Convection parameterisations

Part II

WaVaCS summerschool
Autumn 2009
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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

Examples of convection schemes for larger scale models

Convection schemes

- more than 50 schemes in the peer – reviewed literature
- all schemes fulfill the characteristics described previously, but differ:
  - in the closure assumptions
  - in the detailedness
  - in the (numerical) formulations
- some schemes are more useful for meso – scale, others for global modelling
- each model with a resolution of more than a few km needs a convection parameterisation to treat non – resolved smaller clouds

Convection schemes

- Sometimes a differentiation between schemes and concepts is not straight – forward, e.g. the "moisture adjustment" scheme of Manabe et al (1965) is both a scheme, but also a concept on which other schemes are based.
- Organisation of convective clouds is one of the most outstanding issues for convection parameterisations.
- All schemes perform an adjustment of moisture and energy by redistribution and precipitation processes.
- **All schemes will have an impact on the model results.**

Arakawa – Schubert – Scheme (I)

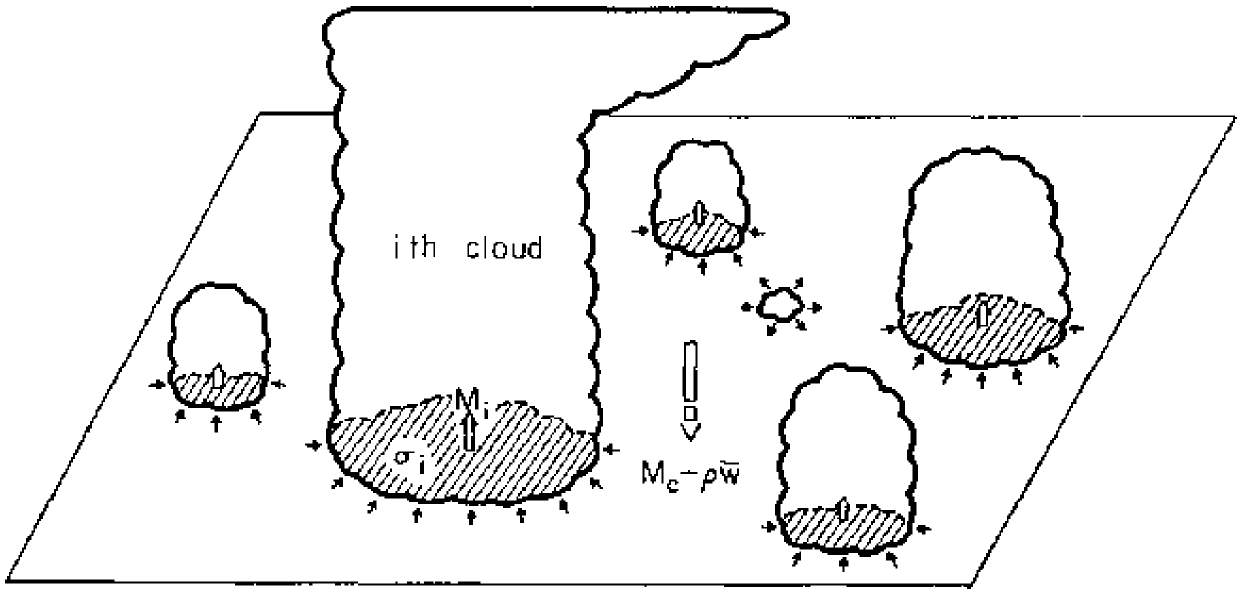


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

Arakawa, 1974

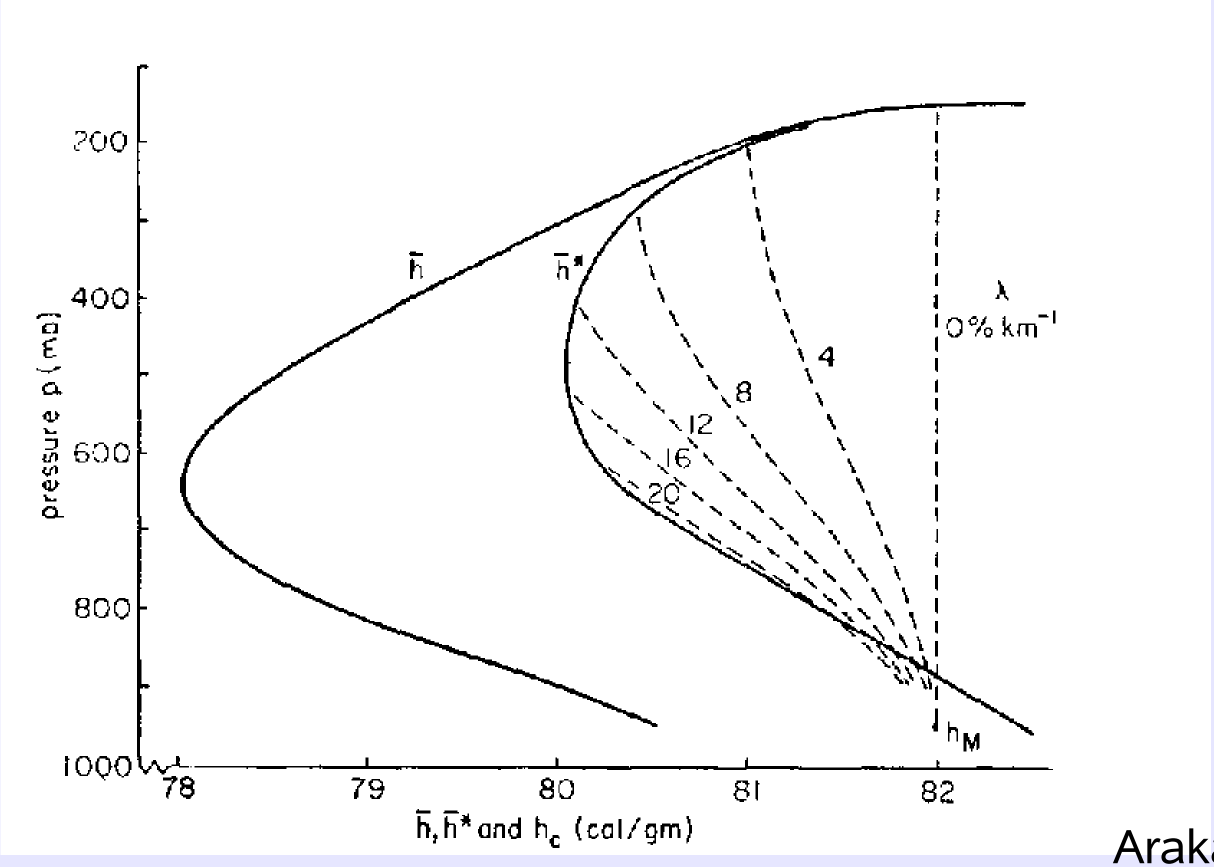
Arakawa – Schubert – Scheme (II)

- originally presented by Arakawa & Schubert (Journal of Climate, 1974)
- considers three types of clouds:
  - shallow PBL clouds
  - deep clouds originating from the PBL
  - mid – level convection (deep clouds originating from above the PBL)
- inclusion of mass – balancing subsidence
- treatment of entraining up – and downdrafts
- combination of type I and type II closure

Arakawa – Schubert – Scheme (III)

- a spectral (in terms of cloud height) distribution of clouds

$$M_c(z) = \int_0^{\lambda_{max}} m_B(\lambda)\eta(z,\lambda)d\lambda$$



Arakawa, 1974

Arakawa – Schubert – Scheme (IV)

- cloud base conditions from boundary layer scheme (mixed layer s_M, q_M, h_M)
- no feedback on the sub – cloud layer
  (in the original version, updates include a downdraft model)
- some drawbacks:
  - solution is not a 100% positive definite

  => complicated to implement in a GCM
- several updates / implementation strategies

Convective Cloud Field Model (I)

- substantial extension to Arakawa – Schubert (Nober & Graf, ACP, 2005)
- single cloud model + cloud spectrum calculations
- entraining parcel model (at a very high vertical resolution of 100m)
- “cloud” (=entraining parcel) types, that can exist at different initial conditions

Convective Cloud Field Model (II)

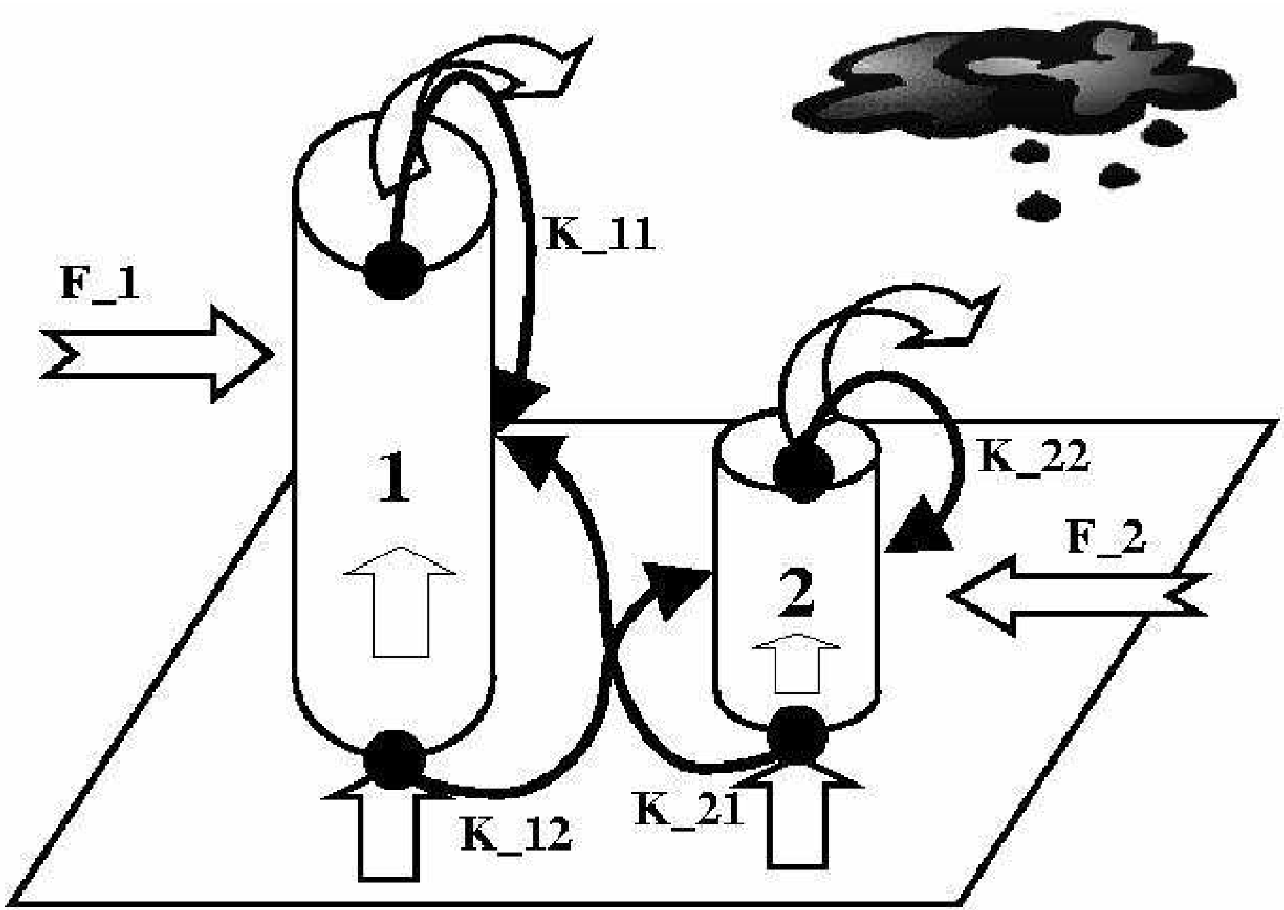


Fig. 4. Graphical description of the Convective Cloud Field Model.

Nober & Graf, 2005

Convective Cloud Field Model (III)

- existence of the different cloud types determined by the Lotka – Volterra equation (principles of population dynamics)

$$\frac{dn_i}{dt} = n_i \cdot r_i \left(1 - \sum_{j=1}^{N} \alpha_{ij} \cdot n_j \right)$$

n_i	=	population member
r_i	=	environmental factor
α_{ij}	=	interaction matrix factors

- individual clouds compete for CAPE
- Lotka – Volterra equation for clouds is mostly not chaotic, but yields a stationary solution!

Convective Cloud Field Model (IV)

- individual clouds depend on boundary layer parameters for triggering of convection
- generalisation of Arakawa – Schubert:
  - kinetic energy equilibrium is not assumed
  - using an explicit cloud model
  - stationarity is not assumed => dynamical evolution over sub – timesteps

=> diagnostic at the end of a GCM timestep

Tiedtke – Scheme (I)

- original description (1989), but with many modifications (also updates depending on the base model)
- **Mass flux scheme of a cloud ensemble** (better of a mass flux ensemble): $M = \sum_i M_i = \sum_i \bar{\rho} \sigma_i w_i$
- original: moisture – convergence closure, updates: CAPE relaxation closure
- used in ECMWF, ECHAM, COSMO, REMO,……

Tiedtke – Scheme (II)

- basic equations:

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

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

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

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

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

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

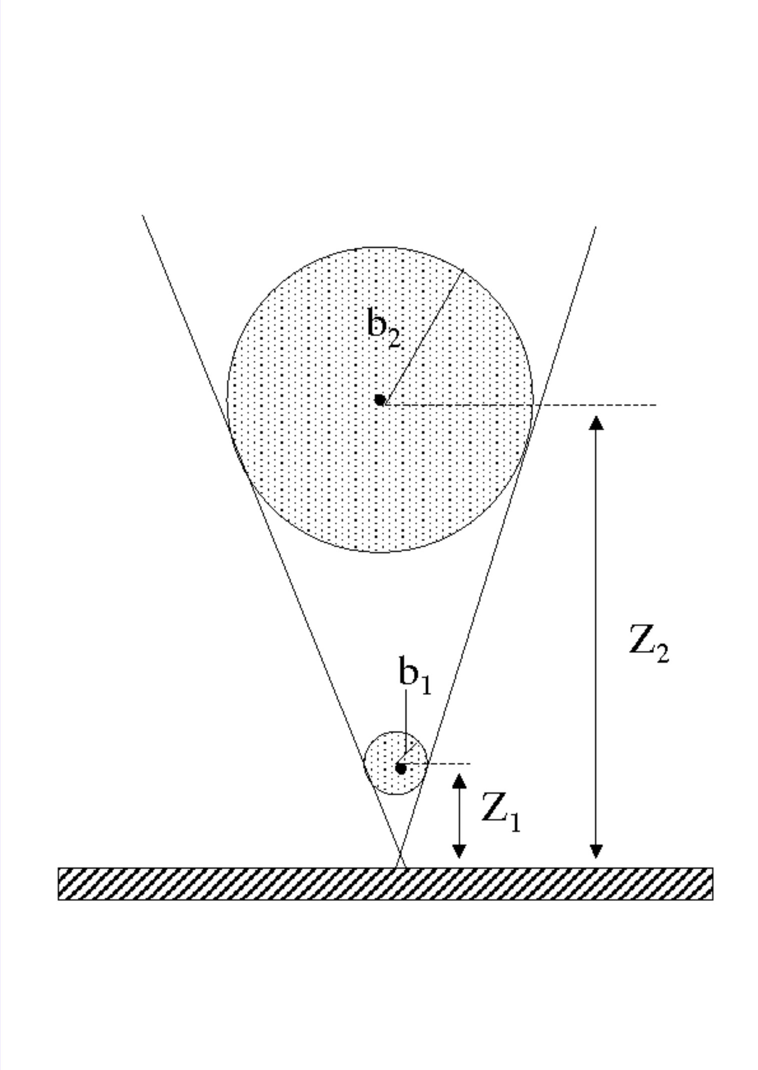
E = Entrainment
D = Detrainment
c_u = release of latent heat from condensation
P_u = precipitation formation

