# Climate of the Ocean

## Lecture 1: Introduction and fundamental processes of the climate system

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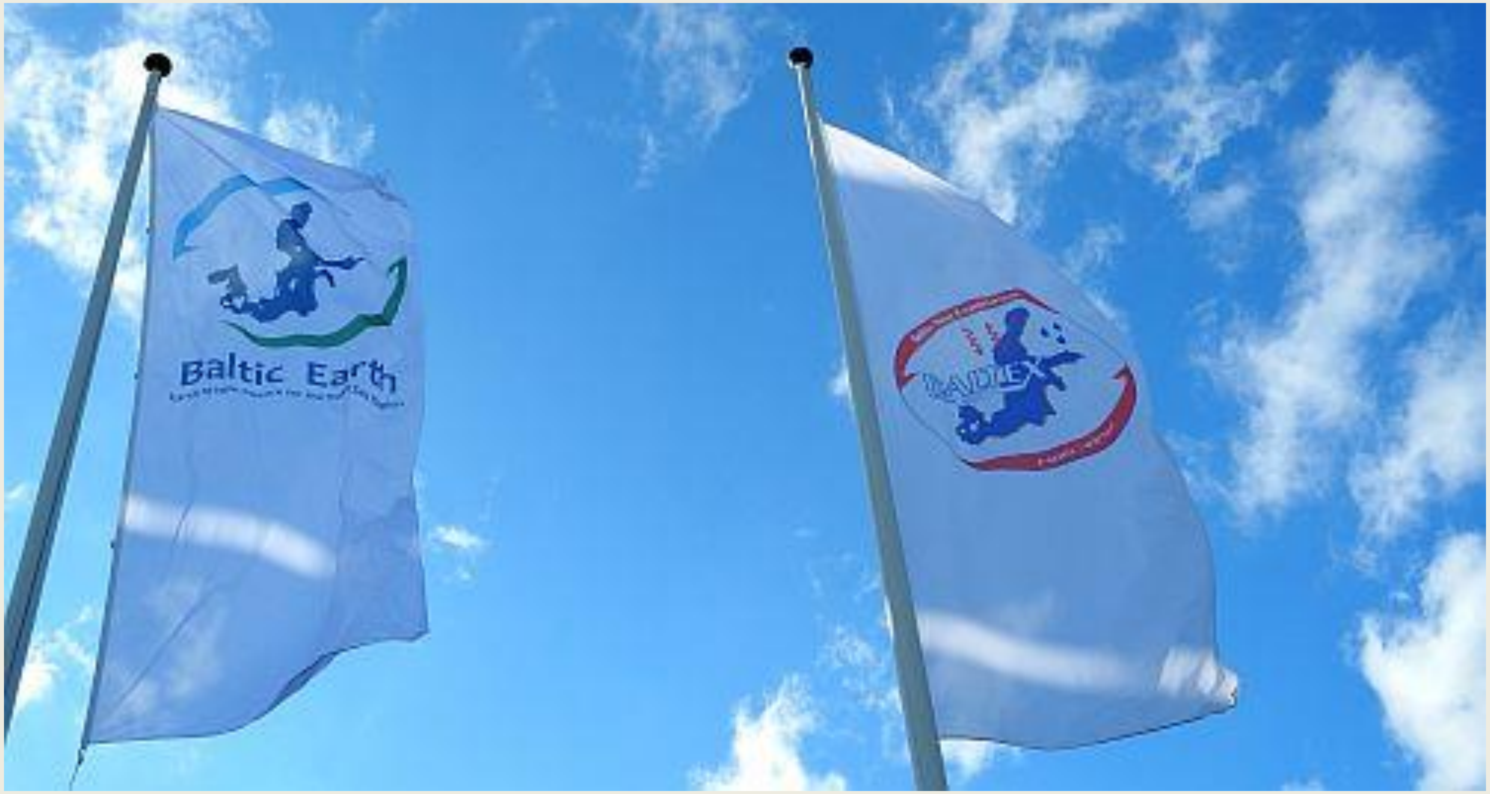
# General information

- about the course: Climate of the Ocean (winter term), Climate of the Baltic Sea Region (summer school at the end of August/beginning of September), both are part of the master in physics at Rostock University
- Professor in physical oceanography at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and Rostock University
- Baltic Earth www.baltic.earth

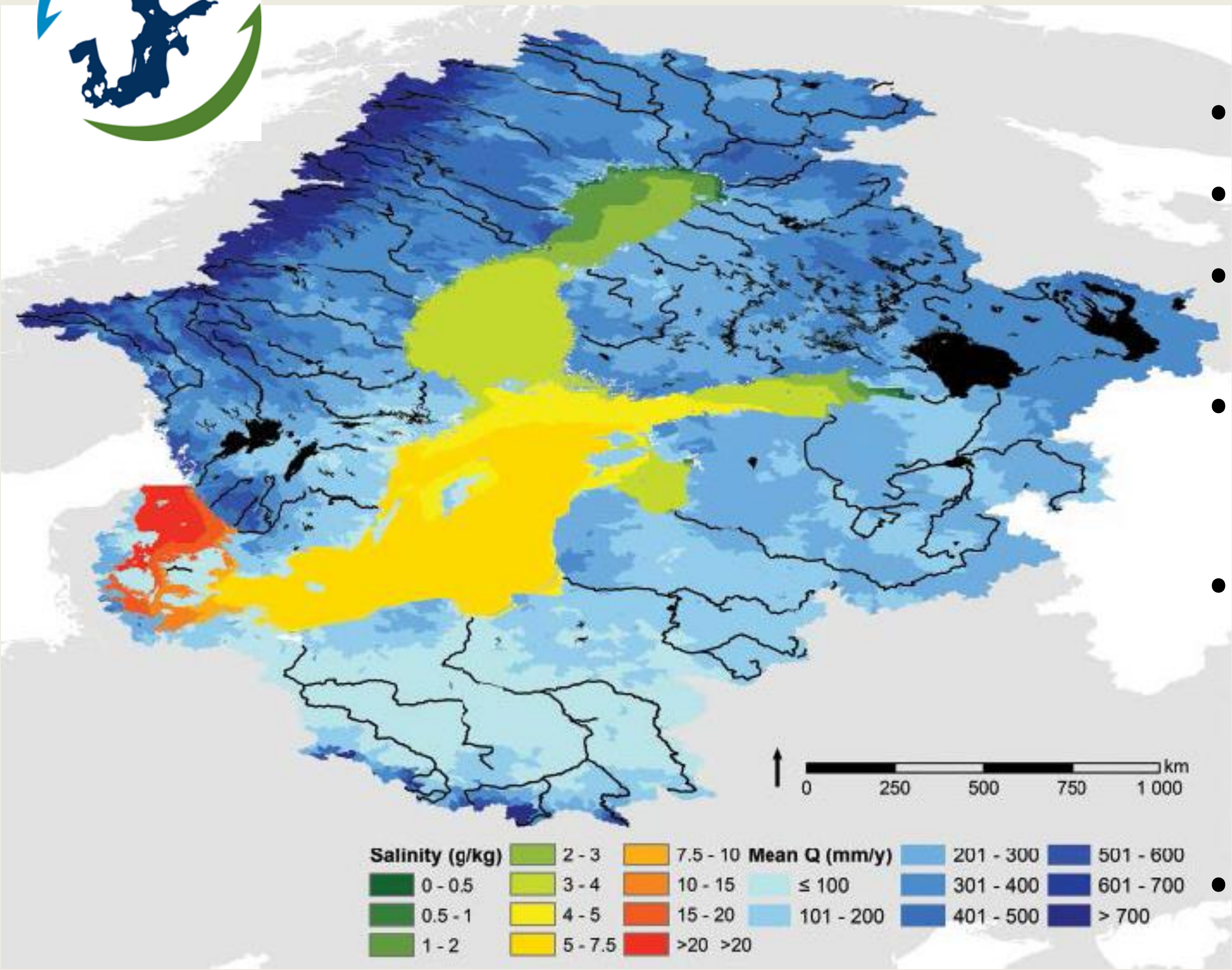
# Baltic Earth

http://www.baltic.earth/




**Earth System Science for the Baltic Sea basin**

# The Baltic Sea region

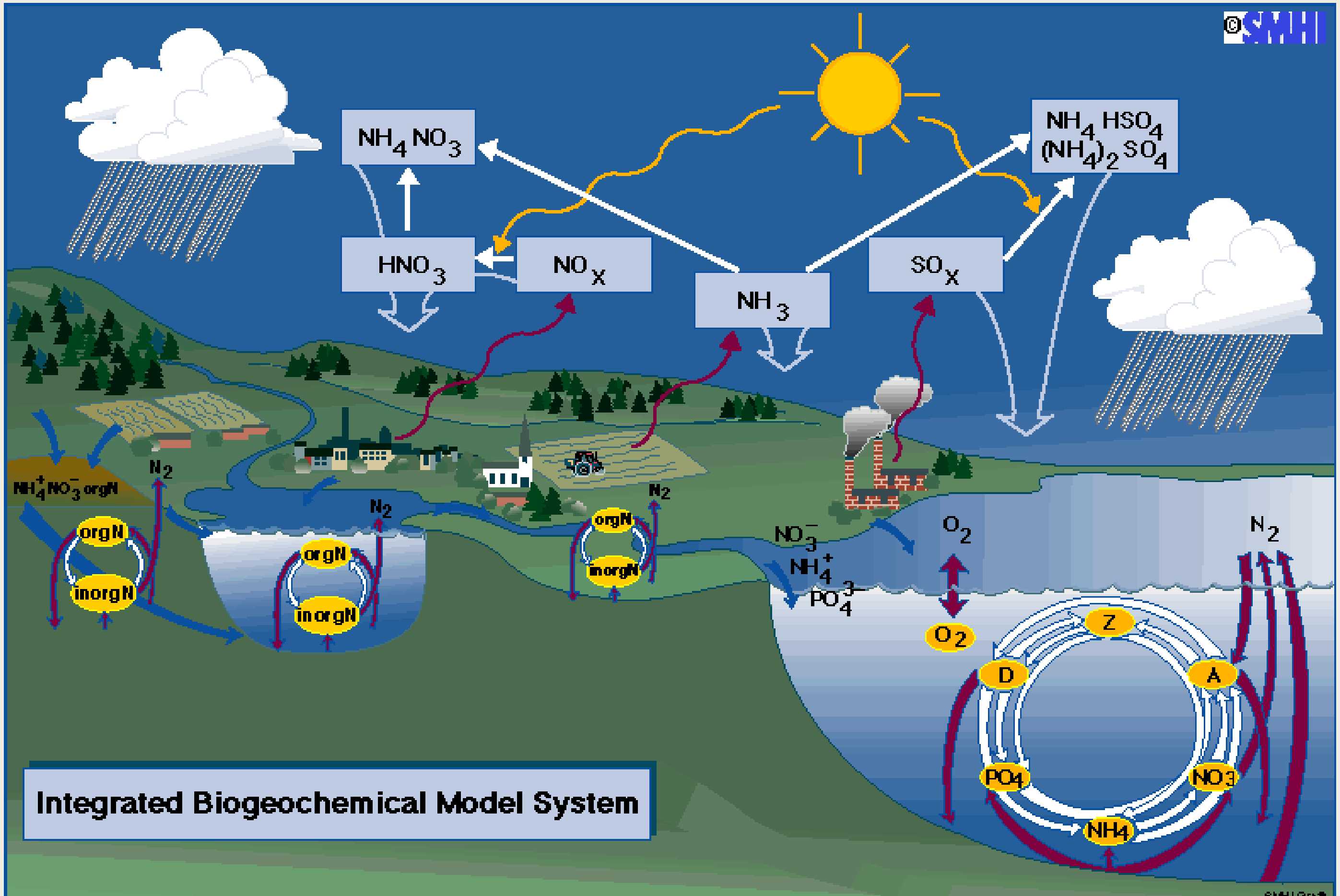



Meier et al. (2014, Eos)

- Basin: 2.13 Mill. km² (20% of the European continent)
- Baltic Sea: 380 000 km²
- 85 million in *14 countries*
- Variable climate and topography
- Considerable seasonal, inter-annual, decadal and long-term variations
- Unique, challenging region for climate and environmental studies (data, models and observations, budgets)
- Environmental issues of concern

Baltic Earth
Earth System Science for the Baltic Sea Region

# Earth System Science for




*Earth system science treat the Earth as an integrated system and seeks a deeper understanding of the physical, chemical, biological and human interactions that determine the past, current and future states of the Earth*

# Information about the course

- Rostock University (master in physics): 3 ECTS (15 lectures á 90 min, tutorials and exercises, 45 minutes examination)
- October 12, 19, 26
- November 2, 9, 16,23, 30
- December 7, 14, 21
- January 4, 11, 18, 25
- Compensation for two lectures in December and January 12 x 15 min = 180 min, hence 13:15-15:00 without break

# Course content

1. Fundamental processes of the climate system (greenhouse effect, radiation balance, climate sensitivity, stability and feedbacks)
2. Basic methods of the analysis and modeling of the climate system with focus on the ocean
3. Equations of motion of the large-scale circulation with focus on the ocean
4. Coupled atmosphere – ocean – sea-ice models
5. Spatial and temporal variability of the climate system
6. Anthropogenic climate change and natural climate variability (externally and internally driven climate variability)

# Other courses

- WS: Einf in die Atmosphärenphysik und Physik des Ozeans
- WS: Klima des Ozeans
- WS: Prozesse im Küstenozean
- WS: Dynamik der Atmosphäre

- SS: Klima in der Ostseeregion (Summer school)
- SS: Theoretische Ozeanographie
- SS: Numerische Methoden
- SS: Physik des Klimas

# Literature

- IPCC (www.ipcc.ch, open access)
- BACC I and II (www.baltic.earth, open access)
- NOSCCA (http://link.springer.com/book/10.1007/978-3-319-39745-0, open access)
- Peixoto and Oort: Physics of the Climate (1992)
- Olbers, Willebrand and Eden: Ocean Dynamics, Springer (2012)
- Papers (Knutti 2010, Pages 2k consortium 2013, Hargreaves and Annan 2014, etc.)
- Lectures from Askö 2015 available as youtube movies @www.baltic.earth, Askö 2016 (pdf)

# Literature

- Courtesy: Lectures from Ulrich Cubasch
- Lecture notes: Dietmar Dommenget http://users.monash.edu.au/~dietmard/teaching/dommenget.climate.dynamics.notes.pdf
- Hamburger Bildungsserver http://bildungsserver.hamburg.de/klimawandel/ (only in German)

# Relevant books for the Baltic Sea

BACC II Author Team (2015). Second assessment of climate change for the Baltic Sea basin. Regional climate studies. Berlin, Springer.

Feistel, R., Nausch, G. and N., Wasmund (Eds), 2008. State and Evaluation of the Baltic Sea, 1952–2005. A detailed 50-year survey of Meteorology and Climate, Physics, Chemistry, biology, and Marine Environment. John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Fennel, W. and T., Neumann, 2004. Introduction to modelling the Marine Ecosystems. Elsevier Oceanography Series 72.

Leppäranta, M. and K. Myrberg, 2009. Physical oceanography of the Baltic Sea. Praxis publishing Ltd, Chiester, UK, Springer-Verlag Berlin Heidelberg New York ISBN 978-3-540-79702-9.

