Water vapour in GCMs

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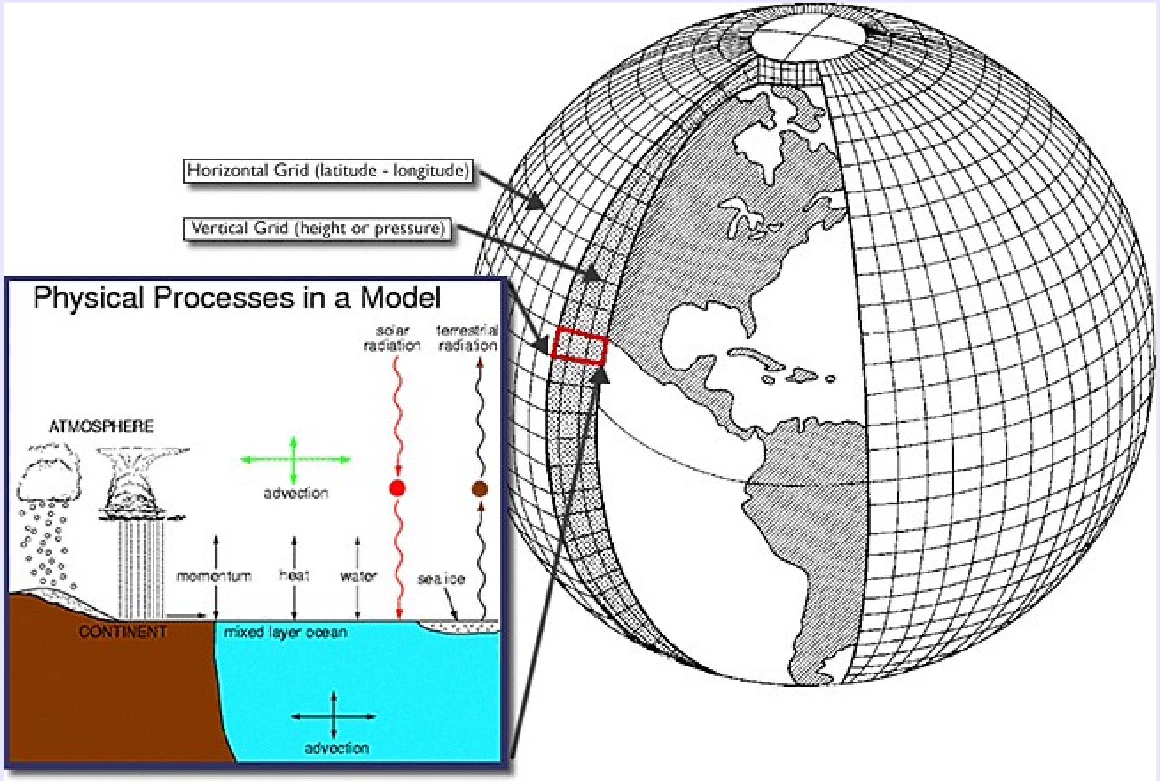
What is a GCM ?

- 2 definitions:
  - General Circulation Model:
    - a mathematical model of the general circulation of a planetary atmosphere or ocean, based on the Navier-Stokes-Equations on a rotating sphere including thermodynamical descriptions of various forms of energy
  - Global Climate Model:
    - models consisting of atmospheric general circulation models as well as models describing other parts of the Earth system (e.g. Ocean, sea-ice, biosphere,.....)

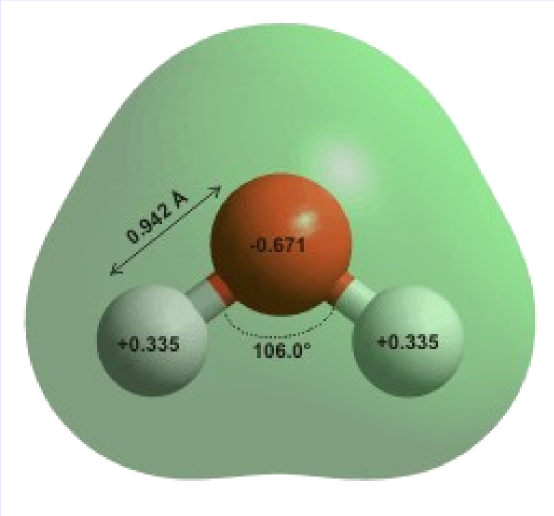
GCM vs. CTM

- CTM = chemistry transport model
- a CTM must be driven by externally provided meteorological data (temperature, winds, pressure, etc.), but usually has its own representation of the hydrological cycle
- a GCM creates consistently its own meteorological data
  - computationally more expensive (-)
  - physically more consistent / feebacks possible (+)
  - can be nudged to observed / externally provided meteorological data

Interaction of a very small molecule with the global atmosphere



grid box size of a GCM
(100 km * 100 km * 500m)

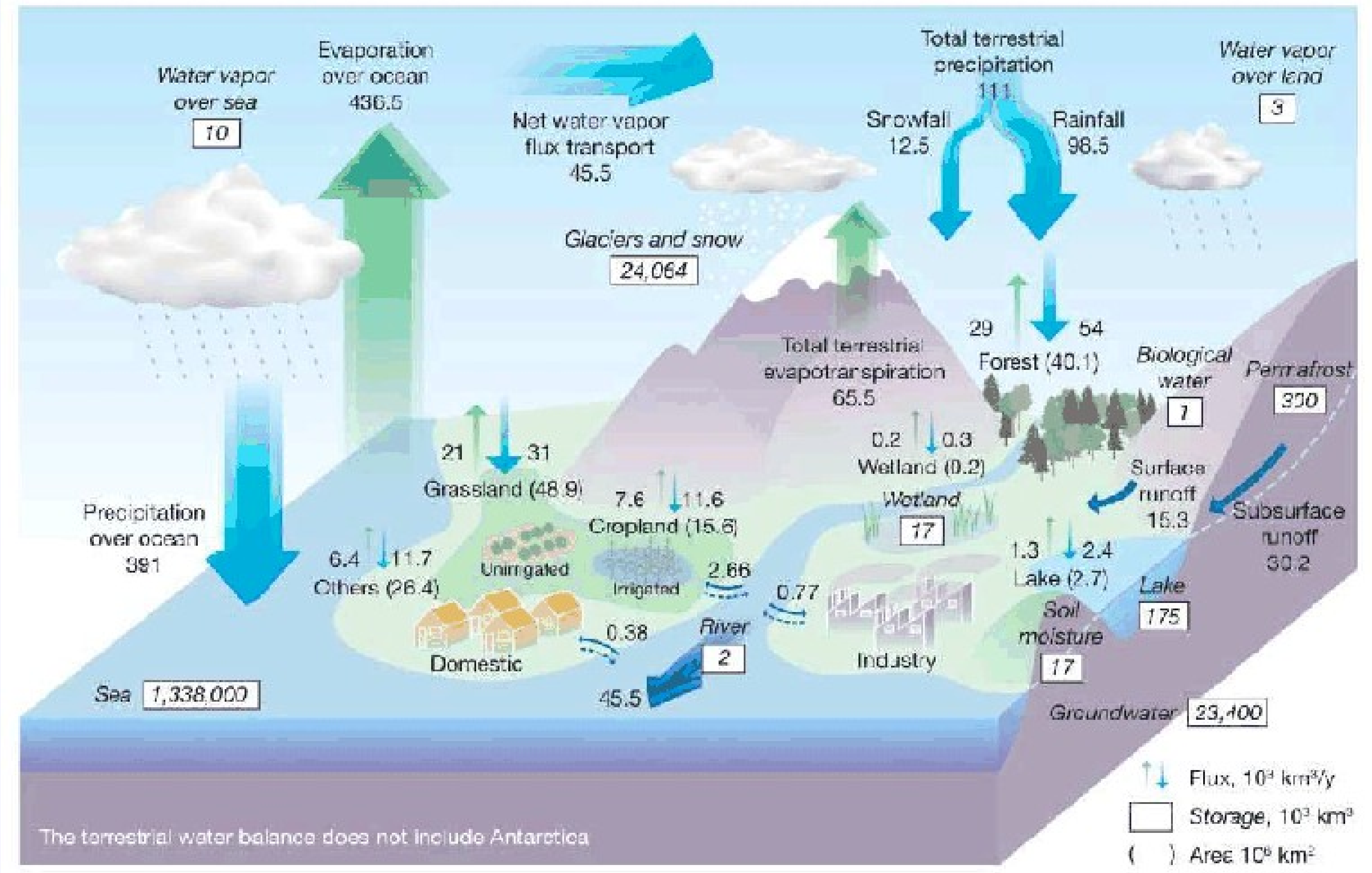


size of a water molecule
(10^{-10} m)

Problem of scales

Almost all processes involving water vapour
have to be parameterised and cannot be resolved in GCMs.

The global water cycle



Changes and Impacts of water vapour

- Distinction between two aspects:
  - a process modifies the water vapour distribution (e.g. cloud formation)
  - water vapour influences a physical/chemical process, but is neither consumed or produced (e.g. radiation)
- Processes involving water vapour very often impact the energy budget of the atmosphere / models via latent heat transformations

Water vapour: budget equation

- models contain a budget equation for water vapour (and for other forms of water)
- looks like continuity equation, but with the specific humidity q instead of the air density

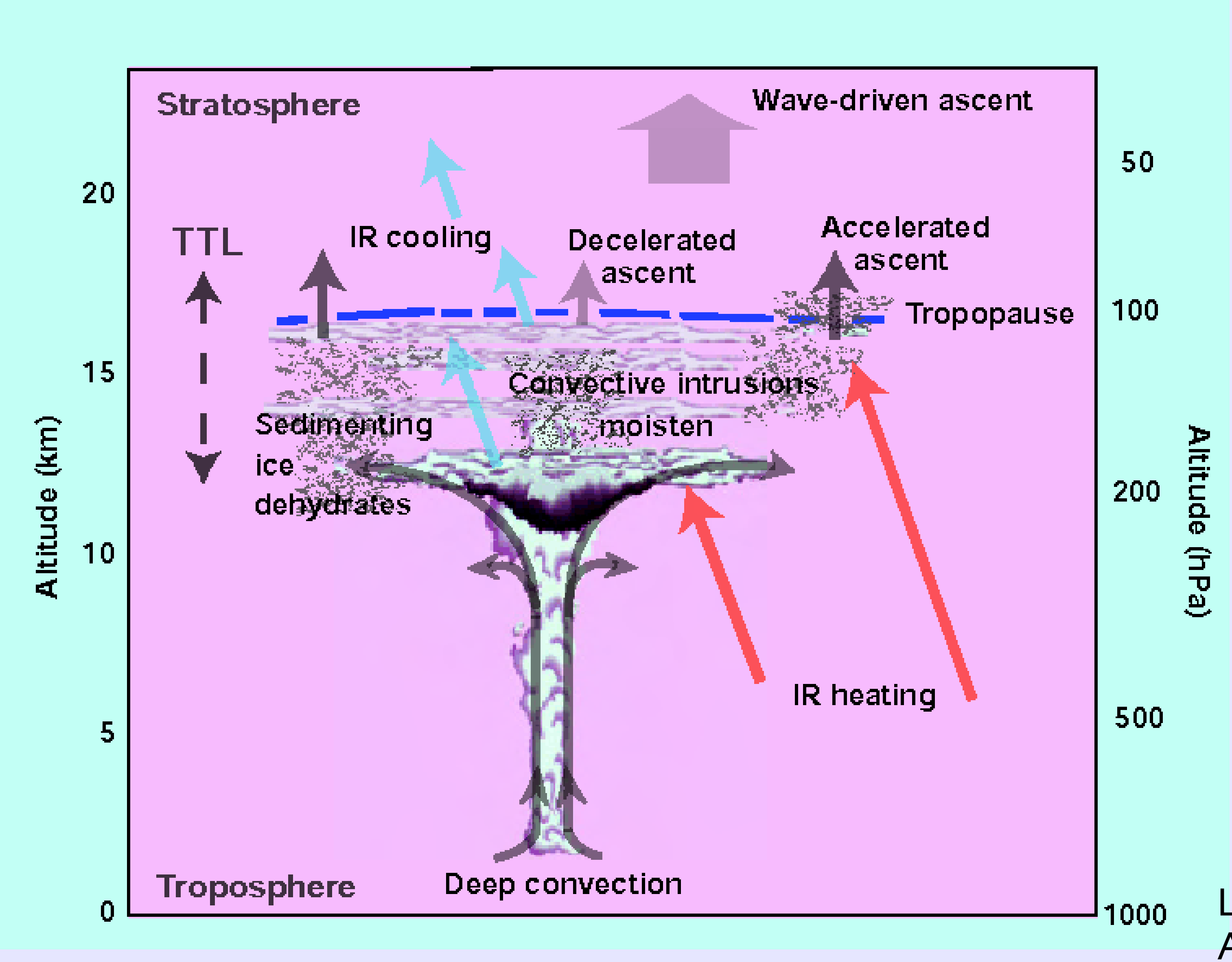
$$\frac{d}{dt} q = P - L$$

$$\frac{\partial}{\partial t} q + \vec{v} \cdot \nabla q = P - L$$

$$\frac{\partial}{\partial t} q = -\vec{v} \cdot \nabla q + P - L$$

local change of q   transport of q   Production   Loss

Where does stratospheric water vapour come from ?



Lelieveld et al. ACP,2007

Chemistry –
a water vapour source ?

Chemistry

- several chemical reactions produce H_2O:
  - HO_x chemistry:
    $$H_2O_2 + OH \rightarrow H_2O + HO_2$$
    $$HO_2 + OH \rightarrow H_2O$$
  - NO_y chemistry:
    $$HONO + OH \rightarrow NO_2 + H_2O$$
    $$HNO_3 + OH \rightarrow NO_3 + H_2O$$
    $$HNO_4 + OH \rightarrow NO_2 + H_2O + O_2$$
  - Halogen chemistry:
    $$HCl + OH \rightarrow Cl + H_2O$$
    $$CH_3Br + OH \rightarrow Br + H_2O + CH_2$$
    $$HOCl + OH \rightarrow ClO + H_2O$$
  - C – chemistry:
    $$CH_3O_2 + HO_2 \rightarrow HCHO + O_2 + H_2O$$
    $$HCHO + OH \rightarrow CO + HO_2 + H_2O$$
    $$C_2H_6 + OH + O_2 \rightarrow CH_4O_2 + H_2O$$
    $$CH_4 + h\nu \rightarrow CO + x_1 H_2 + x_2 H_2O$$
    $$CH_4 + OH \rightarrow CH_3O_2 + H_2O$$
  - and many more......

Chemistry

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  - HO_x chemistry:
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    $$HO_2 + OH \rightarrow H_2O$$
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    $$CH_4 + h\nu \rightarrow CO + x_1 H_2 + x_2 H_2O$$
    $$CH_4 + OH \rightarrow CH_3O_2 + H_2O$$
  - and many more......

IRRELEVANT
FOR THE TROPOSPHERIC
WATER BUDGET!

Chemistry

- several chemical reactions produce H_2O:
  - The chemically produced water vapour is much smaller than the H_2O that is transported / well mixed in the **troposphere**.
  - Reactions are important for the other products, but not the water vapour.
- some GCMs keep H_2O constant for chemistry
  - Water is not consumed or produced by chemistry
  - reasonable approximation for the **troposphere**

Chemistry

- BUT

$$CH_4 + h\nu \rightarrow CO + x_1 H_2 + x_2 H_2O$$
$$CH_4 + OH \rightarrow CH_3O_2 + H_2O$$

- important in the **stratosphere / mesosphere**:
  - low water vapour, but relatively high CH_4 content
  - can contribute up to 25% of the total water

=> can form stratospheric / mesospheric clouds

Chemistry – a water vapour sink ?

Important chemical reactions

(consuming water vapour)

- only two major gas phase reactions

$$H_2O + O^1(D) \rightarrow 2OH$$

  - very important, main source of OH in the atmosphere
  - $O^1(D)$ peaks in the upper stratosphere / mesosphere, H_2O near the surface => peak production in the upper troposphere

$$H_2O + h\nu \rightarrow H + OH$$

  - revelant only in the upper stratosphere, otherwise photolysis rate is too small
- some heterogeneous reactions on stratospheric aerosols

Important chemical reactions

(consuming water vapour)

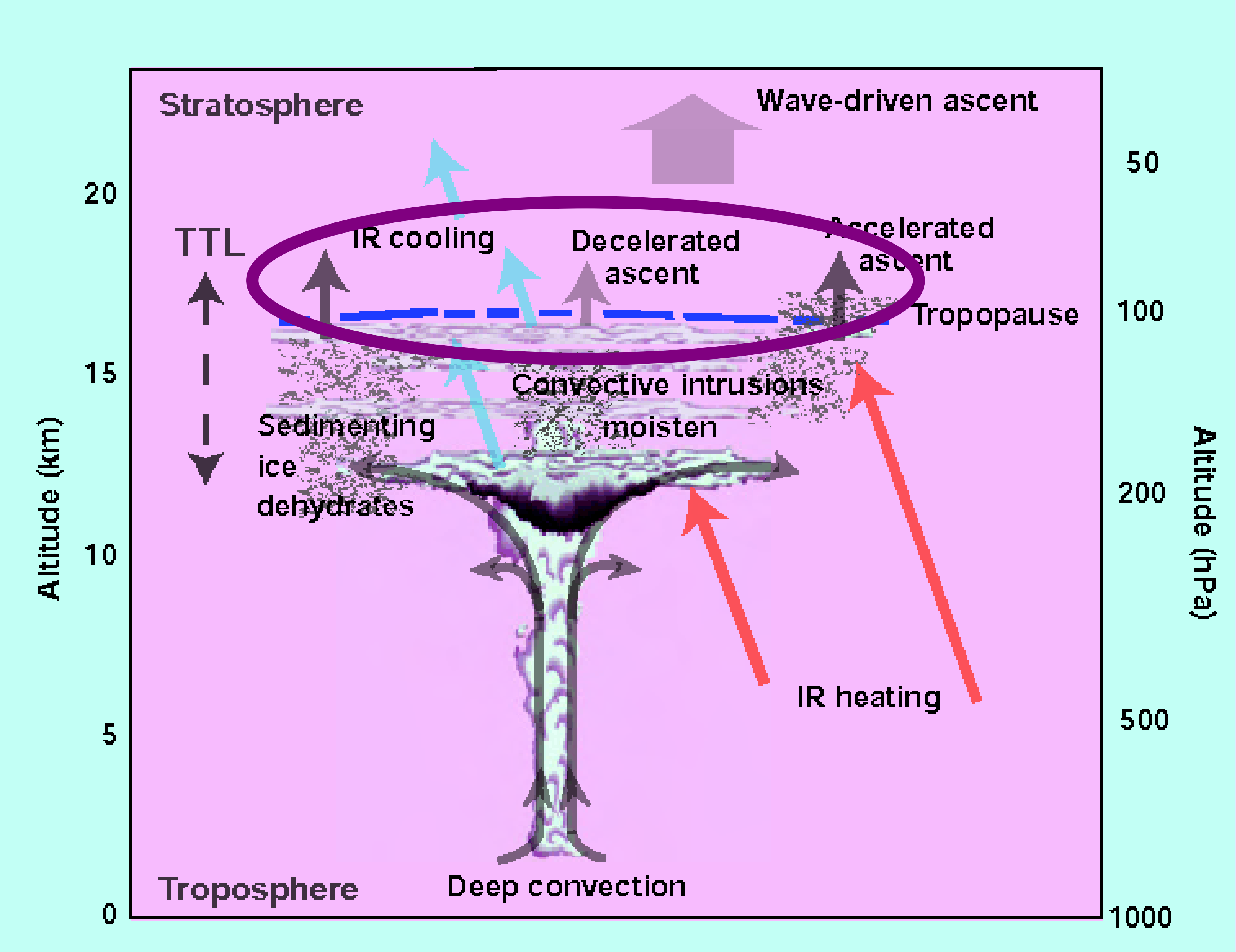
$$H_2O + O^1(D) \rightarrow 2OH$$

- OH peaks in the stratosphere / mesosphere, but also has a tropospherical enhancement
- OH is the main oxidant = driver for atmospheric chemistry

=> **THIS reaction is really IMPORTANT !**

- impact on H_2O in the troposphere is negligible
- both reactions have enhanced reaction rates in the stratosphere / mesosphere, where H_2O is rare => **H_2O sink for the upper atmosphere**

Quantification of fluxes ?



