Climate of the Baltic Sea Region

Introduction and fundamental processes of the climate system

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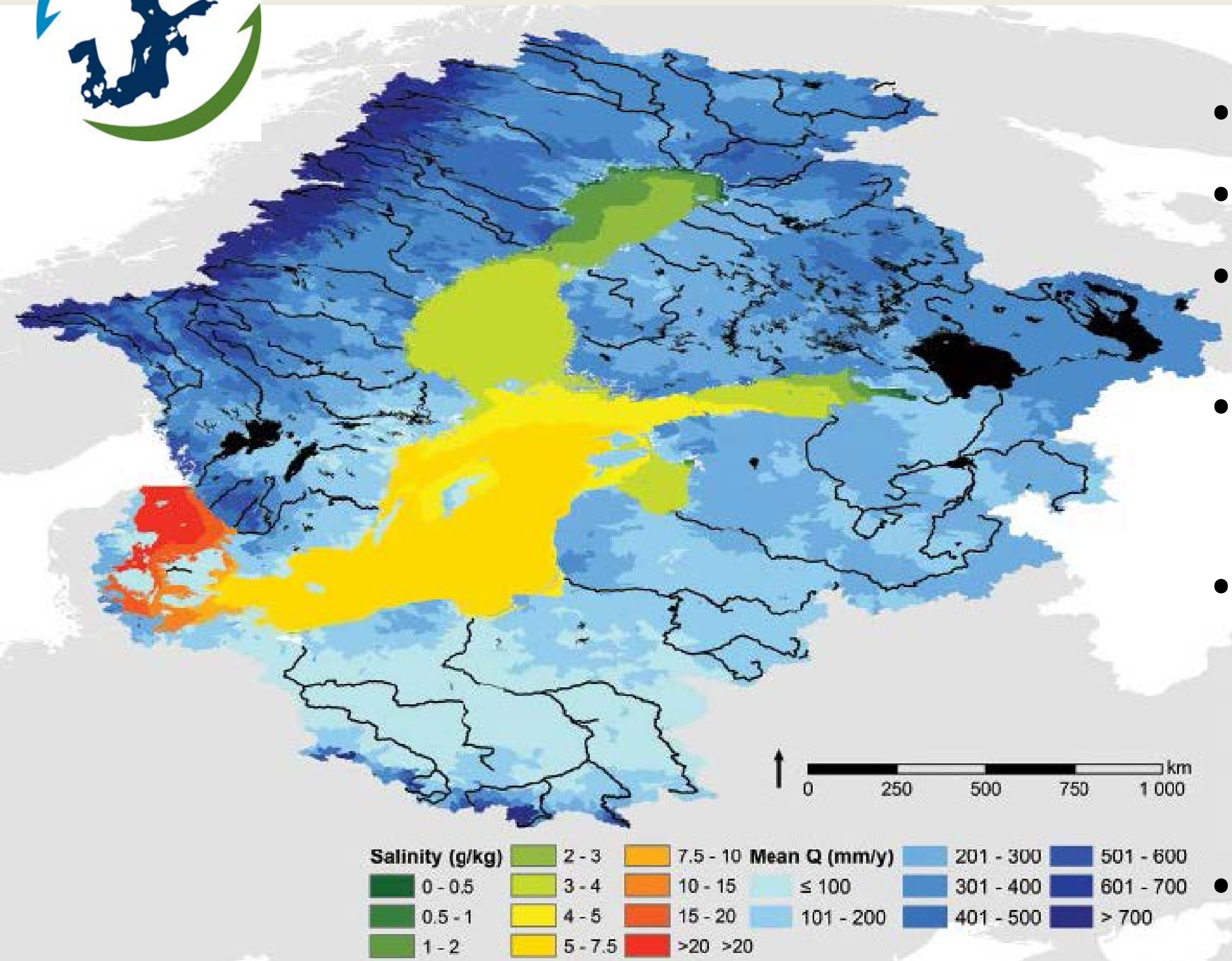
General information

- about the course: Climate of the Baltic Sea Region (part of the master in physics at Rostock University, winter term: Climate of the Ocean)
- Professor at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and Rostock University
- Baltic Earth www.baltic.earth

The Baltic Sea Region

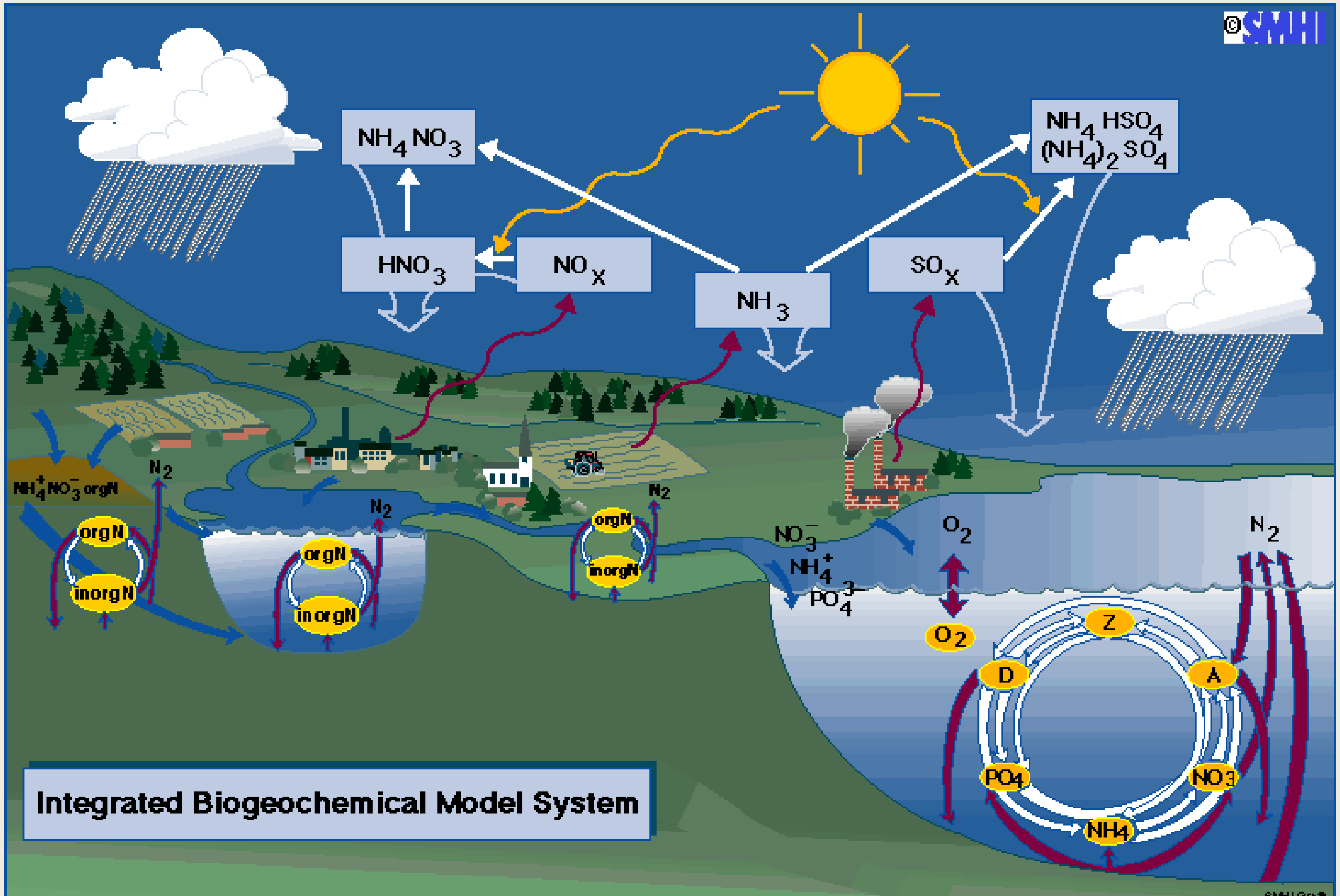


Meier et al. (2014, Eos)

- 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

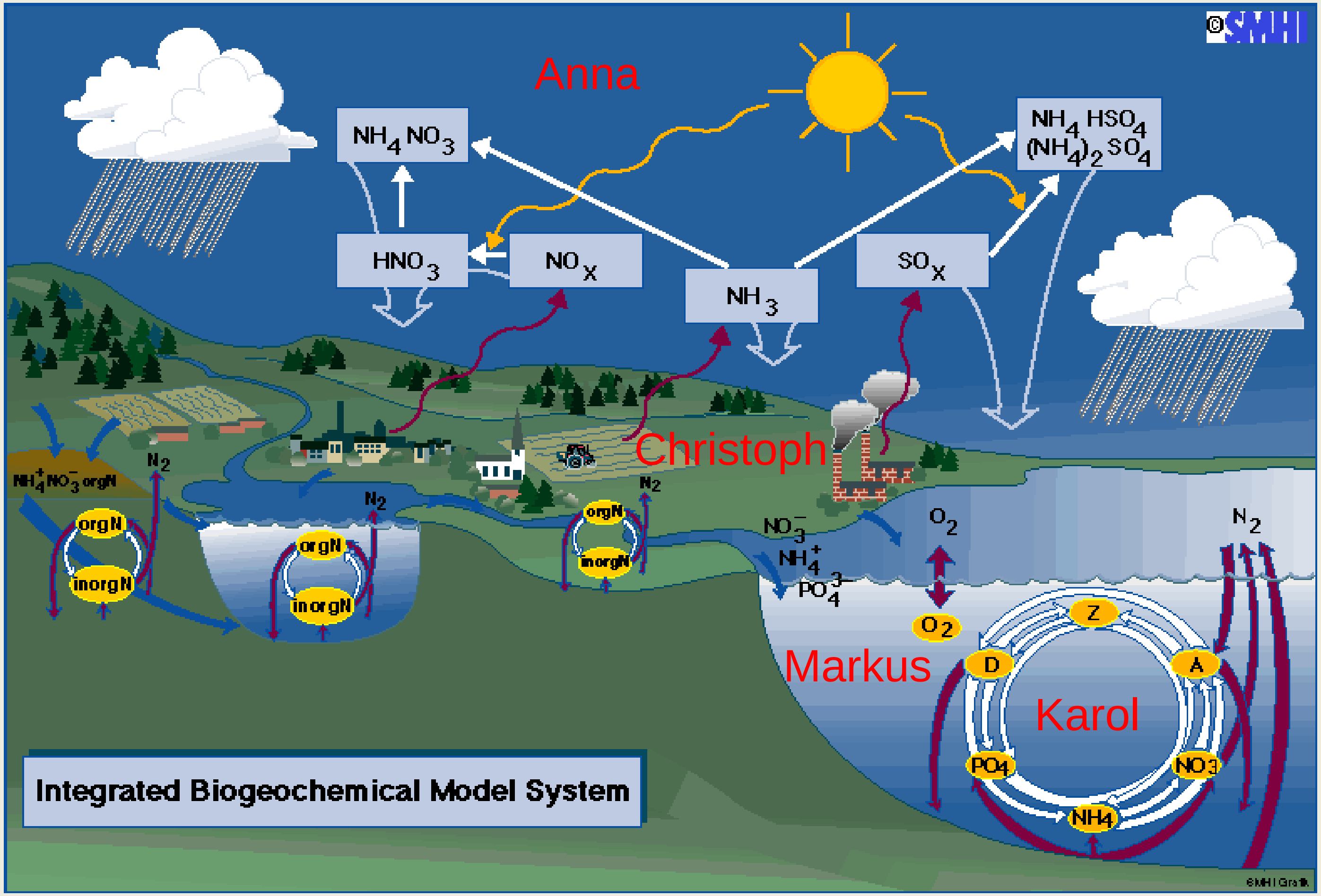
Earth System Science for the Baltic Sea Region



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

Earth System Science for the Baltic Sea Region

Baltic Earth
Earth System Science for the Baltic Sea Region
Marcus



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Vision of Baltic Earth

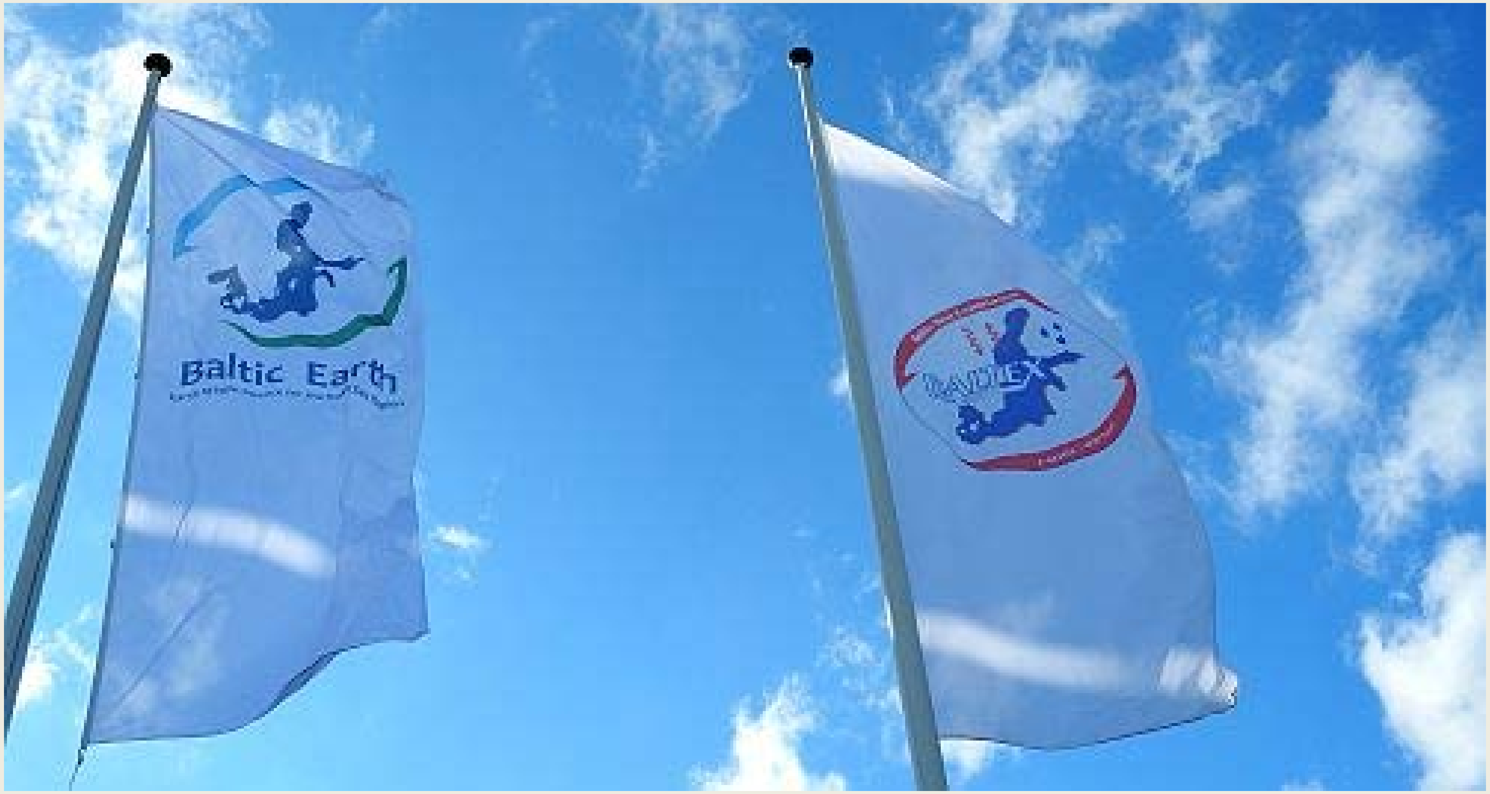
To achieve an improved Earth System understanding of the Baltic Sea region

- **Interdisciplinary** and **international** collaboration (conferences, workshops, etc.)
- **Holistic view** on the Earth system of the Baltic Sea region, encompassing processes in the **atmosphere**, on **land** and in the **sea** and also in the **anthroposphere**
- "**Service to society**" in the respect that **thematic assessments** provide an overview over knowledge gaps which need to be filled (e.g. by funded projects)
- **Education** (summer schools)
- Inherits the BALTEX network of scientists and infrastructure

Baltic Earth
Earth System Science for the Baltic Sea Region

Baltic Earth

http://www.baltic.earth/



Earth System Science for the Baltic Sea basin

Information about the course

- Rostock University (master in physics): 3 ECTS (21 lectures á 90 min, tutorials and exercises, 90 minutes examination)
- ECTS form back latest on 30 September 2018
- Diploma from Baltic Earth
- Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and Baltic Earth Secretariat (HZG) provided the funding
- reimbursement form (back latest on 30 September 2018, berit.recklebe@io-warnemuende.de)

- Tutorials and exercises (statistical analysis, run your own climate model, discussion about climate models, physical oceanography)
- Group work (four groups)
- Logistics on Askö (limited drinking water supply, more information about the meals from Oskar Nyberg, vegetarian food, BBQ on Sunday, bar?)