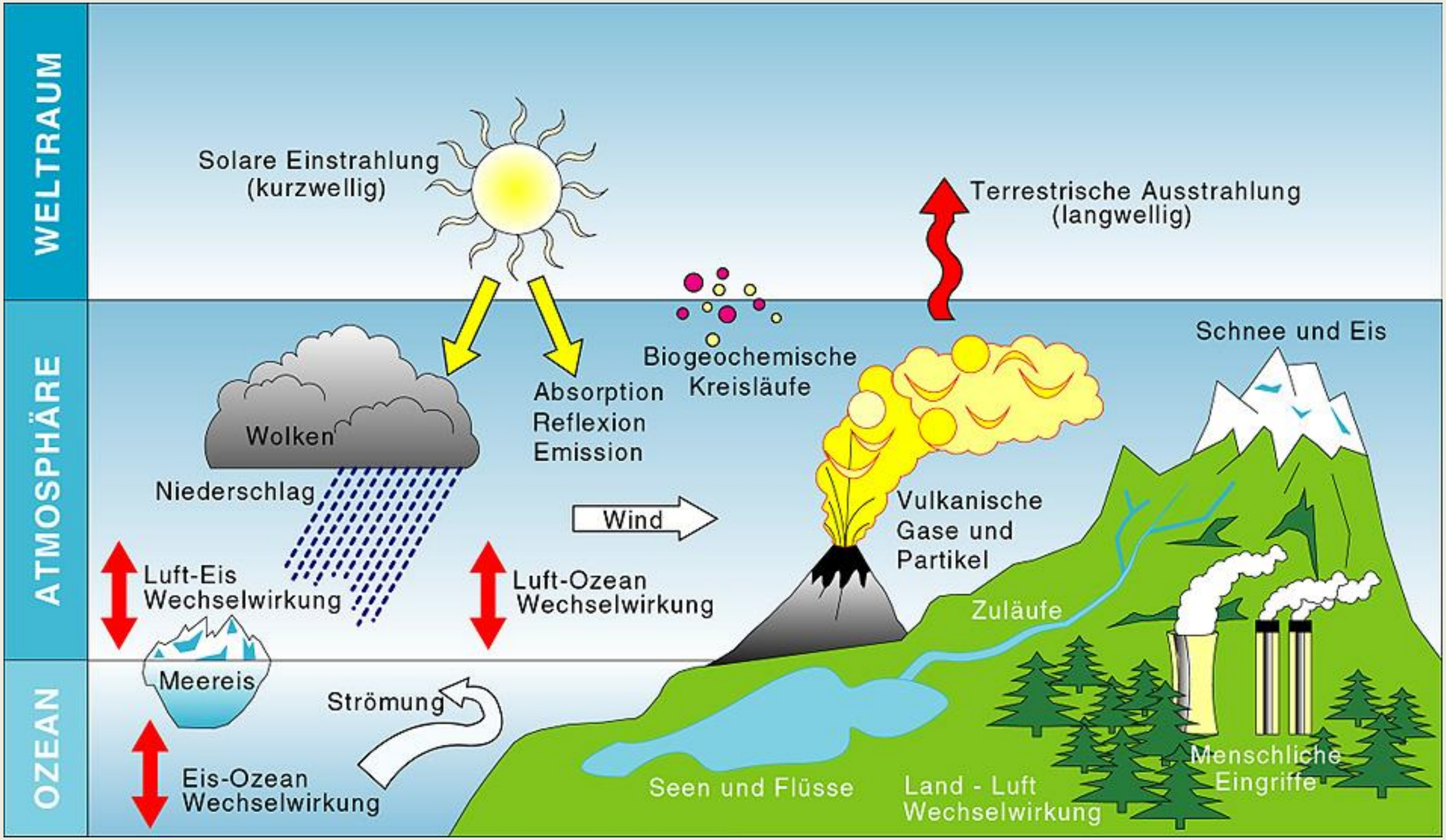
Wulff, F., L. Rahm & P. Larsson (Eds), 2001. A Systems Analysis of the Baltic Sea. Ecological Studies, Vol. 148. Springer, Berlin.

# Questions?

# Definition of climate

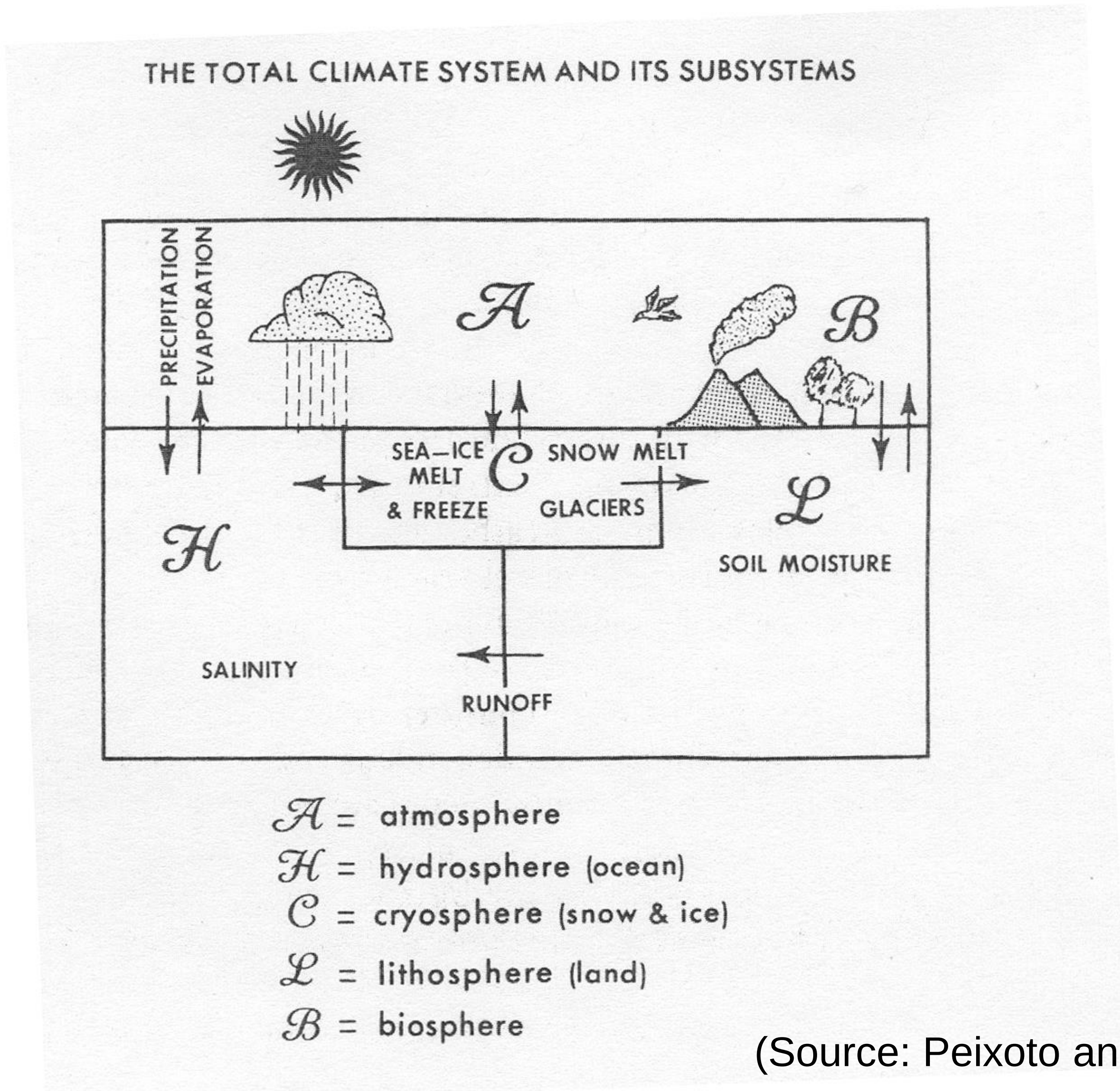
- Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from month to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO).

(Houghton, J. T., et al. (eds.), 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 881 p.)




**The climate system**

**(Source: Hamburger Bildungsserver)**



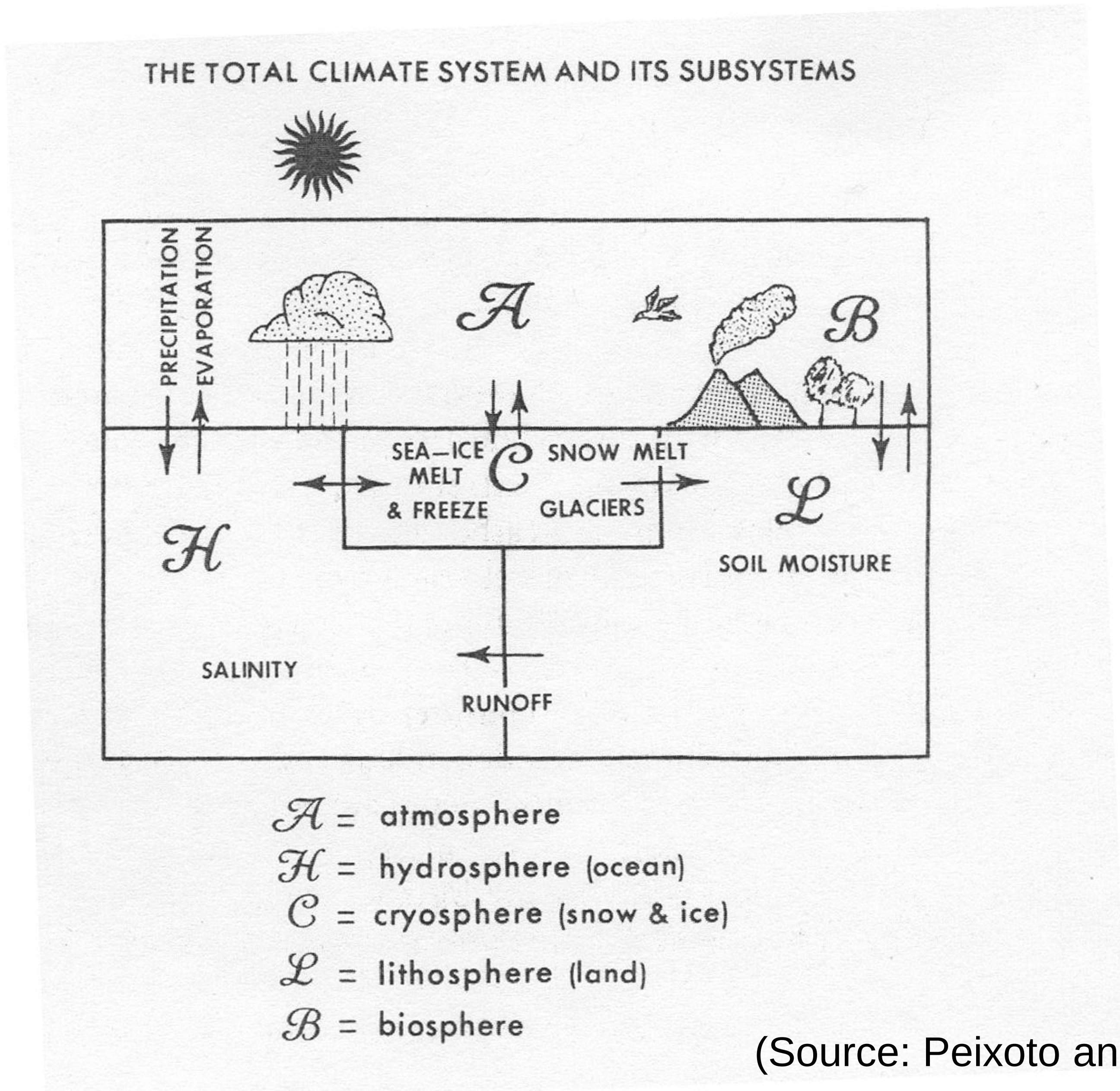

(Source: Peixoto and Oort 1992)

# *A*: atmosphere

- small heat capacity, fast response time to an imposed change
- time scales:
  - annual cycle,
  - synoptic activities (days to weeks)
  - decadal variability

  variations are called “weather”

(Courtesy: U. Cubasch)



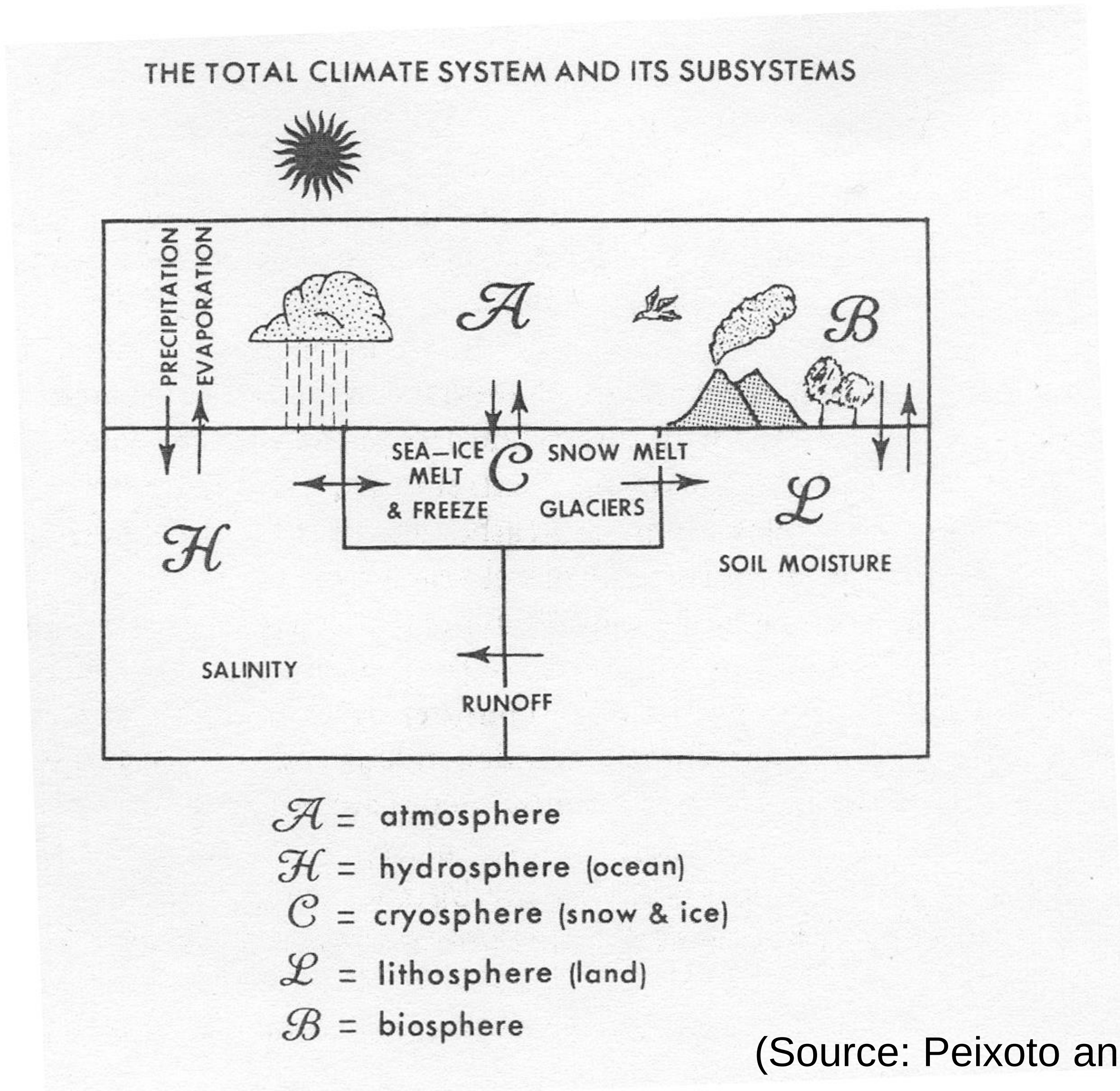

(Source: Peixoto and Oort 1992)