Simulated vertical water vapour fluxes

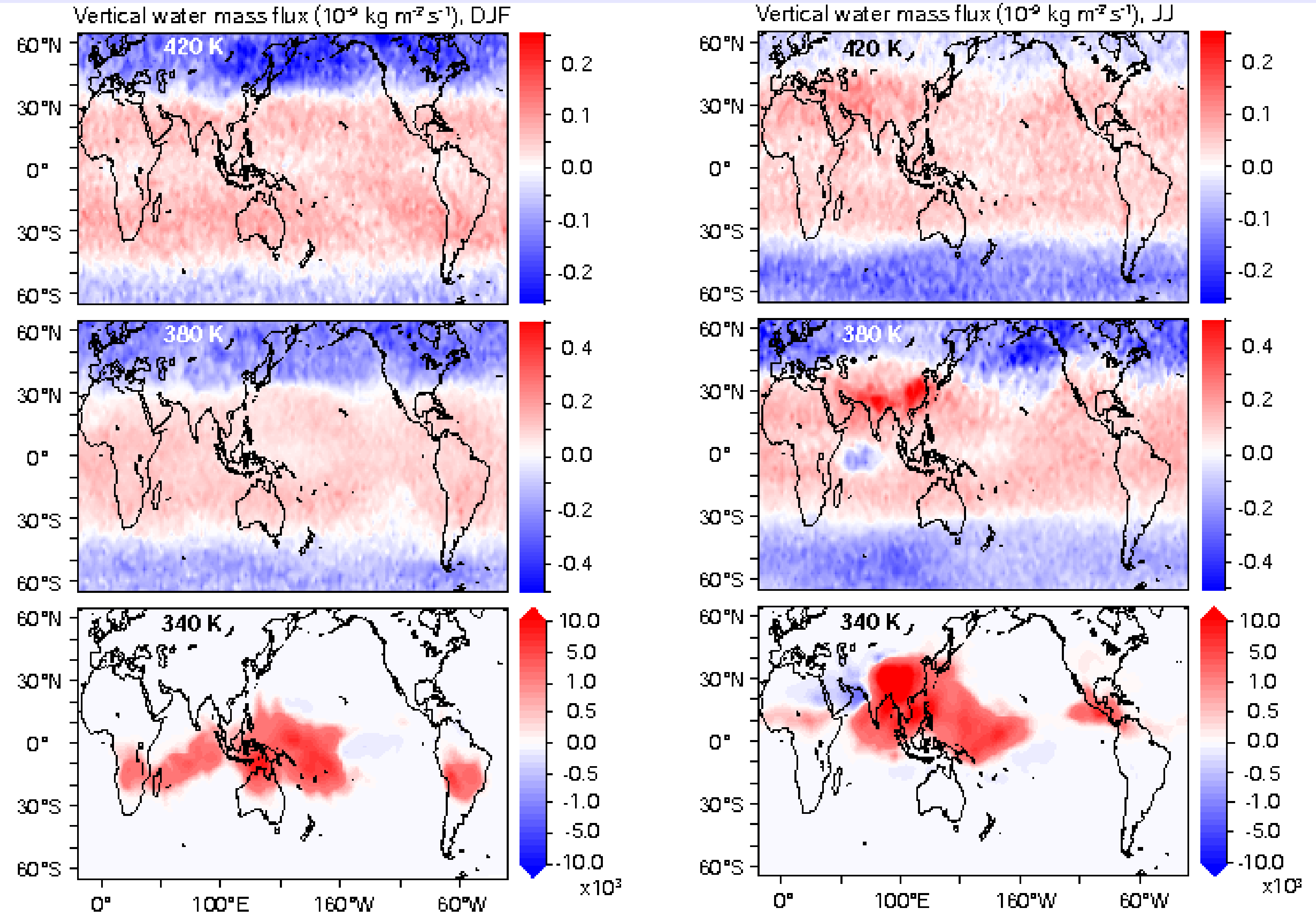


Fig. 13a. Model calculated water mass fluxes across the 340, 380 and 420 K isentropic surfaces, averaged for the periods December–February 2002 and 2003 in units 10^{-9} kg m^{-2} s^{-1} (red is upward). Note the scale changes between panels.

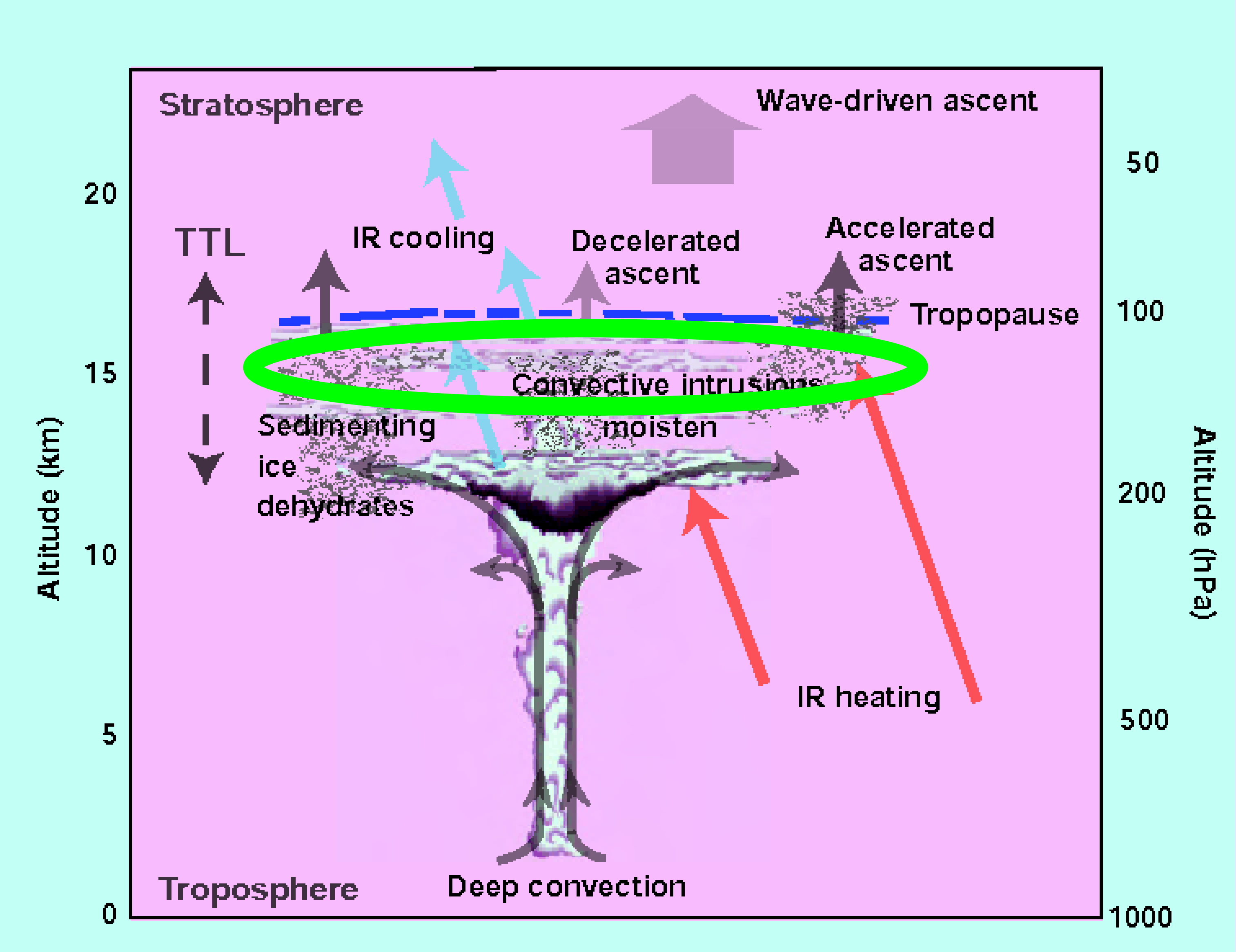
Fig. 13b. Model calculated water mass fluxes across the 340, 380 and 420 K isentropic surfaces, averaged for the periods June–August 2002 and 2003 in units 10^{-9} kg m^{-2} s^{-1} (red is upward). Note the scale changes between panels.

Simulated vertical water vapour fluxes

- Integrated fluxes:
  - At 100 hPa: $23 * 10^3$ kg / s
  - At 75 hPa: $11.2 * 10^3$ kg/s
- Chemical production from CH_4 Oxidation:
  - ca. $3 * 10^3$ kg/s
  - 15% to 25% of the transported H_2O

=> Chemistry is important !

Dehydration in cirrus clouds ?



Simulated cloud ice

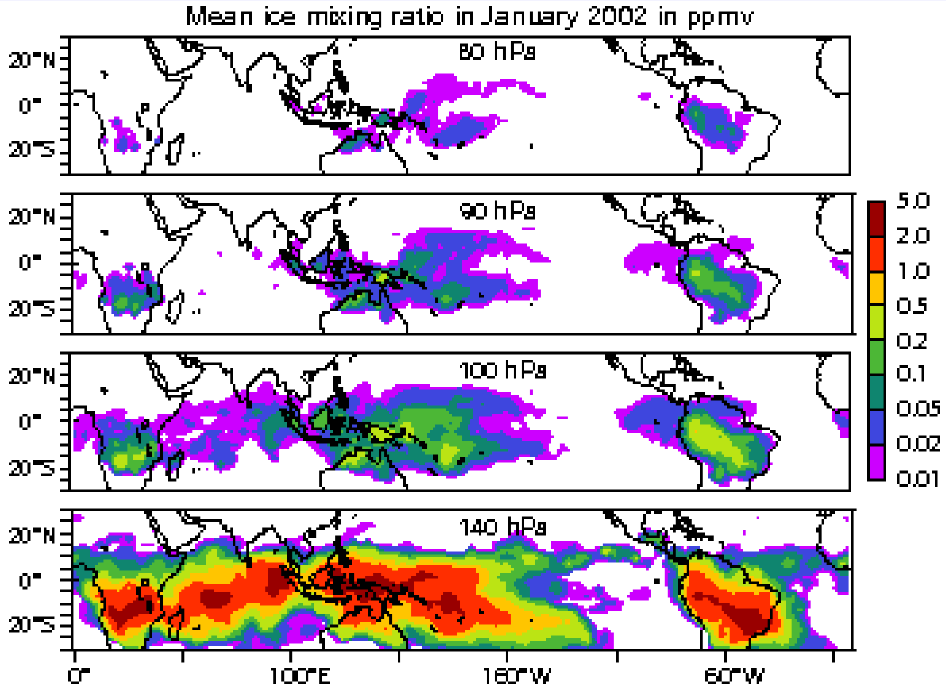


Fig. 11a. Model calculated mean ice water mixing ratios (ppmv) at about 140, 100, 90 and 80 hPa in January 2002.

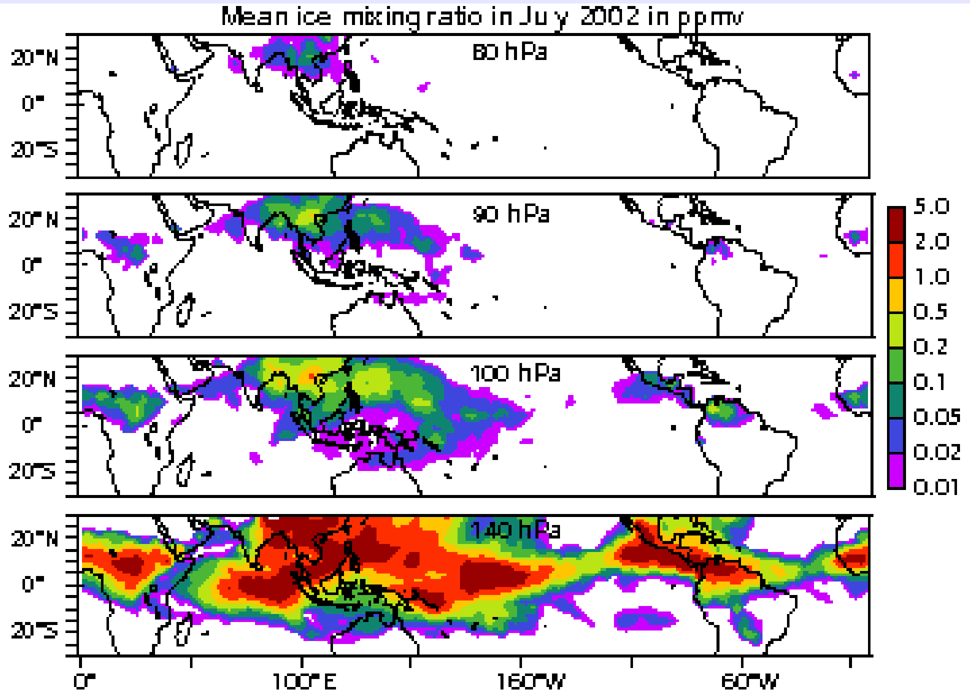


Fig. 11b. Model calculated mean ice water mixing ratios (ppmv) at about 140, 100, 90 and 80 hPa in July 2002.

How is this cloud ice formed?

- Only the standard cloud scheme is used!
- Is this comprehensive enough ?
- How does a typical GCM cloud scheme look like ?

One example of a cloud scheme (I)

- ca. 1300 lines of F90 code
- several lookup - tables for saturation mixing ratios (q_{sat}(T); 400 lines of F90 code)
- computationally efficient (much faster than radiation / chemistry schemes)
- does not take indirect aerosol effects into account
  - constant cloud droplet number concentrations
  - can be easily replaced by diagnostic or prognostic cloud droplet number concentration schemes (add max. 500 more lines of code)

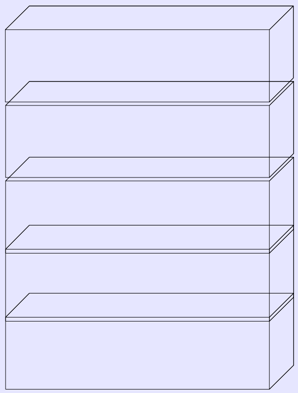
One example of a cloud scheme (II)

- Prognostic quantities are:
  - Water vapour q
  - Cloud water x_l
  - Cloud ice x_i
- Precipitation either liquid (=rain) or solid(=snow)
- Cloud schemes modify the temperature T

One example of a cloud scheme (III)

1) unit conversion of input parameters

2) begin loop over vertical model levels



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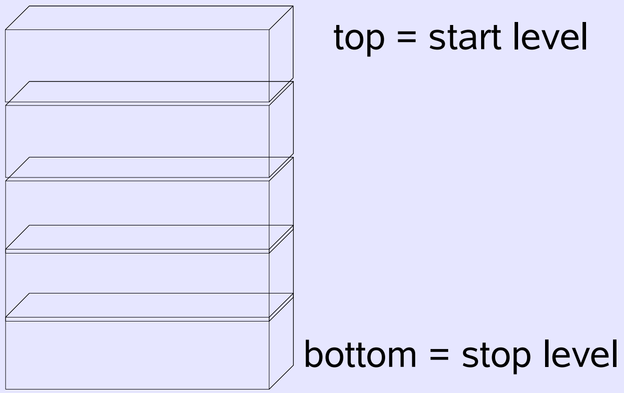
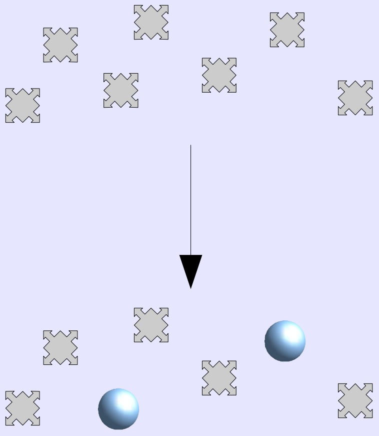


