ECHAM5

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EaSyMS2009, Helsinki, 3-7 August 2009

Reference: MPI Report No. 349 (2003)

http://www.mpimet.mpg.de/wissenschaft/publikationen/reports.html

Model equations ("resolved physics")

- momentum equations
- thermodynamic equation
- dry mass continuity equation
- continuity equations for atmospheric constituents
- hydrostatic equation
- equation of state

Prognostic variables

- vorticity (V)
- divergence (D)
- temperature (T)
- log of surface pressure (ln p_s)
- mass mixing ratios of

  - water vapor
  - cloud liquid water
  - cloud ice

Solution of model equations

- Dry dynamics (V, D, T, $\ln p_s$)
  - horizontal: spectral transform method
  - vertical: finite differences (sigma-pressure)
  - temporal: semi-implicit leap-frog scheme with time filter

- Advection of atmospheric constituents: flux form semi-Lagrangian transport scheme (Lin&Rood, 1996) (mass conserving and positive definite)

- “Parameterized physics” on Gaussian transform grid

“Parameterized physics”

- Radiation
- Convection
- Stratiform clouds
- Vertical diffusion
- Horizontal diffusion
- Gravity wave drag
- Land surface processes

Radiation

Shortwave (Fouquart & Bonnel, 1980)

Processes

- Gaseous absorption
- Rayleigh scattering
- Scattering and absorption by aerosols and clouds

Atmospheric constituents

- H_2O, CO_2, CH_4, N_2O, CFC's, O_3
- Aerosols (climatology)
- Clouds (droplets, ice crystals)

Gaseous absorption

Spectral range (nm)	Absorbers
185-250 (UV)	O_3
250-440 (UV,VIS)	O_3, UMG (CO_2 ...)
440-690 (VIS)	H_2O, O_3, UMG
690-1190 (NIR)	H_2O, UMG
1190-2380 (NIR)	H_2O, UMG
2380-4000 (NIR)	H_2O, O_3, UMG

Cloud optical properties (single scattering properties)

- mass extinction coefficient (droplets, ice)
- single scattering albedo
- asymmetry factor

... all parameterized in terms of the <u>effective radii</u> for cloud droplets and ice crystals based on Mie scattering theory (polynomial fits)

<u>Model input</u>: cloud liquid and ice water content and cloud droplet number concentrations (cdnc)

Longwave (Mlawer et al., 1997)

Processes

- Emission
- Line absorption
- Continuum absorption
- Scattering and absorption by aerosols and clouds

Spectral resolution: 16 bands in the range 10-3000 cm^{-1}
corresponding to 3 - 1000 μm (see Table 11.6 in Rep. 349)

Mass absorption coefficients for clouds are parameterized
In terms of the effective radii for cloud droplets / ice crystals

Cumulus convection (Tiedtke, 1989)

$$dry\ static\ energy\ s = c_p T + gz$$

$$\frac{\partial s}{\partial t} + \vec{v}\nabla s + w\frac{\partial s}{\partial z} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_u\left(s_u - s\right) + M_d\left(s_d - s\right)\right] - \frac{1}{\rho}\frac{\partial}{\partial z}\overline{\left(\rho w' s'\right)}_{turb} + L\left(c - e\right) + Q_{Rad}$$