# *H*: hydrosphere

**ocean, lakes, rivers, precipitation, ground water**

- high heat capacity, small albedo
- the ocean is divided into:
  - **the deep ocean**, depth (1000 m),
  - time scale: 100 – 1000 years
  - **mixed layer,** depth (100 m),
  - Time scale: weeks, months

(Courtesy: U. Cubasch)



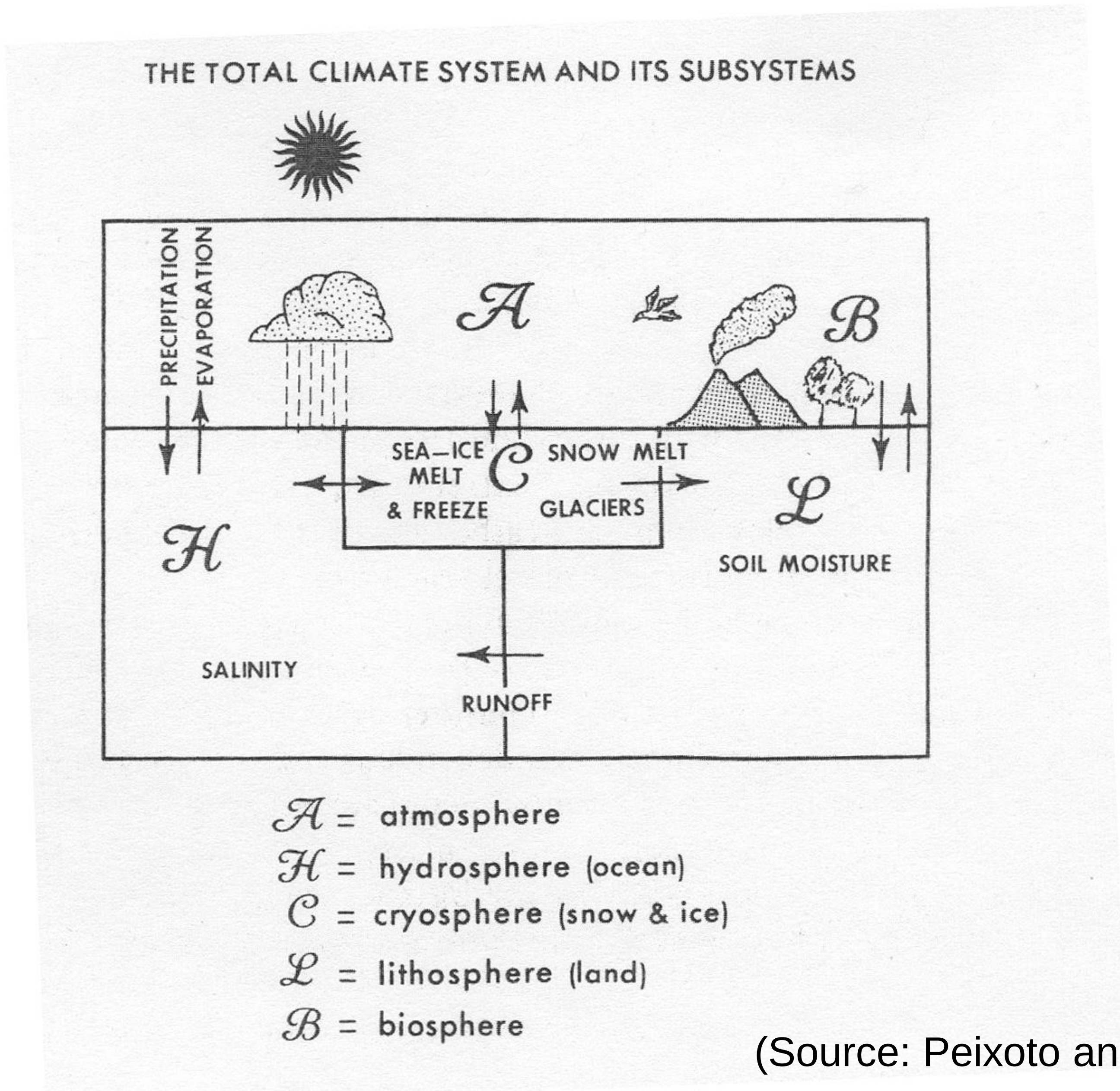

(Source: Peixoto and Oort 1992)

# C: cryosphere

**Inland glaciers of Greenland and Antarctica and other continental glaciers and snow fields, sea ice, permafrost**

- high albedo, small thermal conductivity
- largest freshwater reservoir
- **Time scales:**
  - inland ice: $10^4$ - $10^5$ years
  - Sea ice: 1 - 10 years

(Courtesy: U. Cubasch)




(Source: Peixoto and Oort 1992)

# *B*: biosphere (terrestrial)

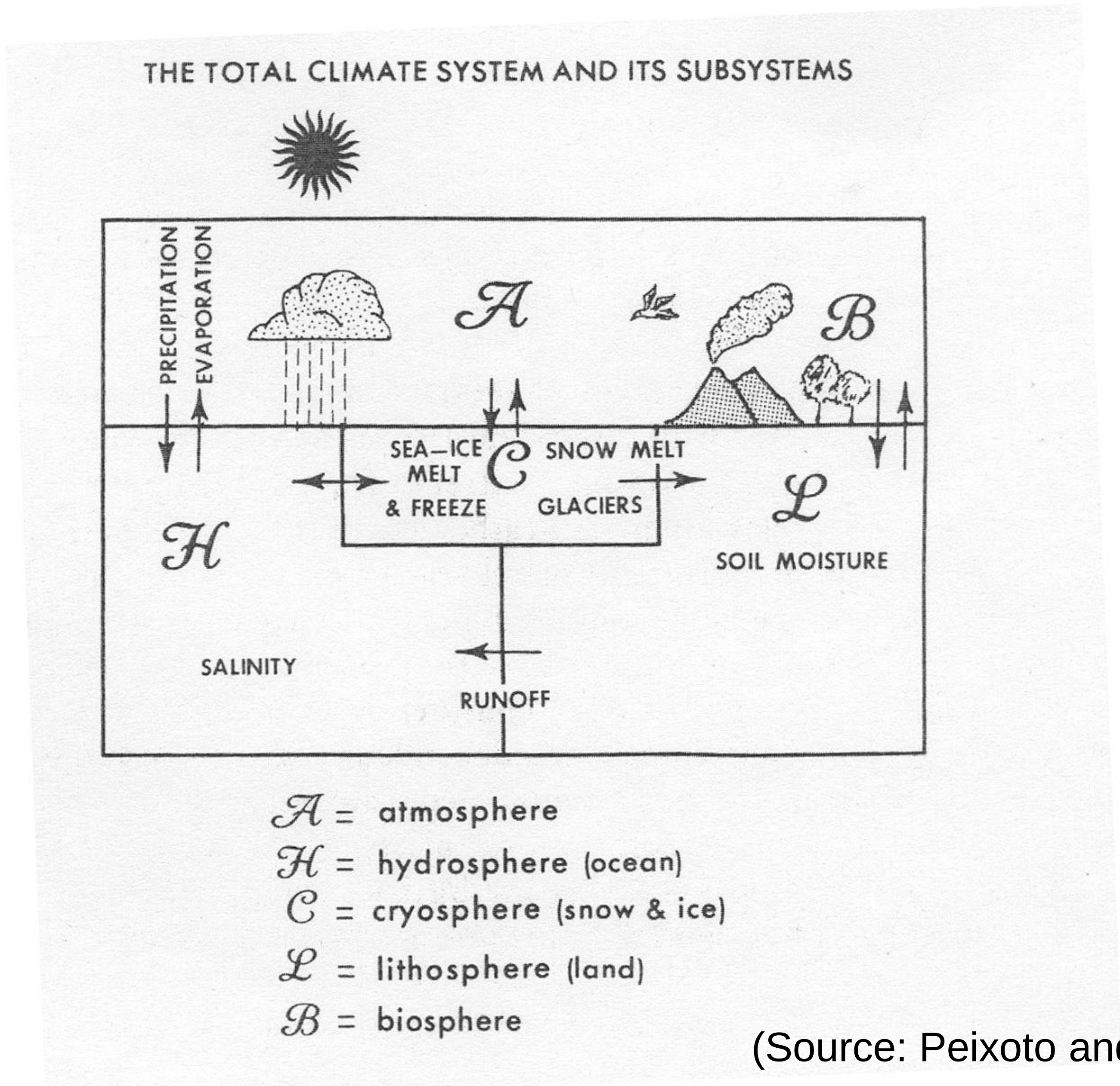
- **Bio-geophysical interaction**: albedo, evaporation, roughness
- **Bio-geochemical** interaction:
  - photosynthesis and respiration of carbon
  - Impact on $CH_4$ emissions
- **Time scales**:
  - physiology (reaction of the stomata): minutes
  - succession: 30 – 150 years,
  - migration: 300 – 1500 years

(Courtesy: U. Cubasch)

# *B*: biosphere (marine)

- carbon pumpe (time scales as in the terrestrial environment)
- $CO_2$- sink / source

(Courtesy: U. Cubasch)




(Source: Peixoto and Oort 1992)

# *P*: pedosphere (outermost layer of the Earth composed of soils)

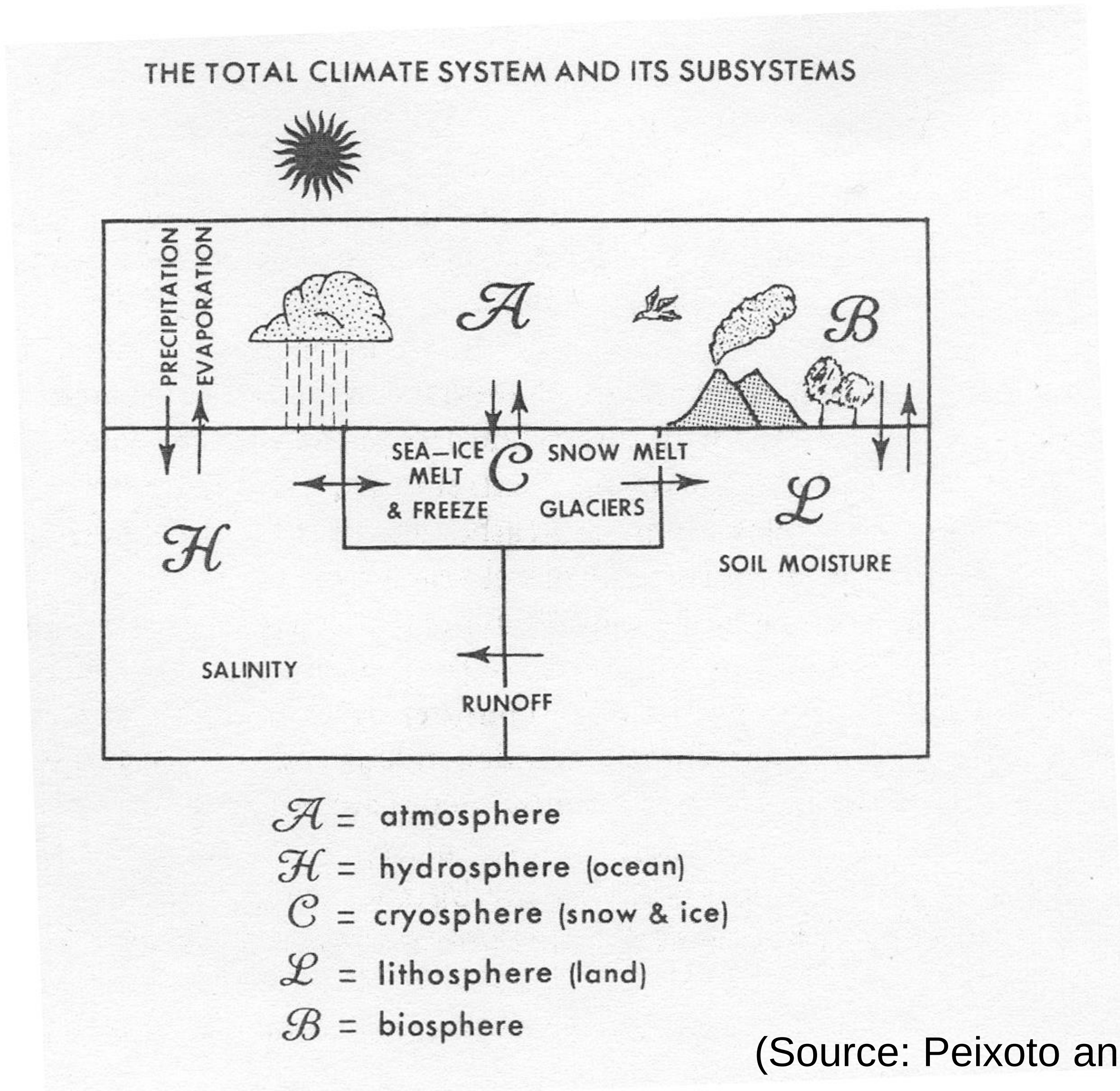
- Time scales of heat and water storage depend on the layer depth:
  - daily cycle: about 10-30 cm
  - annual cycle: few meters

(Courtesy: U. Cubasch)

# *L*: lithosphere (crust and the upper Earth mantle)

- Important impact factors: orography, biogeochemistry (vulkanoes)
- Time scales: $10^7$... years
  - formation of the Himalayas: $10^6$ years
  - Formation of the Alps: $10^6$ years
  - continental drift: $10^8$ years

(Courtesy: U. Cubasch)




(Source: Peixoto and Oort 1992)

Radiation balance (zero order model)

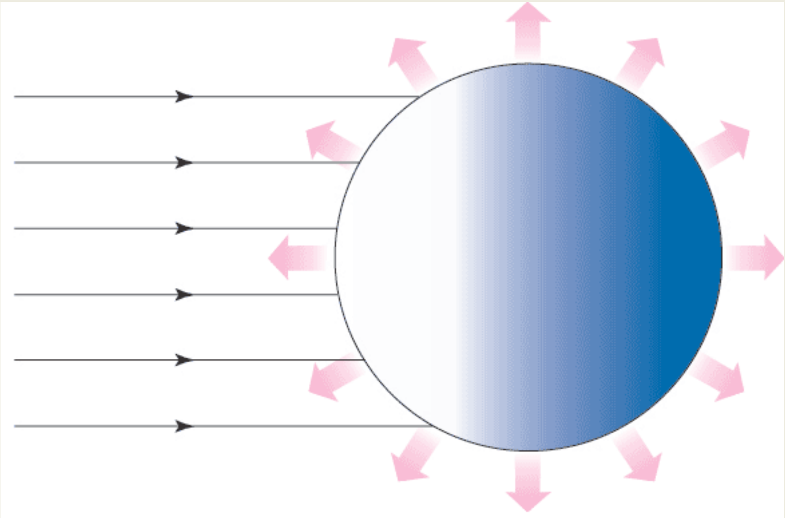
$$\gamma_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal}$$

