

Climate of the Ocean

Lecture 1: Introduction and fundamental processes of the climate system

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(IOW)

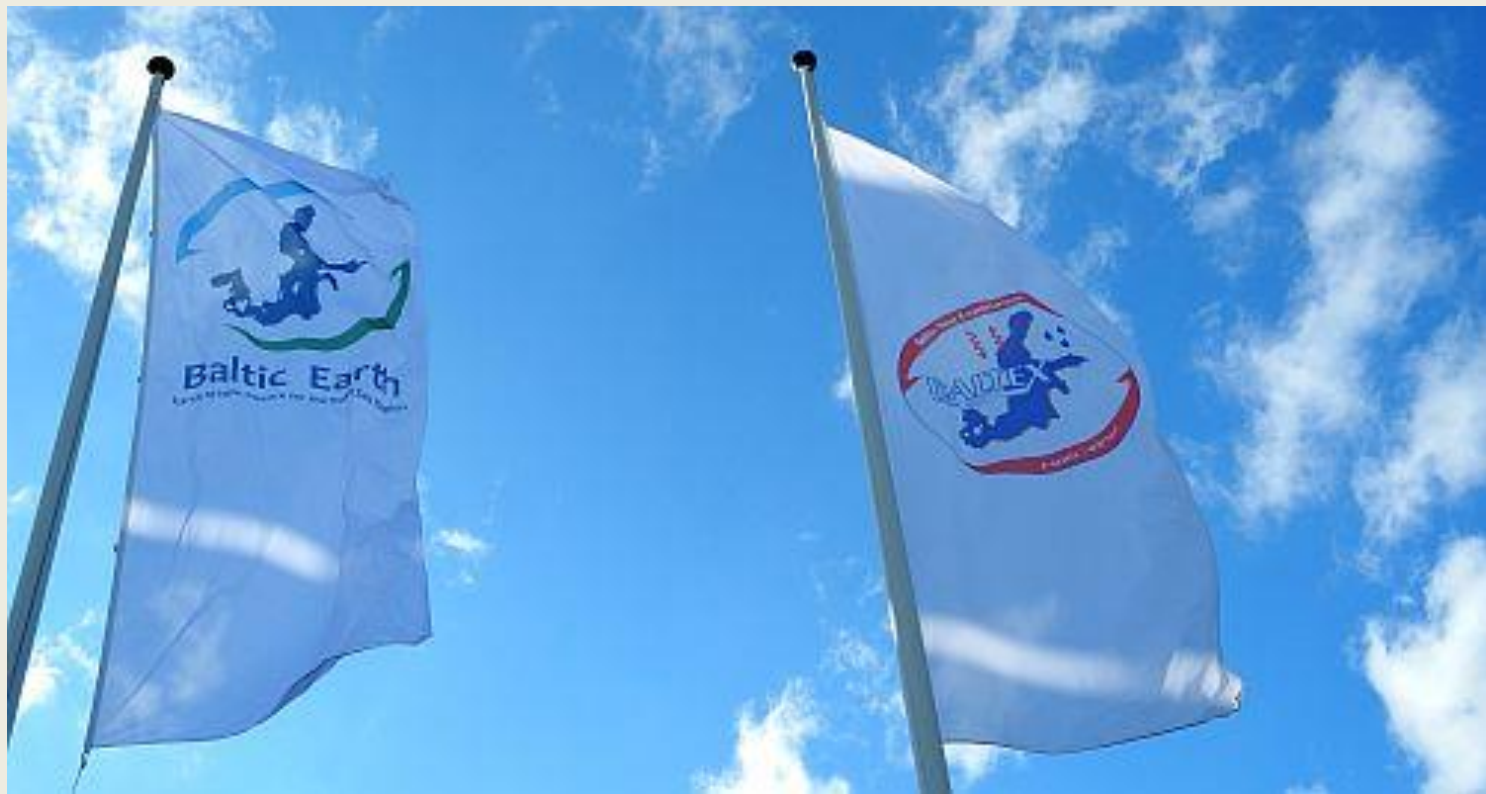
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General information

- about the course: Climate of the Ocean (winter term), Climate of the Baltic Sea Region (summer school 20-27 August, on Askö, Sweden), 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, master thesis
- Baltic Earth www.baltic.earth

Baltic Earth

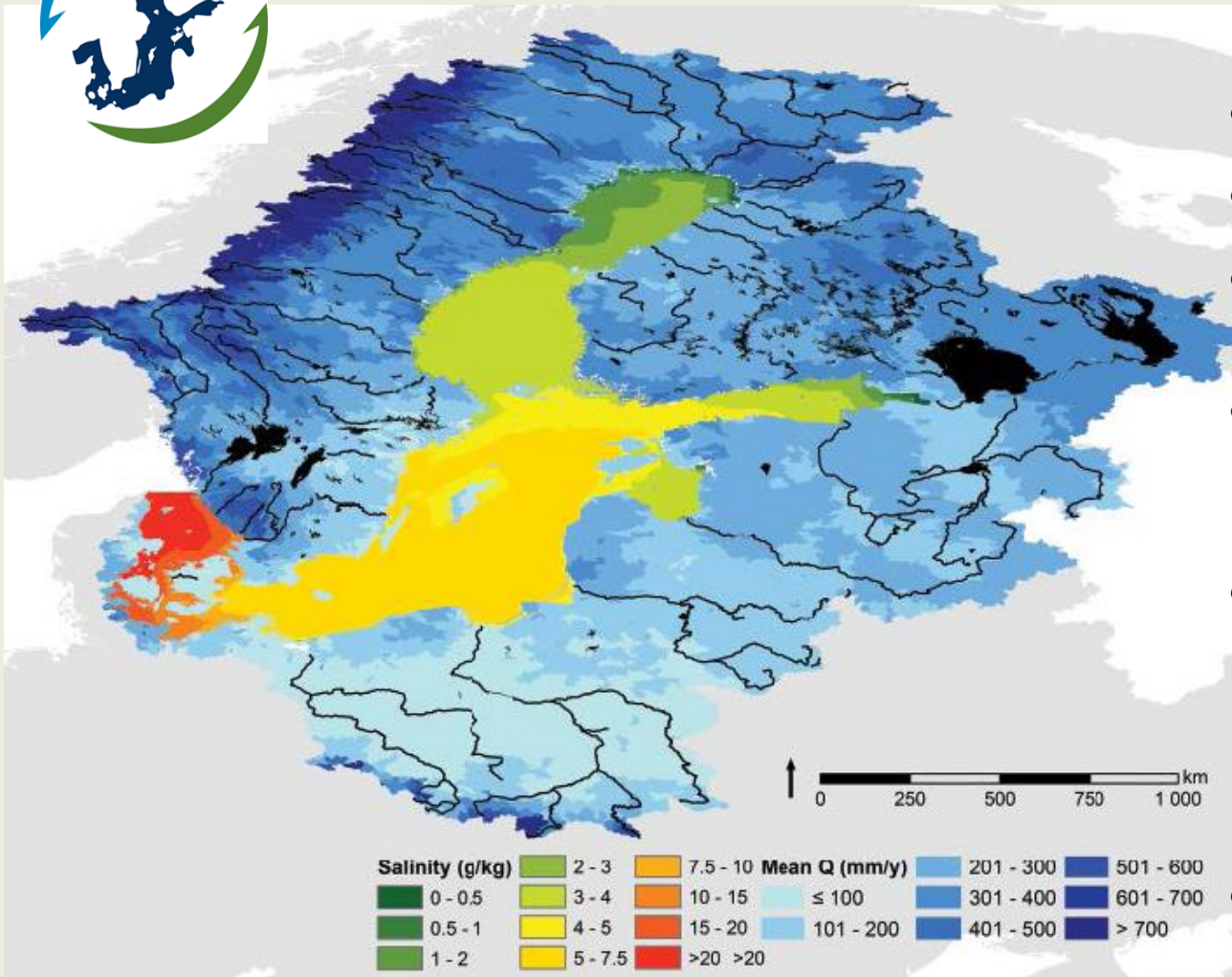
<http://www.baltic.earth/>



Earth System Science for the Baltic Sea basin

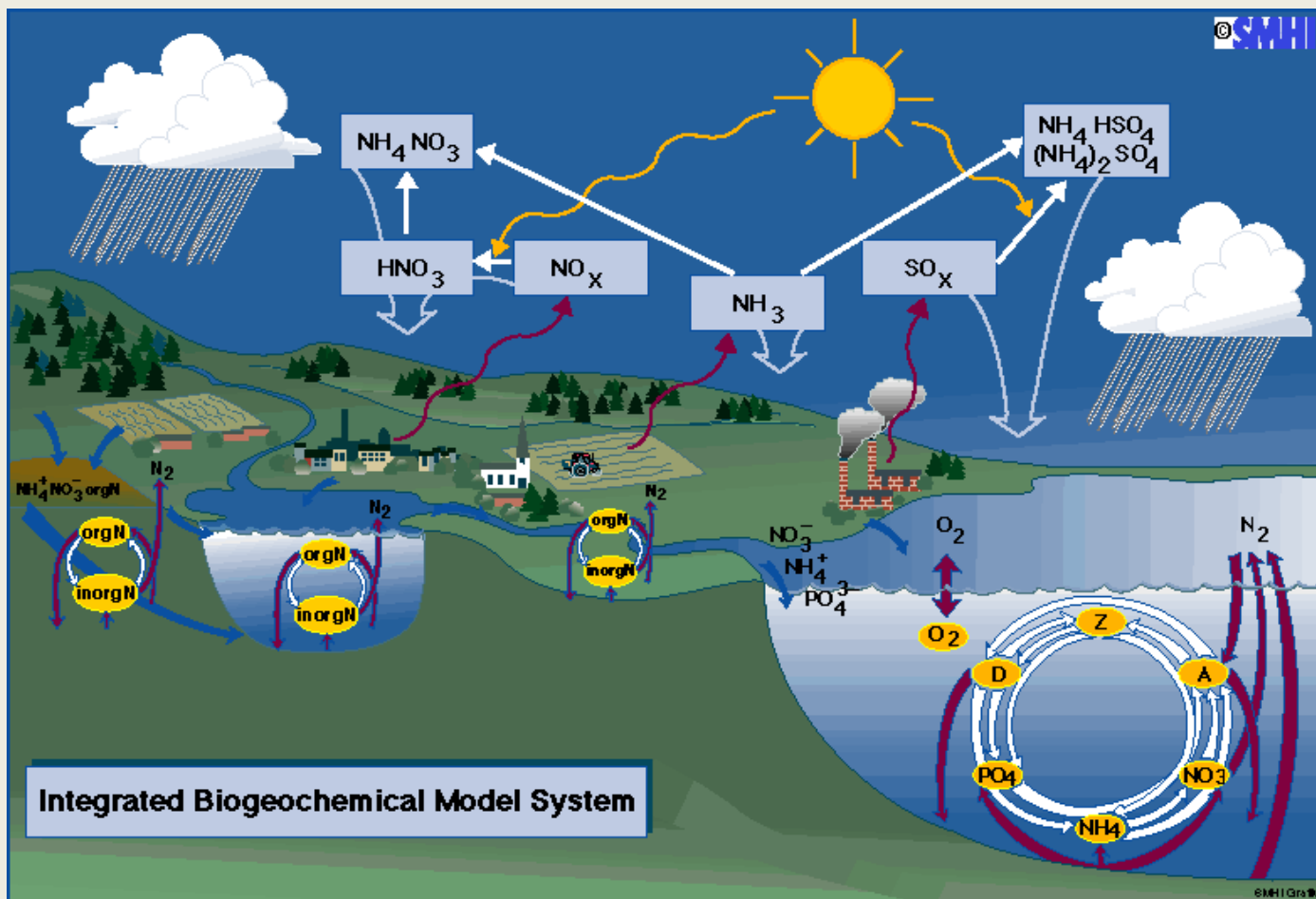


The Baltic Sea region



- 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

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 (14 lectures á 90 min, tutorials and exercises, 45 minutes examination)
- October 18, 25
- November 1, 8, 15, 22, 29
- December 6, 13, 20
- January 10, 17, 24, 31
- Exercises: uneven weeks
- Compensation for one lecture in December 13 x 7 min = 90 min, hence 13:15-15:00 with 8 min 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

- Lecture Notes on Climate of the Ocean, WS 2016/2017

Climate assessments:

- 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)

Literature

Atmospheric and oceanic fluid dynamics:

- James R. Holton: An introduction to dynamic meteorology
- Geoffrey K. Vallis: Climate and the oceans
- Geoffrey K. Vallis: Atmospheric and oceanic fluid dynamics
- Olbers, Willebrand and Eden: Ocean Dynamics, Springer (2012)

Climate of the Baltic Sea Region:

