Introduction to climate

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Outline

What is the climate?

1. The climate: a classification exercise
2. The climate: a set of numbers characterizing energy and water fluxes
3. The climate: the result of physical laws

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1. The climate: a classification exercise

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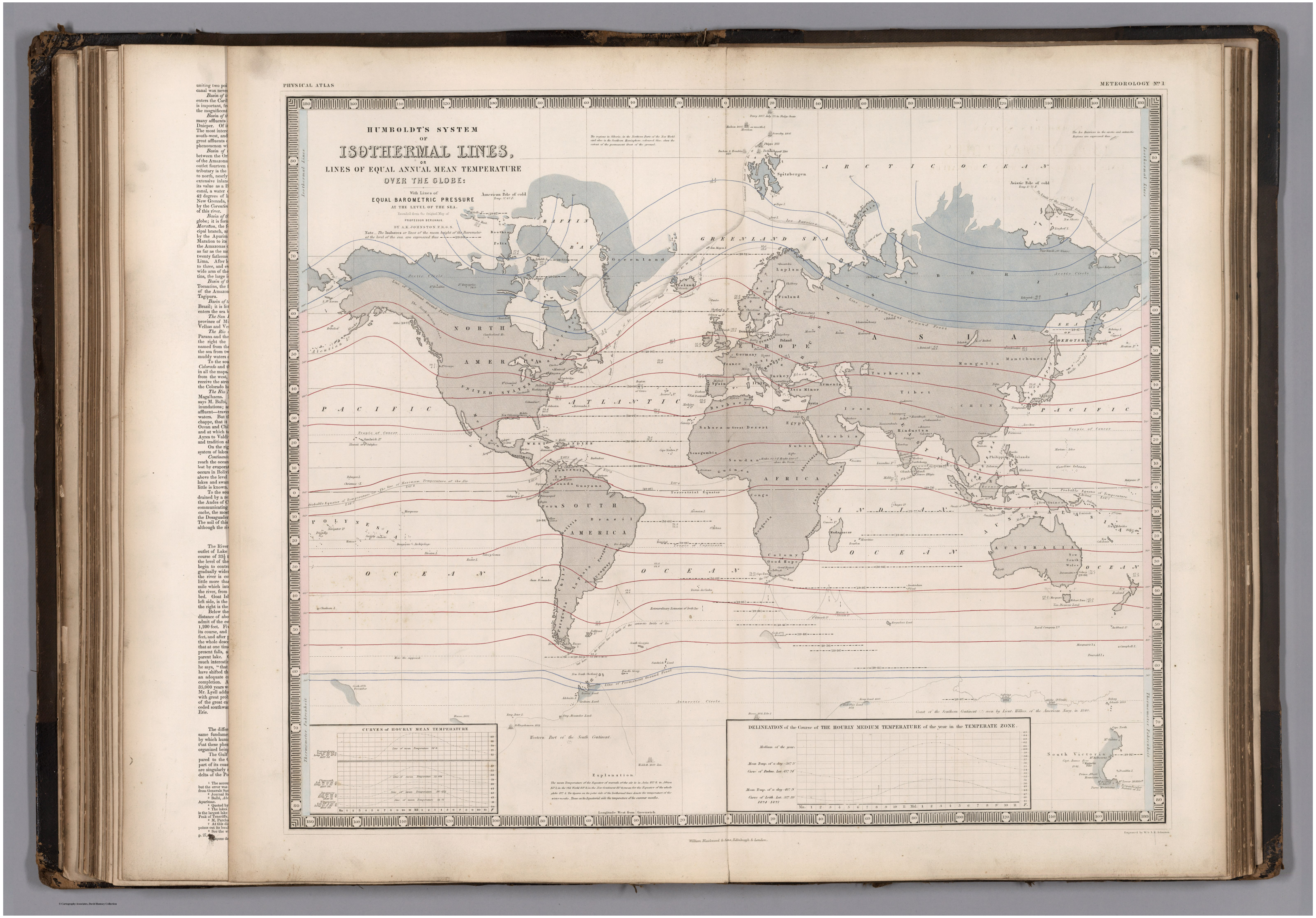
3. The climate: the result of physical laws

1.1 Alexander von Humboldt classification

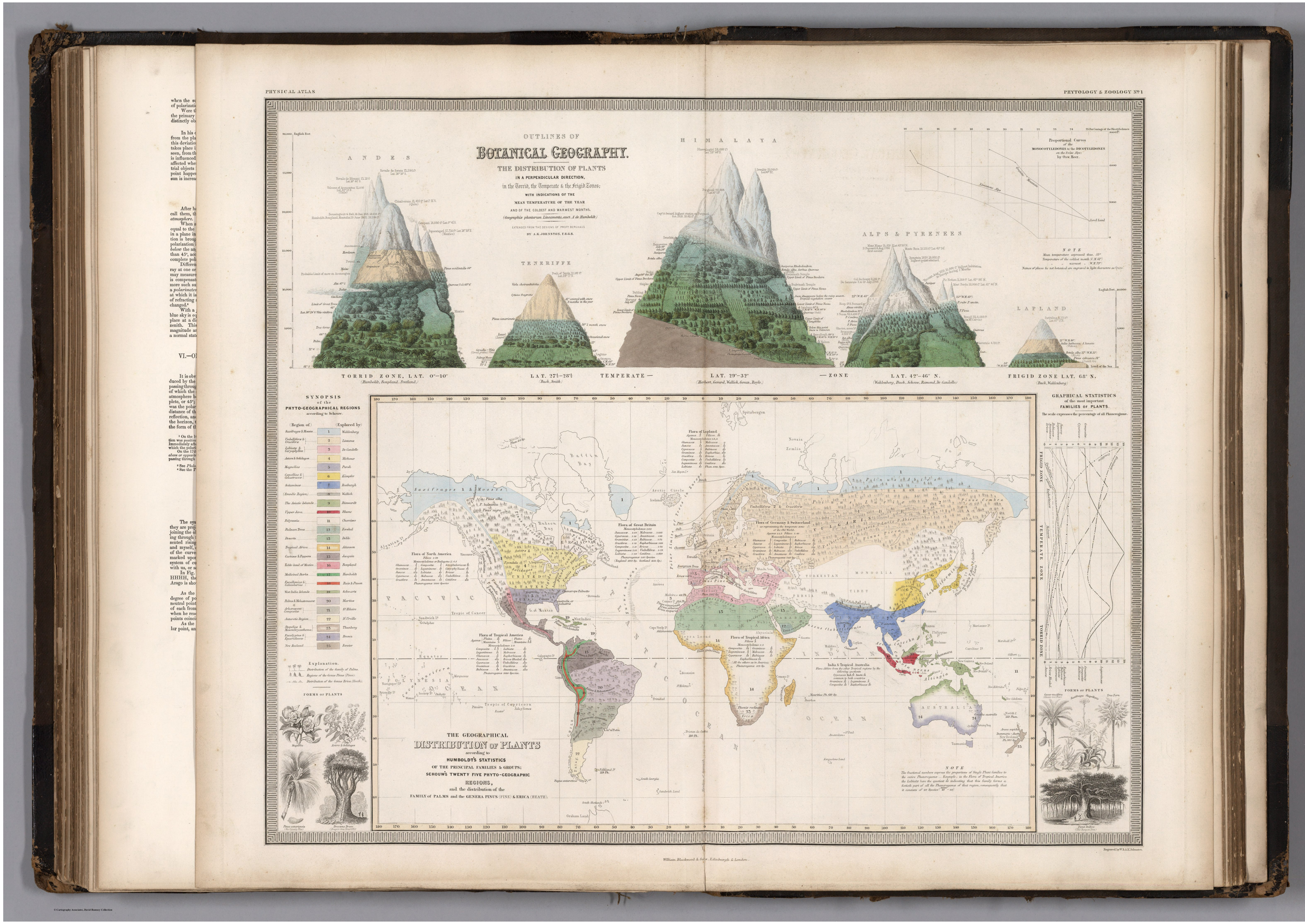
A. v. Humboldt, "Kosmos – Entwurf einer physischen Weltbeschreibung ", 1845-1862