$\gamma_{surf} =$ heat capacity $[J/m^2/K]$
$T_{surf} =$ surface temperature $[K]$
$F_{solar} + F_{thermal} =$ forcing terms $[W/m^2]$

(Source: D. Dommenget)

# A very simple climate model

- Assume balance between outgoing and incoming radiation on long term basis



$$F_E = \sigma T_E^4 = \frac{(1-A)\,S_0}{4} = 239.4\ \mathrm{W\ m^{-2}}$$

$$T_E = \sqrt[4]{\frac{F}{\sigma}} = 255\ \mathrm{K}$$

solar constant ($S_o$) 1368 W $m^{-2}$
planetary albedo (*A*) 30%
Stefan Boltzmann constant
$\sigma = 5.67 \times 10^{-8}$ W $m^{-2}$ $K^{-4}$
$T_E$ radiation temperature

(Courtesy: E. Kjellström)

# Reflection

- Incoming radiation may be reflected by clouds, particles or by the ground
- The albedo (A) is the ratio between reflected and incoming radiation
- Cloud albedo varies (50-90%)
- Global average ca 30% (including clouds)

| **Properties of the ground** | **Albedo (%)** |
|---|---|
| Snow | 75-95 |
| Old snow | 50-70 |
| Ice | 30-40 |
| Sand | 20-30 |
| Grass | 15-20 |
| Forest | 5-20 |
| Water | 3-10 |
| Water (Sun close to horizon) | 10-100 |

(Courtesy: E. Kjellström)

# Radiation balance of various planets

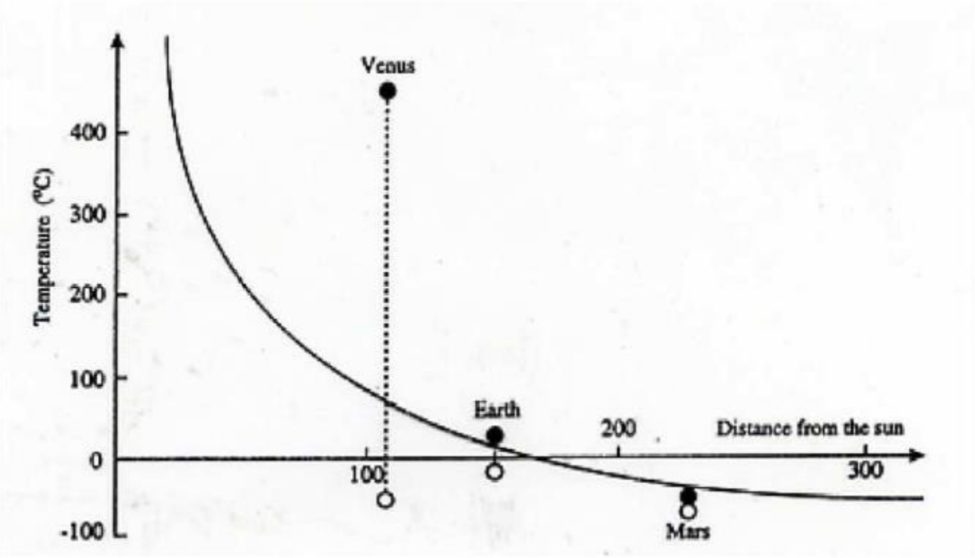
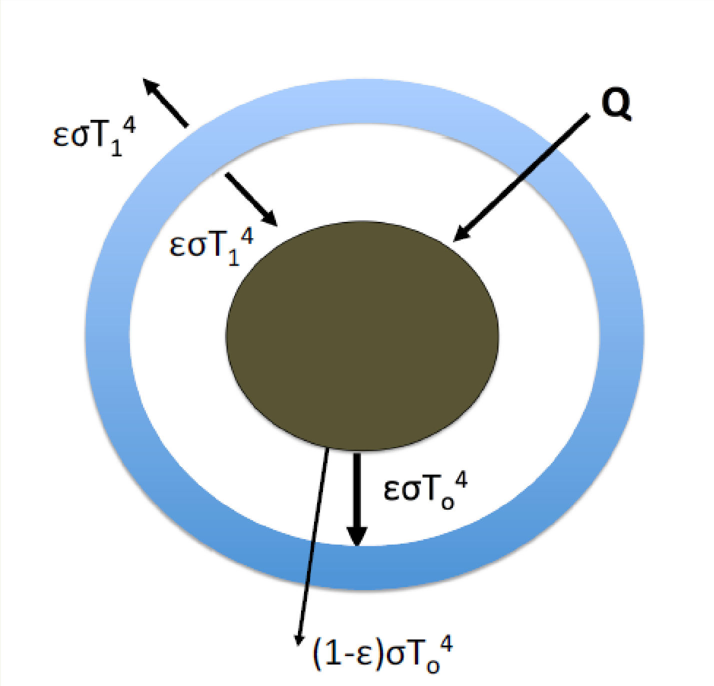



Figure 2.5: Distance from the Sun versus radiation temperature of a black body absorbing the incoming sun light (solid line). The black filled circles mark the observed $T_{surf}$ of Venus, Earth and Mars and the black unfilled circles mark the radiation temperature of the planets according to their abserved albedo.

(Source: D. Dommenget)

# Greenhouse effect illustrated by Greenhouse shield models




$$Q = \frac{1}{4}(1-\alpha_p)S_0$$

Earth surface: $Q - \sigma T_0^4 + \epsilon\sigma T_1^4 = 0$

atmosphere: $+\epsilon\sigma T_0^4 - 2\epsilon\sigma T_1^4 = 0$

space: $\sigma T_{rad}^4 = \epsilon\sigma T_1^4 + (1-\epsilon)\sigma T_0^4 = Q$

$$\Rightarrow T_{surf}^4 = \frac{1}{1-\frac{1}{2}\epsilon} T_{rad}^4$$

$$\Rightarrow \epsilon = 2\left(1 - \frac{T_{rad}^4}{T_{surf}^4}\right) = 0.77$$

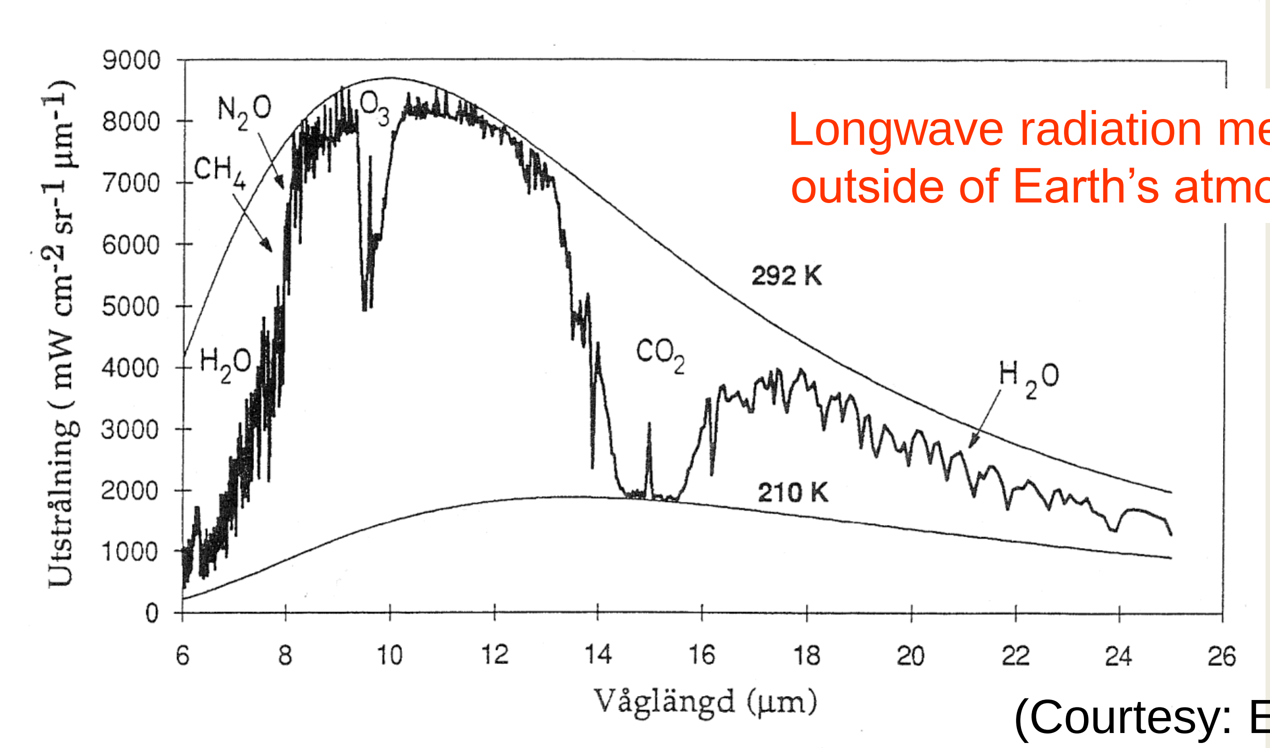
$T_0 = T_{surf}$
$T_1 = T_{atm}$
$T_1$=temperature of the atmosphere
ε<1 emissivity
Atmosphere absorbs the portion ε of the thermal radiation

(Source: D. Dommenget)

Exercise: prove and calculate $T_{surf}$, $T_{atm}$

# Longwave radiation

- Emitted radiation at the Earth's surface 4-100μm (maximum at around 10μm)
- Absorption in the atmosphere in wavelength bands




Longwave radiation measured outside of Earth's atmosphere

(Courtesy: E. Kjellström)

# Gaseous constituents

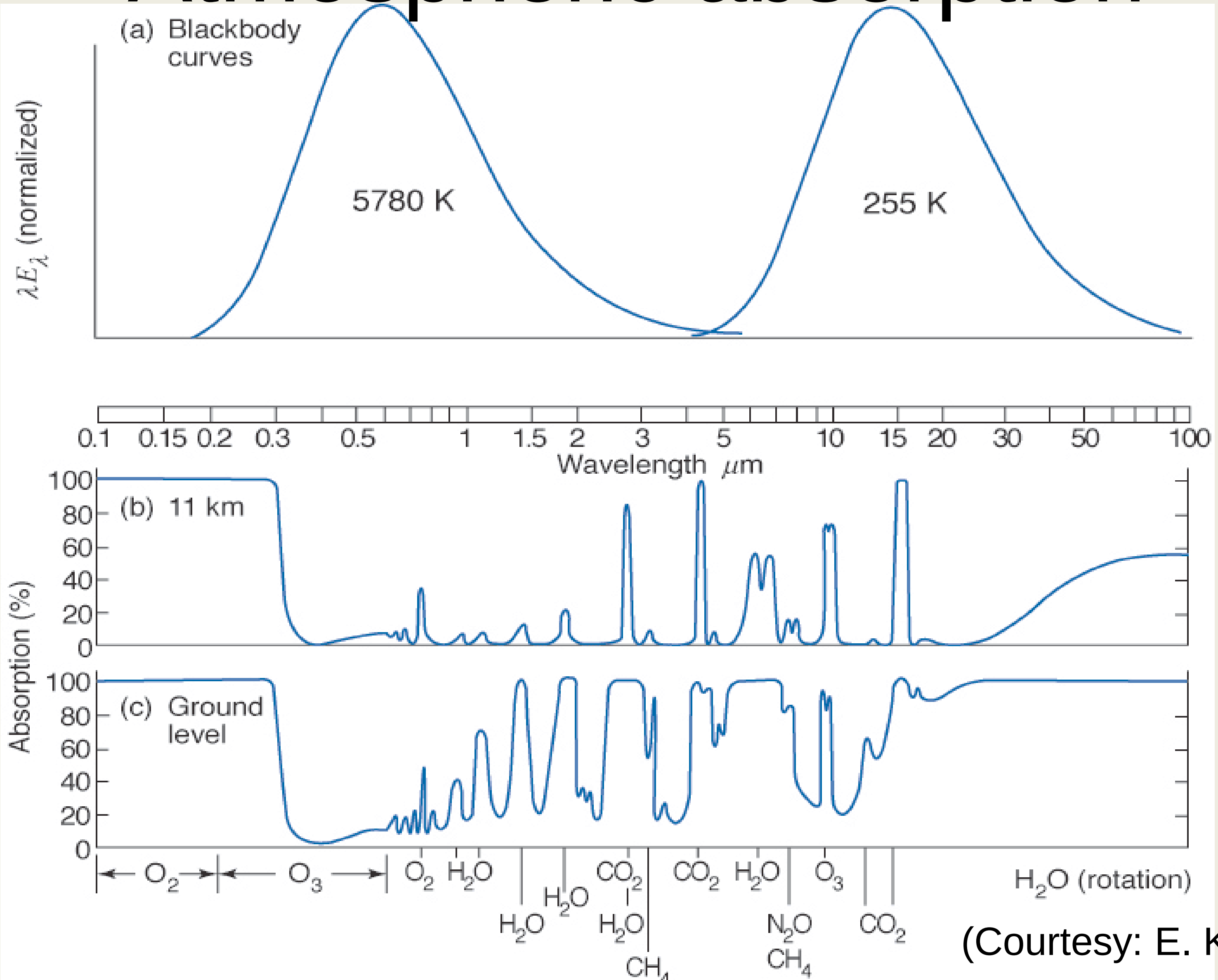
| Constituent | Mol. Wt. | Conc. by vol. |
| --- | --- | --- |
| Nitrogen ($N_2$) | 28.013 | 0.7808 |
| Oxygen ($O_2$) | 32.000 | 0.2095 |
| Argon (Ar) | 39.95 | 0.0093 |
| *Carbon dioxide ($CO_2$)* | *44.01* | *387 ppmv (2009)* |
| Neon (Ne) | 20.18 | 18 |
| Helium (He) | 4.00 | 5 |
| *Methane ($CH_4$)* | *16.* | *1.78 "* |
| Hydrogen ($H_2$) | 2.02 | 0.5 " |
| *Nitrous oxide ($N_2O$)* | *56.03* | *0.3 "* |
| *Ozone ($O_3$)* | *48.00* | *0-0.1 “* |

*In addition*

| | | |
| --- | --- | --- |
| *Water vapor ($H_2O$)* | *18.02* | *variable* |

(Courtesy: E. Kjellström)

