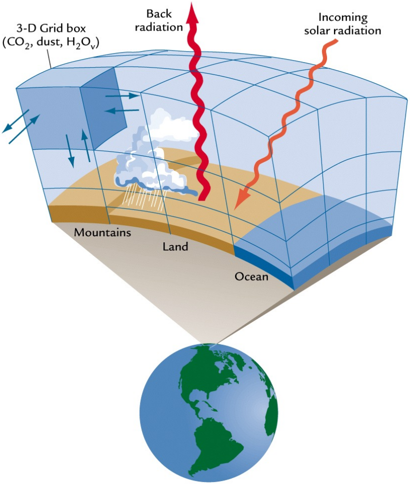
Parameterizations of physical processes



(Ruddiman, 2001)

Governing equations in climate models

$$\frac{\partial \vec{v}}{\partial t} = -\vec{v}\cdot\nabla_h\vec{v} - \omega\frac{\partial \vec{v}}{\partial p} + f\vec{k}\times\vec{v} - \nabla\Phi + \vec{D}_M \quad (1)$$

$$\frac{\partial T}{\partial t} = -\vec{v}\cdot\nabla_h T - \omega\frac{\partial T}{\partial p} + \frac{\omega}{c_p}\frac{RT}{p} + \frac{Q_{rad}}{c_p} + \frac{Q_{pt}}{c_p} + D_H \quad (2)$$

$$\frac{\partial \omega}{\partial p} = -\nabla_h\cdot\vec{v} \quad (3)$$

$$\frac{\partial q}{\partial t} = -\vec{v}\cdot\nabla_h q - \omega\frac{\partial q}{\partial p} + E - C + D_q \quad (4)$$

$$\frac{\partial q_x}{\partial t} = -\vec{v}\cdot\nabla_h q_x - \omega\frac{\partial q_x}{\partial p} + sources - sinks + D_{q_x} \quad (5)$$

$\vec{D}_M = (D_\lambda, D_\phi)$: dissipation and diffusion terms for momentum

D_H, D_q: diffusion terms for heat and moisture

Q_{rad}, Q_{pt}: heating/cooling from radiation and phase transitions

E, C: rates of evaporation and condensation

q, q_x: specific humidity and tracers: cloud water, ice, aerosols

∇_h: horizontal gradient on p levels; $\lambda, \phi =$ latitude, longitude

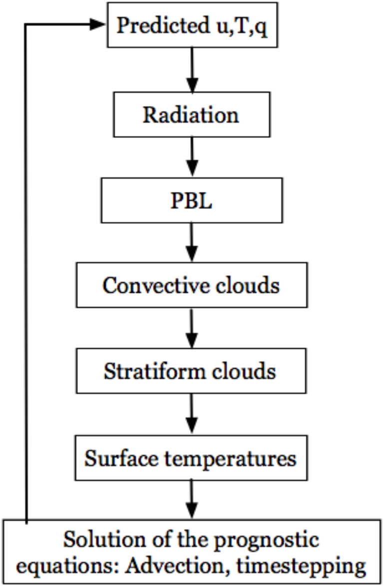
Parameterizations - general aspects

- Any physical process, such as radiation, turbulence, convection, cloud formation, that occurs on scales smaller than the grid of a general circulation model (GCM), must be parameterized.
- The only model variables available for parameterizations are the large-scale fields predicted by the model.
- Relating the subgrid processes to large-scale variables depends on the knowledge of the fundamental physics involved in the process.