- Lectures from Askö 2015 available as youtube movies
@www.baltic.earth, Askö 2016 (pdf), password protected

Literature

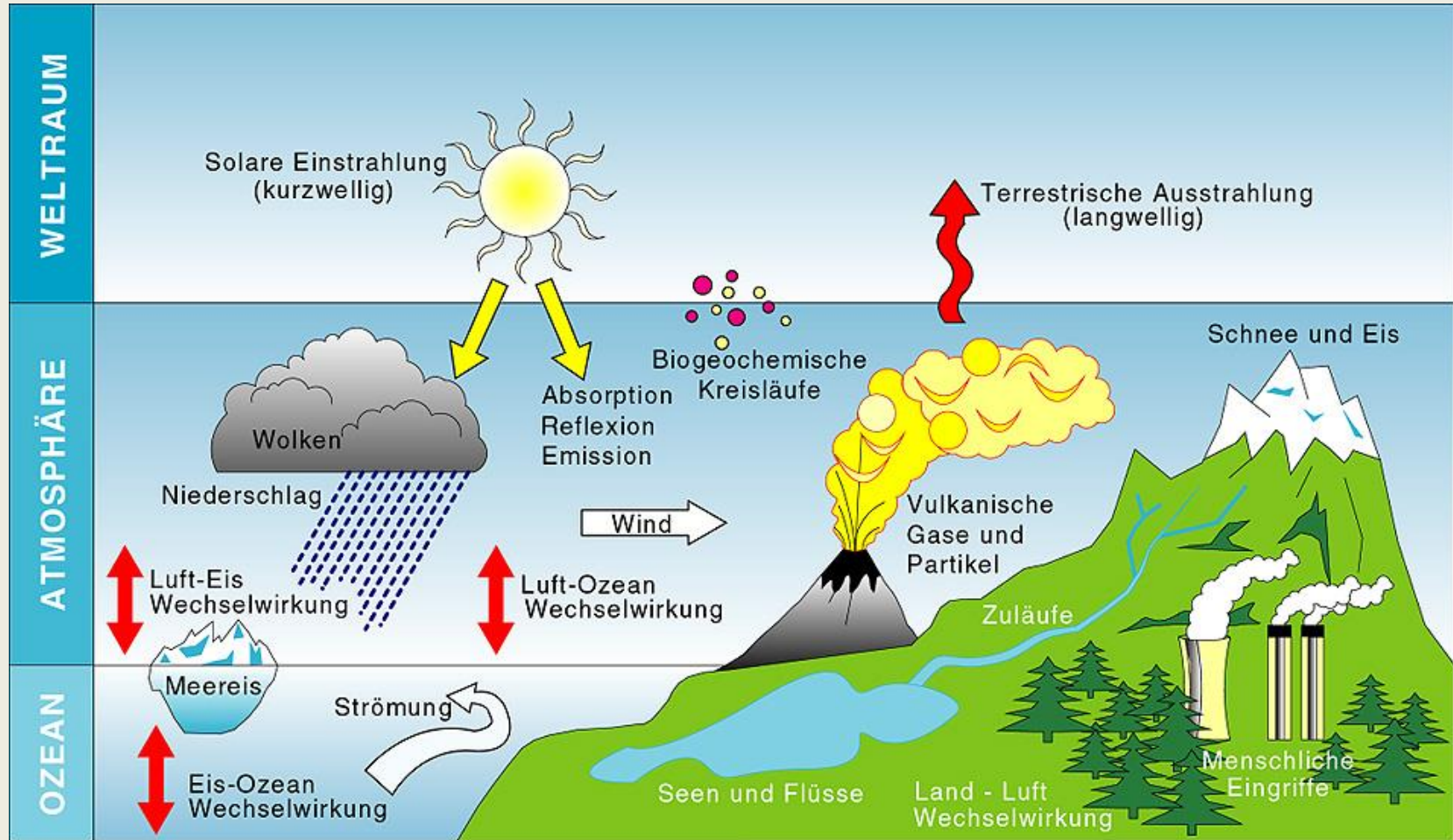
- Courtesy: Lectures from Ulrich Cubasch, Erik Kjellström
- Lecture notes: Dietmar Dommengeset
<http://users.monash.edu.au/~dietmard/teaching/dommengeset.climate.dynamics.notes.pdf>
- Hamburger Bildungsserver
<http://bildungsserver.hamburg.de/klimawandel/> (only in German)

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).

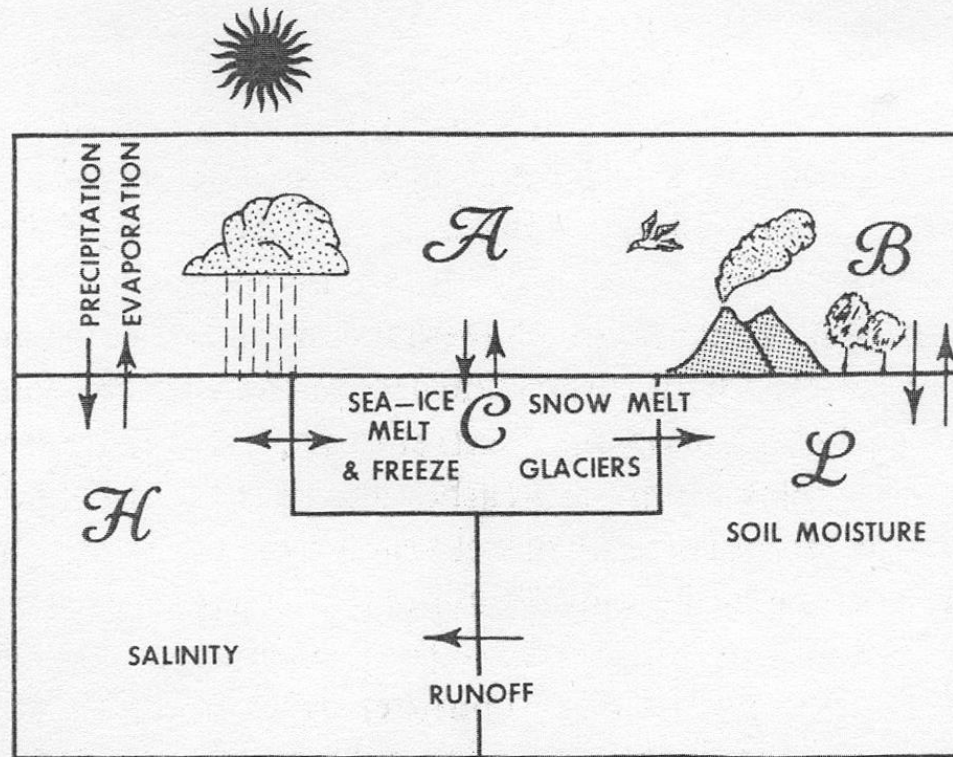
(Houghton, J. T., et al. (eds.), 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 881 p.)



The climate system

(Source: Hamburger Bildungsserver)

THE TOTAL CLIMATE SYSTEM AND ITS SUBSYSTEMS



A = atmosphere

H = hydrosphere (ocean)

C = cryosphere (snow & ice)

L = lithosphere (land)

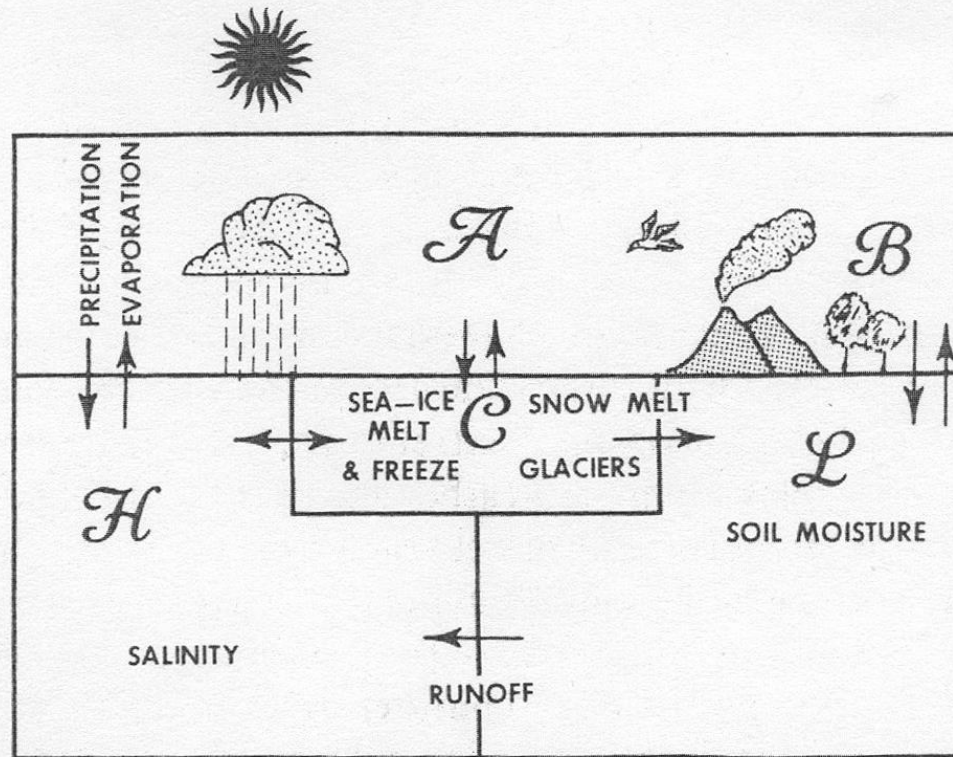
B = biosphere

(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 variabilityvariations are called “weather”

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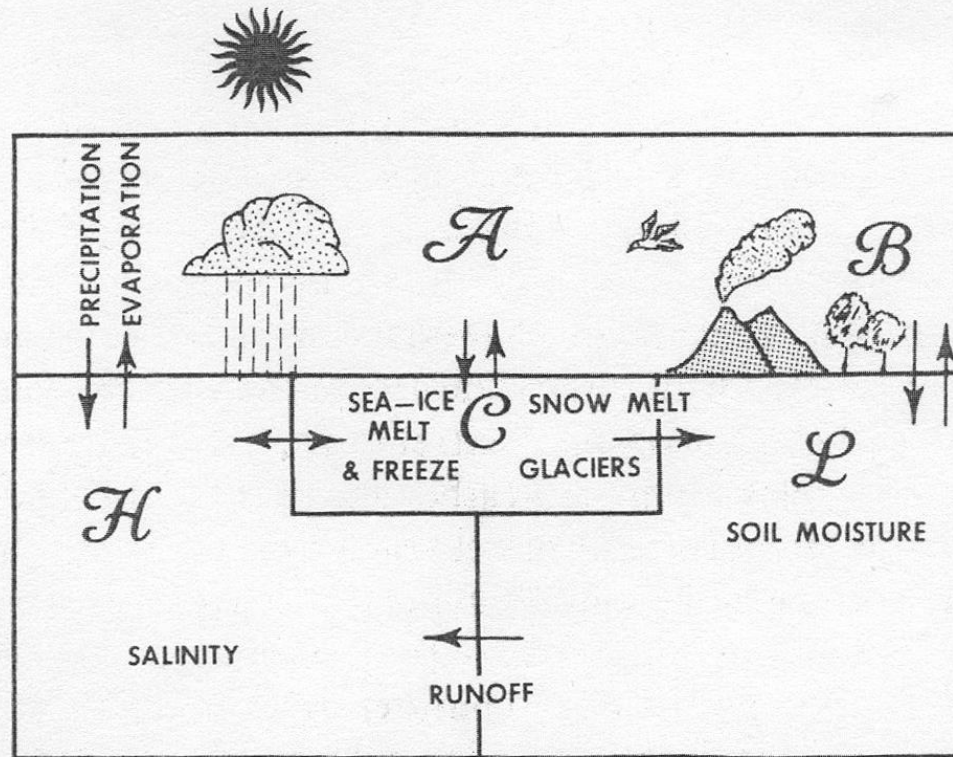
(Source: Peixoto and Oort 1992)

