

Boundary Layers, Transport and Mixing - part 2

Lecture 3, Aarnout van Delden
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Radiative-Dynamical Interaction

Radiative determined state **lacks cold tropical tropopause and does not produce the correct diabatic heating distribution**

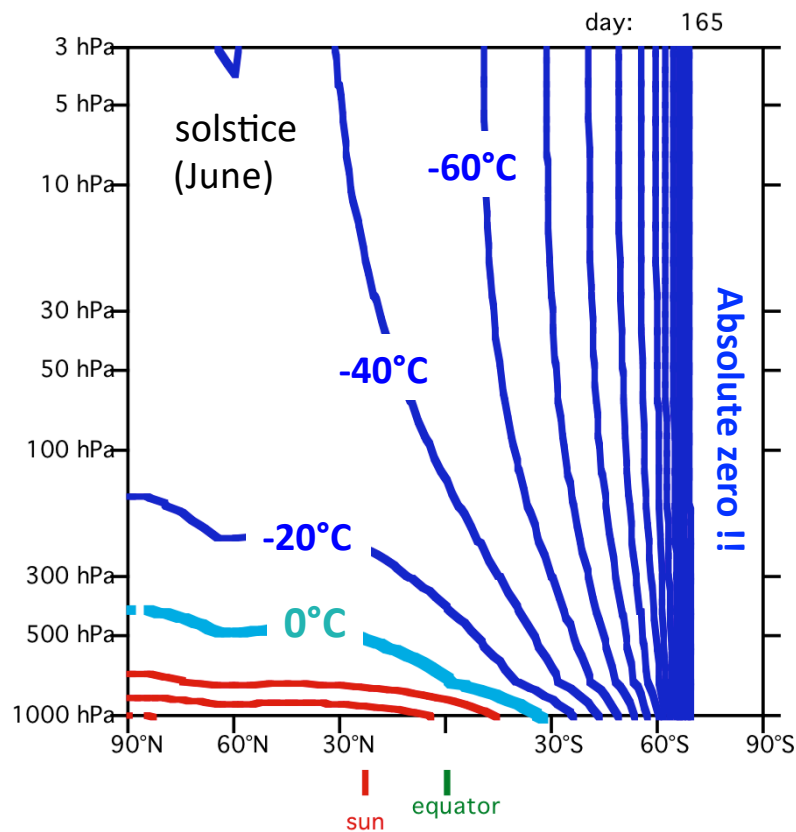
Now we study how dynamics changes the radiatively determined temperature distribution and **establishes a zonal flow, including zonal jets**. Can dynamics induce the cold tropopause?

This question is investigated with a **hydrostatic primitive equation model** in which includes the simple semi-grey radiation scheme

Next, we introduce the water cycle...

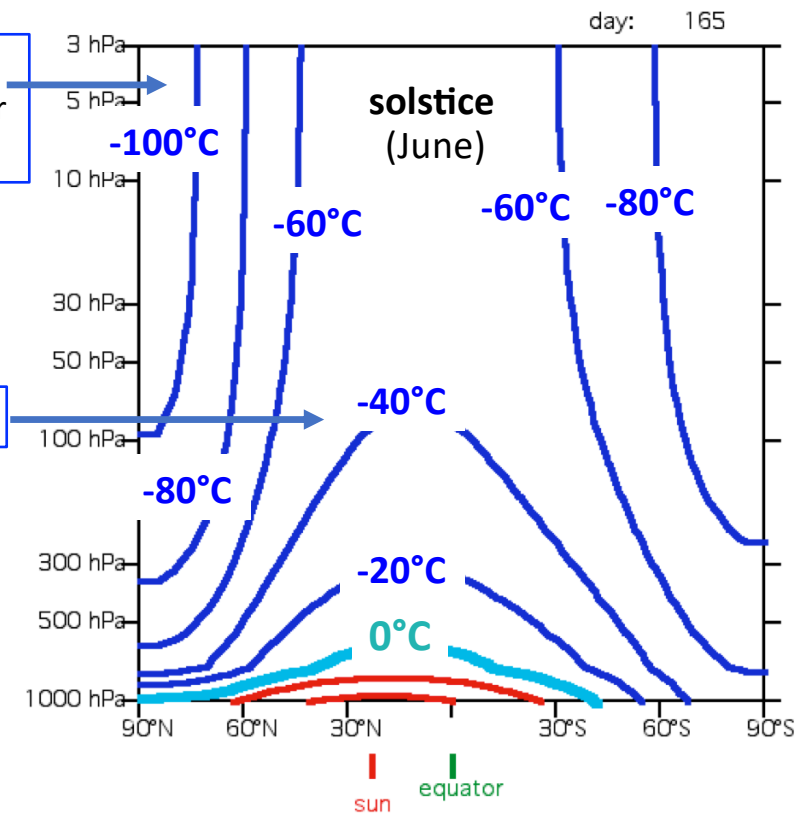
Radiative - equilibrium and – “determined” states

Temperature [$^{\circ}\text{C}$] as a function of latitude and pressure for day 165. **Left panel: *radiative equilibrium***. **Right panel: *radiatively determined state with heat capacity of the Earth’s surface, $C=10^7 \text{ J K}^{-1} \text{ m}^{-2}$*** . The atmosphere is transparent to Solar radiation and contains one well-mixed greenhouse gas. The **cyan contour represents the 0°C isotherm**. Temperatures below 0°C are indicated by **blue** contours. Temperatures above freezing (0°C) are indicated by **red** contours.



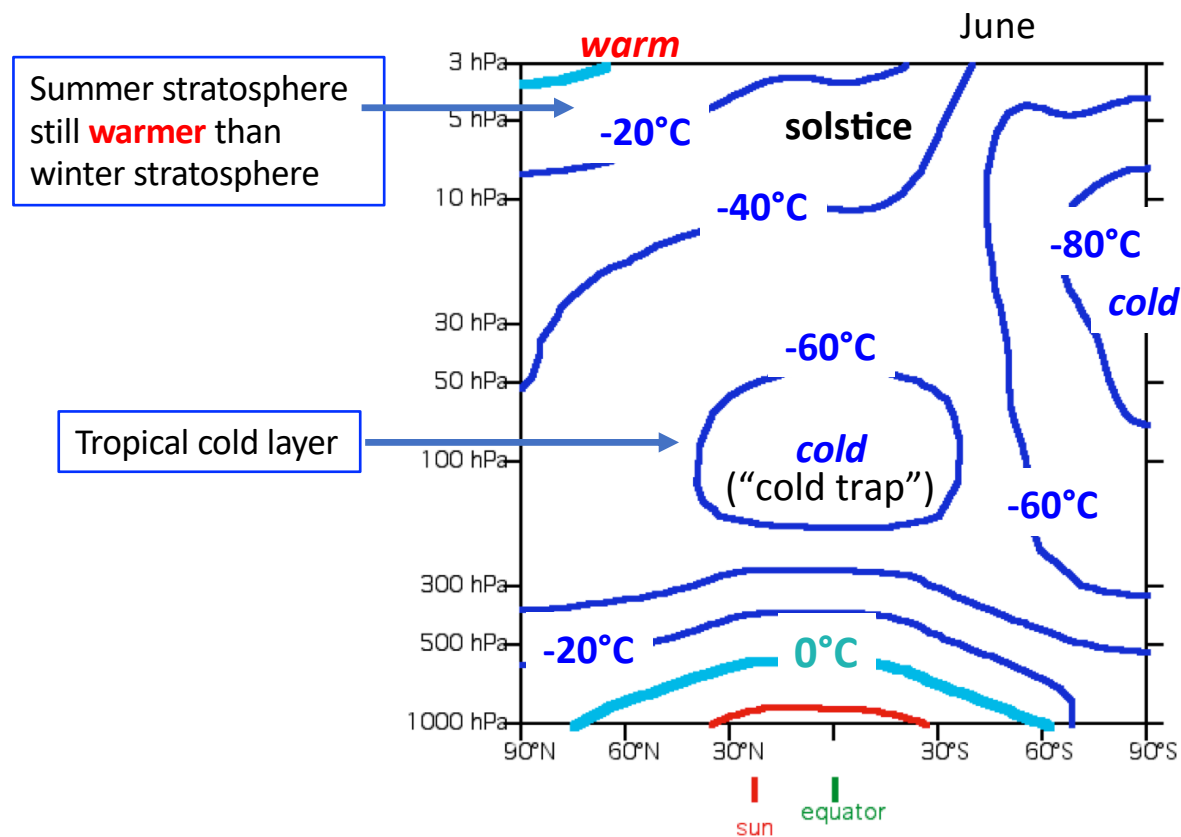
Summer stratosphere still **colder** than winter stratosphere

No tropical cold layer



Observed zonal-mean temperature distribution

Observed (COSPAR International Reference Atmosphere) monthly average zonal average temperature [$^{\circ}\text{C}$] as a function of latitude and pressure for June. Contour interval is 20°C . The cyan contour represents the 0°C isotherm. Temperatures below 0°C are indicated by blue contours. Temperatures above freezing (0°C) are indicated by red contours.



Radiatively “determined” diabatic heating

Radiatively determined tendency of the *potential* temperature [K day^{-1}] (also called **cross-isentropic flow**) as a function of latitude and pressure for day 165 (second year) (just before Solstice) in an atmosphere, which is transparent to Solar radiation and contains one well-mixed greenhouse gas. Contour interval is 0.25 K day^{-1} (zero contour not drawn).

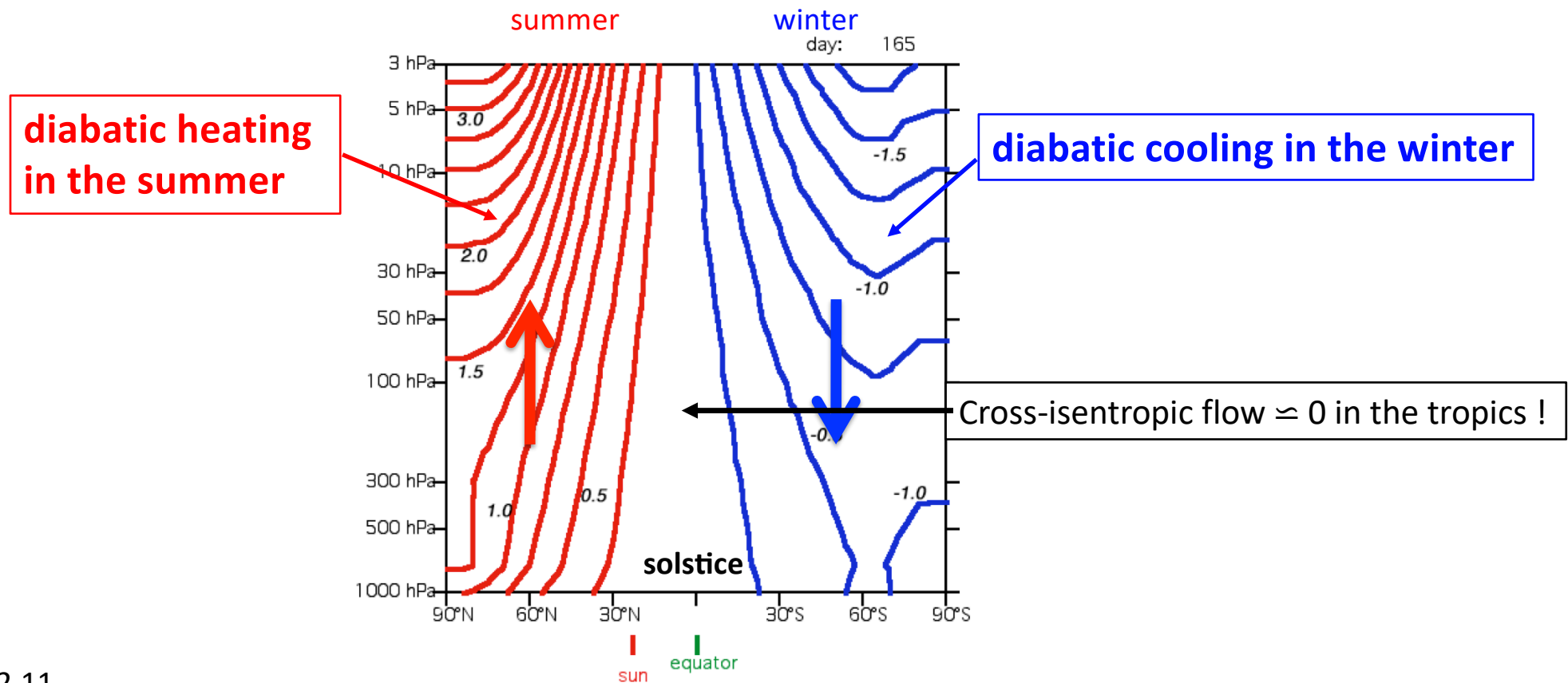


Figure 12.11

“Observed” diabatic heating (re-analysis)

Monthly average tendency of the *potential* temperature [K day^{-1}] (also called cross-isentropic flow) as a function of latitude and potential temperature for June according to the ERA-40 reanalysis. Dotted lines represent isobars, labelled in hPa. The thick black line indicates the zonal mean position of the Earth's surface.

