ECHAM - Theory

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Outline

- Model structure
- Governing equations
- Coordinate system
- Solution method

- Model 'physics' (parameterized part)

Reference: MPI Report No. 349 (2003)

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

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) ; 39 - 90 (80-200 km)

- Horizontal resolutions:

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

Governing prognostic equations

- Vorticity (V)
- Divergence (D)
- Temperature (T)
- Surface pressure (p_s)

and mass mixing ratios of ...

- Water vapour
- Cloud liquid water
- Cloud ice

Hydrostatic equation

Solution method

- Horizontal (V, D, T, p_s): Spectral transform, but ..
  non-linear terms calculated on Gaussian transform grid
  Time integration scheme: semi-implicit

- Vertical: Finite difference method
  (hybrid coordinate system: sigma-pressure)

- Advection of atmospheric constituents:
  Semi-Lagrangian transport scheme

- Parameterized physics calculated on Gaussian grid
  Time integration: leap frog with time filter

Radiation (Chapter 11)

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
- Background aerosol (climatology)
- Clouds

Gaseous absorption

Spectral range (nm)		Absorbers
185-250	(UV)	O_3
250-440	(UV,VIS)	O_3, UMG
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 (liquid, ice)
- single scattering albedo
- asymmetry factor

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

Model input: Liquid and ice water content and the droplet / crystal number concentrations ...
prescribed as a function of height (different for land, ocean)

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 cloud are parameterized
In terms of the effective radii for cloud droplets / ice crystals

Stratiform clouds (chapter 10)

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)

$$C = \int_{r_s}^{\infty} G(r_t)\, dr_t$$

$G(r_t)$ = Probability density function of the total water mixing ratio $r_t = r_v + r_l + r_i$

r_s = saturation mixing ratio

Choice of PDF: 'Beta' suggested by a cloud resolving model

The Beta distribution is characterized by four parameters

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

Simplifications:

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

p is specified (= 2) but the skewness parameter **q** is determined by a prognostic equation.

The lower bound ‘a‘ can be determined from the total cloud water content, and the distribution width (variance) **(b-a)** is determined by another prognostic equation.

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

- turbulent (vertical) transport of total water content
- eddy dissipation (horizontal, vertical)
- convective transport (source of skewness)
- cloud microphysical processes

Cumulus convection (chapter 9)

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

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

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

Cumulus model equations

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

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

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

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

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

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

Types of convection

- shallow (thermally forced)
- mid level (dynamically forced)
- deep (dynamically and thermally forced)

Necessary conditions for convection to form

- Vertical instability
- Moisture convergence

Main problem: Closure (cloud base mass flux)

Deep convection closure (Nordeng, 1994)

$$CAPE = \int_{base}^{top} \left[\frac{g}{T_v}(T_{vc} - T_v) - gl \right] dz$$

$$\left(\frac{\partial T}{\partial t}\right)_{cu} \approx \frac{1}{\rho c_p} M \frac{\partial s}{\partial z}; \qquad \left(\frac{\partial q}{\partial t}\right)_{cu} \approx \frac{1}{\rho} M \frac{\partial q}{\partial z} \qquad M = M_B \eta(z)$$

$$\frac{\partial CAPE}{\partial t} = -\int_{base}^{top} \frac{g}{T_v} \frac{\partial T_v}{\partial t} dz = -M_B \int_{base}^{top} \left[\frac{(1+\delta q)}{c_p T_v} \frac{\partial s}{\partial z} + \delta \frac{\partial q}{\partial z} \right] \eta \frac{g}{\rho} dz$$

$$\frac{\partial CAPE}{\partial t} \approx -\frac{CAPE}{\tau}$$

$$M_B = \frac{CAPE}{\tau} \left\{ \int_{base}^{top} \left[\frac{(1+\delta q)}{c_p T_v} \frac{\partial s}{\partial z} + \delta \frac{\partial q}{\partial z} \right] \eta \frac{g}{\rho} dz \right\}^{-1}$$

Surface fluxes and vertical diffusion (chapter 5)

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

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

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

Vertical diffusion

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

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

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

$$\Lambda_{m,h} = l S_{m,h}$$

$$S_{m,h} = S_{N,m,h}\, g_{m,h}(Ri)$$

Land surface processes (Chapter 6)

Temperature

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

$$R_{net} = (1 - \alpha_s) R_{sd} + \varepsilon (R_{ld} - \sigma T_s^4)$$

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

Water budget (4 reservoirs; m water equivalent)

- Snow $h_{sn,ic}$ (intercepted by the canopy)
- Snow h_{sn} at the ground
- Rain $h_{w,ic}$ (intercepted by the canopy)
- Soil water h_{ws}