Ticks, fästingar, Zecken, …

TBE (Tick-borne encephalitis)

Tim Osborn‘s climate model (energy balance model)

https://crudata.uea.ac.uk/~timo/teaching/model.htm

Literature

- IPCC (www.ipcc.ch)
- BACC I and II (http://www.baltic.earth, open access)
- NOSCCA (http://noscca.hzg.de, open access)
- Papers (Knutti 2010, Pages 2k consortium 2013, Hargreaves and Annan 2014, etc.)
- Lectures from Askö 2015 available as youtube movies @www.baltic.earth, user: BalticEarth, password: Mississippi
- Or at playlist of the University of Stockholm Baltic Sea Centre YouTube channel. https://www.youtube.com/playlist?list=PLjBr9cfayt4SMFDRKcqH_faX1iLCCV5So
- Baltic Earth facebook group

Literature

- Courtesy: Lectures from Ulrich Cubasch, Erik Kjellström, Martin Stendel, Eduardo Zorita
- 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.

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.

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

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

Course content

1. MM: Course introduction and fundamental processes of the climate system (greenhouse effect, radiation balance, climate sensitivity, stability and feedbacks)
2. MM: Large-scale ocean circulation
3. Anna Rutgersson: Climate state and global circulation patterns in the atmosphere, part I and II
4. MM: Statistical analysis of time series
5. Marcus Reckermann: Baltic Earth
6. MM: Climate Modeling – The global and regional perspective, part I and II
7. MM: Oceanography of the Baltic Sea and other regional seas, part I to IV
8. Christoph Humborg: Processes in the Baltic Sea catchment area and eutrophication
9. Christoph Humborg: Terrestrial and marine carbon cycle

Course content

1. MM: History of the Baltic Sea
2. MM: Past changes in extremes
3. MM: Modelling past climate variability of the Baltic Sea
4. MM: Future projections for the Baltic Sea Region
5. Karol Kulinski: Carbon cycle in the Baltic Sea
6. MM and Marcus Reckermann: Science communication
7. Marcus Reckermann: Presentation technique

Questions?

Who are you?

1. From which university are you coming from? 60N, 20E
2. Where are you born?
3. course of studies: Oceanography, Meteorology, Biogeochemistry, Hydrology, others
4. preferred course of studies: -
5. Study: Batchelor, Master, PhD, Others
6. preferred career: science, teacher, industry, state service, others
7. favourite hobby: sport, books, music, nature
8. have you attended a course in physical oceanography? Yes/no
9. have you attende a course in climate sciences? Yes/no
10. course expectations: theory, exercises, soft skills, open for everything
11. how to spend your free time? biking/jogging, swimming/sauna, games/social interactions, working

What is climate?

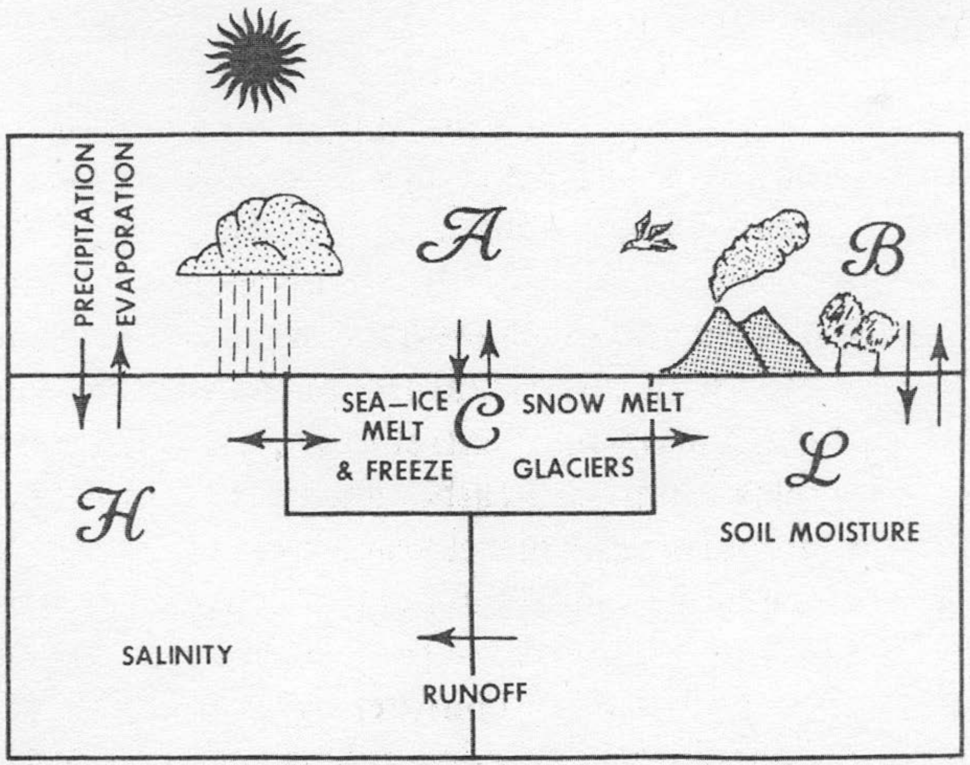
Definition of climate

- 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.)

What is an Earth system approach? What are the components of the Earth climate system?

THE TOTAL CLIMATE SYSTEM AND ITS SUBSYSTEMS



𝒜 = atmosphere

ℋ = hydrosphere (ocean)

𝒞 = cryosphere (snow & ice)

ℒ = lithosphere (land)

ℬ = biosphere

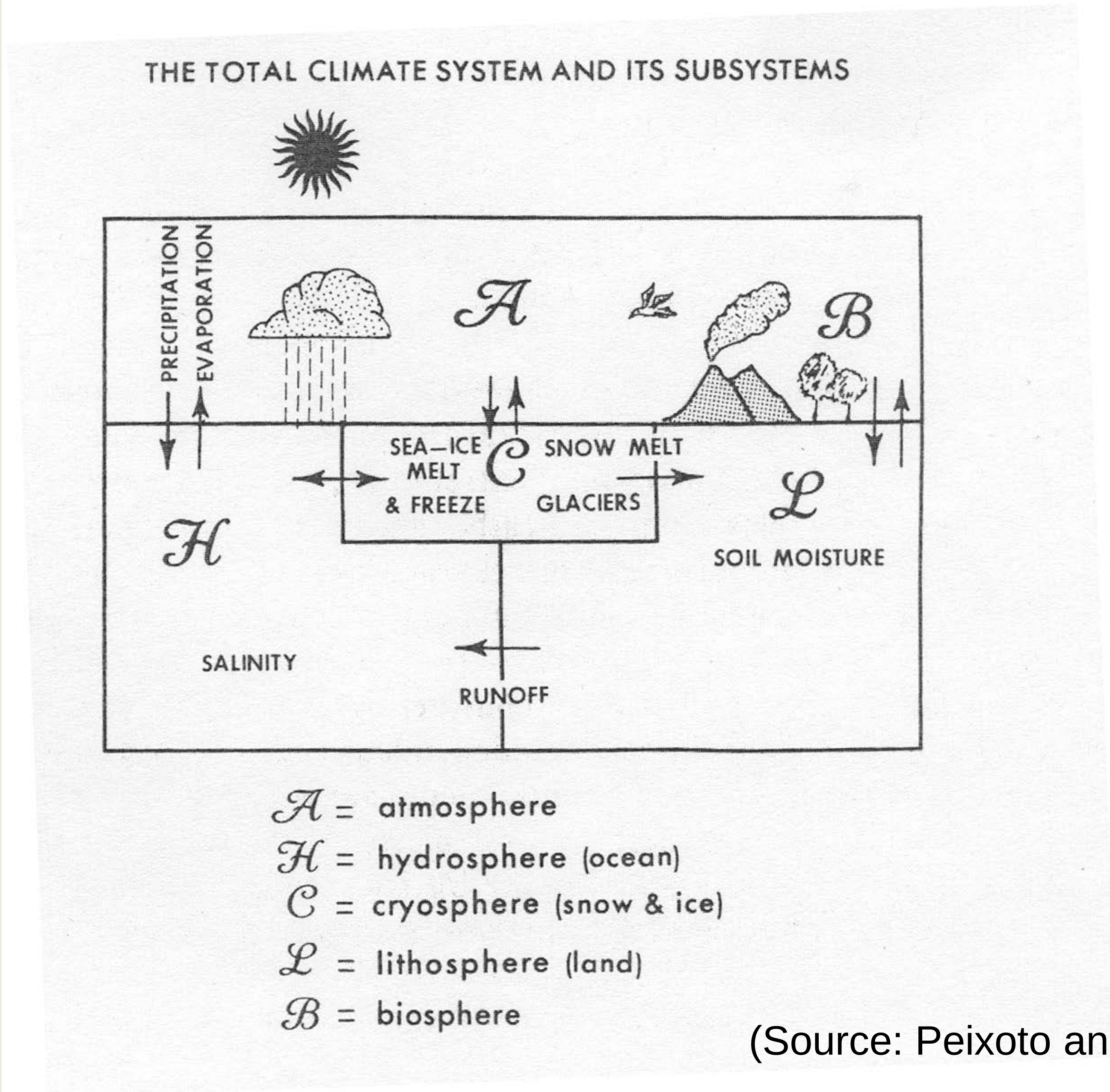
(Source: Peixoto and Oort 1992)

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)



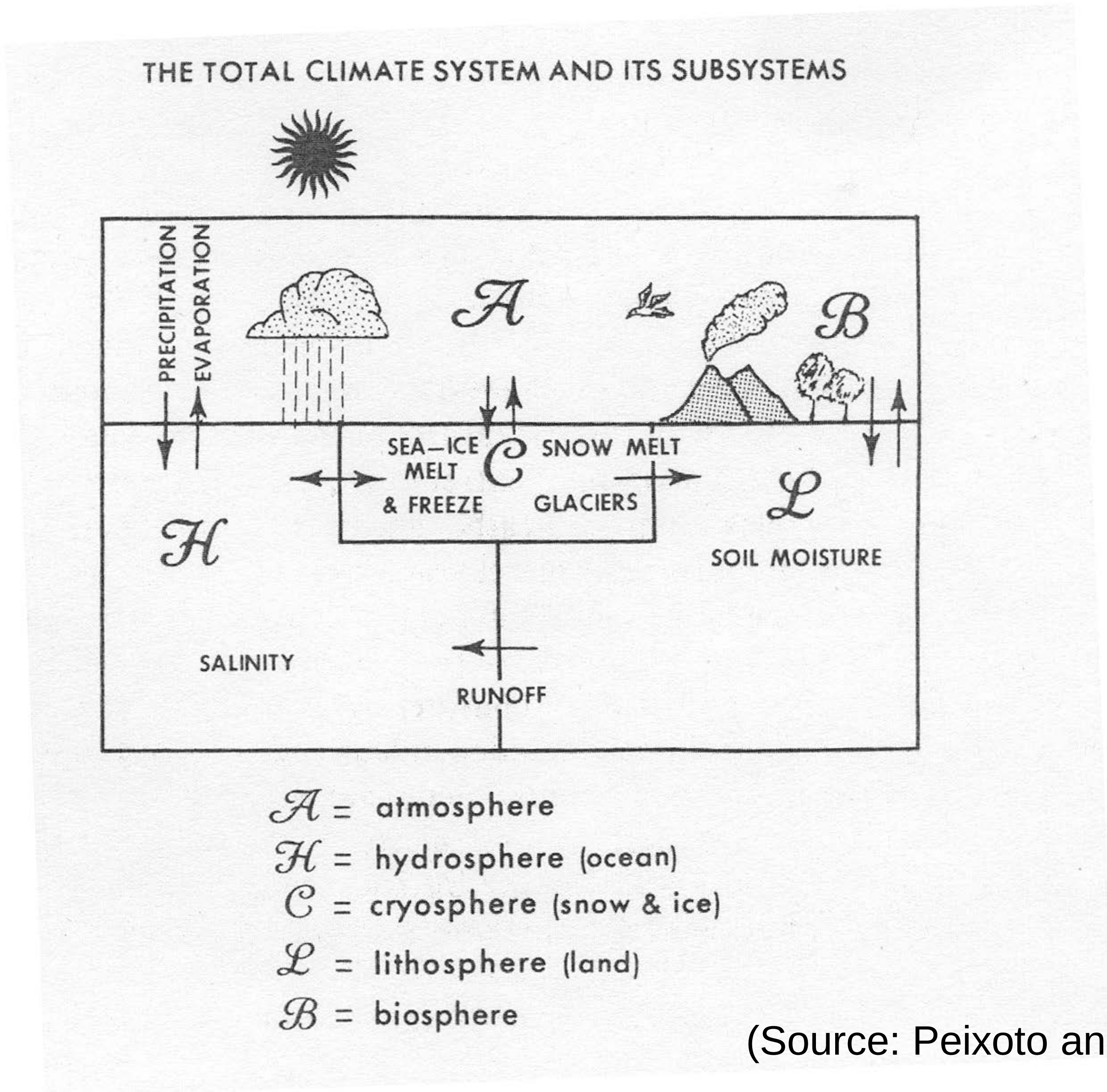
(Source: Peixoto and Oort 1992)

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)