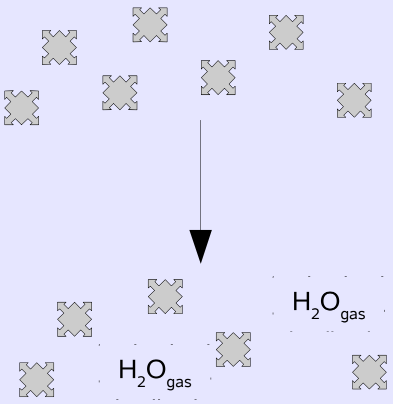
2) begin loop over vertical model levels

3) checking for melting of falling snow from layer above – adjusting snow and rain fluxes accordingly



One example of a cloud scheme (IV)

4) Calculate sublimation of snow, depending on temperature, saturation, sublimation energy and empirical coefficients



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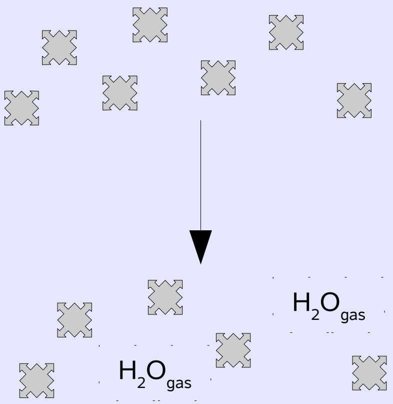
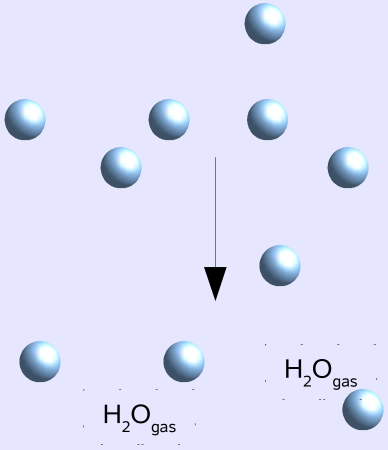


5) as 4) but for evaporation of rain



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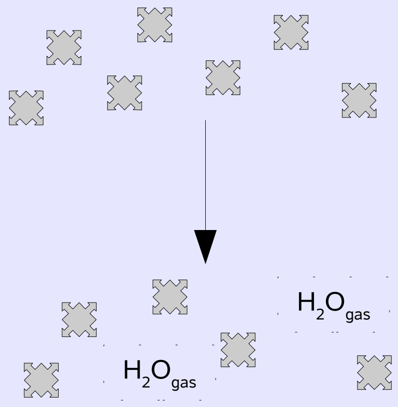

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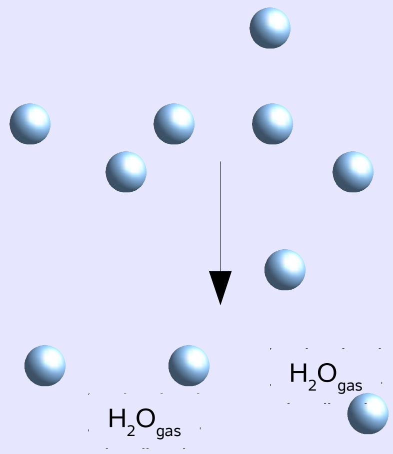
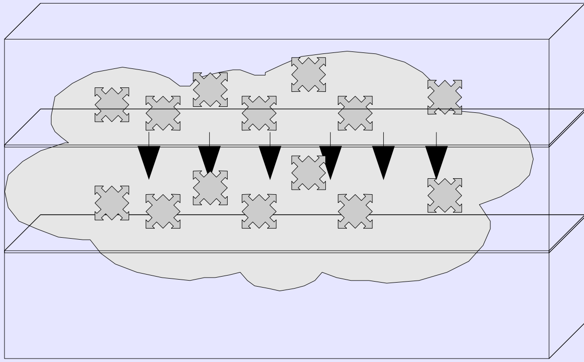
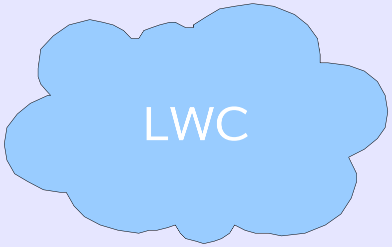


6) adjust cloud ice due to sedimentation (source and sink for each layer) often using a fixed sedimentation velocity



One example of a cloud scheme (V)

7) determining in-cloud water / ice from grid box mean cloud water and cloud cover (differentiating ice clouds, mixed phase clouds and water clouds; depending on temperature regimes)



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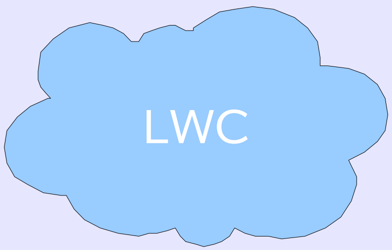
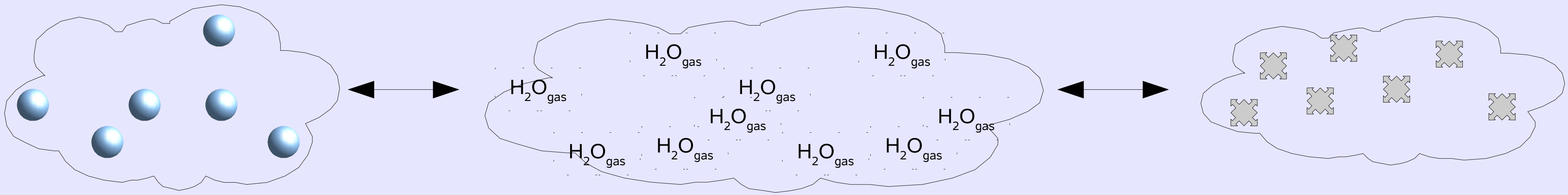


8) calculate condensation / deposition and sublimation / evaporation for each grid box (depending on saturation, temperature)

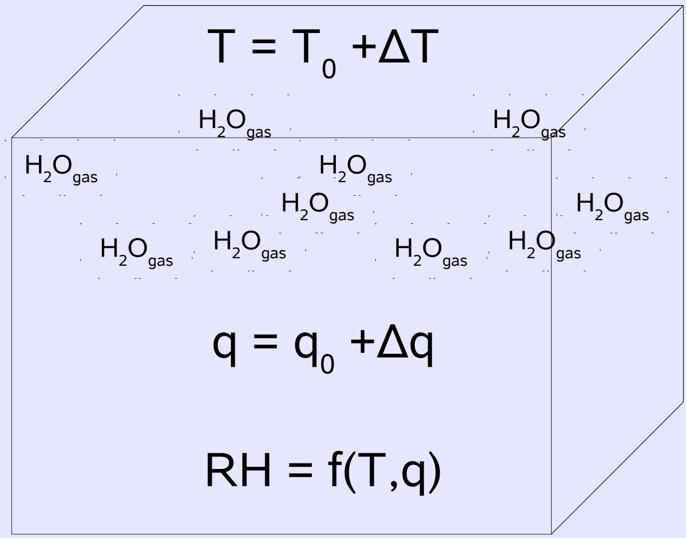


One example of a cloud scheme (VI)

9) Update temperature accordingly due to energy conversions

10) Update moisture tendency

11) Calculate new relative humidity



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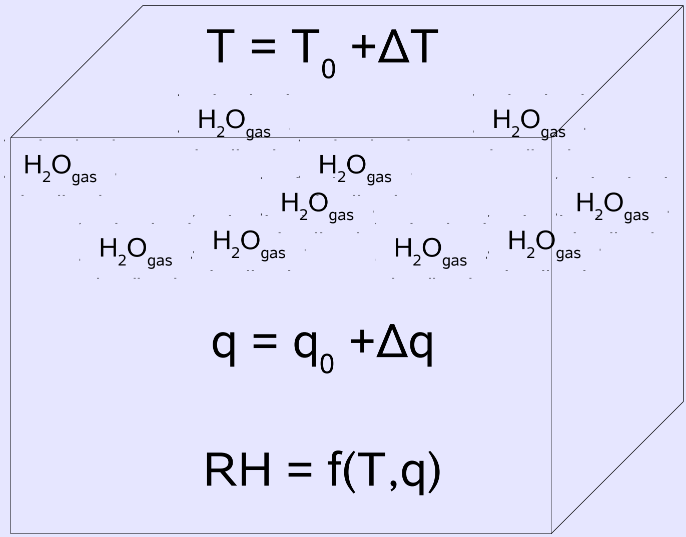
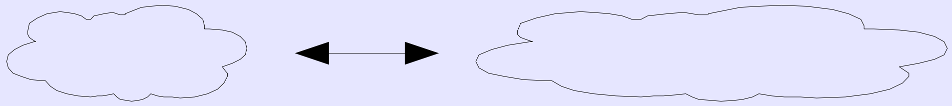
12) Determine new cloud cover





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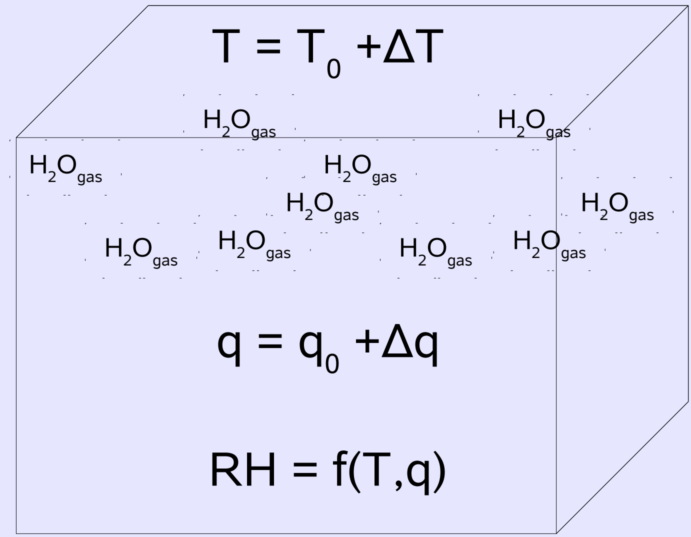

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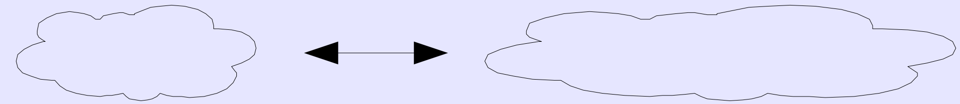
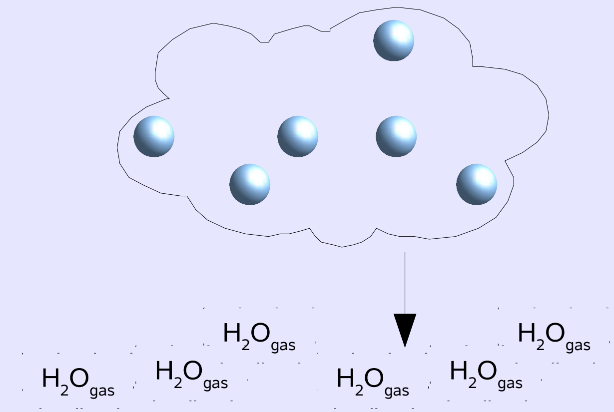
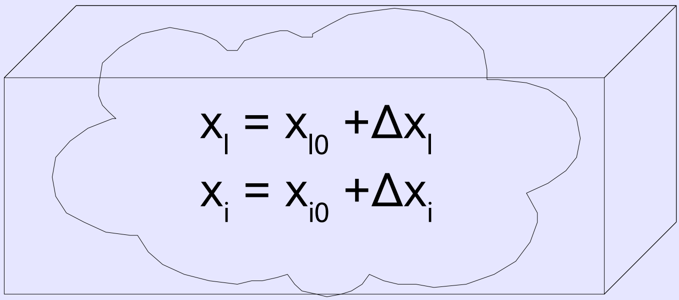


13) Calculate cloud evaporation in cloud free regions (dependent on moisture difference to saturation)



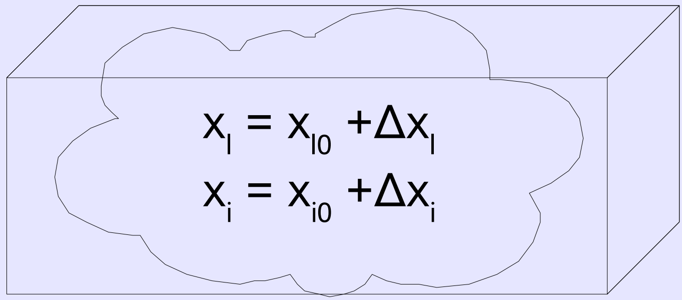
One example of a cloud scheme (VII)

14) update in-cloud water / ice

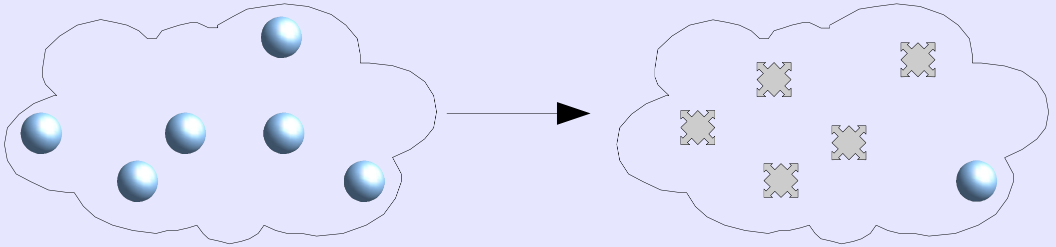


One example of a cloud scheme (VII)

14) update in-cloud water / ice

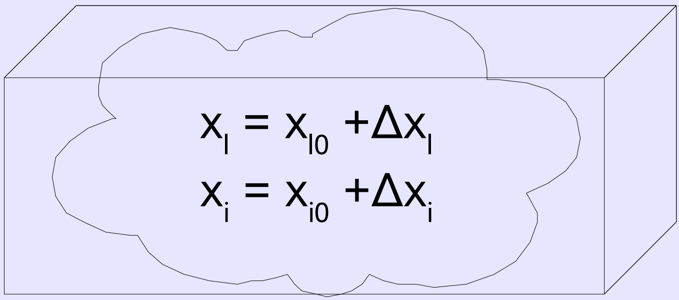


15) calculate cloud water freezing (regime dependent)



One example of a cloud scheme (VII)

14) update in-cloud water / ice



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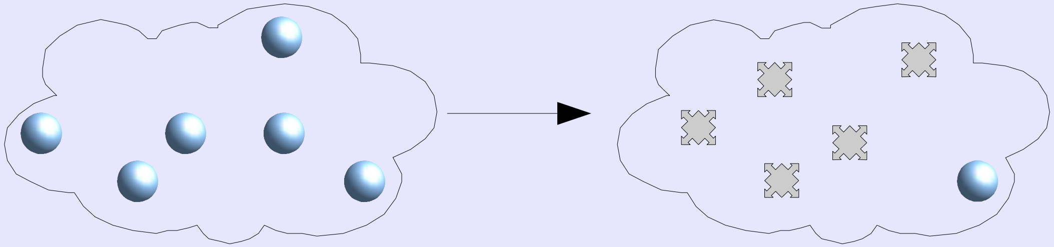
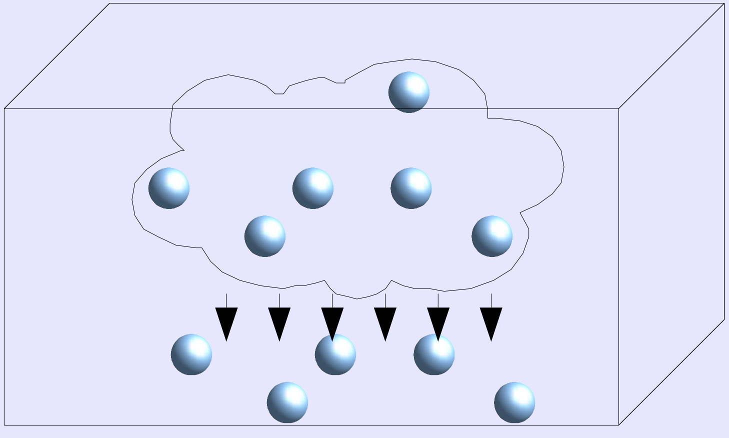
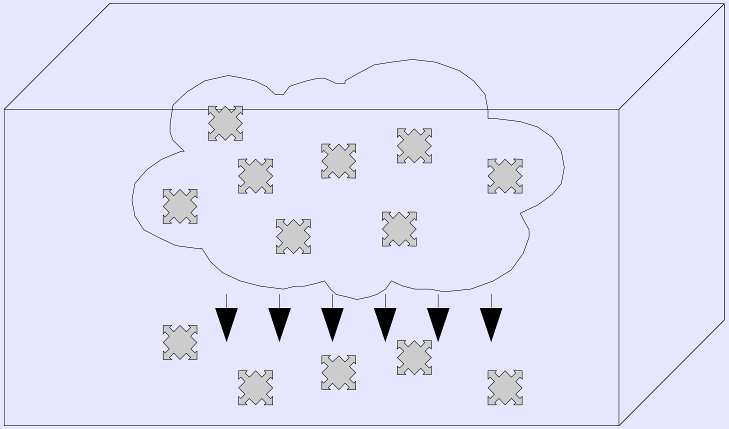


16) calculate cloud / rain droplet microphysics (using arbitrary complexity, empirical coefficients) => converting a fraction of the cloud water to rain water and updating cloud water

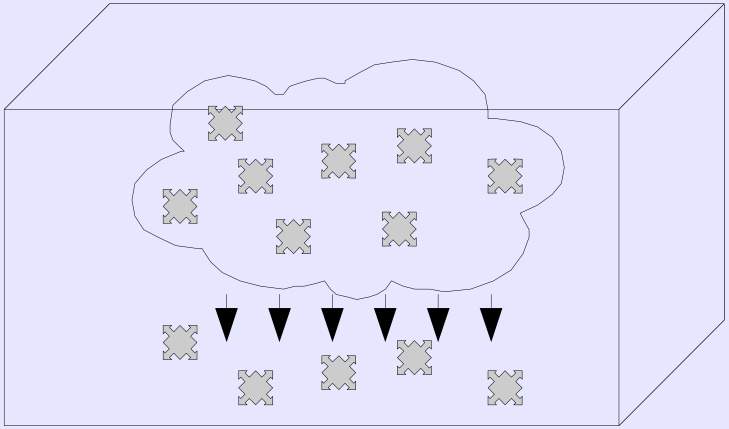


One example of a cloud scheme (VIII)