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

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

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

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

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

Snow and ice albedos

$$\alpha_{sn} = \alpha_{sn,\min} + \left(\alpha_{sn,\max} - \alpha_{sn,\min}\right) f\left(T_s\right)$$

Surface type	$\alpha_{sn,min}$	$\alpha_{sn,max}$
bare land	0.3	0.8
canopy	0.2	0.2
land ice	0.6	0.8
sea ice	0.5	0.75
lake ice	0.5	0.75
snow on ice	0.6	0.8

Land surface albedo depends on

- temperature
- snow cover = f(h_{sn}, σ_z)
- canopy (forest) fractional area
- sky view factor = f(leaf area index)

Horizontal diffusion (chapter 4) ...
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 waves (Chapters 7 and 8)

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)

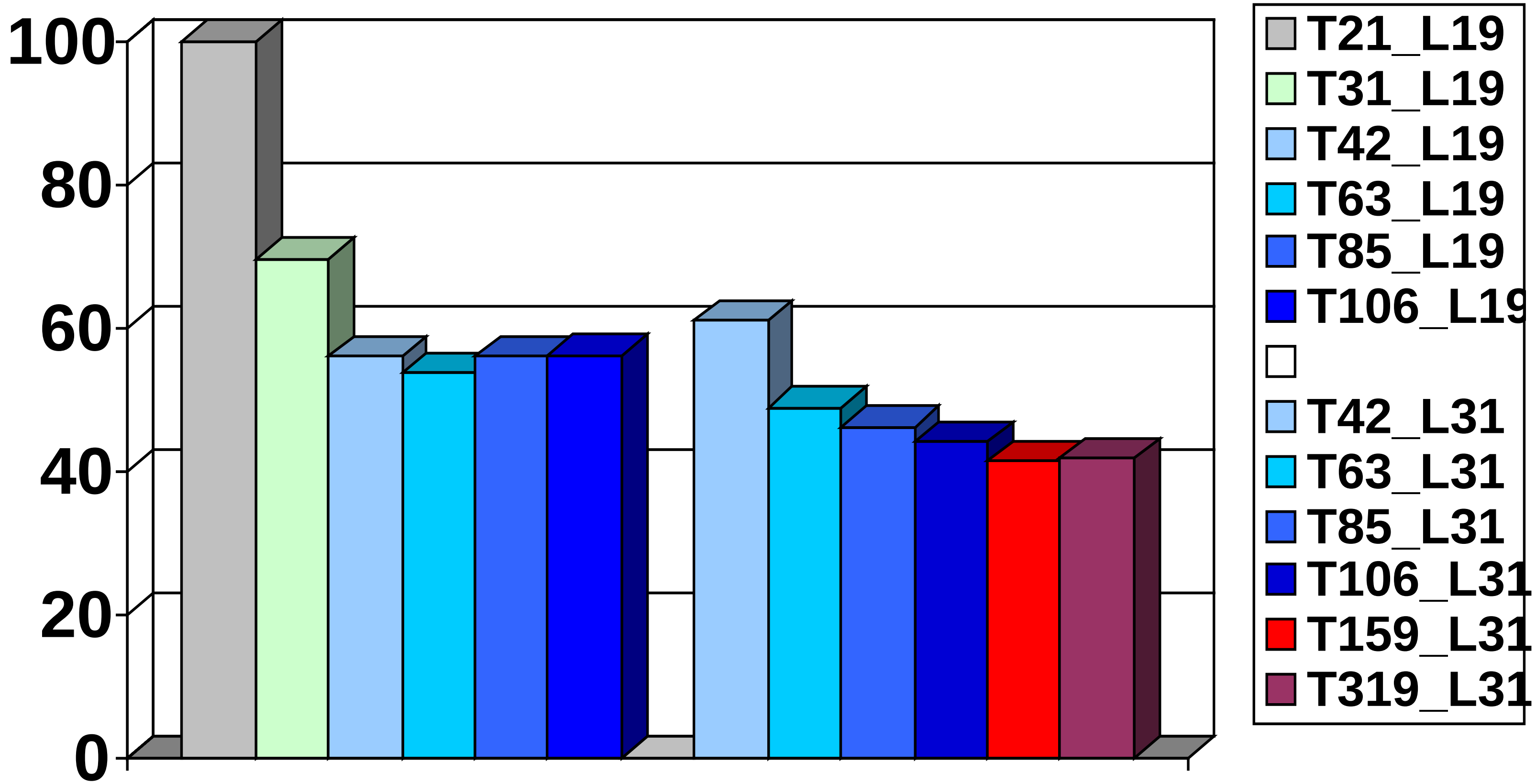
Doppler spread theory (Hines 1991, 1993, 1997)

- 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

Seasonal RMSE in % of T21L19 errors
Reference: ERA40 (1979-1999)



Thank you