- similar set of equations for downdrafts

Tiedtke – Scheme (III)

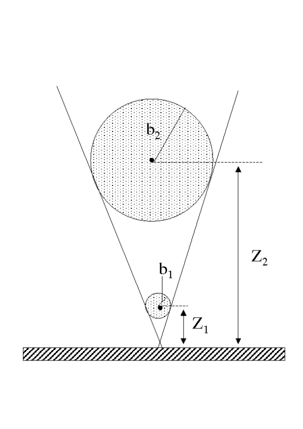
- organised entrainment:
  - for a single cloud of the ensemble:

$$E_i = M_i \epsilon_i$$



Tiedtke – Scheme (III)

- organised entrainment:
  - for a single cloud of the ensemble: $E_i = M_i \epsilon_i$
  - for the whole ensemble: $E = M\epsilon = \sum_i M_i \epsilon_i = \sum_i E_i$
- organised detrainment: $E = M\delta = \sum_i M_i \delta_i = \sum_i D_i$
  - analogous:
- $\frac{\partial M_u}{\partial z} = E_u - D_u$ => $\frac{1}{M_u}\frac{\partial M_u}{\partial z} = \epsilon_u - \delta_u$



Tiedtke – Scheme (IV)

- Transport of momentum:

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

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

  - Entrainment of momentum into the convective plume from the surrounding air
  - vertical momentum displacement by mass – balancing subsidence
  - convection induced pressure changes

Tiedtke – Scheme (IV)

- Transport of momentum:

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

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

  - Entrainment of momentum into the convective plume from the surrounding air
  - vertical momentum displacement by mass-balancing subsidence
  - convection induced pressure changes

NOT USED IN THIS SCHEME

Tiedtke – Scheme (V)

- adjustment closure:

$$\frac{\partial \bar{T}}{\partial t} \approx \frac{1}{\bar{\rho} c_p} \frac{\partial \bar{s}}{\partial z}$$

$$\frac{\partial \bar{q}}{\partial t} \approx \frac{1}{\bar{\rho}} \frac{\partial \bar{q}}{\partial z}$$

- using CAPE relaxation:

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

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

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

$$M = M_B * \eta(z)$$

Tiedtke – Scheme (V)

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

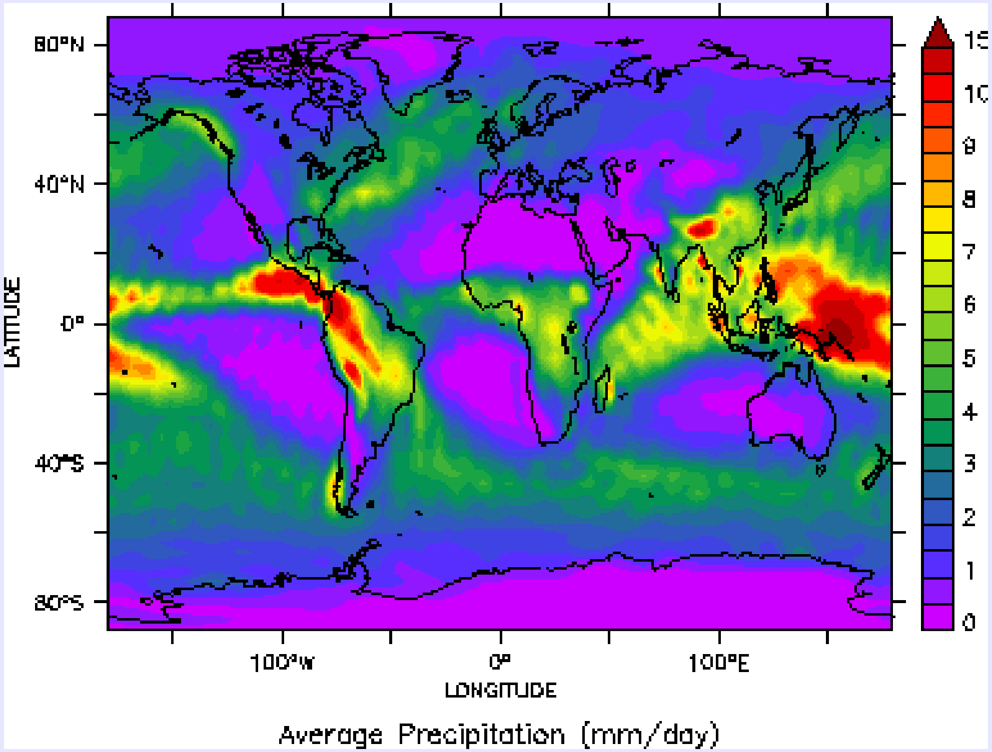
- initially M_B is calculated from moisture convergence, since η is not know initially

$$\tau = MIN(3\cdot 3600, 2\cdot 3600\cdot 63/NN)$$

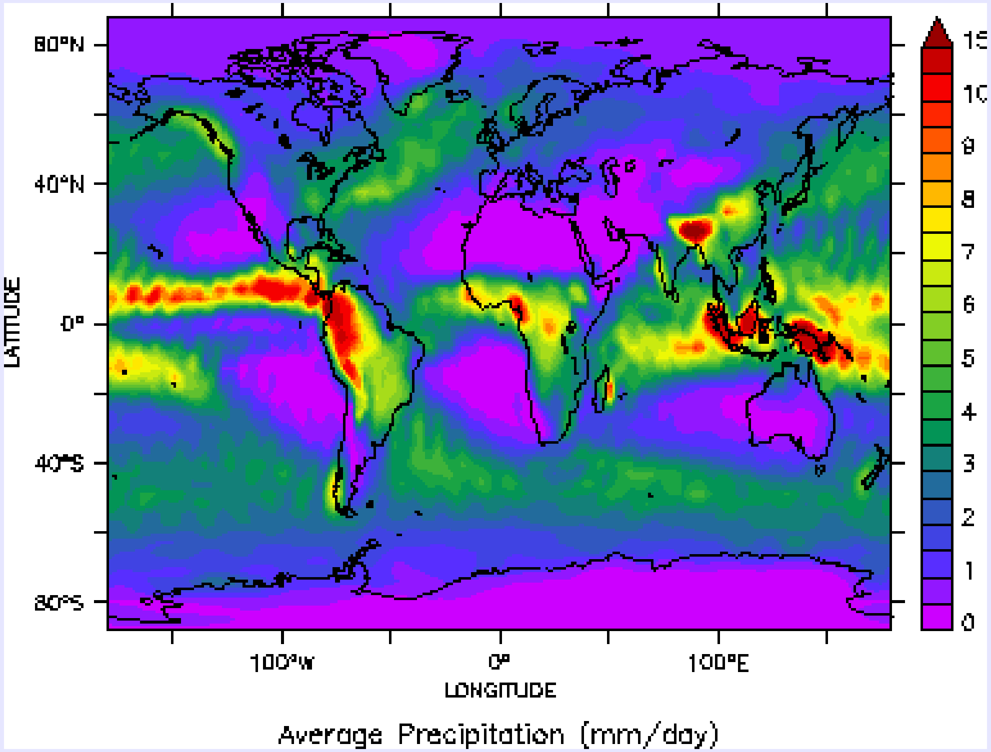
- τ should be smaller with increasing resolution (NN is the spectral resolution)

Tiedtke – Scheme (V)

5 year average precipitation using the Tiedtke – scheme with 2 different closures



CAPE closure



Moisture convergence closure

Tiedtke – Scheme Flowchart (VI)

- Define constants, parameters and specific values (T,q,q_{sat},s), initialise updraft and downdraft values
- Calculate cloud base, cloud base mass flux from moisture convergence and boundary moisture supply
- Cloud ascent in absence of downdrafts (ascent for an entraining / detraining plume, including phase transitions and momentum)
- Downdraft calculation:
  - Level of free sinking (LFS)
  - moist descent (descent for an entraining / detraining plume, dry - adiabatically descent, including phase transitions and momentum)

Tiedtke – Scheme Flowchart (VI)

- Recalculate cloud base mass flux from CAPE calculations including downdraft effects
- Recalculate ascent (as before, same routine)
- Adjustment of convective fluxes
- Evaporation of precipitation in sub – cloud layer
- Final Tendencies for T and q, u and v

Super - Parameterisation

- Running a Cloud Resolving Model (CRM) in each GCM grid box (first proposed by Grabowski, 2001)
- CRMs with a grid size of 1 km resolve convection
- Eliminates artificial distinction between large – scale and convective clouds, only this CRM is required
- CRMs can be used in 2D (oriented orthogonal to the main wind direction of that grid box) or 3D configuration
- Require lots of computational resources

- First studies show a weaker cloud forcing than in traditional GCMs

Global Cloud Resolving Model

- Running a fine resolution model for the whole globe
- Initiatives in Japan (Earth Simulator) and USA
- $\Delta x_{min} = 2$ km
- Planning, testing (aqua – planet) and implementation phase
- Require even more resources than super – parameterisations (USA project plans realtime simulations)
- Create huge amounts of data (1 Tb for hourly snapshot)

Convection Schemes for Mesoscale Models

Convection in Mesoscale Models

- convection still not resolved (Δx = 10 to 50 km)
- less distinction between convective (subgrid – scale) and grid – scale condensation / precipitation formation
- organisation of convection more important
- hydrostatic assumption not valid for all host models

=> Specially designed schemes for this scale

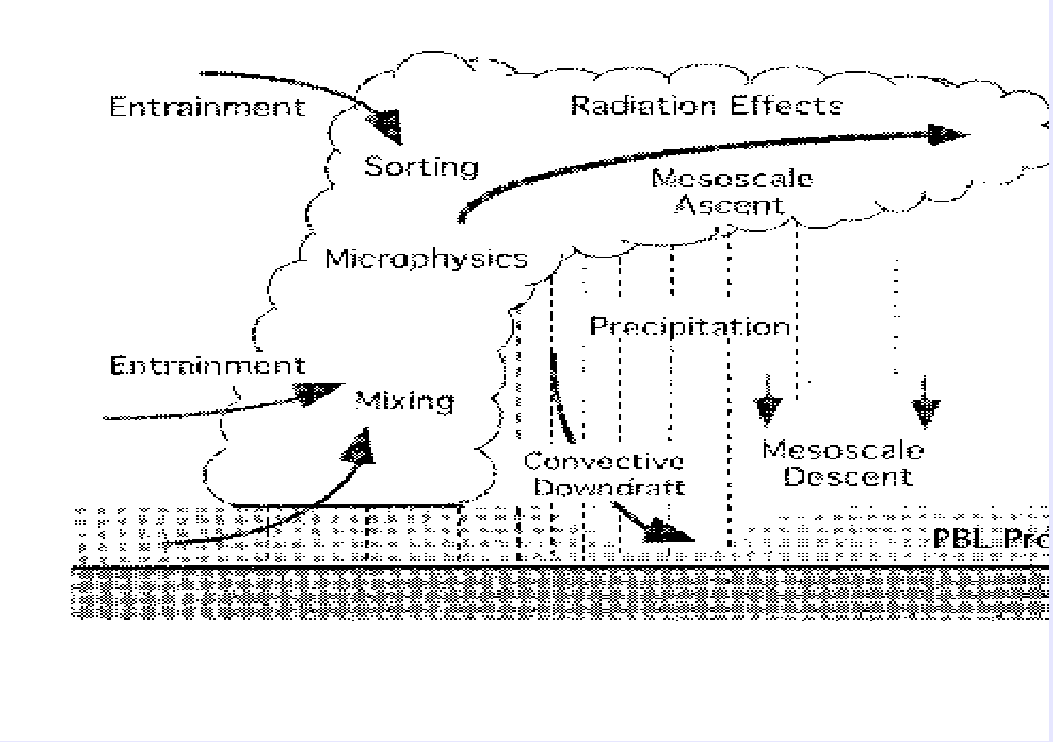
Scale separation

- larger scale schemes require a (spectral) gap between resolved and parameterised scales
  - eddies have much smaller time scale than grid – scale motions => influence can be diagnosed
- dependent on input values similar clouds appear "convective" (=parameterised) or "large-scale" (=resolved)

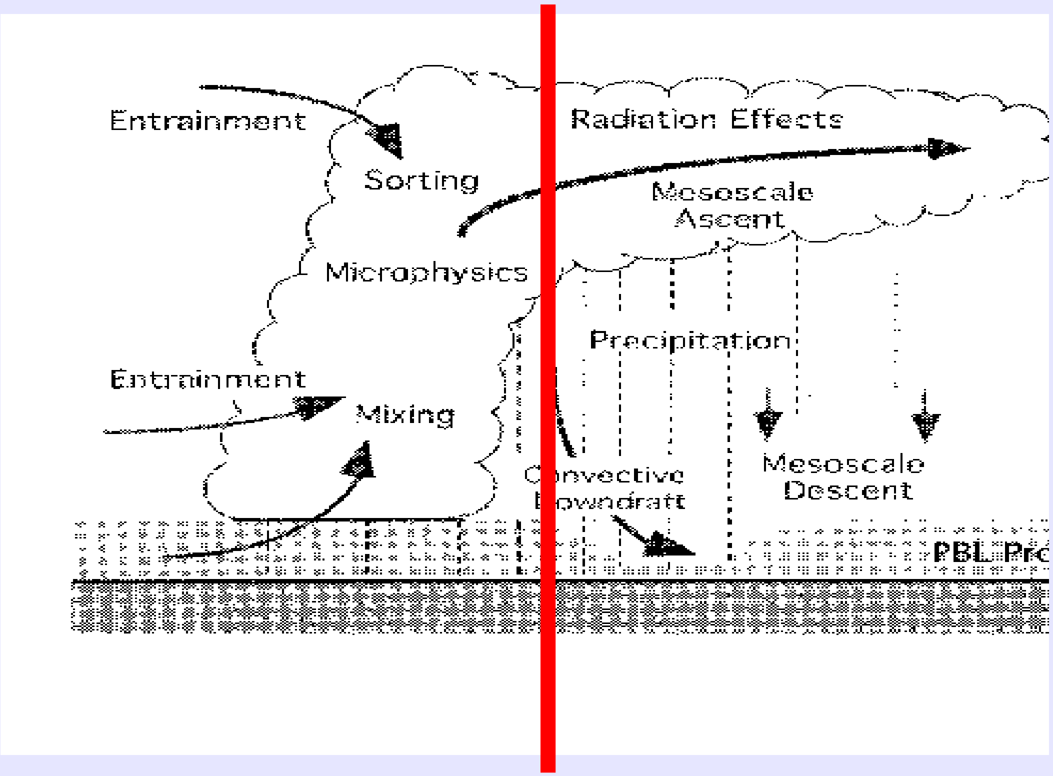
=> Hybrid approach:

- evaporation, condensation and vertical momentum fluxes parameterised
- moisture and heat fluxes from detrained water between the clouds not parameterised

Organisation of convection



Organisation of convection

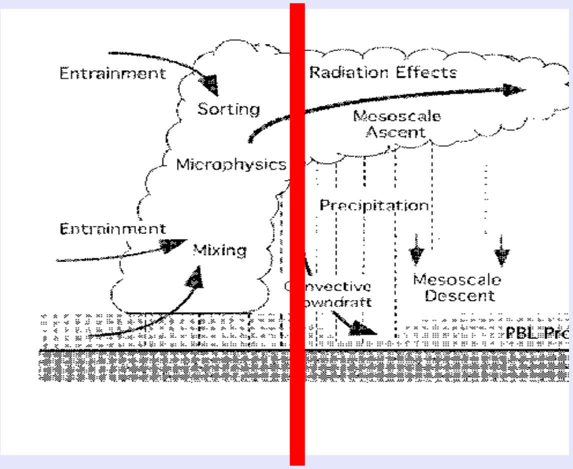


- Outflow might be in the next grid box
- Precipitation might get horizontally advected

=> Next grid box: grid – scale moisture enhancement

- Mass balancing subsidence is not in the same grid box
- Downdrafts initiate further convection (squall line)

Organisation of convection



- HYMACS (Küll, EGU 2009)
  (<u>Hy</u>brid <u>Mas</u>s flux <u>C</u>onvection <u>S</u>cheme)
- parameterise updraft / downdraft only

=> <u>Net mass transport by convection scheme</u>

- subsidence treated by the grid scale motion
- simple cloud parcel model
- standard trigger and closure approaches

- applied in COSMO at dx = 7 km

Convection scheme application

Convection scheme application

- Implementation of several convection schemes in the EMAC (ECHAM5/MESSy Atmospheric Chemistry) model (Tost et al., 2006, ACP; 2007 ACP, 2009 ACPD)
- Impact of the convection scheme on the climate system
- Impact of the convection scheme on atmospheric chemistry

Convection submodel

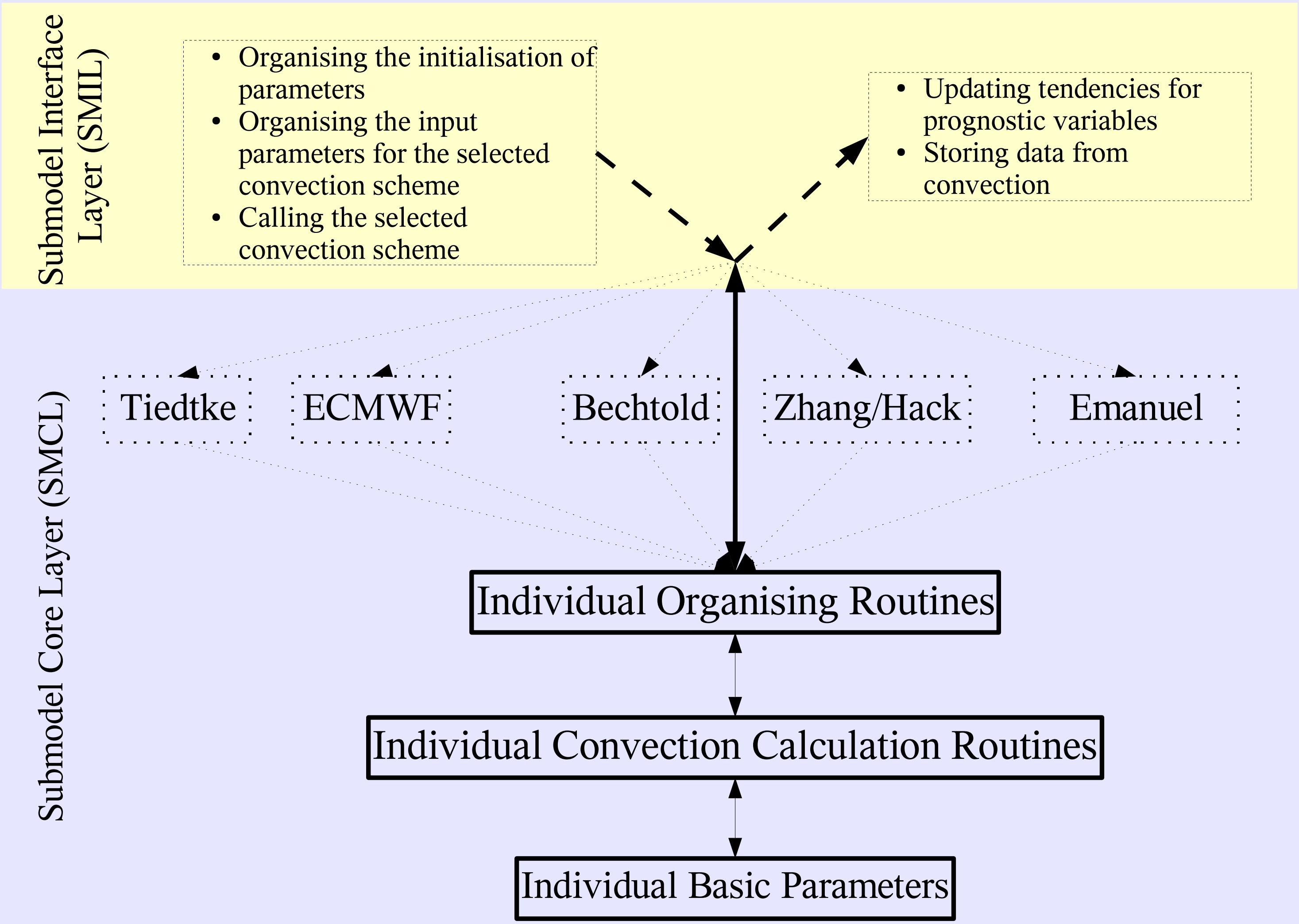
- 5 running schemes implemented (2 more in preparation):
  - Tiedtke (1989 original) and Tiedtke – Nordeng (1994)
  - ECMWF (IFS cycle 29) (Tompkins 2004; modified Tiedtke)
  - Zhang – McFarlane – Hack (1995, 1994)
  - Bechtold (2001)
  - Emanuel (2001)

Convection submodel

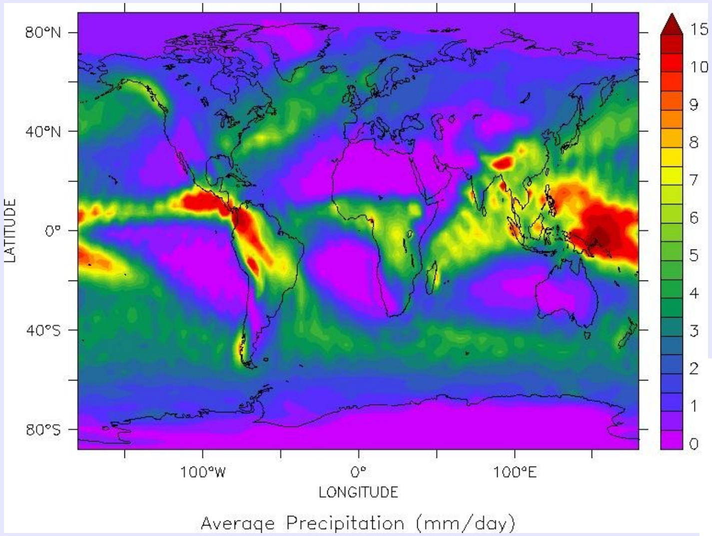
- All schemes are mass flux schemes
  (except the Hack extension of ZH)
- Process formulation differs

	Tiedtke	ECMWF	Zhang-McFarlane-Hack	Bechtold
Closure (deep)	CAPE / moisture convergence	CAPE	CAPE	CAPE
Entrainment	turbulent and organised	turbulent	turbulent	turbulent
Closure (shallow)	moisture convergence	1.) moist static energy 2.) w* (Grant and Brown, 1999)	moist static energy	CAPE
Trigger condition	$T_v^p + \Delta T > T_v^{env}$ $\Delta T = 0.5\,K$	$w_u > 0$ with w_u from entrainment and buoyancy (Jakob and Siebesma, 2003)	Zhang-McFarlane: $T_v^p + \Delta T > T_v^{env}$ $\Delta T = 0.5\,K$ Hack: $h_c - h_c^* > 0$	$\Theta_v^p + \frac{\Delta T}{\Pi} > \Theta_v^{env}$ $\Delta T = 6 \cdot \lvert\bar{w}\rvert^{1/3}$
Precipitation formation	$\Delta r = r_u^c/(1 + c_t \cdot \Delta z)$	proportional to $1/w_u$	Zhang-McFarlane: $\Delta r = c_0 \cdot r_u^c$ Hack: $\Delta r = (1-\beta) \cdot r_u^c$	$\Delta r_r + \Delta r_s = (r_u^c + r_u^i) \cdot \{1 - exp(-c_{pr} \Delta z / w_u)\}$

Convection submodel

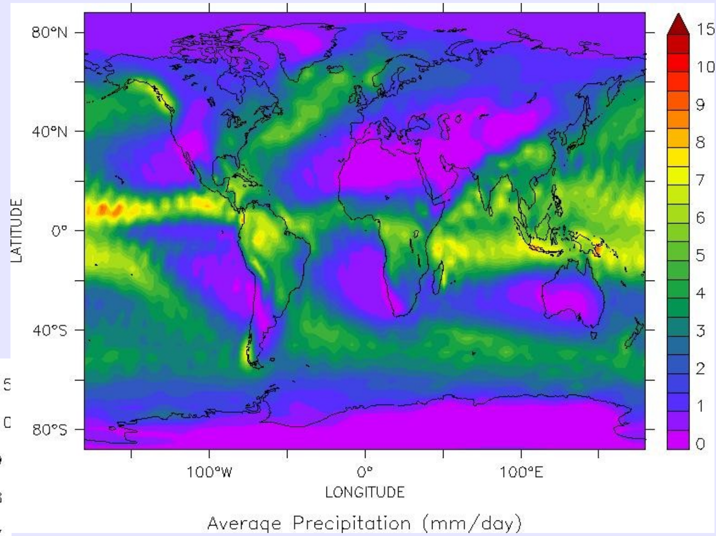


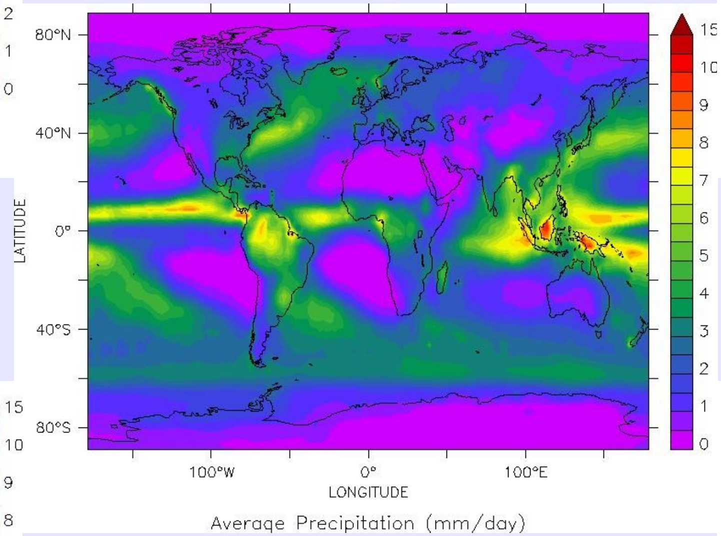
Precipitation Distribution (I)



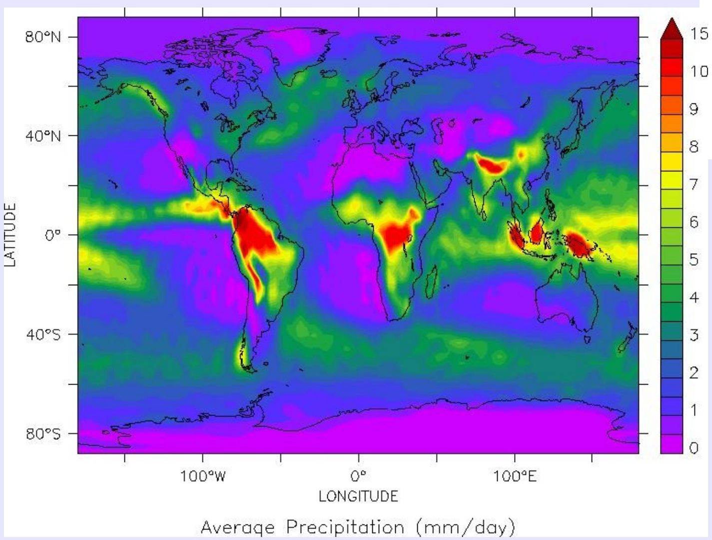
Tiedtke-Nordeng

ECMWF



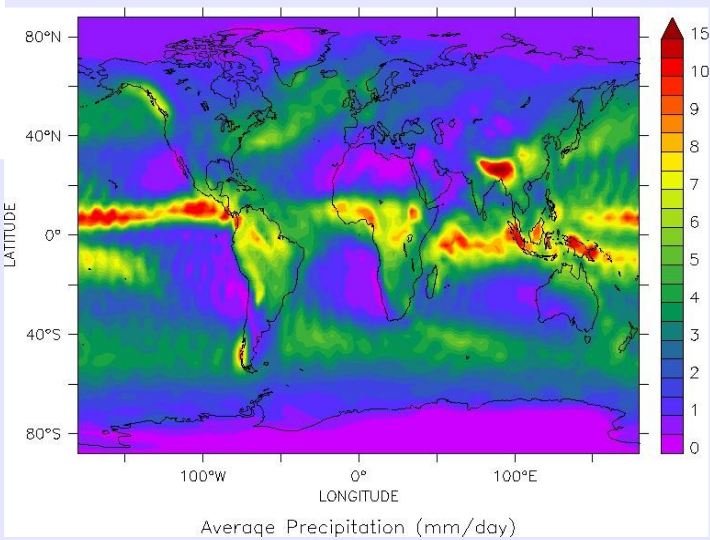


Observations (GPCP)