Parameterized processes

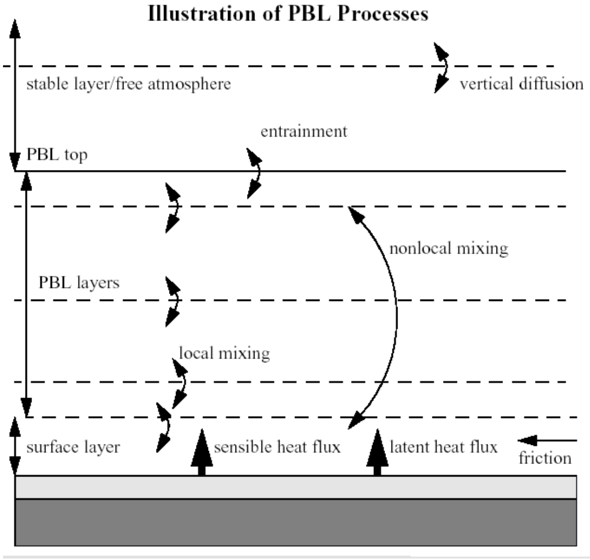
- Planetary boundary layer and surface processes - usually predict turbulent kinetic energy
- Clouds:
  - Cloud microphysics (liquid and ice)
  - optional: partial cloud cover
- Convection - usually mass flux approach
- Radiation - usually 2 stream approach for shortwave (SW, solar) and longwave (LW, terrestrial) radiation
- Mechanical dissipation of kinetic energy (gravity wave drag)
- Aerosols/trace gases: sources, sinks and subgrid-scale transport

Typical flow chart in a GCM



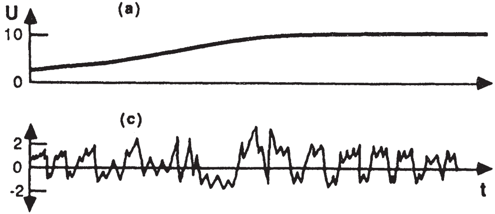
Outline of the 4 parameterization lectures

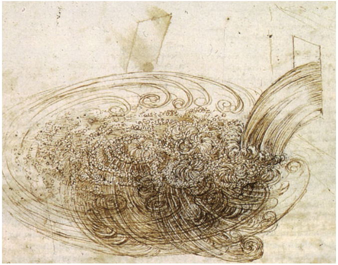
- Today: Basics atmospheric science necessary for the following lectures
- Parameterization of the planetary boundary layer (PBL) and surface processes (April 2)
- Parameterization of large-scale clouds (April 2/16)
- Parameterization of convection (April 16/23)
- Parameterization of radiation (April 23)
- More details on atmospheric radiation (see lecture "Radiation and climate change" by Wild, FS)
- More details on convection (see lecture "Cloud dynamics" by Lohmann, FS)
- More details on land-surface processes (see lecture "Land-atmosphere-climate interactions" by Seneviratne, HS)



www.mmm.ucar.edu/mm5/documents/MM5_tut_Web_notes/MM5/mm5.htm

Turbulence and eddies





Decomposition of flow into mean and turbulence:

$$u = \overline{u} + u' \tag{6}$$

(Stull, 1988; wikipedia)

PBL - general remarks

- PBL is the link between the Earth's surface and the free atmosphere.
- The interaction of the atmosphere with the Earth's surface involves the exchange of heat, momentum, moisture and chemical species and hence is an important component of climate system modelling.
- The PBL's structure is dominated by surface processes that generate turbulent motions on a range of spatial scales.
- The height of the PBL is 2 km or less.
- PBL processes are parameterized in GCMs because their vertical grid is too coarse to properly resolve the PBL

Schematic of the planetary boundary layer (PBL)