1.1 Alexander von Humboldt classification



David Rumsey map collection

1.1 Alexander von Humboldt classification



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David Rumsey map collection

1.2 Vladimir Köppen classification

- Most well-known climate classification

  Köppen classification (1884, 1918, 1936) with later additions by Geiger (1954)

1.2 Vladimir Köppen classification

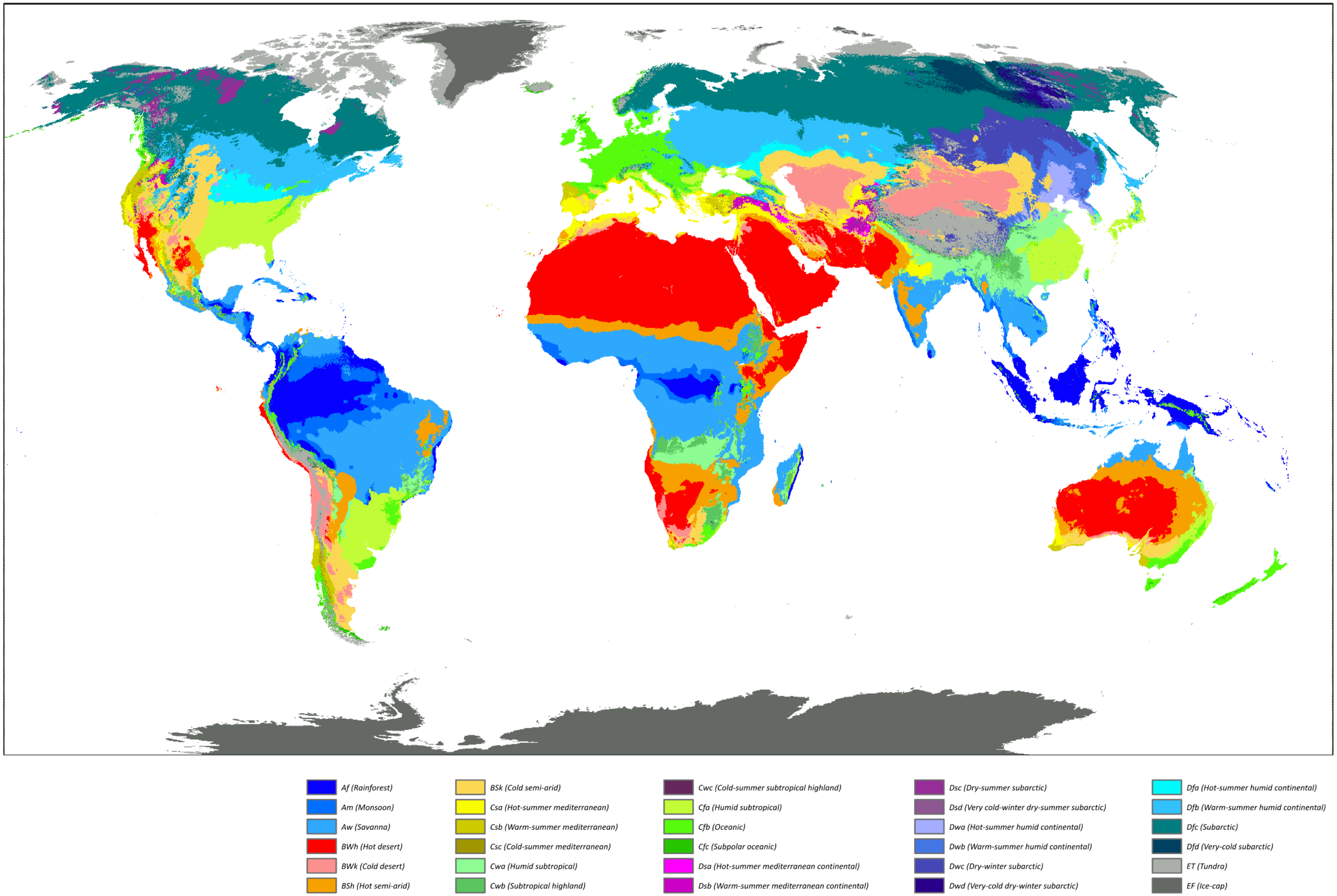
- The Köppen climate classification divides the climate into five main groups
    - Tropical (A), dry (B), temperate (C), continental (D), polar (E)

- Based on monthly averaged temperature (A, C, D, E) or yearly averaged temperature and monthly precipitation (B)

- Each main group is divided into subgroups based on precipitation, e.g. Af, Am, Aw, As

- Some of these subgroups are further divided based on temperature, e.g. Cfa, Cfb, Cfc

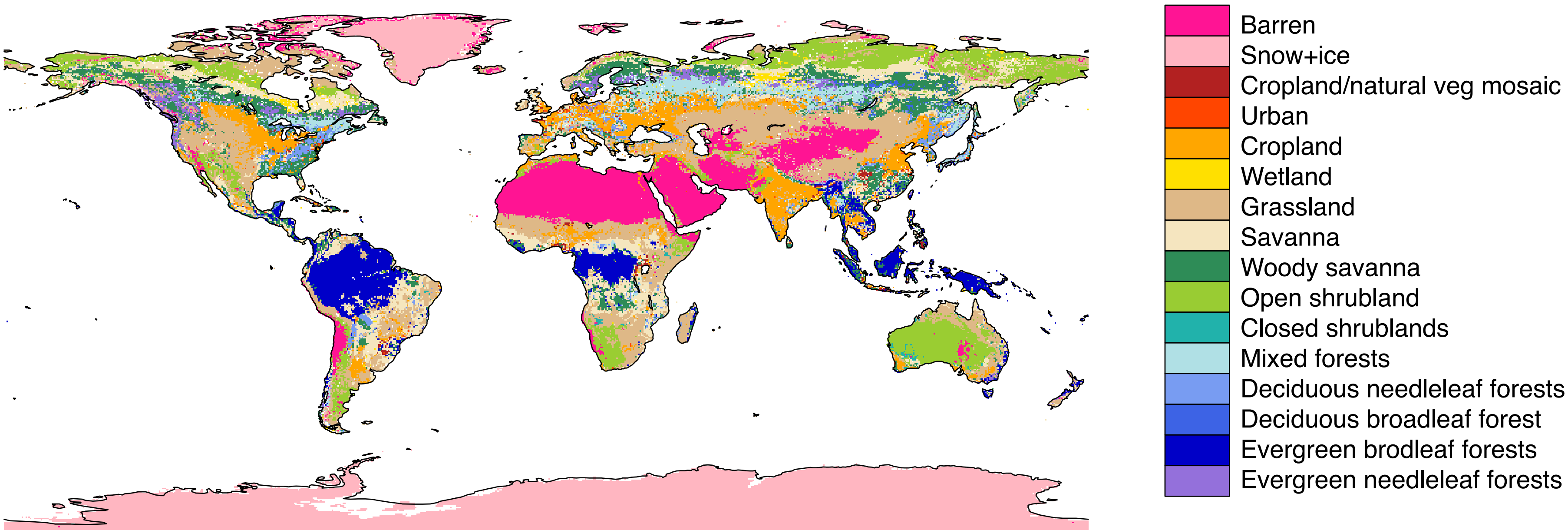
1.2 Vladimir Köppen classification



*Isotherm used to distinguish temperate (C) and continental (D) climates is -3°C
Climate types calculated from data from WorldClim.org (1970-2000 normals)

Coordinate system: Robinson
Map created by Adam Peterson on 20 February, 2019

1.2 Vladimir Köppen classification



1. The climate: a classification exercise

- Descriptive view
- Based on easily observed properties of the climate system: temperature, precipitation
- Expresses link vegetation-climate
- Indirectly expresses differences in water and energy fluxes
- Doesn’t say much about the drivers of the climate system

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What is the climate?