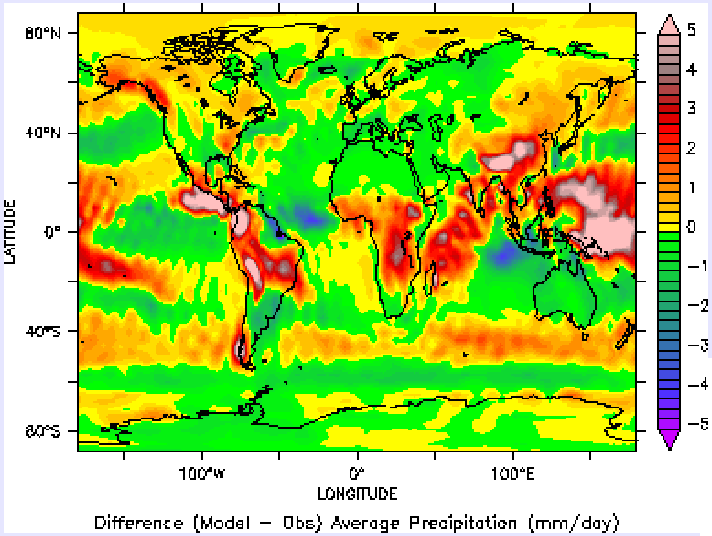


Zhang-McFarlane-Hack

Bechtold

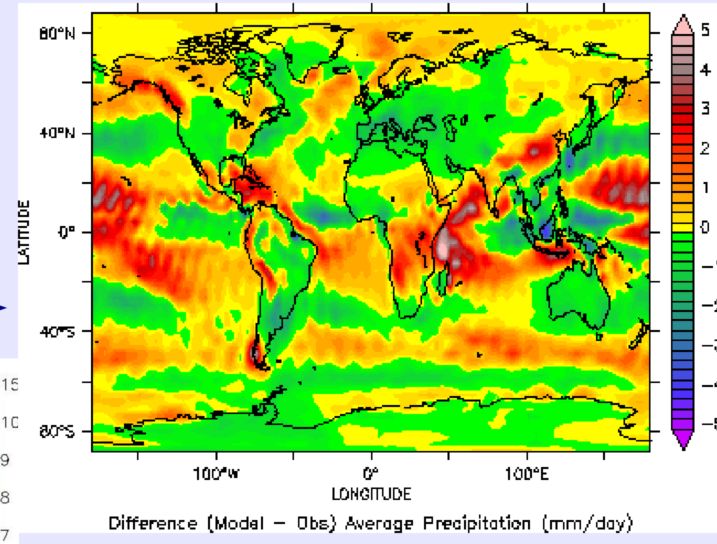


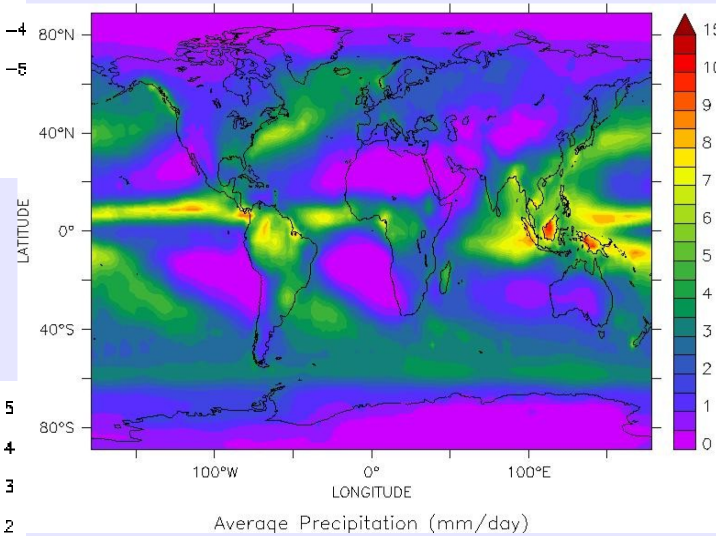
Precipitation Distribution (II)



Tiedtke-Nordeng

ECMWF





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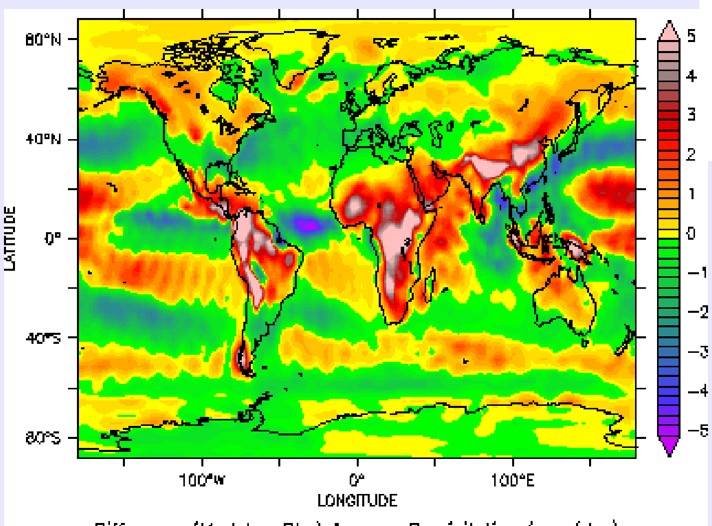
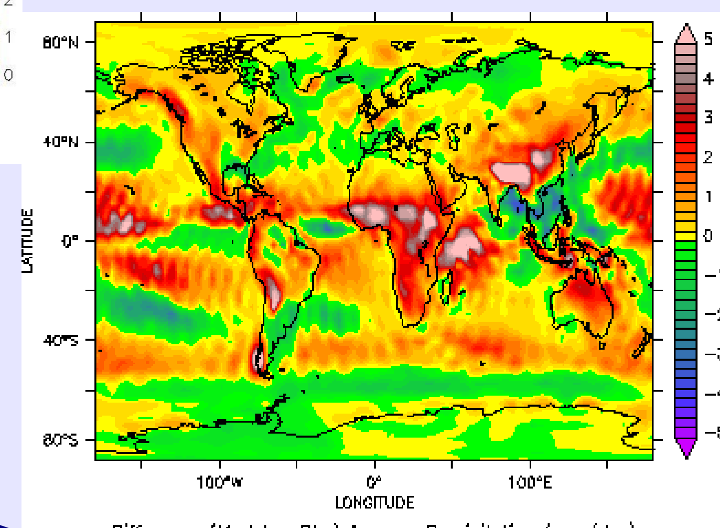


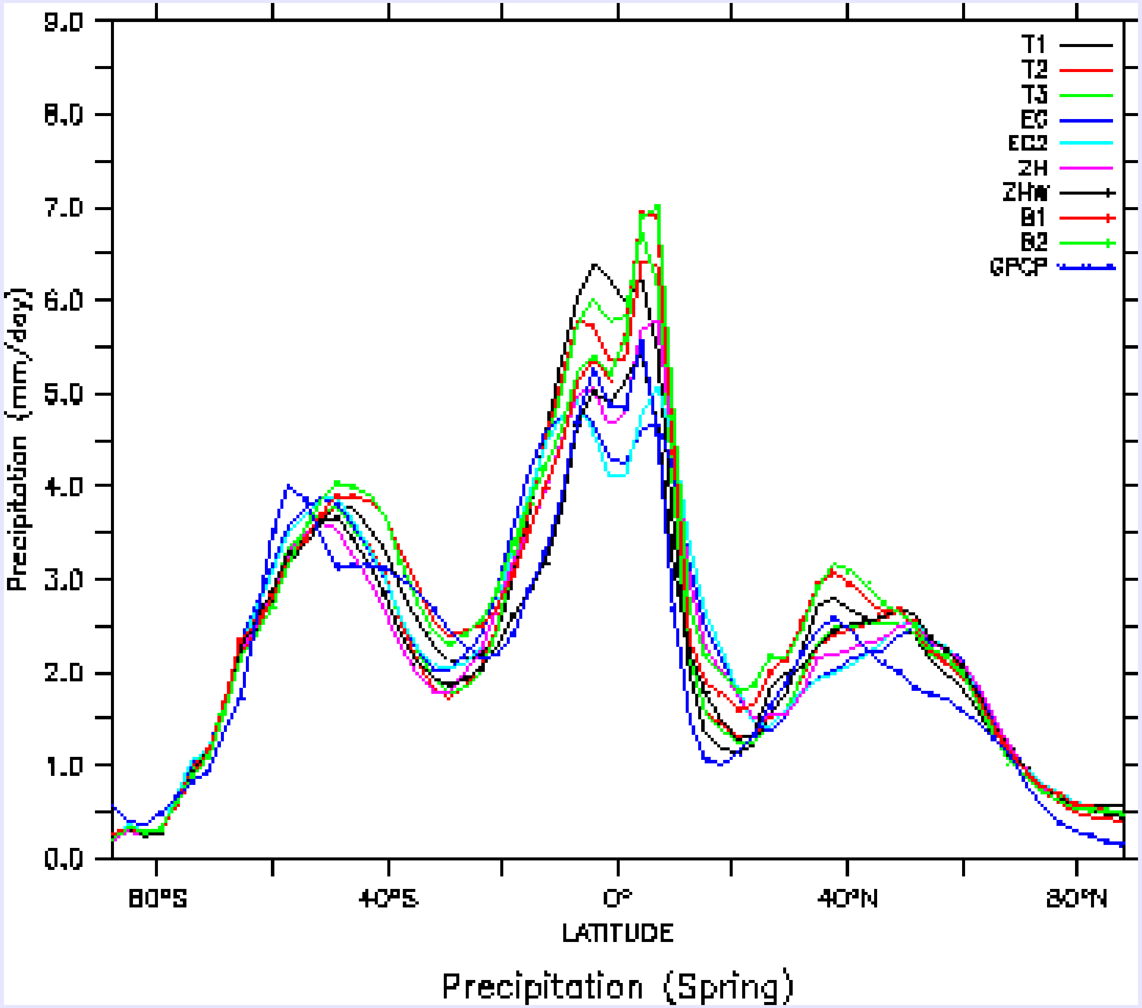
Zhang-McFarlane-Hack

Bechtold



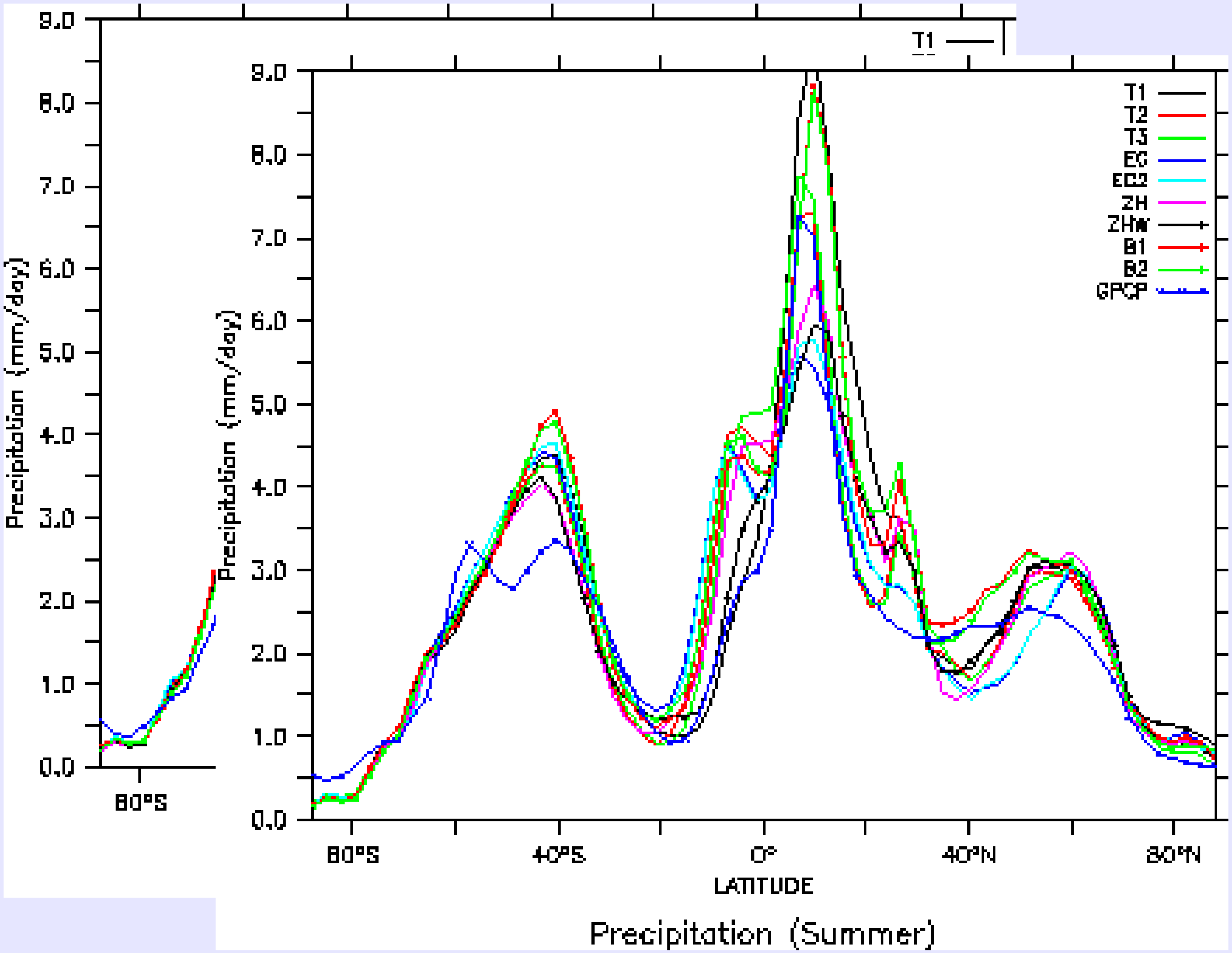
Precipitation Distribution (III)