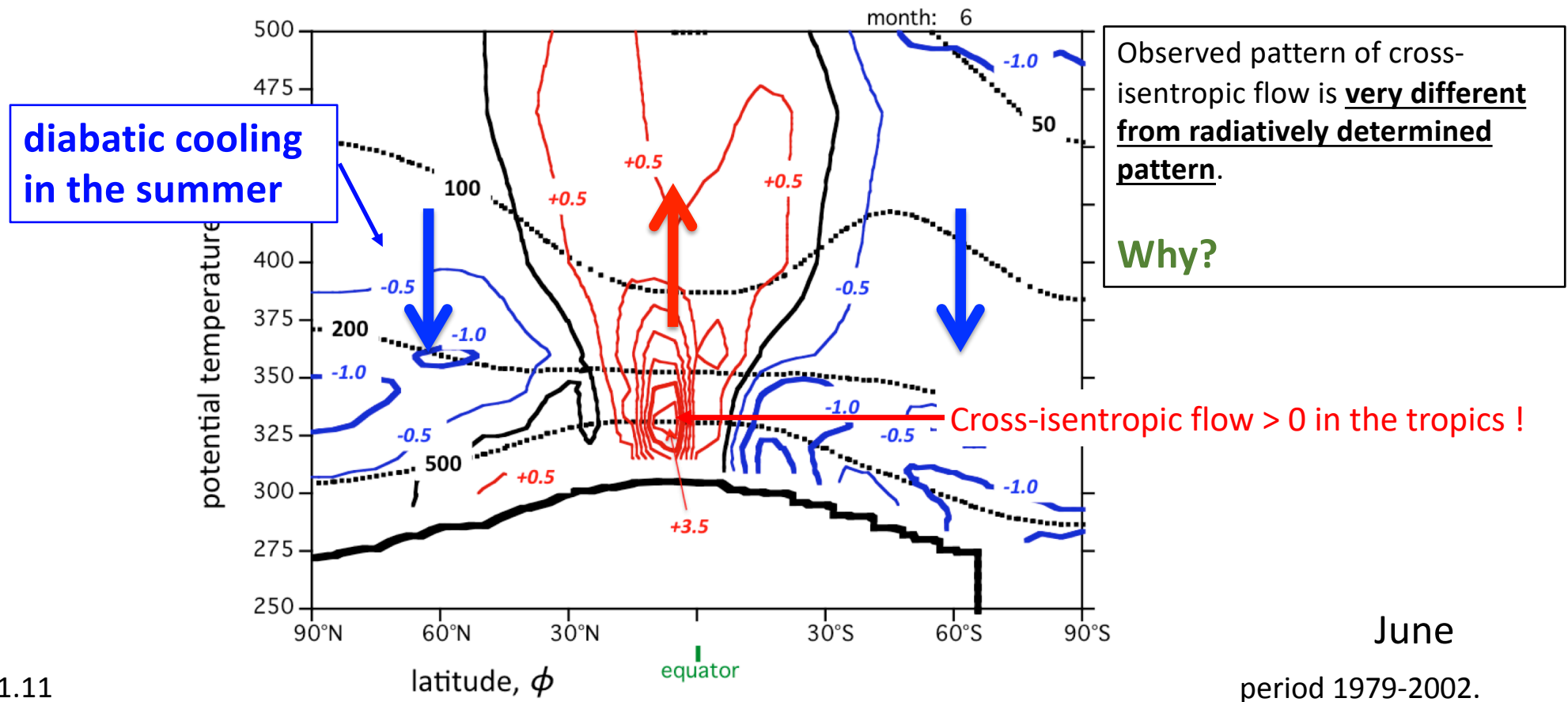


Figure 11.11

A model of zonally symmetric radiative-dynamical adjustment

Couple the radiation model to the “dynamical core” of a primitive equation model.

Assumptions on radiation are identical to previous assumptions: the atmosphere contains **one well-mixed greenhouse** gas as a proxy for CO₂, which acts as a **grey absorber/emitter** of radiation. Later we will add water vapour, which is also a greenhouse gas, but not well mixed!

The model is 2-dimensional (coordinates: y, η) ($\eta = p/p_s$)

Based exactly the same equations as any hydrostatic weather prediction model, assuming that all derivatives in the west-east (x) direction are zero.

(chapter 10 lecture notes)

The model is hydrostatic: $\frac{\partial \Phi}{\partial \eta} = -\frac{RT}{\eta}$ (diagnostic equation to determine Φ from T)

↑
geopotential = gz

Dynamical Core: prognostic model equations in flux form

Neglecting the effects of curvature in the continuity equation (10.22), this equation becomes

$$\frac{\partial p_s}{\partial t} + \frac{\partial p_s v}{\partial y} + p_s \frac{\partial}{\partial \eta} \left(\frac{d\eta}{dt} \right) = 0 . \quad \text{H: sensible heat flux convergence} \quad (12.15)$$

The other governing **prognostic equations** become (see eqs. 10.25, 10.26, 10.27 and 10.29),

$$\frac{\partial p_s \theta}{\partial t} = -\frac{\partial p_s v \theta}{\partial y} - \frac{\partial}{\partial \eta} \left(p_s \theta \frac{d\eta}{dt} \right) + p_s H + \frac{p_s \theta J}{c_p T} ; \quad \text{J: diabatic effects due to radiation and latent heat} \quad (12.16)$$

$$\frac{\partial p_s u}{\partial t} = -\frac{\partial p_s u v}{\partial y} - \frac{\partial}{\partial \eta} \left(p_s u \frac{d\eta}{dt} \right) + \left(f + \frac{u \tan \phi}{a} \right) p_s v + p_s D + p_s F_x ; \quad \text{D: planetary wave drag} \quad (12.17)$$

F_x and F_y : friction in the boundary layer

$$\frac{\partial p_s v}{\partial t} = -\frac{\partial p_s v^2}{\partial y} - \frac{\partial}{\partial \eta} \left(p_s v \frac{d\eta}{dt} \right) - \left(f + \frac{u \tan \phi}{a} \right) p_s u - p_s \frac{\partial \Phi}{\partial y} + RT \frac{\partial p_s}{\partial y} + p_s F_y ; \quad (12.18)$$

$$\frac{\partial p_s}{\partial t} = -\int_0^1 \frac{\partial p_s v}{\partial y} d\eta . \quad (12.19)$$

NOTE: no moisture flux equation !

Numerical solution: finite differences on regular grid

Domain:

$y = 90^{\circ}\text{S} - 90^{\circ}\text{N}$

$\sigma = 0.025 - 0.975$

Grid distance:

$\Delta y = 2^{\circ}$

$\Delta\sigma = 0.05$ (≈ 5 hPa)

Dynamical time step = 20 seconds

Radiation time step = 600 seconds

Advection equation in flux form, including pressure gradient and Coriolis:

McCormack scheme

Model run with seasonal cycle

(Solar radiation drives the circulation ; no water)

The model is **initialised** on January 1

Initially, the atmosphere is **isothermal** and **in rest**.

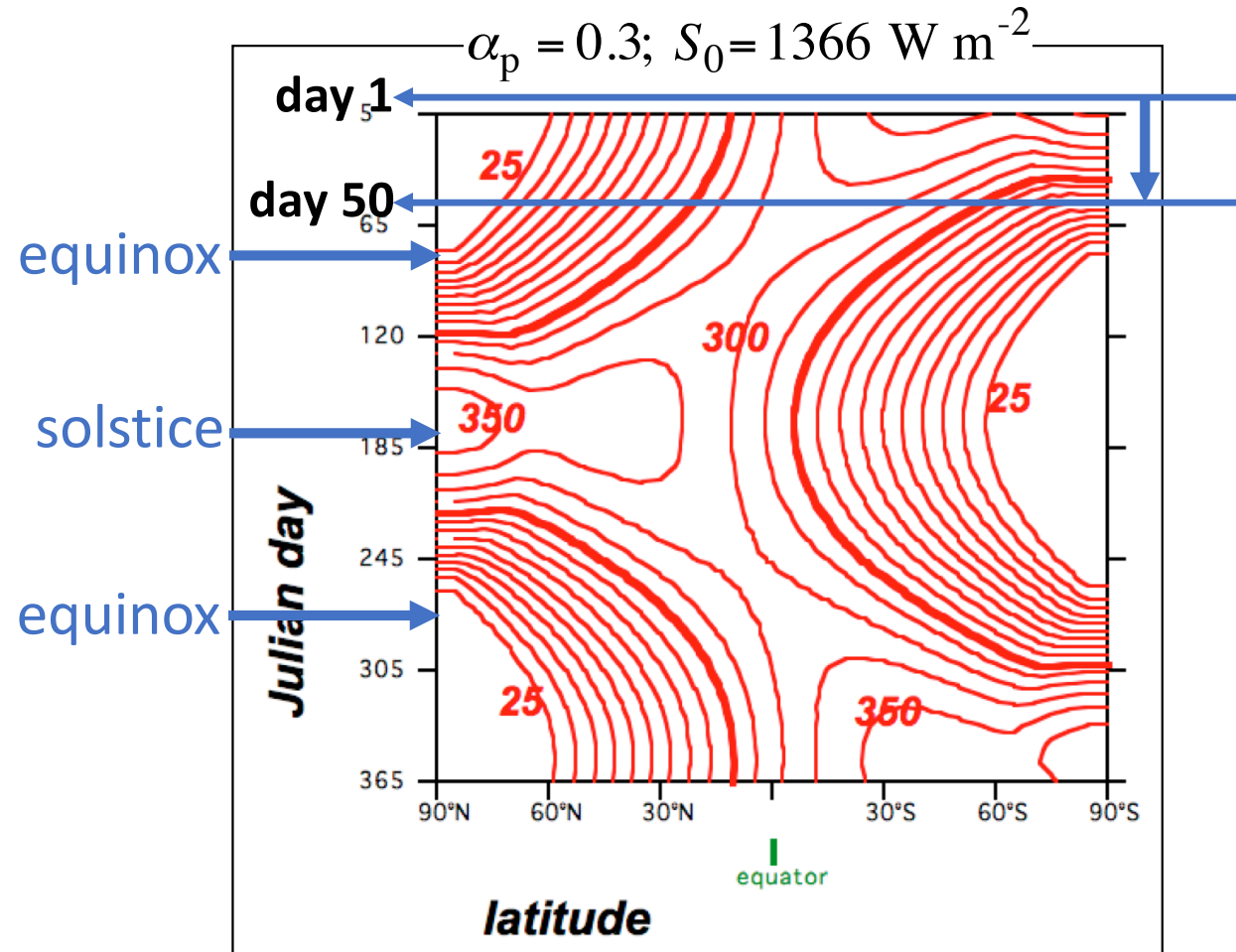
The atmosphere contains **one well-mixed greenhouse** gas as a proxy for CO₂.

There is no water (the water cycle is incorporated later)

The heat capacity of earth's surface, and **$C=10^7 \text{ J K}^{-1} \text{ m}^{-2}$**

Absorbed Solar radiation at the earth's surface

Absorbed Solar radiation (ASR)
(indicated in W m^{-2}) as a function of latitude and time for a planet with a **uniform albedo, α_p , equal to 0.3**. Contour interval is 25 W m^{-2} . **Thick contour** corresponds to 250 W m^{-2} .



Model run with seasonal cycle

(Solar radiation drives the circulation; no water)

A tropical meridional cross-equatorial **Hadley circulation** forms within a few days

Temperature is modified by the Hadley circulation such that the **cross-equatorial temperature gradient is eliminated**

However, the structure of the **zonal wind is not realistic**, as we see in the following slide

Meridional circulation radiative-dynamical adjustment

(no water !)

$$\partial T_{eq} / \partial y = 0$$

(consistent with thermal wind balance at the equator; section 1.30)

Meridional circulation (arrows), temperature [°C] and zonal wind velocity, u (black contours, contour interval: 5 m s⁻¹) after 50 days of integration. Thin black contours correspond to negative values of u (i.e. westward wind). Red arrows indicate upward motion; blue arrows indicate downward motion. Arrows are drawn only if $|\omega| > 0.001$ Pa s⁻¹.

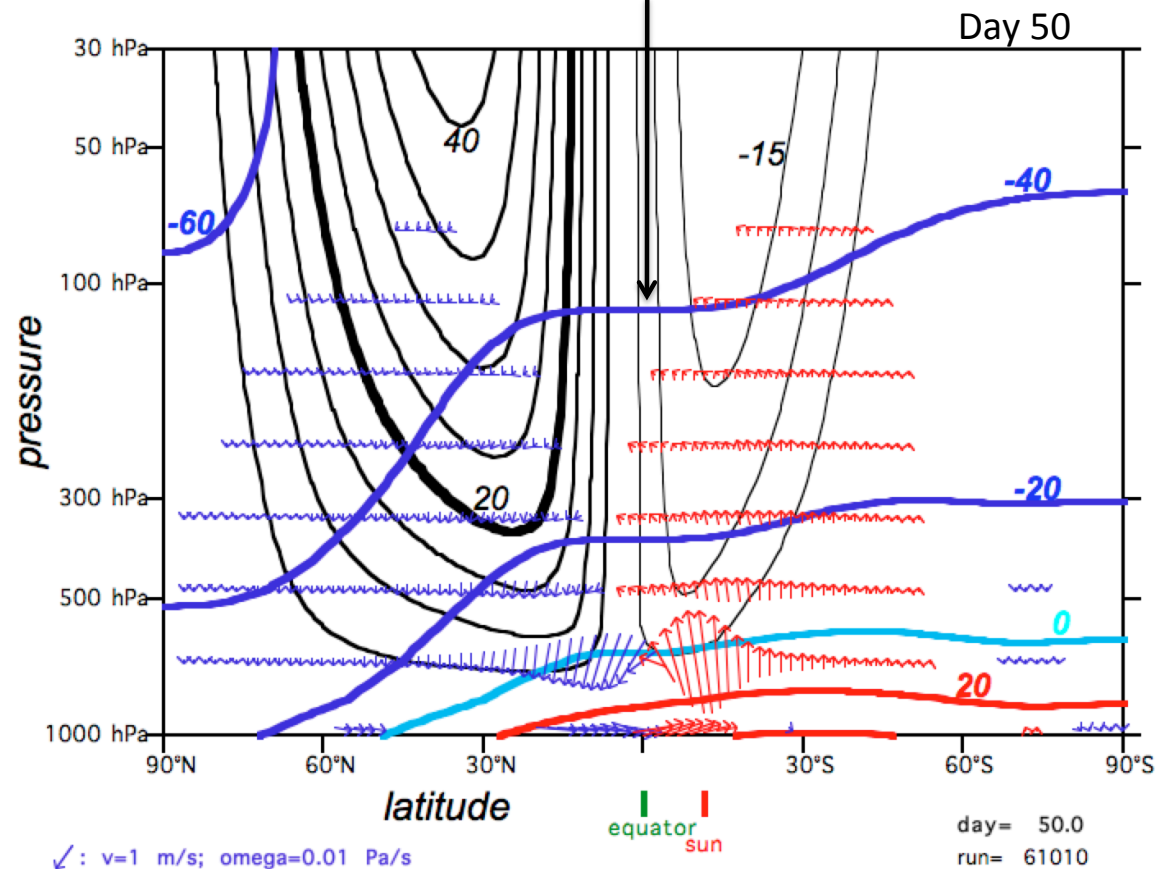


Figure 12.14

Influence of dynamics on temperature

Temperature [°C] determined by radiation only (left panel) and temperature determined by dynamics *and* radiation (right panel) for day 50 after initialization on January 1 of a two-dimensional model of a **dry isothermal (290 K) atmosphere in rest** containing one well-mixed greenhouse gas and no ozone. Contour interval is 20°C. The heat capacity of the Earth's surface is $10^7 \text{ J kg}^{-1} \text{ m}^{-2}$.