1. The climate: a classification exercise

2. The climate: a set of numbers characterizing energy and water fluxes

3. The climate: the result of physical laws

2.1 Energy fluxes

	SWd	SWu	LWd	LWu	SH	LH
TOA	340	100	0	239		
SFC	185	25	342	398	21	82

in W m^{-2}

Wild et al. (2015)

2.1 Energy fluxes

	SWd	SWu	LWd	LWu	SH	LH
TOA	340	100	0	239		
SFC	185	25	342	398	21	82

in W m^{-2}

Wild et al. (2015)

- At equilibrium, energy is conserved:

TOA SWd – SWu + LWd – LWu = 0

SFC SWd – SWu + LWd – LWu – SH –LH = 0

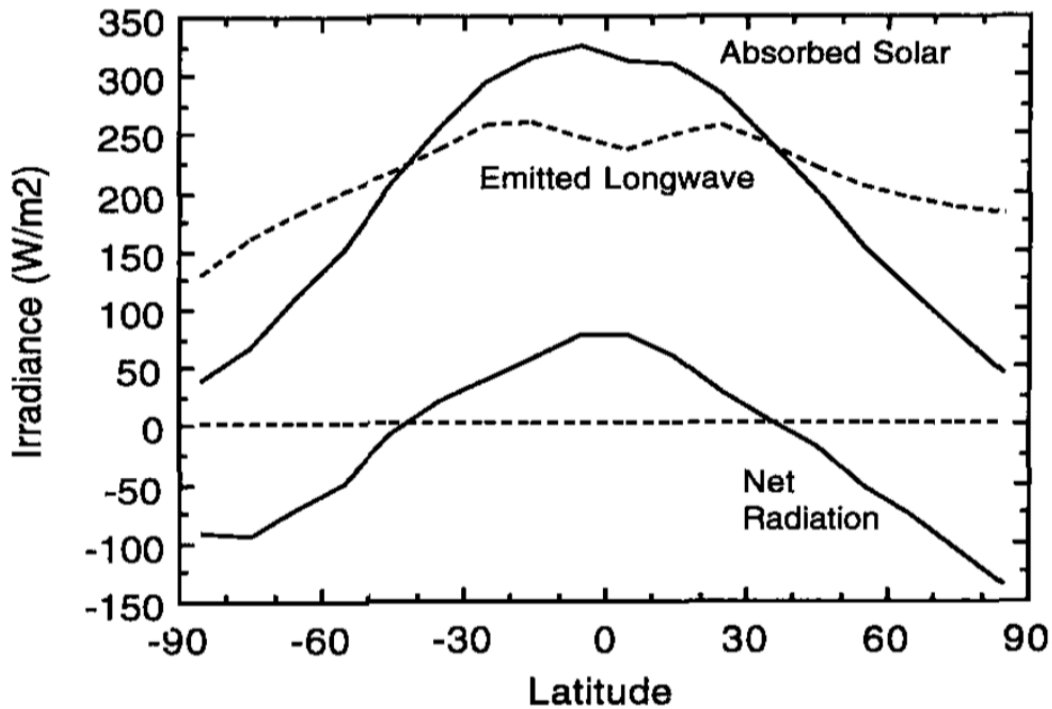
ATM TOA – SFC = 0

Atmosphere absorbs 80 W m^{-2} solar radiation, emits 183 W m^{-2} longwave radiation and absorbs 103 W m^{-2} surface fluxes

2.1 Energy fluxes

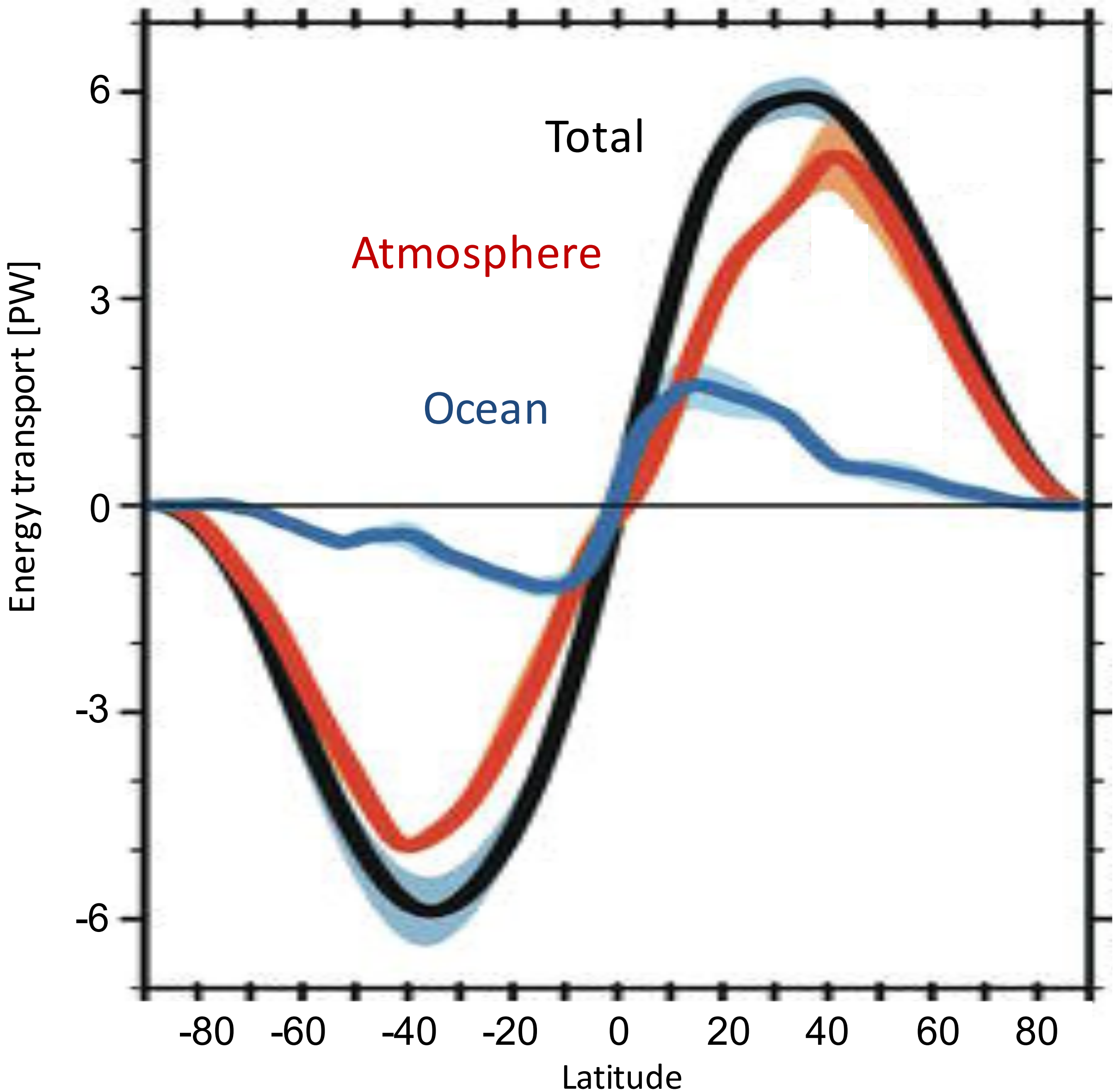
- At a point, energy is not balanced $\Longrightarrow$ Storage and Energy transport