Spring zonal average



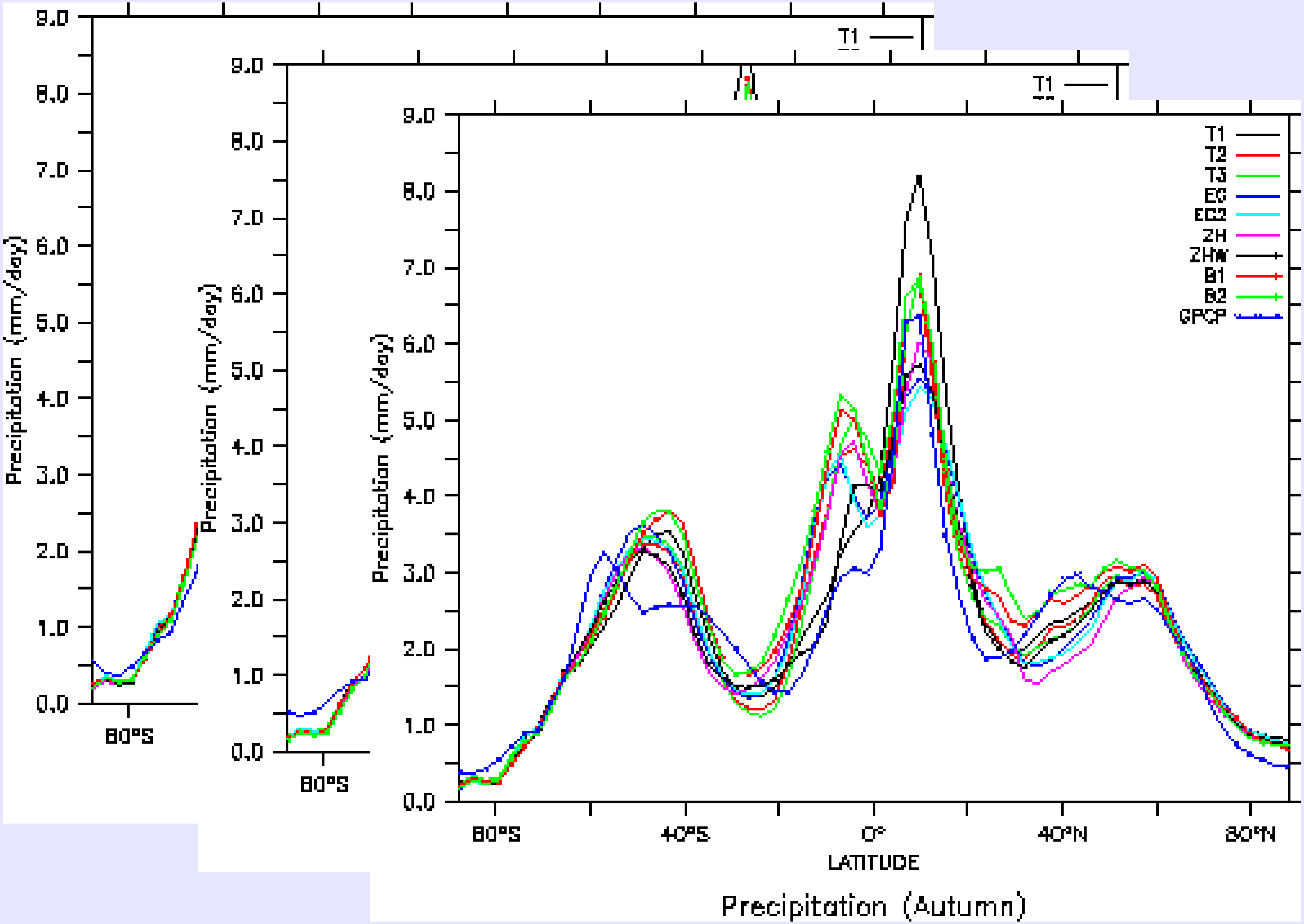
Precipitation Distribution (III)

Summer zonal averages



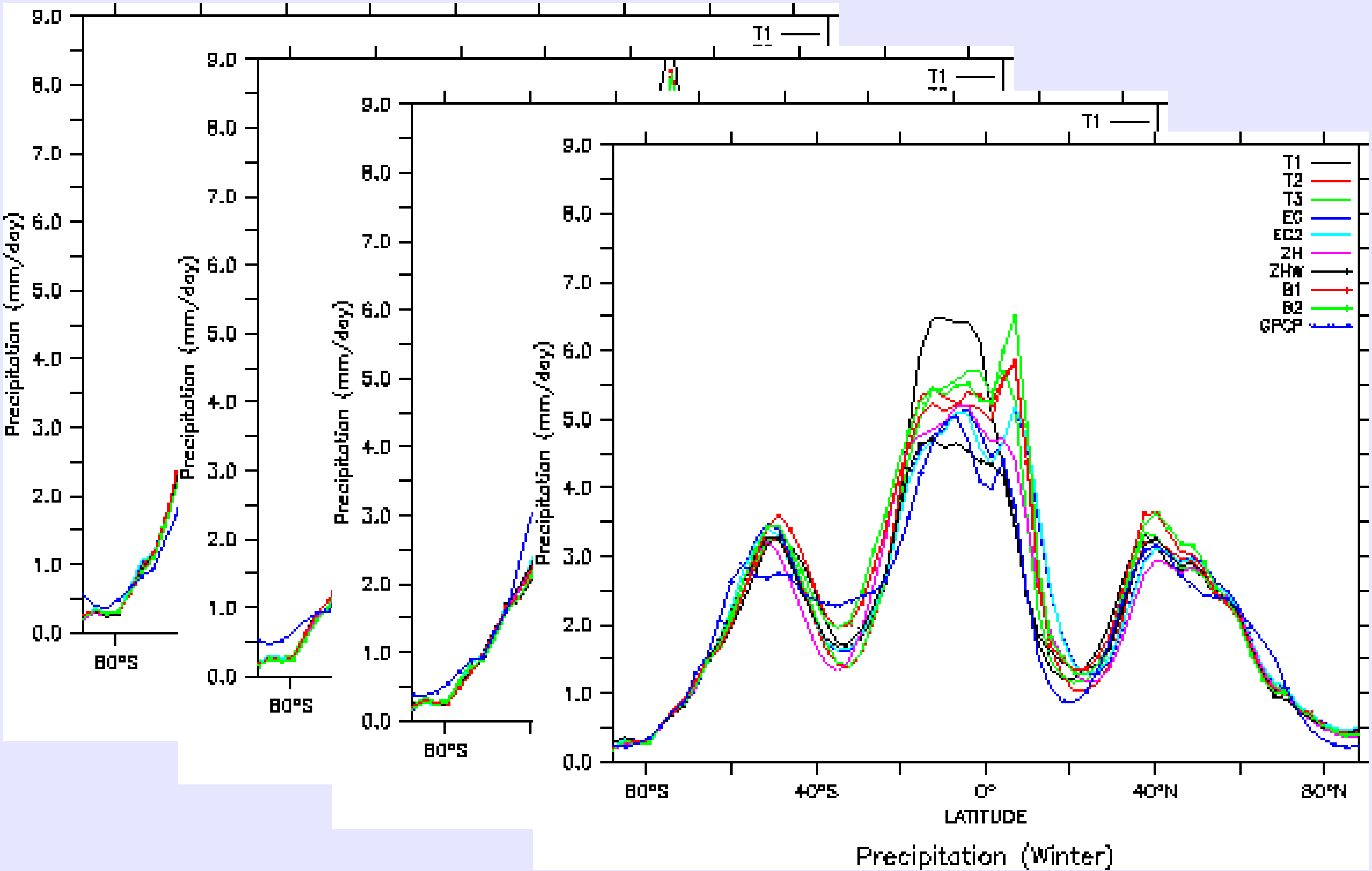
Precipitation Distribution (III)

Autumn zonal averages



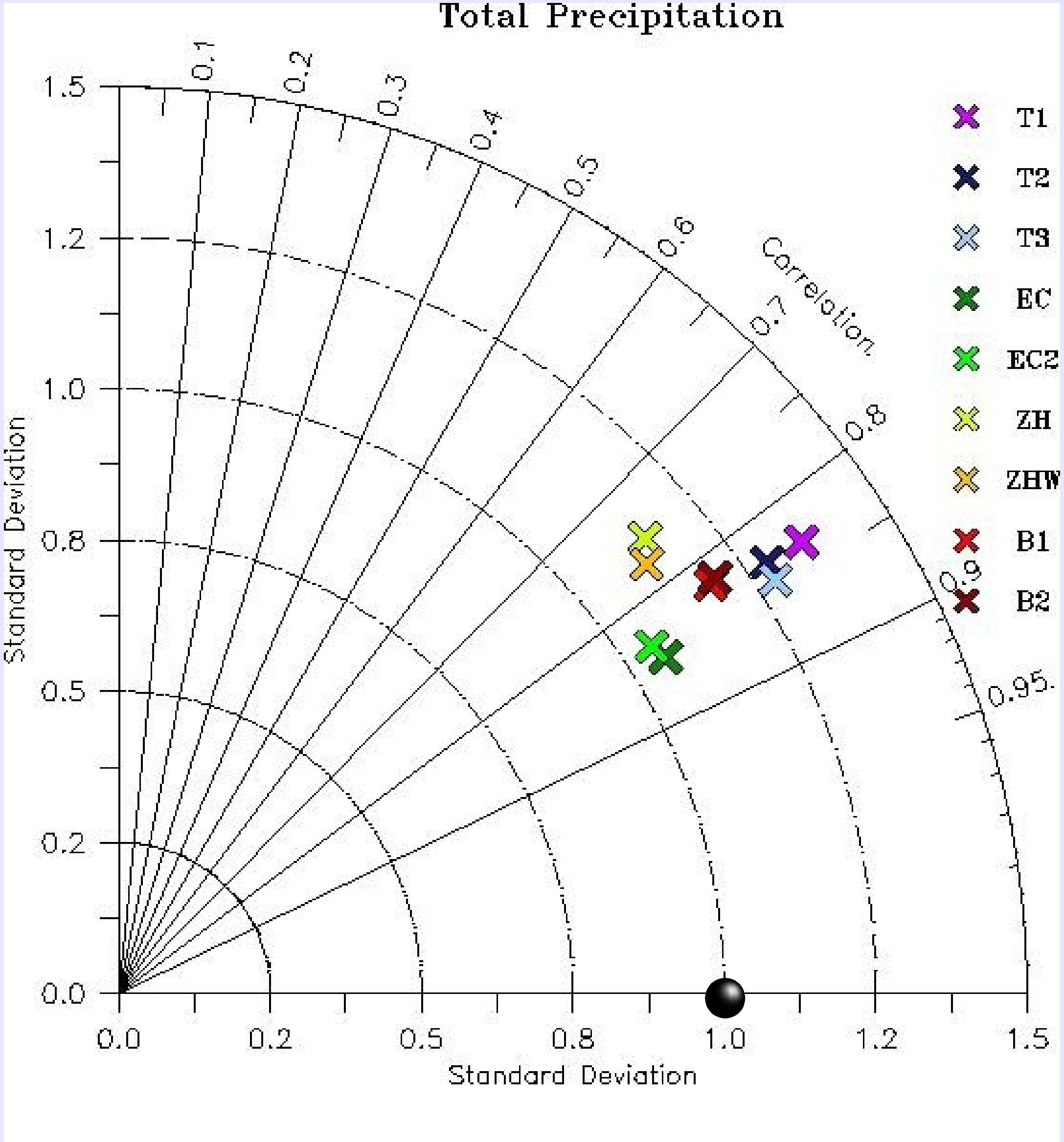
Precipitation Distribution (III)

Winter zonal averages



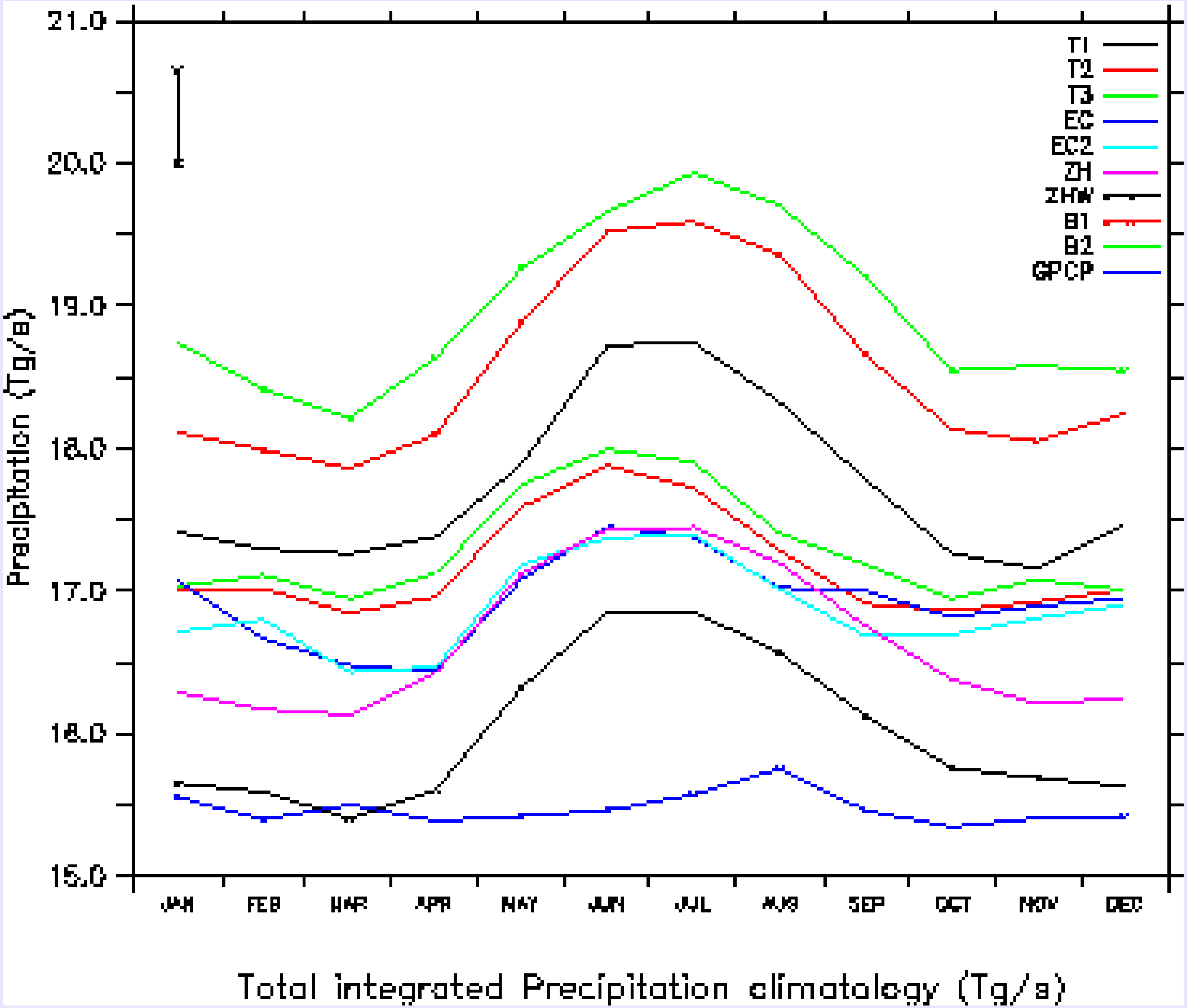
Precipitation Distribution (IV)

Taylor diagram



Precipitation Distribution (V)

Annual cycle



Precipitation Distribution (VI)

Contribution of convective and large – scale rain

Table 4. Average fraction of large-scale and convective precipitation for the different simulations, limited from 40° S to 40° N. The convective precipitation fraction according to TRMM 3A25 data is 51.9% for the low resolution and 50.1% for the high resolution data.