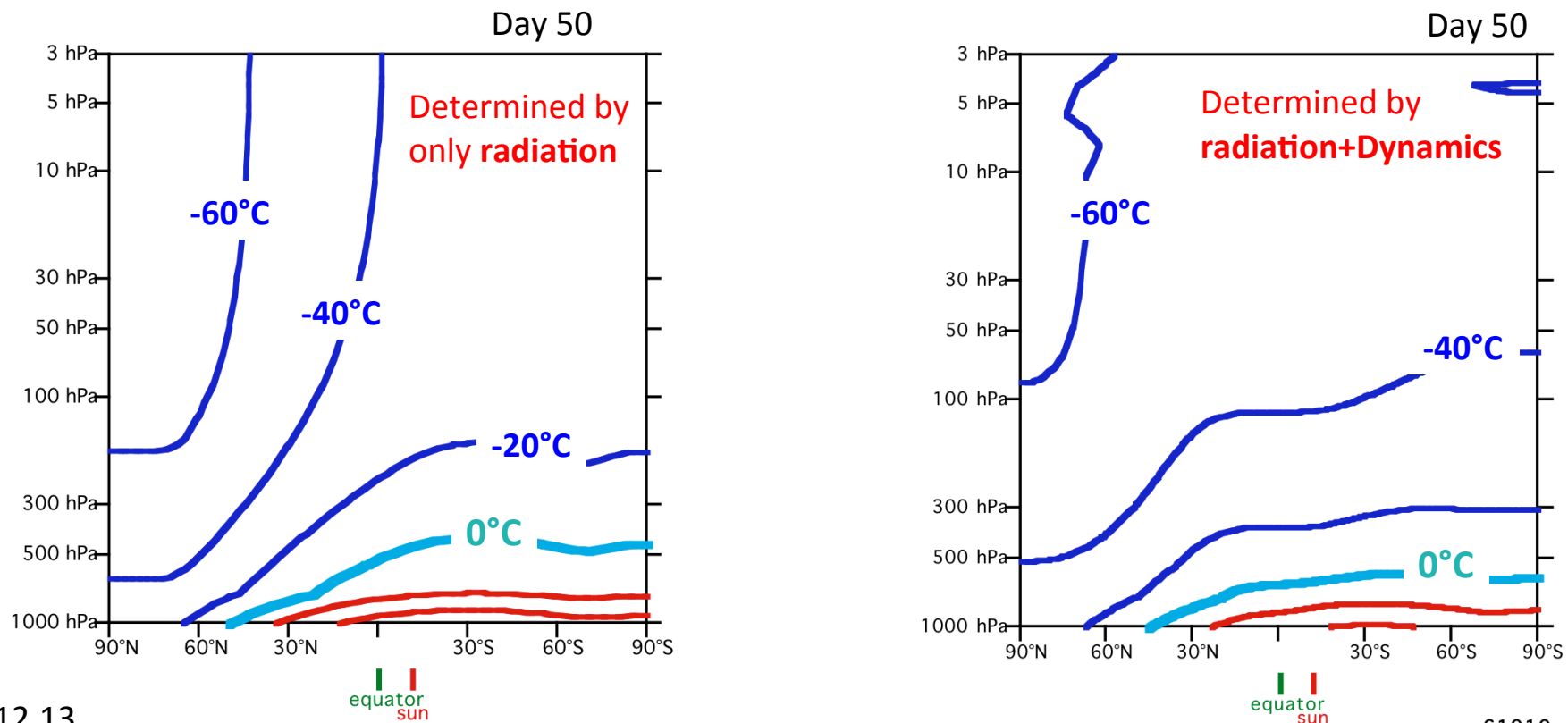


Figure 12.13

Influence of dynamics on temperature

Temperature [°C] determined by radiation only (left panel) and temperature determined by dynamics *and* radiation (right panel) for day 50 after initialization on January 1 of a two-dimensional model of a **dry isothermal (290 K) atmosphere in rest** containing one well-mixed greenhouse gas and no ozone. Contour interval is 20°C. The heat capacity of the Earth's surface is $10^7 \text{ J kg}^{-1} \text{ m}^{-2}$.

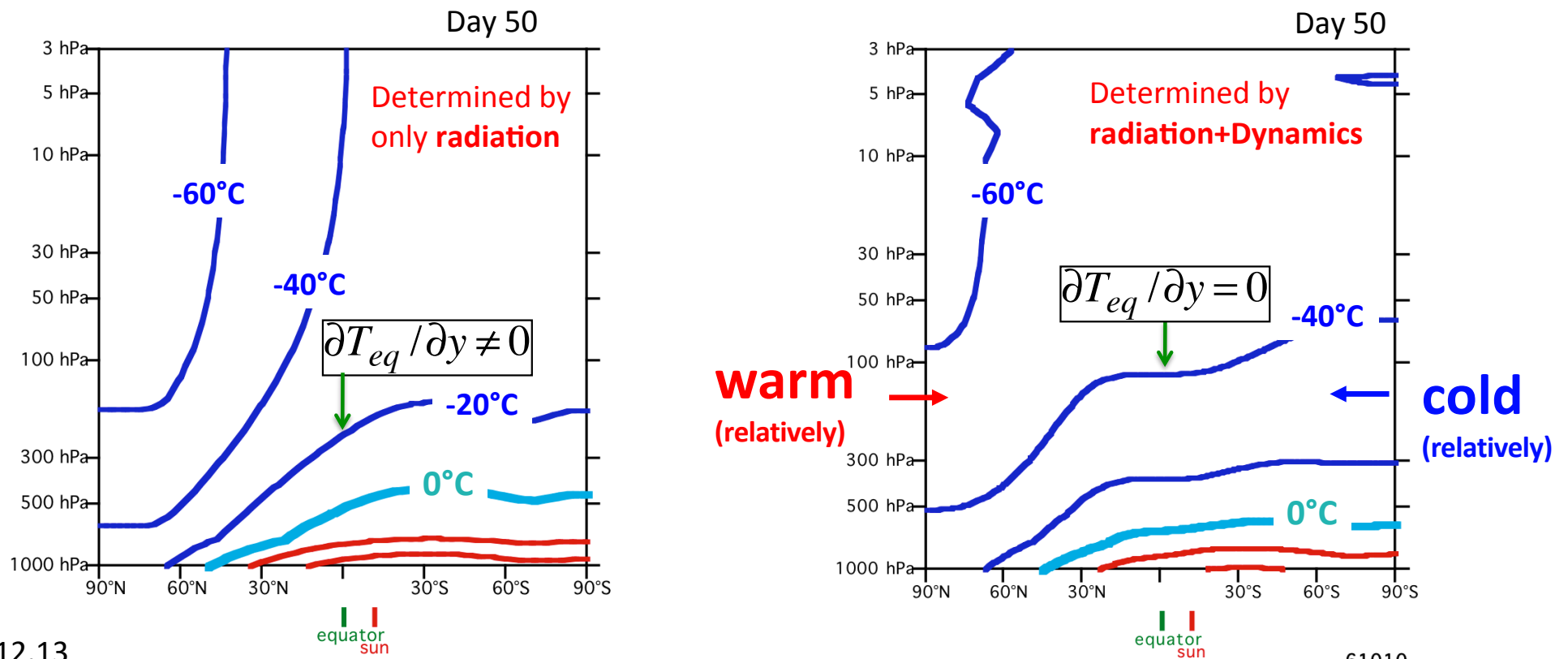


Figure 12.13

Meridional circulation radiative-dynamical adjustment

Radiatively determined cross-equatorial temperature gradient is reduced to zero by dynamics.

$$\partial T_{eq} / \partial y = 0$$
 (consistent with thermal wind balance at the equator; section 1.30)

Winter Hadley cell:

Upward motion in summer hemisphere;
Downward motion in winter hemisphere

downward motion warms

Upward motion cools

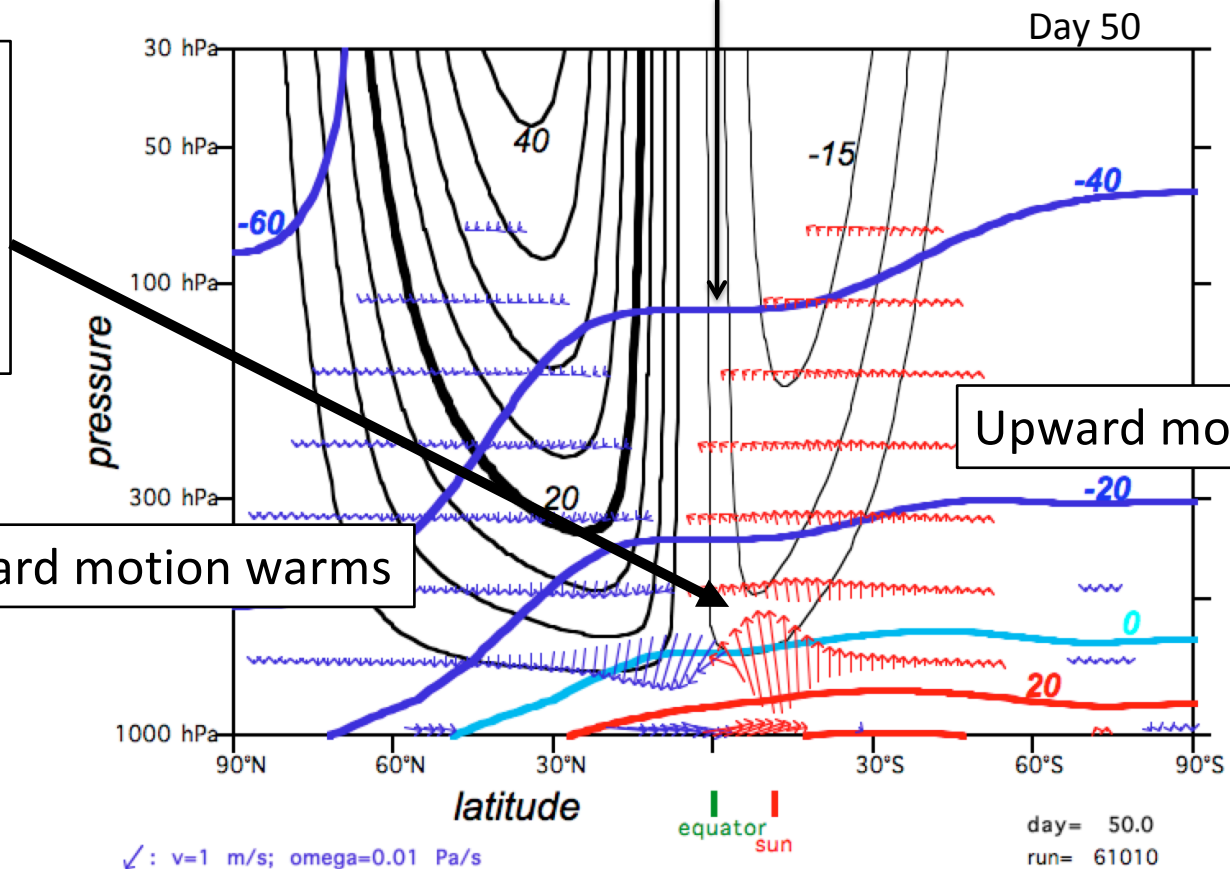


Figure 12.14

Meridional circulation radiative-dynamical adjustment

Some aspects of the solution are not realistic:

The subtropical jet and the stratospheric winter jet are separated.

No tropical “cold trap”.