17)as 16) but for ice

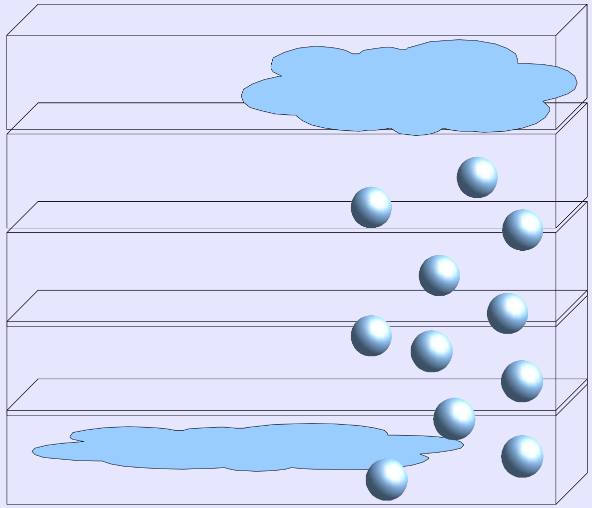
One example of a cloud scheme (VIII)



17) as 16) but for ice

18) convert rain / snow into a flux for input for the next level

19) add melted fraction from 3) to rain flux



20) determine precipitation cover, update cloud cover (overlap assumptions)

One example of a cloud scheme (IX)

21) check for positive definiteness and update tendencies for all prognostic quantities (moisture, cloud water, cloud ice, temperature, etc.)

$$T = T_0 + \Delta T > 0$$
$$q = q_0 + \Delta q > 0$$
$$x_l = x_{l0} + \Delta x_l > 0$$
$$x_i = xi_{i0} + \Delta x_i > 0$$

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$$x_i = xi_{i0} + \Delta x_i > 0$$

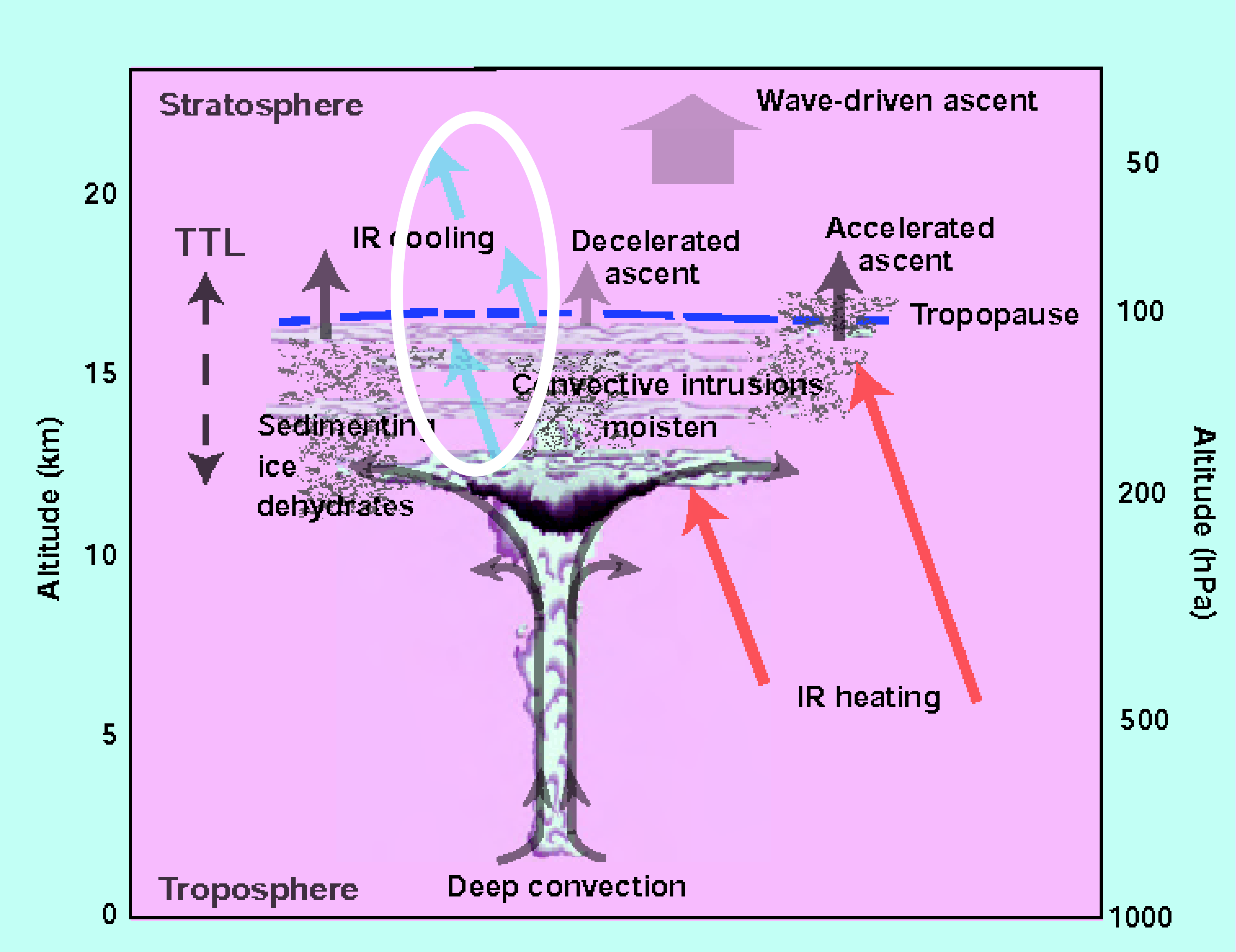
22) calculate additional diagnostics (IWV, accumulated surface precipitation, etc.)

$$IWV = \sum_{k=1}^{nlev} q(k)$$
$$rain_{acc} = rain_{acc} + rain$$

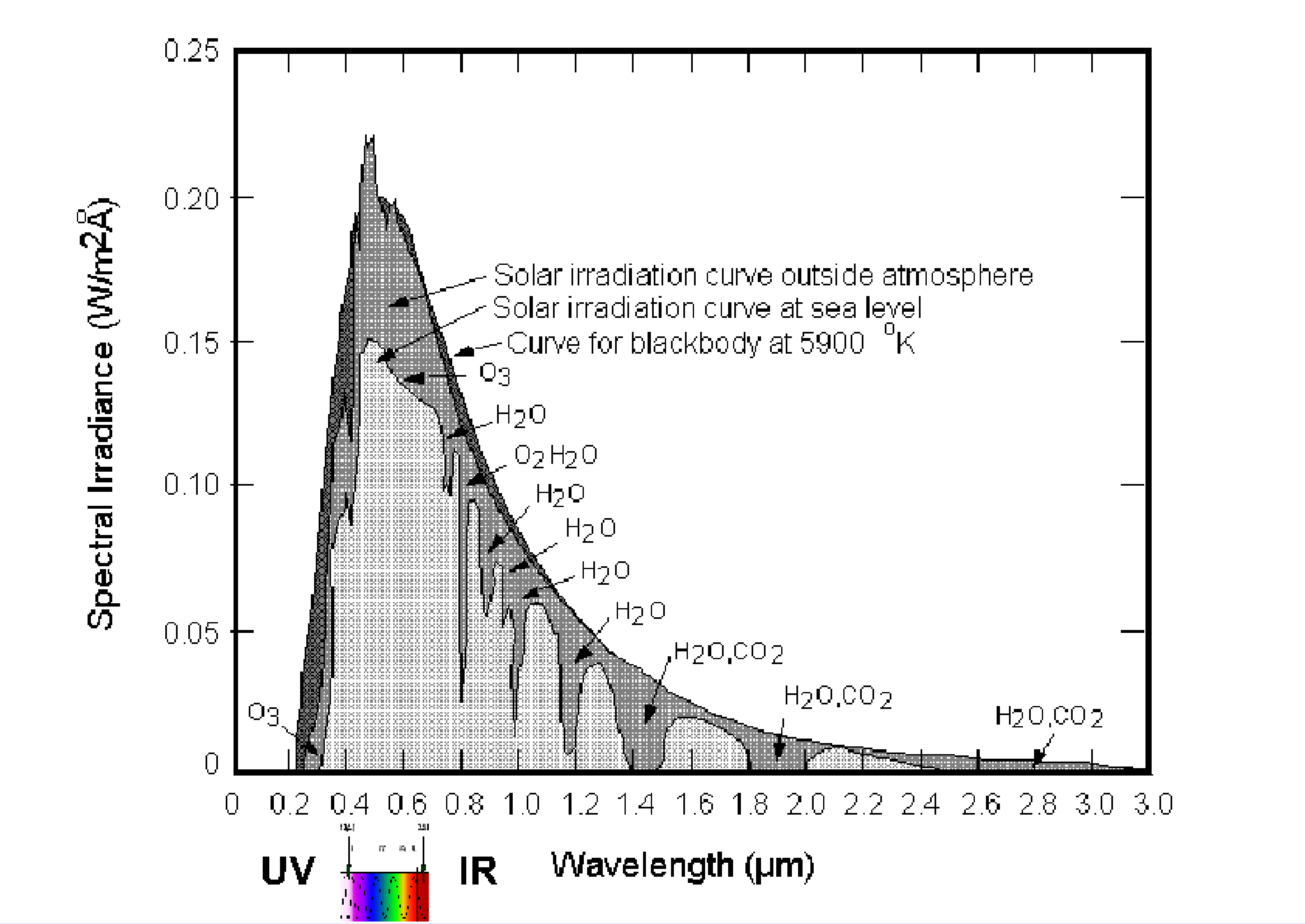
GCM cloud schemes (X)

- some (most nowadays) have included indirect aerosol effects
  - cloud albedo effects
  - cloud lifetime effects
  - including aerosol activation parameterisations, prognostic treatment of cloud droplet / ice crystal numbers, etc.
  - direct changes to water vapour by including indirect aerosol effects are minor, but the effects on the total hydrological cycle are substantial

Ascent by radiative heating



Water vapour effects on radiation

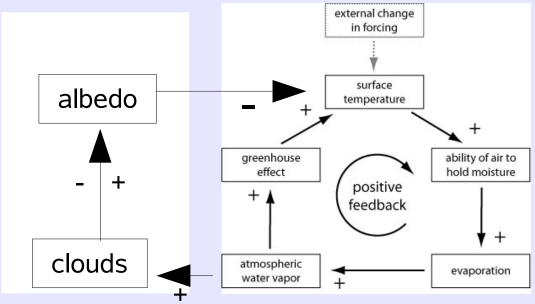


Water vapour effects on radiation

- absorption by H_2O at many wavelengths
- absorption in the GCM follows the Beer – Lambert – Law: $$I(\lambda) = I_0(\lambda) * \exp(-\tau(\lambda) * z)$$
- optical thickness $\tau = \tau(O_2, O_3, H_2O, CO_2, \ldots..)$
- operator splitting:
  $\tau = \tau(O_2) + \tau(O_3) + \tau(H_2O) + \tau(CO_2) + \ldots..$
- calculated at several spectral bands in the short wave and long wave spectrum
  - long wave is more important for H_2O

Water vapour effects on radiation

- $\tau = \tau_{gases} + \tau_{cloud\ water} + \tau_{cloud\ ice} + \tau_{aerosol}$
- column process: every grid box depends on the column above it
- no change in water vapour
- change in temperature => change in RH
- enables feedback studies (water vapour feedback)
- enhanced effects including clouds
- radiation fog



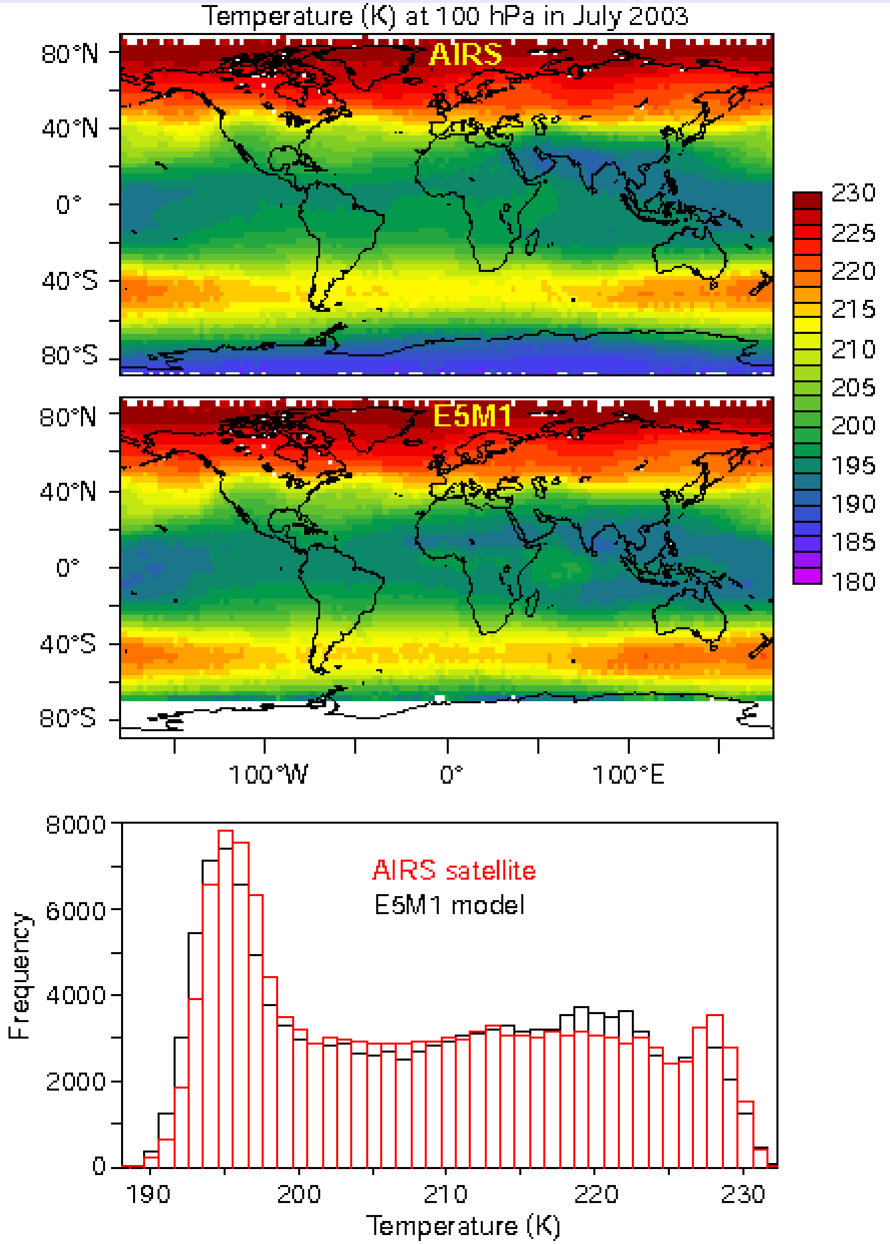
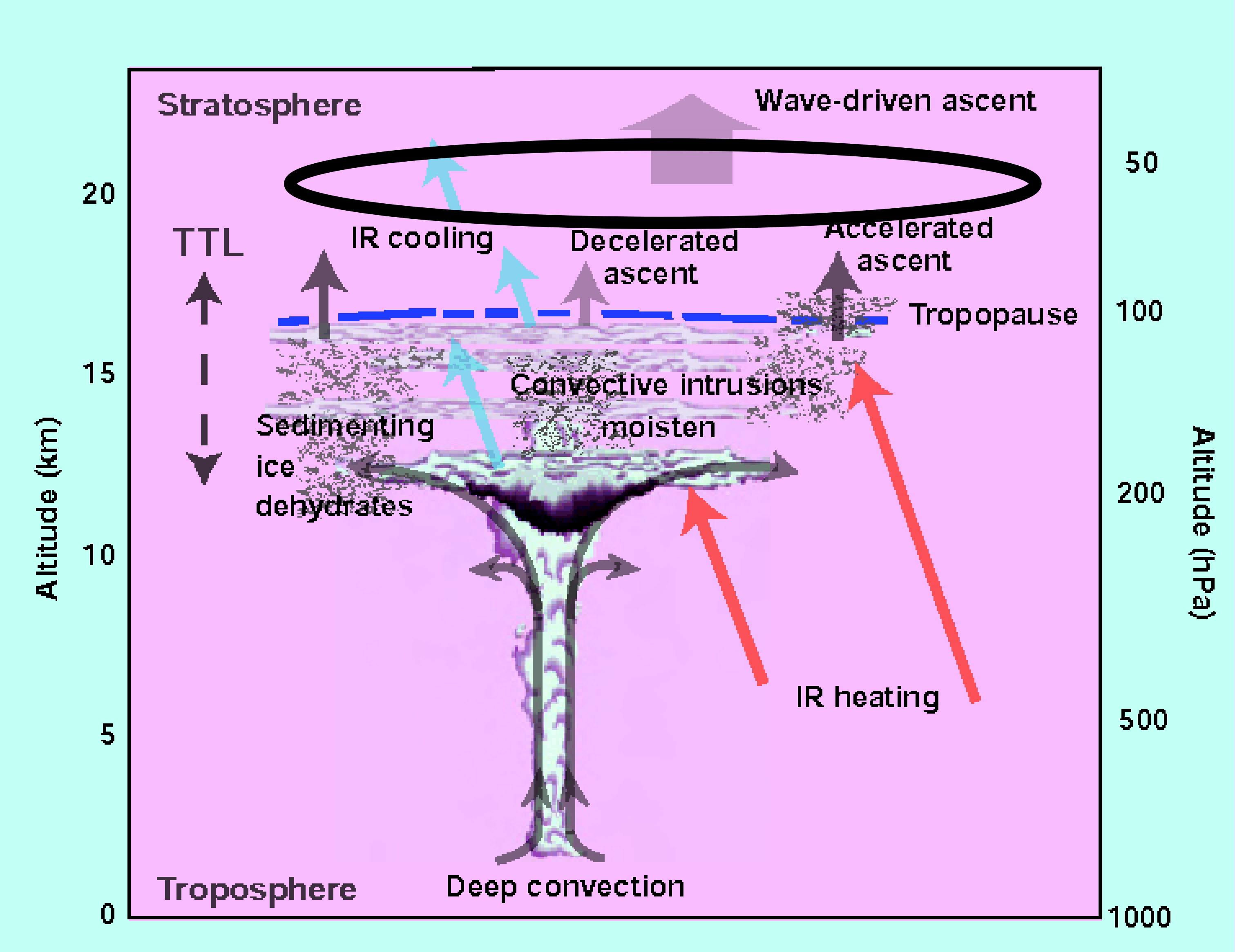