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

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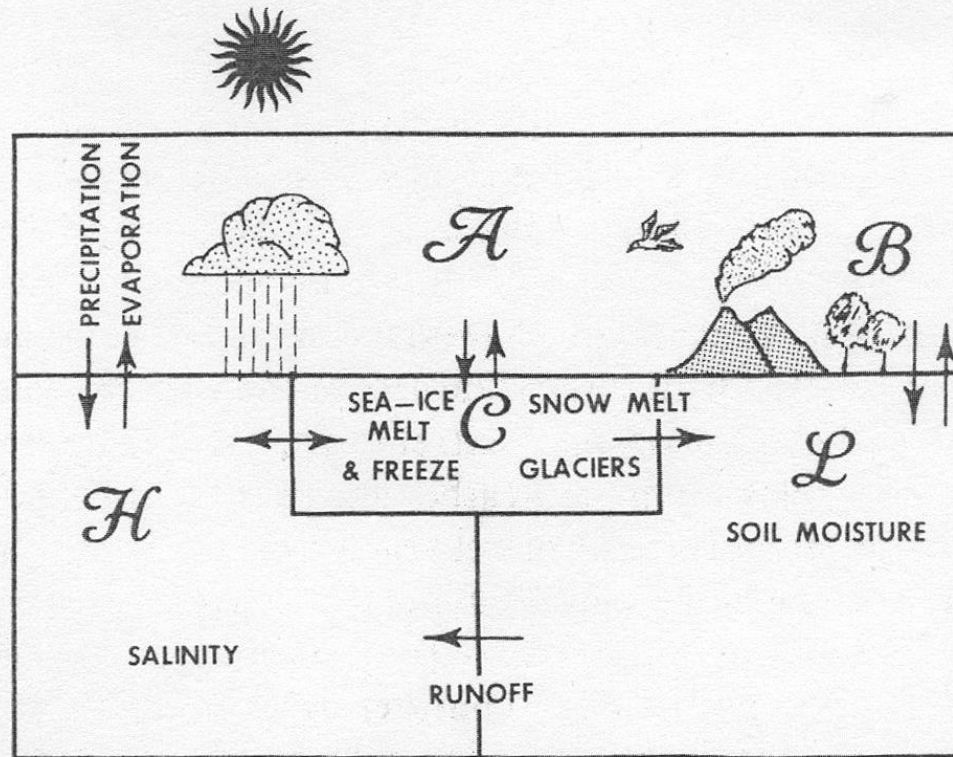
(Source: Peixoto and Oort 1992)

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

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(Source: Peixoto and Oort 1992)

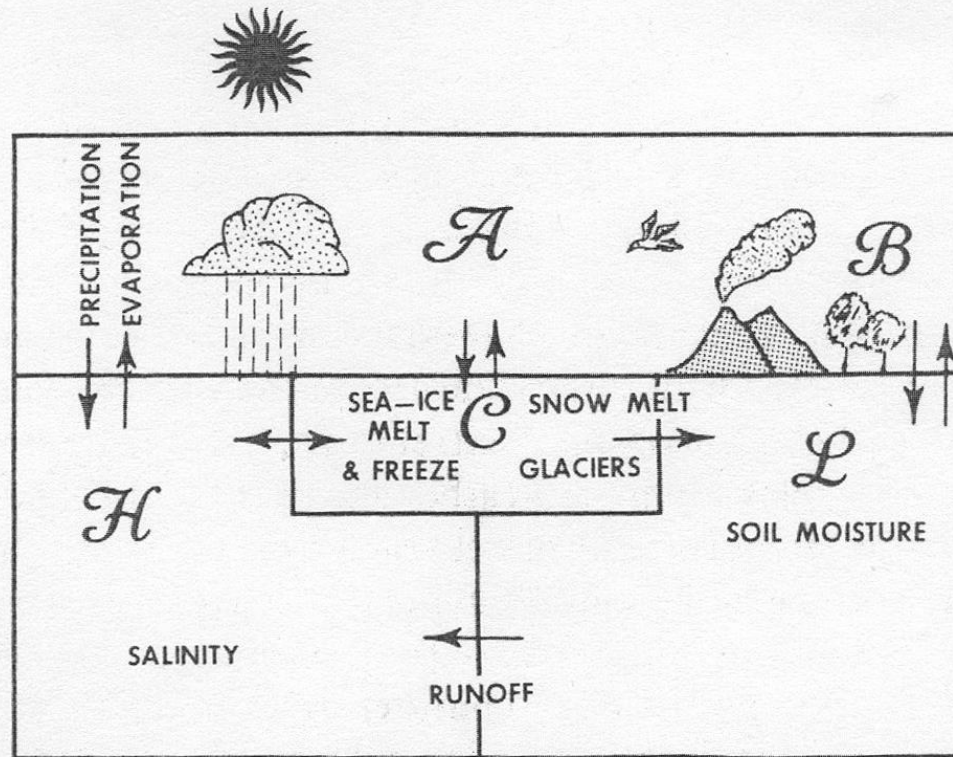
***B*: biosphere (terrestrial)**

- **Bio-geophysical interaction:** albedo, evaporation, roughness
- **Bio-geochemical interaction:**
 - photosynthesis and respiration of carbon
 - Impact on CH₄ emissions
- **Time scales:**
 - physiology (reaction of the stomata): minutes
 - succession: 30 – 150 years,
 - migration: 300 – 1500 years

***B:* biosphere (marine)**

- carbon pump (time scales as in the terrestrial environment)
- CO₂- sink / source

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(Source: Peixoto and Oort 1992)

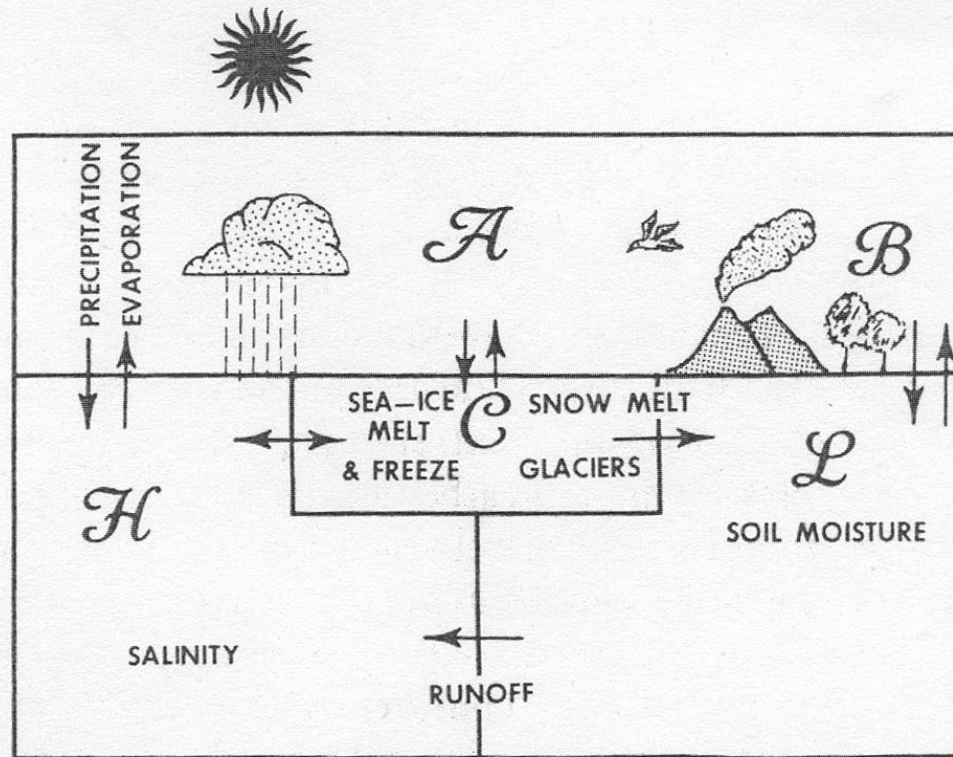
***P*: pedosphere (outermost layer of the Earth composed of soils)**

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

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

THE TOTAL CLIMATE SYSTEM AND ITS SUBSYSTEMS



- A = atmosphere
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(Source: Peixoto and Oort 1992)

Radiation balance (zero order model)

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

γ_{surf} = heat capacity [$J/m^2/K$]

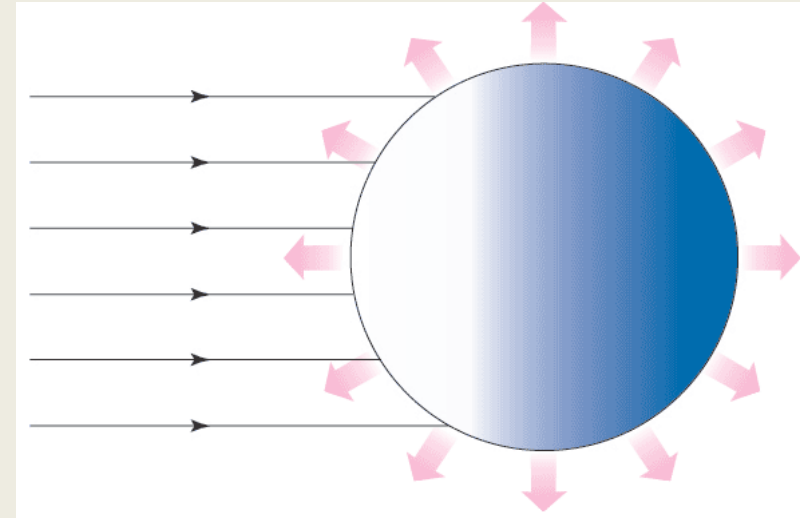
T_{surf} = surface temperature [K]

$F_{solar} + F_{thermal}$ = forcing terms [W/m^2]

(Source: D. Dommenges)

A very simple climate model

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



$$F_E = \sigma T_E^4 = \frac{(1 - A) s_0}{4} = 239.4 \text{ W m}^{-2}$$

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

solar constant (s_0) 1368 W m^{-2}

planetary albedo (A) 30%

Stefan Boltzmann constant

$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

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

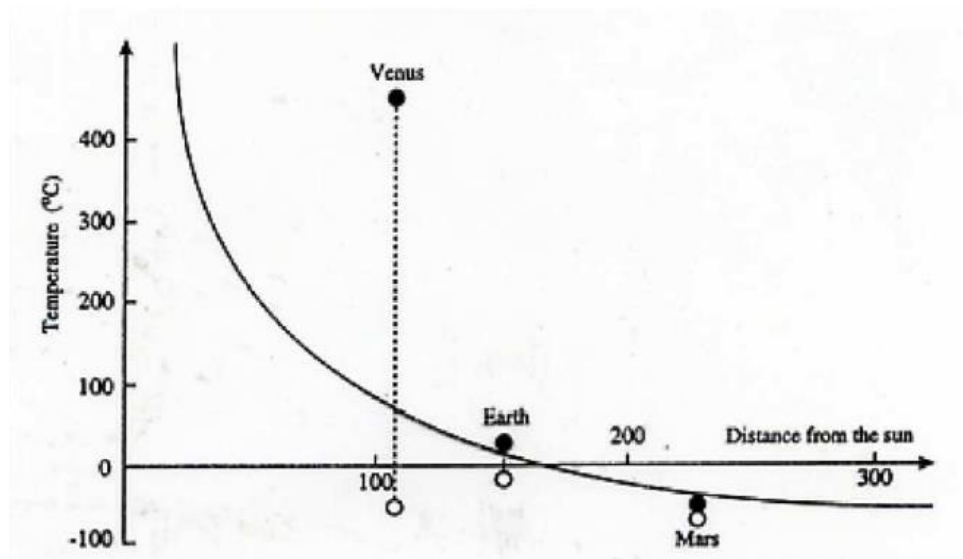
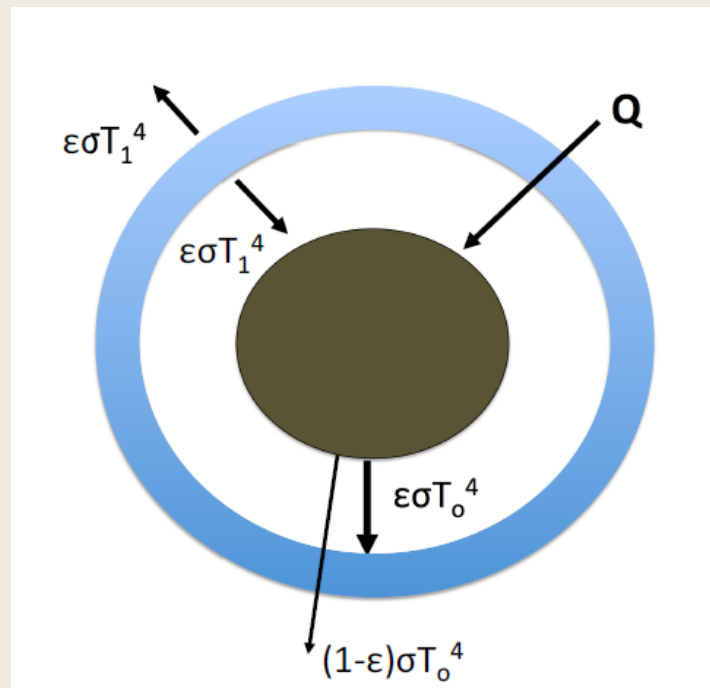


Figure 2.5: Distance from the Sun versus radiation temperature of a black body absorbing the incoming sun light (solid line). The black filled circles mark the observed T_{surf} of Venus, Earth and Mars and the black unfilled circles mark the radiation temperature of the planets according to their observed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