- Averaged over a year, the storage term is negligible
- Energy is transported from the tropics to the pole
- Drive atmospheric and oceanic circulation



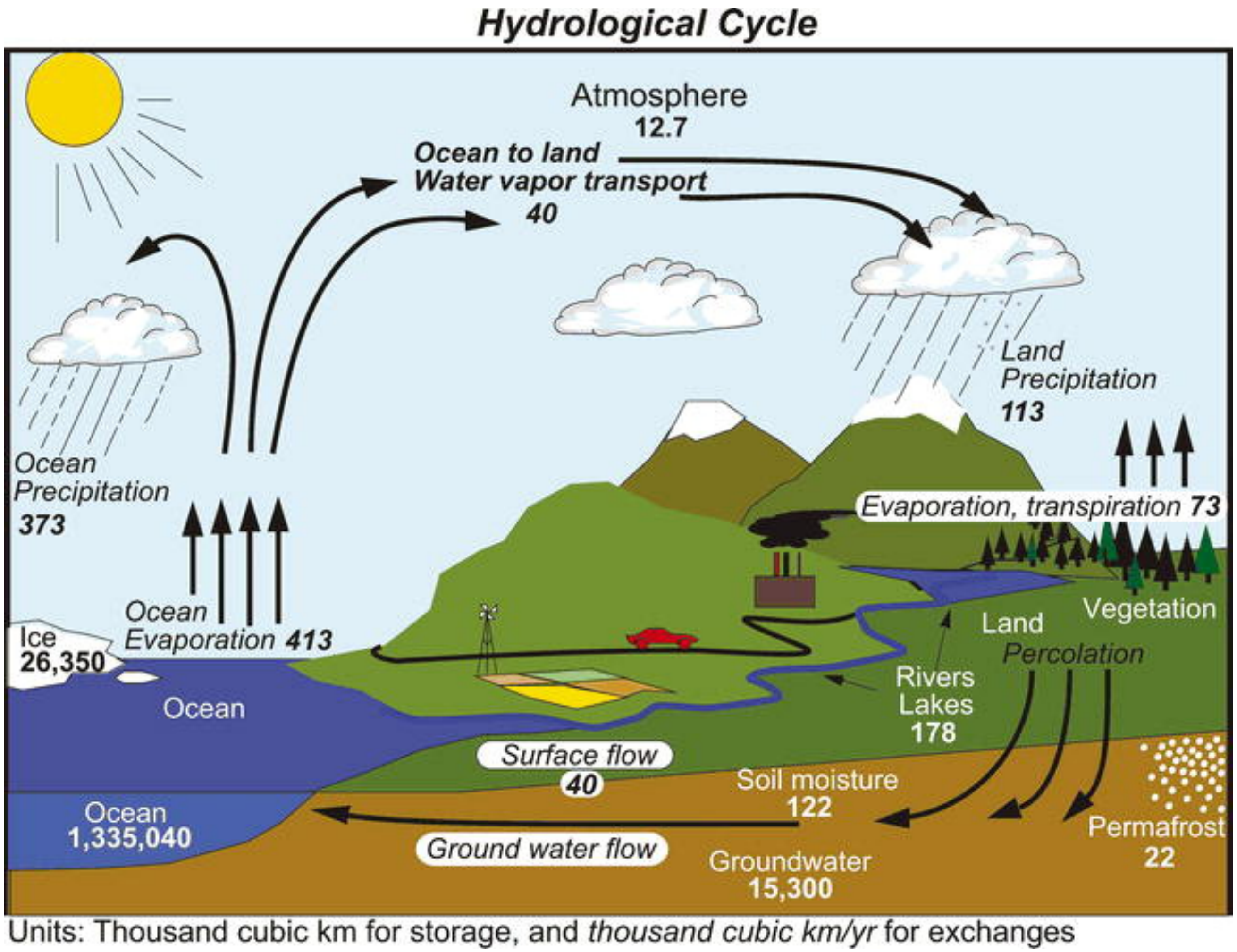
Hartmann (1994)

2.1 Energy fluxes



Fasullo and Trenberth (2008)

2.2 Water fluxes



Trenberth et al. (2007)

2.2 Water fluxes

- Water is also conserved

  GLOBAL P = ET

- Or, using energy budget:

$$\mathrm{P} = \mathrm{ET} = \mathrm{R}_{\mathrm{net}}^{\mathrm{sfc}} - \mathrm{R}_{\mathrm{net}}^{\mathrm{toa}} - \mathrm{SH}$$

- Precipitation approximately compensates radiative cooling

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LAND

$$\frac{\partial \mathrm{S}}{\partial t} = \mathrm{P} - \mathrm{ET} - \mathrm{Runoff}$$

ATM

$$\frac{\partial \mathrm{W}}{\partial t} = -\nabla_H \cdot Q - (\mathrm{P} - \mathrm{ET})$$

Q is the vertically integrated two-dimensional water vapor flux

2. The climate: a set of numbers

- Descriptive view
- Rely on a combination of satellite, ground measurements and model simulations, still uncertainties on the derived fluxes, in particular at the surface
- Link to underlying conservation of energy and water

TOA	SWd – SWu + LWd – LWu = 0	**GLOBAL**	P = ET
SFC	SWd – SWu + LWd – LWu – SH –LH = 0	**LAND**	$\frac{\partial \mathrm{S}}{\partial t} = \mathrm{P} - \mathrm{ET} - \mathrm{Runoff}$
ATM	TOA – SFC = 0	**ATM**	$\frac{\partial \mathrm{W}}{\partial t} = -\nabla_H \cdot Q - (\mathrm{P} - \mathrm{ET})$

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How much of the climate properties can we explain by simple conceptual models?

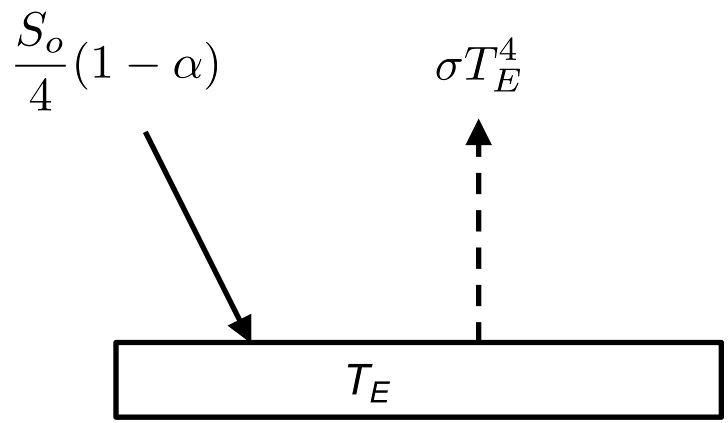
1. Zero-dim energy balance model	*Hom. radiation, no atmosphere*
2. One-dim energy balance model	*Hom. radiation, one-layer atmosphere*
3. Radiative equilibrium	*Hom .radiation, vertically-resolved atmosphere*
4. Radiative convective equilibrium	*Radiation and convection*
5. Aquaplanet	*Radiation, convection, rotation and meridional variations*

3.1 Zero-dim energy balance model

- Earth (atmosphere+surface) modeled as one layer, no separate atmosphere

- At equilibrium, incoming and outgoing radiative fluxes must compensate:

$$\frac{S_o}{4}(1-\alpha) = \sigma T_E^4$$



- T_E = 255 K

- Observed T_E is 288 K!