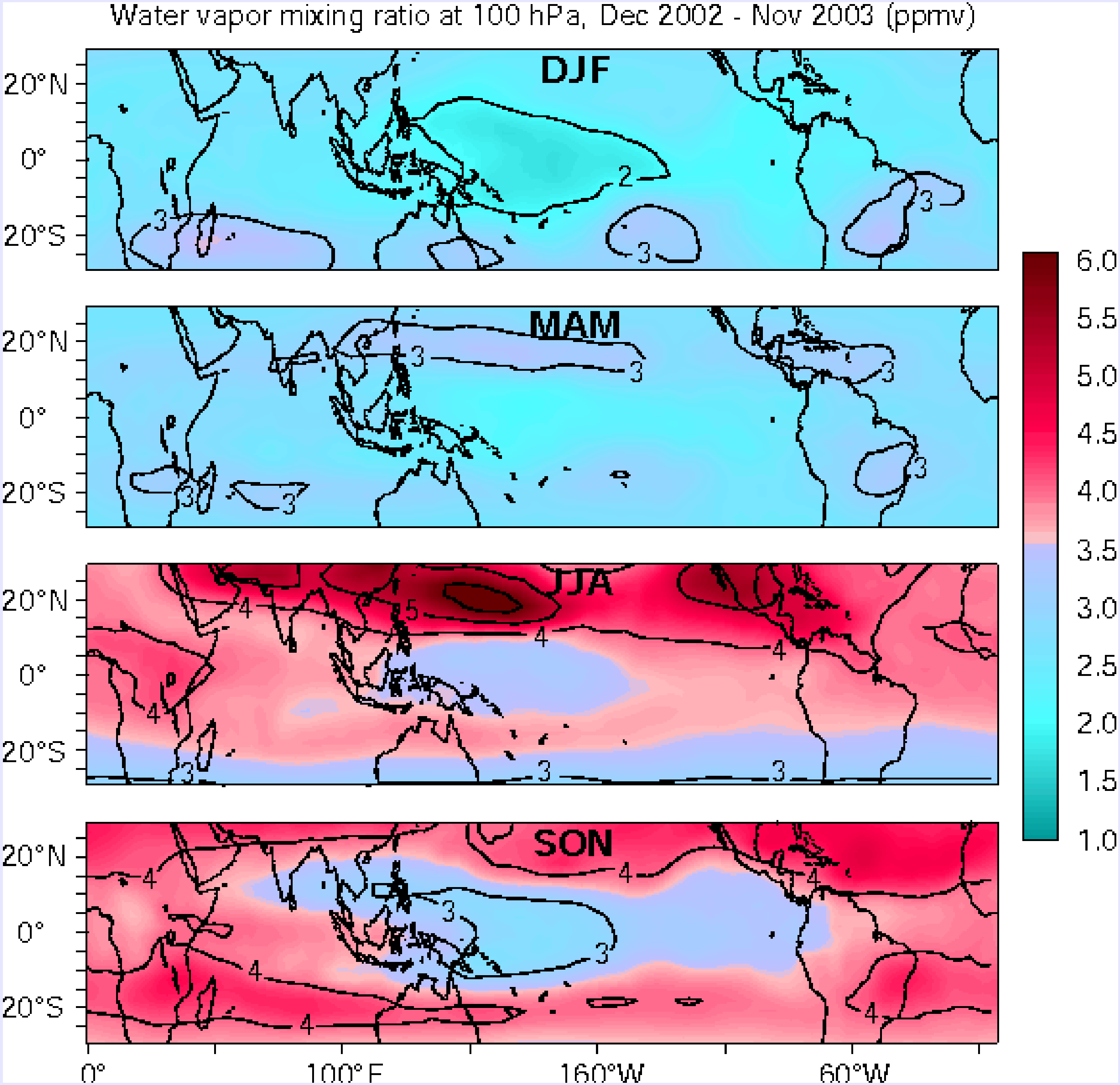
Fig. 5b. Comparison of E5M1 temperature calculations with AIRS satellite measurements at 100 hPa for July 2003. The upper panel shows the "ascending node" AIRS data, taken during daylight conditions outside the Antarctic region, and the middle panel the corresponding daytime E5M1 results.

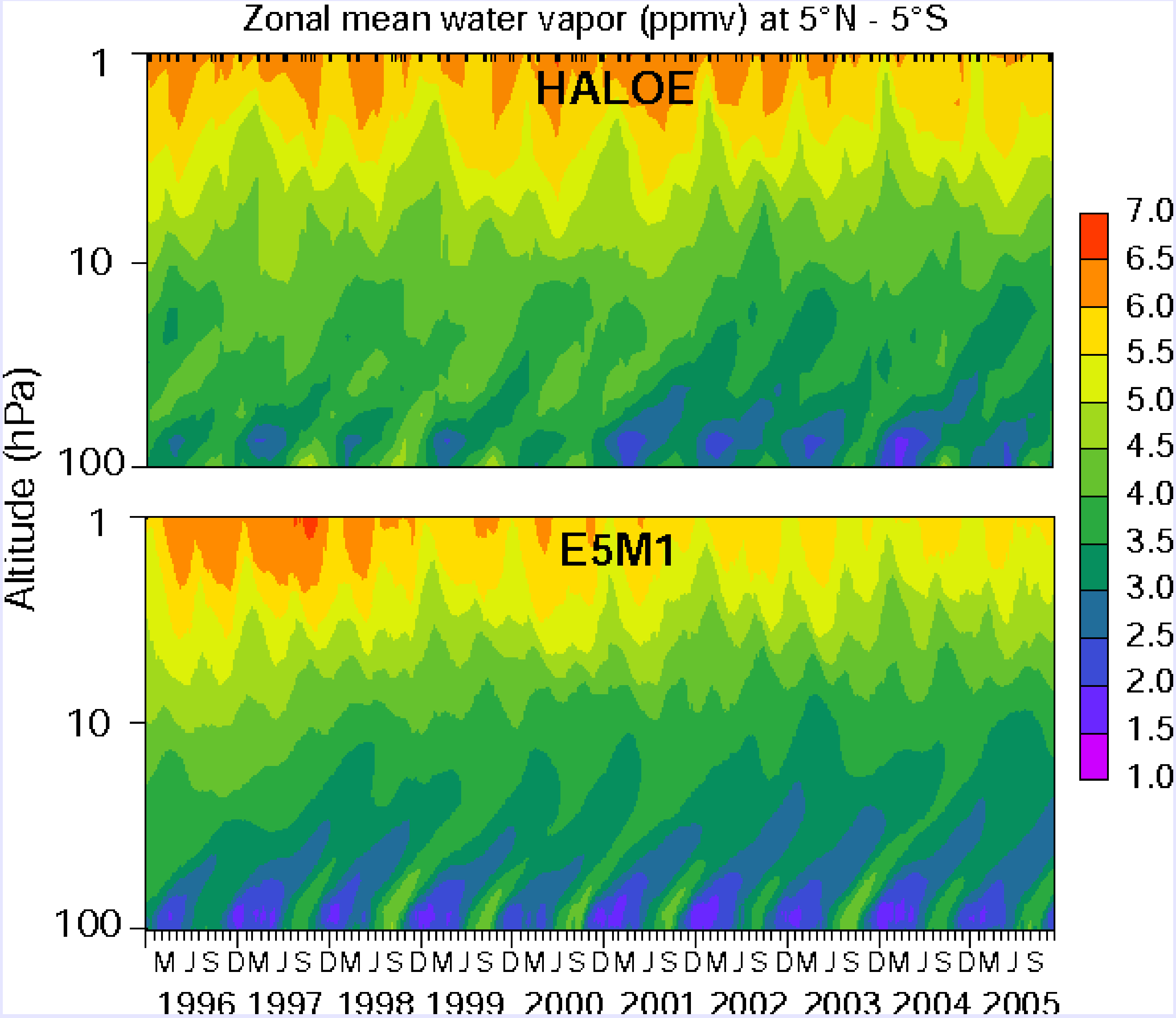
IR – cooling driven by the temperature!

Well represented ?

How does water in the stratosphere compare to observations?




Water vapor mixing ratio at 100 hPa, Dec 2002 - Nov 2003 (ppmv)
DJF
MAM
JJA
SON
20°N
0°
20°S
0°
100°E
160°W
60°W
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0


Zonal mean water vapor (ppmv) at 5°N - 5°S
HALOE
E5M1
Altitude (hPa)
1
10
100
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
M J S D M J S D M J S D M J S D M J S D M J S D M J S D M J S D M J S D M J S
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005

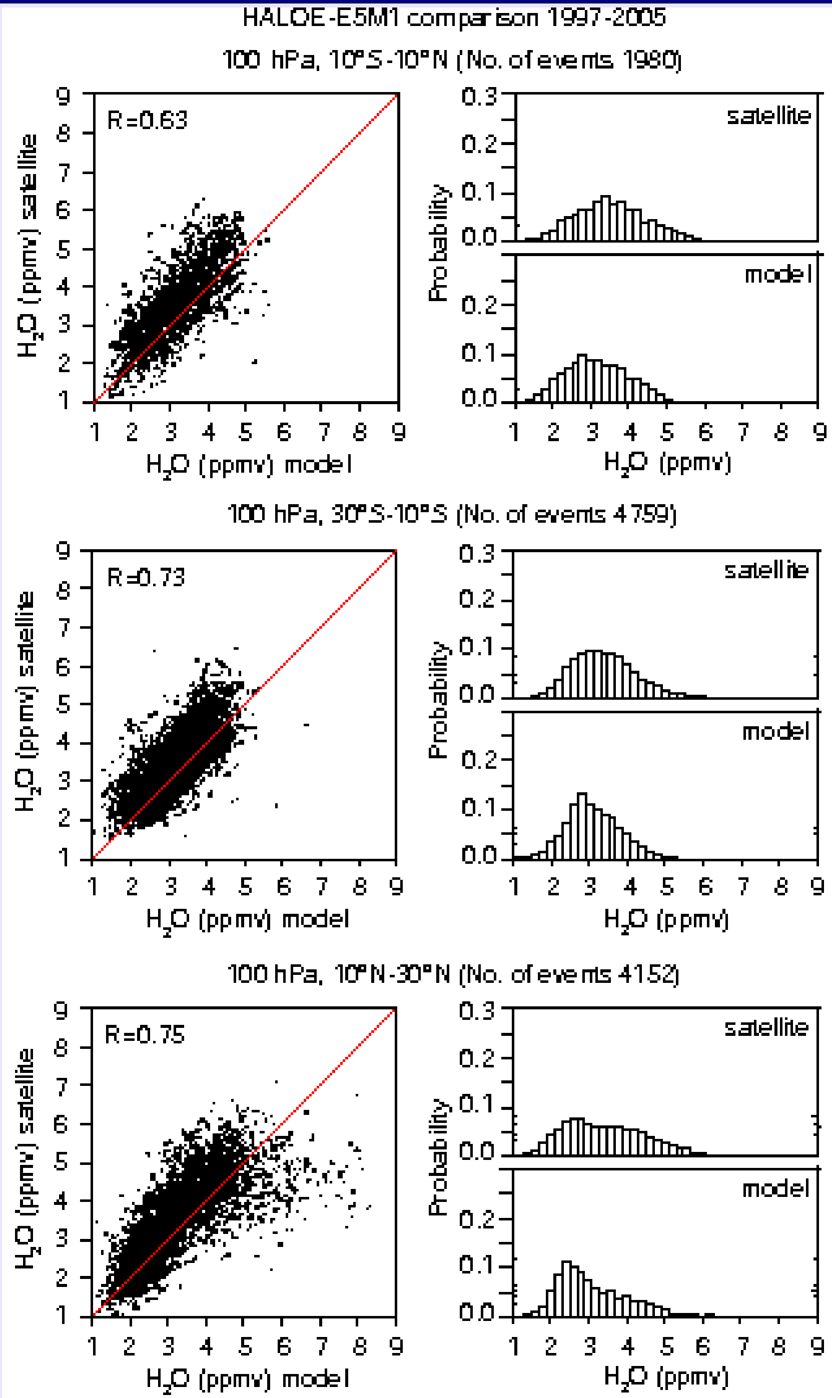


Fig. 7. Comparison of ESM1 water vapor calculations with HALOE at 100 hPa for the period 1997–2005.