(Source: D. Dommenges)

Greenhouse effect illustrated by Greenhouse shield models



$$T_0 = T_{\text{surf}}$$

$$T_1 = T_{\text{atm}}$$

T_1 = temperature of the atmosphere

$\epsilon < 1$ emissivity

Atmosphere absorbs the portion ϵ of the thermal radiation

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

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

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

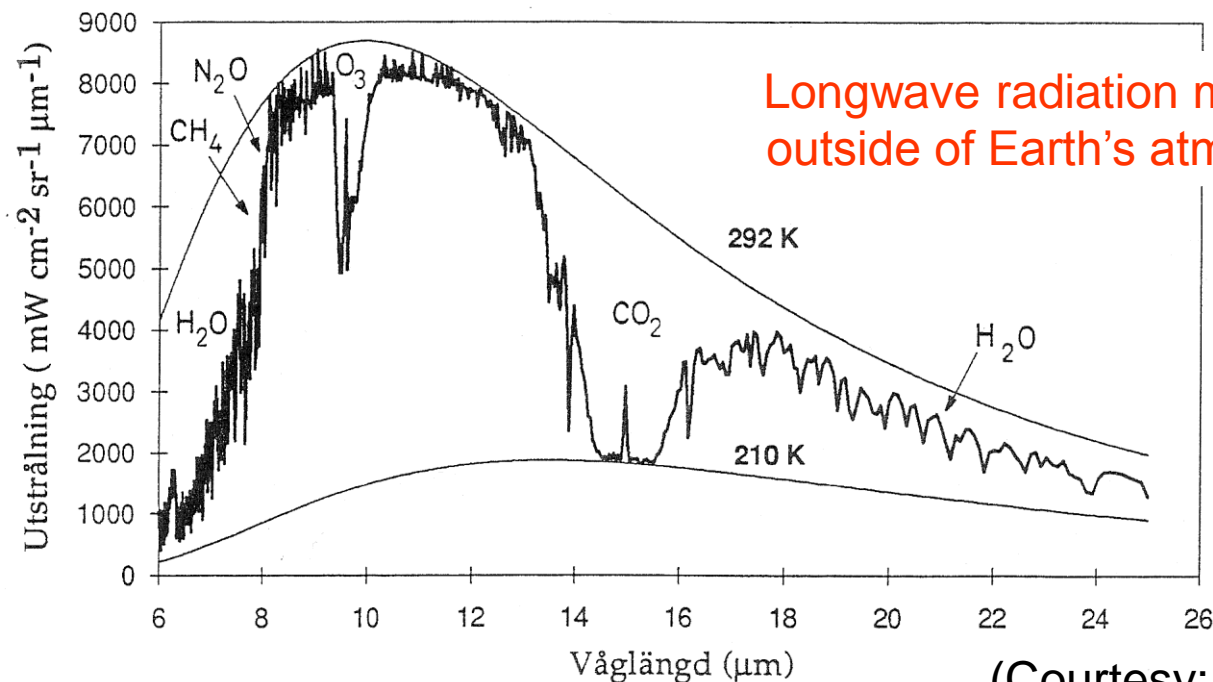
$$\Rightarrow \epsilon = 2\left(1 - \frac{T_{\text{rad}}^4}{T_{\text{surf}}^4}\right) = 0.77$$

(Source: D. Dommenges)

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

Longwave radiation

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



(Courtesy: E. Kjellström)

Gaseous constituents

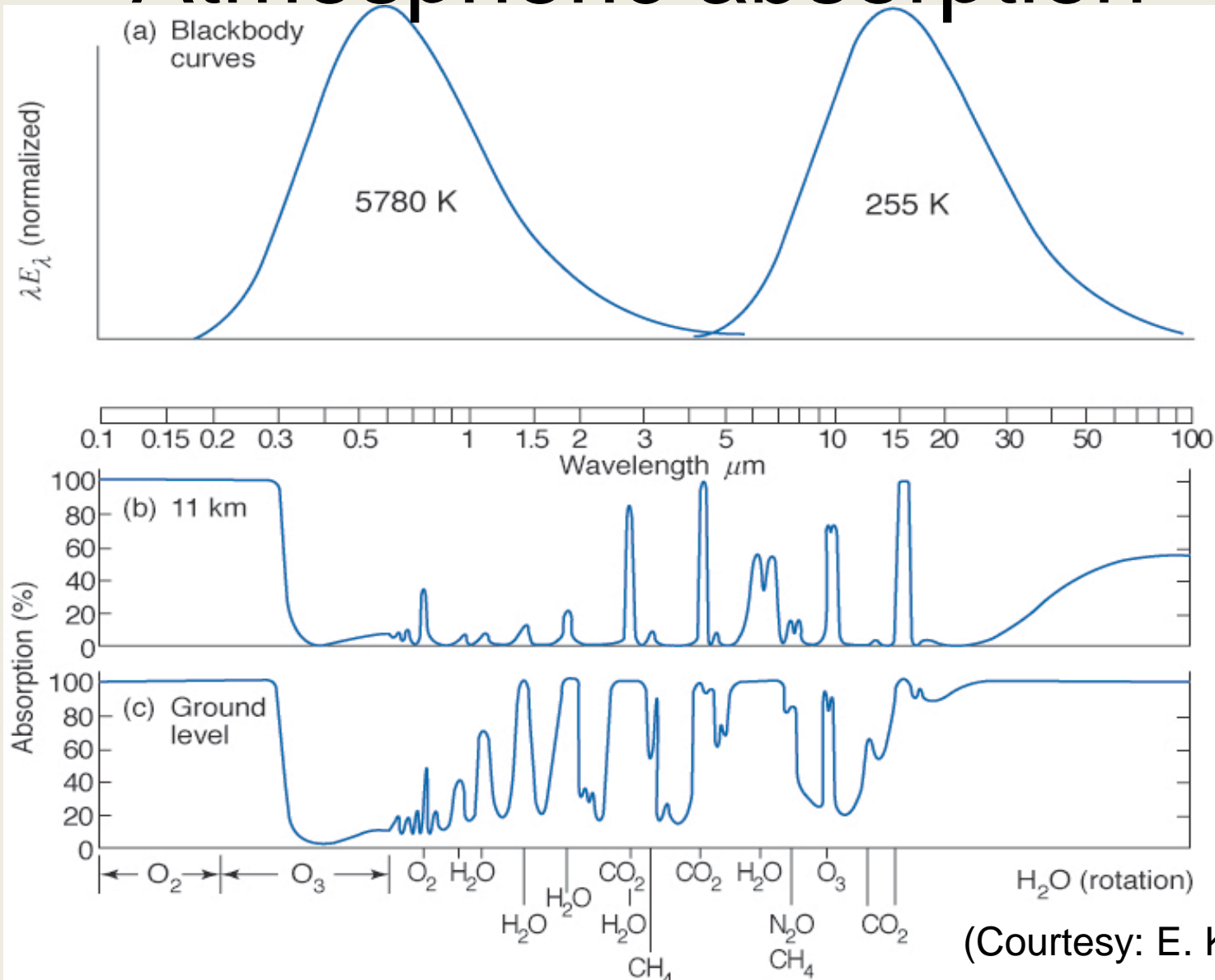
Constituent	Mol. Wt.	Conc. by vol.
Nitrogen (N_2)	28.013	0.7808
Oxygen (O_2)	32.000	0.2095
Argon (Ar)	39.95	0.0093
<i>Carbon dioxide (CO_2)</i>	<i>44.01</i>	<i>387 ppmv (2009)</i>
Neon (Ne)	20.18	18
Helium (He)	4.00	5
<i>Methane (CH_4)</i>	<i>16.</i>	<i>1.78 "</i>
Hydrogen (H_2)	2.02	0.5 "
<i>Nitrous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

In addition

<i>Water vapor (H_2O)</i>	<i>18.02</i>	<i>variable</i>
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(Courtesy: E. Kjellström)

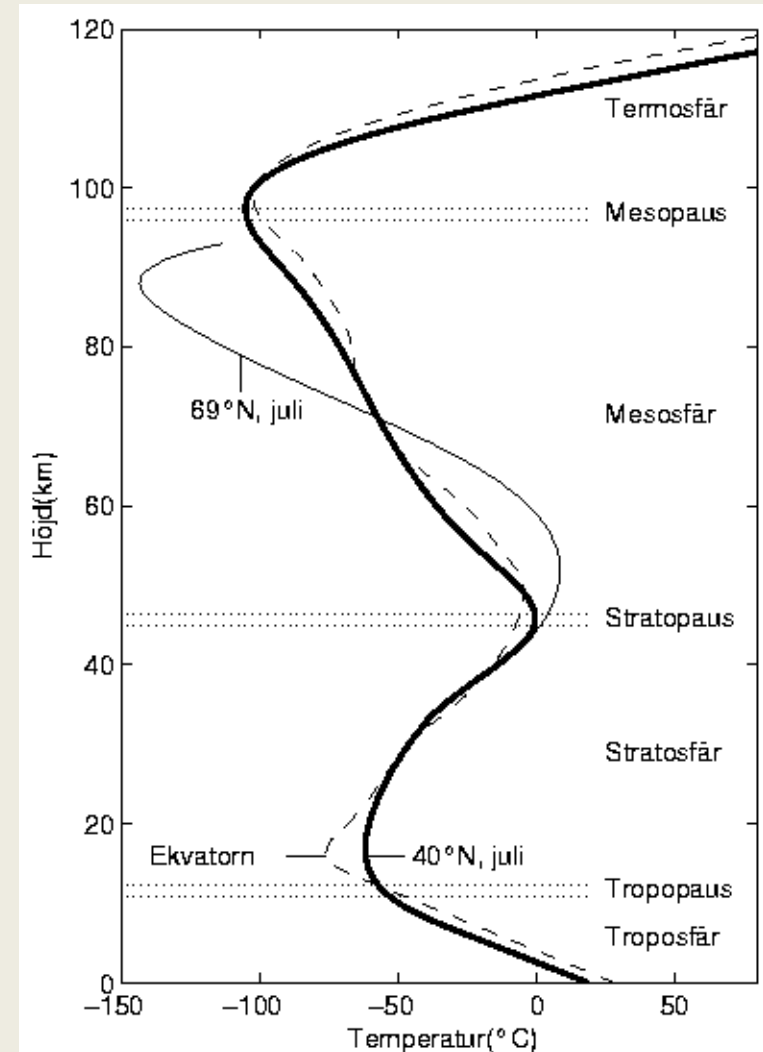
Atmospheric absorption



(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

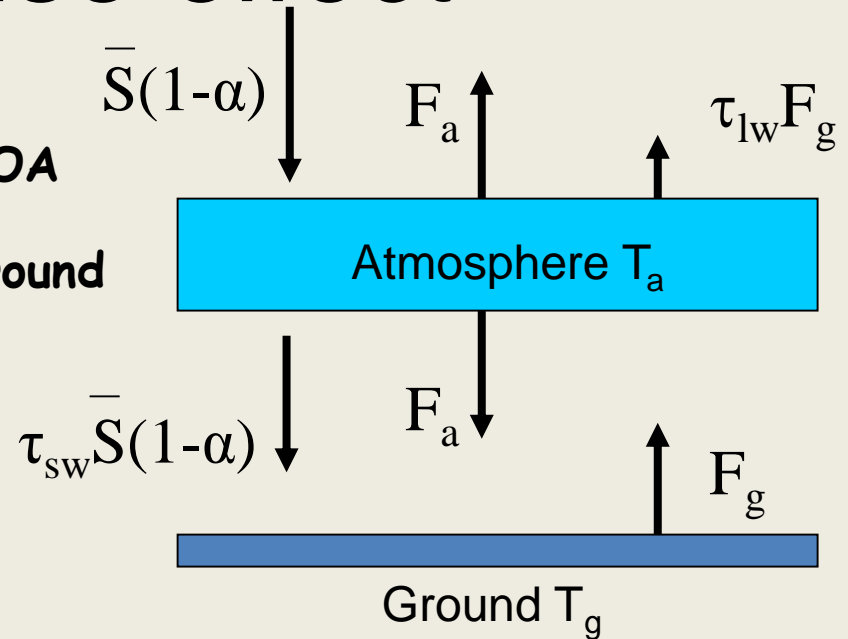
$$\begin{cases} \bar{S}(1-\alpha) = F_a + \tau_{lw} F_g & \text{At the TOA} \\ F_g = F_a + \tau_{sw} \bar{S}(1-\alpha) & \text{At the ground} \end{cases}$$