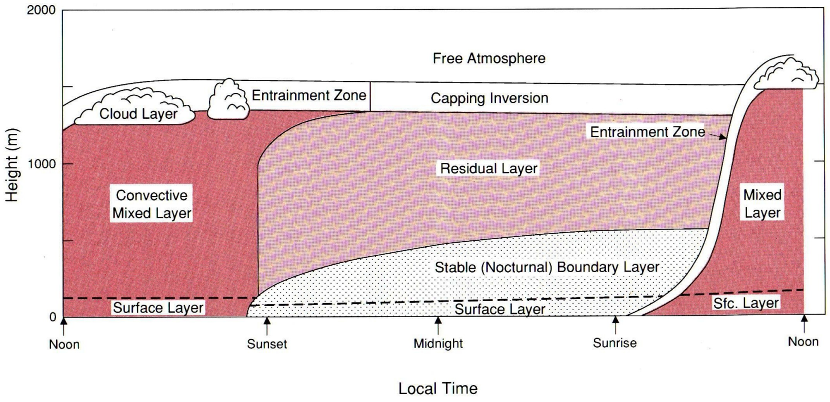
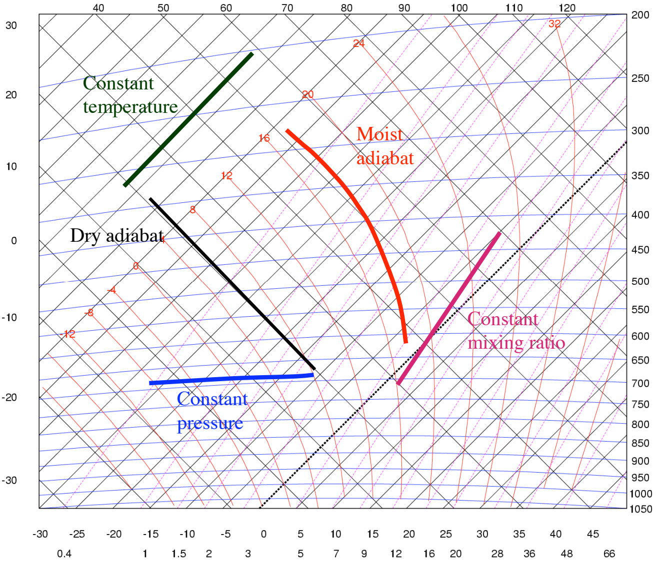


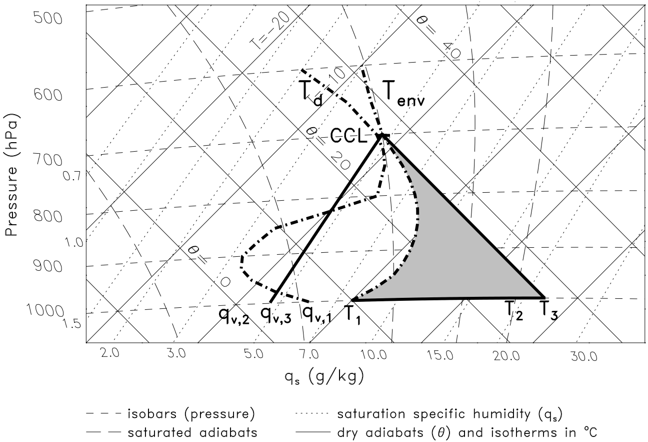
Fig. 10.19 Schematic of the atmospheric boundary layer. Note the presence of the surface layer, the mixed layer and a nocturnal stable layer. Also note the vertical scale of these atmospheric layers. From Stull (1988).

(Trenberth, Climate System Modeling, 1992)

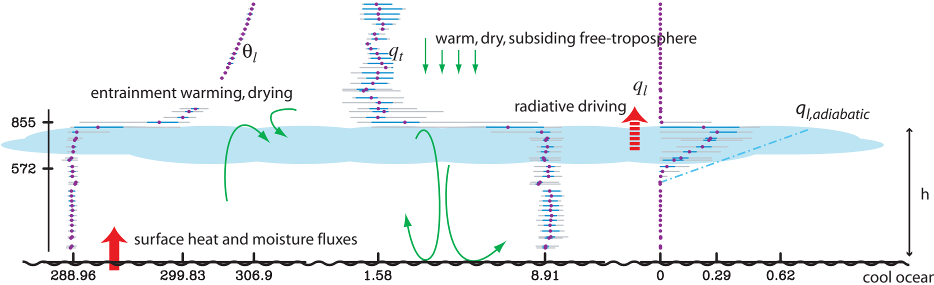
Thermodynamic chart (Bechtold, ECMWF lecture)