- In reality, atmosphere makes it difficult for the surface to radiate energy because some of it is absorbed and radiates back down

S_o solar constant : 1361 W m^{-2}
α albedo : 0.3
σ Stefan-Boltzmann constant : 5.67 10^{-8} W m^{-2} K^{-4}

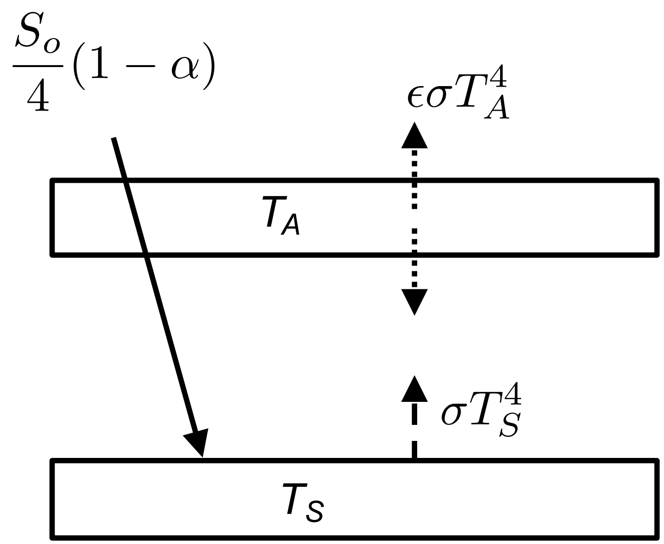
3.2 One-dim energy balance model

- Atmospheric layer separated from the surface
- Atmosphere transparent for shortwave but absorbs and emits longwave, “greenhouse effect”
- Surface radiative balance:

$$\frac{S_o}{4}(1-\alpha)+\epsilon\sigma T_A^4=\sigma T_S^4$$

- Atmospheric radiative balance:

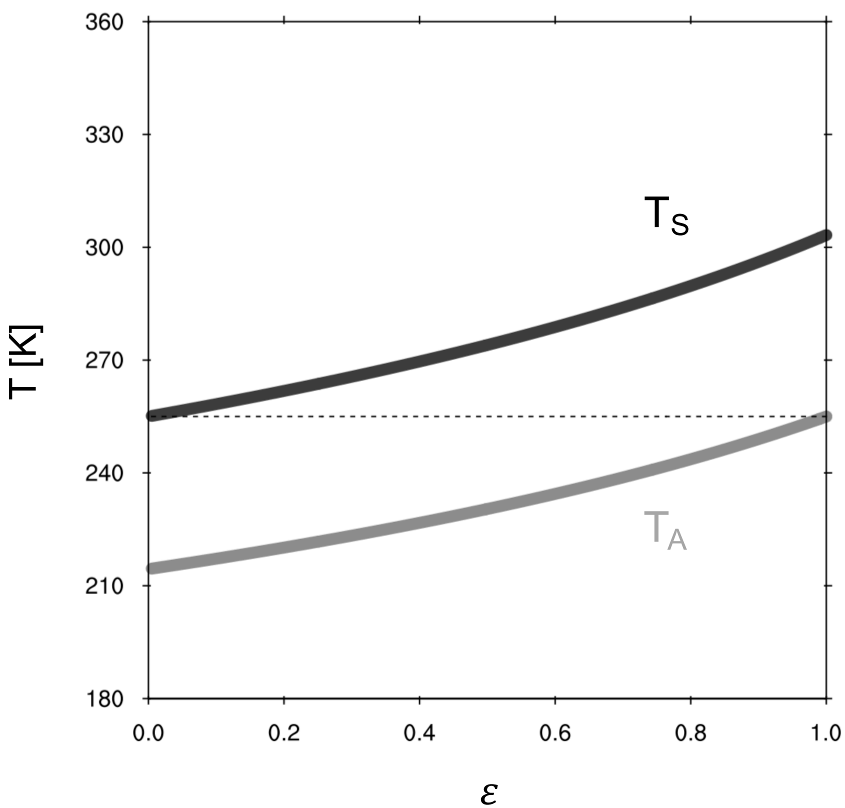
$$\epsilon\sigma T_S^4=2\epsilon\sigma T_A^4$$



S_o solar constant : 1361 W m^{-2}
α albedo : 0.3
σ Stefan-Boltzmann constant : 5.67 10^{-8} W m^{-2} K^{-4}