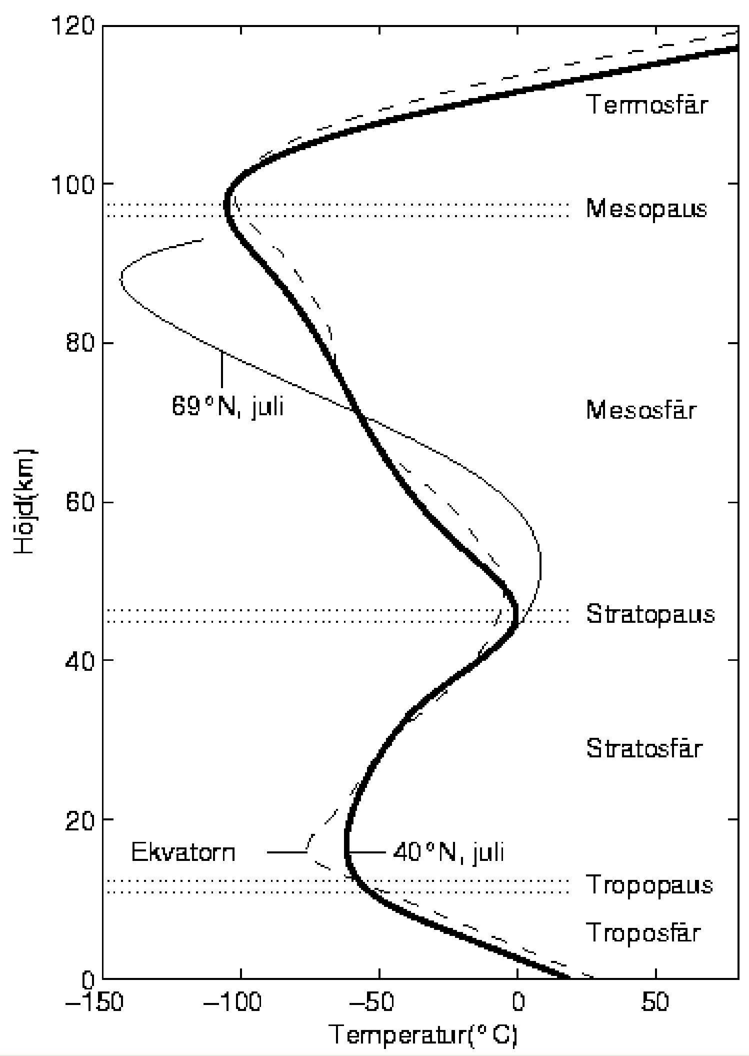
# Atmospheric absorption




(Courtesy: E. Kjellström)

# Vertical distribution of temperature

- Troposphere, Stratosphere, Mesosphere and Thermosphere
- Tropopause, Stratopause, Mesopause
- Most water vapour and thereby related clouds and weather exists in the troposphere
- Ionosphere (upper part of the mesosphere and the thermosphere)




(Courtesy: E. Kjellström)

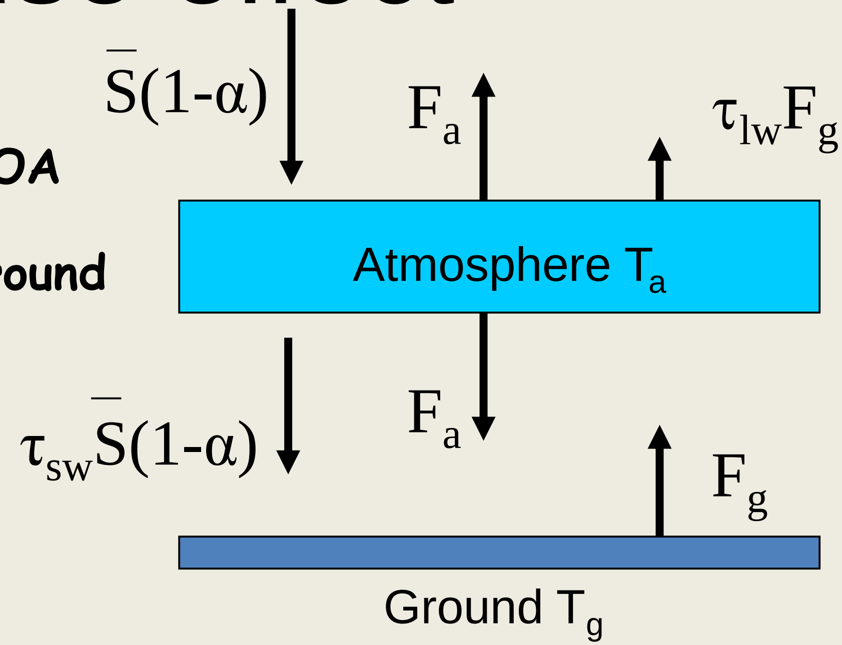
# The greenhouse effect

- Most incoming solar radiation (shortwave) passes through the atmosphere
- Outgoing terrestrial radiation (longwave) is absorbed and reemitted in the atmosphere
- Reemission takes place at higher levels where temperatures are lower
- This implies that less energy escapes to space than what would be the case without an atmosphere
- The net effect is a warming of the surface

(Courtesy: E. Kjellström)

# A simple model including the greenhouse effect

$$\begin{cases} \bar{S}(1-\alpha) = F_a + \tau_{lw} F_g & \textbf{At the TOA} \\ F_g = F_a + \tau_{sw} \bar{S}(1-\alpha) & \textbf{At the ground} \end{cases}$$




eliminate $F_a$

$$F_g = \sigma T_g^4 = \bar{S}(1-\alpha)\frac{1+\tau_{sw}}{1+\tau_{lw}}$$

$\bar{S} = 342\ \mathrm{Wm}^{-2}$, $\alpha = 0.31$, $\tau_{sw} = 0.71,\ \tau_{lw} = 0.10$ transmissivity

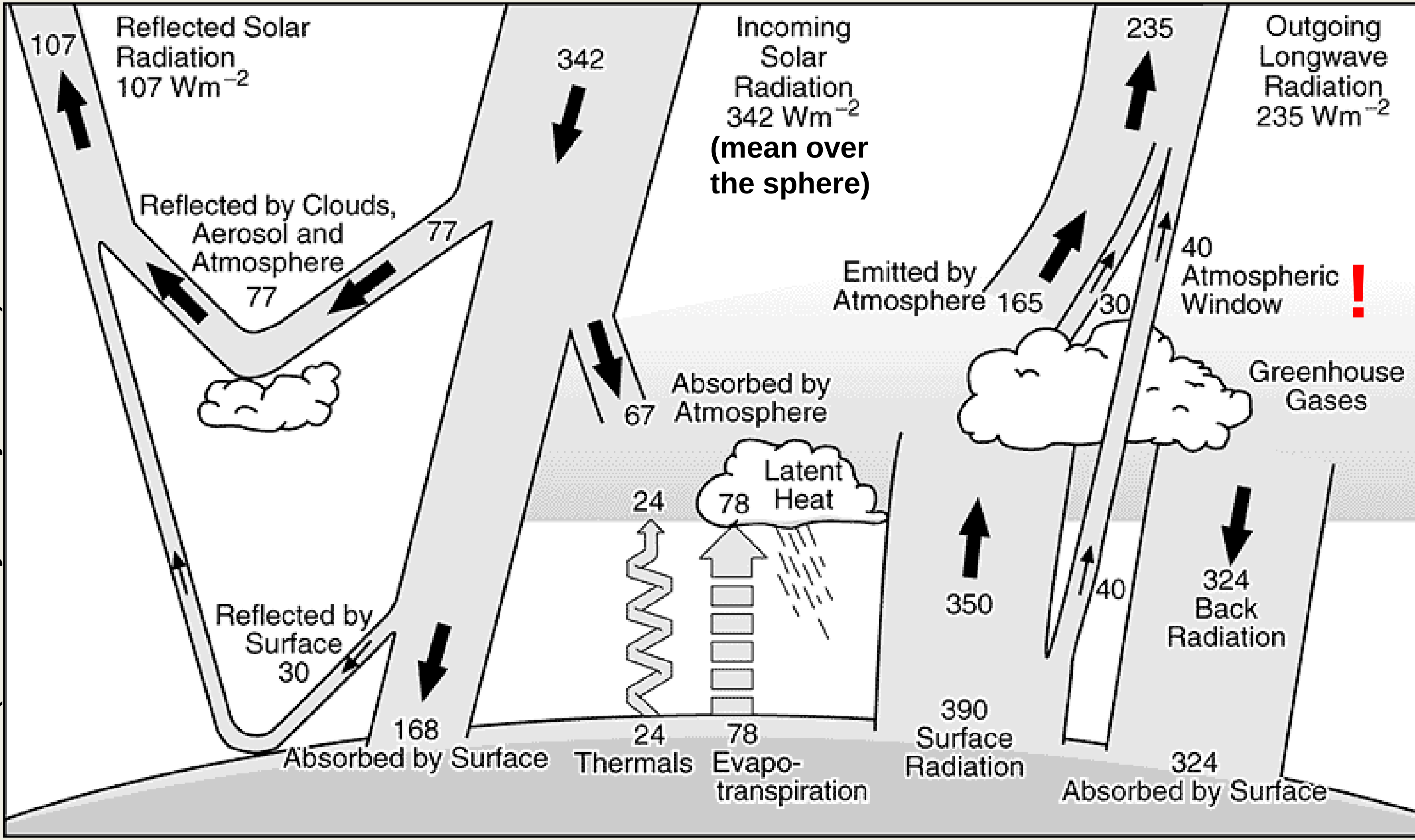
$\Rightarrow T_g \approx 284\mathrm{K} = 11^\circ\mathrm{C}$

(Courtesy: E. Kjellström)

# Global energy balance

Albedo=107/342=31%

342-107=235!!



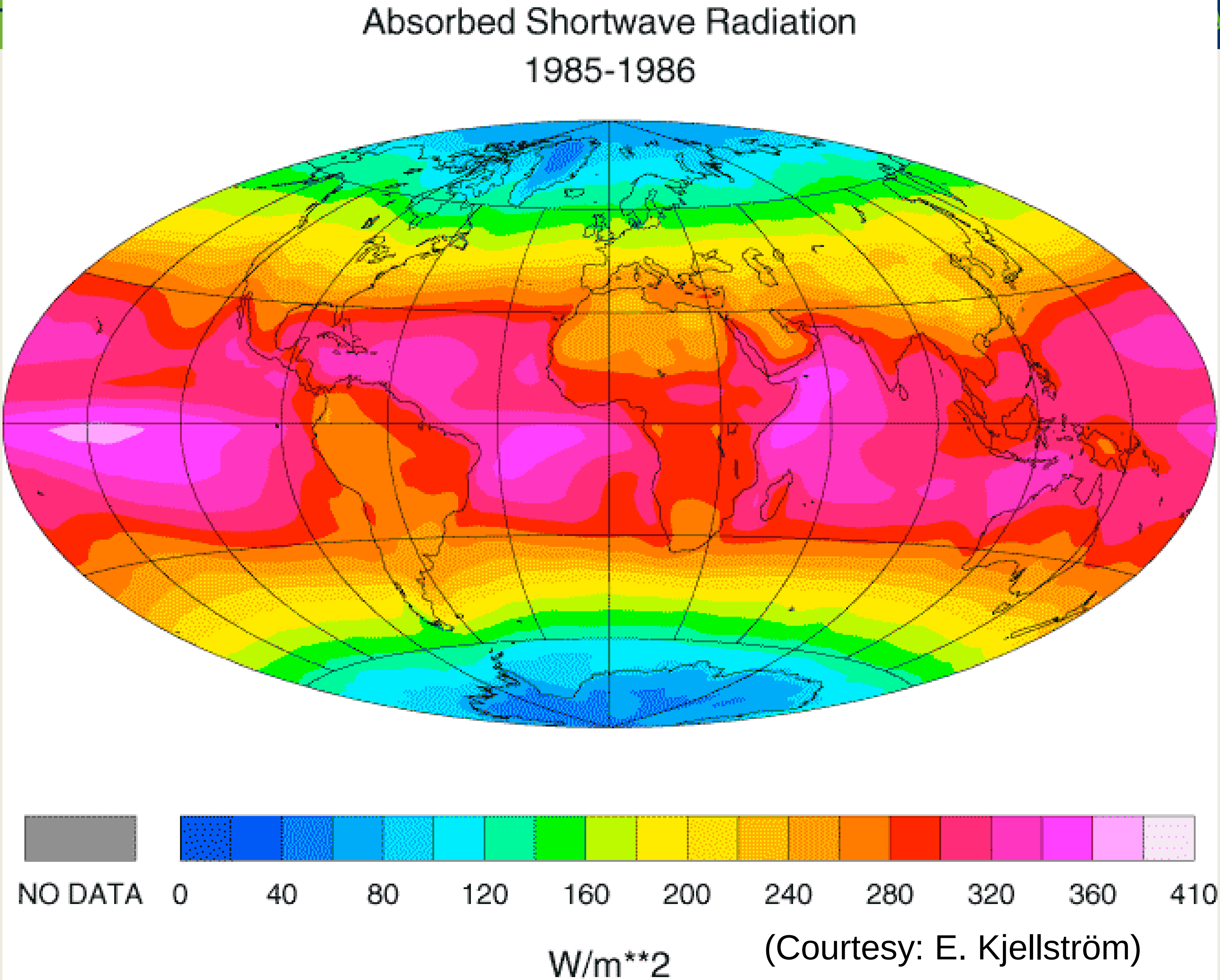

(Courtesy: E. Kjellström)

Absorberat i mark/hav=168/342=49%

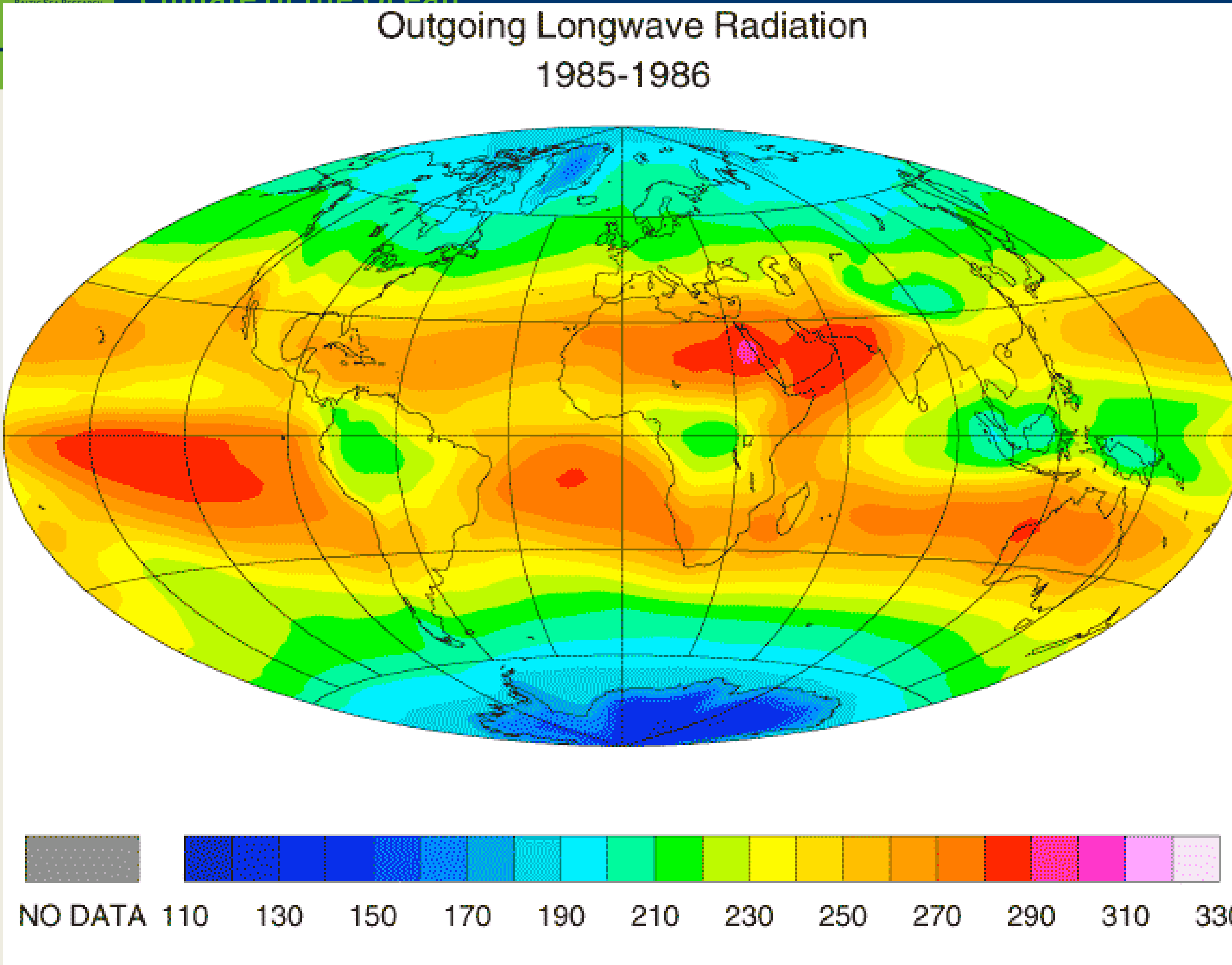
168-24-78-390+324=0!!