Convective condensation level (CCL)



Stratocumulus-topped boundary layer

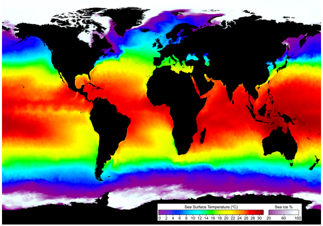


where θ_l = liquid water potential temperature, q_t = total water content (sum of cloud water (q_l) and specific humidity) and $q_{l,adiabatic}$ = maximum possible liquid water content

(Stevens, Ann. Rev. Earth Planet Sci., 2005)

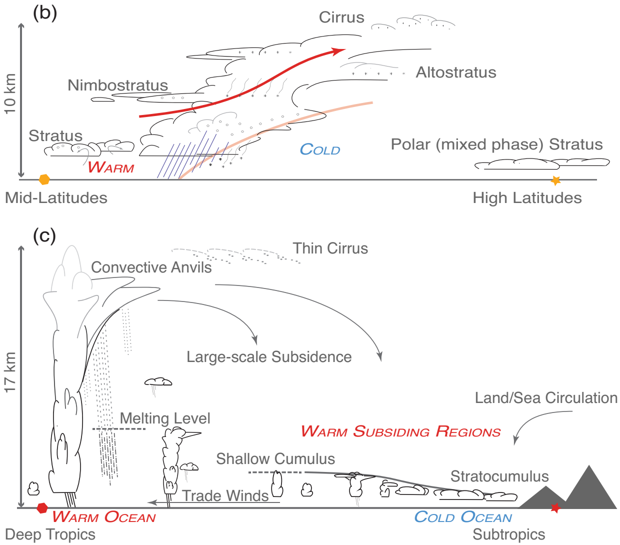
Importance of Sc-topped BL

- The Sc-topped boundary layer is a very widespread phenomenon with importance for global climate
- These clouds mainly form in regions of large-scale subsidence (e.g. subtropical anticyclones, overturning circulation of Hadley-cell), or in response to cold air outbreaks
- Stratocumulus found predominantly at West coast of continents in regions of cold SST

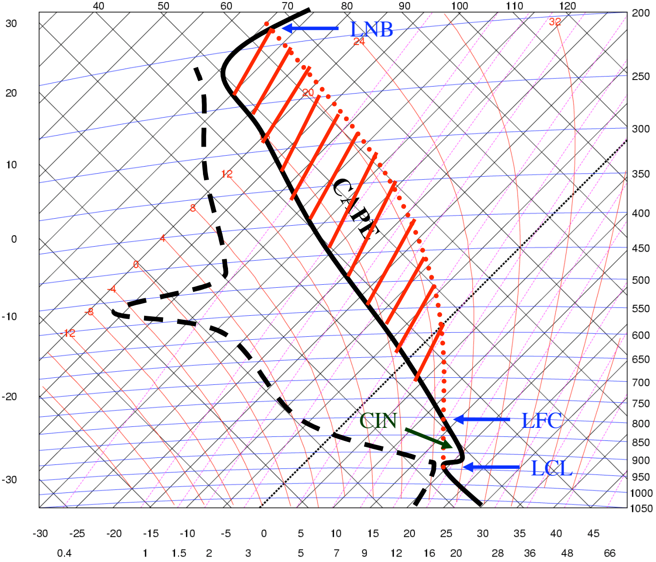


http://www.noc.soton.ac.uk/o4s/euroargo/argoeu_4.php

Cloud types and occurence (AR5, Boucher et al. 2013)



Tephigram for convection (Bechtold, ECMWF lecture)



Triggering of convection

Generate instabilities:

- Heat the surface
- Cool aloft

Overcome convective inhibition (CIN):

- Vertical forcing (large-scale, mountains ...)
- Surface processes (heat/moisture flux)

Role of convection:

Warming of air parcels:

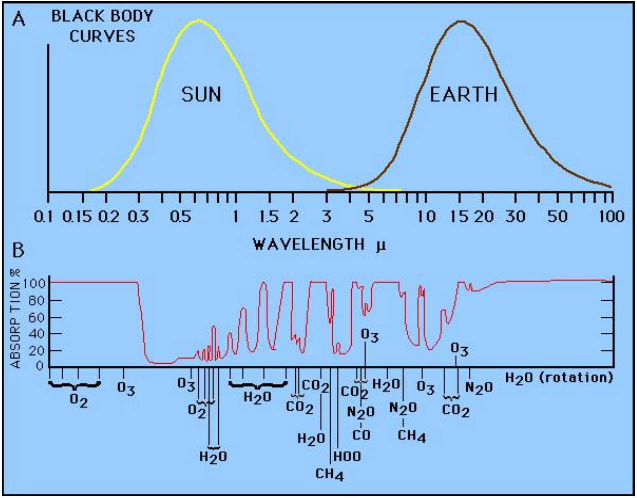
- Downward motion (adiabatic compression) (dyn)
- Condensation of water vapour on droplets (th)
- Freezing of droplets (th)
- Deposition of water vapour on ice crystals (th)

Cooling of air parcels:

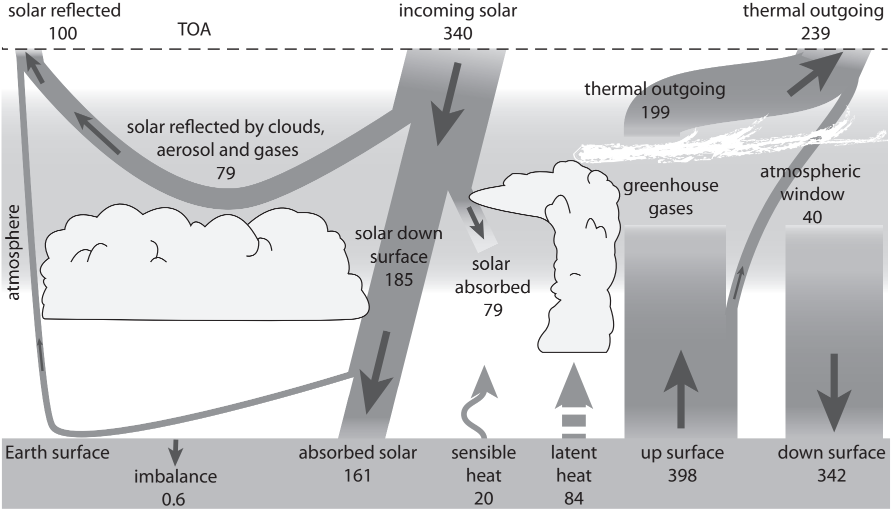
- Upward motion (adiabatic expansion) (dyn)
- Evaporation of droplets (th)
- Sublimation of ice crystals/graupel/hail (th)
- Melting of ice crystals/graupel/hail (th)

Dynamics (dyn) / Thermodynamics (th)

Radiation Spectrum



Annual mean energy budget in W/m^2



Climate change

- If the system is perturbed (e.g. by doubling CO_2), then the initial balance will be perturbed:

$$\Delta F = \Delta R + \Delta H + \lambda \Delta T_s \tag{7}$$

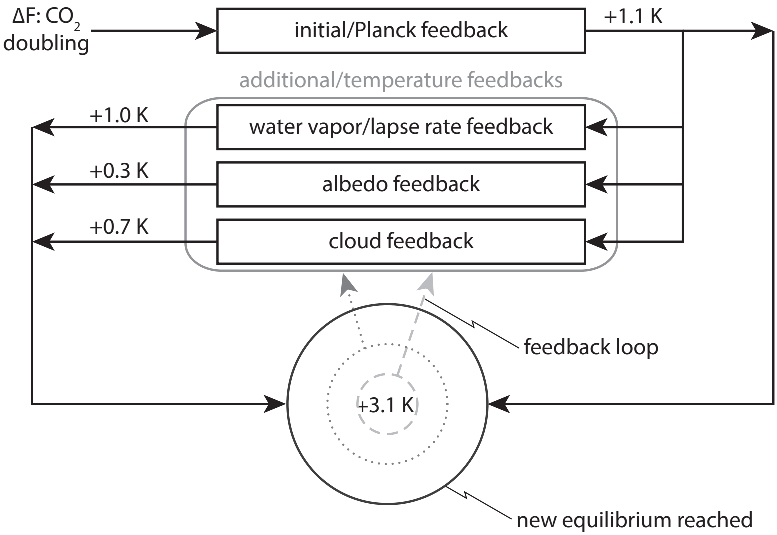
where Δ: perturbation to the system, ΔF: radiative forcing, ΔR: radiative imbalance at the top of the atmosphere (TOA), ΔH: ocean heat uptake, ΔT_s: change in global mean surface temperature, λ: feedback parameter

- If a radiative forcing is imposed, first $\Delta F = \Delta R$. Over time, land and ocean will warm.
- In equilibrium: $\Delta R = \Delta H = 0$ so that:

$$\Delta F = \lambda \Delta T_s \tag{8}$$

- In case of a doubling of CO_2, $\Delta F = 3.7$ W m^{-2} [Myhre et al. (1998), IPCC (2013)]

Summary of feedbacks



Planck feedback

- Decomposition of feedback parameter λ (X: albedo, water vapor/lapse rate, cloud):

$$\lambda = \frac{\Delta F}{\Delta T_s} = \frac{\partial F}{\partial T_s} + \sum_X \frac{\partial F}{\partial X}\frac{\Delta X}{\Delta T_s} \tag{9}$$

- With $\Delta X = 0$, the Stefan-Boltzman law

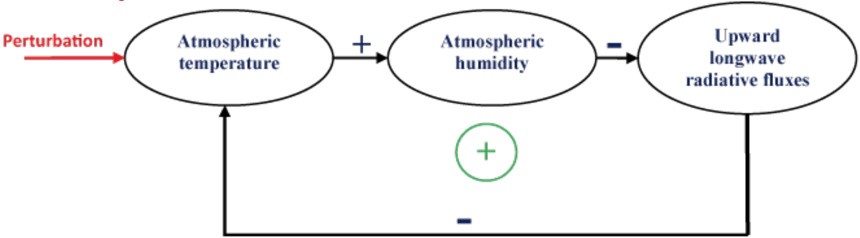
$$F(T_s) = \epsilon\sigma T_s^4 \tag{10}$$

results in a Planck feedback of

$$\frac{\partial F}{\partial T_s} = \frac{4F}{T_s} = \frac{4 \cdot 235\,\mathrm{Wm^{-2}}}{288\,\mathrm{K}} = 3.2\,\mathrm{Wm^{-2}K^{-1}} \tag{11}$$

which yiels a warming of 1.1 K for a doubling of CO_2.