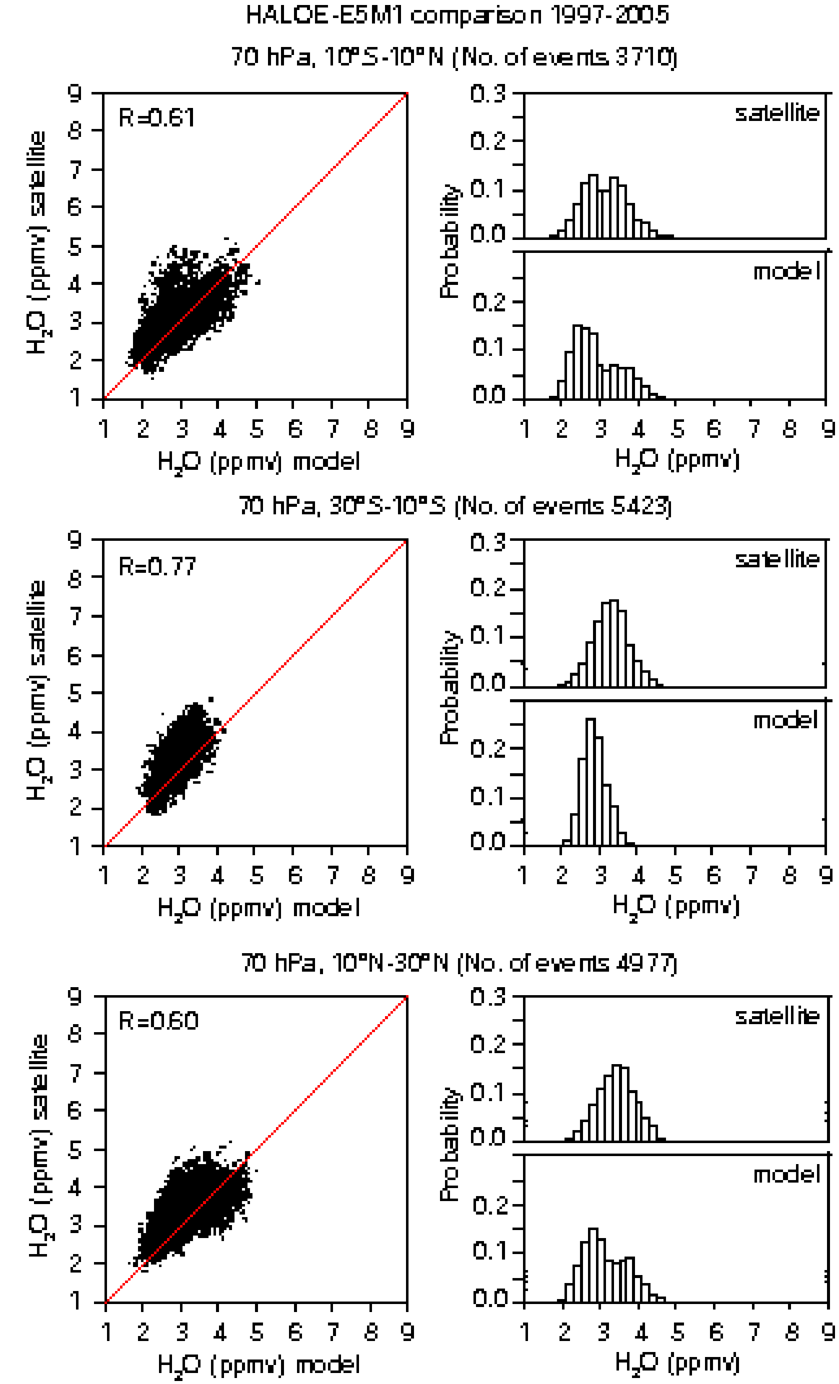
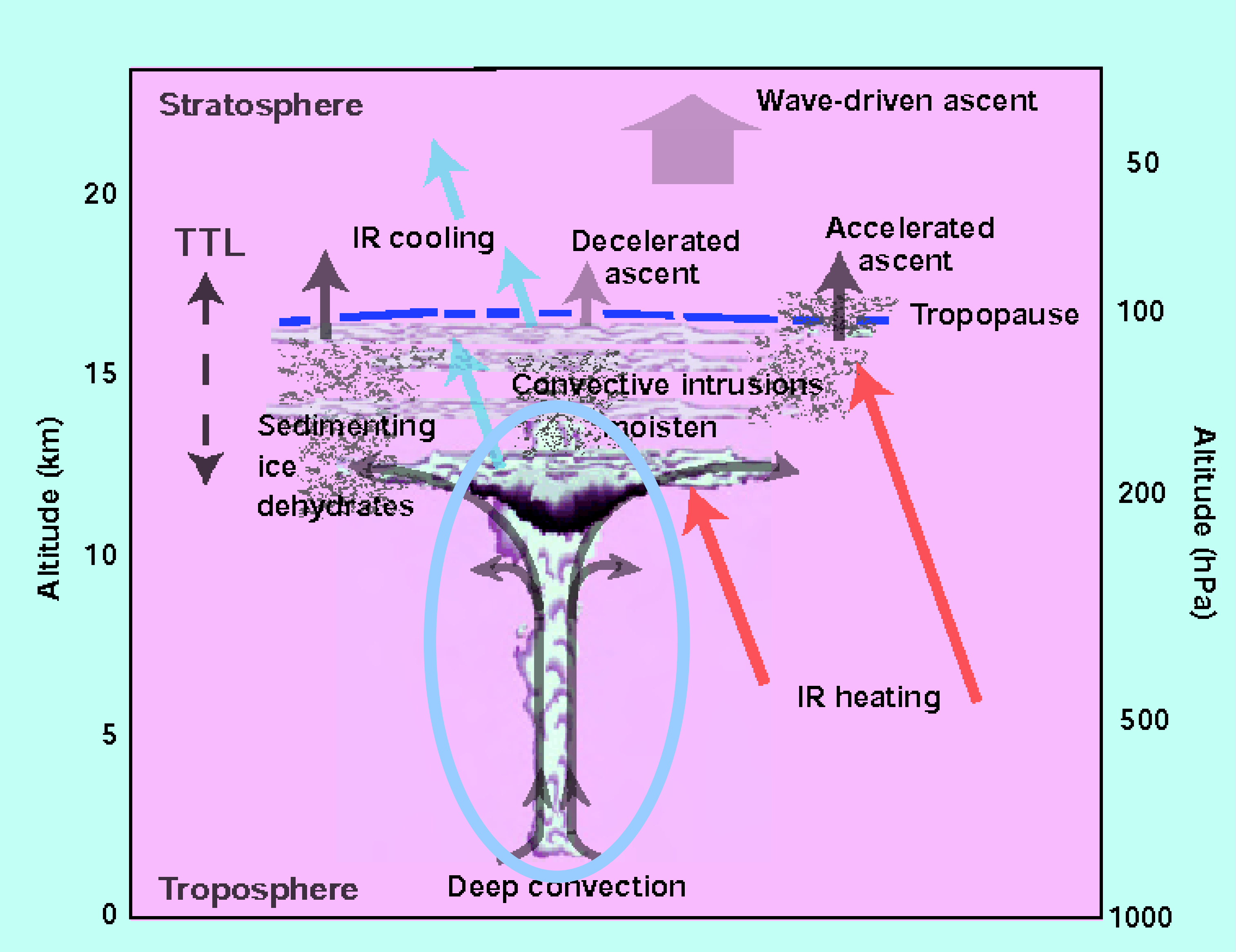
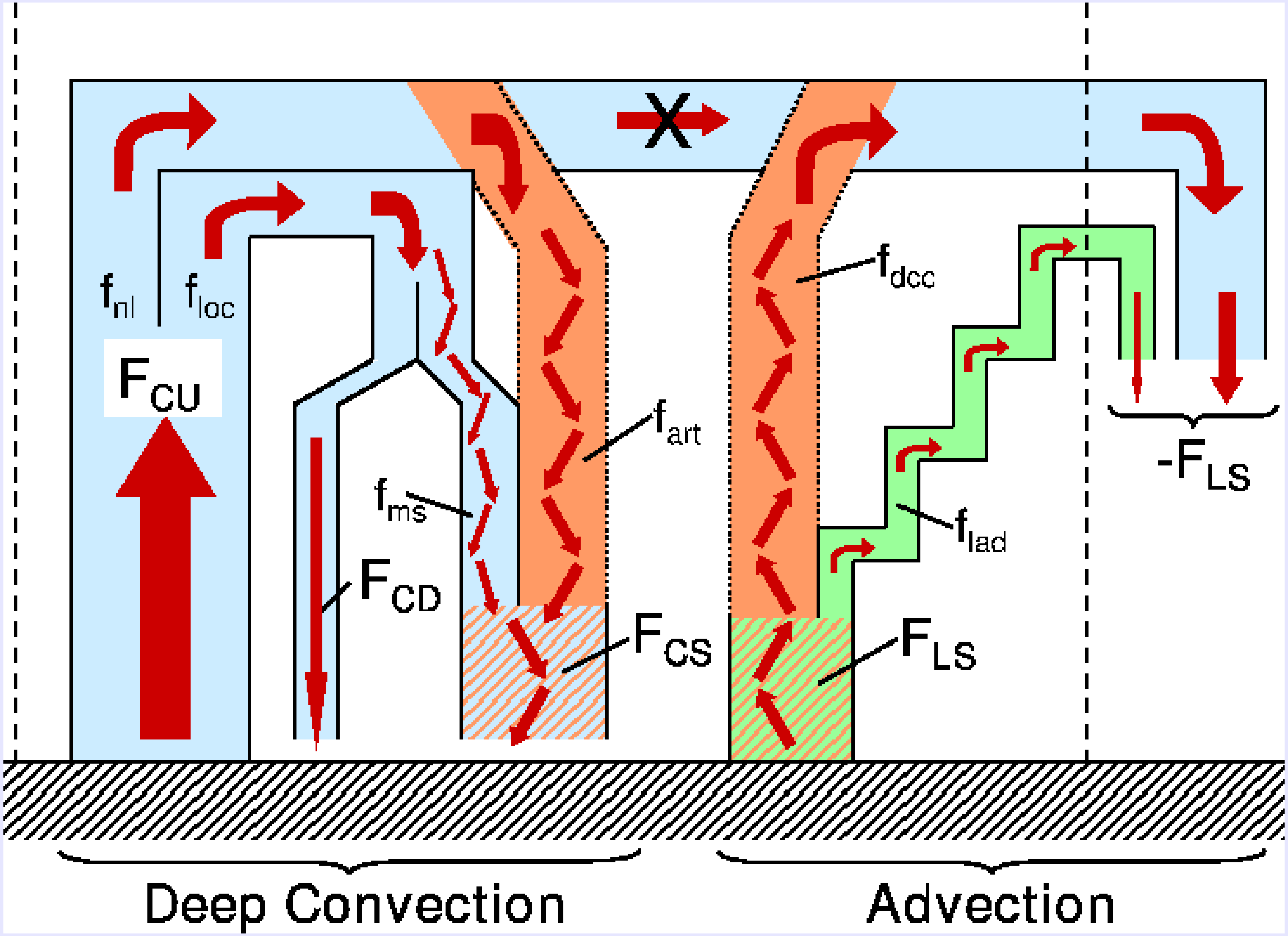


Fig. 8. Comparison of ESM1 water vapor calculations with HALOE at 70 hPa for the period 1997–2005.

How does water reach the upper troposphere?



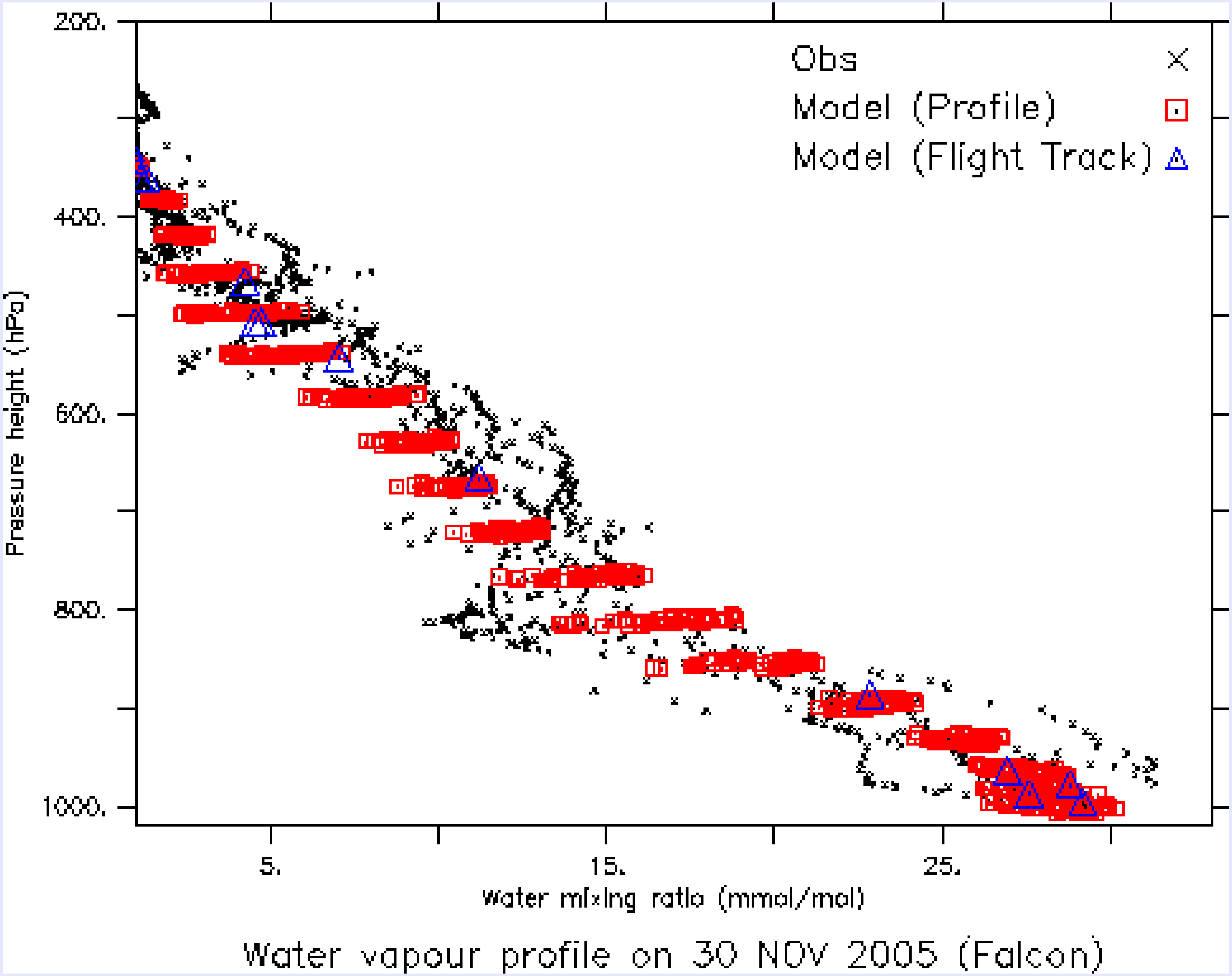
Convection (again!)



- Convection usually occurs combined with large – scale ascent

Example – Hector

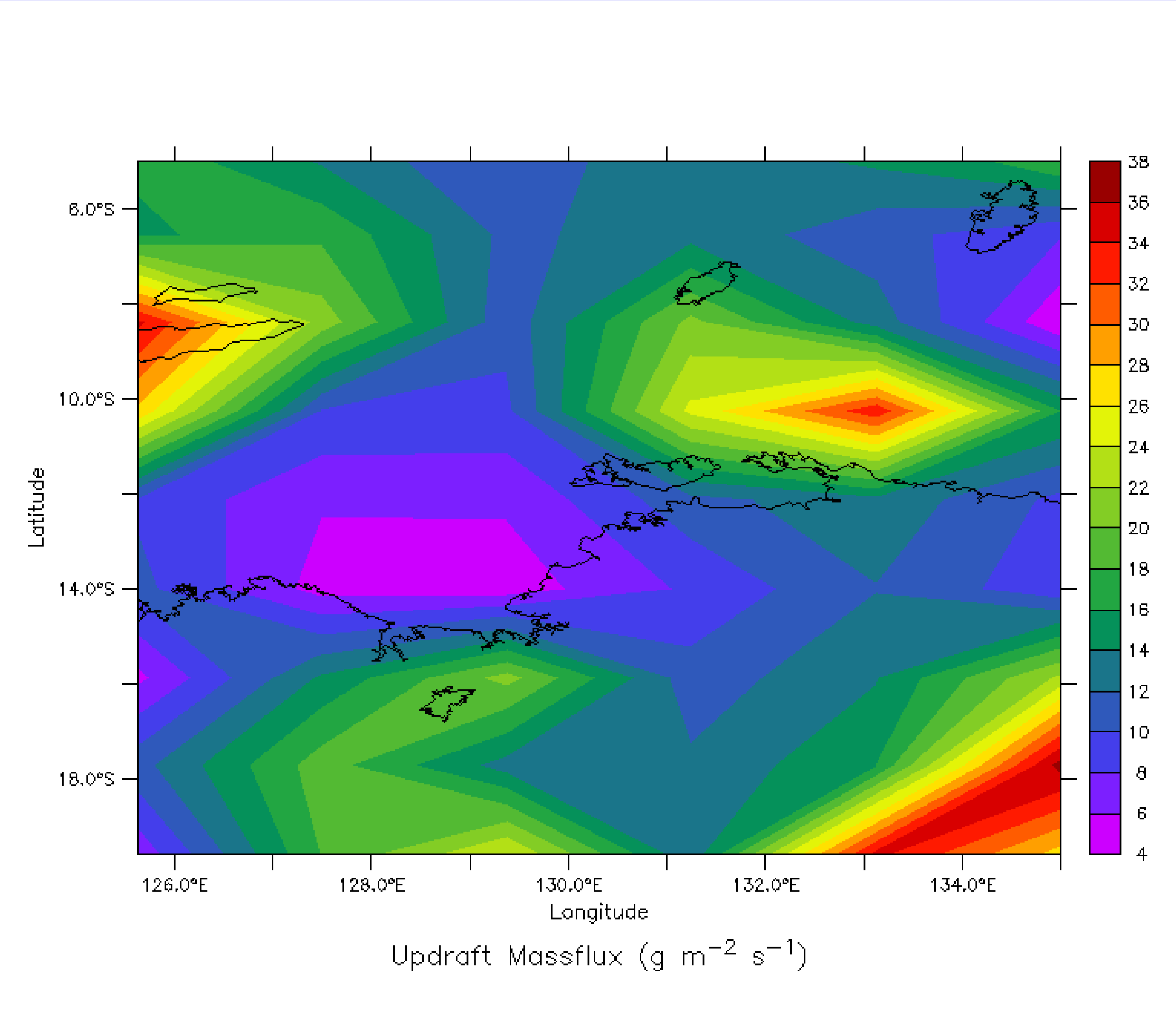
Example – Hector



Comparison of global model data with aircraft observations:

Online sampling data at aircraft position or using vertical profile data at aircraft position (max. time resolution = each model timestep)

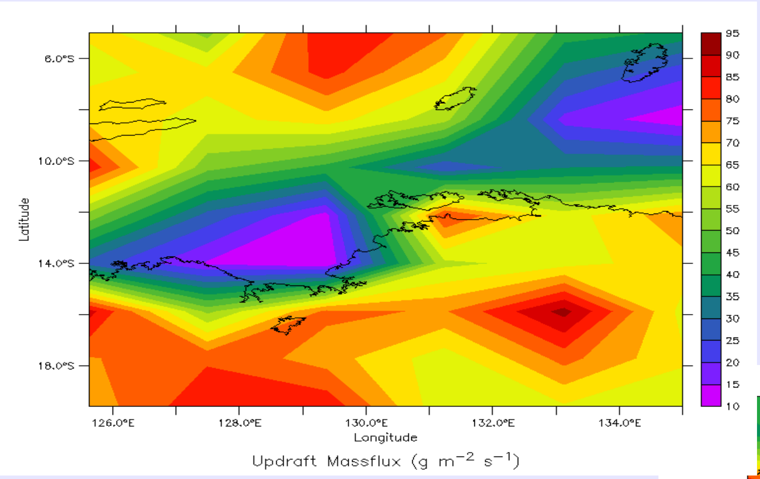
Example – Hector



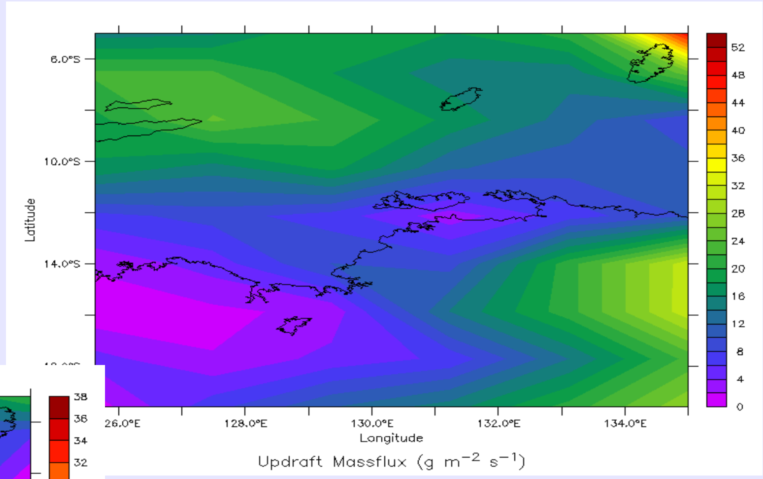
Not 100% correct location of a convective system, but acceptable

Mass Fluxes ($g/(m^2s)$)