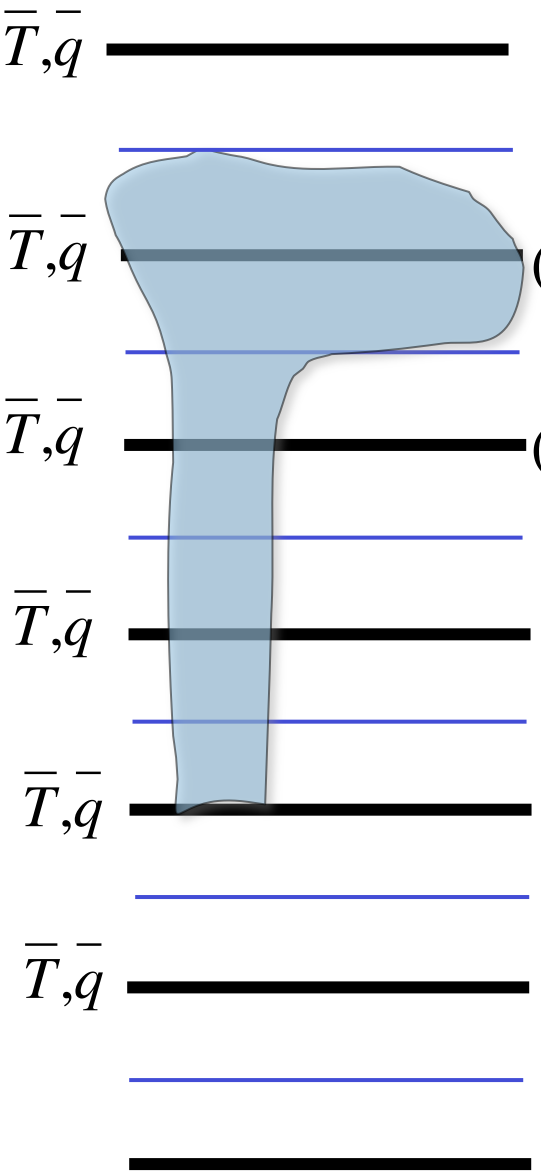
$$\frac{\partial q}{\partial t} + \vec{v}\nabla q + w\frac{\partial q}{\partial z} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_u\left(q_u - q\right) + M_d\left(q_d - q\right)\right] - \frac{1}{\rho}\frac{\partial}{\partial z}\overline{\left(\rho w' q'\right)}_{turb} - \left(c - e\right)$$

Types of convection

- Shallow (cloud thickness ≤ 200 hPa)
- Deep (cloud thickness > 200 hPa)
- Mid-level (at cloud base: RH>90%, upward motion)

Shallow and deep convection have their roots in the PBL, mid-level convection can also start higher up

Occurrence of deep/shallow convection checked first, then mid-level convection



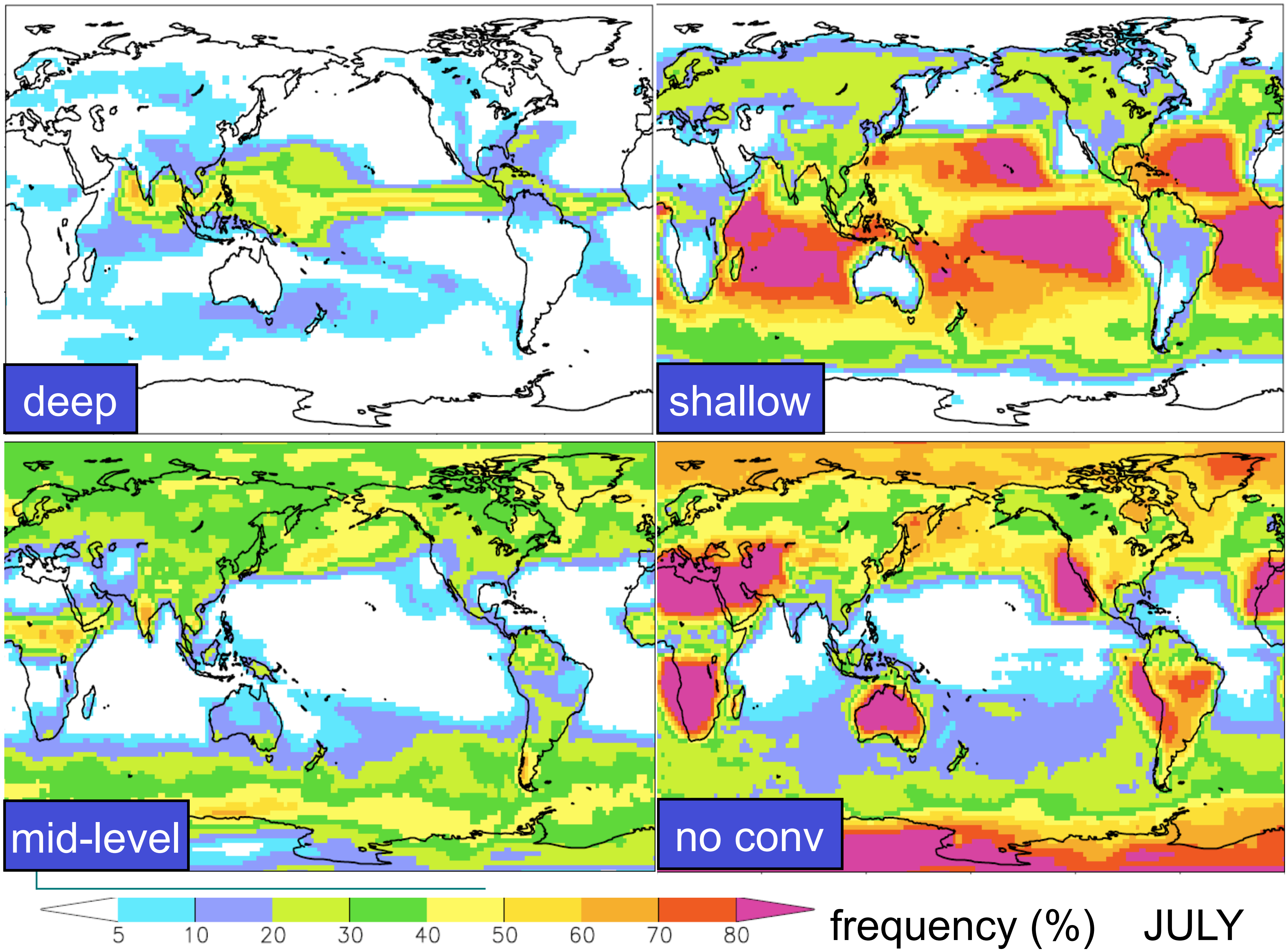
$(T_v^p + \Delta T) \leq \bar{T}_v$ detrainment level