eliminate F_a

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

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

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

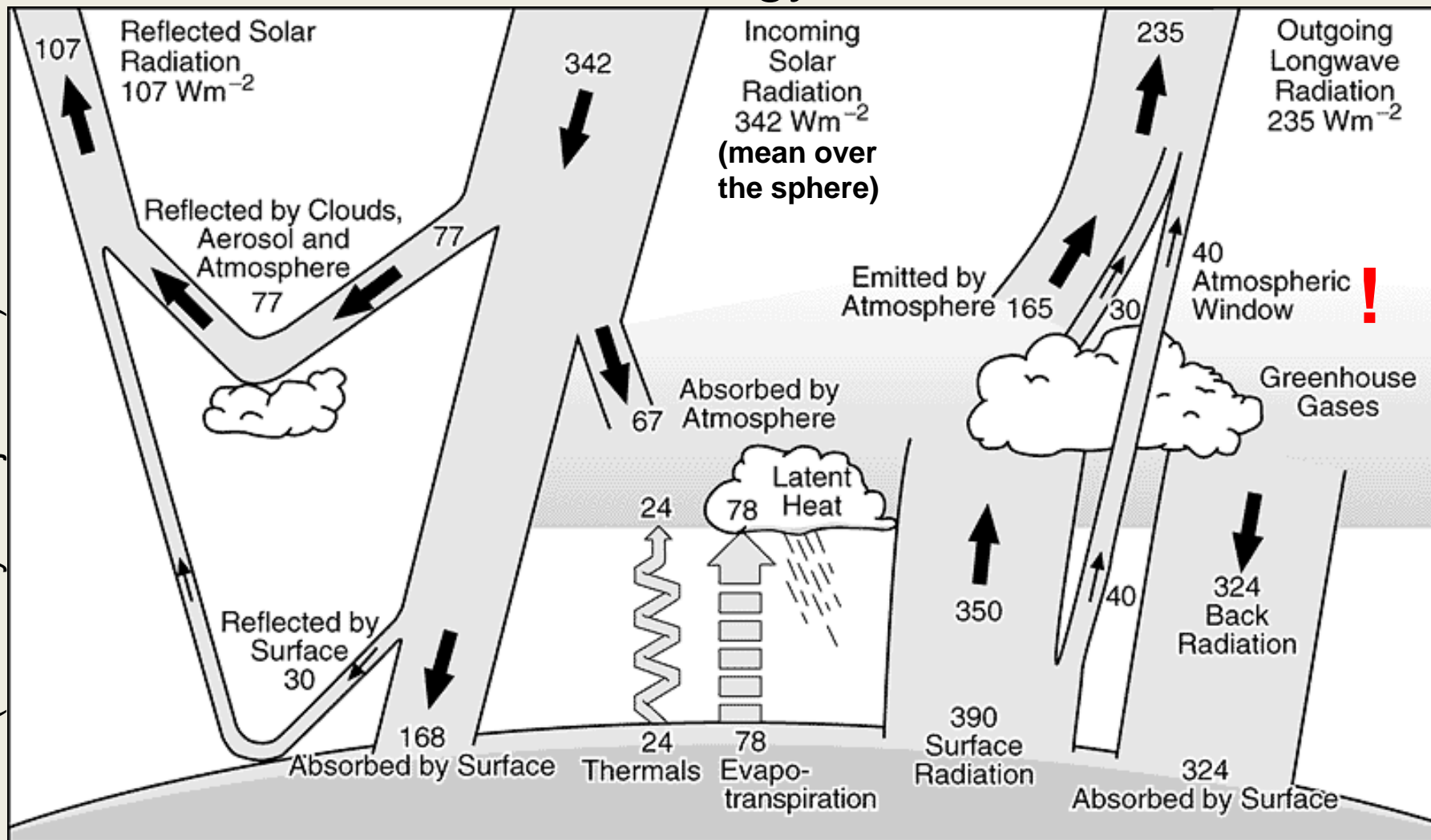


(Courtesy: E. Kjellström)

Global energy balance

Albedo=107/342=31%

342-107=235!!



Absorbed in the sea/land = 168/342=49%

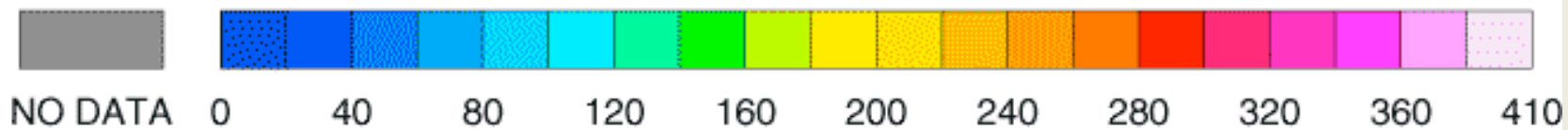
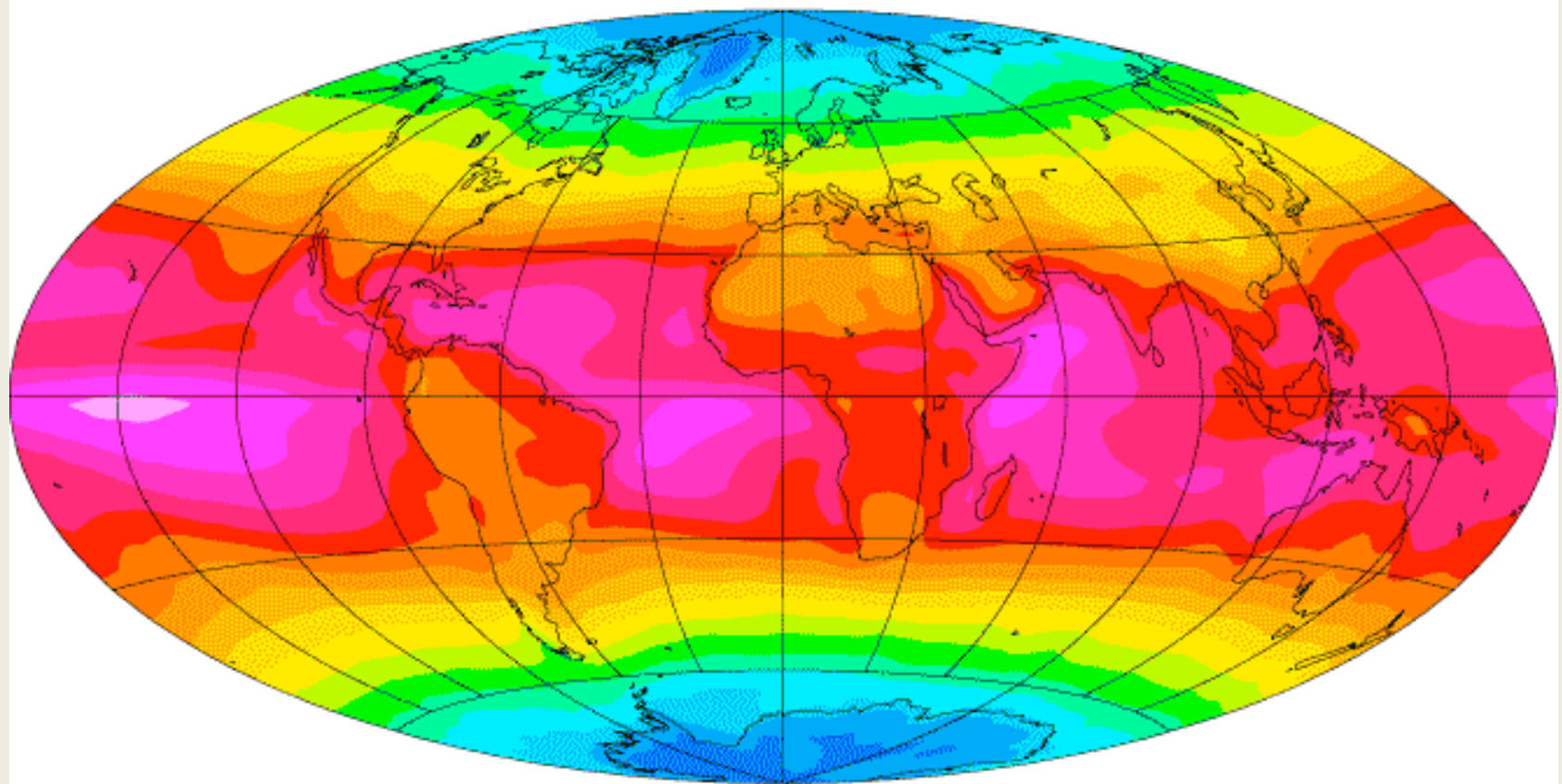
168-24-78-390+324=0!!

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

Atmospheric transmissivity (lw)=40/390=0.10



Absorbed Shortwave Radiation 1985-1986

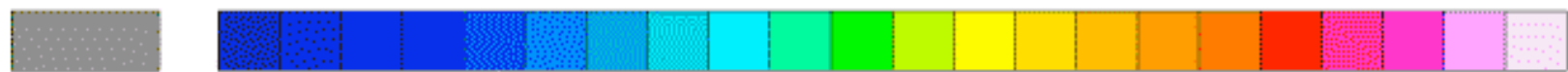
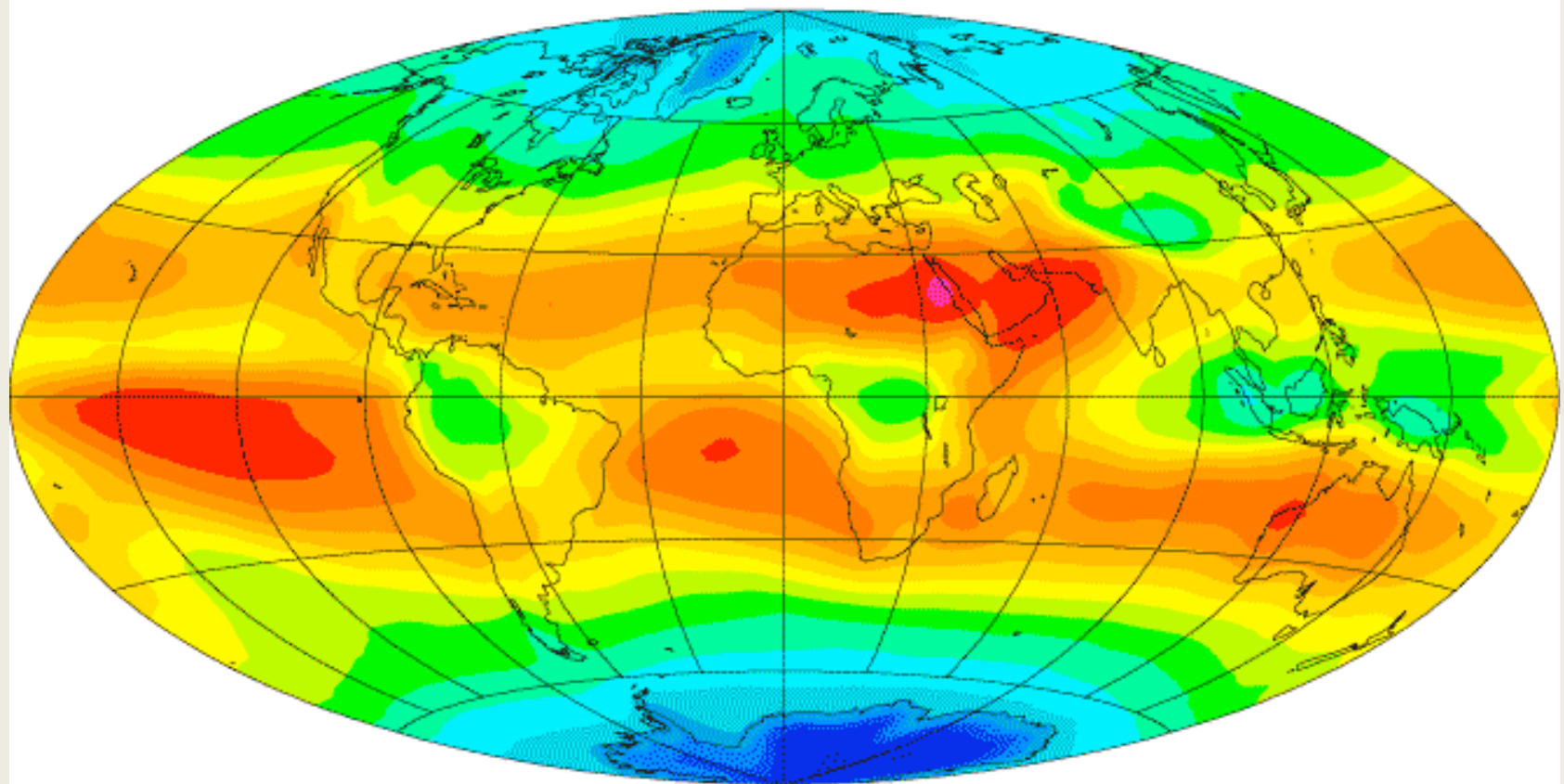