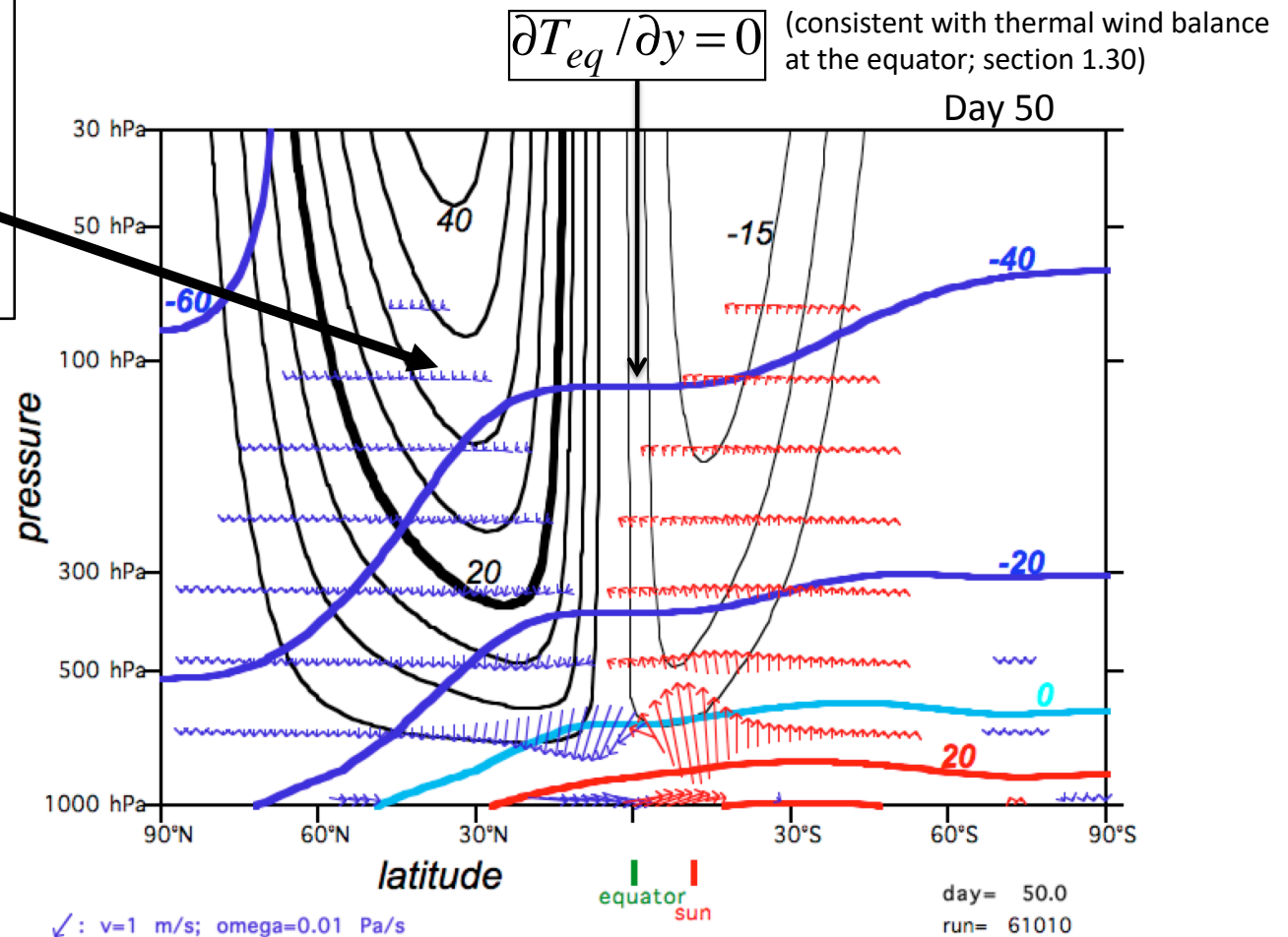
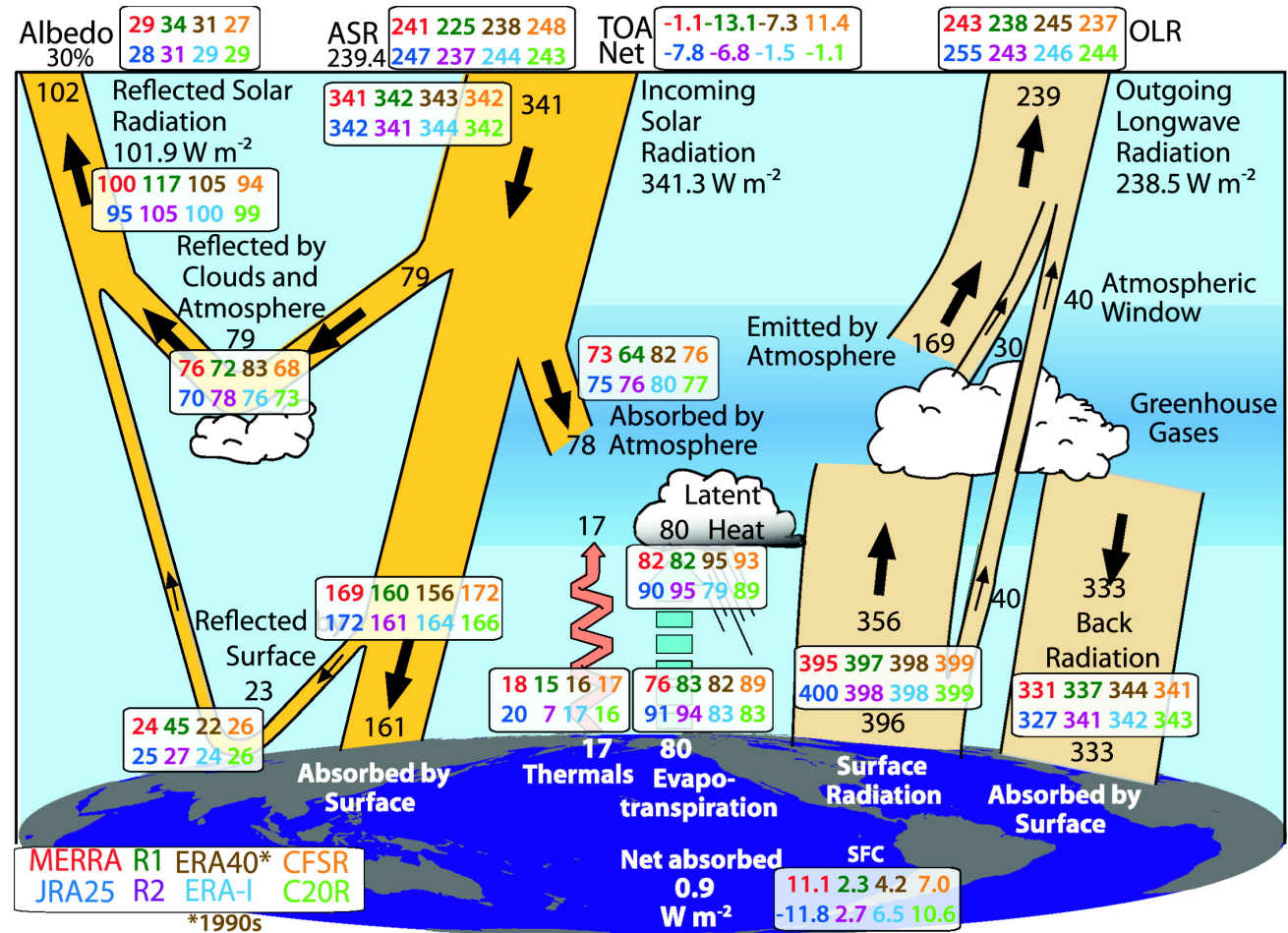


Figure 12.14

The water cycle

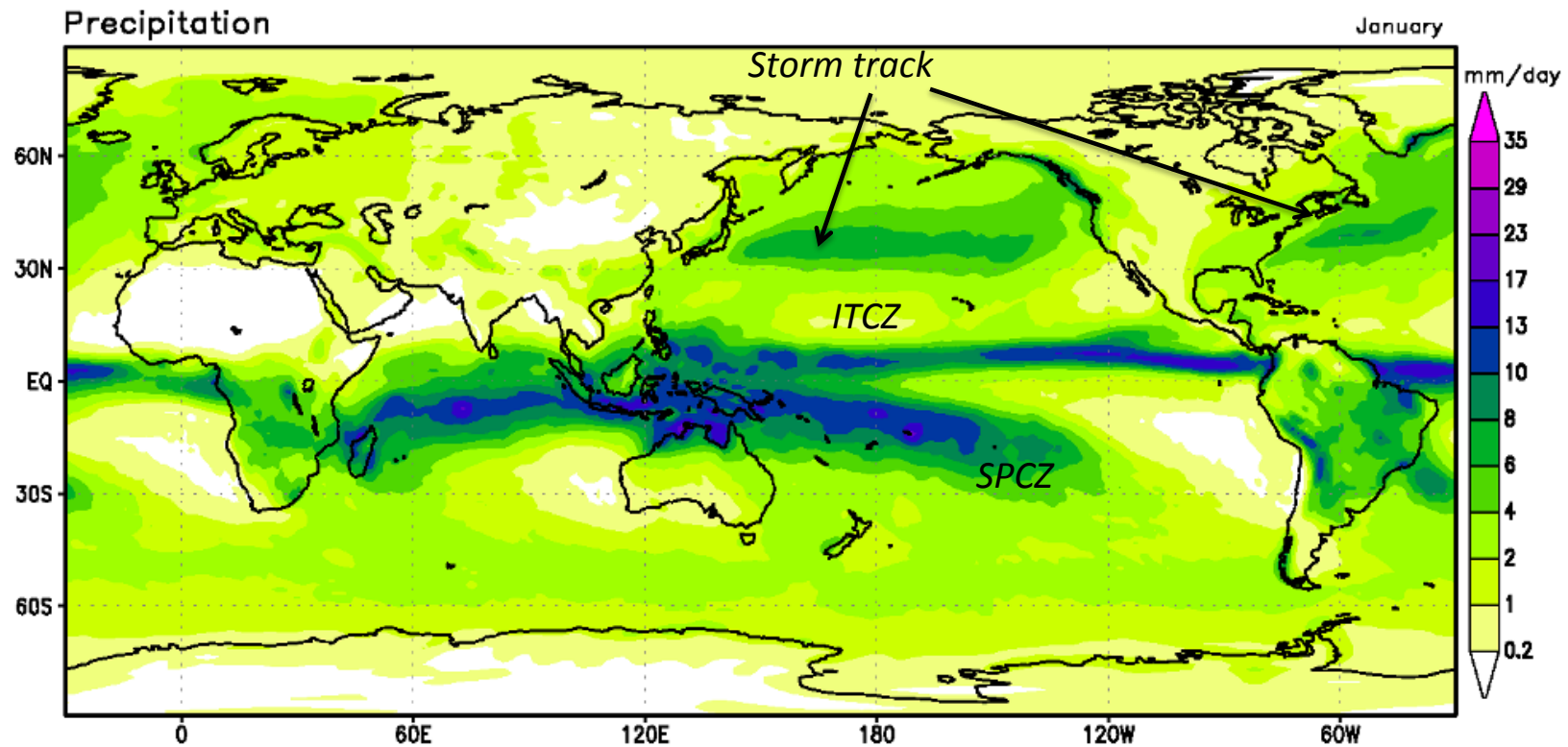
Will inclusion of a water cycle make the model outcome more realistic?

Values shown in black are based on observations for 2000–05. Superposed are values from the various re-analyses for the period, 2002–08, except for ERA-40, which is for the 1990's (color coded, W m^{-2}). Above the graphic, values are given for albedo (%), Absorbed Solar Radiation (ASR), net Top of the Atmosphere (TOA) radiation, and Outgoing Long-wave Radiation (OLR). The box labeled SFC near the bottom gives the net flux absorbed at the surface.



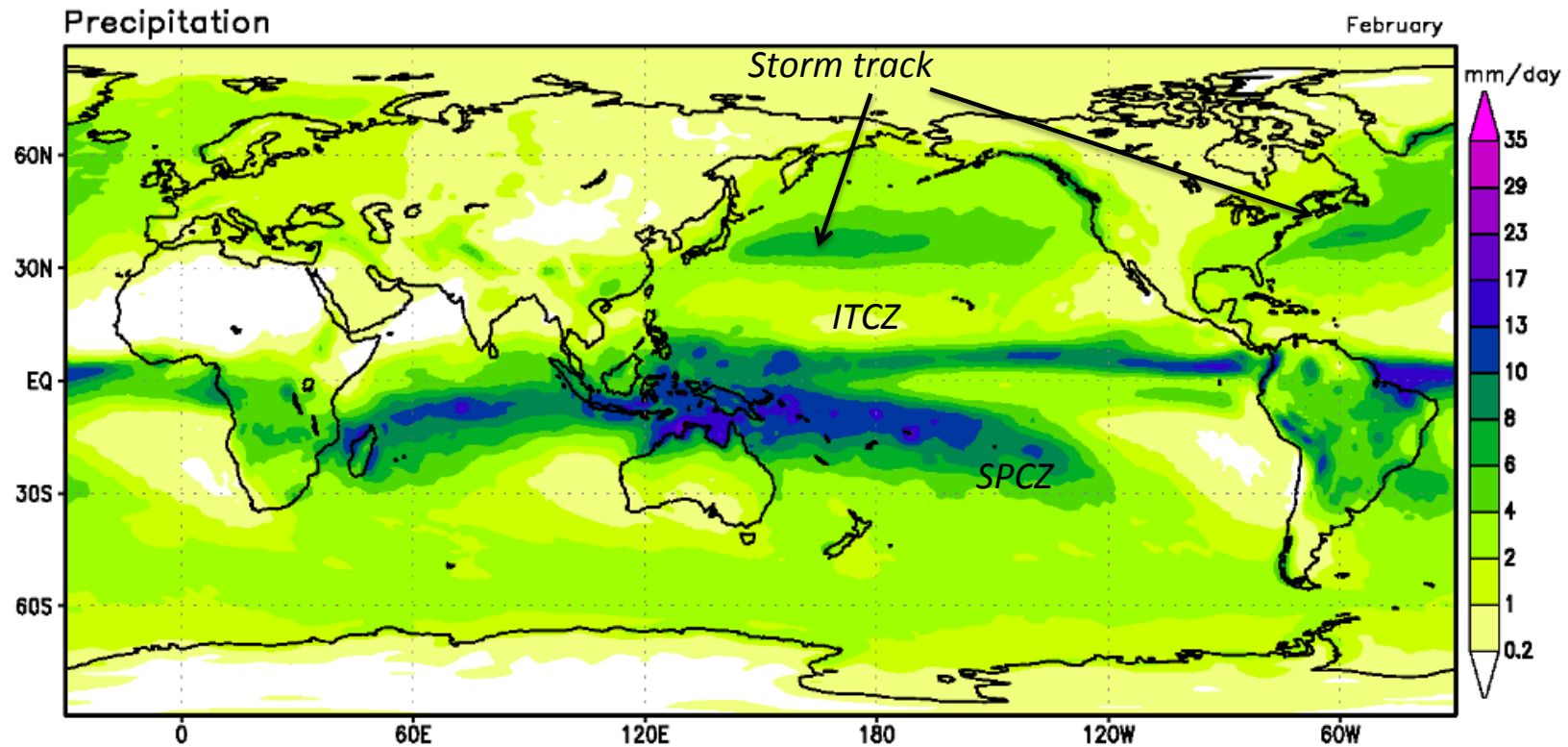
Japanese reanalysis (JRA) of precipitation between 1979 and 2004