Water Vapour Feedback

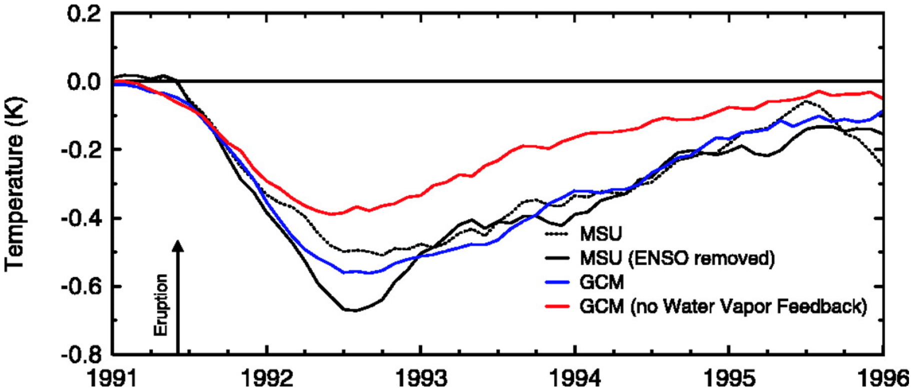


http://stratus.astr.ucl.ac.be/textbook/chapter4_node7.html

- Oberservations show that Relative Humidity remains constant
- Thus an increase in Temperature leads to an increase in specific humidity based on the abundance of water and the Clausius Clapeyron relation:

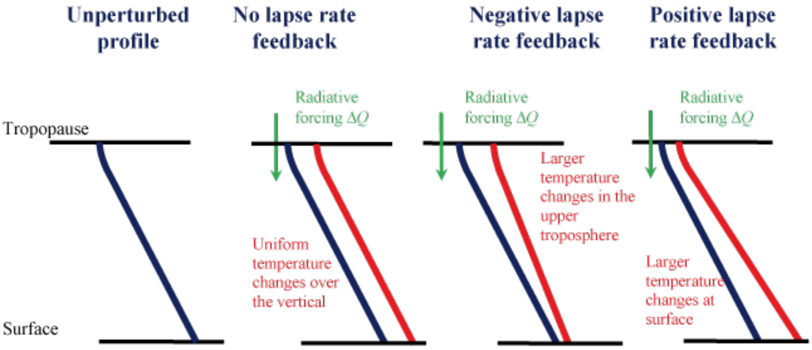
$$\frac{dq_s}{q_s} = \frac{de_s}{e_s} = \left(\frac{L}{R_v T}\right) \frac{dT}{T} \tag{12}$$

Water vapour feedback



(Soden et al., Science, 2002)

Lapse Rate Feedback



http://stratus.astr.ucl.ac.be/textbook/chapter4_node7.html

- Temperature changes of different magnitude at different altitudes lead to a changed lapse rate in the atmosphere.

Lapse Rate Feedback

In tropics:

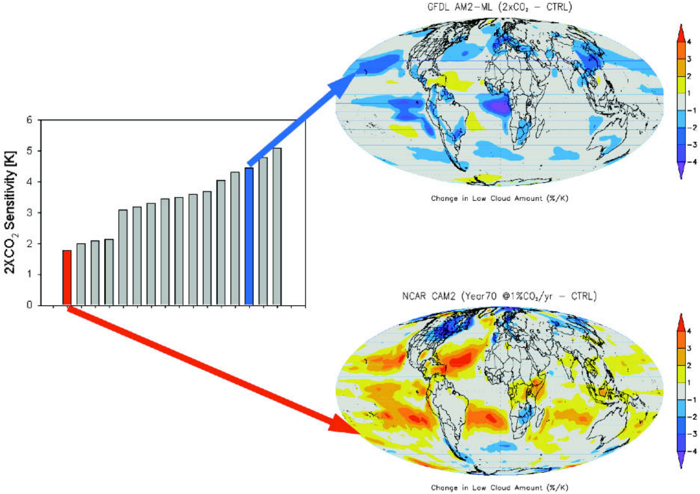
- Increased warming of upper troposphere due to increased transport of heat and moisture by convection
- Increased temperatures in upper troposphere lead to increased outgoing LW radiation
- Negative lapse rate feedback on T_S

in mid-latitudes:

- Particularly in winter increased low-level warming
- positve lapse rate feedback on T_S

Global mean lapse rate feedback is negative (i.e. effect in tropics dominates) and offsets the positive water vapour feedback.

Importance of low clouds for climate change



Model response to $2xCO_2$ and change in low cloud amount (Stephens, JC, 2005)

Cloud feedback

- The radiative effect of an individual cloud depends on its height and optical thickness, the insolation, and the characteristics of the underlying surface
- Thus, climate models are needed to estimate the cloud feedback