W/m^2

(Courtesy: E. Kjellström)



Outgoing Longwave Radiation 1985-1986



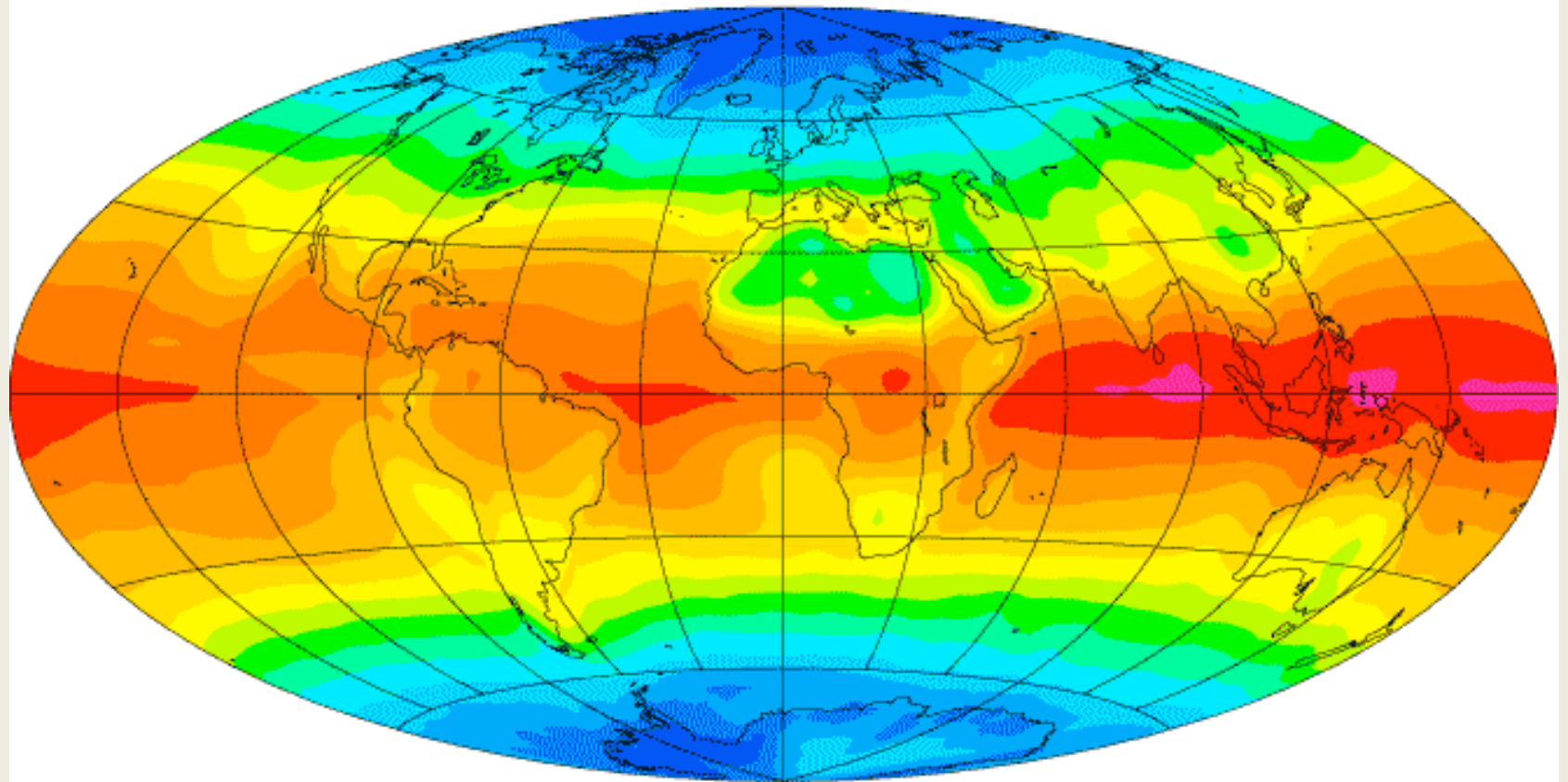
NO DATA 110 130 150 170 190 210 230 250 270 290 310 330

W/m**2

(Courtesy: E. Kjellström)



Net Radiation 1985-1986



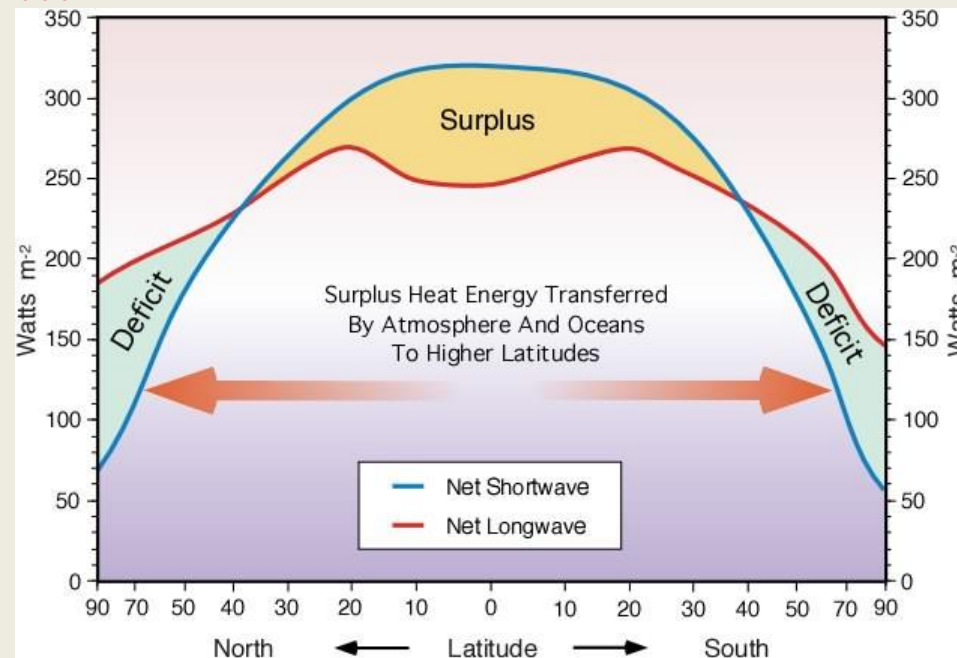
NO DATA -180 -150 -120 -90 -60 -30 0 30 60 90 120 150

W/m^2

(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)

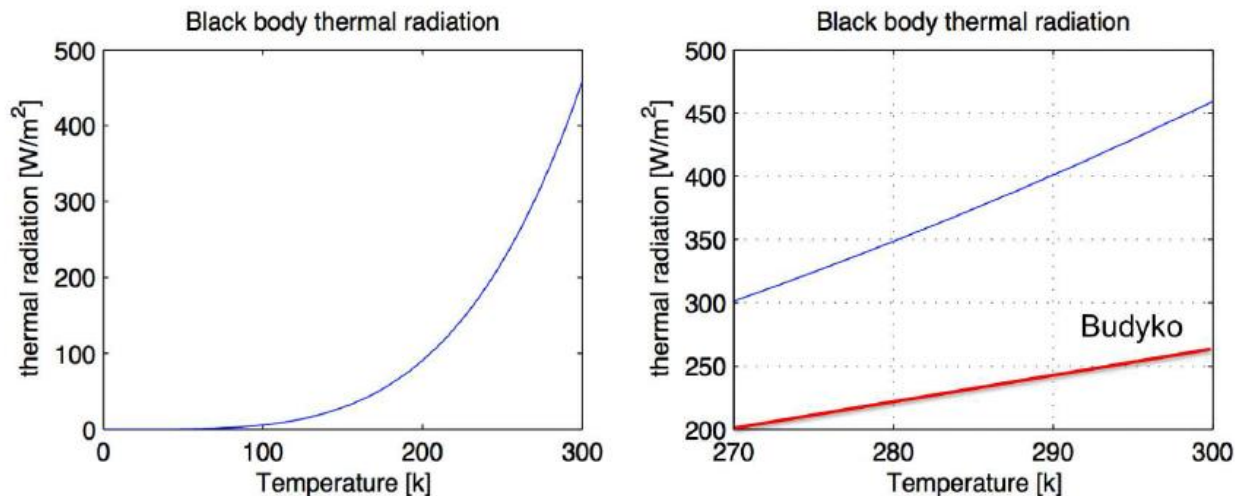
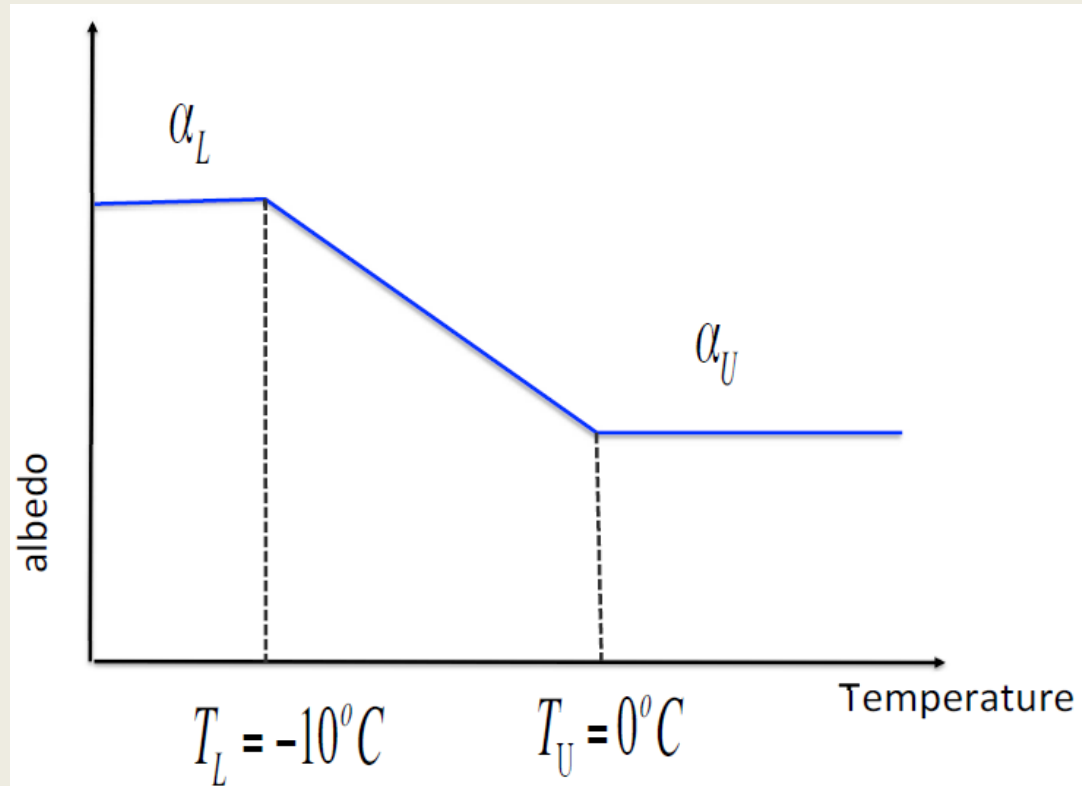


Figure 2.10: Black body thermal radiation: left: Black body thermal radiation for a wide range of temperatures. right: Black body thermal radiation (blue line) for a range of temperature closer to the earth climate in comparison to the Budyko linear model (red line).