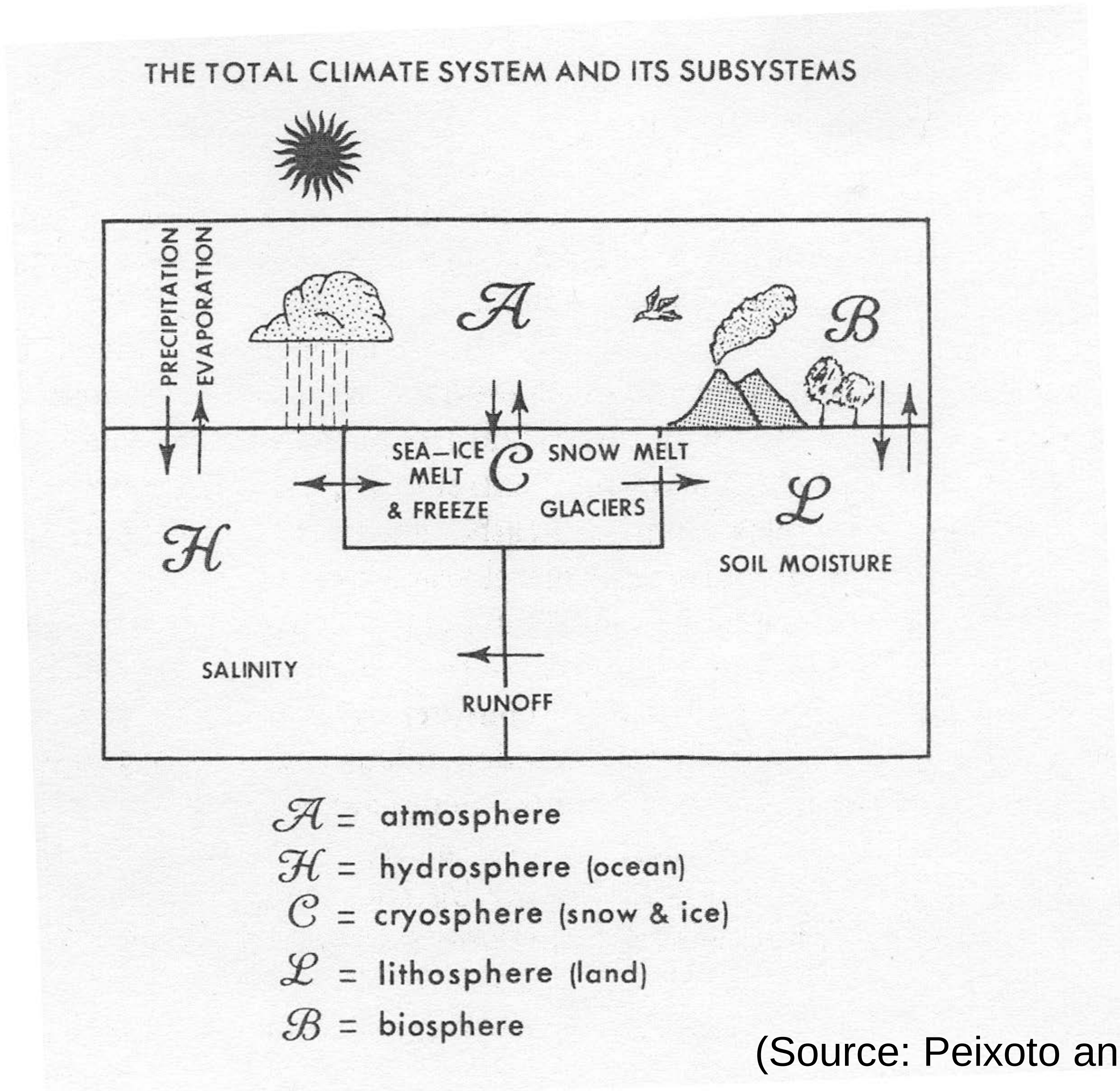
(Source: Peixoto and Oort 1992)

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)

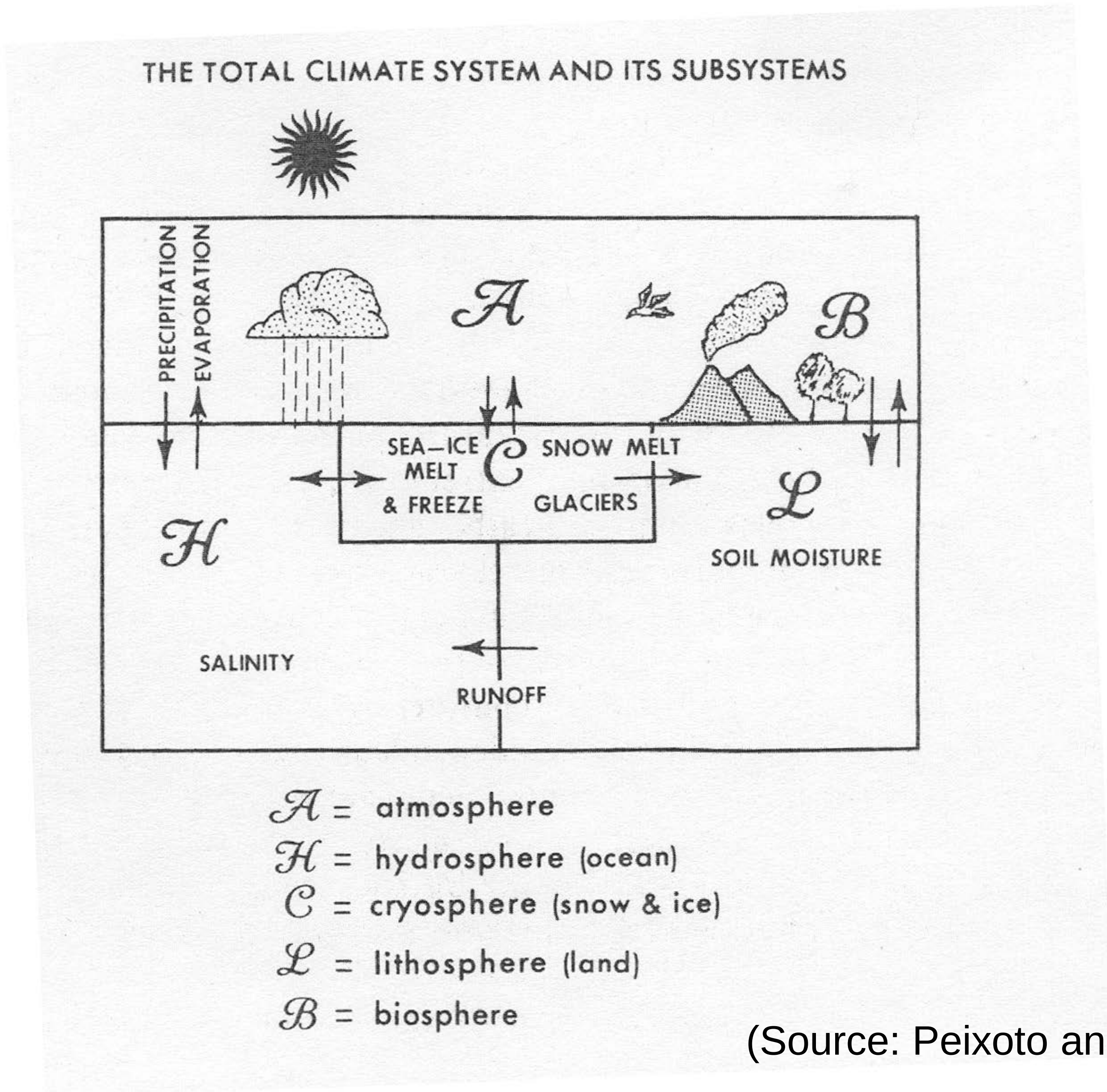
- **Bio-geophysical interaction**: albedo, evaporation, roughness
- **Bio-geochemical** interaction:
  - photosynthesis and respiration of carbon
  - impact on CH_4 emissions
- **Time scales**:
  - physiology (reaction of the stomata): minutes
  - succession: 30 – 150 years,
  - migration: 300 – 1500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

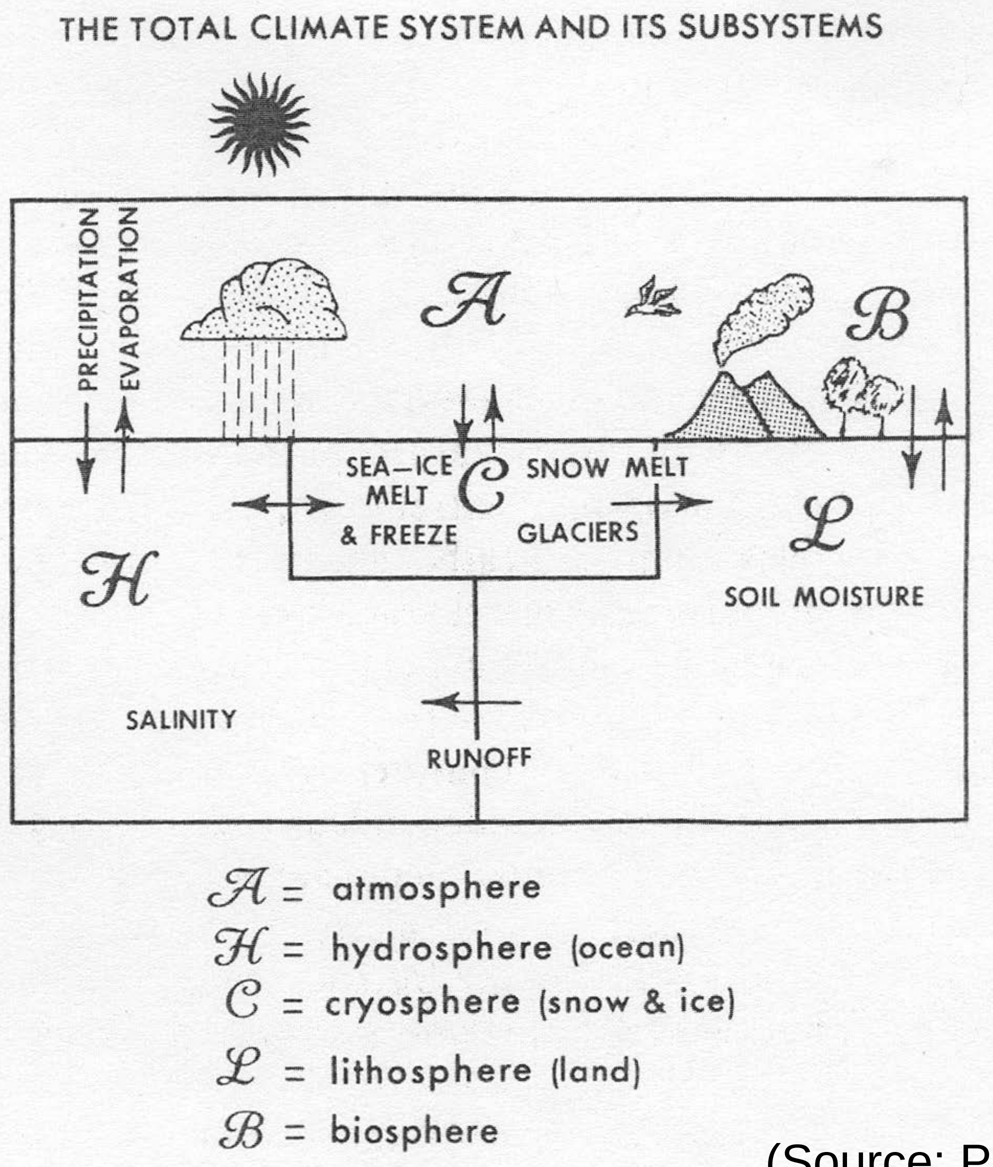
- Time scales of heat and water storage depend on the layer depth:
  - daily cycle: about 10-30 cm
  - annual cycle: few meters

(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)

What would be a very simple climate model based on the radiation balance?

Radiation balance (zero order model)

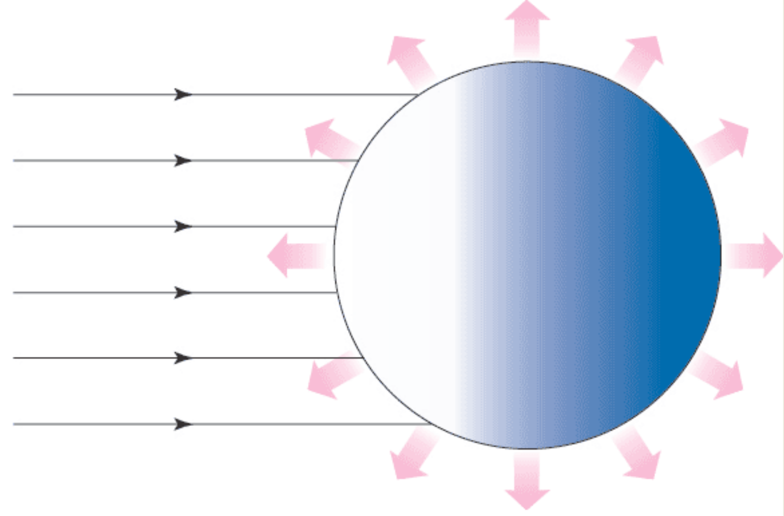
$$\gamma_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal}$$

$\gamma_{surf} =$ 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
Observed global mean T_{surf}=288 K = 15ºC

(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

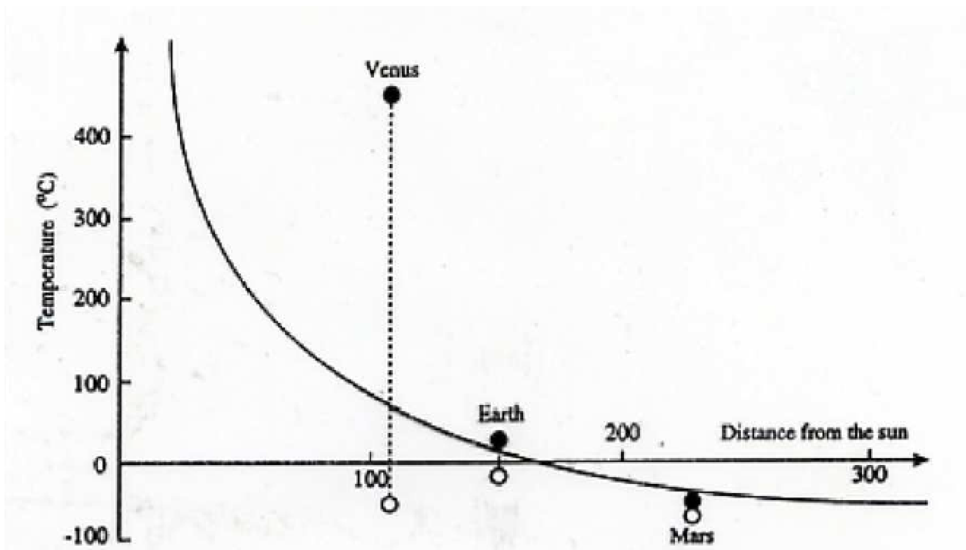
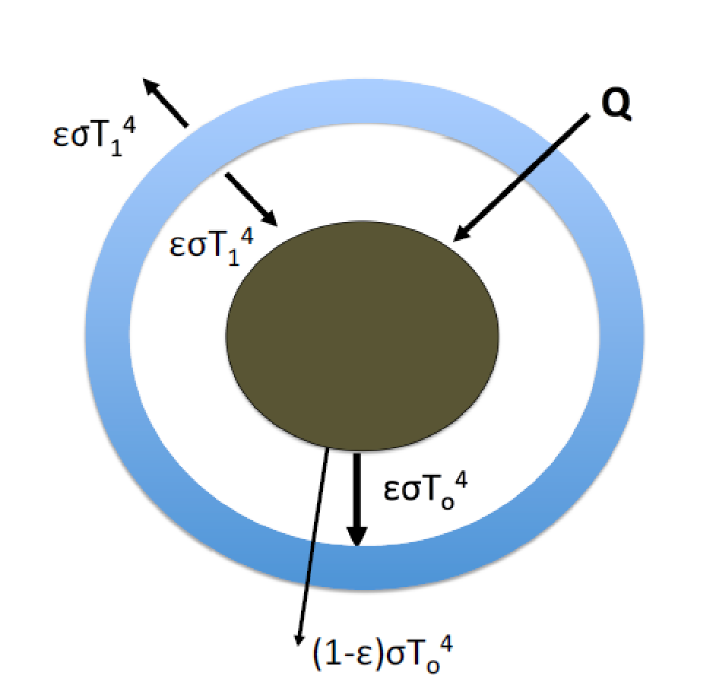