3.2 One-dim energy balance model

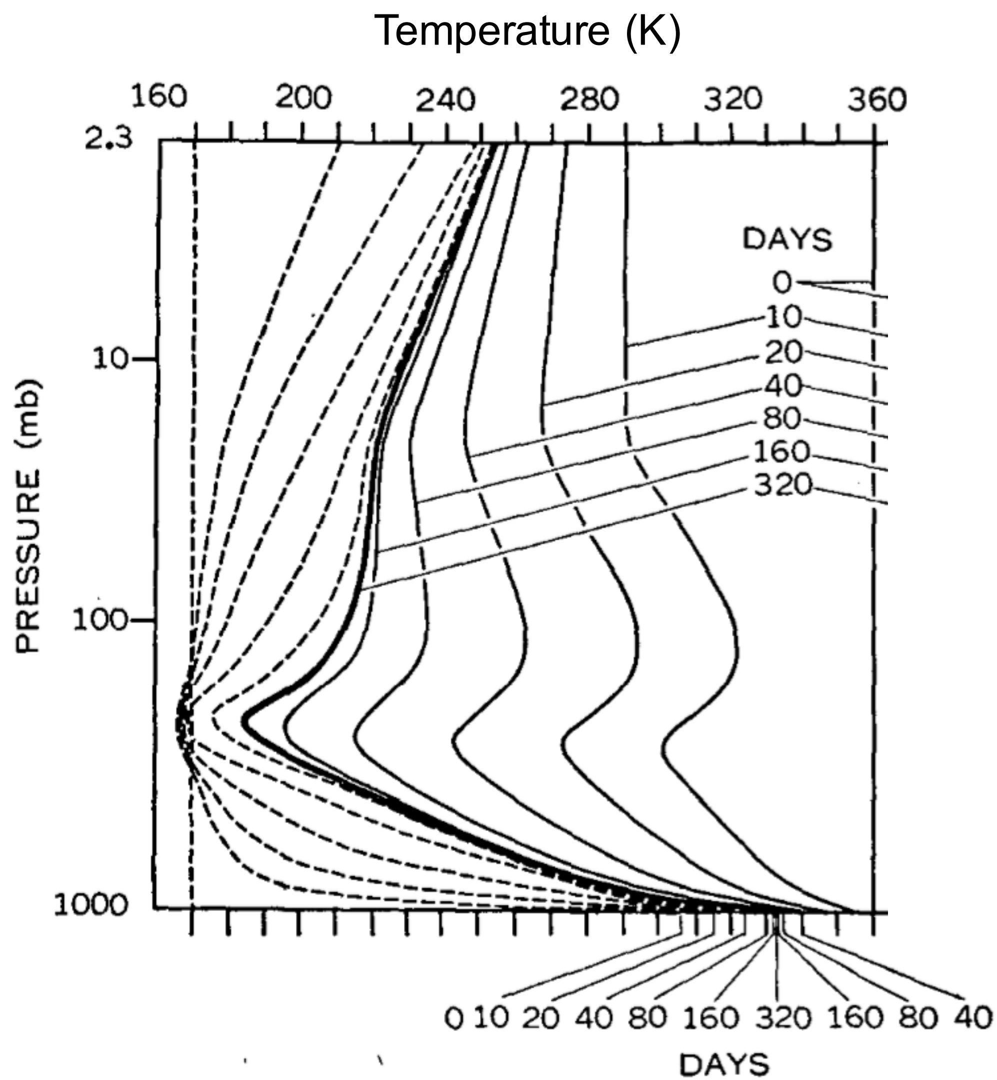
- T_s = 288 K for ε=0.77



3.3 Radiative equilibrium

- Add multiple layers in the vertical
- Gaseous absorbers (water vapor and ozone) prescribed
- No cloud
- Annual mean insolation
- Surface albedo of 0.102

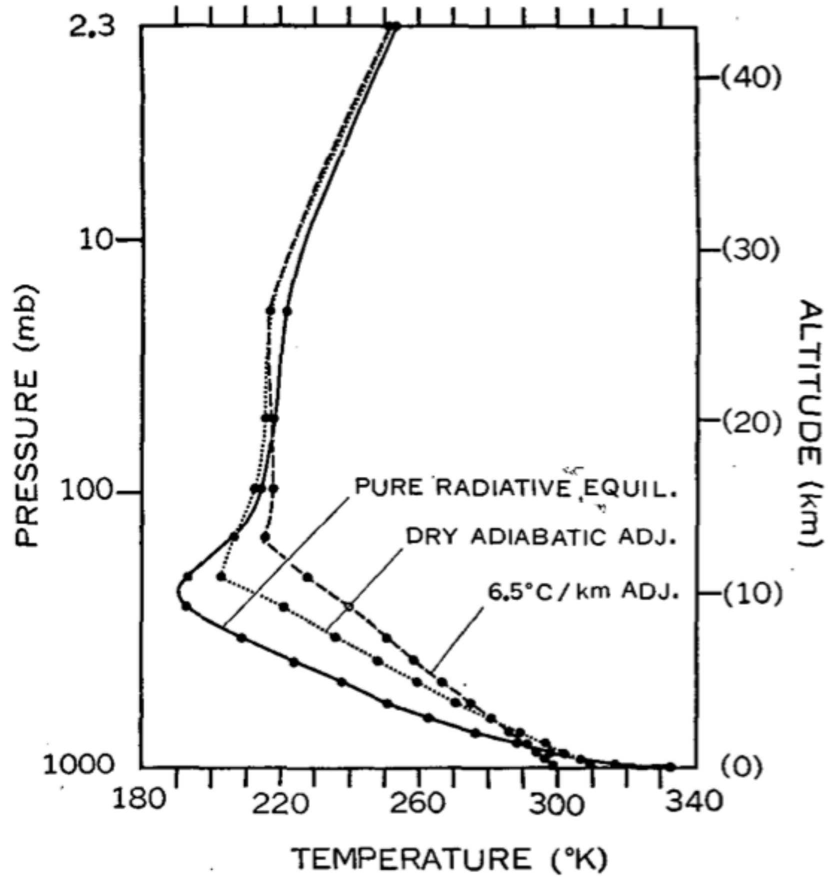
- Tropopause too cold
- Surface temperature too warm
- Lapse rate unstable!



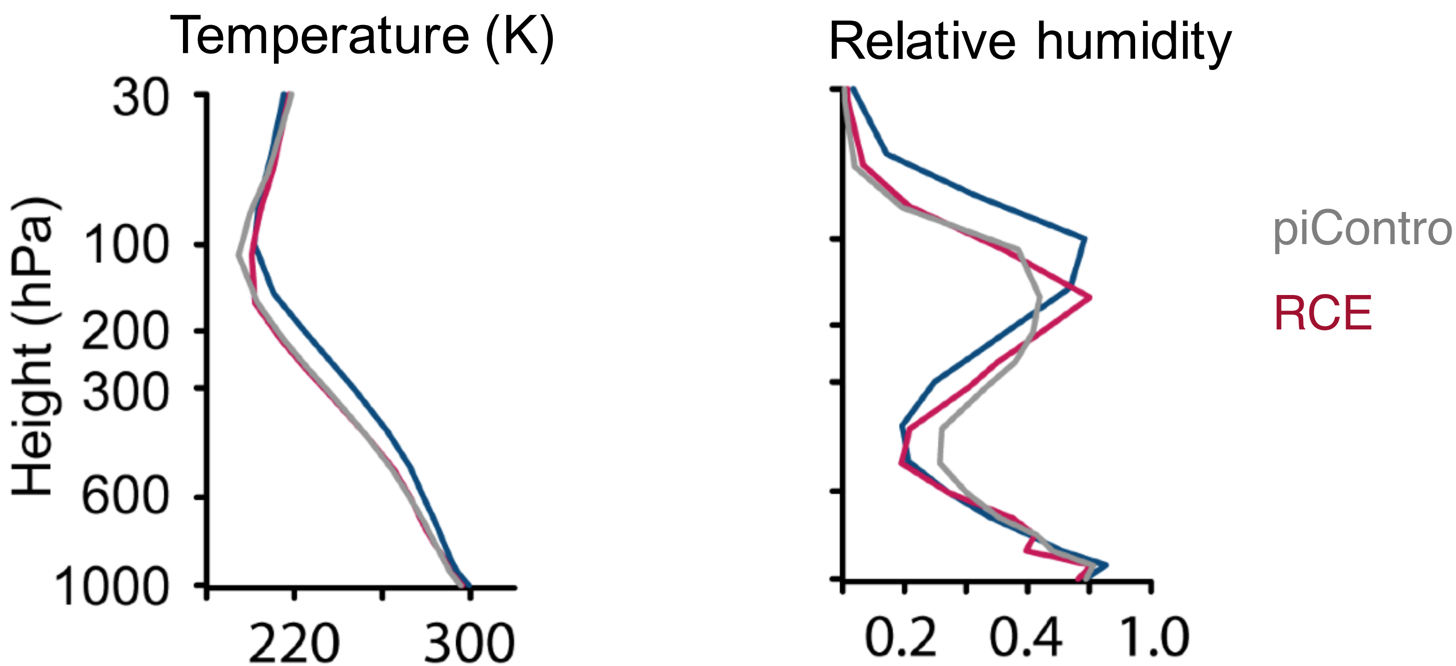
Manabe and Stickler (1964)

3.4 Radiative Convective Equilibrium

- As soon the temperature profile gets unstable, convection will in reality sets in
- Simple convective parameterization: set lapse rate back to dry or moist adiabat lapse rate
- Able to reproduce the observed mean tropical temperature profile!
- RCE: radiation destabilizes the atmosphere, convection stabilizes it
- Convection is faster than radiation and wins in the troposphere: temperature follows moist adiabat
- In the stratosphere, radiative equilibrium