<http://ds.data.jma.go.jp/gmd/jra/atlas/eng/atlas-tope.htm>



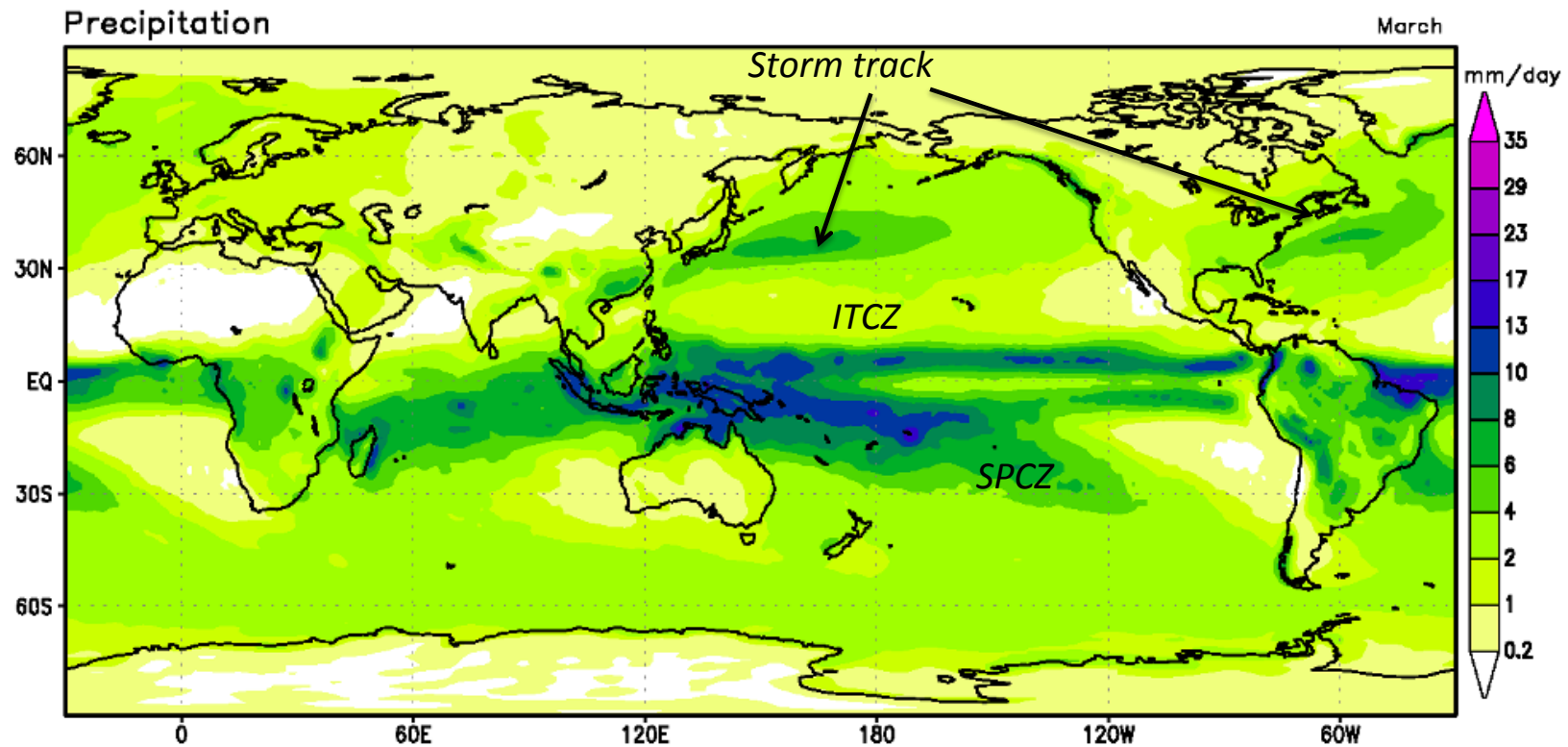
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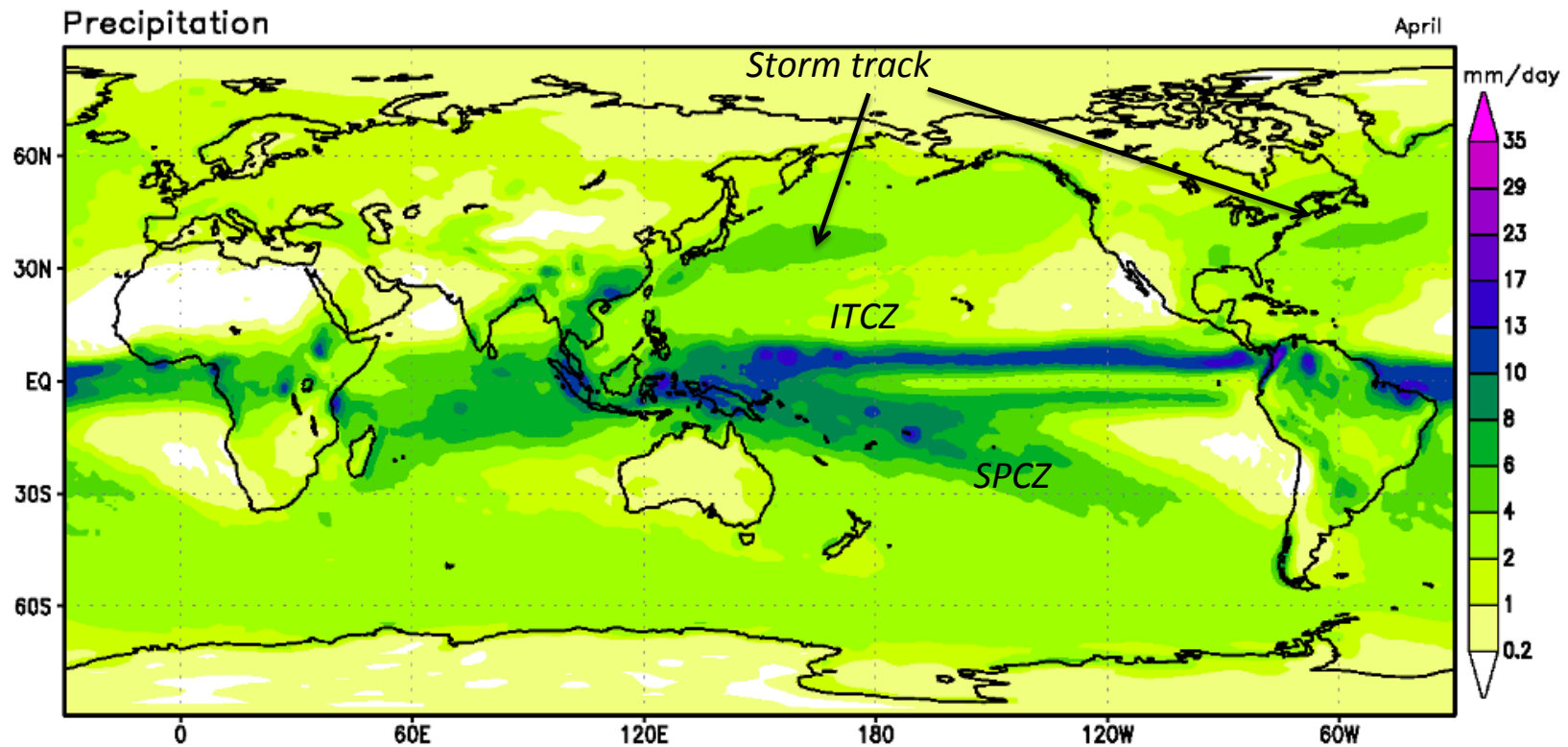
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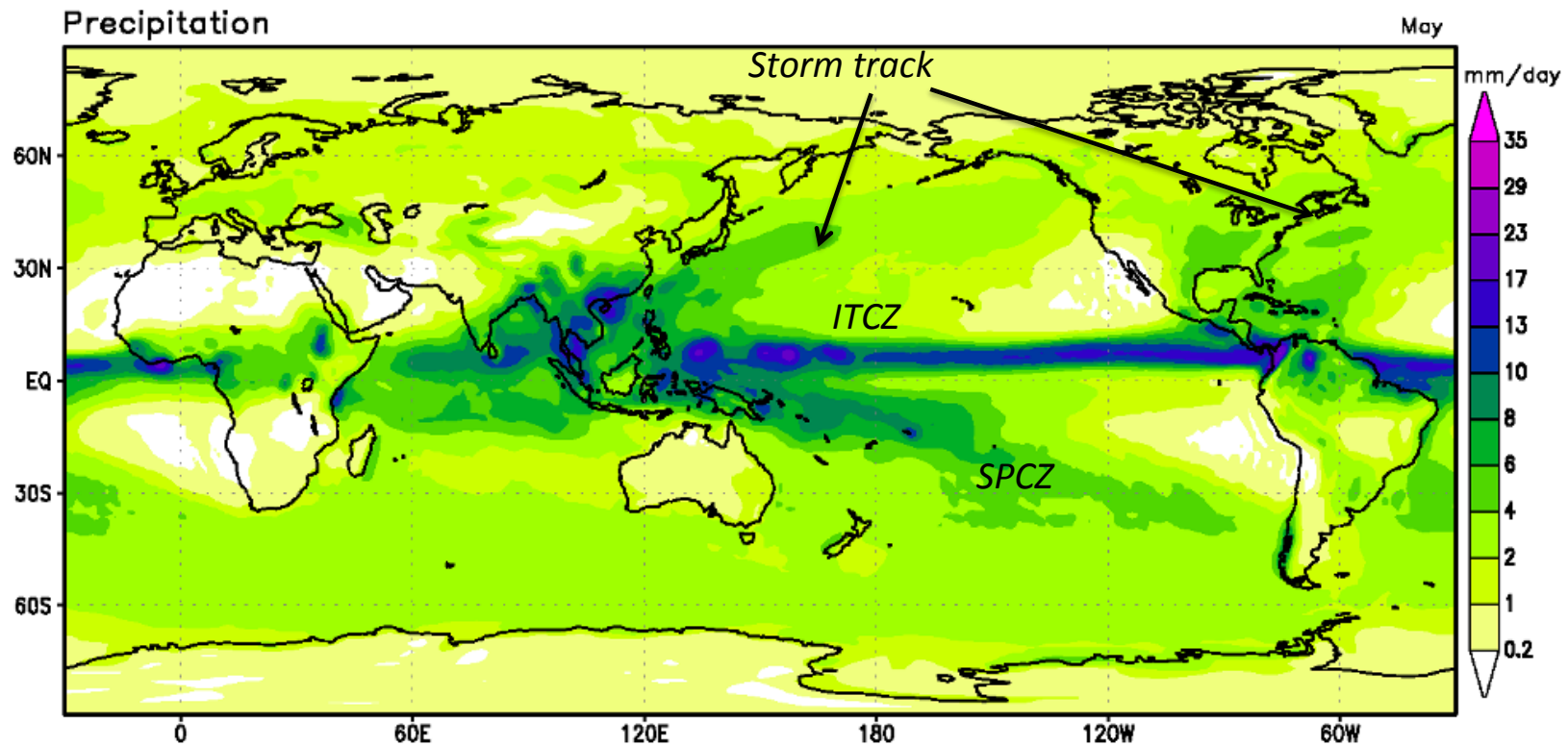
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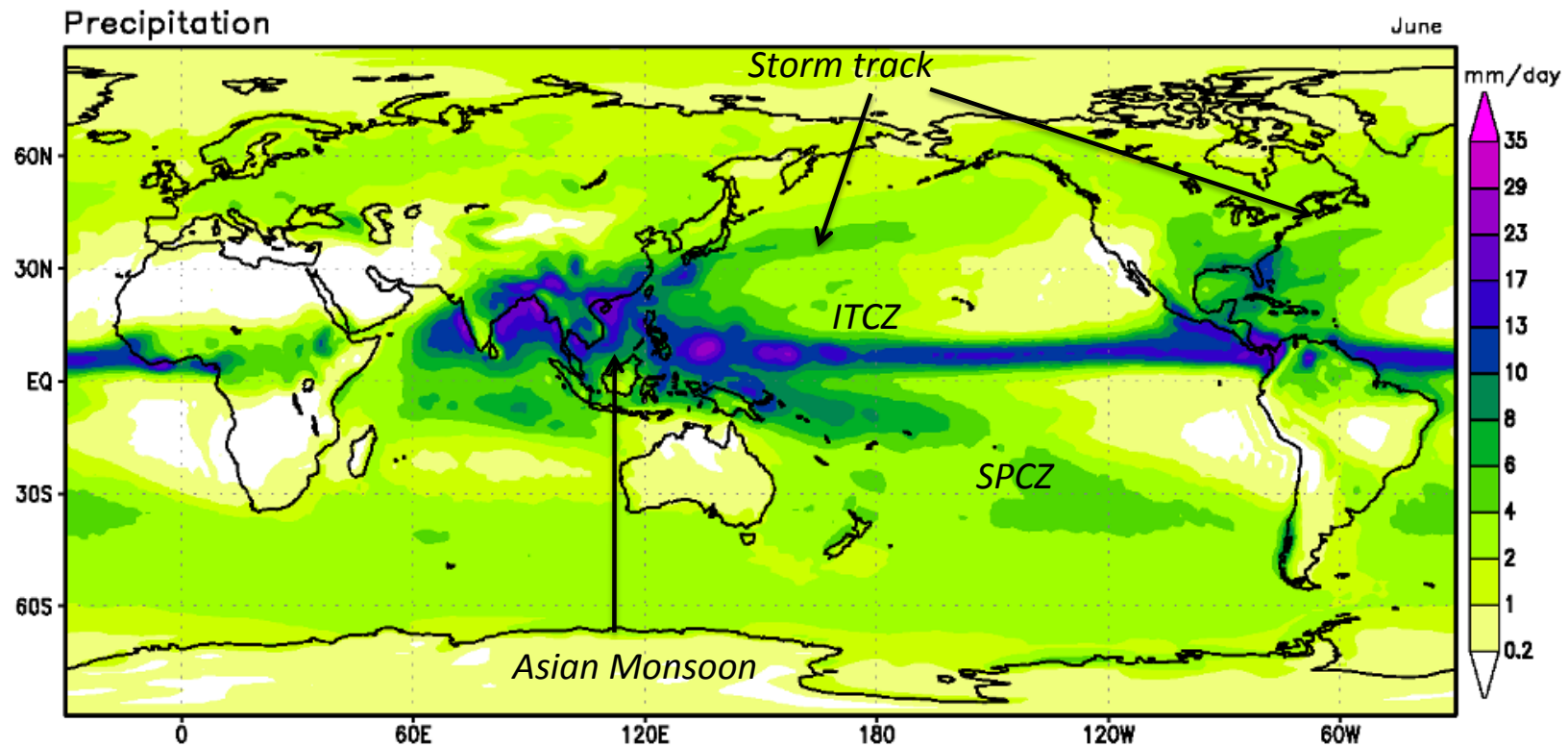