Figure 2.5: Distance from the Sun versus radiation temperature of a black body absorbing the incoming sun light (solid line). The black filled circles mark the observed T_{surf} of Venus, Earth and Mars and the black unfilled circles mark the radiation temperature of the planets according to their absorved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

(Source: D. Dommenget)

Explain the greenhouse effect

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

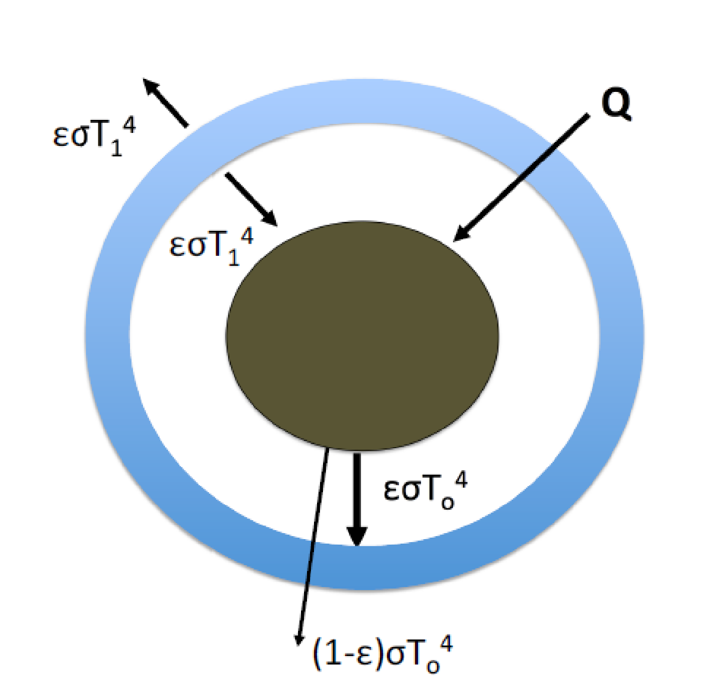
space: $\sigma T_{rad}^4 = \epsilon\sigma T_1^4 + (1-\epsilon)\sigma T_0^4 = Q$

Exercise: calculate T_{surf}, ε

$T_0 = T_{surf}$
$T_1 = T_{atm}$
T_1=temperature of the atmosphere
ε<1 emissivity
Atmosphere absorbs the portion ε of the thermal radiation, emissivity of a mass describes the ability to absorb and emit thermal radiation

(Source: D. Dommenget)

Greenhouse effect illustrated by Greenhouse shield models



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

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

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

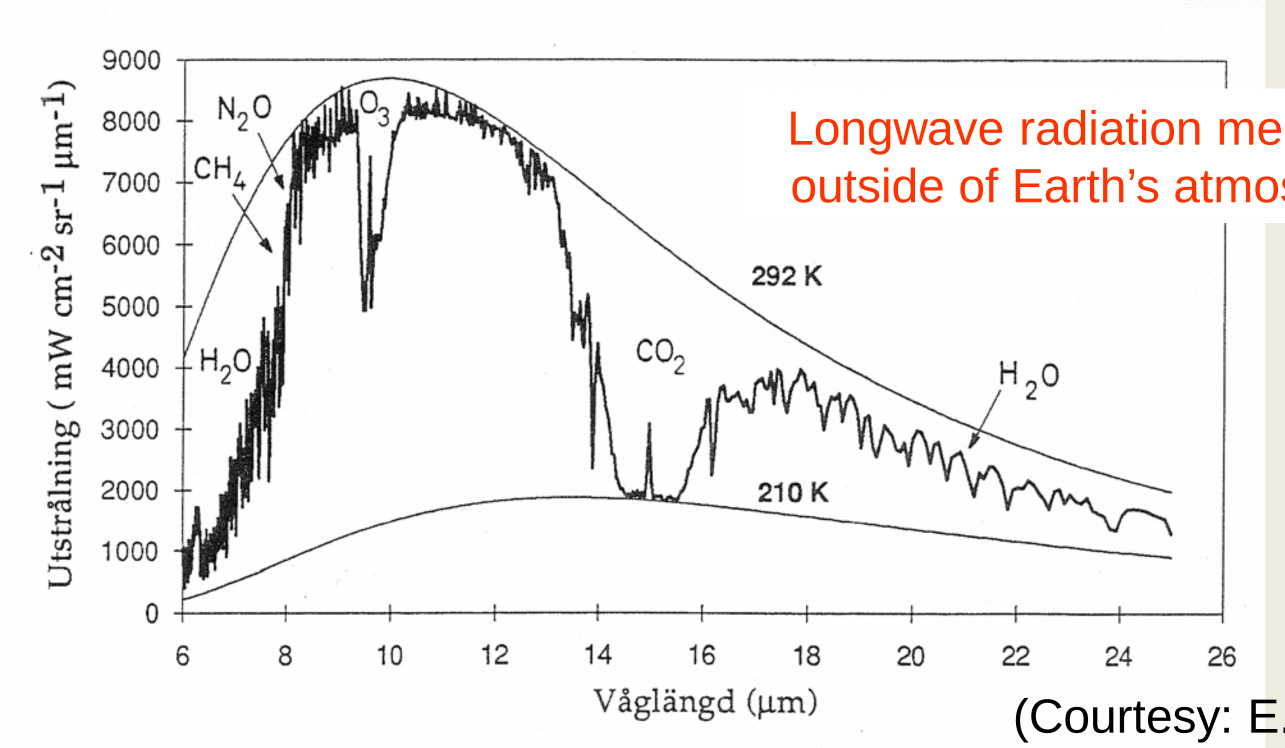
$T_0 = T_{surf}$
$T_1 = T_{atm}$
T_1=temperature of the atmosphere
ε<1 emissivity
Atmosphere absorbs the portion ε of the thermal radiation

(Source: D. Dommenget)

List three important greenhouse gases.

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)

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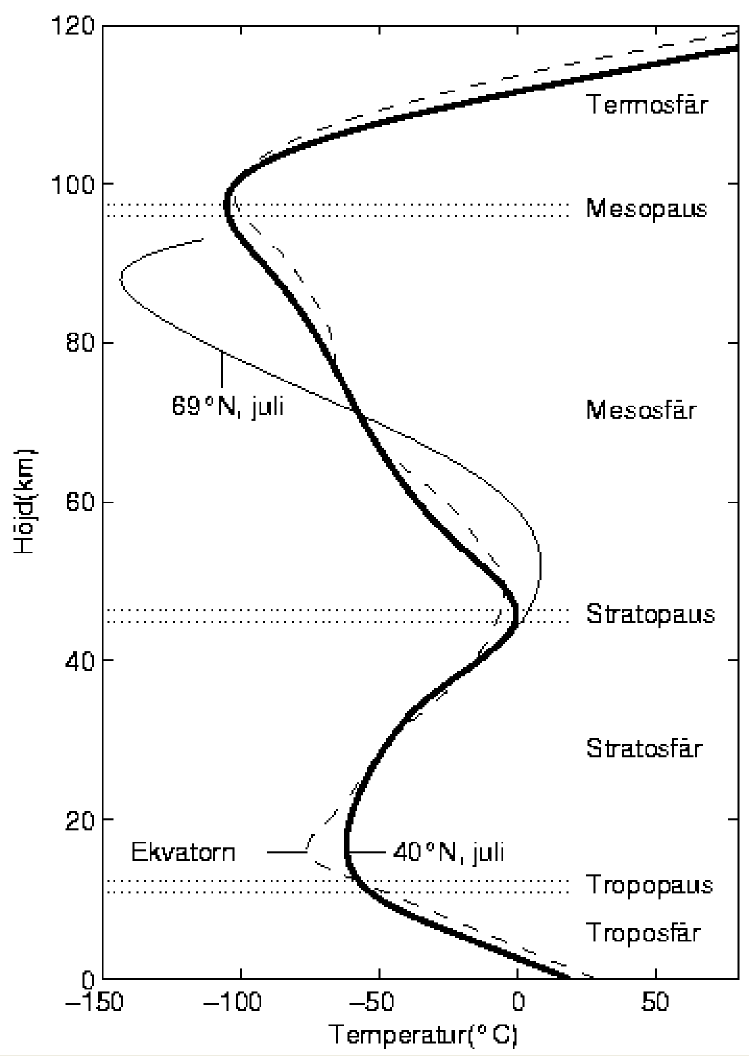
Climate relevant

(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

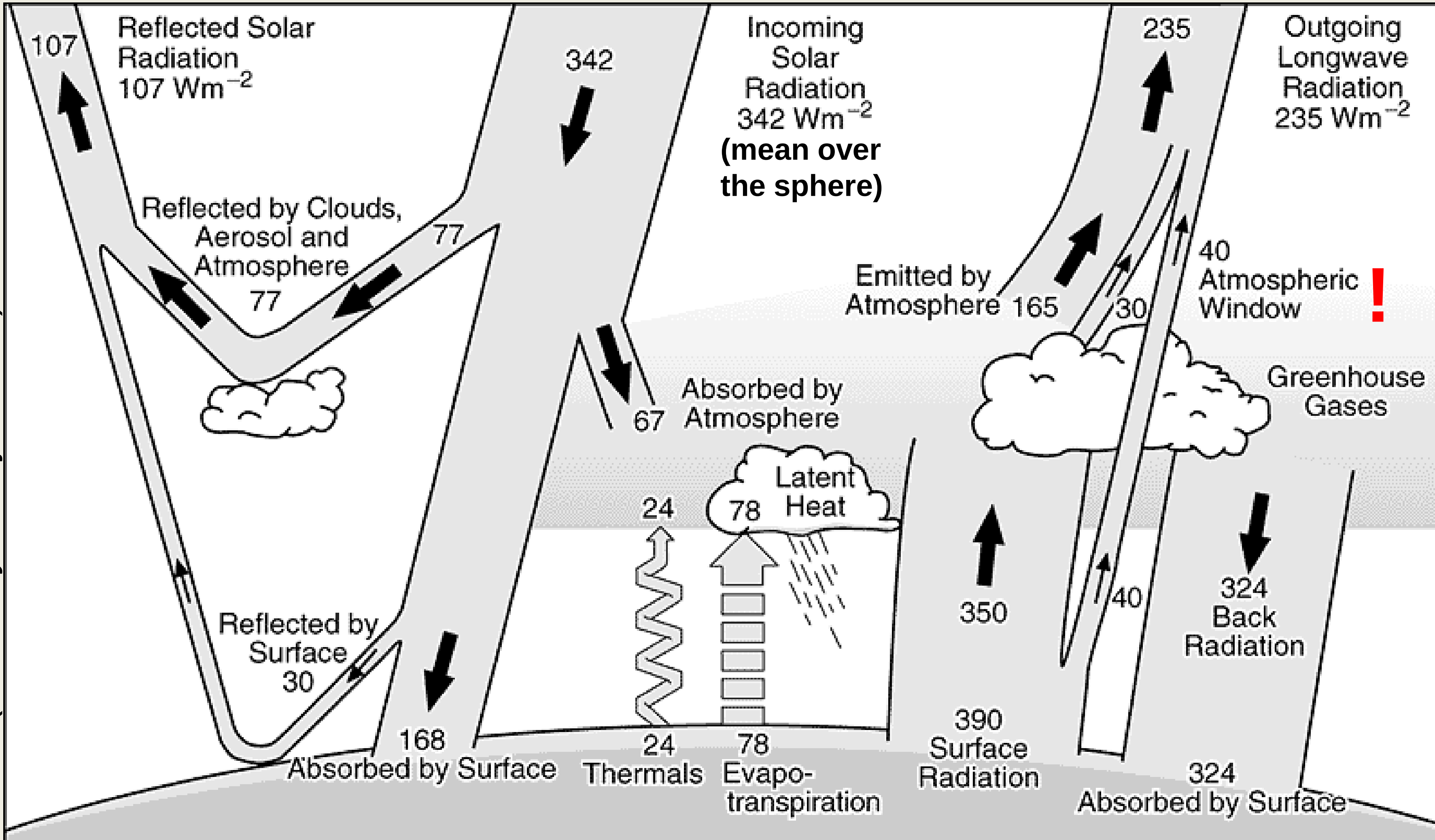
(Courtesy: E. Kjellström)

Global energy balance

Albedo=107/342=31%

342-107=235!!

(Courtesy: E. Kjellström)



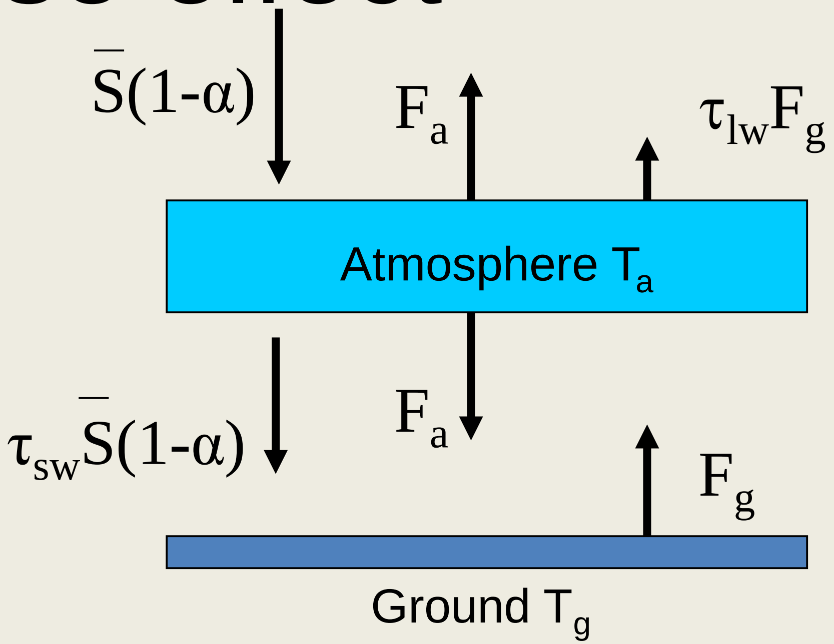
Ratio of surface and incoming sw radiation =168/342=49%