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

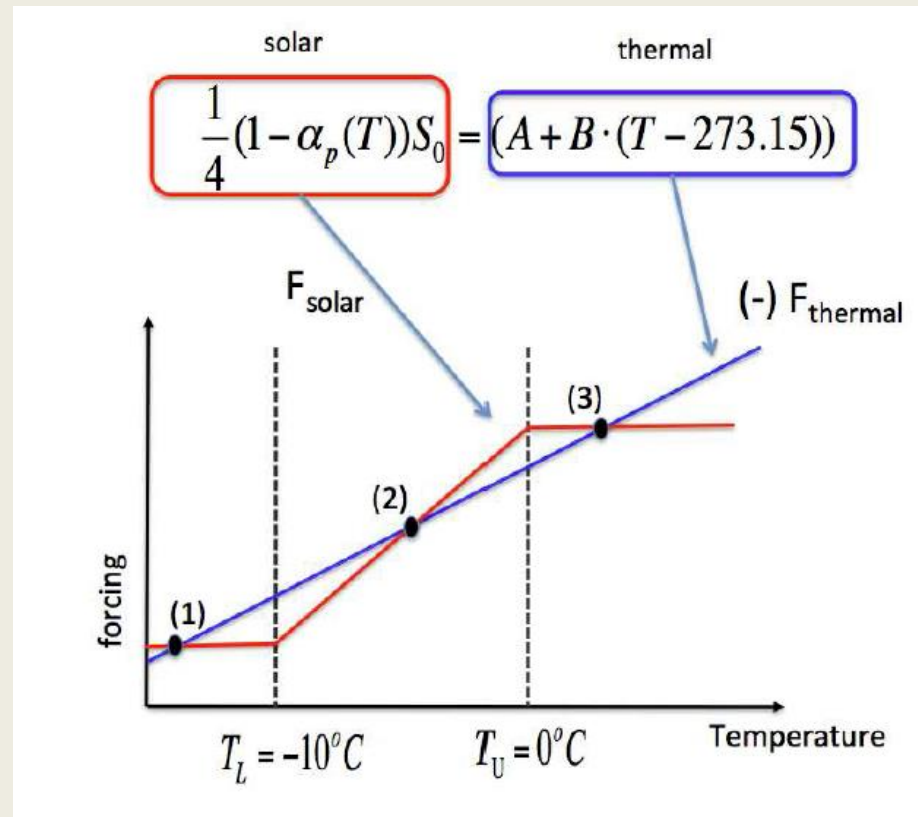
(Source: D. Dommenges)



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

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

(Source: D. Dommenges)



(1) Totally ice covered earth

$$T_{\text{surf}}^{(1)} = \frac{(1 - \alpha_L)Q - A}{B} = -35.2^\circ\text{C}$$

(2) Partially ice covered earth (present day)

$$T_{\text{surf}}^{(2)} = \frac{Q(1 - \alpha_L)\Delta T - A\Delta T + QT_L\Delta\alpha}{B\Delta T + Q\Delta\alpha} = -4.0^\circ\text{C}$$

(3) Ice free world

$$T_{\text{surf}}^{(3)} = \frac{(1 - \alpha_U)Q - A}{b} = +17/0^\circ\text{C}$$

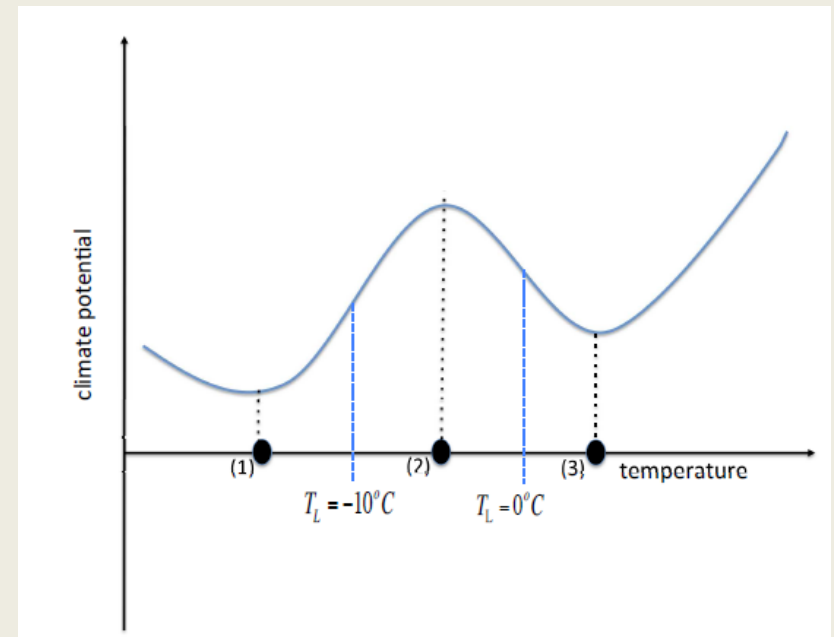
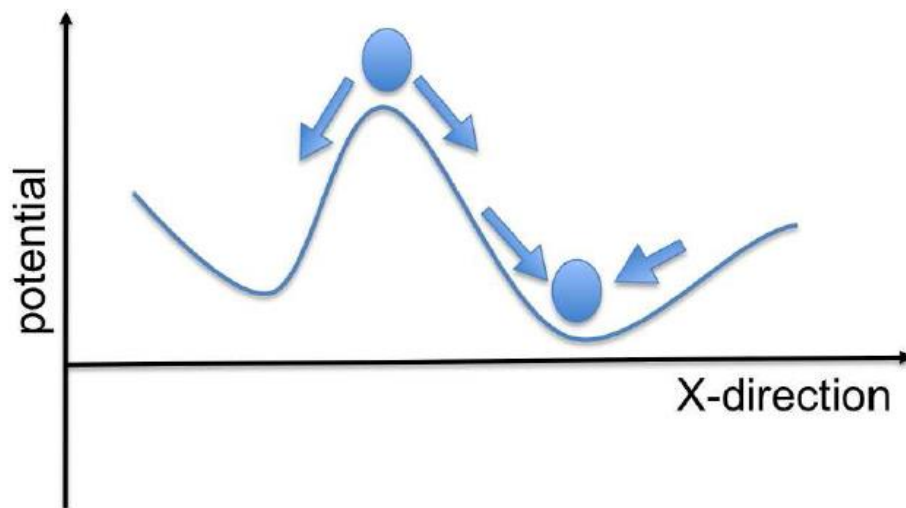
(Source: D. Dommenges)

Climate potential

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

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

Analog: Mechanics <->
Climate



(Source: D. Dommenges)

Climate stability

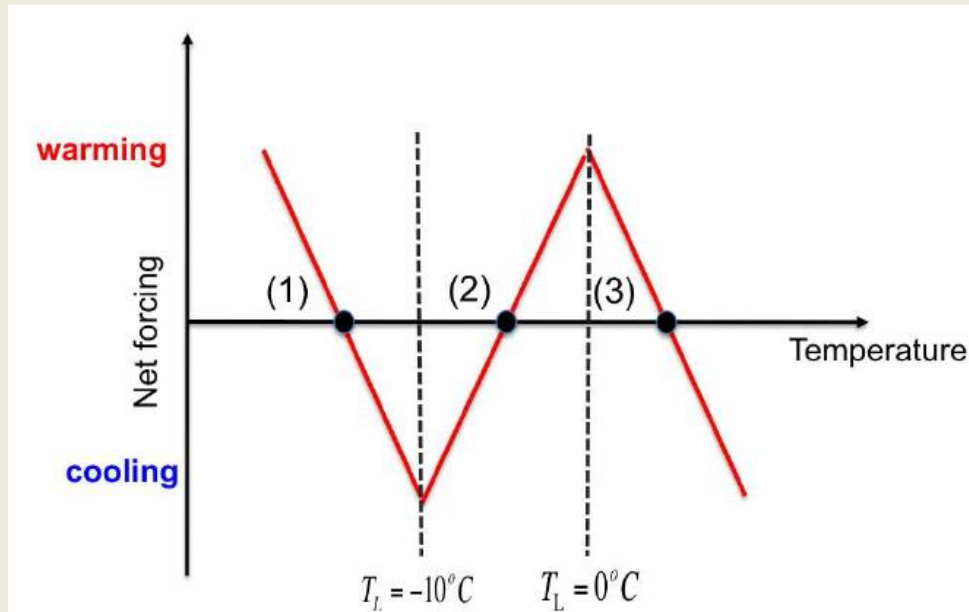
For stable equilibrium:

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

And for unstable equilibrium:

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

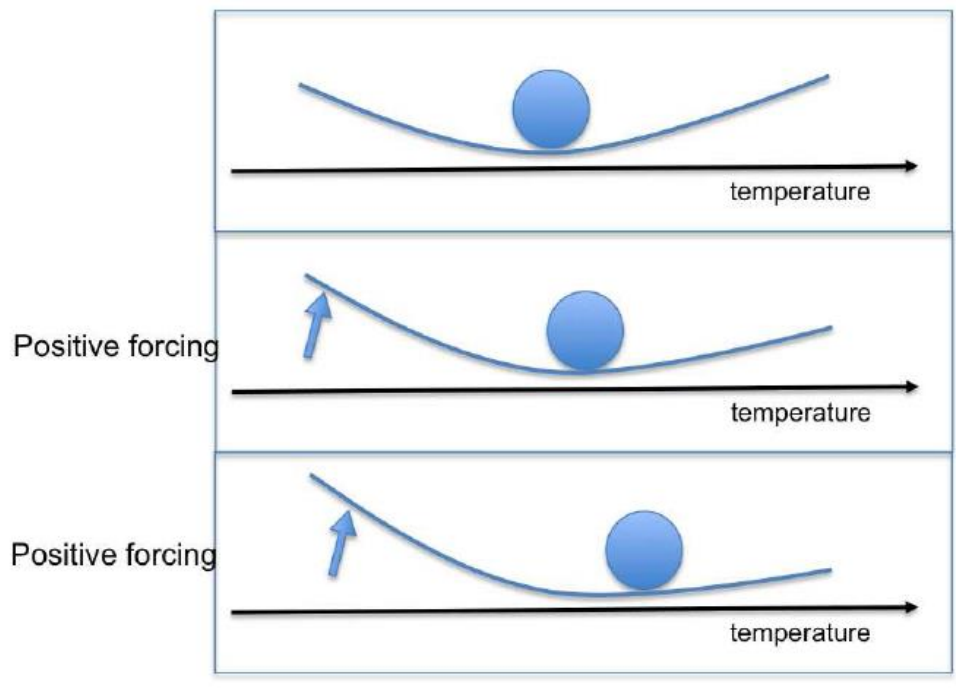
$$F_{net} = ((1 - \alpha_p(T_{surf})) \cdot Q - (A + B \cdot (T_{surf} - 273.15)))$$



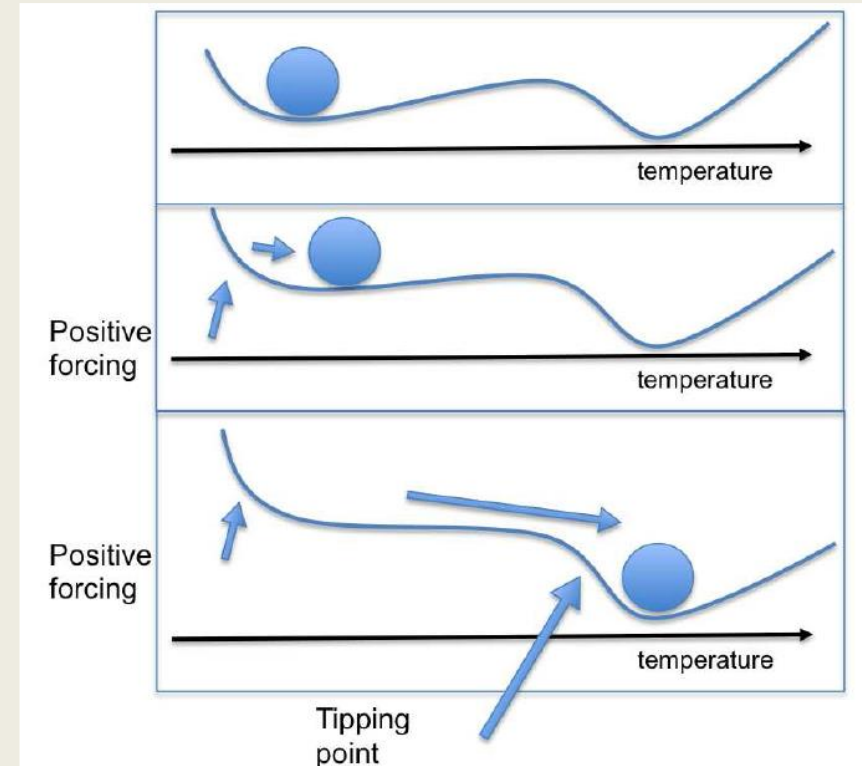
- | | |
|---|------------|
| (1) Totally ice covered earth | → stable |
| (2) Partially ice covered earth (present day) | → unstable |
| (3) Ice free world | → stable |

(Source: D. Dommenges)

Tipping points



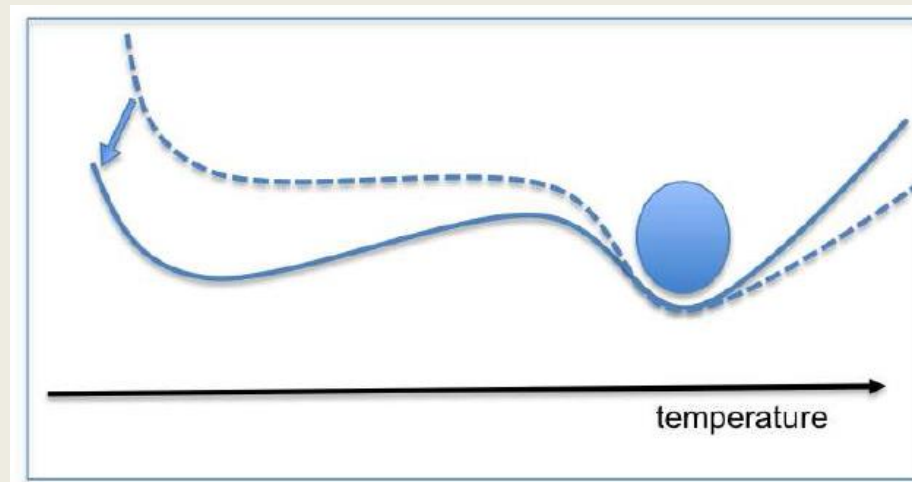
Zero order model (no feedbacks)