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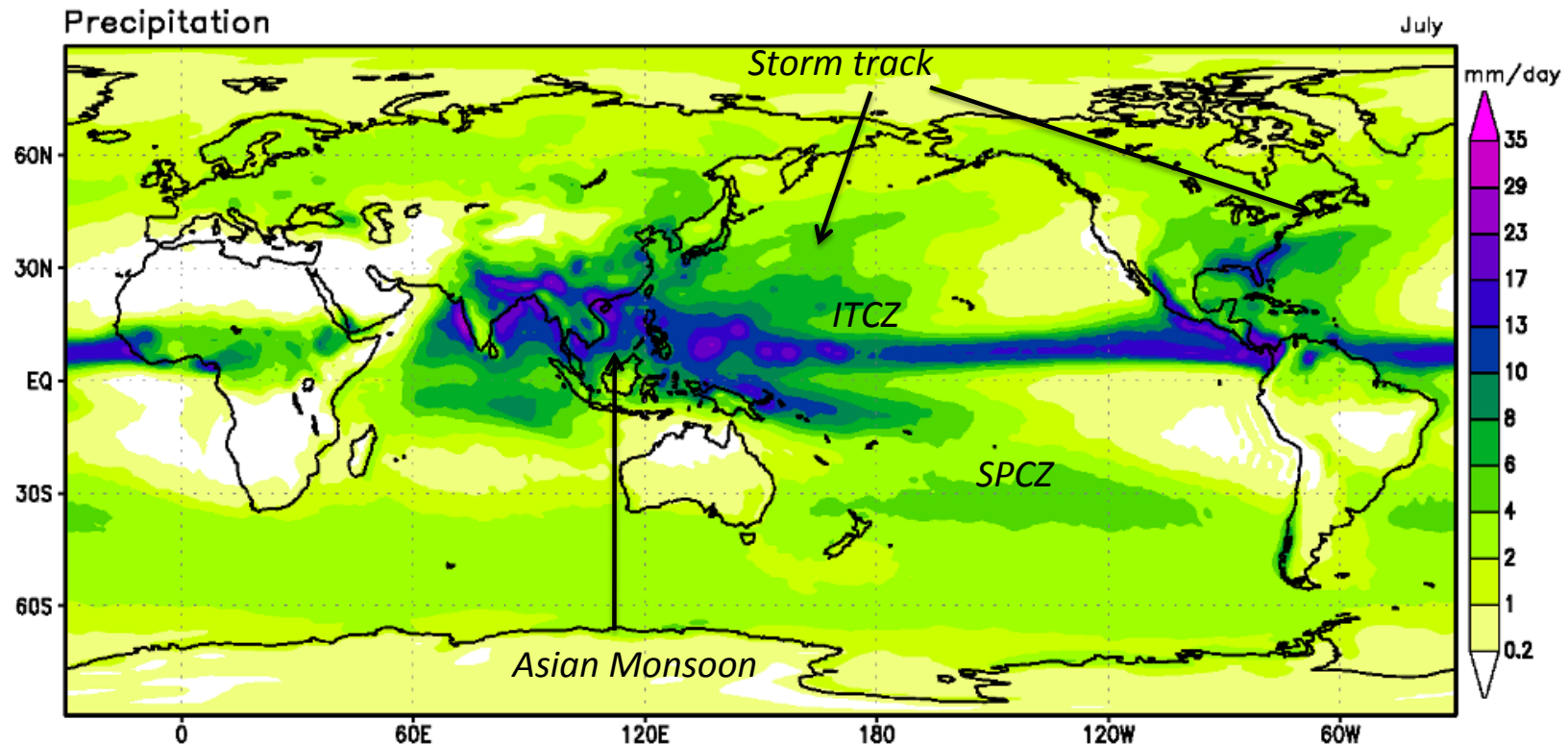
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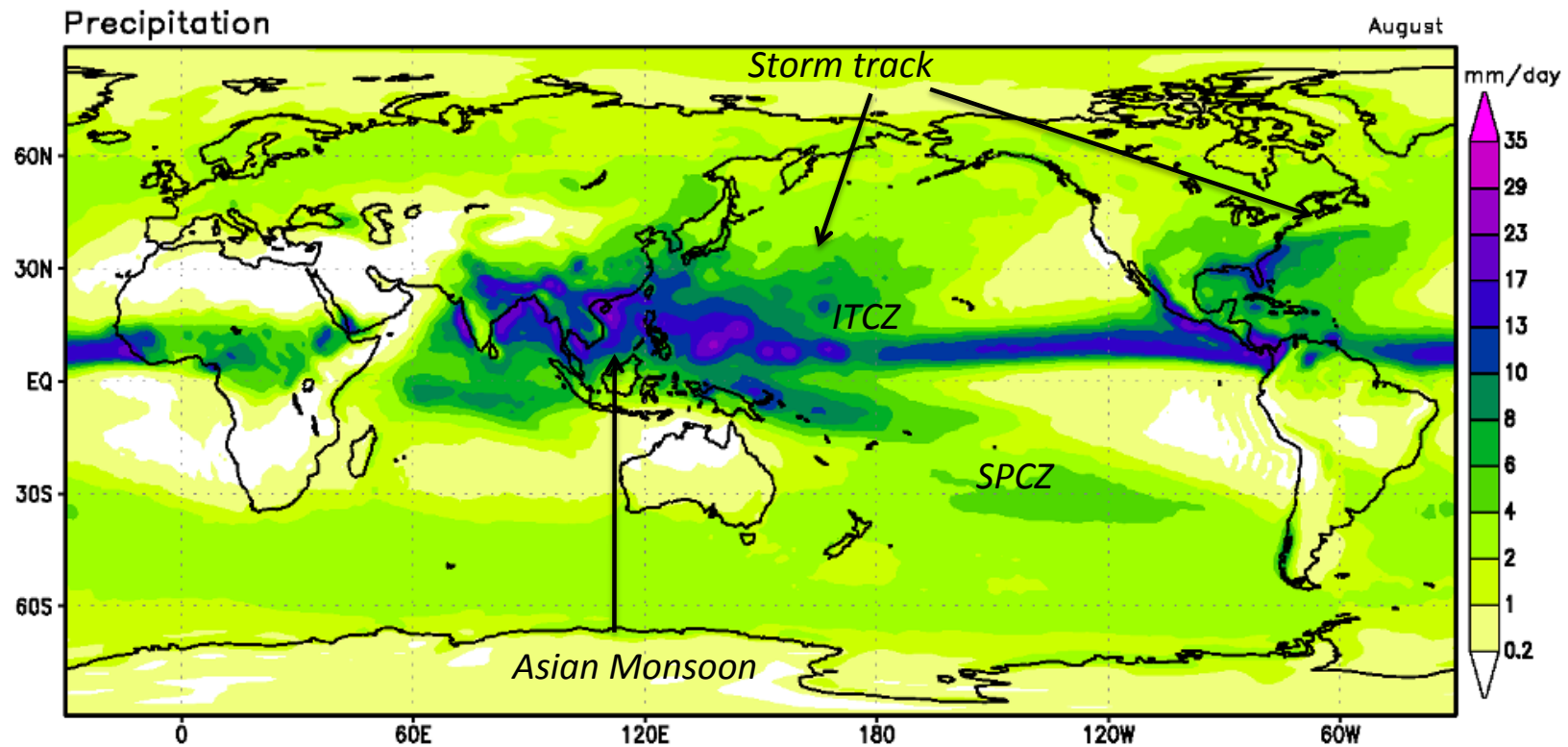
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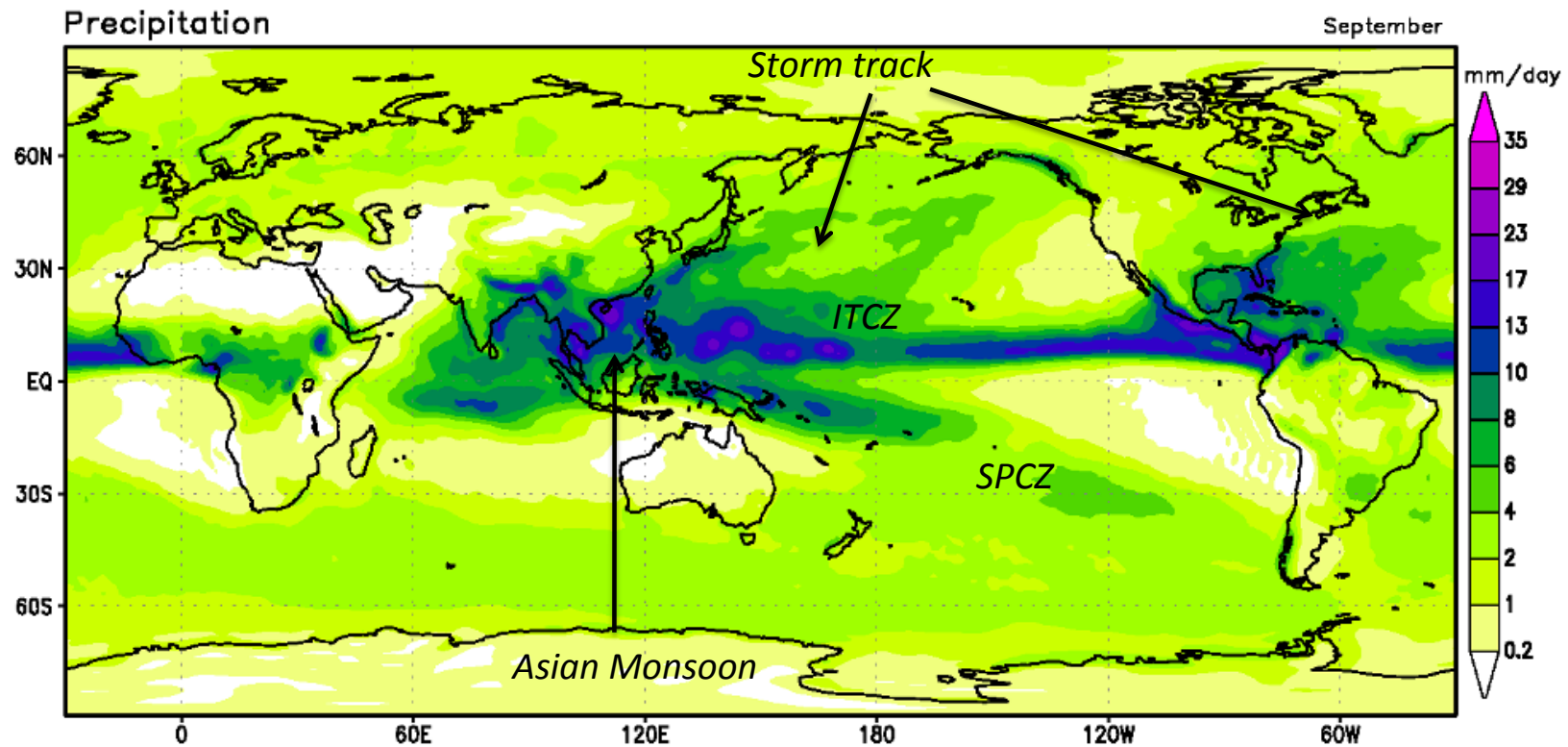
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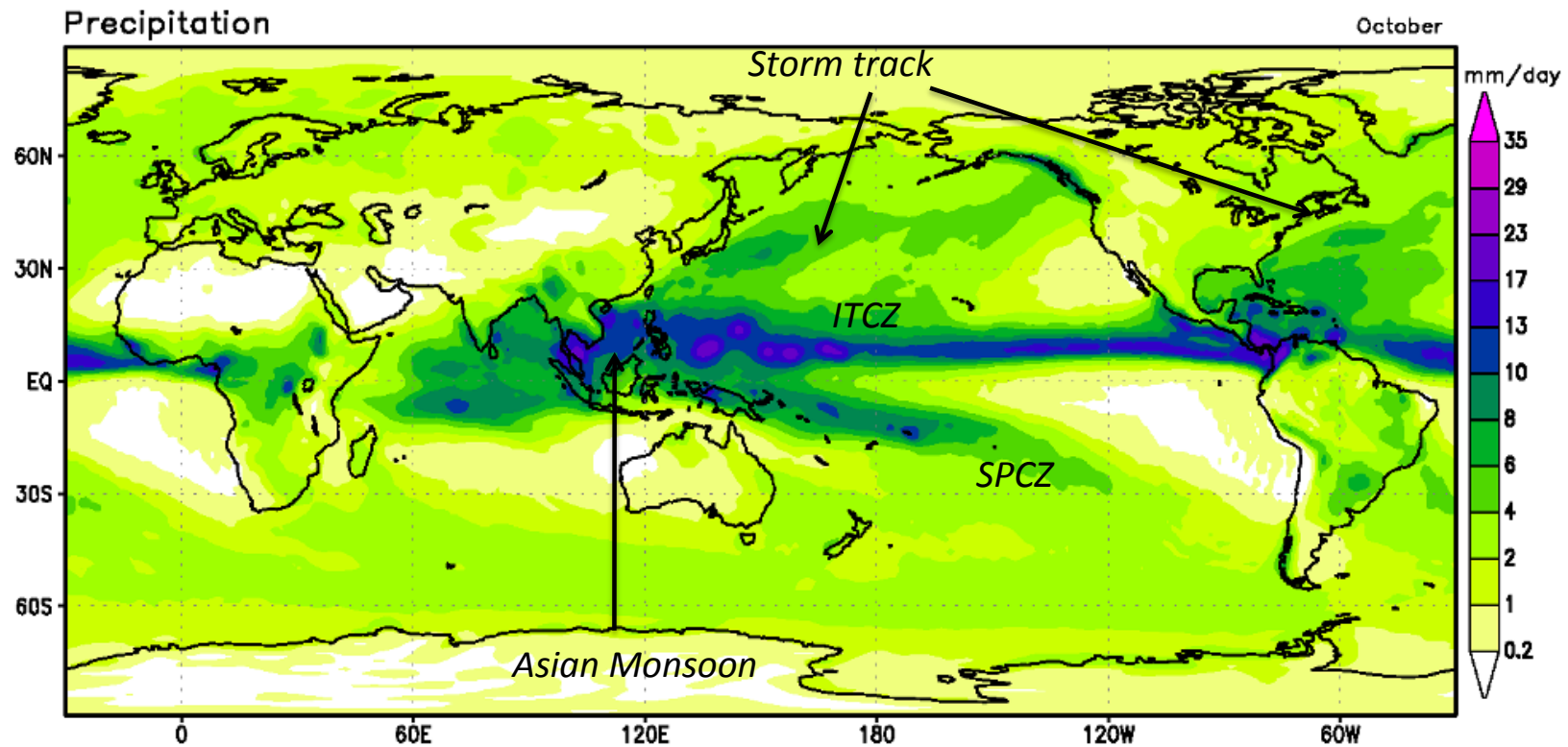