$(T_v^p + \Delta T) > \bar{T}_v$ cloud top level

$(T_v^p + \Delta T) > \bar{T}_v$

$(T_v^p + \Delta T) > \bar{T}_v$ cloud base level

T_v^p from dry adiabatic ascent starting in the near-surface layer (humidity conserved)



deep
shallow
mid-level
no conv
5
10
20
30
40
50
60
70
80
frequency (%)
JULY

Closure assumptions

- Shallow convection: Moisture convergence in PBL
- Deep convection: CAPE > 0 (Nordeng, 1994)
- Mid-level convection: RH>0.9; upward motion at cloud base

$$CAPE = \int_{base}^{top} \left[\frac{g}{\overline{T}_v} \left(T_v^p - \overline{T}_v \right) - g l^p \right] dz$$

Parameterizations

- cloud base mass flux
- turbulent entrainment/detrainment
- organized entrainment/detrainment
- precipitation, evaporation

Cumulus model equations (updrafts)

$$\frac{\partial M_u}{\partial z} = E_u - D_u \qquad = \quad \text{entrainment - detrainment}$$

$$\frac{\partial M_u s_u}{\partial z} = E_u \bar{s} - D_u s_u + L\rho c_u$$

$$\frac{\partial M_u q_u}{\partial z} = E_u \bar{q} - D_u q_u - \rho c_u$$

$$\frac{\partial M_u l_u}{\partial z} = -D_u l_u + \rho c_u - \rho P_u$$

$$\frac{\partial M_u u_u}{\partial z} = E_u \bar{u} - D_u u_u$$

$$\frac{\partial M_u v_u}{\partial z} = E_u \bar{v} - D_u v_u$$

Stratiform clouds

Governing equations for water vapor, cloud liquid water and cloud ice include the following processes:

- Transport by advection and subgrid-scale processes
- Convective detrainment (source term)
- Sedimentation of cloud ice
- Condensation / deposition
- Evaporation of cloud droplets / sublimation of cloud ice
- Evaporation of rain / sublimation of snow and falling ice
- Melting of snow and falling ice
- Freezing of cloud droplets
- Autoconversion of cloud droplets ==> rain formation
- Aggregation of ice crystals ==> snowfall
- Accretion of droplets/crystals by rain and snow

Cloud cover

(i) Relative humidity based (Sundqvist et al., 1989)