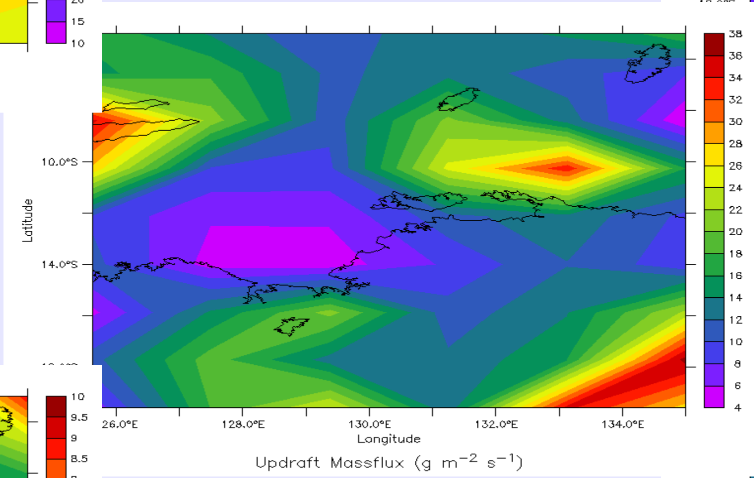
EC

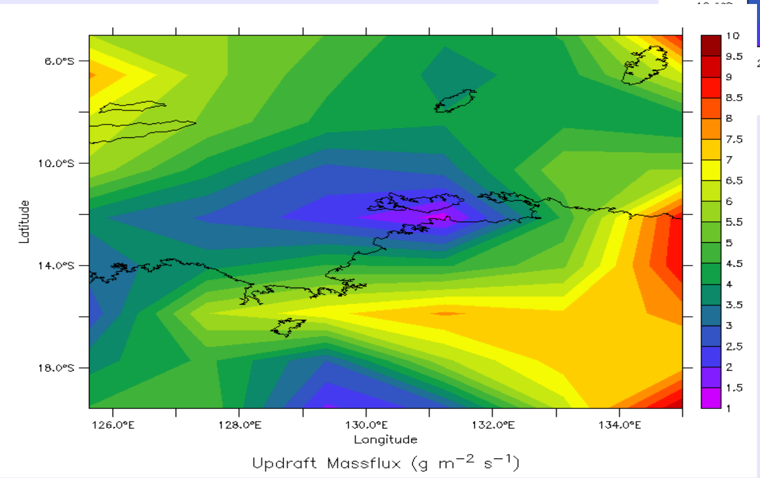


ZHW

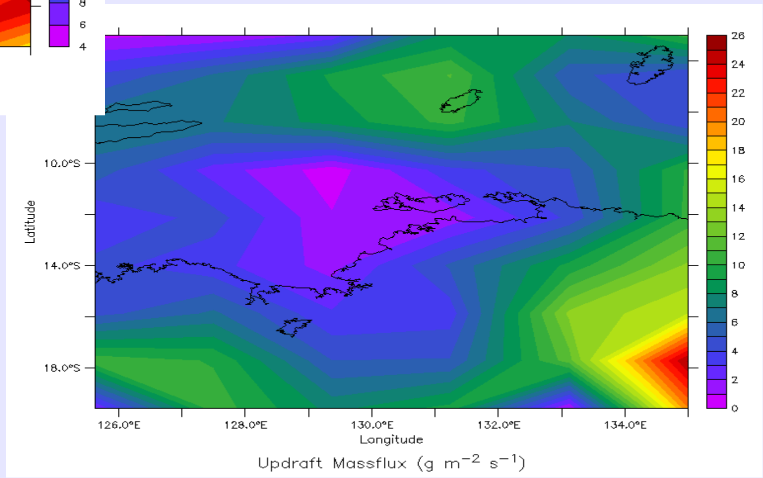


T1



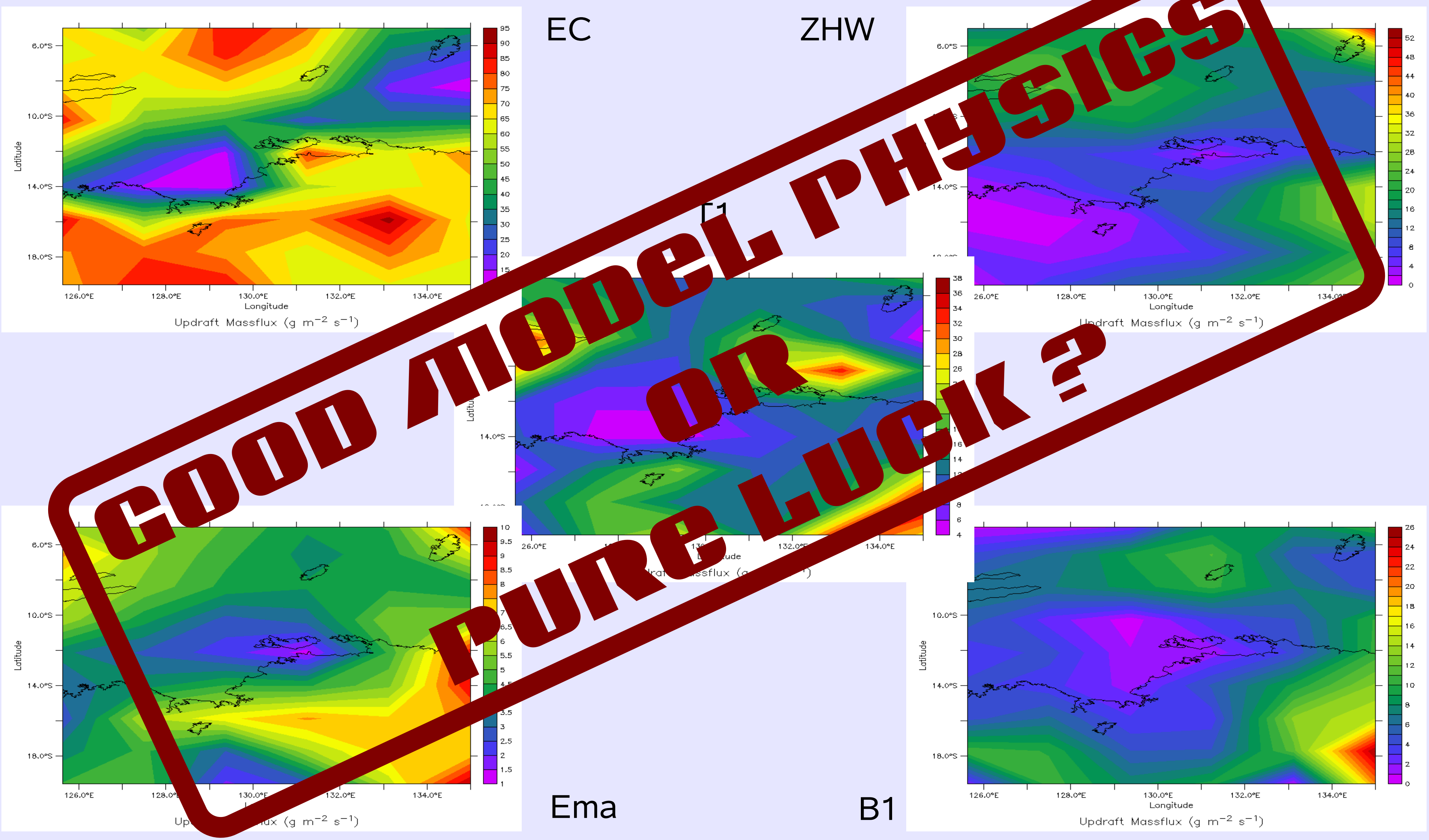


Ema

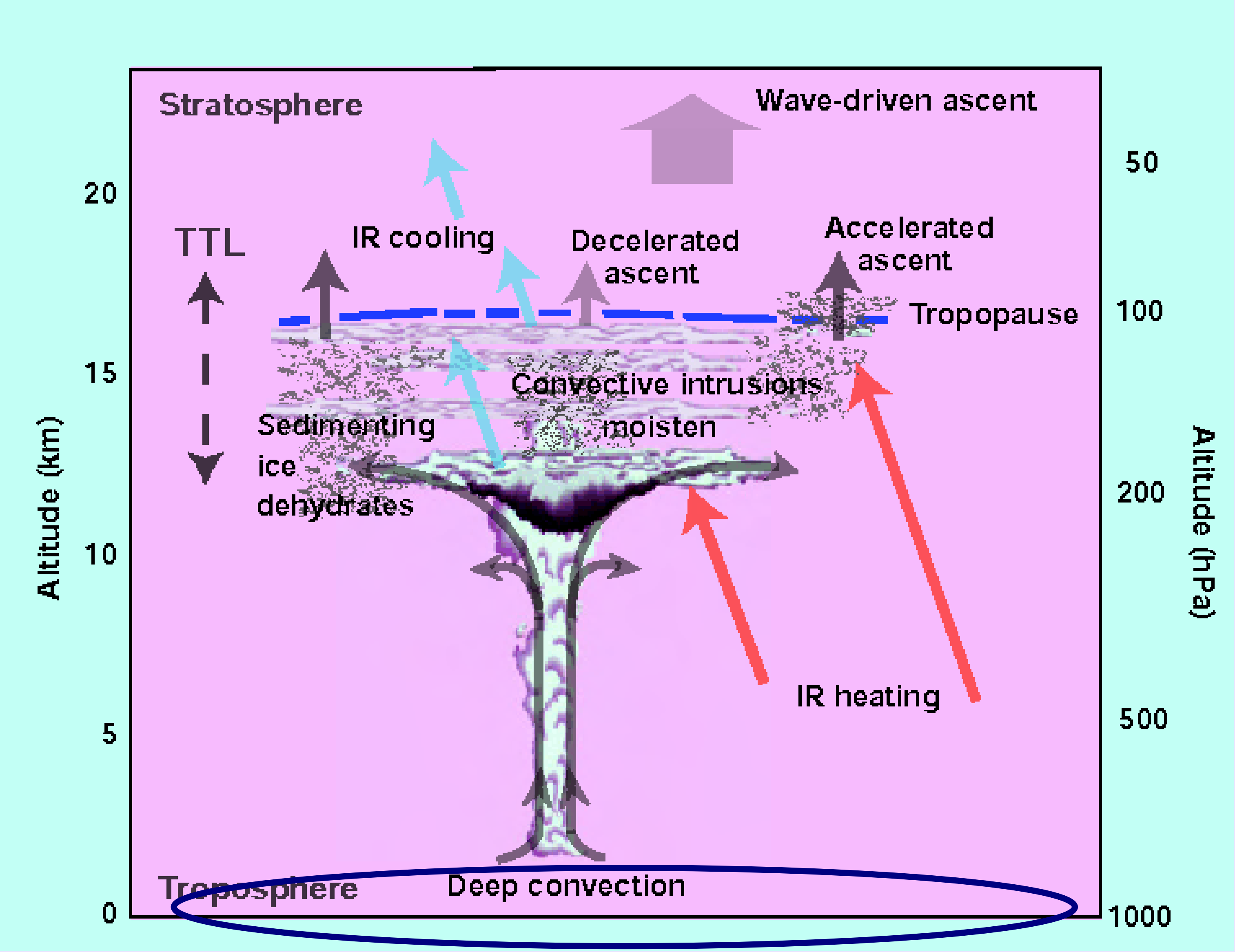


B1

Example – Hector

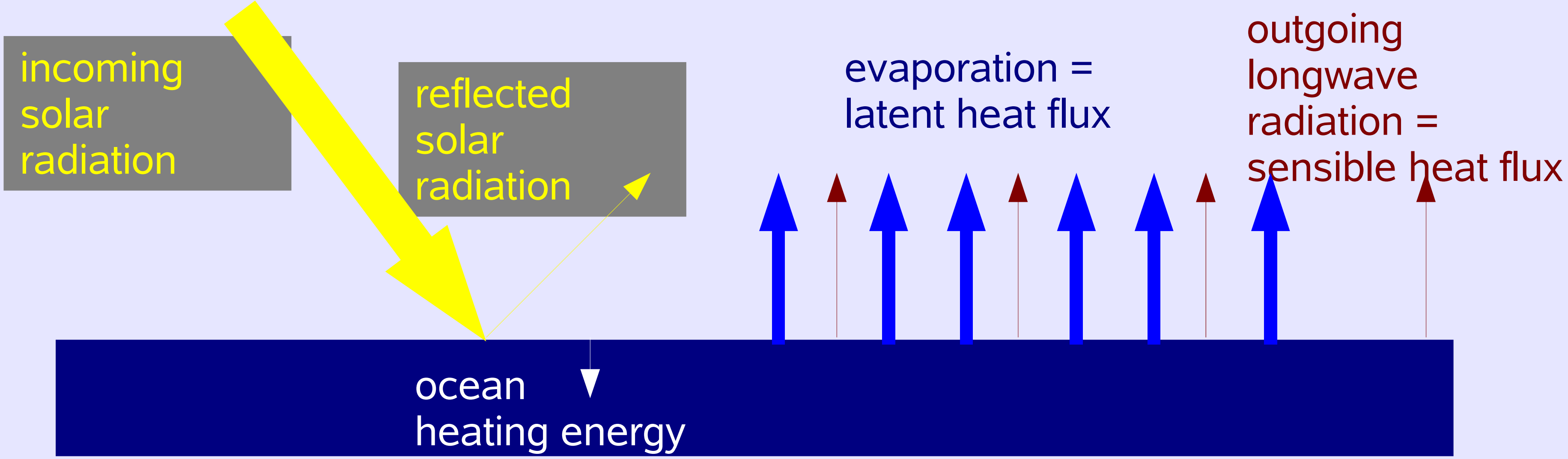


Where does the water come from ?



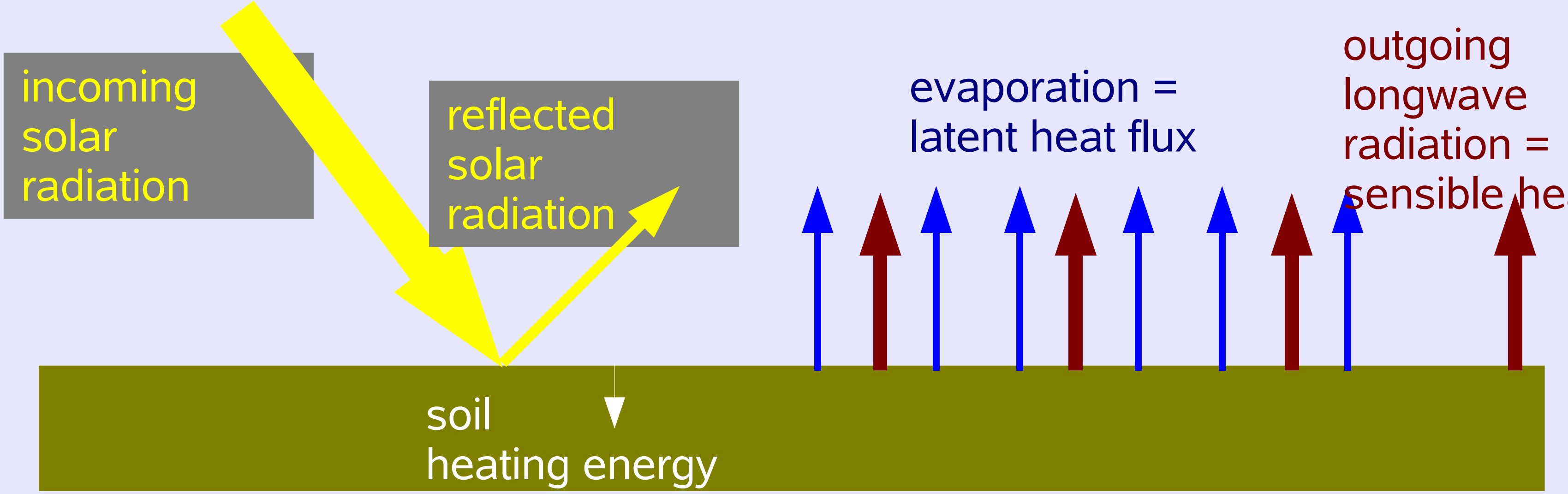
Oceanic evaporation

- ocean = unlimited water reservoir
- in-going energy flux and sea surface temperature determine the total evaporation

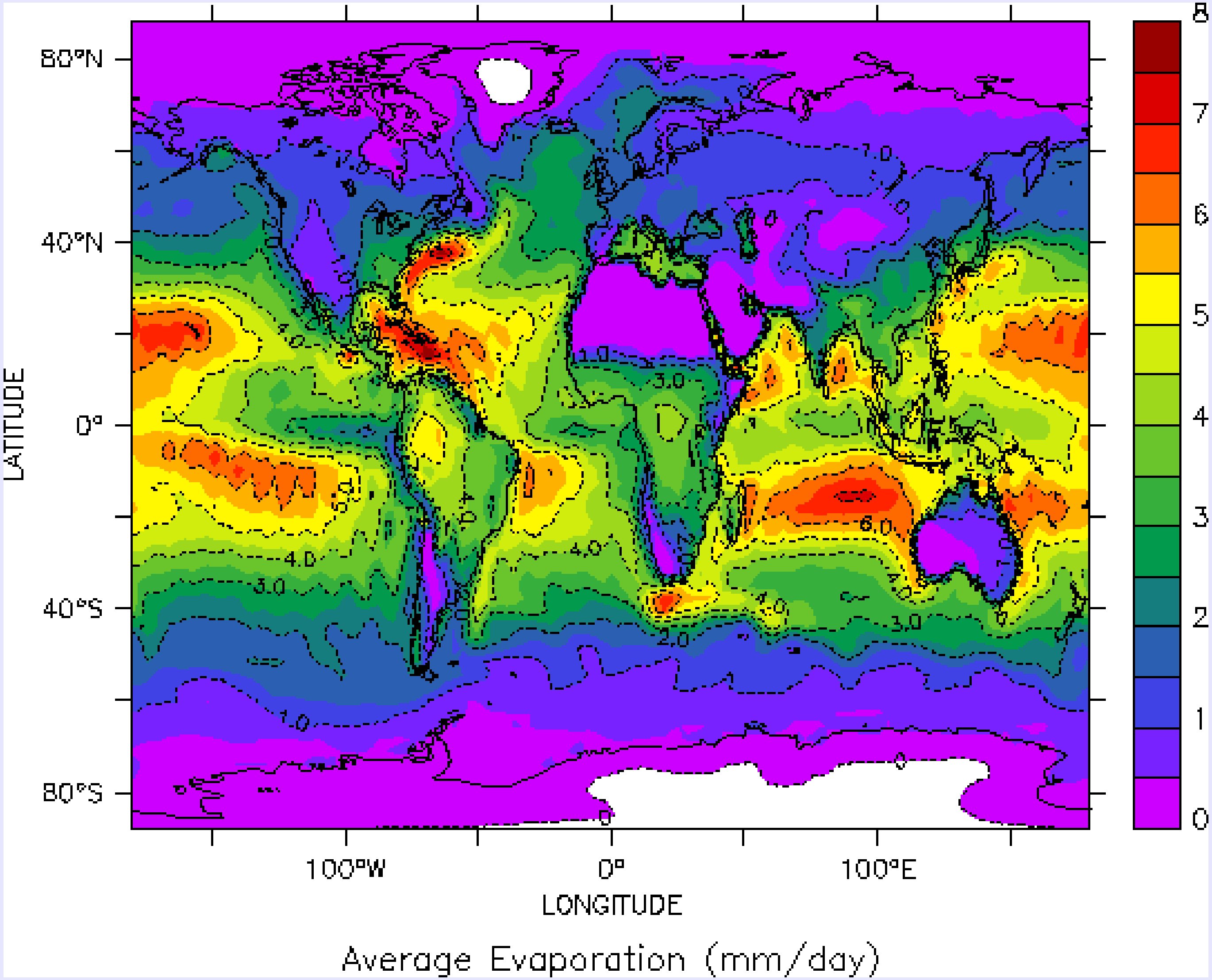


Evaporation from the land surface

- soil moisture = limited water reservoir
- in-going energy flux and land surface temperature determine the total evaporation