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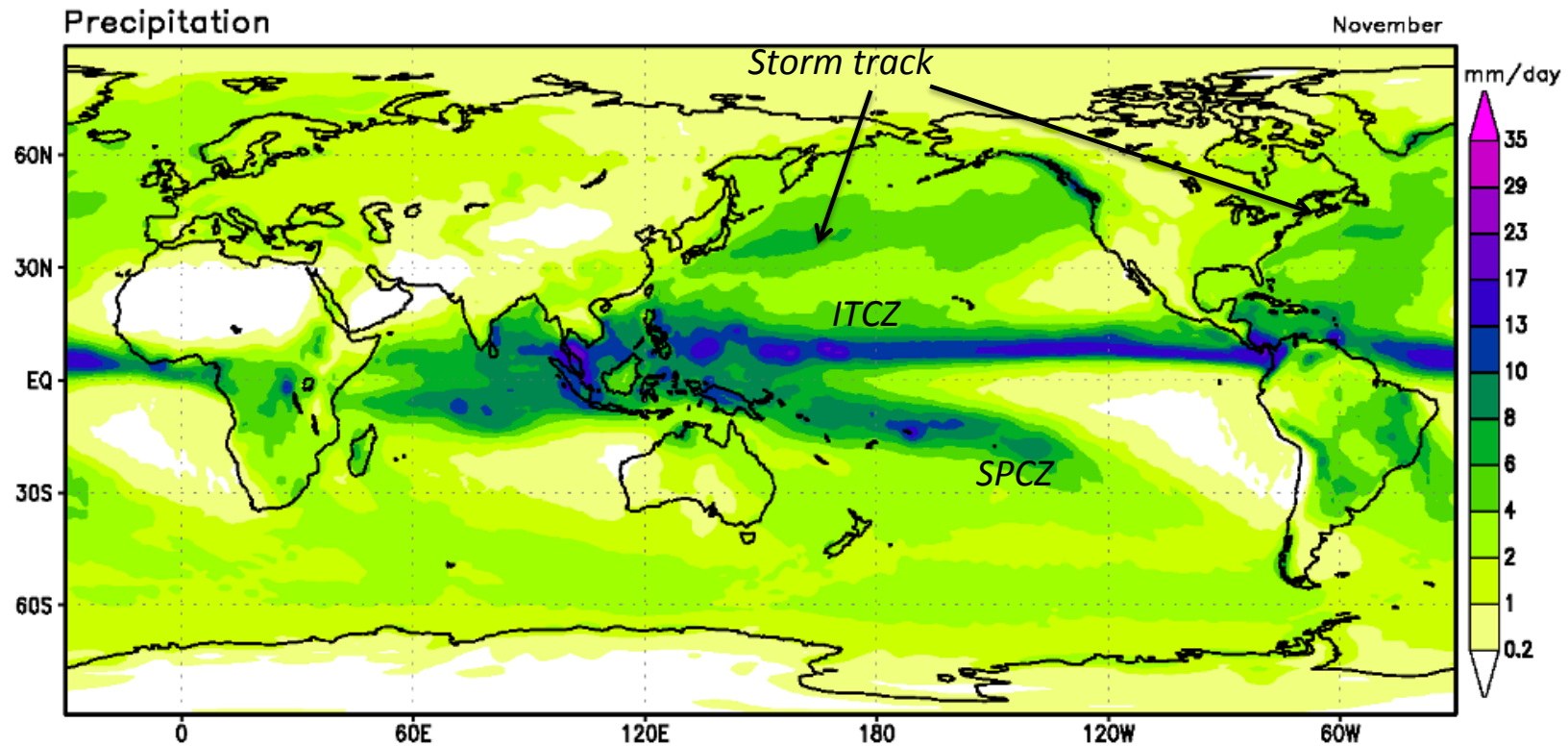
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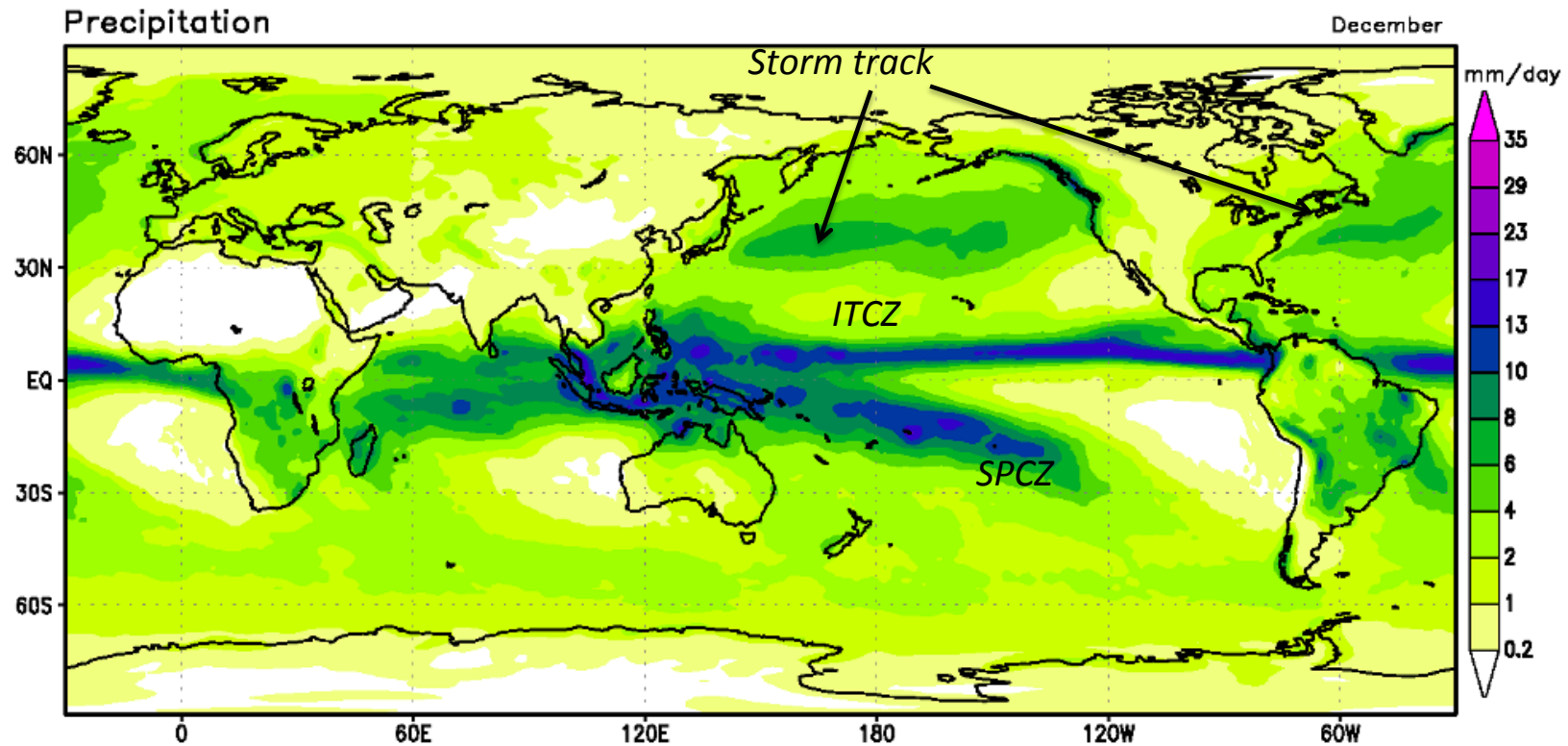
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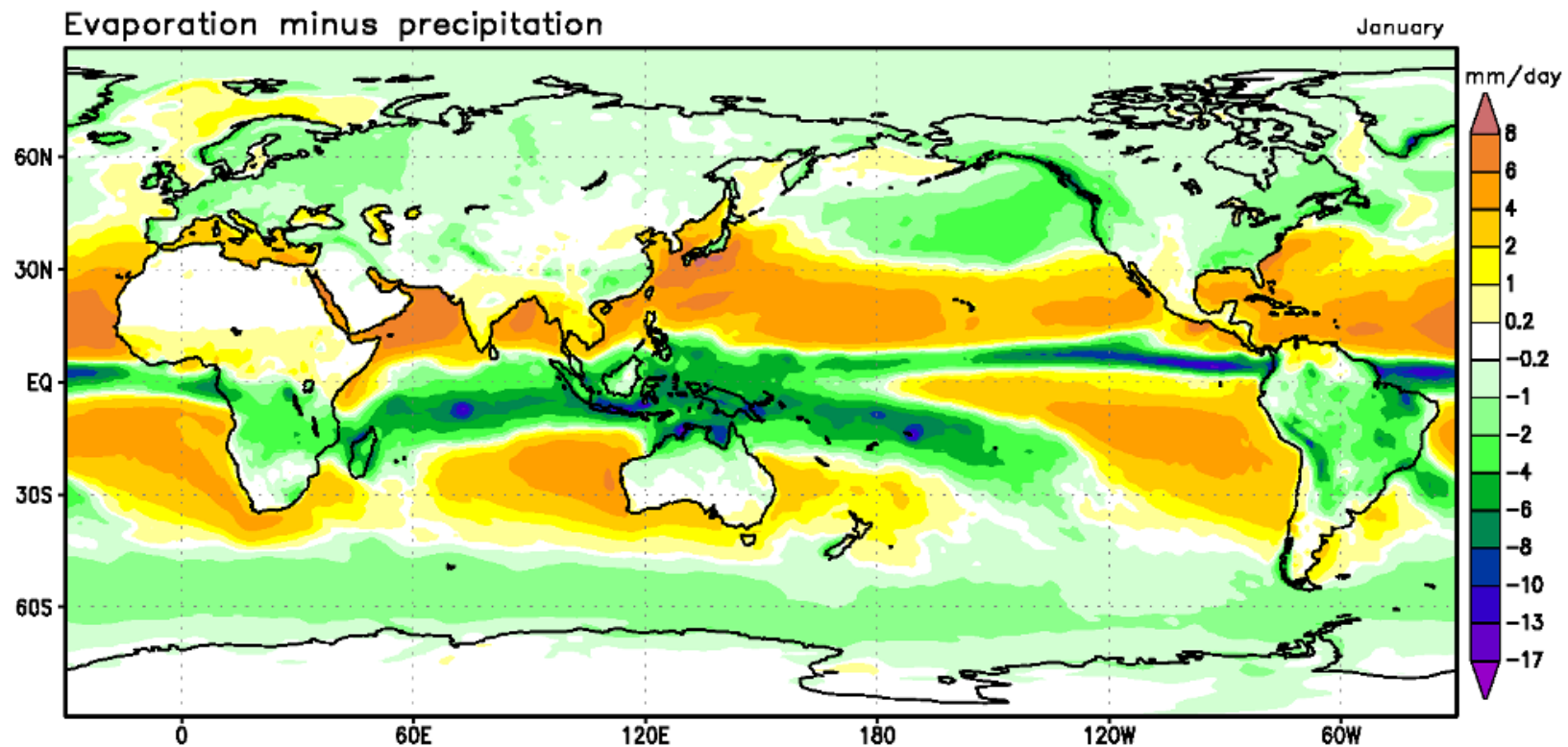
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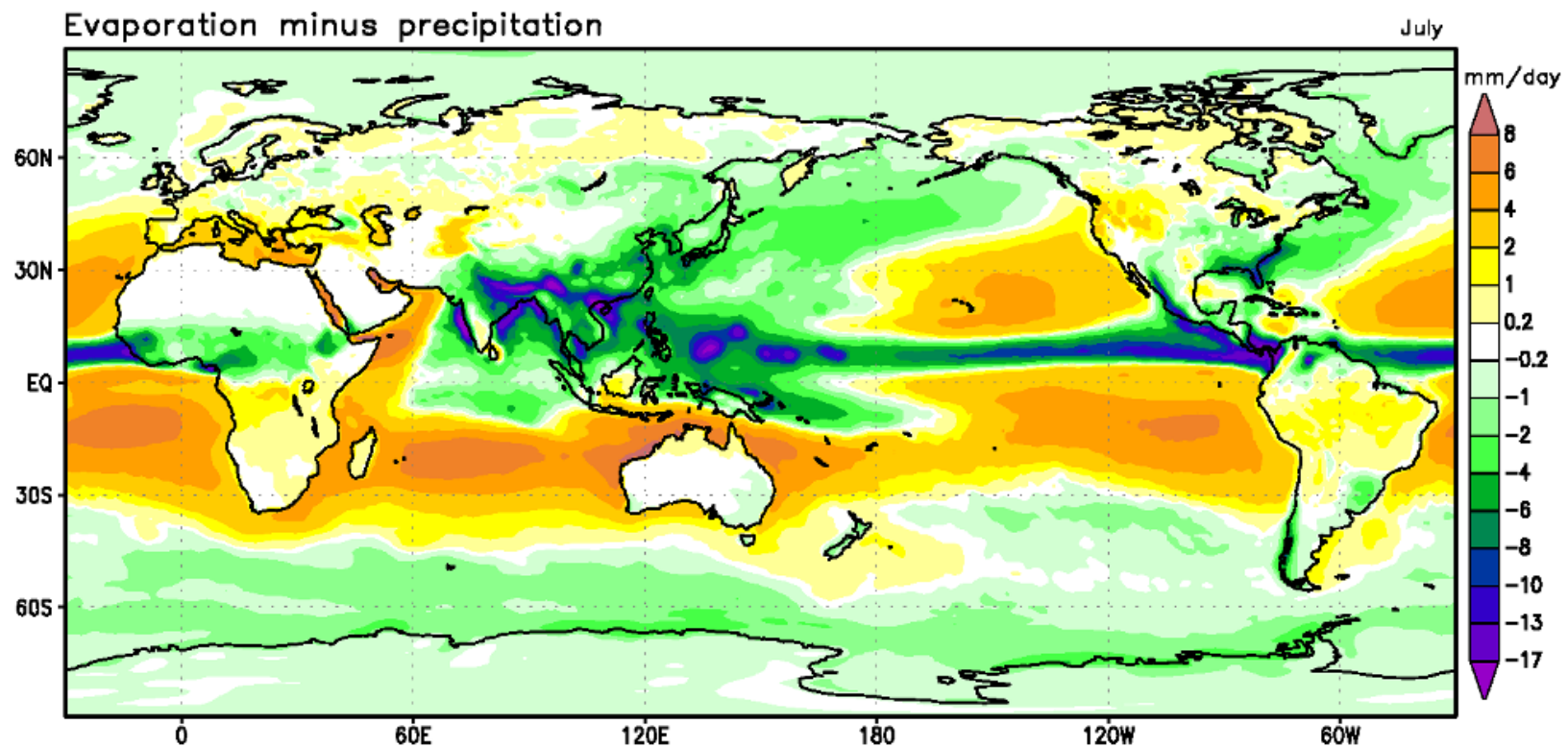
Japanese reanalysis (JRA) of Evap-Precip between 1979 and 2004