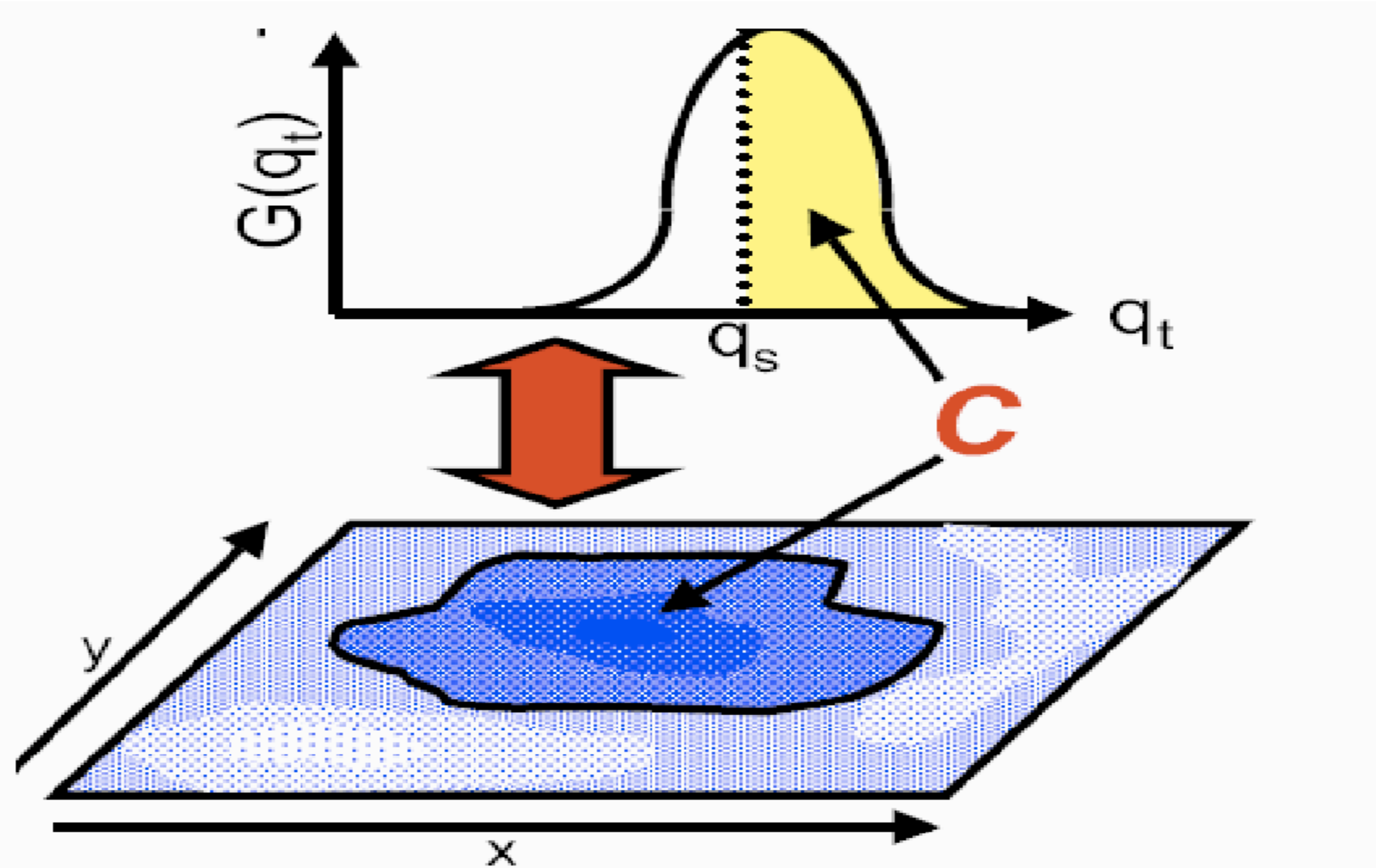
(ii) Statistical-dynamical model (Tompkins, 2002)

$$C = \int_{q_s}^{\infty} G(q_t)\,dq_t$$

$G(q_t)$ = probability density function of the total water mixing ratio

$$q_t = q_{vapor} + q_{liquid} + q_{ice}$$

q_s = saturation vapor mixing ratio


G(q_t)
q_s
q_t
C
y
x

Choice of PDF

'Beta distribution' (suggested by a cloud resolving model) is characterized by four parameters

- lower and upper bounds (a, b)
- two shape parameters (p, q)

Only the bell-shaped regime is allowed ($p > 1$; $q > 1$) and only symmetry ($p = q$) or positive skewness ($q > p$)

p is specified (= 2) but the skewness parameter q is determined from a prognostic equation
The lower bound 'a' can be diagnosed from the total water
The width (b-a) is determined by a prognostic equation

Subgrid-scale processes involved in solving the prognostic equations for the distribution moments (b-a, q)

- turbulence (shear generation, transport, dissipation)
- convective mass fluxes
- cloud microphysical processes

Surface fluxes and vertical diffusion

$$\overline{(w'\chi')}_S = -C_\chi |V_L| (\chi_L - \chi_S)$$

$$C_{m,h} = C_N f_{m,h} (R_{iB}, \frac{z_L}{z_{0m}}, \frac{z_L}{z_{0h}})$$

$$C_N = \frac{k^2}{\ln\left(\frac{z_L}{z_{0m}}\right) \ln\left(\frac{z_L}{z_{oh}}\right)}$$