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

Atmospheric transmissivity (1-ϵ) (sw) =168/(342-107)=0.71

Atmospheric transmissivity (lw) =40/390=0.10

A simple model including the greenhouse effect

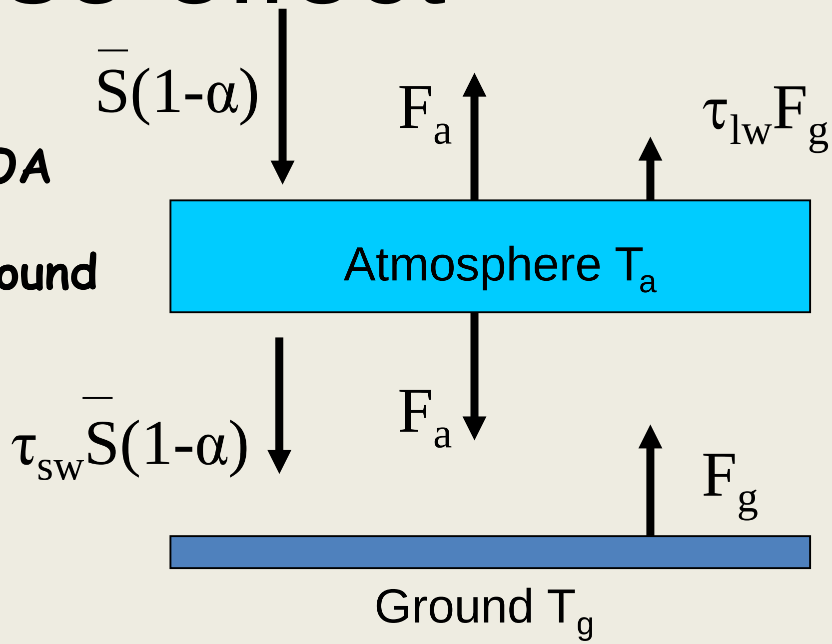


$$\overline{S} = 342\ \mathrm{Wm}^{-2},\ \alpha = 0.31,\ \tau_{sw} = 0.71,\ \tau_{lw} = 0.10$$

transmissivity

A simple model including the greenhouse effect

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



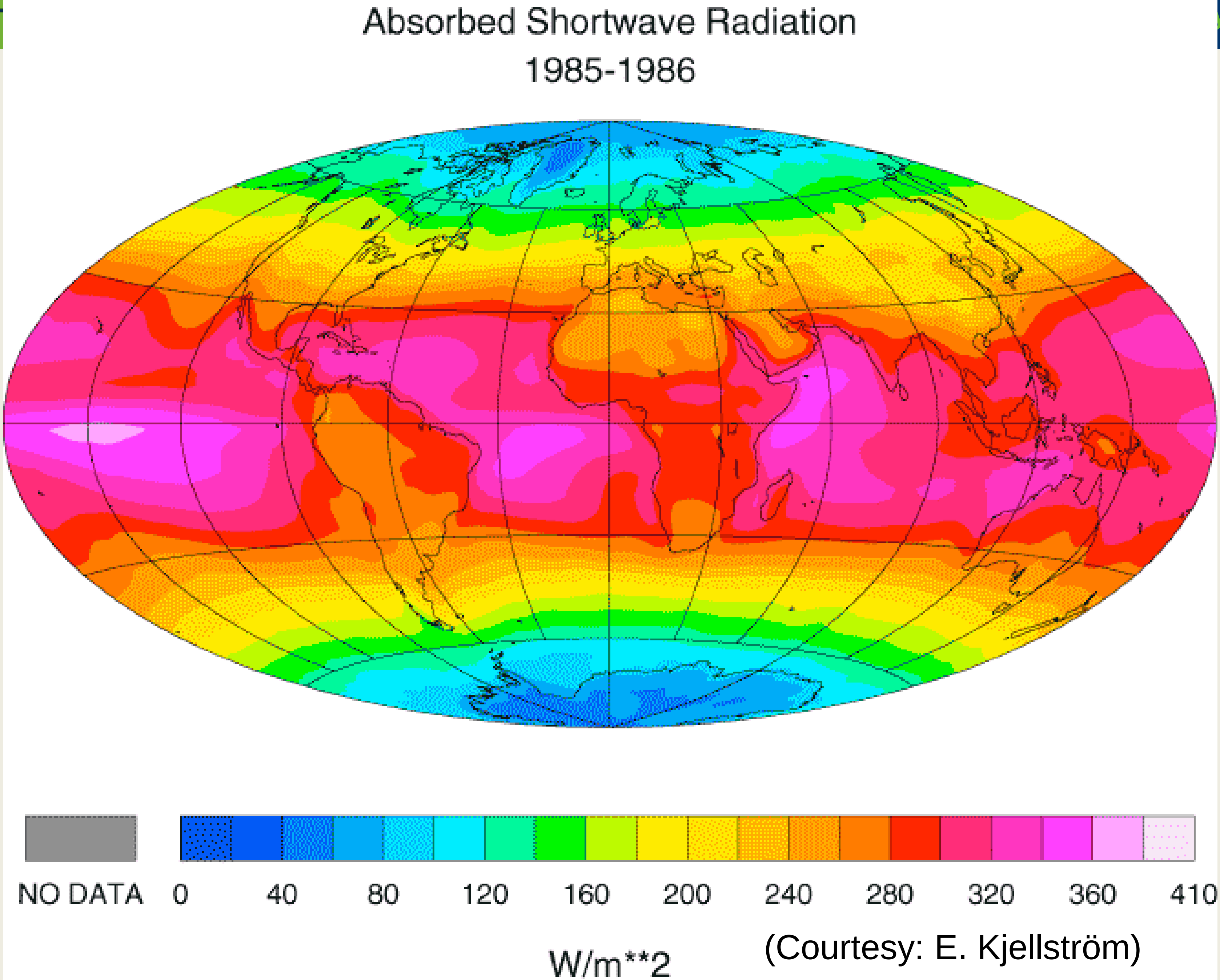
eliminate F_a

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

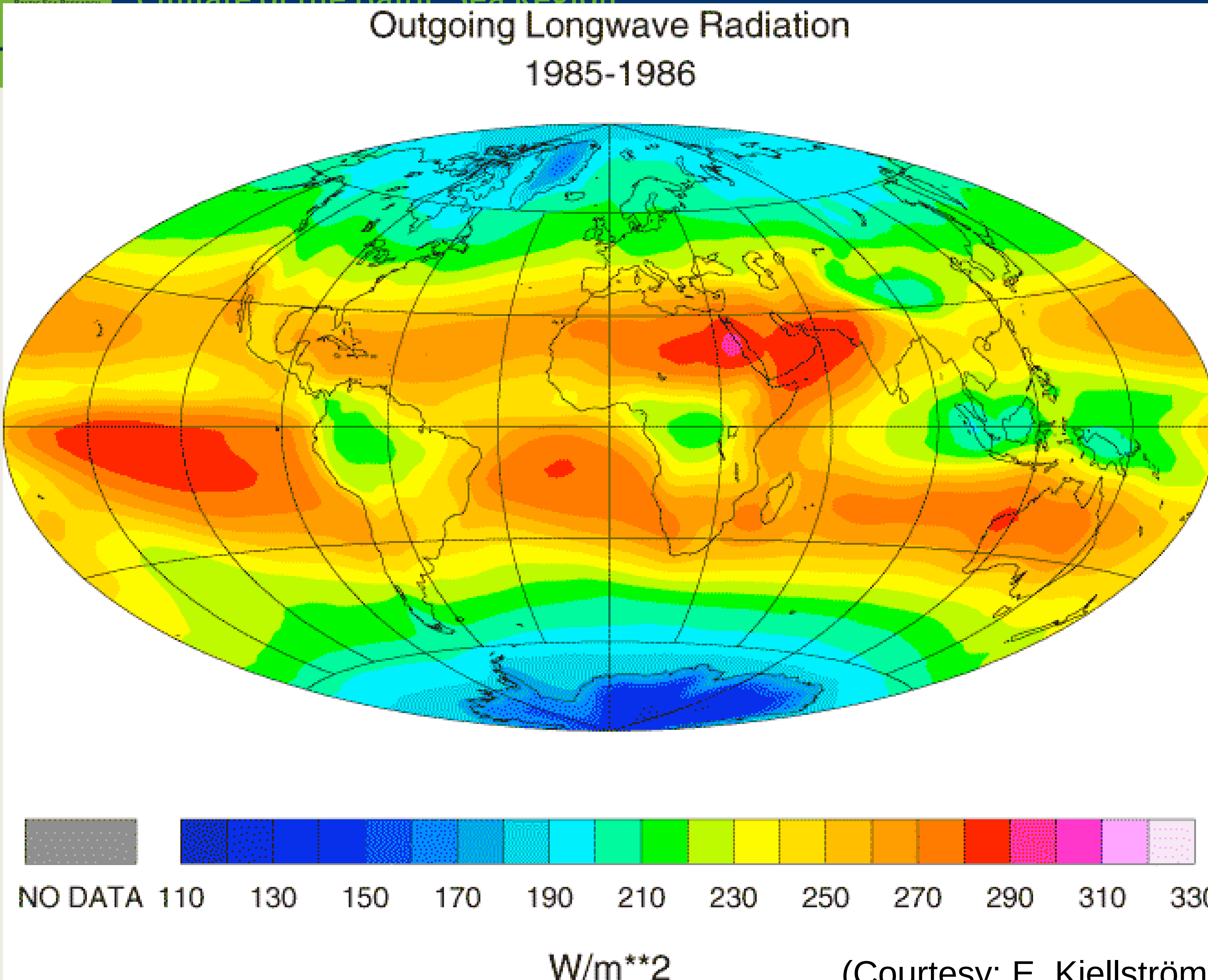
$\bar{S} = 342\ \text{Wm}^{-2}$, $\alpha = 0.31$, $\tau_{sw} = 0.71$, $\tau_{lw} = 0.10$ transmissivity

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

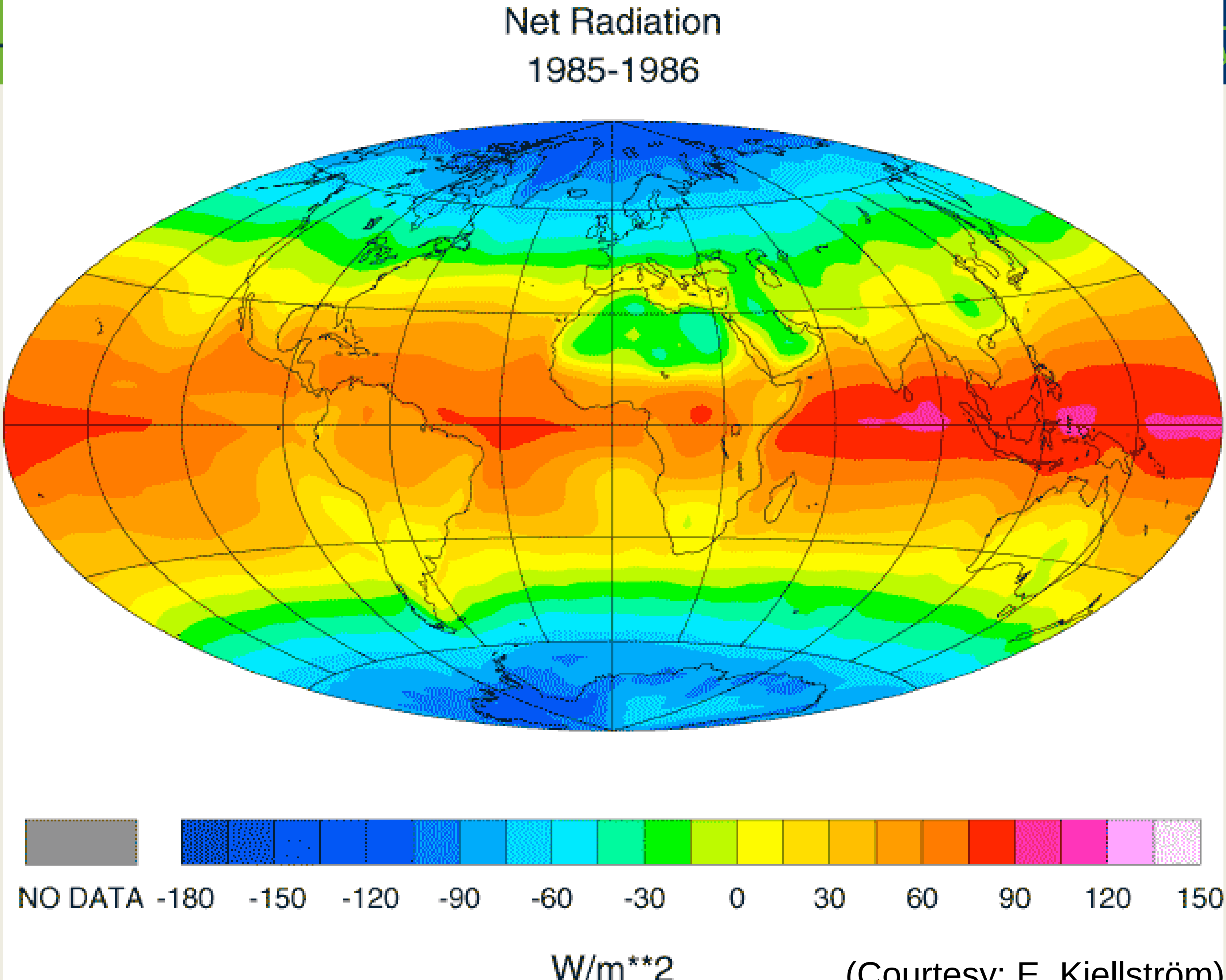
(Courtesy: E. Kjellström)



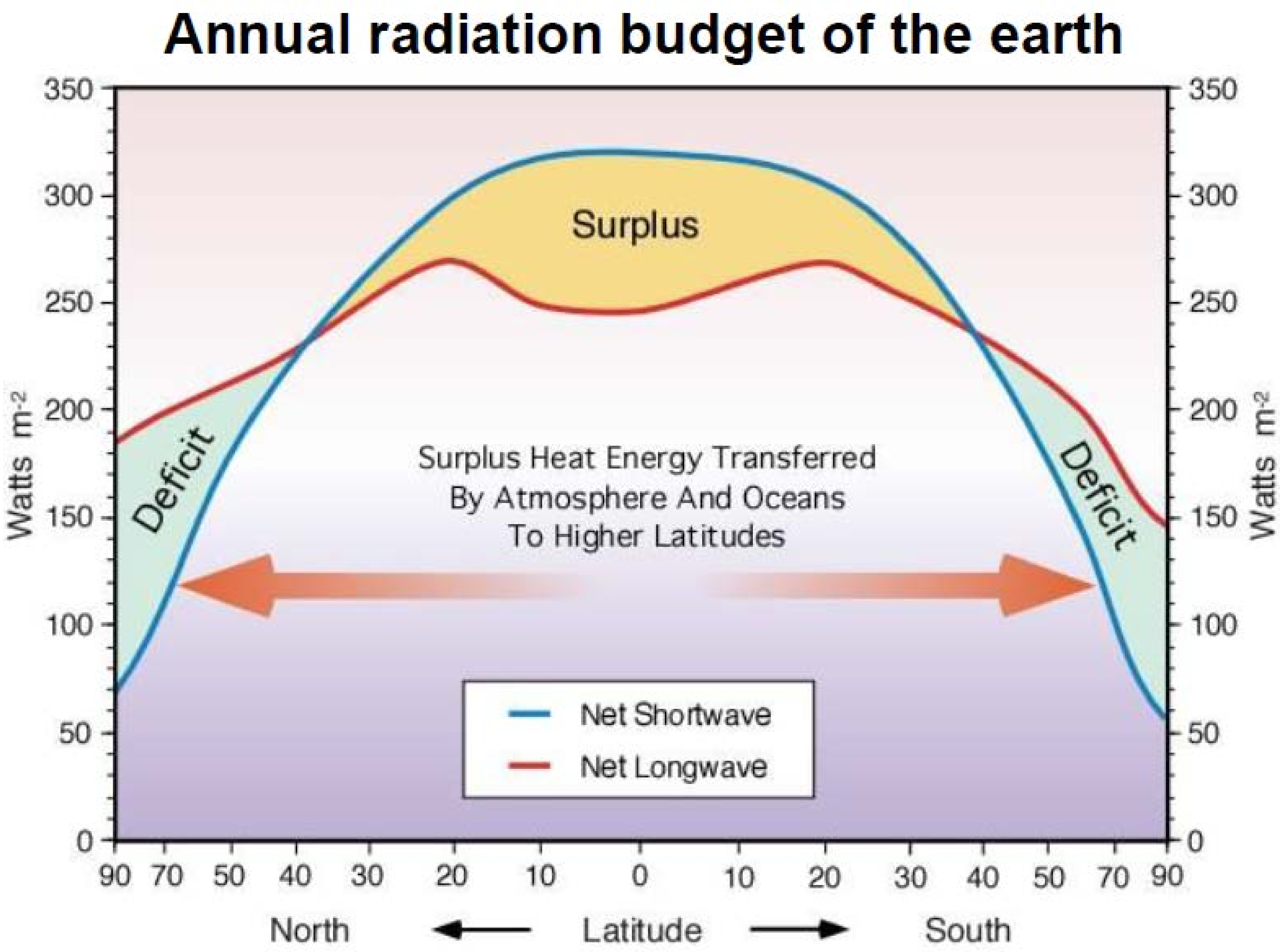
(Courtesy: E. Kjellström)