Global evaporation



from ECHAM5 model
6 year average

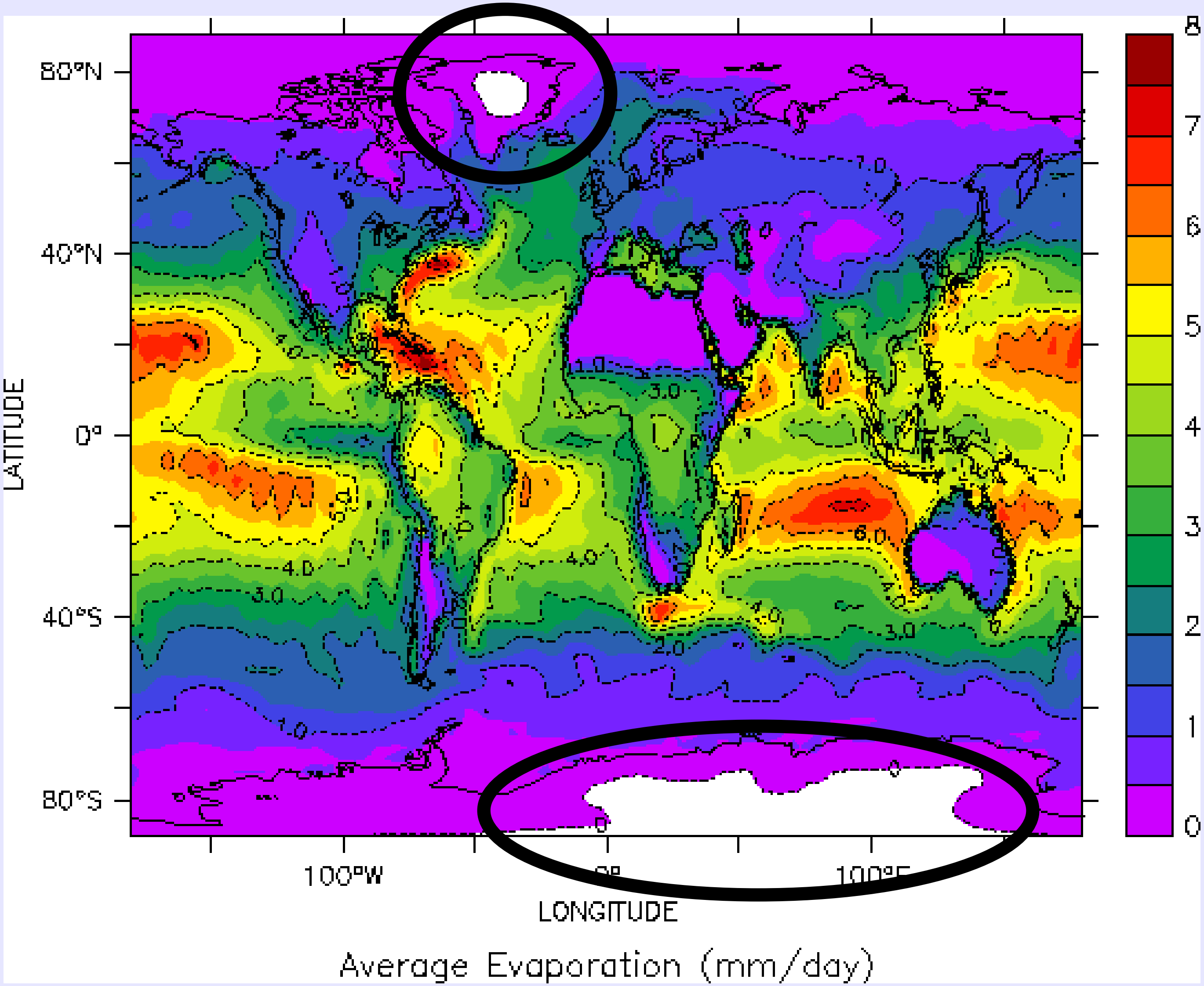
Evaporation from the surface

- effective evaporation is strongly dependent on vertical mixing, especially vertical diffusion

=> evaporation flux is often directly used as the lowest level moisture input flux

- calculating evaporation is “relatively” simple, but a good description of soil moisture is much more difficult, determining the continental evaporation and low level moisture

Deposition to snow surfaces



from ECHAM5 model
6 year average

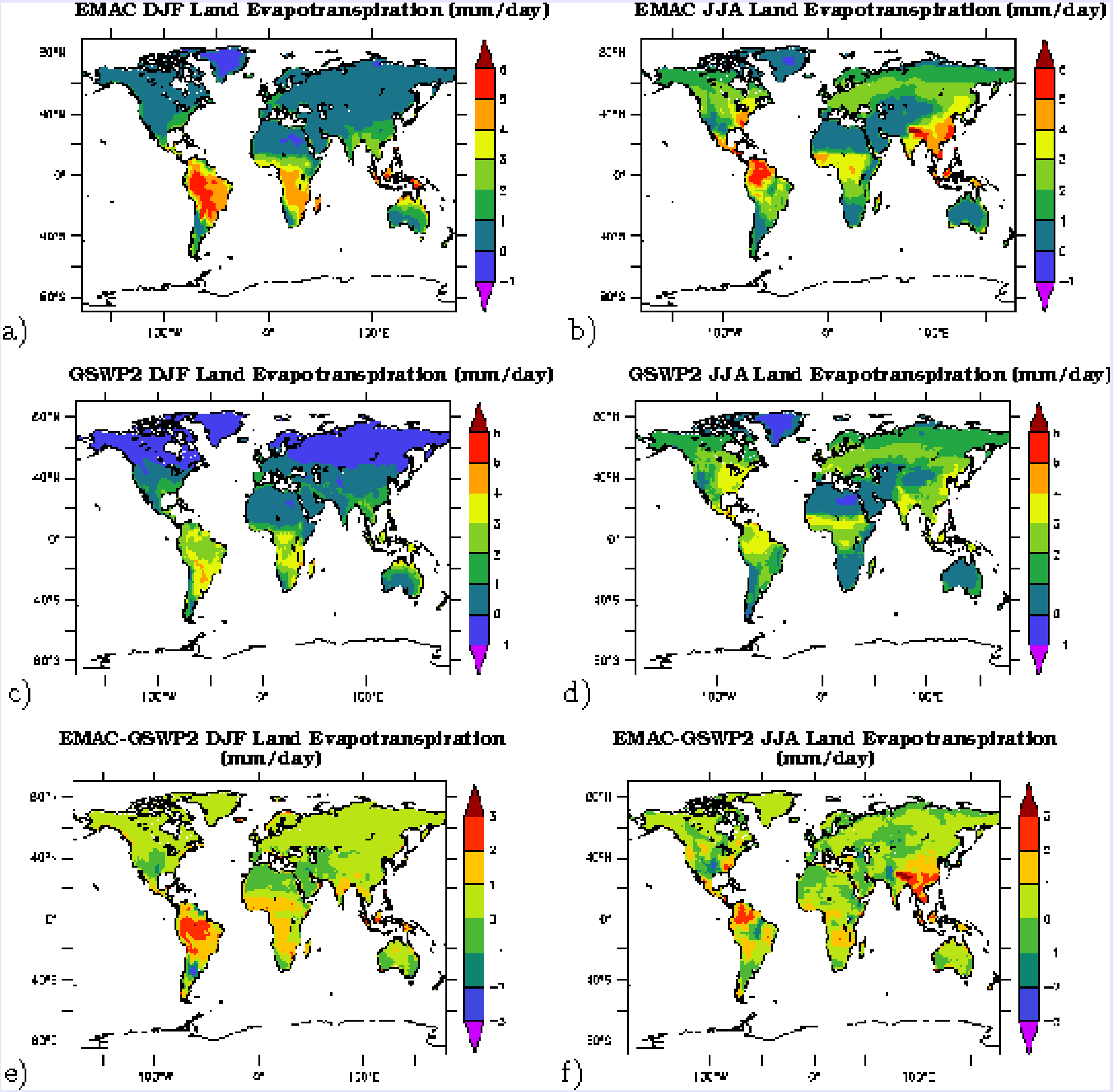
Deposition to snow surfaces

- evaporation and vertical diffusion scheme can calculate water vapour deposition on snow/ice surfaces as well

$$(\overline{w'q'})_s = -C_q * |\vec{v}_l| * (q_s - q_l)$$

- $q_s < q_l$ results in deposition, can happen over ice surfaces (partly model artefact, partly realistic)

Evaporation

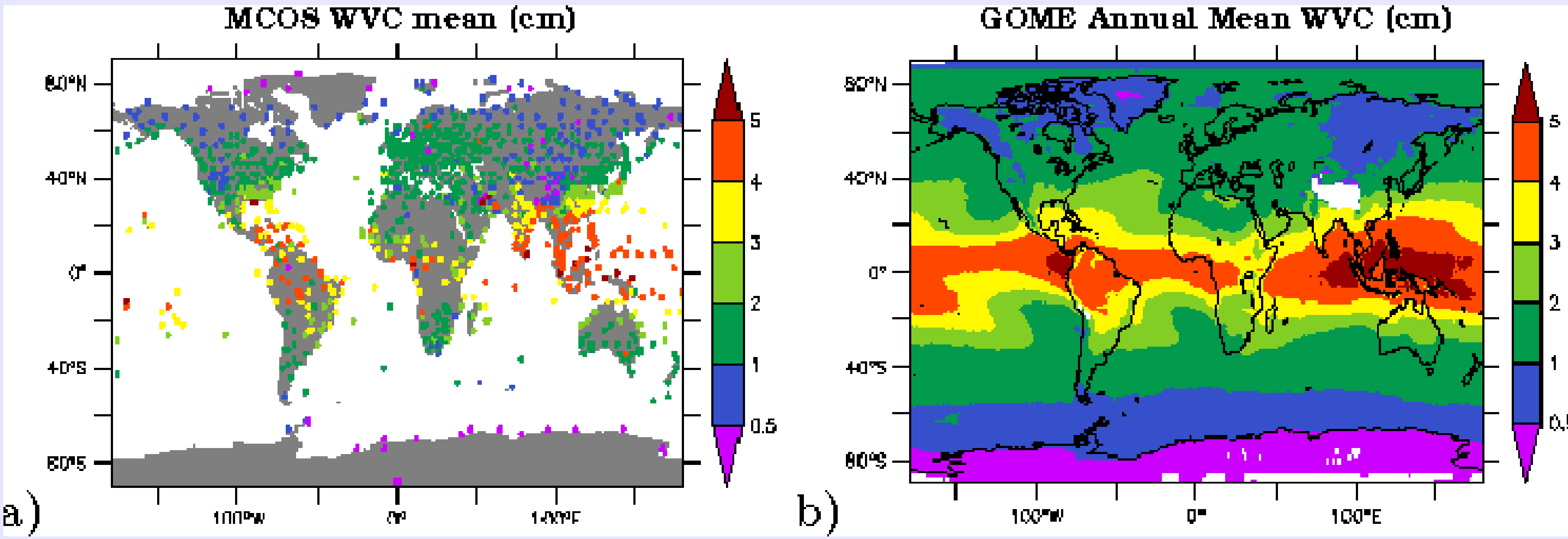


How well is evaporation represented by the model ?

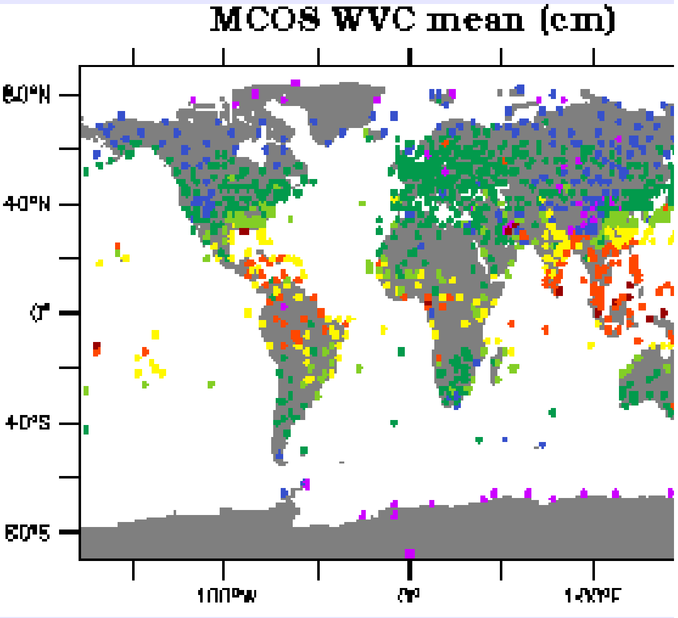
Comparing atmospheric moisture: Model data vs. Observations

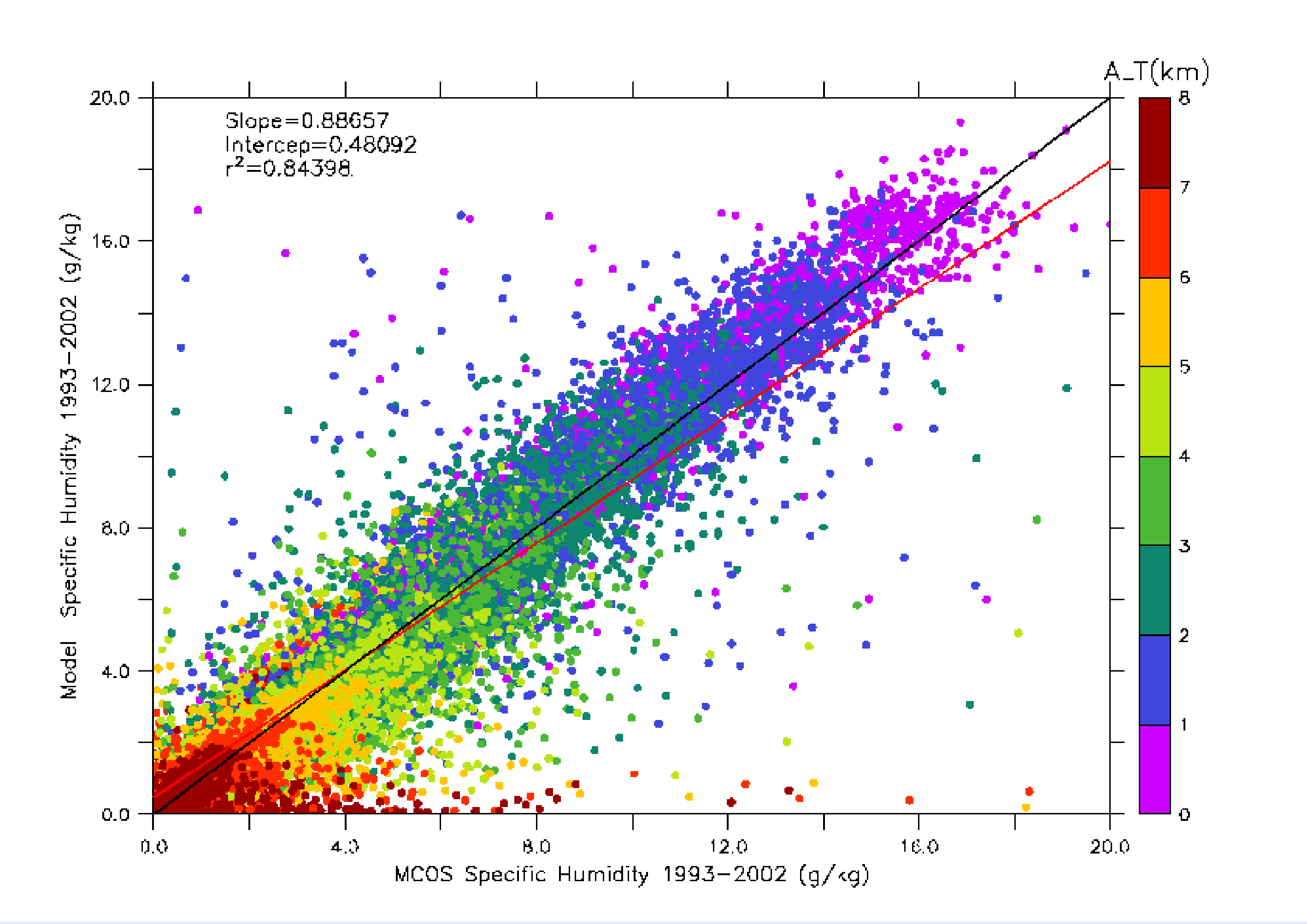
- Satellite data (including vertical profiles) (global coverage, but retrieval algorithms are used)
- Ground based data (including vertical profiles) (point measurements, often not continuous)
- In situ = sondes, aircraft (point measurements, sondes sometimes with good continuity)

Comparing atmospheric moisture: Model data vs. Observations



Comparing atmospheric moisture: Model data vs. Observations

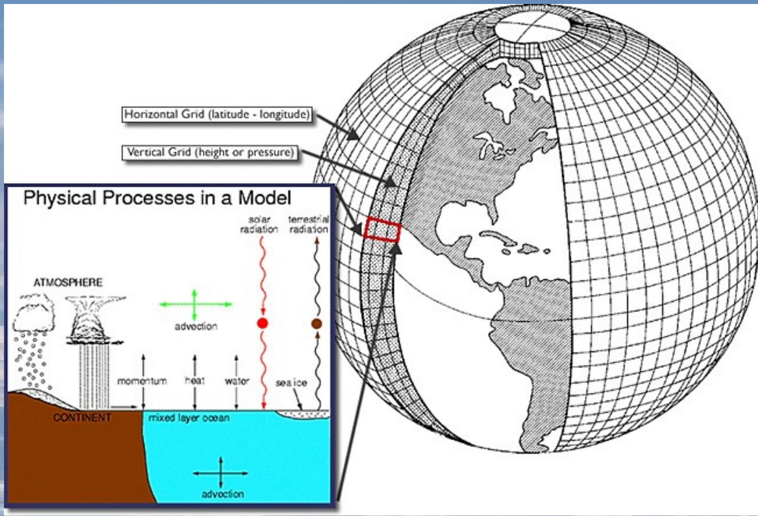




Summary

Summary

- GCMs can reproduce “relatively well” the atmospheric humidity.
- To explain phenomena complex feedback mechanisms sometimes have to be taken into account => Models must be comprehensive
- A lot of phenomena can be explained with the simplified parameterisations used in GCMs (including their respective uncertainties)



Simplified,
but not simple !

THE END!