Atmosfärens transmisitivitet (sw)=168/(342-107)=0.71

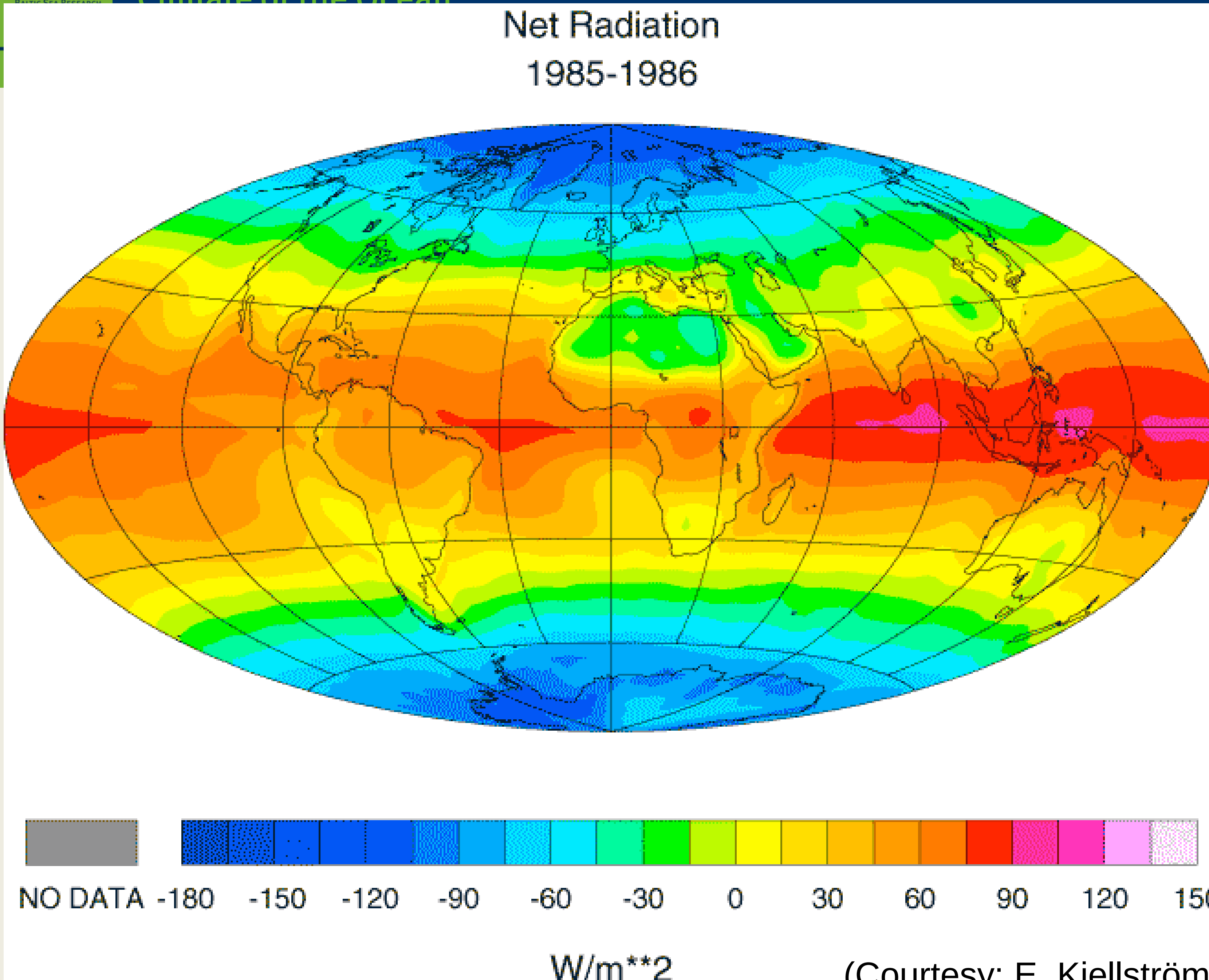
Atmospheric transmissivity (lw)=40/390=0.10




(Courtesy: E. Kjellström)



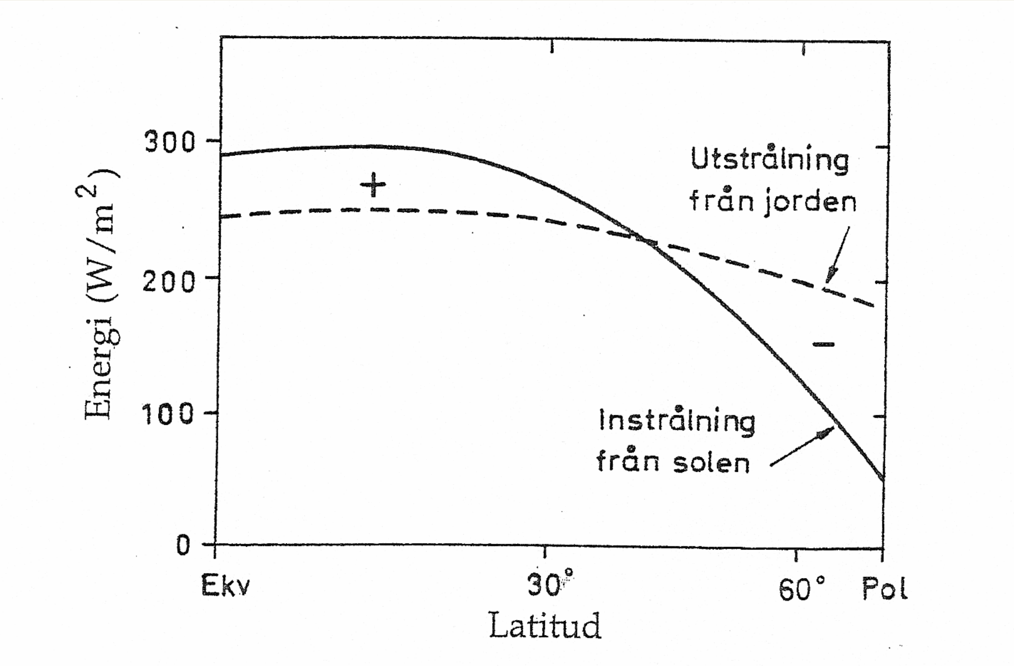

(Courtesy: E. Kjellström)




(Courtesy: E. Kjellström)

# Radiation balance of the Earth

- Net energy gain (loss) at low (high) latitudes …




- … leads to heat transport in the atmosphere and oceans

(Courtesy: E. Kjellström)

# Greenhouse model with ice-albedo feedback (Budyko, 1969)

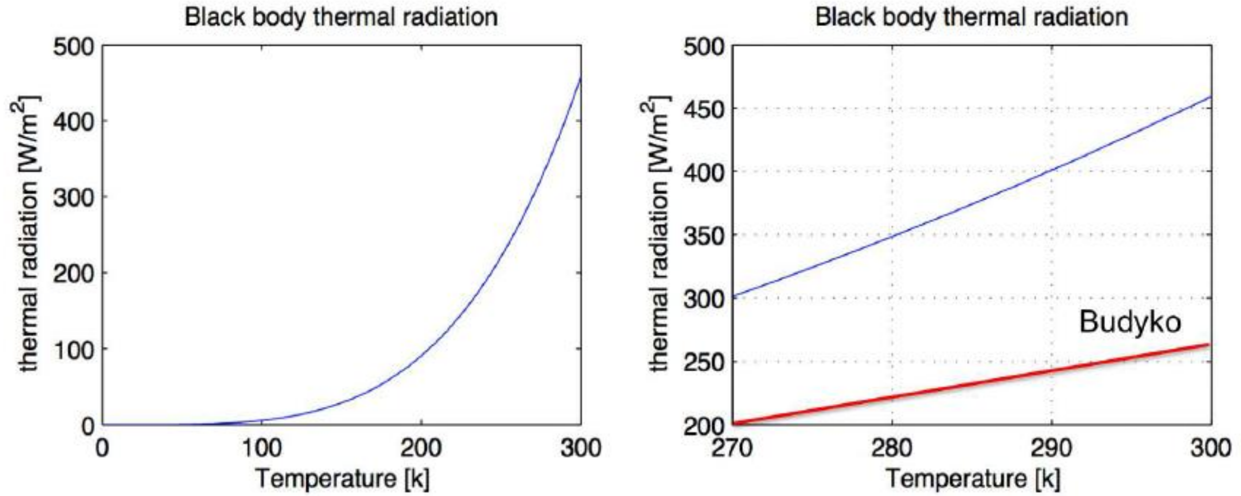
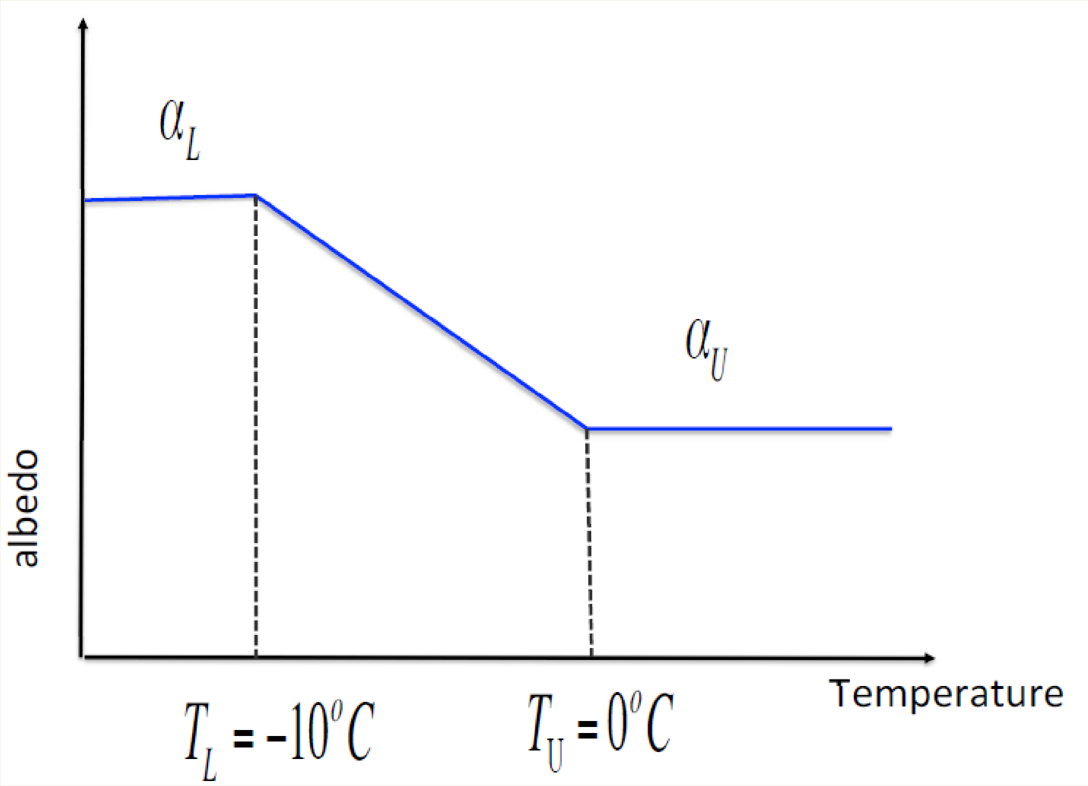



Figure 2.10: Black body thermal radiation: left: Black body thermal radiation for a wide range of temperatures. right: Black body thermal radiation (blue line) for a range of temperature closer to the earth climate in comparison to the Budyko linear model (red line).

$$-F_{thermal} = A + B \cdot (T_{surf} - 273.15)$$

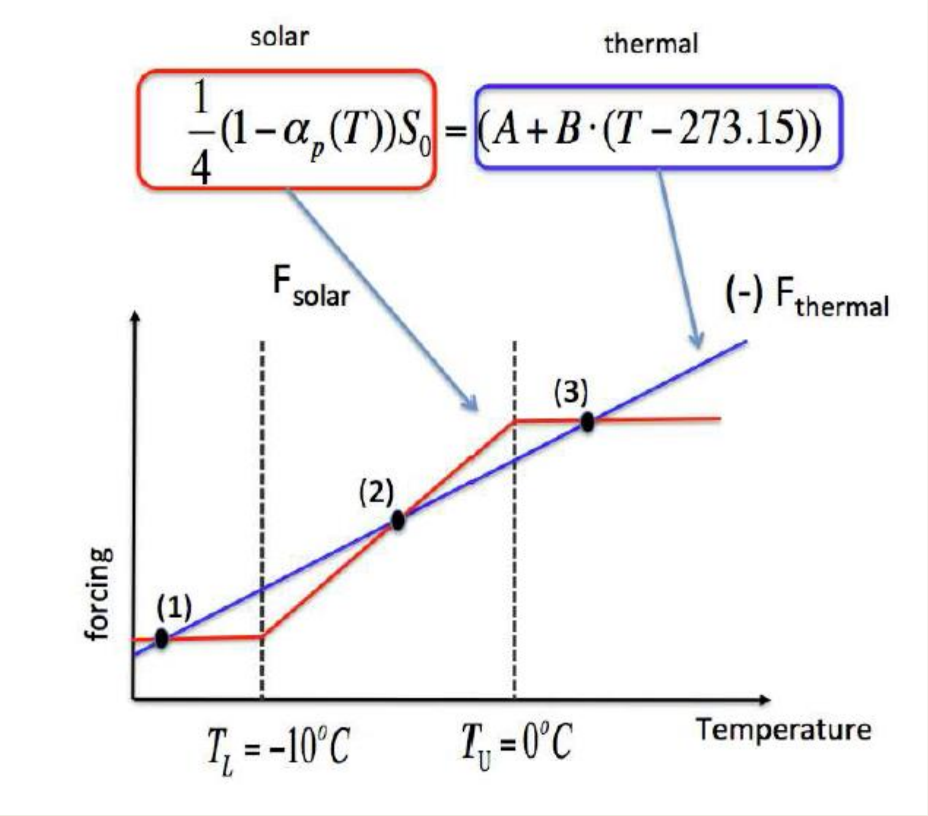
(Source: D. Dommenget)




$$\alpha_L = 0.62 \quad \alpha_U = 0.3$$

$$\gamma_{surf}\frac{dT_{surf}}{dt} = ((1-\alpha_p(T_{surf}))\cdot Q - (A + B\cdot(T_{surf} - 273.15))$$

