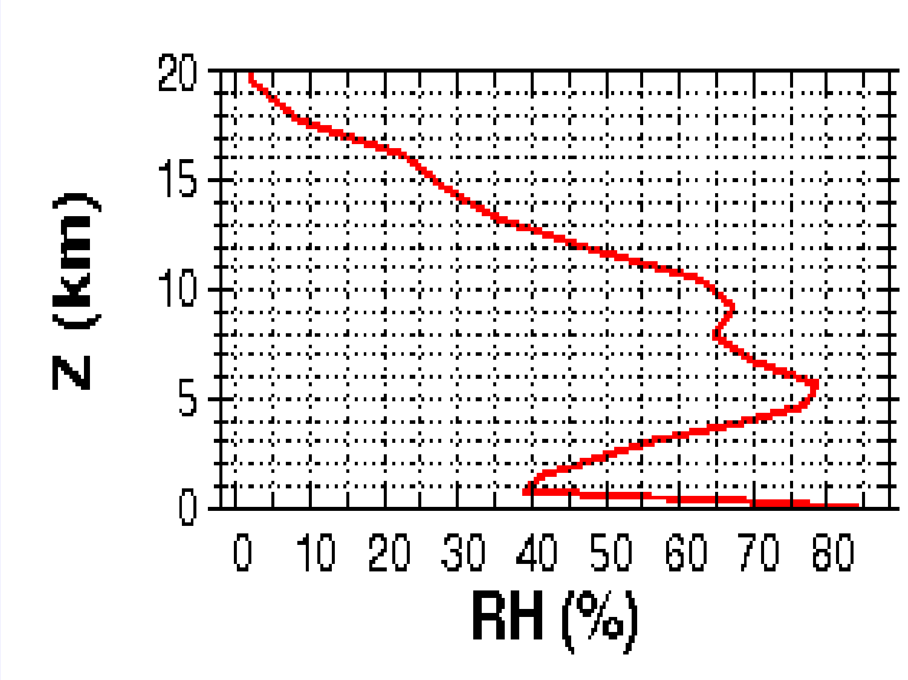


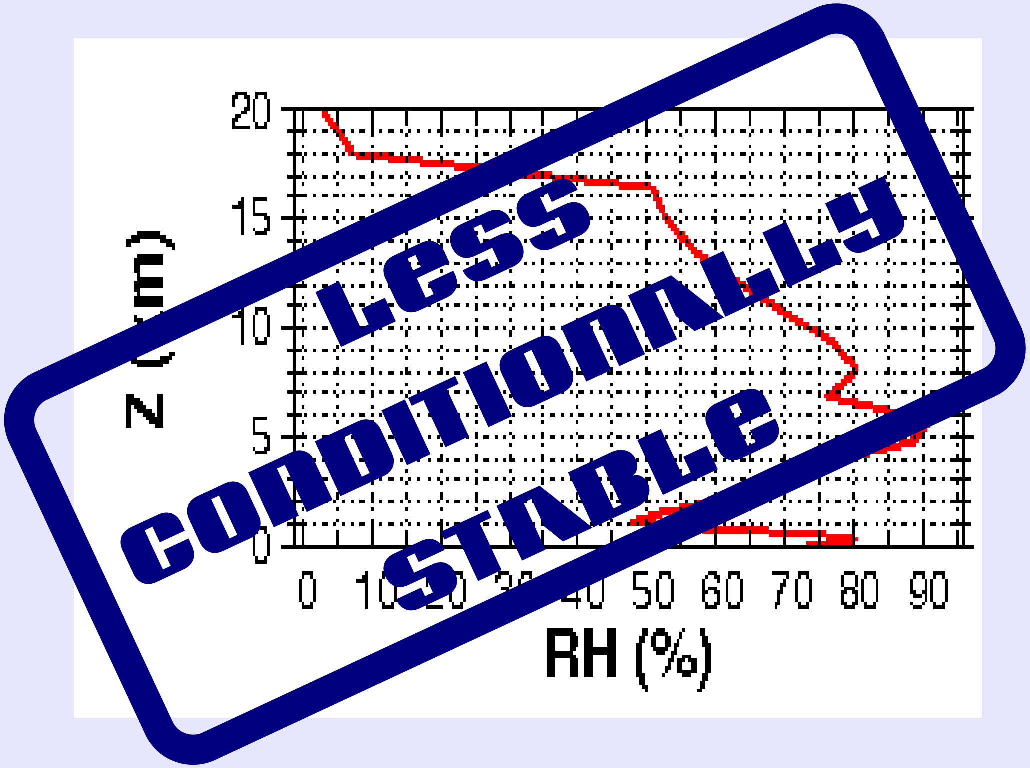


- enhanced mid and upper tropospheric humidity
  (with substantially higher T, RH is higher because of substantially enhanced specific humidity)

Case3:
land and ocean

- Moisture?