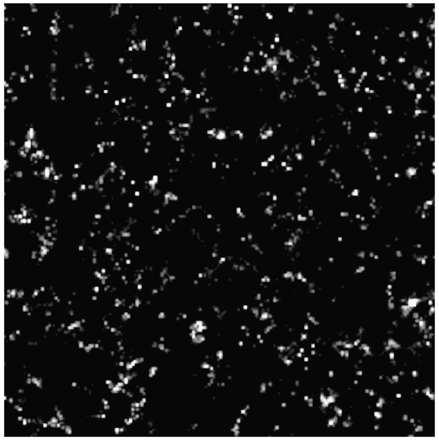
Manabe and Stickler (1964)

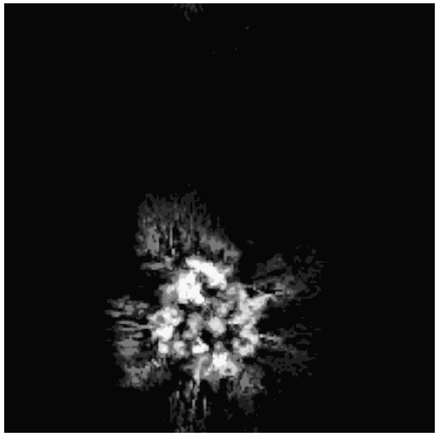


Popke et al. (2013)

What about the spatial distribution of convection?

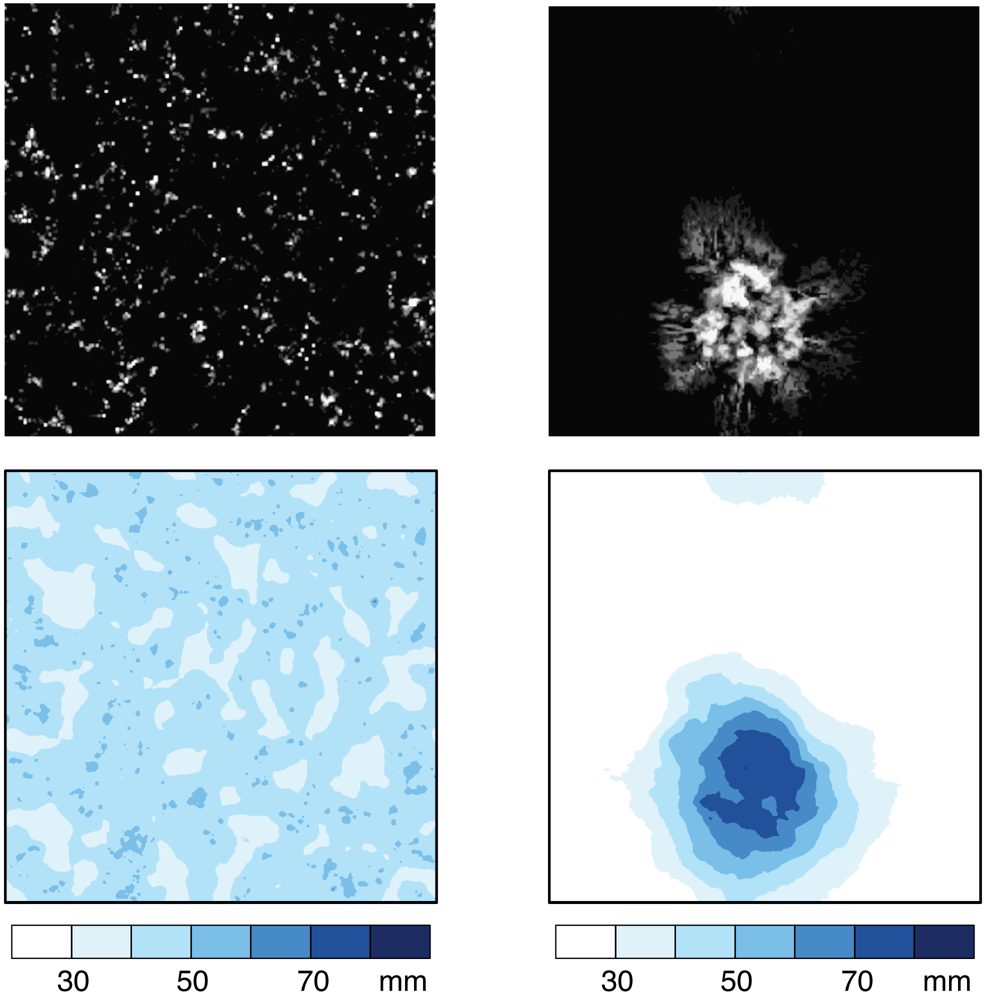
- Convection organizes in a blob





What about the spatial distribution of convection?

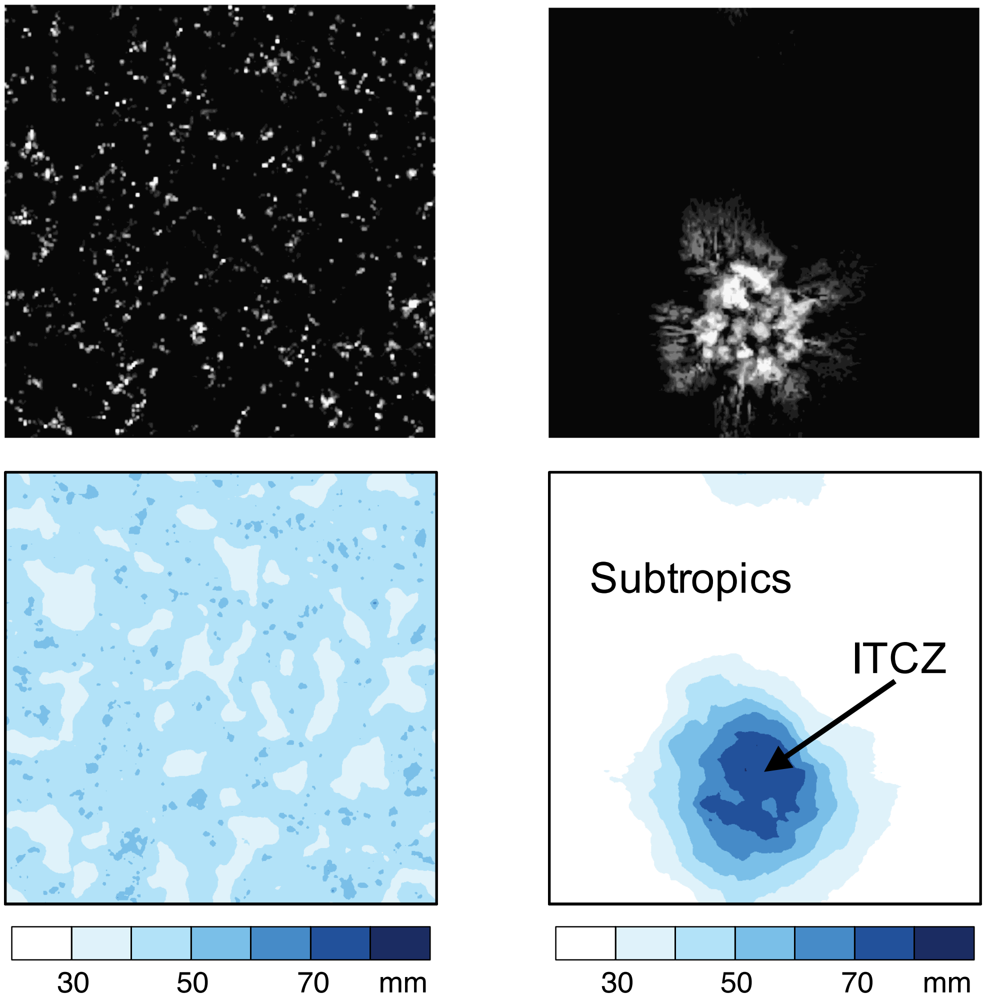
- Convection organizes in a blob
- Organization is accompanied by a strong drying