<http://ds.data.jma.go.jp/gmd/jra/atlas/eng/atlas-tope.htm>



Japanese reanalysis (JRA) of Evap-Precip between 1979 and 2004

<http://ds.data.jma.go.jp/gmd/jra/atlas/eng/atlas-tope.htm>



Important features of the water cycle as revealed by the re-analysis

Precipitation and associated latent heating of the atmosphere is dominated by precipitation in the ITCZ, which is a narrow zone (width is about 1000-3000 km), near the equator.

Most water evaporates from the subtropical oceans, equatorward of a latitude = $\pm 40^\circ$ (see also the next slide).

Zonal mean evaporation & precipitation

Units: $\text{kg m}^{-2} \text{ day}^{-1}$

NCEP reanalysis 2, 1979-2008 average

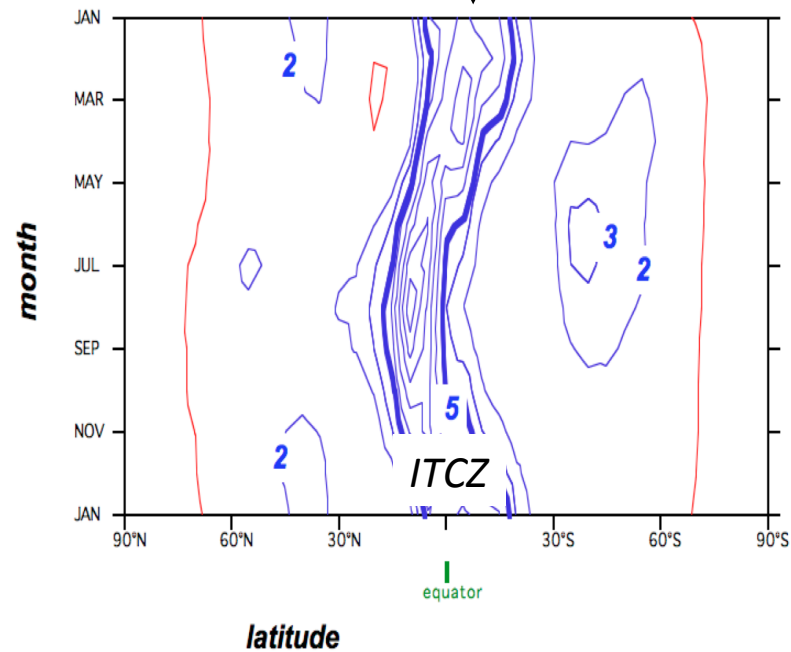
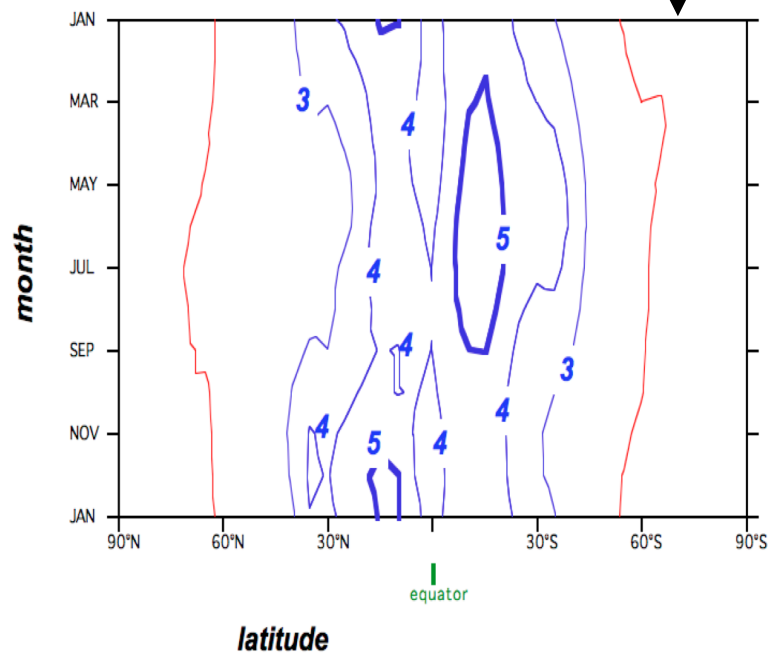


Fig 12.16 & 17

The water cycle

Will inclusion of a water cycle make the model outcome more realistic?

Water cycle consists of the following five components:

1. *Evaporation of water at the earth's surface*

Driven by net radiation at the surface:

About 100 W m^{-2} is available *

* With $L=2.5 \times 10^6 \text{ J kg}^{-1}$, this is equivalent $3.45 \text{ kg m}^{-2} \text{ day}^{-1}$ of water

2. **Transport** of water vapour to ITCZ and mid-latitudes

3. *Condensation of water vapour in clouds* ← **Latent heat release**

4. **Precipitation**

5. Run-off

The water-cycle in the 2D-model

Details: section 12.7

1. **Evaporation**, E_s , is computed from the surface sensible heat transport, H_s , assuming a Bowen ratio, $B=H_s/E_s=0.25$ (at all latitudes)
2. **Vertical sensible heat transport** is computed from a dry convective adjustment scheme (section 2.8 and eq. 12.21)
3. 80 % of the **locally evaporated water** is precipitated locally (at the same place as where it is evaporated)
4. The remainder is added to the local **precipitation in the ITCZ**. This excess precipitation is distributed according to a Gaussian function of latitude centred at the position of the ITCZ.
5. The central latitude of **the ITCZ follows the latitude of the overhead sun** and has a meridional scale (diameter) of about 3000 km (see eq. 12.39-40 for the definition of the ITCZ)
6. Latent heat release is assumed to occur within clouds...
Cloud base is at 900 hPa everywhere
Cloud top is at 400 hPa in mid-latitudes and at 200 hPa in the ITCZ
7. **Clouds do not interact with radiation !**

Water vapour distribution

Water vapour is distributed according to

$$\rho_v(z) = \rho_v(0) \exp\left(-\frac{z}{H_v}\right)$$

Density of water vapour

Scale height: 2 km

The density of water vapour depends on the temperature (Clausius Clapeyron):

$$PW = \rho_v(0)H_v = \frac{RH_g e_s(T_g)}{R_v T_g} H_v \left[\text{kg m}^{-2} \right]$$

Relative humidity at the earth's surface is fixed at 75%.

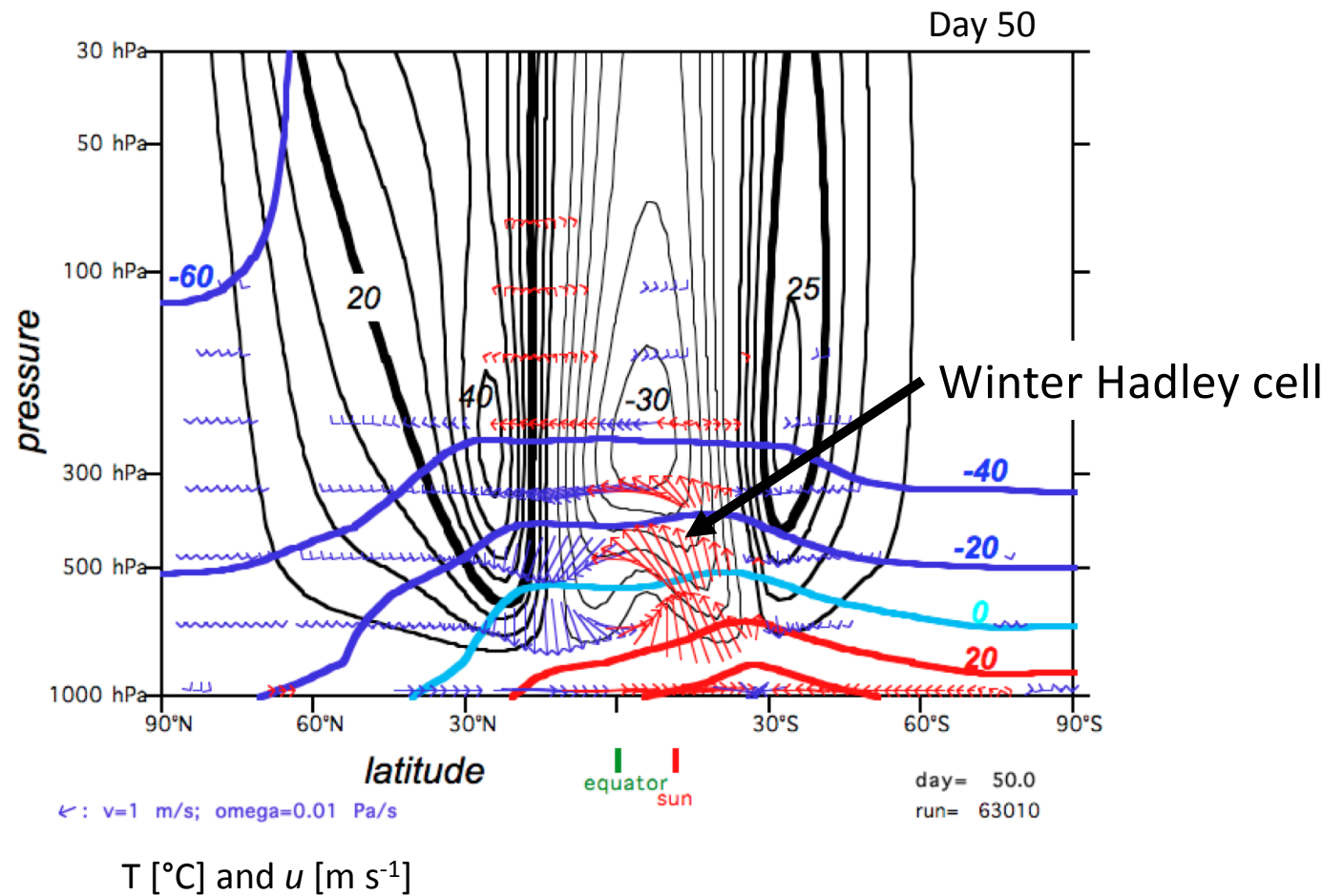
Water vapour interacts with thermal (long wave) radiation as a grey absorber.

Temperature, circulation and zonal wind with water cycle

50 days after initialization on 1 January with an isothermal (290 K) atmosphere at rest

Tropical cold point still missing!

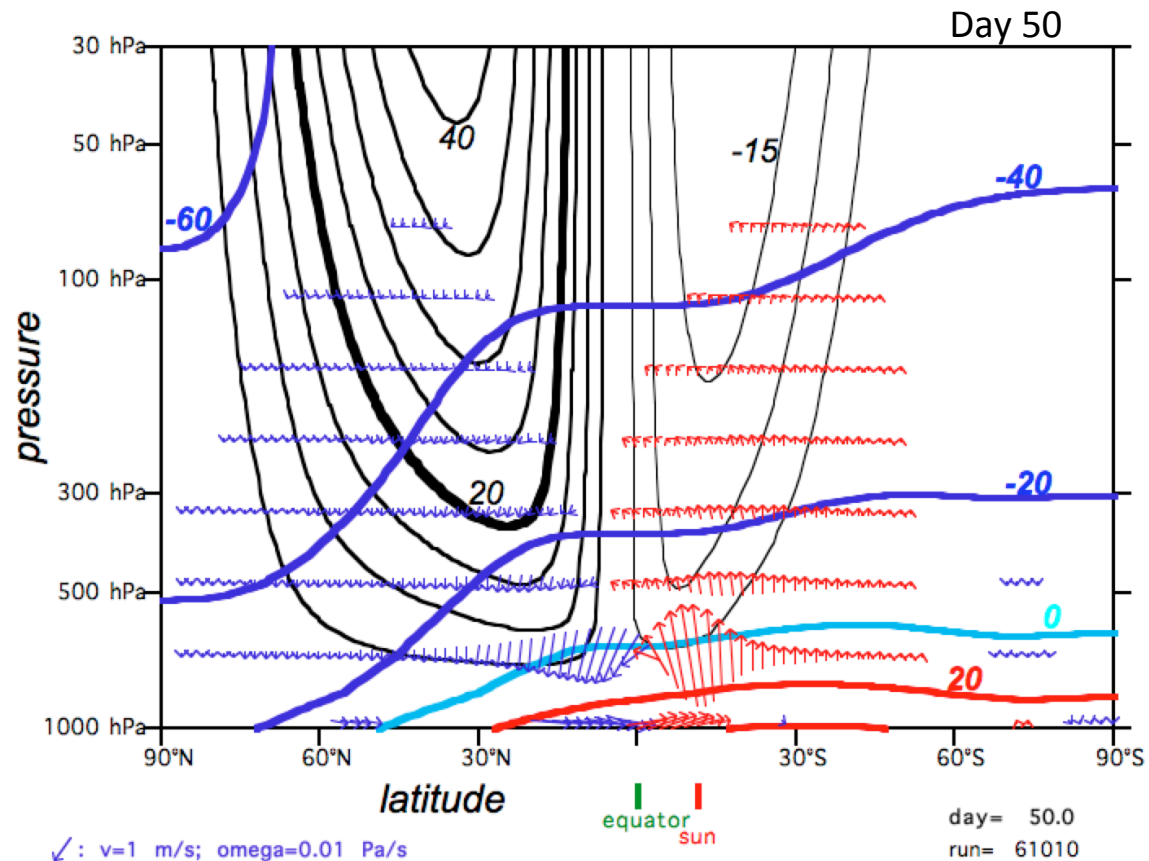
Zonal wind distribution looks unrealistic: one jet in each hemisphere...



Temperature, circulation and zonal wind, no water cycle

50 days after initialization on 1 January with an isothermal (290 K) atmosphere at rest

Water cycle warms the lower levels in the tropics and summer hemisphere and cools the upper atmosphere and the low levels at lower latitudes in the winter hemisphere.



Assignment 3 : "What-if questions"

50%

Deadline: Fri. 18 June 2021

PROBLEM 12.7 Influence of Earth's rotation rate

How would the Hadley circulation and the zonal mean zonal jets be affected if we would double the value of the Coriolis parameter? Will the subtropical jet intensify or weaken? Will the subtropical jet be displaced poleward or equatorward? The Held-Hou theory (chapter 8) may give some indications here. **Keep your answer short (no more than 500 words).**

PROBLEM 12.8. Influence of carbon dioxide (CO₂)

How would the Hadley circulation and the zonal mean zonal jets be affected if we would double the carbon dioxide concentration? Will the subtropical jet intensify or weaken? Will the subtropical jet be displaced poleward or equatorward? What will happen to the annual mean global mean temperature at the surface? What will happen to the annual mean global mean temperature at 10 hPa? Will the water cycle intensify or weaken? There is plenty of literature on this problem. Try to find this literature and base your answer on it. **Keep your answer relatively short (no more than 800 words).** See the **animation** of run 4a (similar to run 6 in table 12.2) ([https://webspace.science.uu.nl/~delde102/Wind&Tropopause_Run4a%20\(Converted\)](https://webspace.science.uu.nl/~delde102/Wind&Tropopause_Run4a%20(Converted)))

PROBLEM 12.9. Influence of thermal inertia

How does the value of the thermal inertia coefficient of the earth's surface (C) affect the (seasonal cycle of the) subtropical jet and the zonal wind in the stratosphere? What will happen (and why) to the modelled subtropical jets and stratospheric zonal winds if we *decrease* the value of C by a factor of 50 compared to run 4a? See the **animation** of run 4a (see problem 12.8). **Keep your answer relatively short (no more than 500 words).**

See the paper: <https://webspace.science.uu.nl/~delde102/DiabaticDynamicalAdjustment.pdf> and the model-animations on <https://webspace.science.uu.nl/~delde102/GeneralCirculation.htm> .

Answers need not be completely correct. Arguments should be logical and consistent.

Next:

**Lecture by Michiel van den Broeke:
Wednesday, 2 June, 2021, online**

Lecture 4, BLT&M-2: 4 June, 10:00-11:45, BBG 083

The missing element: the effect of waves and eddies

Lecture 5, BLT&M-2: 11 June, 10:00-11:45, BBG 061

Interpretation of the model results