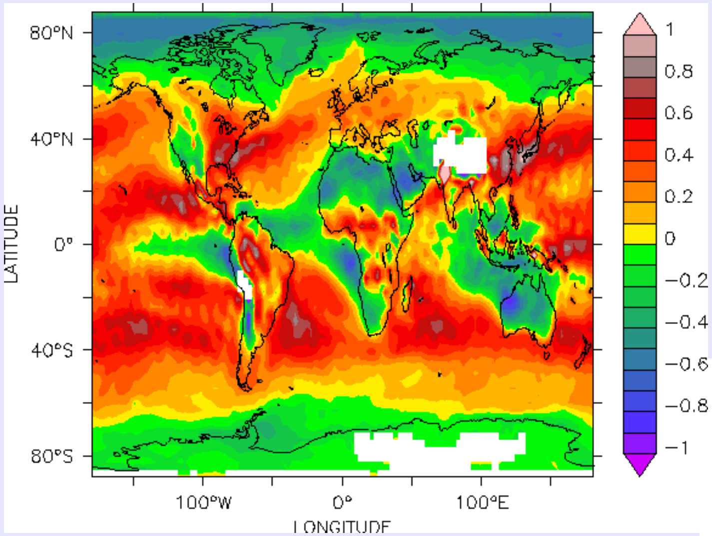
Simulation	Convective Precipitation Fraction [%]	Large-scale Precipitation Fraction [%]
T1	62.4	37.6
T2	75.4	24.6
T3	74.5	25.5
EC	75.5	24.5
EC2	78.1	21.9
ZH	95.0	4.5
ZHW	89.2	10.8
B1	74.1	25.9
B2	73.8	26.2

!

Moisture content of the atmosphere

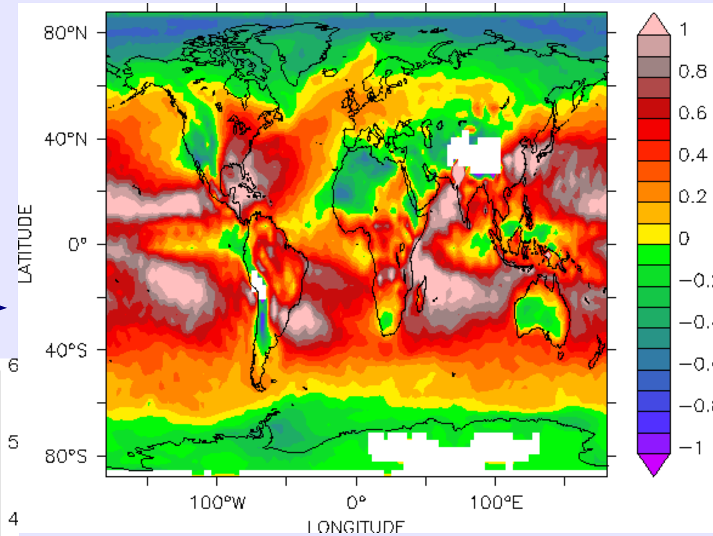
- Comparison with IWVC (Integrated Water Vapour Columns) observed from GOME satellite
- Be careful:
  - Satellite “observations” of such quantities have errors too !
  - Retrieval algorithms (= computer models, including simplifications and parameterisations) required to translate raw satellite data into quantities as IWVC

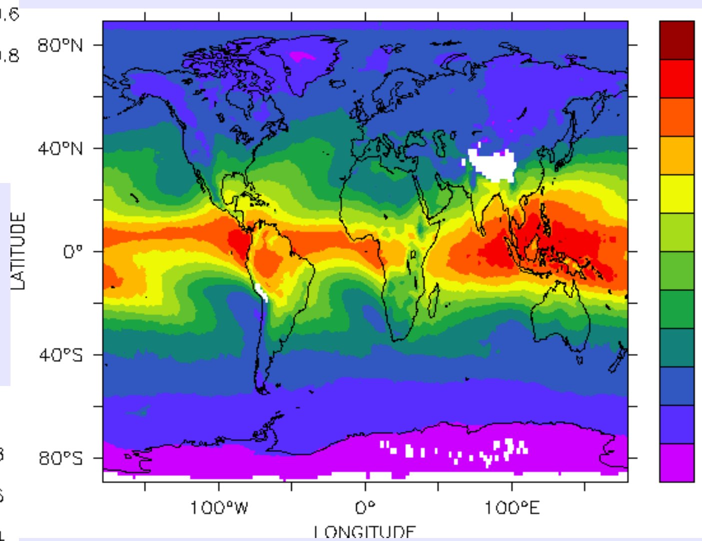
IWVC



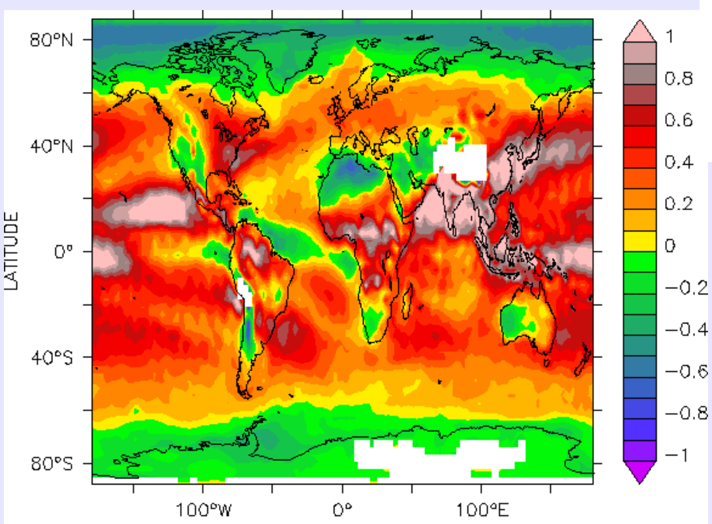
Tiedtke-Nordeng

ECMWF



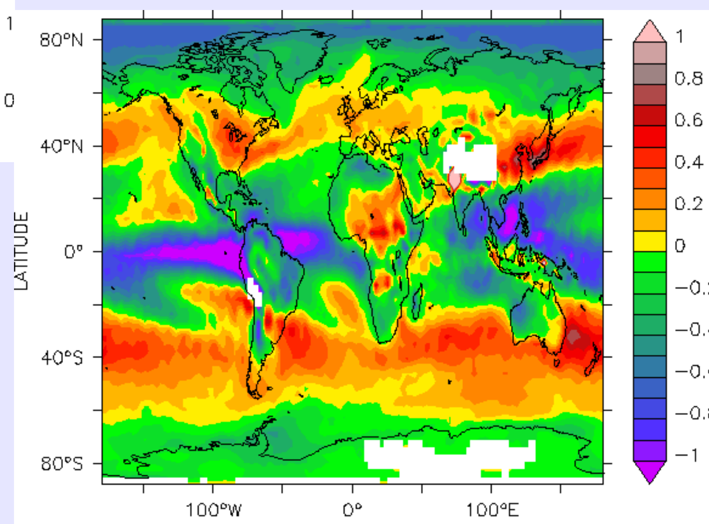


Observations (GOME)



Zhang-McFarlane-Hack

Bechtold

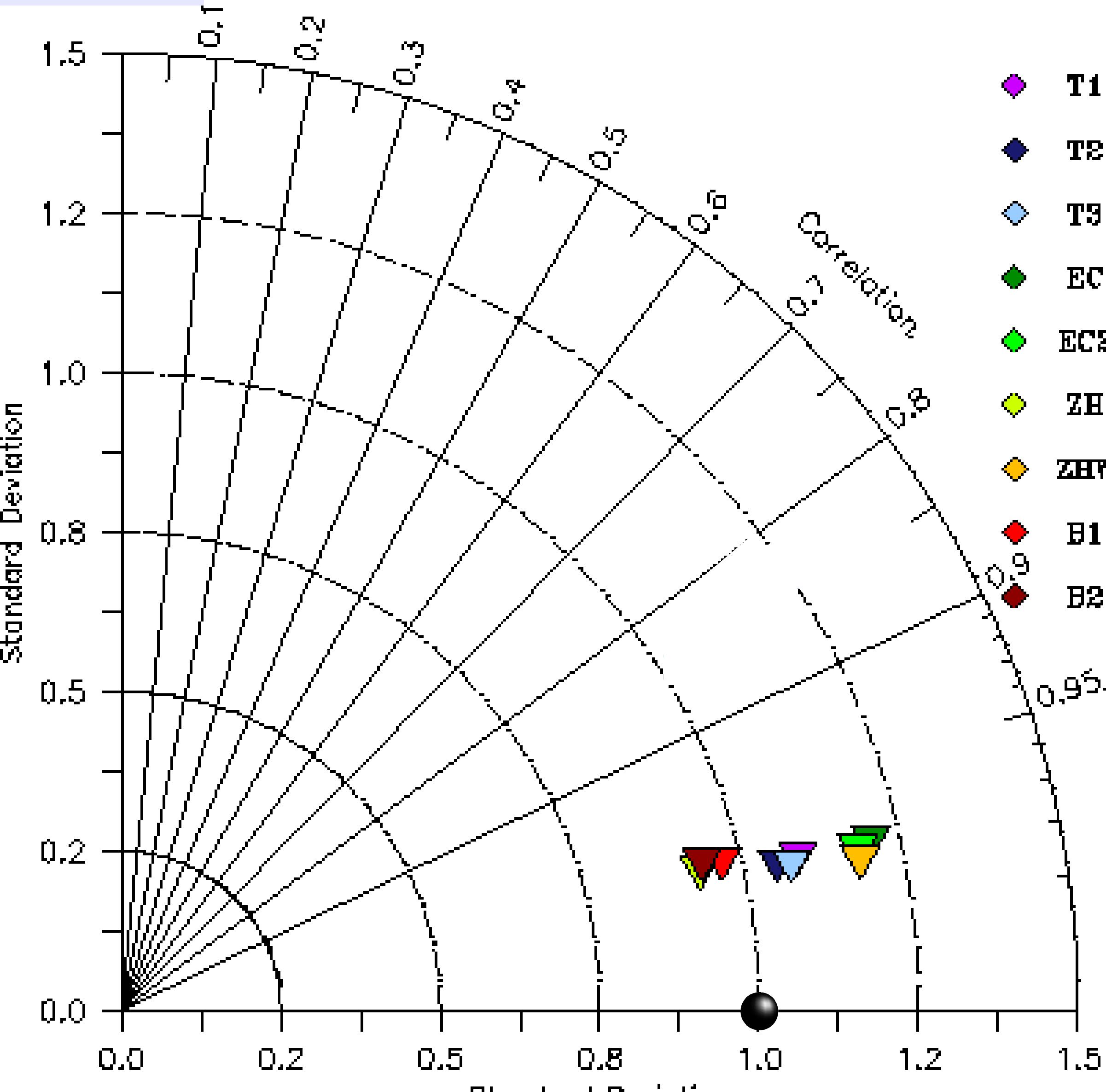


IWVC

Table 6. Comparison of the simulated and observed (GOME&SSM/I) IWVC values and distributions. The mean observed vertically integrated water vapour column is 2.33 cm. For both model and observations the mean values are area weighted. The root mean square error (RMSE) is calculated after the bias has been subtracted. R^2 is the correlation coefficient, the linear regression between model and observations is listed in terms of slope and intercept.

–	mean [cm]	bias [cm]	bias [%]	RMSE [cm]	R^2	slope	intercept
T1	2.51	0.17	7.4	0.30	0.94	1.01	0.13
T2	2.44	0.11	4.8	0.28	0.94	0.97	0.16
T3	2.48	0.15	6.3	0.27	0.94	0.99	0.14
EC	2.66	0.33	14.2	0.36	0.94	1.09	0.09
EC2	2.62	0.28	12.2	0.33	0.94	1.07	0.08
ZH	2.26	−0.07	−3.0	0.35	0.91	0.86	0.23
ZHW	2.67	0.34	14.4	0.31	0.95	1.09	0.10
B1	2.31	−0.02	−0.7	0.33	0.93	0.90	0.19
B2	2.25	−0.09	−3.7	0.35	0.92	0.87	0.19

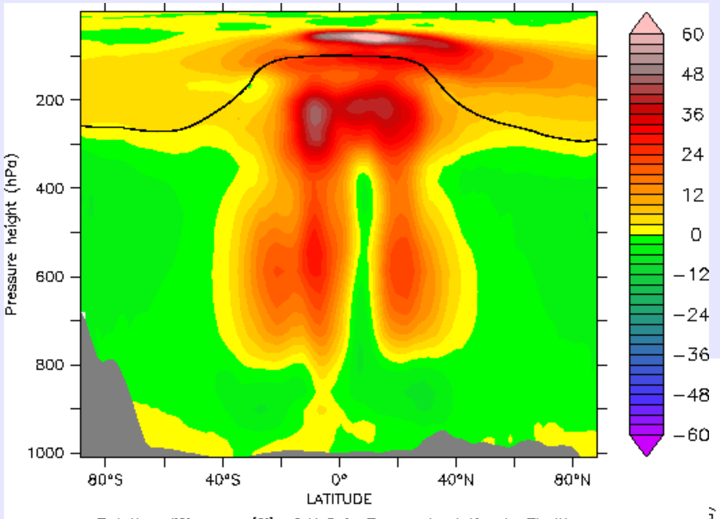
IWVC



IWVC values and distributions. The mean observed vertically
tions the mean values are area weighted. The root mean square
correlation coefficient, the linear regression between model and

RMSE [cm]	R^2	slope	intercept
0.30	0.94	1.01	0.13
0.28	0.94	0.97	0.16
0.27	0.94	0.99	0.14
0.36	0.94	1.09	0.09
0.33	0.94	1.07	0.08
0.35	0.91	0.86	0.23
0.31	0.95	1.09	0.10
0.33	0.93	0.90	0.19
0.35	0.92	0.87	0.19

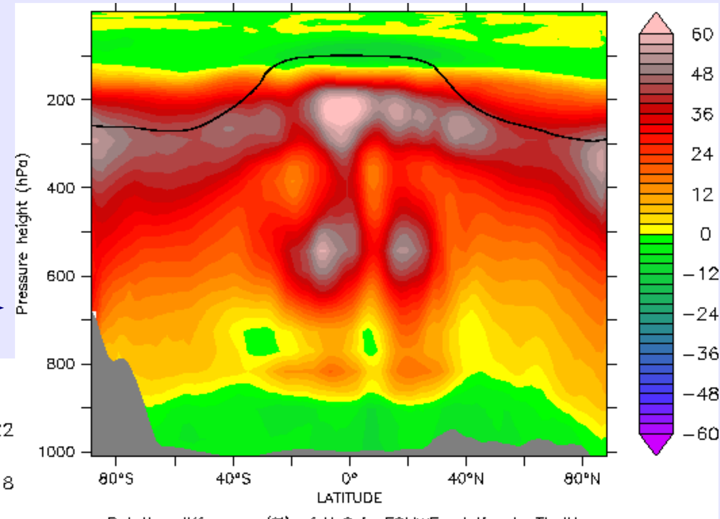
Zonal mean moisture differences



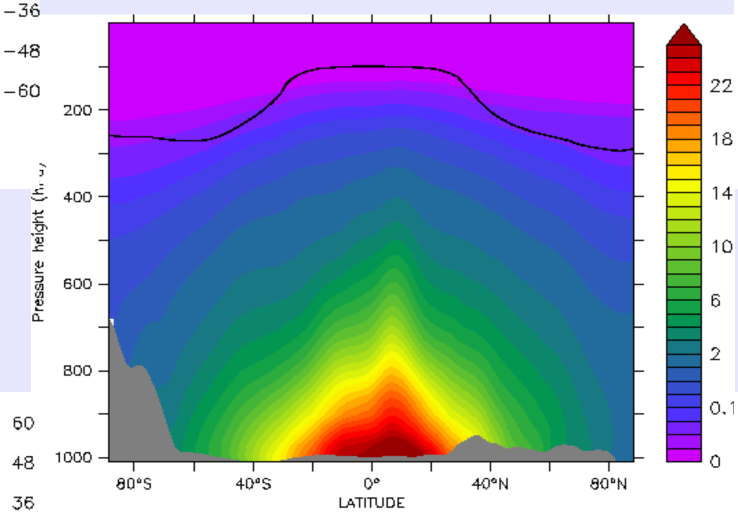
Relative difference (%) of H_2O in Emanuel relative to Tiedtke