(Source: D. Dommenget)



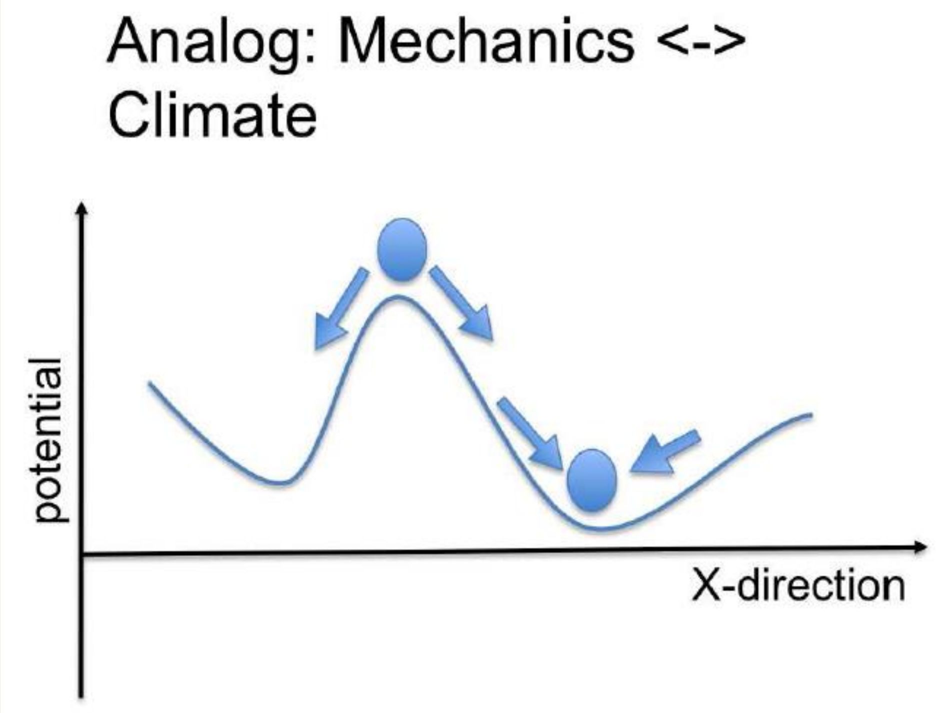

| | |
|---|---|
| (1) Totally ice covered earth | $T^{(1)}_{surf} = \frac{(1-\alpha_L)Q-A}{B} = -35.2^oC$ |
| (2) Partially ice covered earth (present day) | $T^{(2)}_{surf} = \frac{Q(1-\alpha_L)\Delta T - A\Delta T + QT_L\Delta\alpha}{B\Delta T + Q\Delta\alpha} = -4.0^oC$ |
| (3) Ice free world | $T^{(3)}_{surf} = \frac{(1-\alpha_U)Q-A}{b} = +17/0^oC$ |

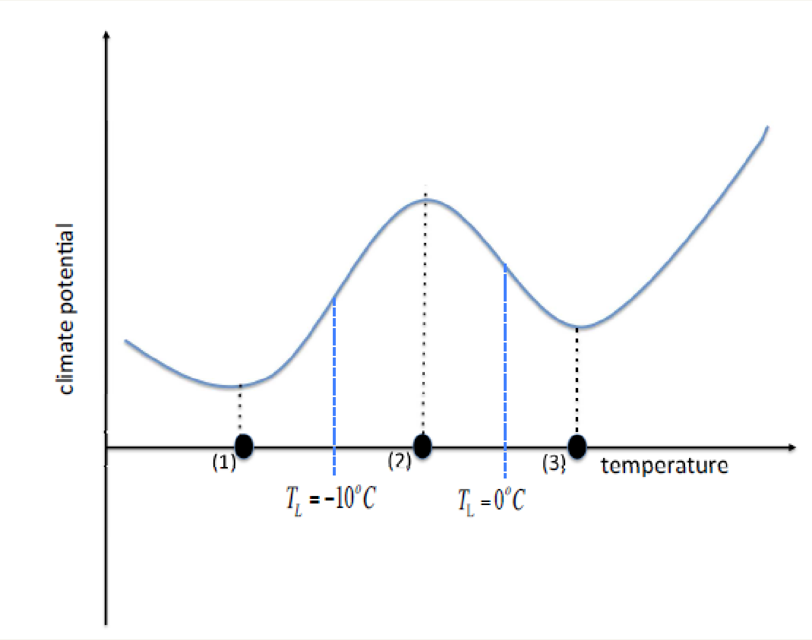
(Source: D. Dommenget)

# Climate potential

$$P(T_{surf}) = -\int F_{net} \quad dT_{surf}$$

$$P_{Budyko}(T_{surf}) = -\int (1-\alpha_p(T_{surf}))Q - (A + BT'_{surf}) \quad dT_{surf}$$




(Source: D. Dommenget)

# Climate stability

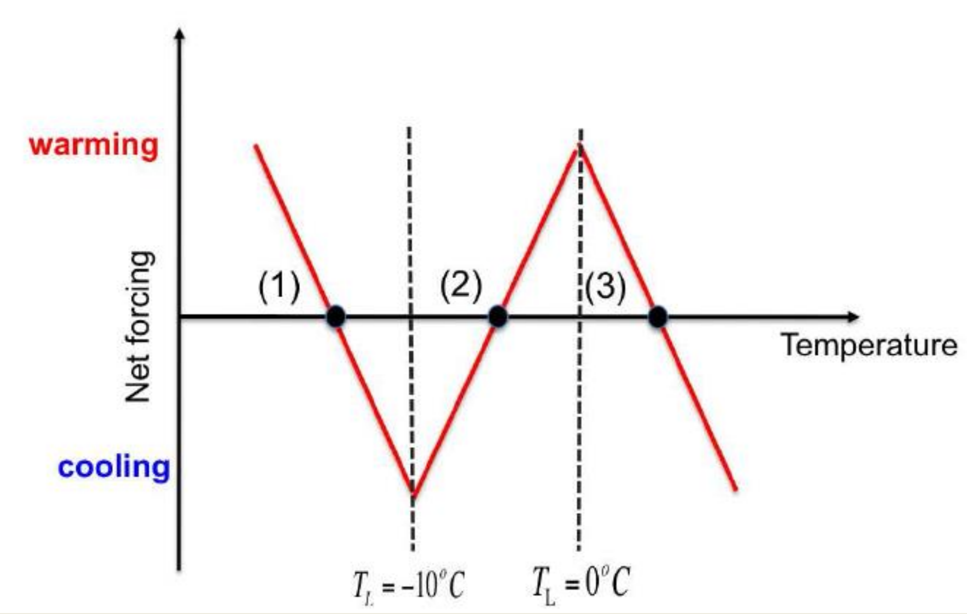
For stable equilibrium:

$$\frac{dF_{net}}{dT}(T^{eq}_{surf}) < 0$$

And for unstable equilibrium:

$$\frac{dF_{net}}{dT}(T^{eq}_{surf}) > 0$$

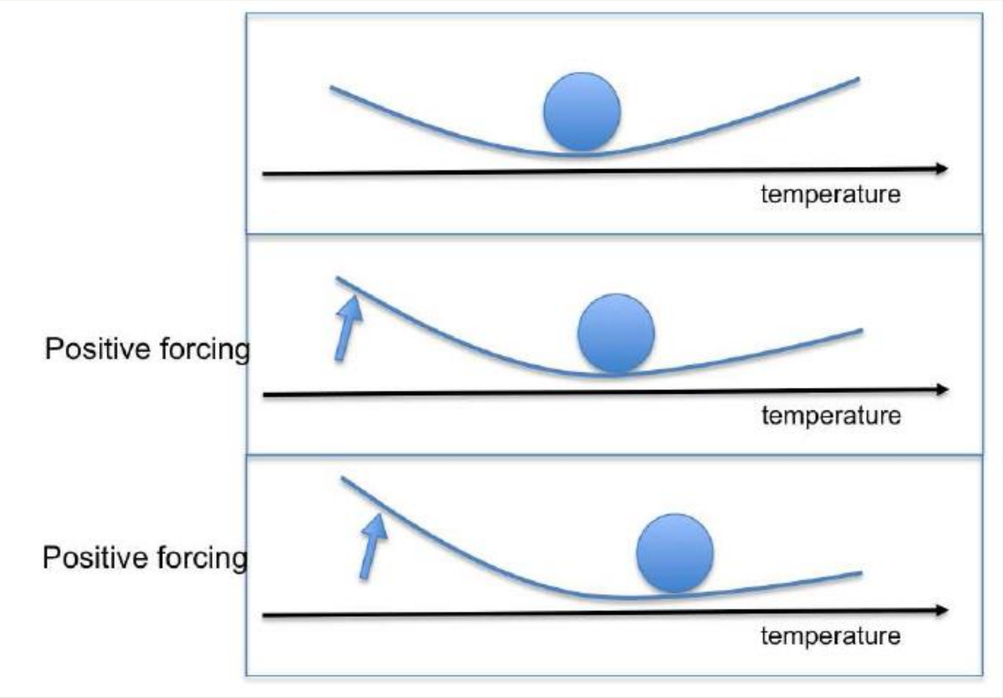
$$F_{net} = ((1 - \alpha_p(T_{surf})) \cdot Q - (A + B \cdot (T_{surf} - 273.15))$$

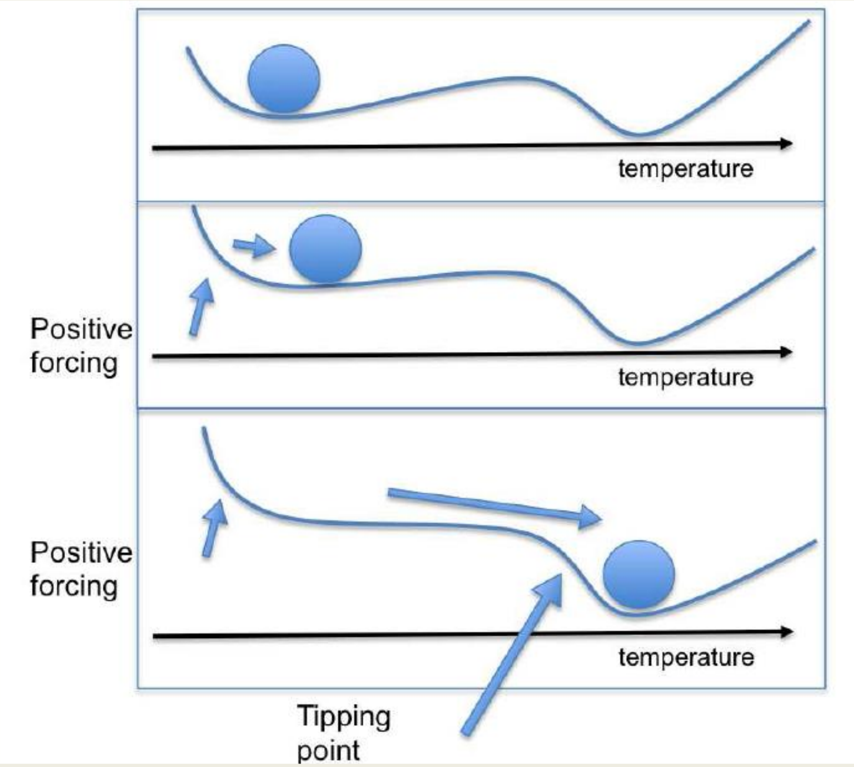



| | | |
|---|---|---|
| (1) | Totally ice covered earth | → stable |
| (2) | Partially ice covered earth (present day) | → unstable |
| (3) | Ice free world | → stable |

(Source: D. Dommenget)

# Tipping points



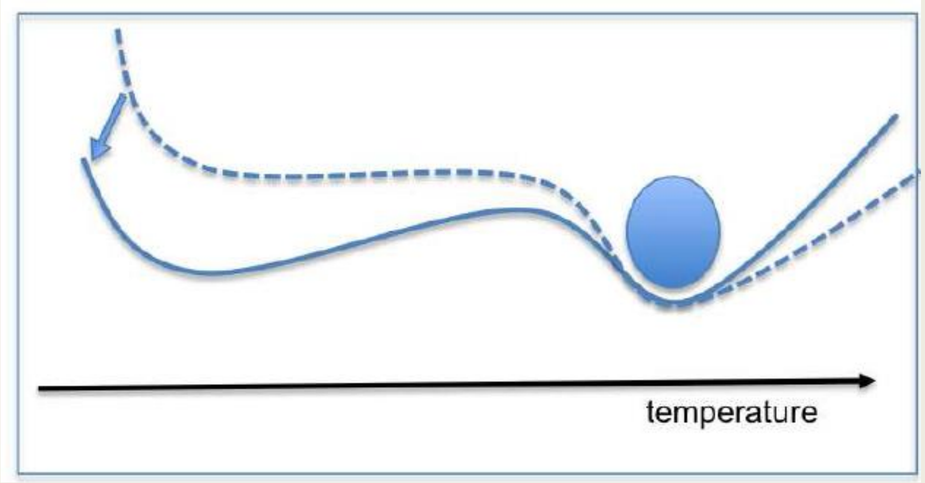




Zero order model (no feedbacks)

Budyko model with the ice-albedo feedback

(Source: D. Dommenget)

# Tipping point: climate change is irreversible




(Source: D. Dommenget)

# Climate sensitivity

$$\lambda := \frac{\Delta T}{\Delta Q}$$

Temperature change (or any other climate variable of interest) per change in forcing

$$\Rightarrow \Delta T = \lambda \cdot \Delta Q$$

Example 1: IPCC (2007)

$$\rightarrow \lambda = \frac{\Delta T}{\Delta Q} = \frac{3.0K}{6W/m^2} = 0.5K/\left(\frac{W}{m^2}\right)$$

Example 2: Zero order model

$$T = \left(\frac{1}{\sigma}\frac{(1-\alpha_p)}{4}S_0\right)^{\frac{1}{4}} = \left(\frac{Q}{\sigma}\right)^{\frac{1}{4}}$$

$$\lambda = \frac{dT}{dQ} = \frac{1}{\sigma}\frac{1}{4}\left(\frac{Q}{\sigma}\right)^{\frac{1}{4}-1} = \frac{1}{\sigma}\frac{1}{4}\frac{\left(\frac{Q}{\sigma}\right)^{\frac{1}{4}}}{\left(\frac{Q}{\sigma}\right)} = \frac{1}{4}\frac{\left(\frac{Q}{\sigma}\right)^{\frac{1}{4}}}{Q} = \frac{1}{4}\frac{T_{rad}}{Q} \approx \frac{1}{4}\frac{255K}{240W/m^2} = 0.27K/\left(\frac{W}{m^2}\right)$$