(Courtesy: E. Kjellström)



(Courtesy: E. Kjellström)



http://www.physicalgeography.net

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

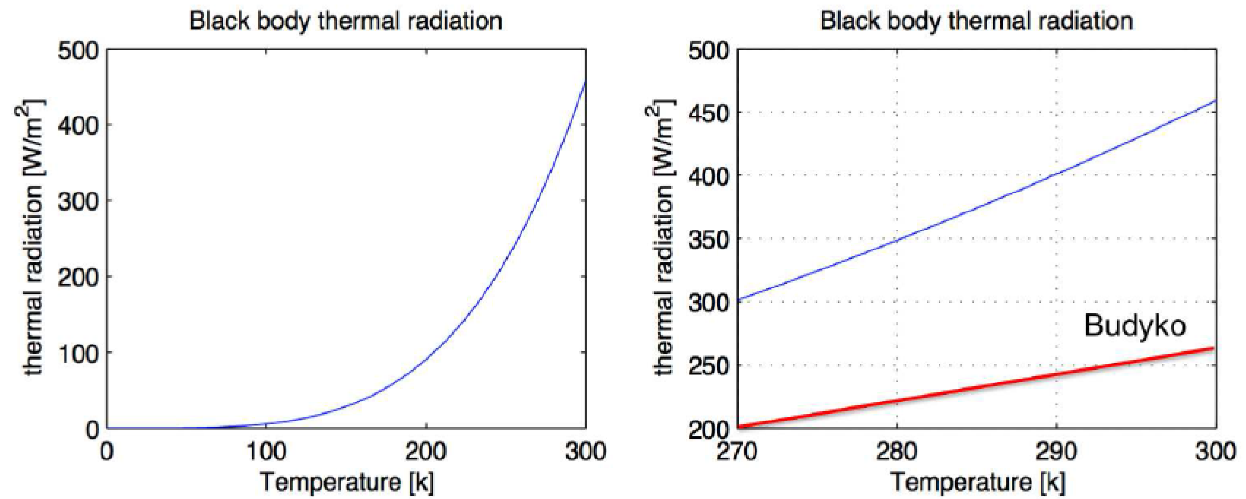
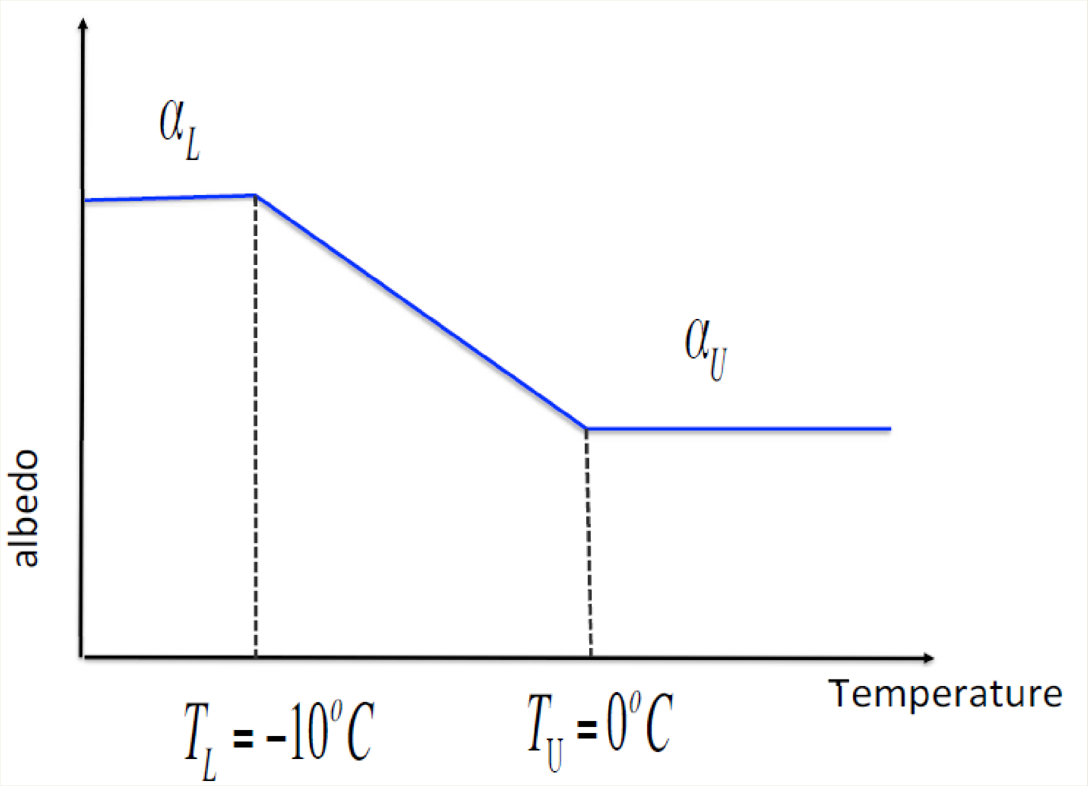


Figure 2.10: Black body thermal radiation: left: Black body thermal radiation for a wide range of temperatures. right: Black body thermal radiation (blue line) for a range of temperature closer to the earth climate in comparison to the Budyko linear model (red line).

$$F_{thermal} = -\sigma T_{surf}^4$$

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

(Source: D. Dommenget)



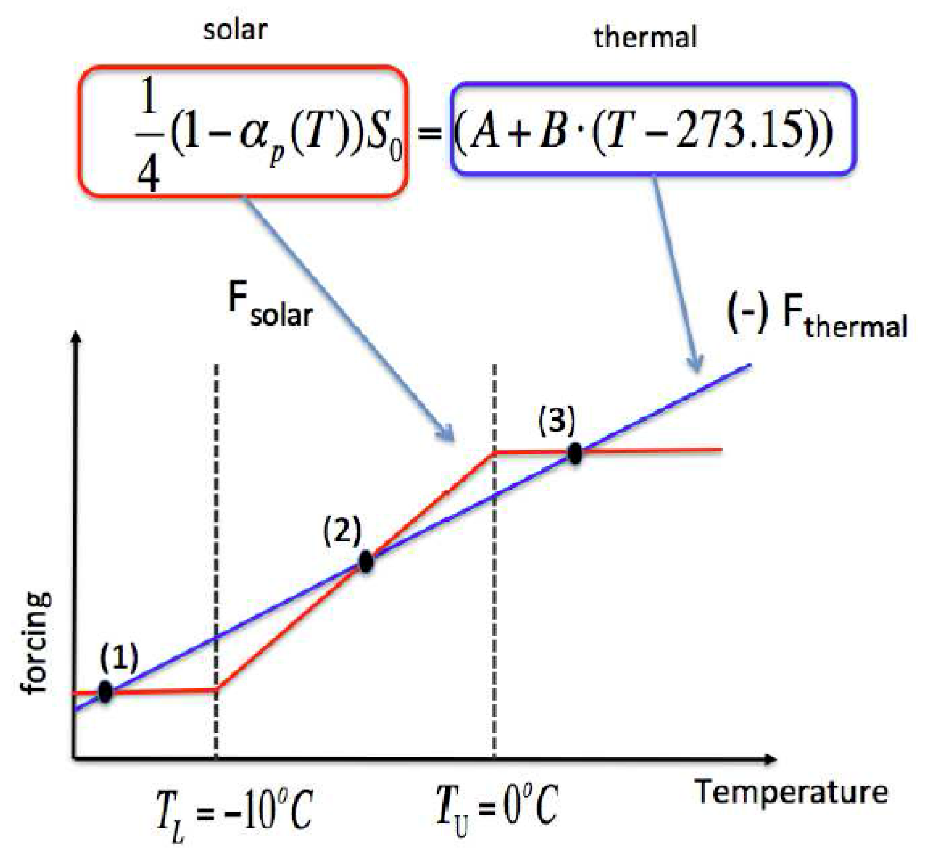
$$\alpha_L = 0.62 \quad \alpha_U = 0.3$$

Q=S_0/4

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

(Source: D. Dommenget)

(Source: D. Dommenget)



$\alpha_L = 0.62 \quad \alpha_U = 0.3$
$T_L = -10^oC \quad T_L = 0^oC$
$\Delta\alpha = \alpha_U - \alpha_L = -0.32$
$\Delta T = T_U - T_L = 10^oC$

(1) Totally ice covered earth $\quad T^{(1)}_{surf} = \frac{(1-\alpha_L)Q-A}{B} = -35.2^oC$

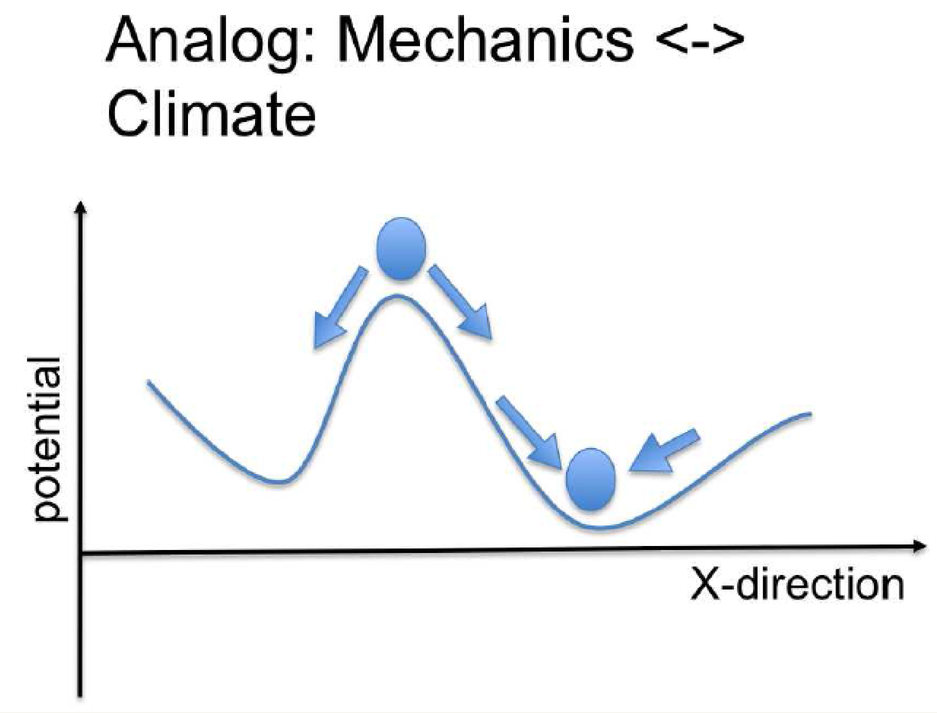
(2) Partially ice covered earth (present day) $\quad T^{(2)}_{surf} = \frac{Q(1-\alpha_L)\Delta T - A\Delta T + QT_L\Delta\alpha}{B\Delta T + Q\Delta\alpha} = -4.0^oC$

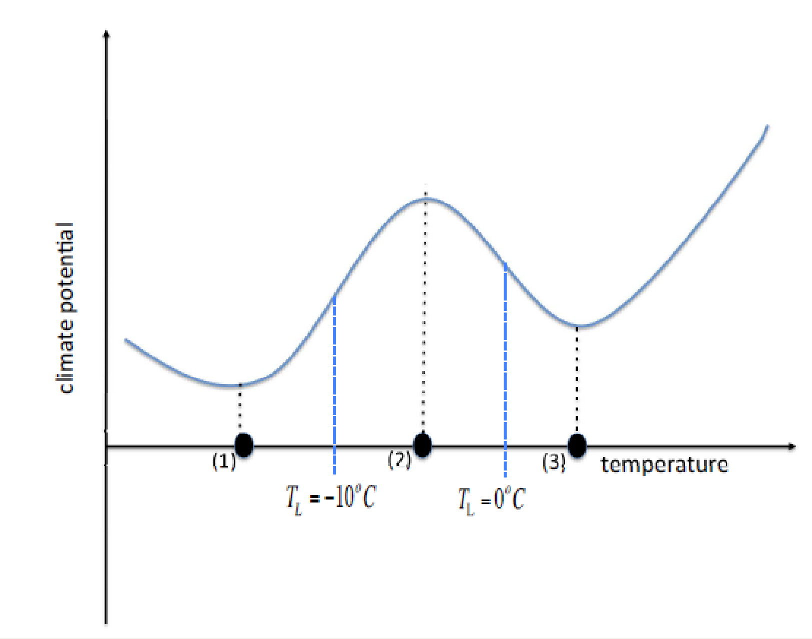
(3) Ice free world $\quad T^{(3)}_{surf} = \frac{(1-\alpha_U)Q-A}{b} = +17/0^oC$

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

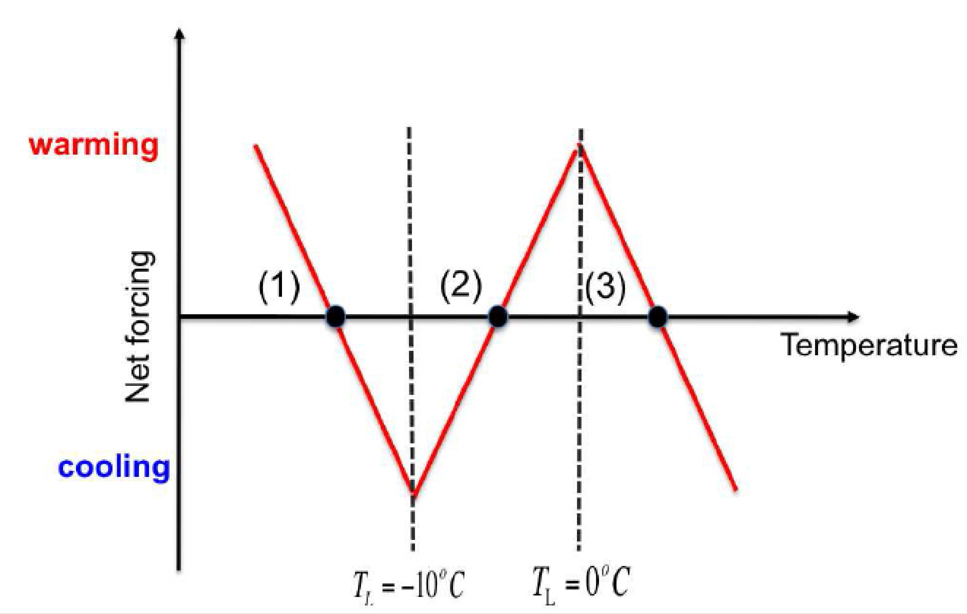
For stable equilibrium:

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

And for unstable equilibrium:

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

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

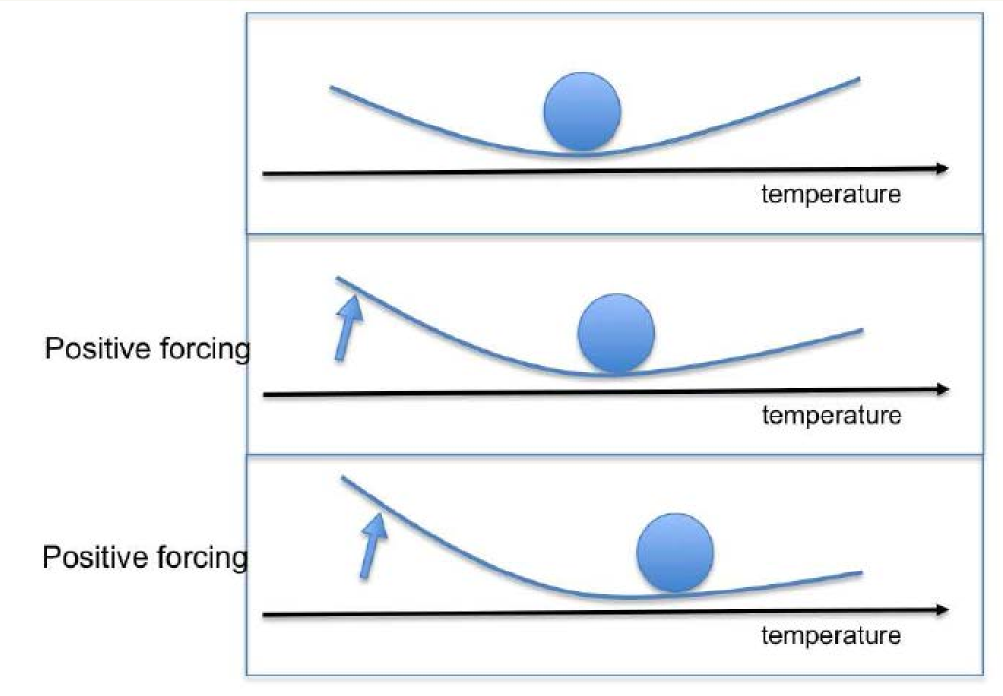


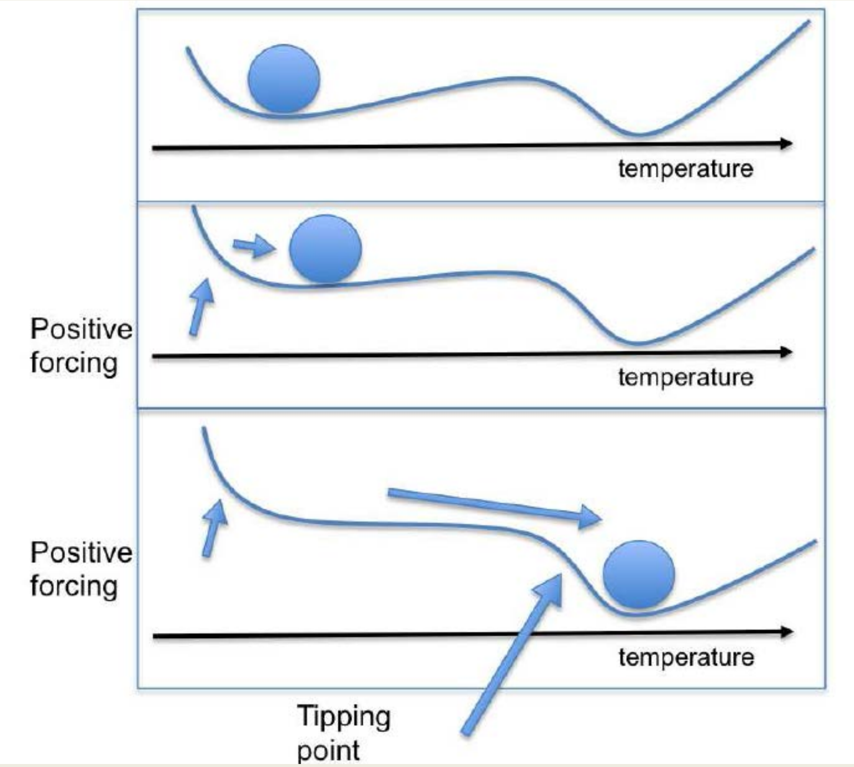
(1)	Totally ice covered earth	→ stable
(2)	Partially ice covered earth (present day)	→ unstable
(3)	Ice free world	→ stable

(Source: D. Dommenget)

What is a tipping point of the climate system?

Tipping points



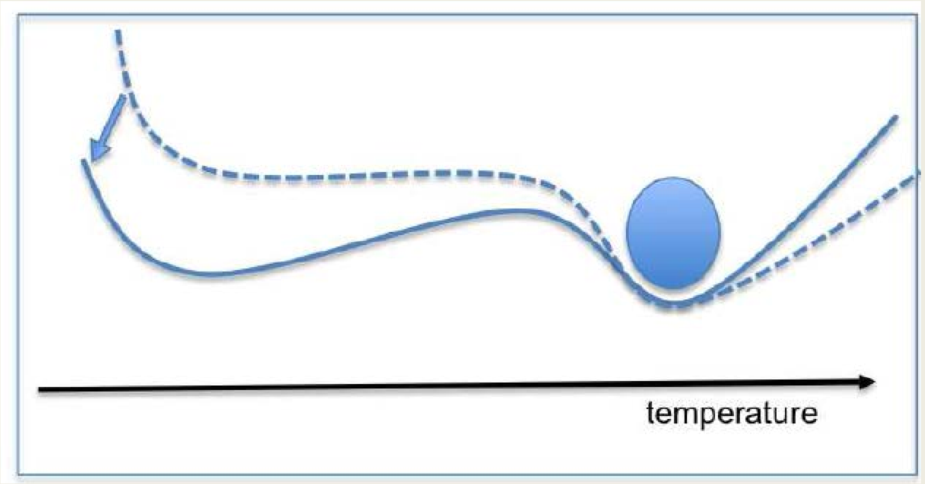


Zero order model (no feedbacks)

Budyko model with the ice-albedo feedback

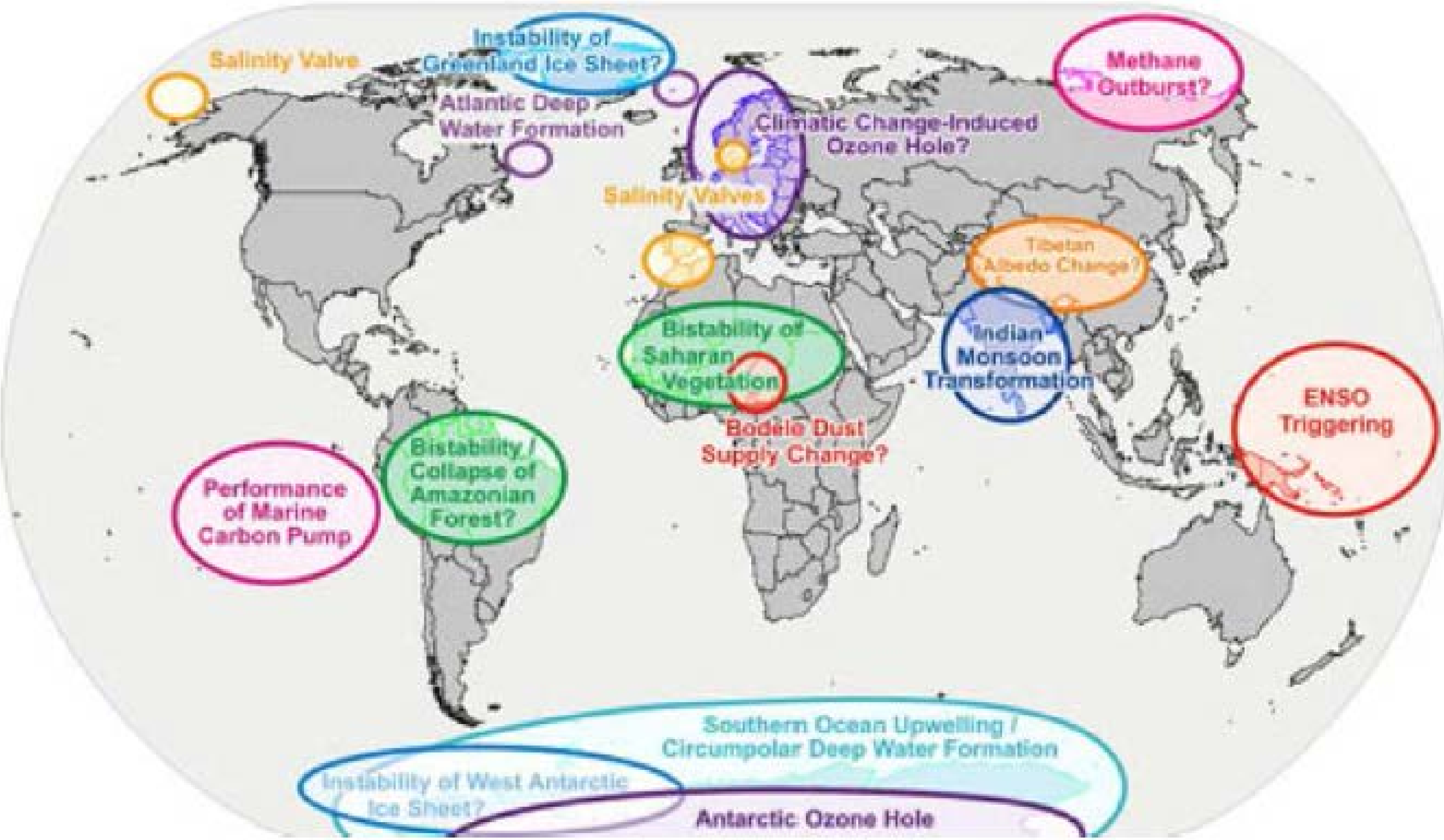
(Source: D. Dommenget)

Tipping point: climate change is irreversible



(Source: D. Dommenget)

Tipping Points in the Earth System



What is climate sensitivity?

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

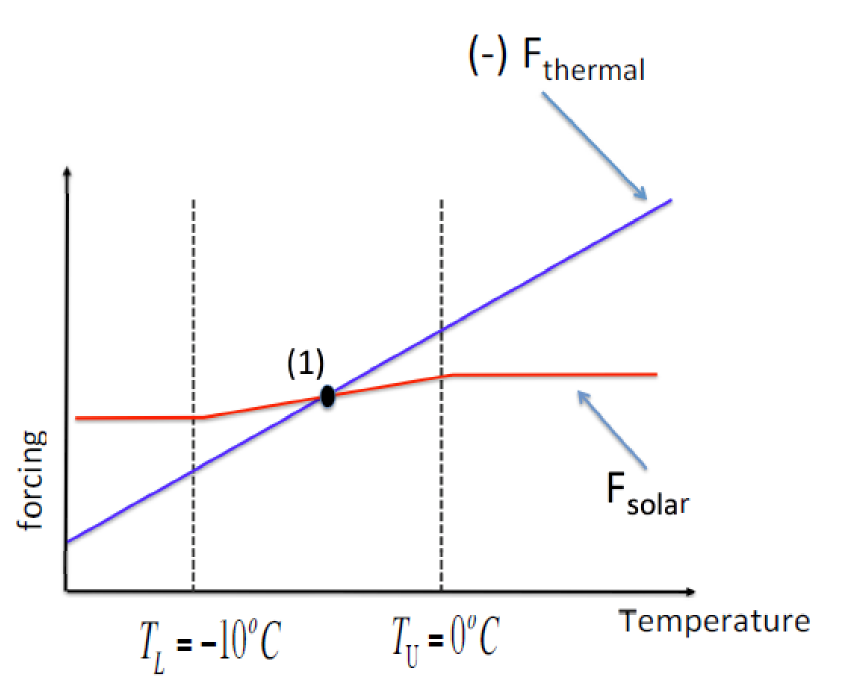
Example 3: Budyko model without ice-albedo feedback (α_P=0.3)

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

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

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)

What is a climate feed back?

Feedbacks

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

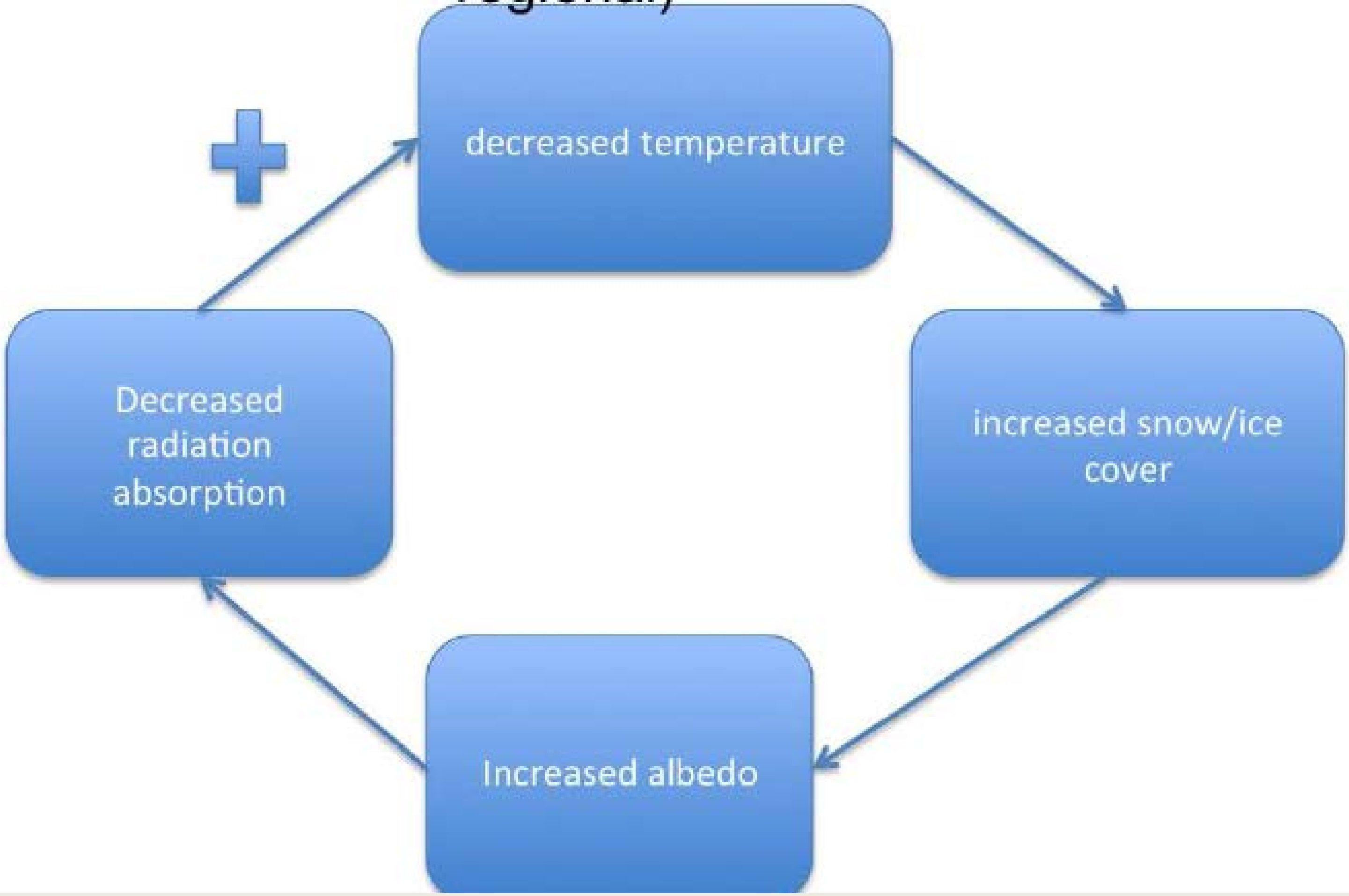
Example: simple linear climate model $$\gamma \frac{dT}{dt} = C_f \cdot T + Q$$ Climate feedback parameter C_f