Emanuel

ECMWF

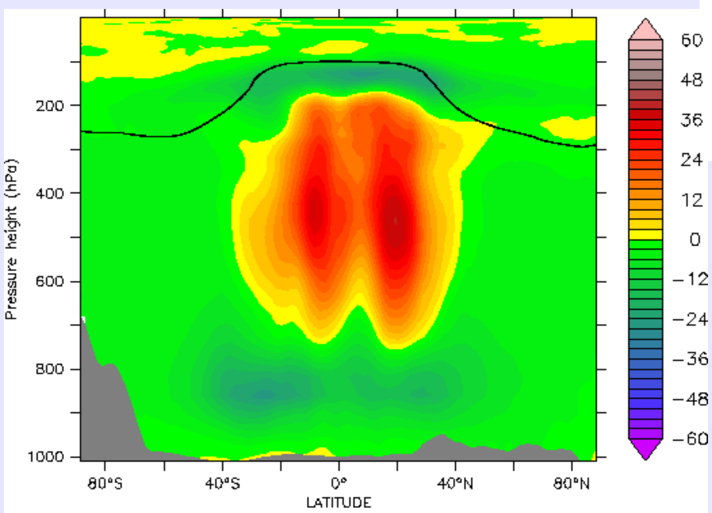


Relative difference (%) of H_2O in ECMWF relative to Tiedtke



H_2O zonal average (mmol/mol)

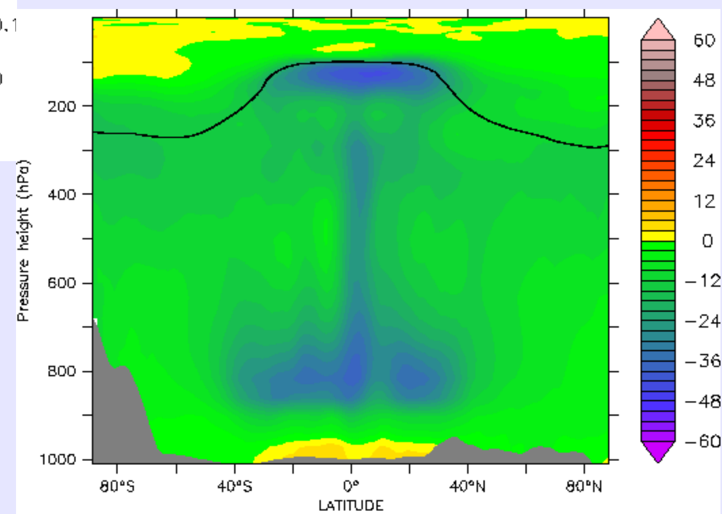
Tiedtke-Nordeng



Relative difference (%) of H_2O in ZHW relative to Tiedtke

Zhang-McFarlane-Hack

Bechtold

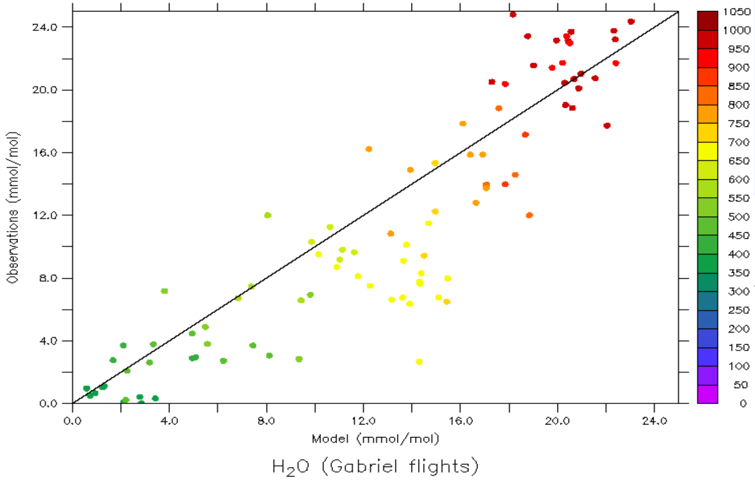


Relative difference (%) of H_2O in Bechtold relative to Tiedtke

Scatter plots for field campaigns

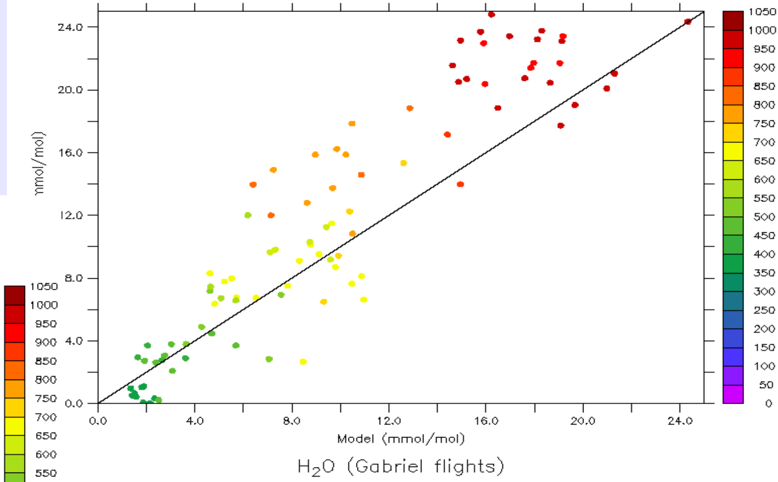
EC

$R^2 \approx 0.81$



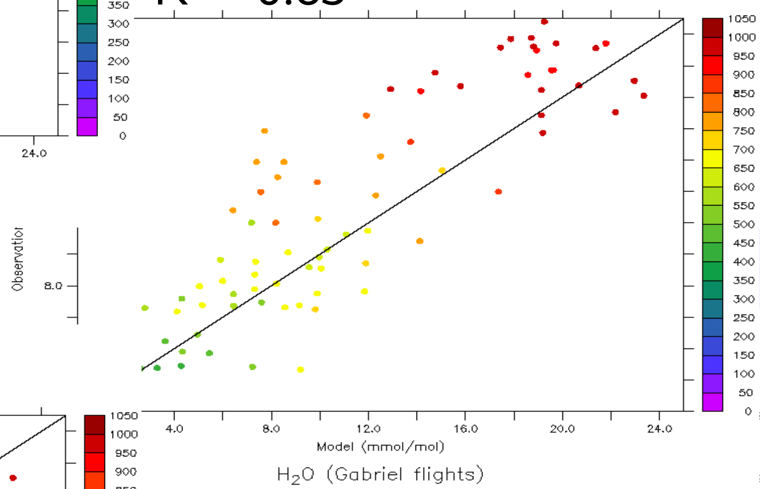
ZHW

$R^2 \approx 0.85$

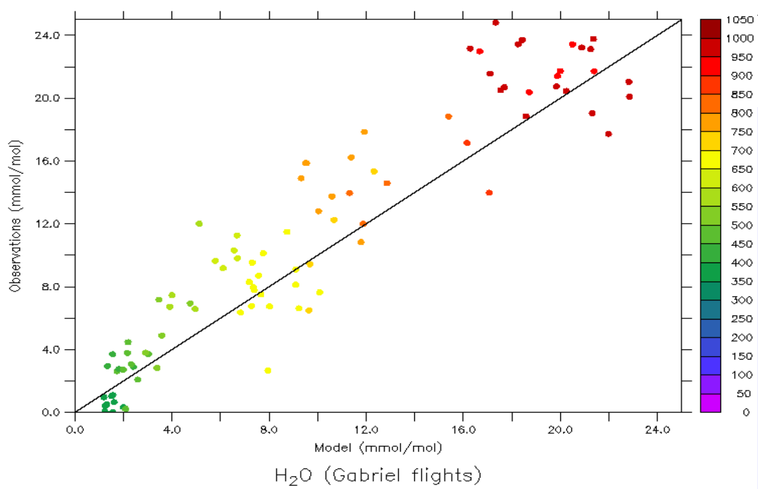


T1

$R^2 \approx 0.83$

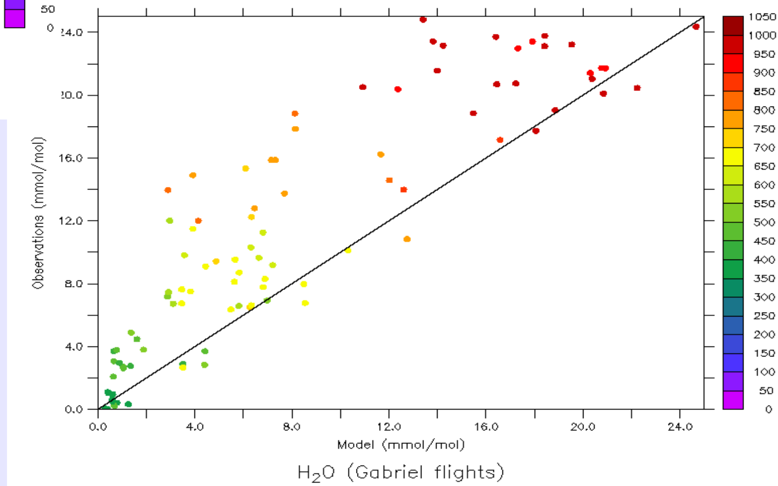


$R^2 \approx 0.89$



Ema

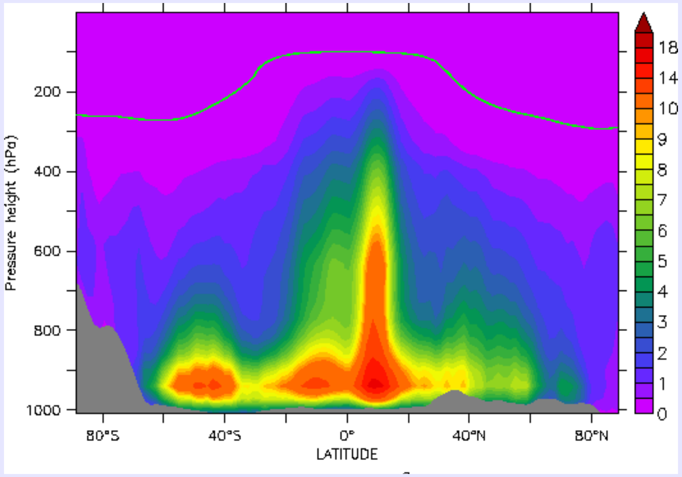
$R^2 \approx 0.80$



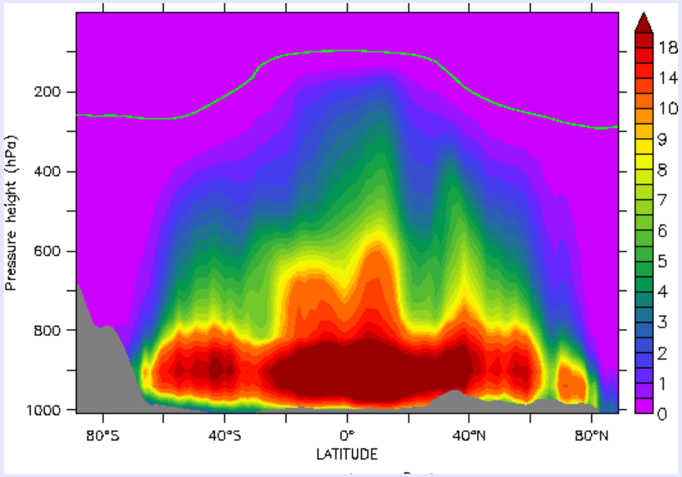
B1

Convective Massfluxes

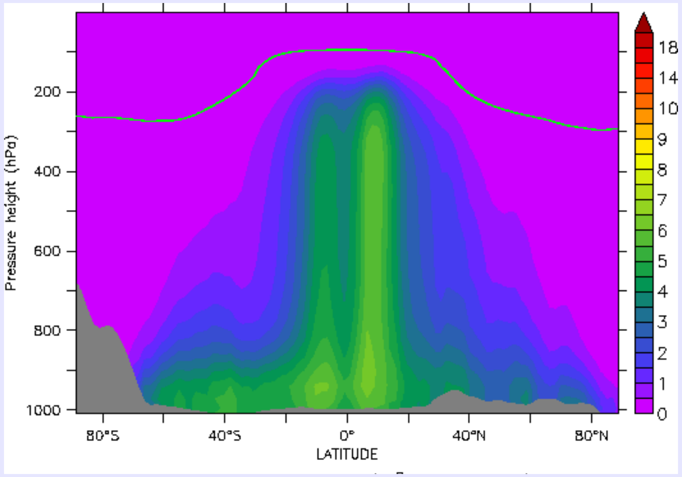
zonal (global) and temporal average [g/(m^{2}s)]