Vertical diffusion

$$\overline{w'\chi'} = -K_\chi \frac{\partial \chi}{\partial z}$$

$$K_{m,h} = \Lambda_{m,h}\sqrt{E}$$

$$E = \left(u'^2 + v'^2 + w'^2\right)/2$$

$$\frac{\partial E}{\partial t} = -\frac{\partial \overline{w'E}}{\partial z} - \overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} + \frac{g}{\theta_v}\overline{w'\theta_v{}'} - \varepsilon$$

$$\Lambda_{m,h} = l_{mix} S_{m,h}(Ri)$$

$$l_{mix} = kz/(1 + kz/\lambda)$$

Land surface processes

Temperature

$$C_L \frac{\partial T_s}{\partial t} = R_{net} + LE + H + G$$ Surface

$$C_s \frac{\partial T}{\partial t} = -\frac{\partial G}{\partial z} = -\frac{\partial}{\partial z}\left(-\lambda_s \frac{\partial T}{\partial z}\right)$$ 5 layers

C_s = volumetric heat capacity
λ = thermal conductivity

Water budget (4 reservoirs; m water equivalent)

- Snow $h_{sn,ic}$ (canopy) $\leq h_{icres} = h_0 LAI$
- Snow h_{sn} at the ground
- Rain water $h_{rw,ic}$ (canopy) $\leq h_{icres} = h_0 LAI$
- Soil water h_{ws} (bucket) $\leq h_{wsmax}$

LAI = leaf area index

Budget equations for the 4 reservoirs
Units: kg/(m²s)

$$\rho_w \frac{\partial h_{sn,ic}}{\partial t} = c_v S - E_{sn,ic} - \rho_w h_{sn,ic}\left[U\left(T_c\right) + U\left(v_c\right)\right]$$

$$\rho_w \frac{\partial h_{sn}}{\partial t} = (1 - c_v)S - E_{sn} - M_{sn} + \rho_w h_{sn,ic} U\left(v_c\right)$$

$$\rho_w \frac{\partial h_{rw,ic}}{\partial t} = c_v R - E_{rw,ic} + \rho_w h_{sn,ic} U\left(T_c\right)$$

$$\rho_w \frac{\partial h_{ws}}{\partial t} = \left(1 - c_v\right)R - E_{ws} + M_{sn} + M_{sn,ic} - R_s - D$$

Horizontal diffusion ...

applied to χ = vorticity, divergence, temperature

$$\frac{\partial \chi}{\partial t} = -(-1)^q K_\chi \nabla^{2q} \chi \qquad (q = 1,2,\ldots)$$

$$\frac{\partial \chi_n}{\partial t} = -K_\chi \left\{ n(n+1)a^{-2} \right\}^q \chi_n$$

$$\tau(n_0) \equiv \tau_0 = K_\chi^{-1} \left\{ n_0(n_0+1)a^{-2} \right\}^{-q}$$

Order (2q) and damping time scale τ_0 as a function of model resolution and model level

Level (τ_0)	T31 (12 h)	T42 (9 h)	T63 (7 h)	T106 (3 h)	T159 (2 h)	T319 (1 h)
1	2	2	2	2	2	2
2	2	2	2	2	2	2
3	2	2	2	2	2	2
4	4	4	4	4	4	4
5	6	6	6	6	6	4
6	8	8	8	8	6	4
≥ 7	10	10	8	8	6	4

Gravity wave drag

Main GW sources affecting the momentum budget are

- Orographic obstacles
- Tropospheric sources (convection, condensation, fronts ...)

Representation of orographic obstacles

- std. dev., anisotropy, slope, orientation, mean, max, min

Processes

- low-level drag (blocking of flow by high mountains)
- gravity wave drag on the resolved flow when GW become unstable and break (stratosphere, mesosphere)

Middle atmosphere models only (top at 80km or 200km)

Doppler spread theory (Hines 1991, 1993, 1997)

- GW sources in the troposphere
- Dissipation in the mesosphere (momentum flux deposition)

Required input

- Sources (currently, continuous broad-band spectrum)
- Horizontal wind variance
- Large scale flow
- Buoyancy frequency