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

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

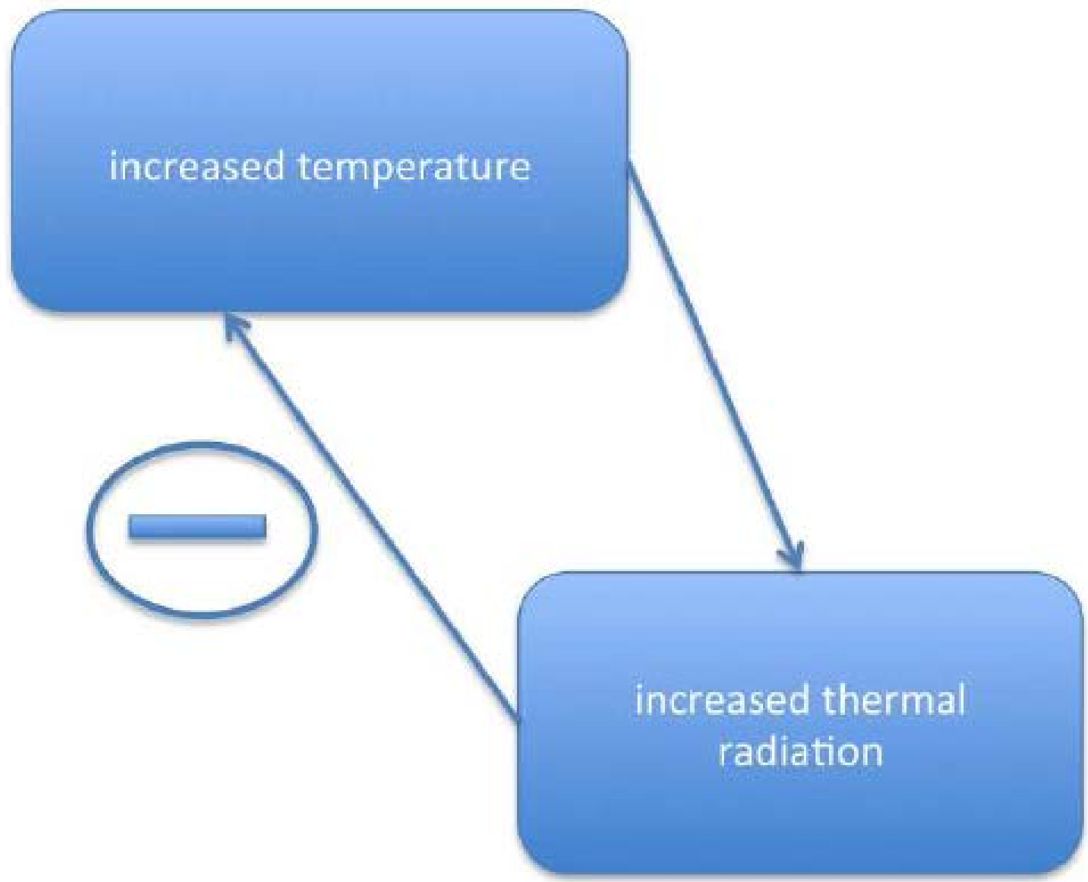
(Source: D. Dommenget)

Examples: Ice-Albedo (fast, strong, regional)

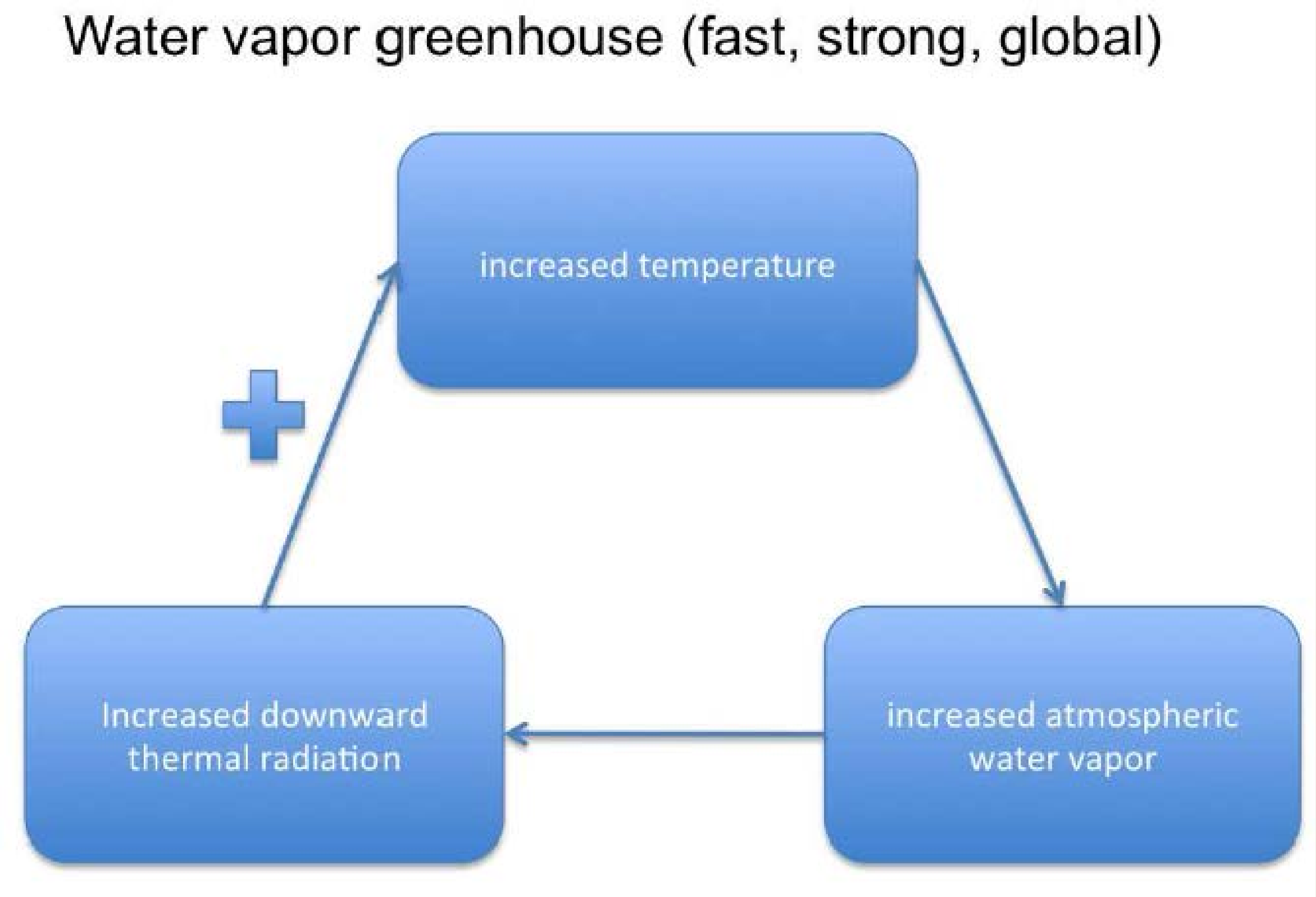


(Source: D. Dommenget)

Black body radiation (fast, strong, global)

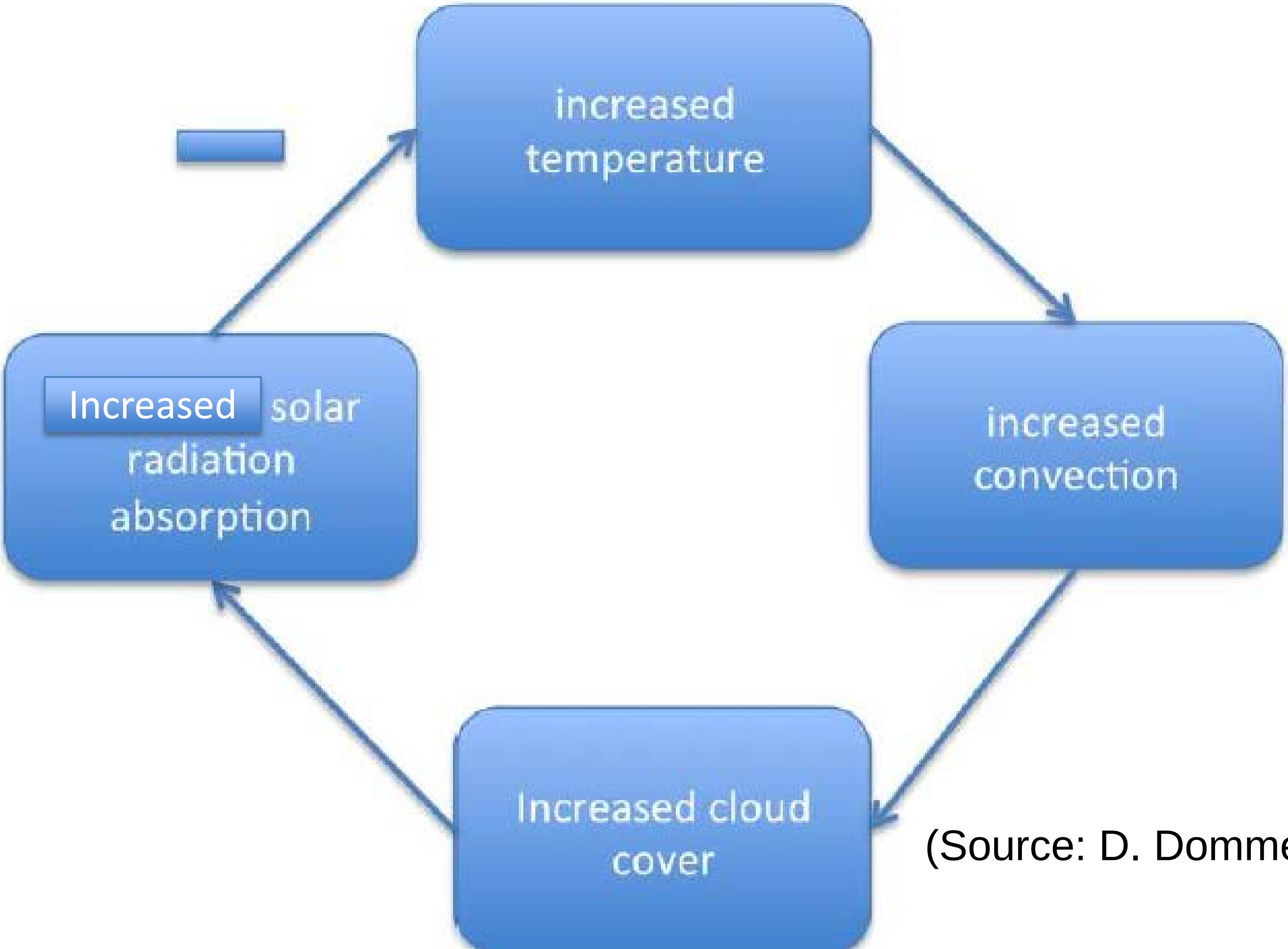


(Source: D. Dommenget)



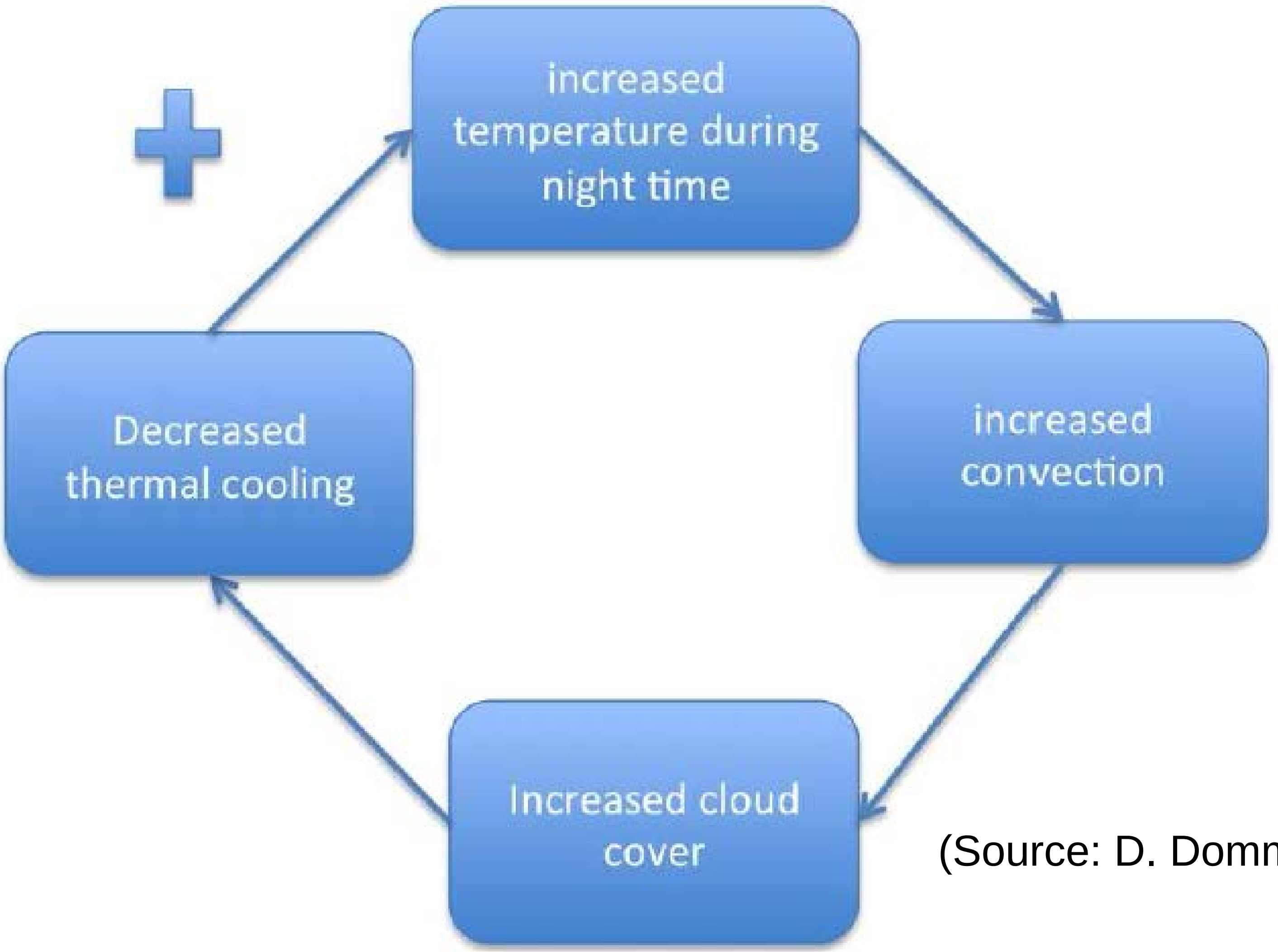
(Source: D. Dommenget)

Clouds ***solar*** (fast, potentially strong, global)



(Source: D. Dommenget)

Clouds ***thermal*** (fast, potentially strong, global)



(Source: D. Dommenget)

Feedback	Time scale	Scale/strength	Sign
Ocean-carbon	1000 yrs	Strong/global	Positive
Biosphere-vapour	10-100 yrs	Regional	Positive
Carbon sinks	1-100 kyrs	Global	Negative
Circulation	1-10 yrs	Regional, global	Negative

Feedback	Forcing Q	Feedback
Black body radiation	$-\sigma T^4$	$-4\sigma T^3 = -5.4\frac{W}{m^2}\frac{1}{K}$
Greenhouse	$+g\sigma T^4$	$+4\sigma T^3 = +2.0\frac{W}{m^s}\frac{1}{K}$
Ice-albedo	$(1-\alpha_p)Q \propto -\frac{\Delta\alpha}{\Delta T}QT$	$-\frac{\Delta\alpha}{\Delta T}Q = 10\frac{W}{m^2}\frac{1}{K}$

Regional feedbacks: 10-100 W/m^2 1/K

(Source: D. Dommenget)

Global feedbacks: <5 W/m^2 1/K (black body radiation)

Thank you very much for your attention!