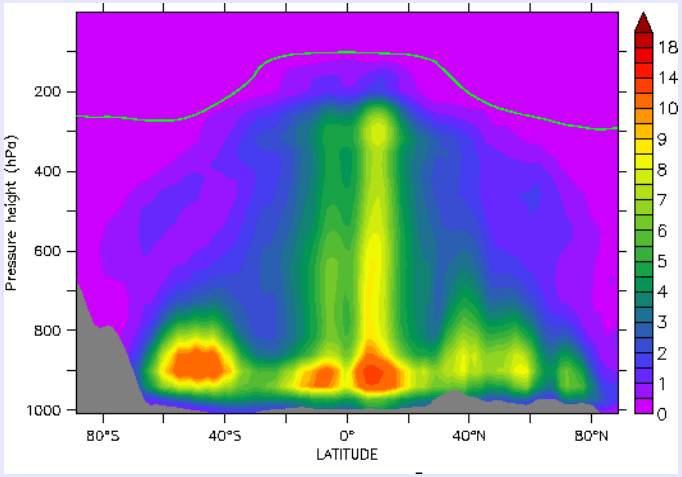
Tiedtke



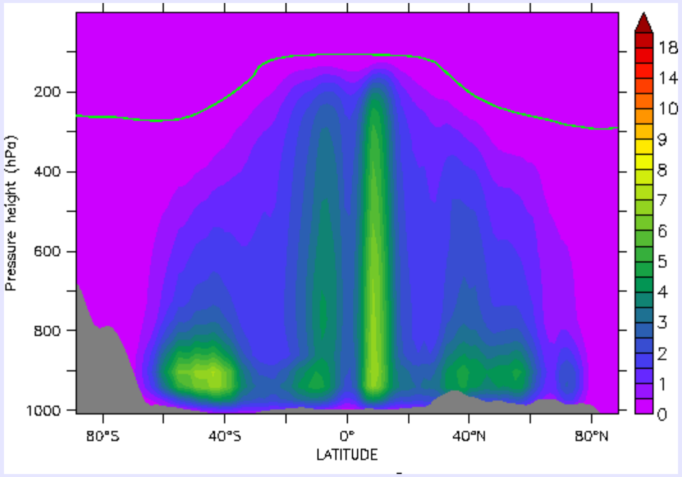
ECMWF



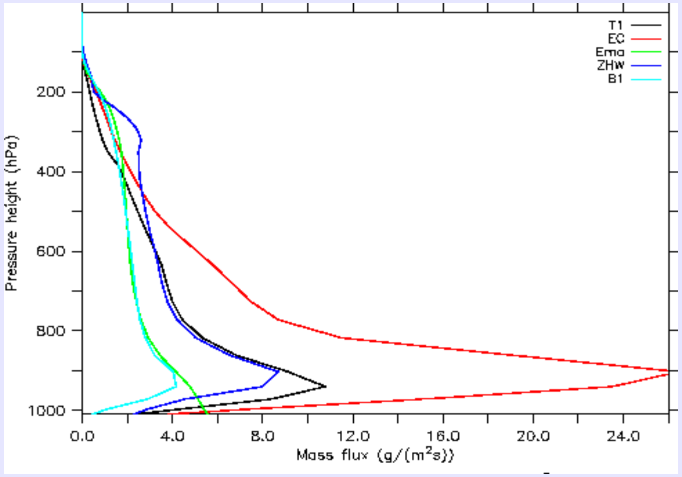
Emanuel



Zhang-McFarlane-Hack-Wilcox



Bechtold

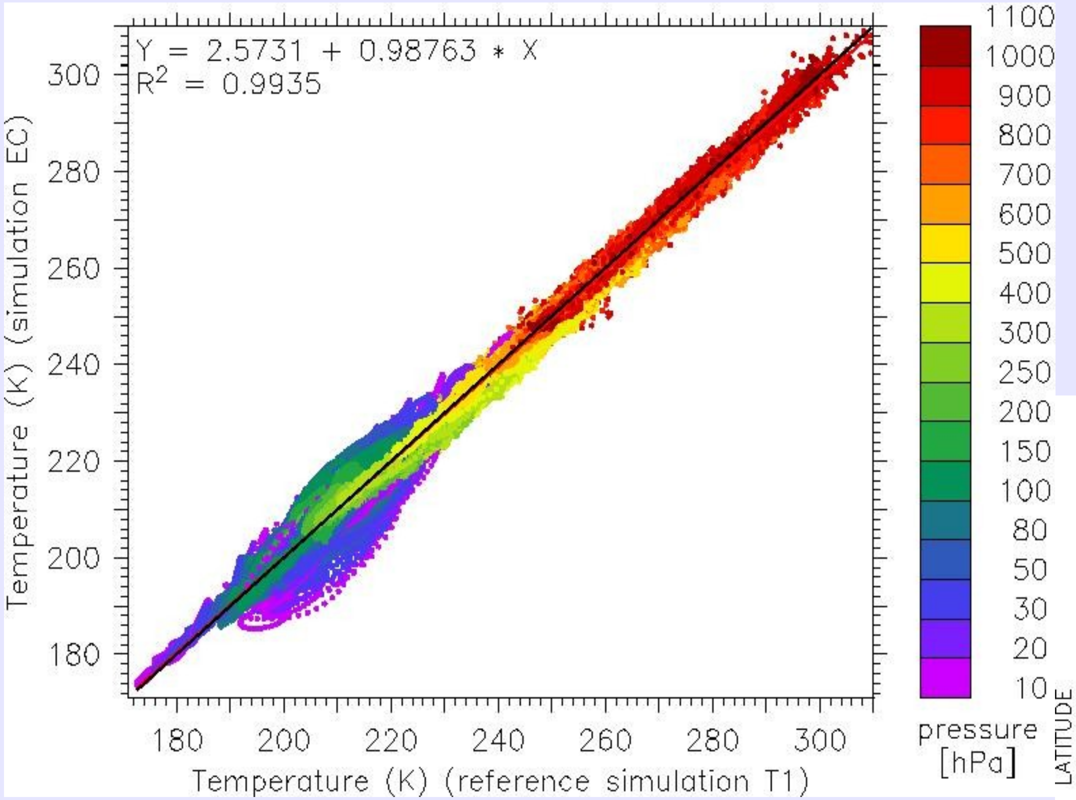


Global average profiles

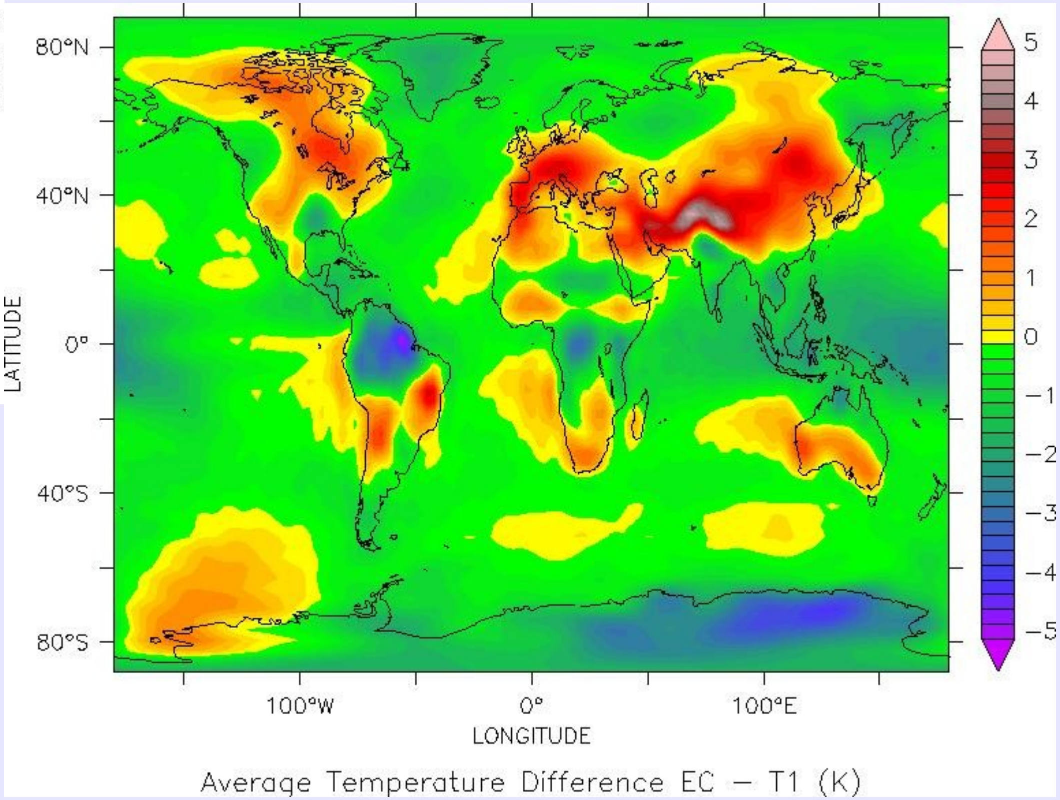
Convection Scheme Impacts: Energy

Simulation	Net solar radiation at the surface	Net thermal radiation at the surface	Latent heat flux (L * evaporation)	Sensible heat flux (residual)	Thermal radiation top of the atmosphere
T1	167.9	−55.96	−86.92	−25.02	−235.0
T2	171.3	−57.24	−84.10	−29.94	−233.2
T3	171.2	−57.07	−84.74	−29.41	−233.5
EC	150.8	−50.20	−85.13	−15.51	−232.3
EC2	149.7	−49.63	−84.25	−15.81	−232.0
ZH	178.1	−61.87	−81.88	−34.32	−233.7
ZHW	169.1	−57.97	−77.56	−33.61	−227.1
B1	152.5	−50.13	−85.46	−16.94	−231.5
B2	157.1	−51.62	−88.49	−16.99	−236.5

Convection Scheme Impacts: Temperature



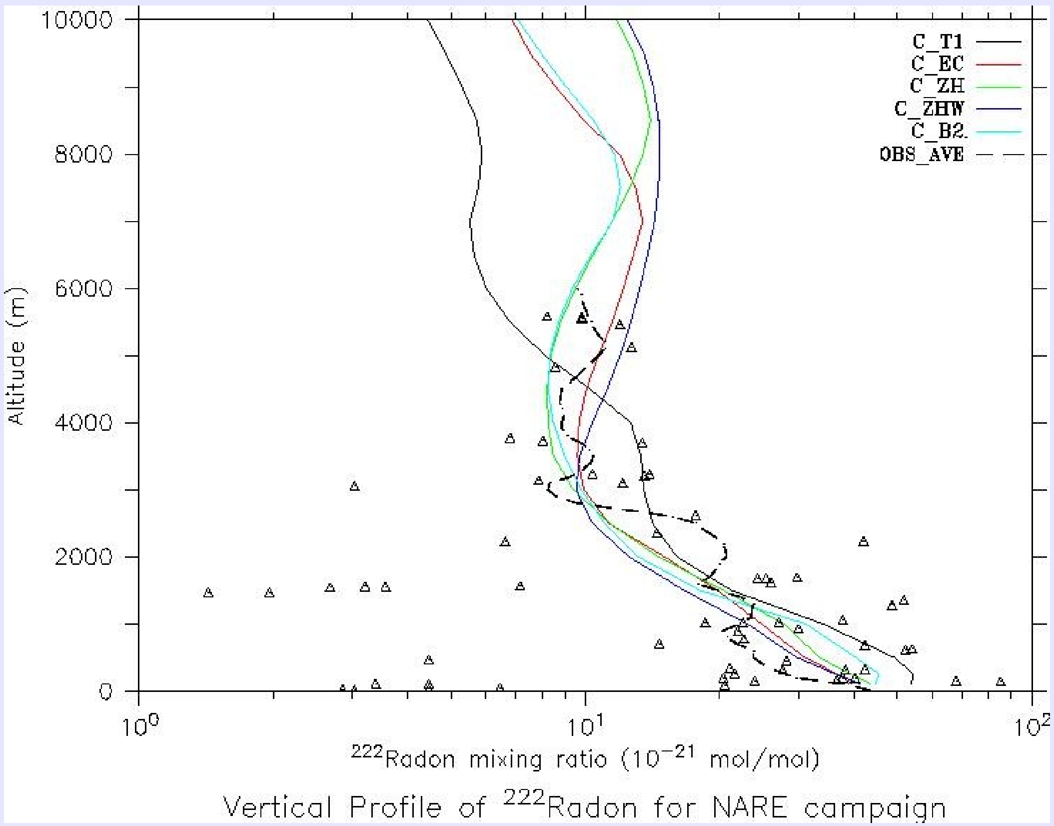
Comparison of the temperature in a simulation with the ECMWF convection scheme to the reference simulation using the Tiedtke scheme

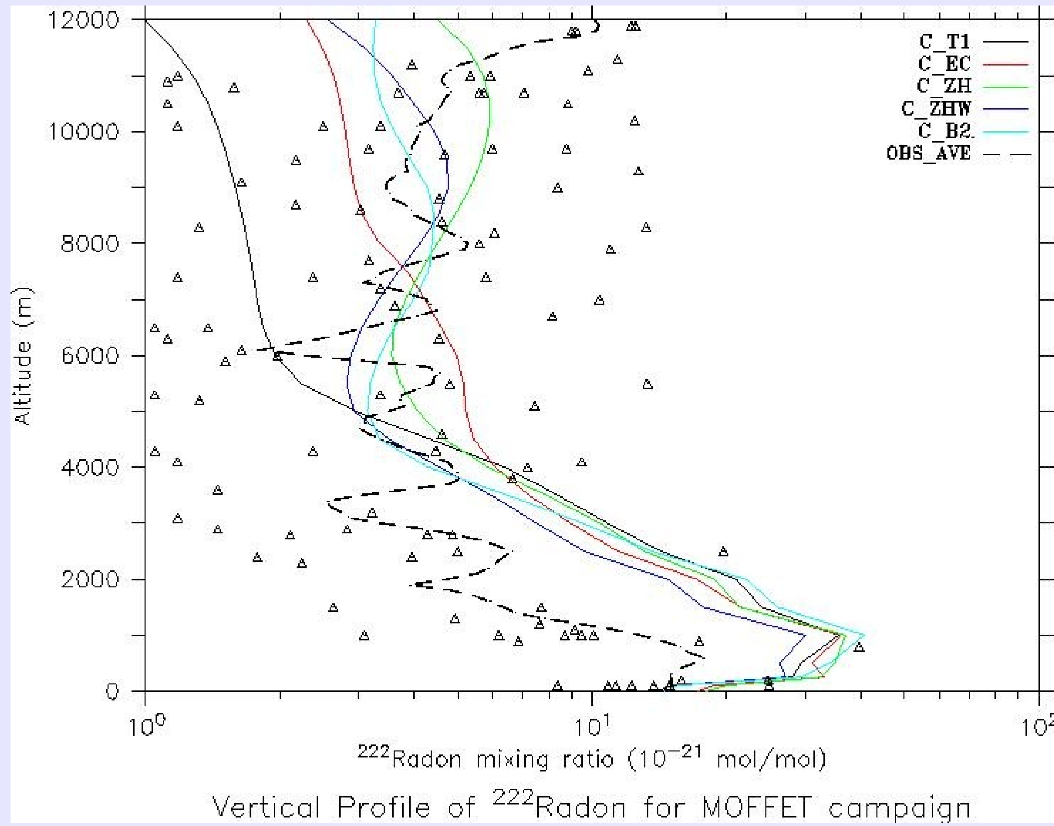


Convection Scheme Impacts

- Implications not only for air mass, energy and moisture redistribution (vertical mixing of the troposphere)
- Transport of trace gases and aerosols => Implications for atmospheric chemistry
- Scavenging of trace gases and aerosols by convective precipitation
- Implications for lightning parameterisations, which use convective cloud properties

Convection Scheme Impacts: Trace gases (^{222}Rn)





Summary

Summary (I)

- A variety of convection parameterisations exists.
- Some schemes have benefits and other drawbacks.
- There is no “best” scheme.
- Computational time spent on convection is almost unlimited – choice of detail depends on the scientific question to be answered.

Summary (II)

- **Small changes in the formulation of a scheme can have big impact, e.g. closure, triggering, microphysics,...**
- Feedback on the hydrological cycle
- Feedback on other meteorological parameters.
- Feedback on transport properties.