3.4 Radiative Convective Equilibrium

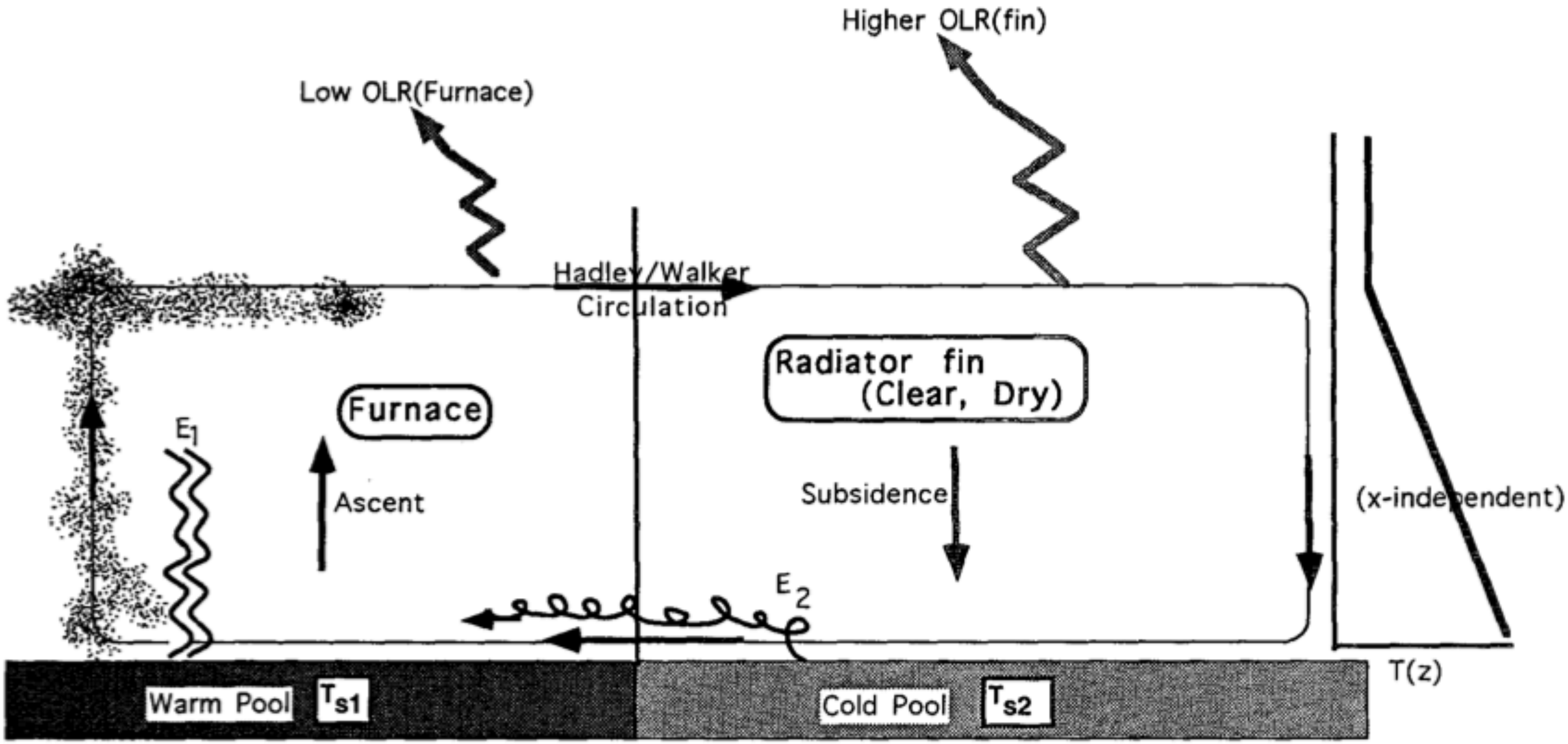
What about the spatial distribution of convection?

- Convection organizes in a blob
- Organization is accompanied by a strong drying
- A simple analog to the ITCZ and its subtropics?



3.4 Radiative Convective Equilibrium

- Need the subtropics to avoid falling into a greenhouse state

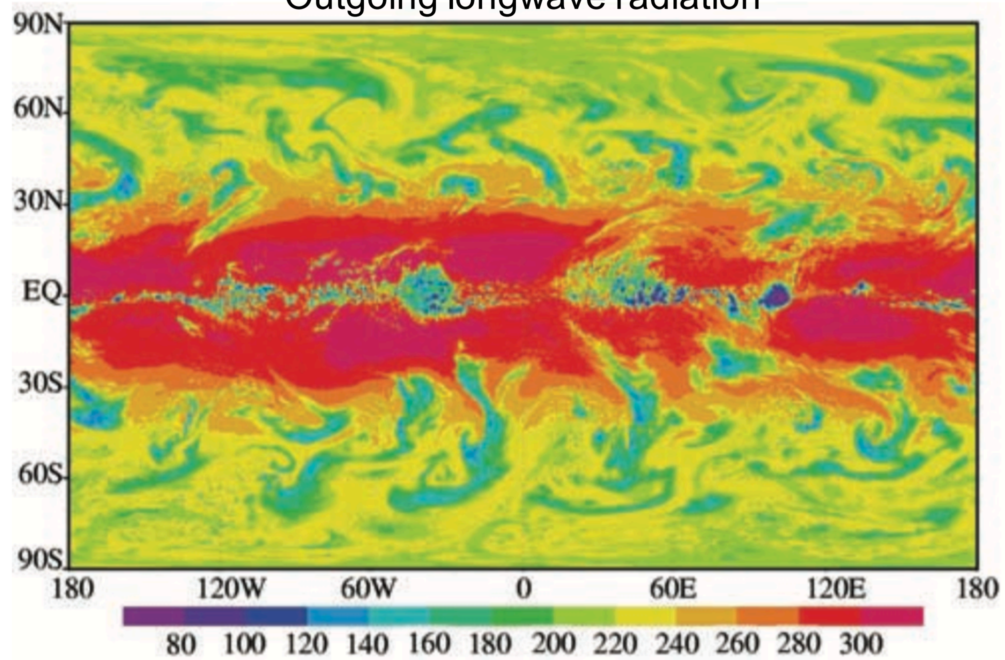


Pierrehumbert (1994)

3.5 Aquaplanet

- Water surface
- Zonally varying SST
- Zonally varying insolation
- Rotation
- Many of the observed features are reproduced

Outgoing longwave radiation



Tomita et al. (2005)

3. The climate: the result of physical laws

- Simple conceptual model can reproduce basic properties of the climate system
- Observed surface temperature can be understood from a 1-dimensional energy balance model, but needs greenhouse effect
- Observed stratospheric tropical temperature profile can be understood from pure radiative equilibrium
- Observed tropospheric tropical temperature profile can be understood from a statistical equilibrium between convection and radiation
- But need dry areas to cool the planet
- Need aquaplanet set-up for extratropical storms to develop

Conclusions

What is the climate?

1. The climate: a classification exercise
   - Descriptive view based on easily observed quantities whose variations result from energy/water fluxes
2. The climate: a set of numbers characterizing energy and water fluxes
   - Energy and water balances provide constraints on the climate
3. The climate: the result of physical laws
   - Greenhouse effect, Radiative Convective Equilibrium, Furnace-radiator fin, aquaplanet