(Source: D. Dommenget)

# Climate sensitivity II

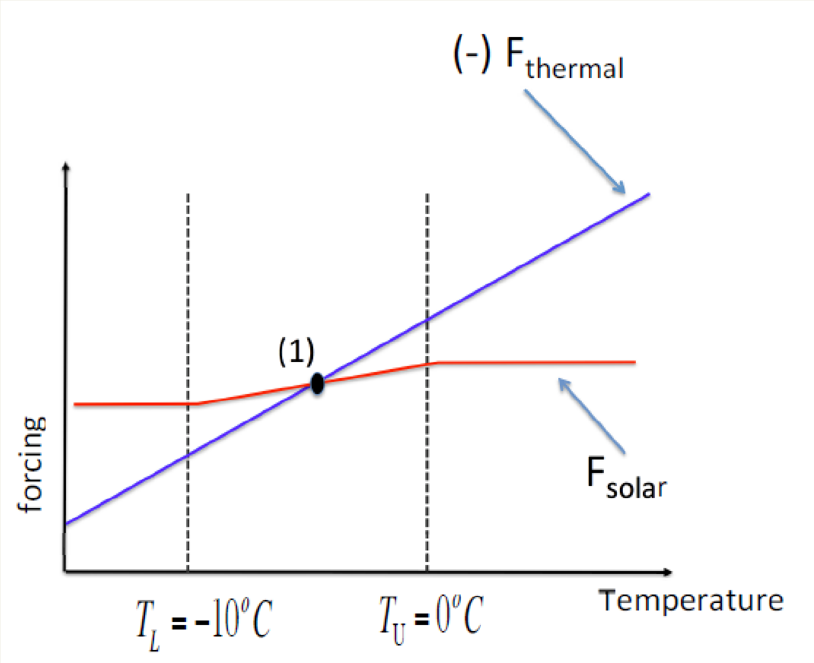
Example 3: Budyko model without ice-albedo feedback ($\alpha_P$=0.3)

$$((1-\alpha_p(T_{surf}))\cdot Q = A + B\cdot(T_{surf}-273.15)$$

$$\Rightarrow \lambda = \frac{(1-\alpha_p)}{B} = 0.33K/\frac{W}{m^2}$$

Example 4: Budyko model with ice-albedo feedback

$$\frac{\Delta\alpha_p}{\Delta T} = -0.003K^{-1}$$




$$\Rightarrow \lambda = 0.66K/\frac{W}{m^2}$$

larger sensitivity due to the positive feedback

(Source: D. Dommenget)

# Feedbacks

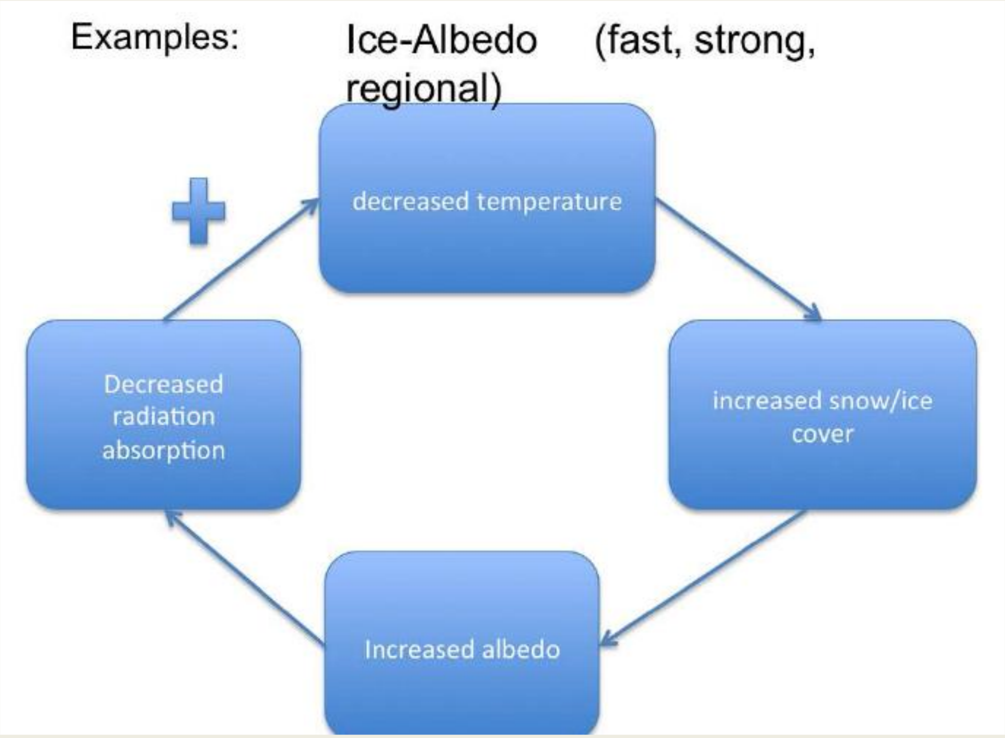
Definition: $$C_f := \frac{dF}{dT_{surf}}$$

Example: simple linear climate model $$\gamma \frac{dT}{dt} = C_f \cdot T + Q$$ Climate feedback parameter $C_f$

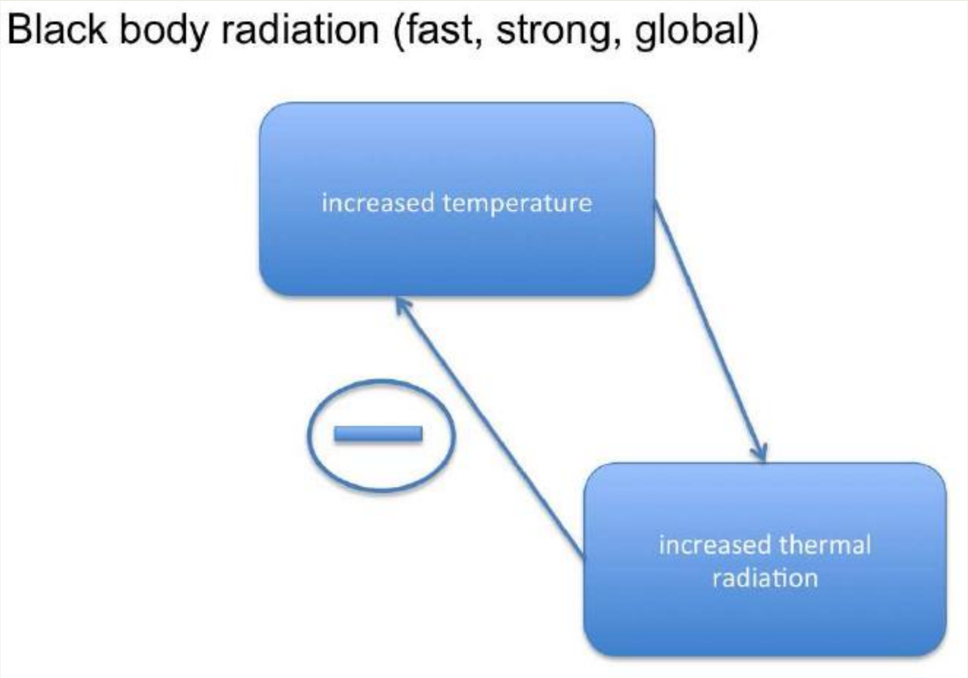
Equilibrium temperature: $$\Rightarrow T_{eq} = \frac{Q}{-Cf}$$

$$\lambda = \frac{dT}{dQ} = \frac{1}{-Cf}$$

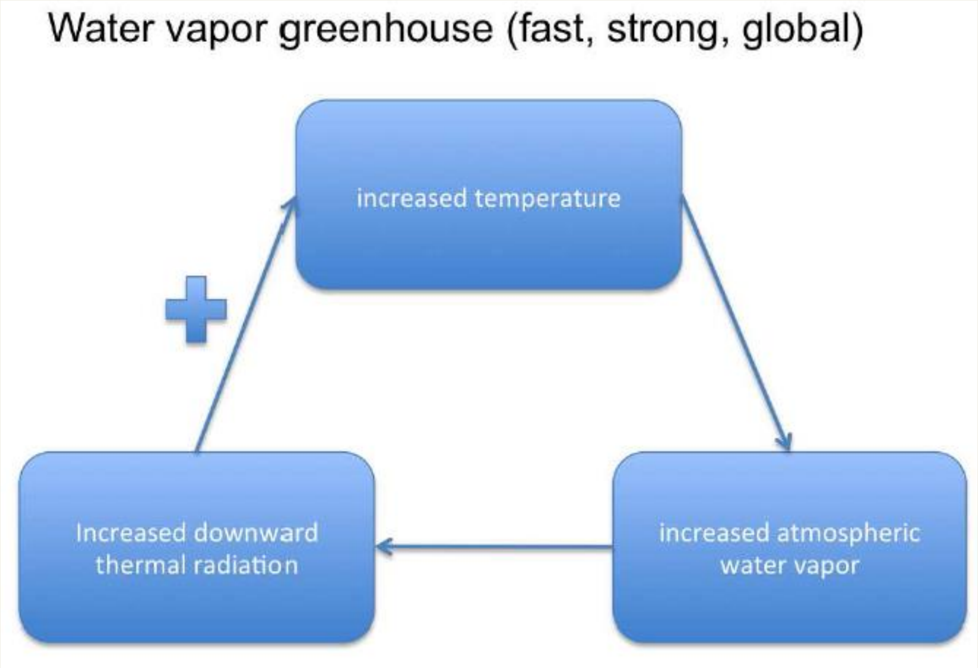
(Source: D. Dommenget)



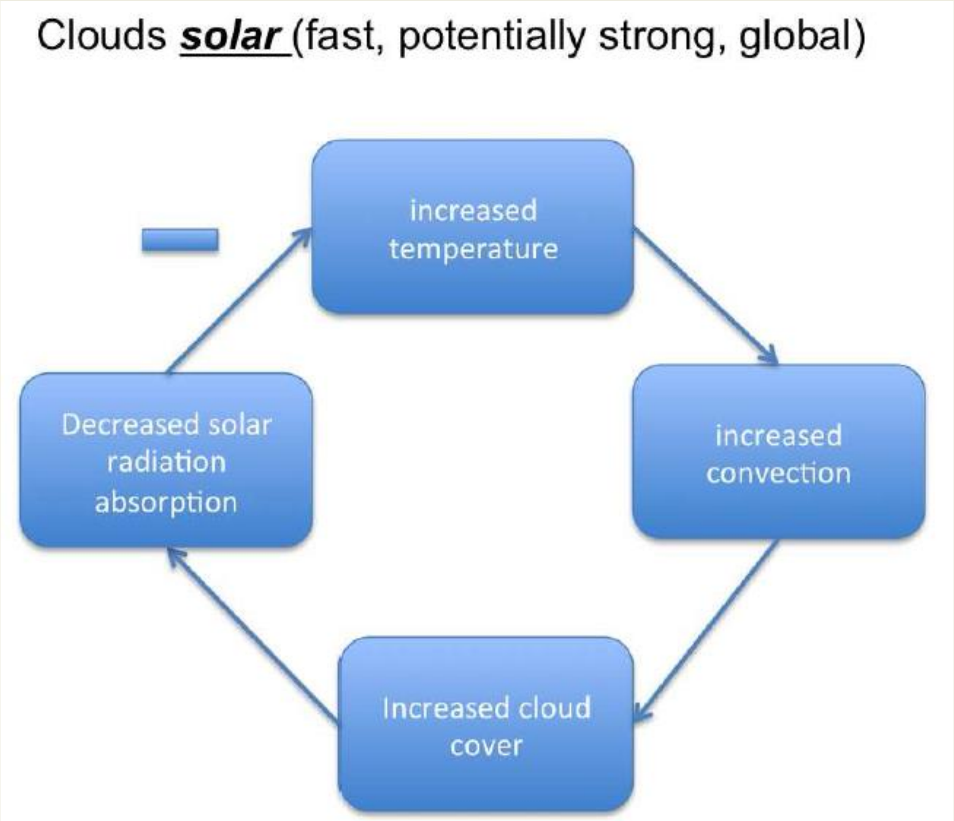

(Source: D. Dommenget)



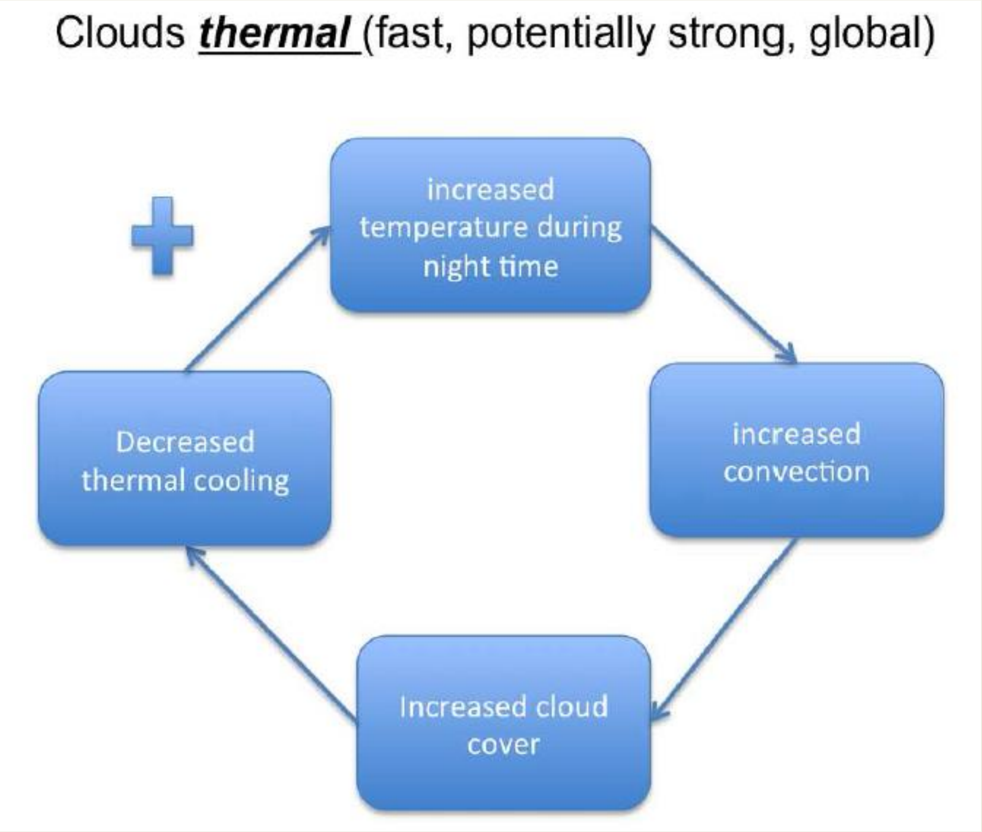

(Source: D. Dommenget)




(Source: D. Dommenget)




(Source: D. Dommenget)




(Source: D. Dommenget)

# Thank you very much for your attention!