Budyko model with the ice-albedo feedback

(Source: D. Dommenges)

Tipping point: climate change is irreversible



(Source: D. Dommenges)

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. Dommenges)

Climate sensitivity II

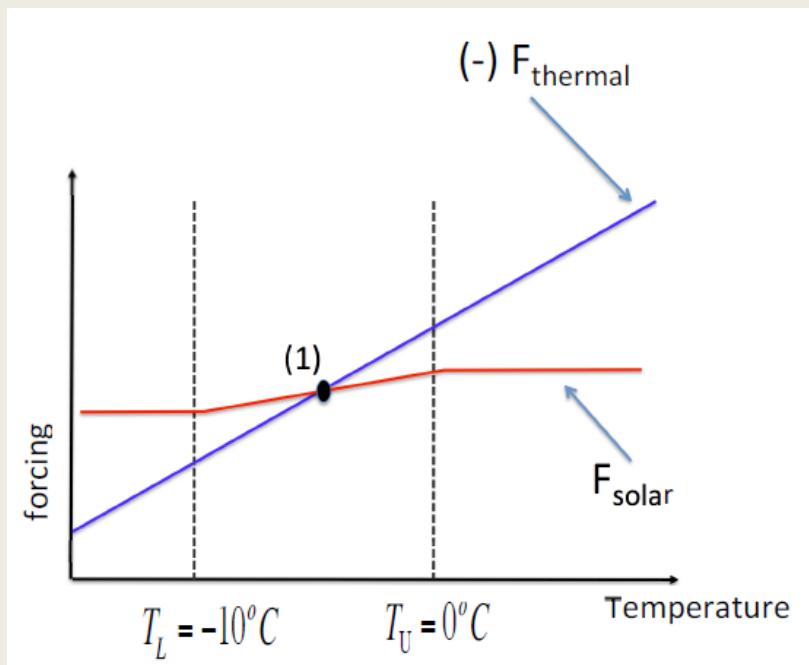
Example 3: Budyko model without ice-albedo feedback ($\alpha_p=0.3$)

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

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

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. Dommenges)

Feedbacks

Definition:

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

Example: simple linear climate model

$$\gamma \frac{dT}{dt} = C_f \cdot T + Q$$

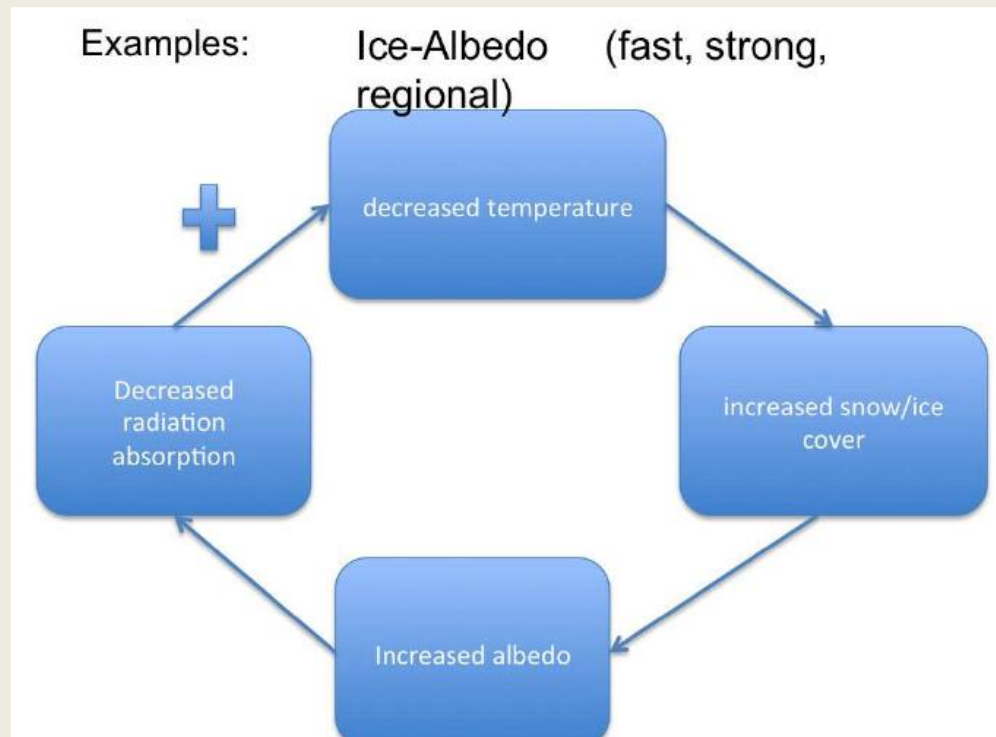
Climate feedback parameter C_f

Equilibrium temperature:

$$\Rightarrow T_{eq} = \frac{Q}{-C_f}$$

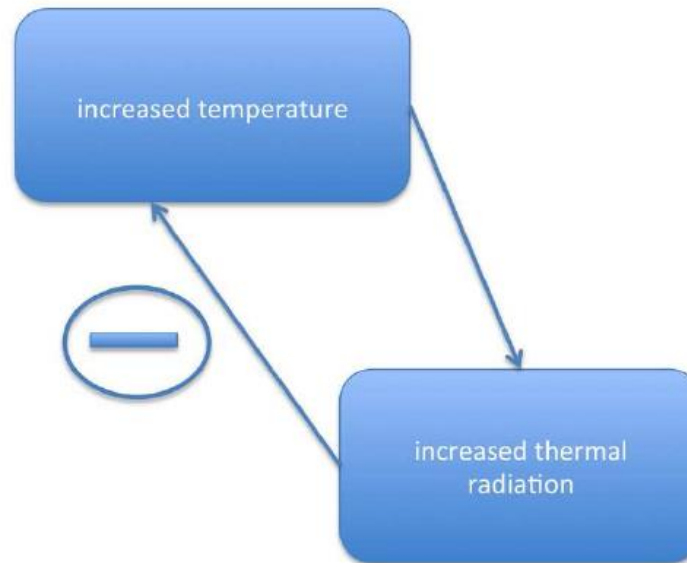
$$\lambda = \frac{dT}{dQ} = \frac{1}{-C_f}$$

(Source: D. Dommenges)



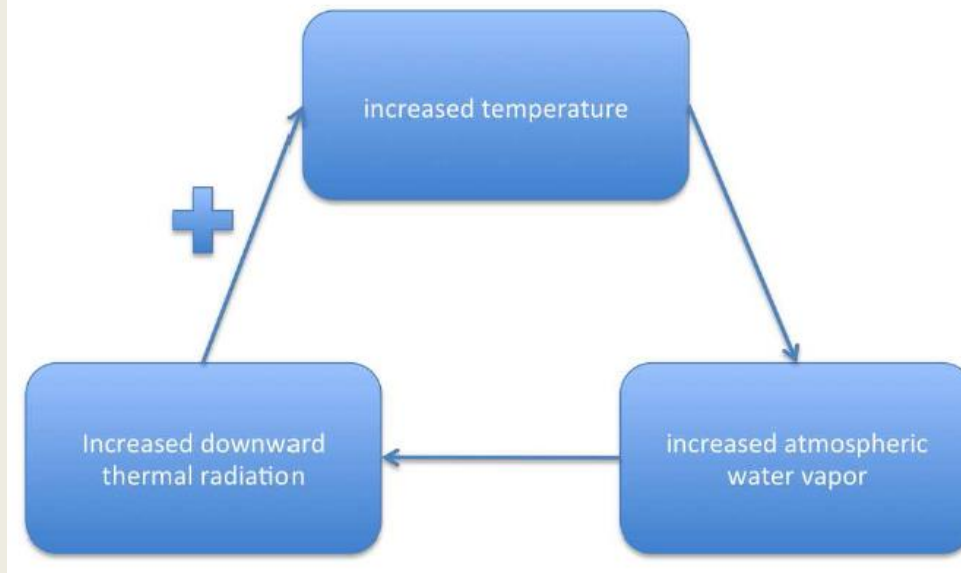
(Source: D. Dommenges)

Black body radiation (fast, strong, global)



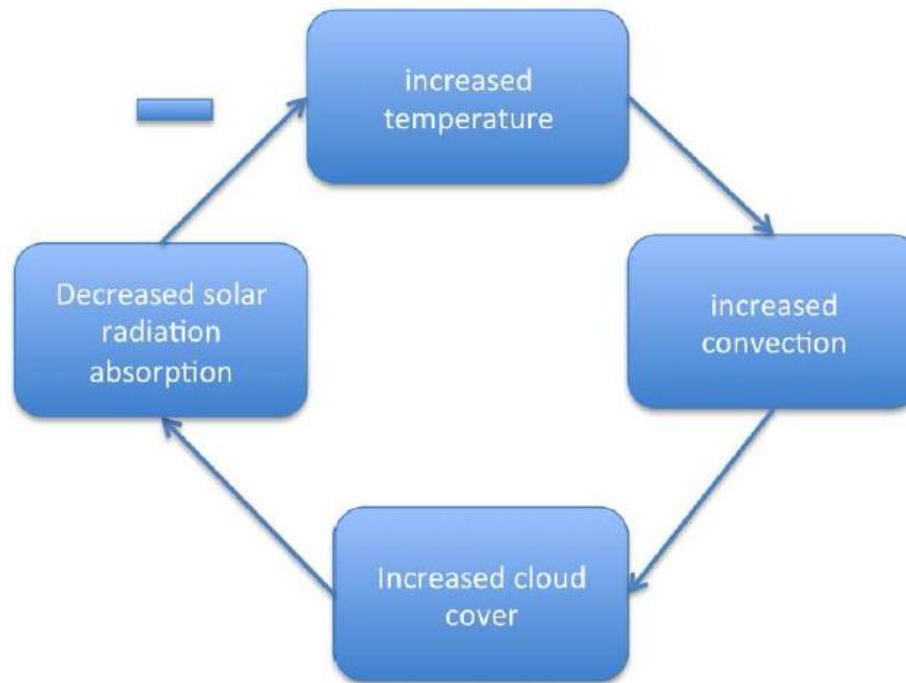
(Source: D. Dommenges)

Water vapor greenhouse (fast, strong, global)



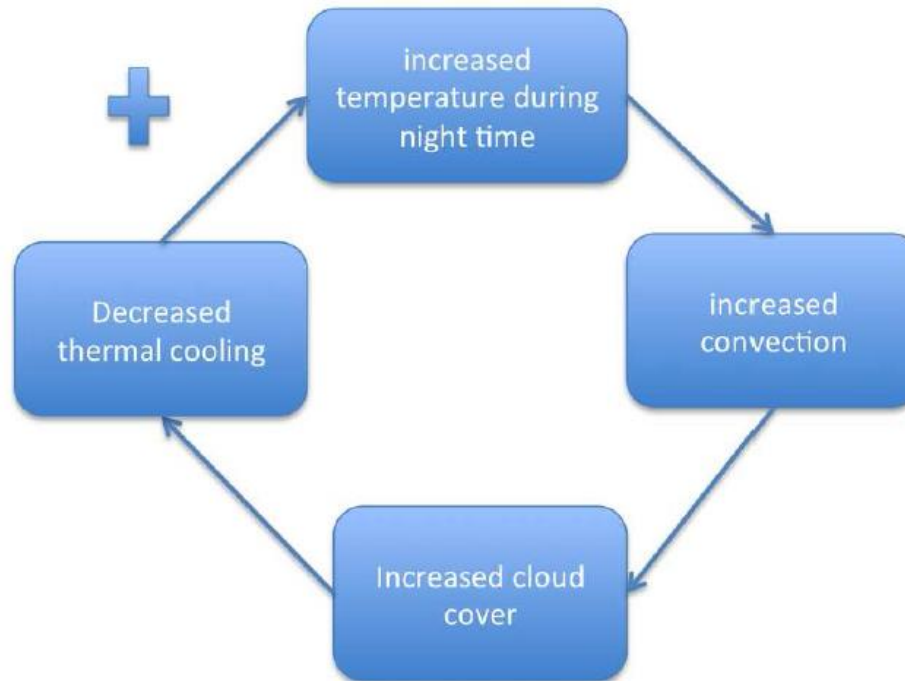
(Source: D. Dommenges)

Clouds solar (fast, potentially strong, global)



(Source: D. Dommenges)

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



(Source: D. Dommenges)

Thank you very much for your attention!