- enhanced mid and upper tropospheric humidity
  (with substantially higher T, RH is higher because of substantially enhanced specific humidity)

Case3:
land and ocean

- Enhanced moisture in the middle and upper troposphere destabilise the atmosphere and favour convective activity balancing the more stable temperature profile
- CAPE:
  - Africa: ca. 509 J/kg
  - Warm Pool: ca. 512 J/kg
- Convective precipitation:
  - Africa: 5.5 mm/day
  - Warm Pool: 8.2 mm/day
- higher available moisture causes more precipitation

One scheme for all regimes

- A convection parameterisation must be applicable:
  - for oceanic and continental convection
  - for tropical and mid – latitude convection
  - for low and high moisture regimes
  - for stable and less stable temperature profiles

  => forcing from the large – scale processes
- redistributes moisture and energy
- provides “adjusting” tendencies for T and q
  => feedback to the large – scale processes

Summary (I)

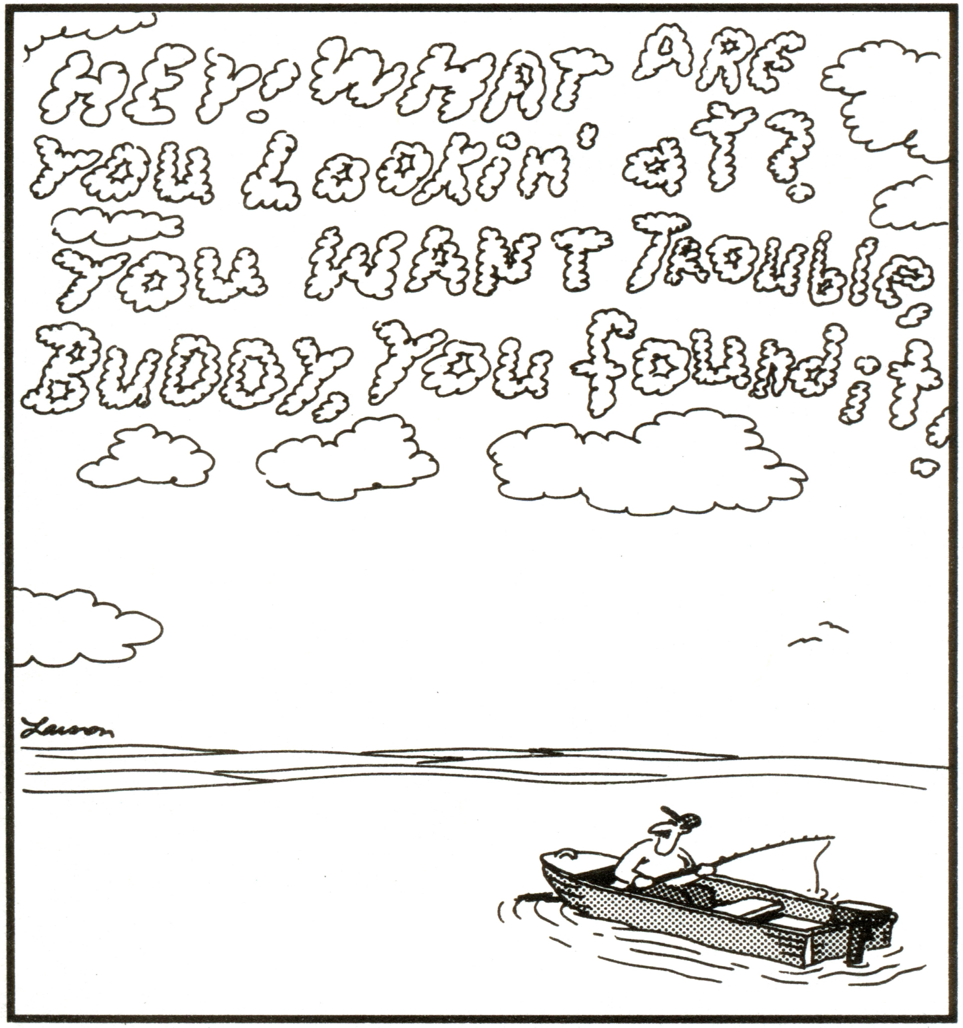
- Convection is **impacted by the large – scale and influences the large – scale** itself.
- Parameterisations relate the large – scale state to the subgrid – scale process by using **closure** assumptions.
  - A variety of closure assumptions (different types and formulations) is used in present parameterisations.
- Convection schemes "adjust" temperature and profile to **stabilise** the atmosphere and to reach a **quasi – equilibrium** state.

Summary (II)

- The forcing for convection can be very different dependent on location.
- Single column model shows that there is a strong response to the external forcing:
  - strong forcing (destabilisation) results in strong convection (and therefore stronger adjustment)
  - **CAPE** is a useful quantity for theoretical considerations of convection and its strength
- One convection parameterisation has been presented, others are different ....

Convection schemes cannot be so different, can they ?

Well, we will see in the next part of the lecture.....



Understanding only German, Fritz was unaware that the clouds were becoming threatening.