Thank you

Model configurations

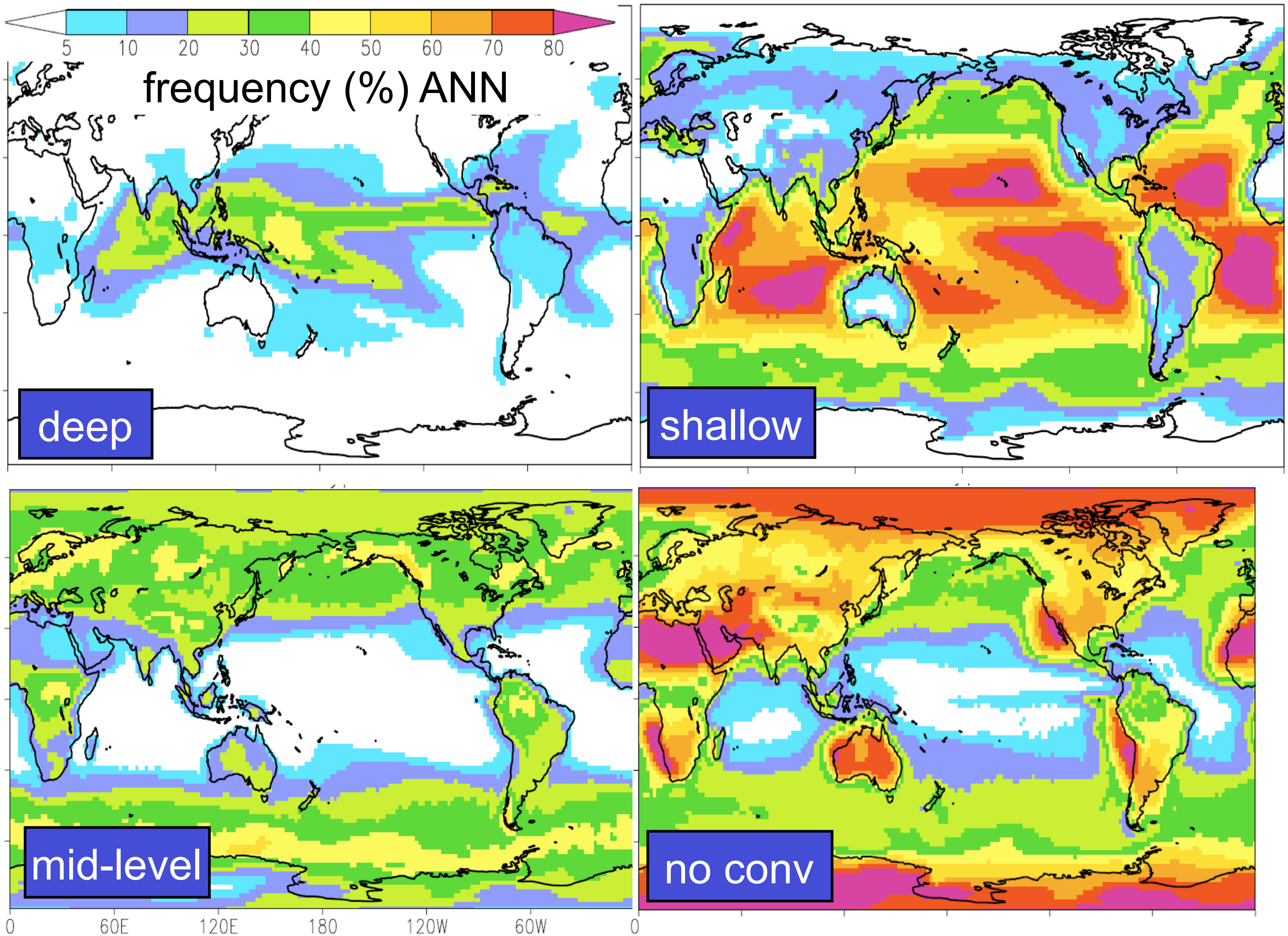
- Vertical domains

  troposphere + lower stratosphere (top level at 30 km)
  stratosphere + lower mesosphere (top level at 80 km)
  mesosphere + lower thermosphere (top level at 200 km)

- Number of levels: 19, 31 (30 km) ; 47 - 95 (80-200 km)

- Horizontal resolutions:

  T21, T31, T42, T63, T85, T106, T159, T213, T319



5
10
20
30
40
50
60
70
80
frequency (%) ANN
deep
shallow
mid-level
no conv
0
60E
120E
180
120W
60W
0